50 Years

Geophysical Institute Karlsruhe

1964 to 2014

Expectations and Surprises

Contributions by

Thomas Bohlen, Klaus-Peter Bonjer, Thomas Forbriger, Karl Fuchs, Ellen Gottschämmer, Oliver Heidbach, Peter Hubral, Petra Knopf, Jürgen Mann, Birgit Müller, Claus Prodehl, Joachim Ritter, Friedemann Wenzel, Helmut Wilhelm, Walter Zürn

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1964 - 2014
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Preface

50 years ago the Geophysical Institute Karlsruhe (GPI) started with the conviction of Stefan Müller that geophysics represents a science with enough potential to merit the establishment of an own institute and a field with enough job opportunities for the students who graduate in geophysics in Karlsruhe. This expectation did materialize in the history of research and education of the past 50 years.

Naturally the research fields changed focus through time, although seismology in its many forms and on its many wavelengths always formed the focus. Reflection and refraction seismology to study the earth's crust and upper mantle has been later supplemented by broadband seismology and even very long-period studies using the facilities of the Black Forest Observatory. An important extension of the institute‘s portfolio was achieved in 1983 when the second chair – applied geophysics – became established and research and education in applied geophysics provided a sound basis for jobs in the hydrocarbon-related exploration industry. The successful introduction of bachelor and master courses with a strong physical flavour in 2008 made geophysics an even more attractive field for students.

There are several ingredients for the positive development of the past 50 years. Among them are certainly the dedication of people working and studying at GPI, the international flair that was created by research group leaders, the many international cooperations in numereous research projects funded by many agencies, institutions and companies. This book displays the essentials and details of the story. For us, geophysics never lost its excitement, as many questions await answers and many new opportunities – experimental, computational, theoretical – emerge. We are certain that this will last another 50 years.

Karlsruhe, 9 March 2014

Friedemann Wenzel and Thomas Bohlen
The directors of the Geophysical Institute

Welcome Address

Reflections on my Experience as an International Guest at the Geophysical Institute, Karlsruhe, Germany

Walter D. Mooney, USGS, Menlo Park, California USA

During the past fifty years, numerous guest researchers have spent time at the Geophysical Institute in Karlsruhe, Germany. The goal of these visits has been to benefit both the guests and staff of the Institute through an exchange of ideas. This essay briefly discusses my personal experience as a guest researcher in 1977. While each guest certainly has a unique experience during his or her visit, I hope that my recollections will to some extent reflect aspects of this experience that are common to all visitors. I also hope to provide a visitor's perspective on the factors that have encouraged the high level of scientific creativity, innovation and discovery at the Geophysical Institute.

I grew up just outside New York City, and I always hoped that someday I would have the opportunity to live in Europe for an extended period of time. That dream became a reality in 1977 when I arrived at the Geophysical Institute of Karlsruhe University for a visit of six months. At the time I was a 25-year-old graduate student studying seismology at the University of Wisconsin in Madison (USA). Robert (Bob) P. Meyer, seismologist and instrument designer, was my supervisor.

Prior to arriving in Karlsruhe, I spent five months collecting active-source seismic field data in the South American Andes of Peru and Colombia. The data collected in Peru were based on seismic shots fired in the Pacific Ocean and recorded on land by a large team of observers from the Instituto Geofisico del Peru, the Carnegie Institution of Washington, and the University of Wisconsin. The Colombian data were much more modest in scope and were collected by a field crew consisting of just two of us. My partner was Hans Jürgen Meyer, a native of Colombia who had studied geophysics with Prof. Rolf Meissner at the Christian-Albrechts University in Kiel. Our investigation in Colombia concerned the deep structure of the western Cordillera (Cordillera Occidental) of the northern Andes. We worked in the botanical splendor of the Cauca Valley (Valle del Cauca) that was visited by the great German naturalist Alexander von Humboldt in 1801, during his extensive exploration of South America and the Caribbean (1799-1804). My field area is vividly described by von Humboldt in his monumental work "Kosmos" (1845, 12 volumes).

The Western Cordillera in Colombia presents unusual geological features. It consists of an accreted block of ocean crust and has a huge Bouguer gravity anomaly that is due to the dense (2.9 g/cc) igneous oceanic rocks (diabase) that are exposed at the surface. A previous offshore/onshore seismic profile recorded in 1973 during Project Narino showed that the accreted crust was probably quite thick, more than 10-15 km. Project Narino was organized by Rolf Meissner (Kiel) and Robert P. Meyer (Wisconsin), two scientists with whom I maintained a life-long association. Ernst Flüh (Kiel) and I used the Project Narino data to calculate competing crustal models of the active margin of western Colombia. H-J Meyer and I undertook the task of acquiring two new seismic profiles in order to resolve the discrepancies in these crustal models for the western Cordillera.

Collecting active-source seismic refraction/wide-angle reflection data can be a great adventure, especially if the fieldwork takes you to an exotic location, such as western Colombia. This was my first opportunity to manage an independent field project. This was before the invention of GPS receivers, so station locations were determined using classical mapping techniques.

The author at age 25 with his field vehicle in coastal Peru, 1976, five months prior to his arrival at the Geophysical Institute. The casual pose seems overly confident, bordering on arrogant, for someone with so little field experience.

Once the field campaign was over, and the storytelling of all our adventures in the field had been shared with friends and colleagues, the hard work of processing and interpreting the seismic data started. I had no problem with the basic processing to create seismic record sections. The challenge was to interpret the data in terms of the deep crustal seismic velocity structure. How to explain the observed seismic traveltimes and particularly the seismic amplitudes? Facing this challenge is where the Geophysical Institute in Karlsruhe entered my life.

Karl Fuchs and Gerhard Müller of the Geophysical Institute had published their landmark paper on the reflectivity method in 1971 (K. Fuchs and G. Müller, Geophys. Journal, 1971), five years before I obtained my field data. This method offered the potential to model not only the traveltimes but also the amplitudes of all phases, particularly the wide-angle reflections that dominate the observed wavefield. Bob Meyer's research assistants, Joe Gettrust and James Luetgert, had succeeded in installing the reflectivity code on our Harris Corporation computer at the University of Wisconsin, but I lacked confidence in its application because the use of synthetic seismograms was quite new to geophysics.

I resolved to request a short-term visit to the Geophysical Institute in order to master the use of the reflectivity code from the originators themselves. I boldly wrote to Karl Fuchs in early 1976 and explained my ambition to come to his institute as a guest. I revised the letter to Prof. Fuchs endlessly. Although I was not able to read or write much in German at the time, I recall that I ended my letter by switching from English to German: "Ich verbleibe in der Hoffnung, daβ Sie meinen Wunsch erfüllen könnte." With his characteristic generosity and openness, Karl wrote back to say that the Geophysical Institute would welcome me as a visitor for six months. The stipend seemed to be very generous. I would receive 2,000 DM each month, a prince's ransom in my mind.

Claus Prodehl was my supervisor during my visit. He was efficient, well-organized, patient and supportive. Much to my surprise, I learned that Claus had spent three years at the US Geological Survey (USGS) in Menlo Park, California, so he had a good understanding of the practical challenges a visitor faces, such as housing, language, and getting settled in a new work environment. Seismologist Rainer Kind (later a professor at the GFZ-Potsdam) occupied the office next to Claus, and he was also a USGS alumnus. Many others in the Geophysical Institute had recent experience as international scholars. Indeed, the Institute seemed to be as much an international research center as it was a German institution. This atmosphere was enhanced by the continuous influx of guest speakers and visitors from around the world, as well as by the global travel and contacts maintained by Karl Fuchs, the institute director.

Claus immediately presented me with a clear goal for my visit: to carry out a reinterpretation of all available seismic refraction data from the western half of West Germany. This exercise was to be a prelude to the launching of a new active-source deep seismic profiling program known as the Rhenish Massif project. Prior to obtaining new research funds, it was necessary to squeeze the last scientific juice from the available seismic refraction data. This task was ideally suited to me since it would require Claus and me to model these data using the new reflectivity method.

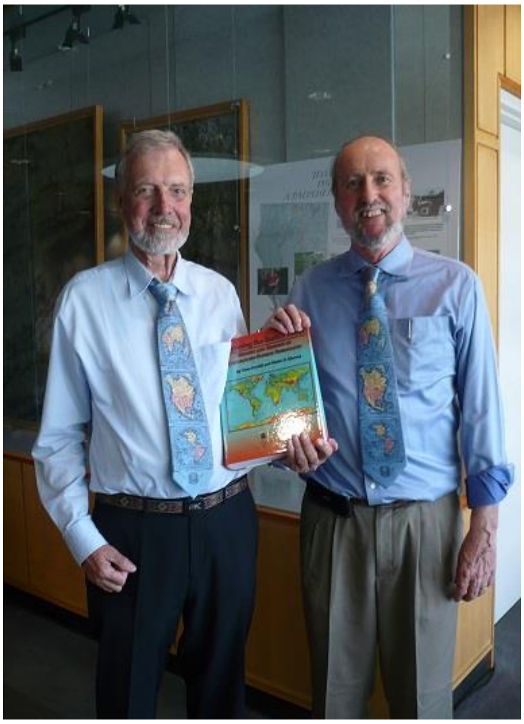
There were more than a dozen seismic refraction profiles to be interpreted. I began by using Gerhard Müller's seismic traveltime modeling program ("Laufzeit") that is based on a one-dimensional velocity-depth function as input. Such traveltime modeling of the data went quickly and was followed by creating a deck of IBM punch-cards for the overnight seismic reflectivity (synthetic seismogram) run. In 1977, the Institute's in-house computer was not capable of running the reflectivity code in a reasonable amount of time, so all runs were made on the big central computer located in the middle of the campus, some 3-4 km distant from the Institute. Fortunately, the computer center was en route to my room at the dormitory where I lived, the HaDiKo Wohngemeinschaft (Hans-Dickmann Kolleg), located in a forested area behind the Karlsruhe Schloss.

The social atmosphere at the Institute was lively, friendly and varied. A group would assemble at noon to travel to the Mensa (dinner hall). I would either ride my bike or hitch a ride in Rainer Kind's car. This was usually the only hot meal for the day; my evening meal consisted of hearty German bread, cheese and beer, and was eaten either at the Institute (at my work desk), or at the dormitory. I kept typical graduate student hours: working past midnight and sleeping until mid-morning.

The visit allowed me to achieve my goal of becoming proficient in the interpretation of seismic-refraction data and resulted in my first journal publication (W. D. Mooney and C. Prodehl, Journal of Geophysics, v. 44, 1978). Shortly thereafter, the Rhenish Massif project was launched, and it succeeded in providing very significant results concerning the structure of the crust and uppermost mantle. Beyond my more limited goal of learning how to interpret seismic refraction data using synthetic seismograms, I gained a much wider scientific and cultural world view, as well as friends with whom I have maintained close associations.

One major scientific byproduct of those early scientific relationships deserves special mention. This is the Kenya Rift International Seismic Project (KRISP), a long-term study that has provided detailed information regarding the deep structure of the Kenya rift. Karl Fuchs and Claus Prodehl invited my USGS colleagues and me to participate in the 1990 KRISP field study, and especially to assist with the loading and shooting of chemical explosions (both in lakes and boreholes) and to provide 200 digital seismographs. The project was a big success thanks to the organizational efforts of Claus Prodehl and Jim Mechie (Karlsruhe), Aftab Khan (University of Leicester, U.K.), G. Randy Keller (Univ. of Texas, El Paso, USA) and Brian Jacob (Dublin Institute for Advanced Studies, Ireland). My visit to the Geophysical Institute in 1977 laid the groundwork for this international scientific field project in 1990. The scientific results filled an entire issue of a journal (C. Prodehl, G.R. Keller and M.A. Khan, editors, Tectonophysics, v. 236, 1994, 483 pages).

My cooperation with people at the Geophysical Institute continued after the 1990 KRISP project, and included summer visits to the USGS in Menlo Park, California, by Karl Fuchs and Claus Prodehl. Indeed, some 35 years after first working with Claus Prodehl, he and I published a book in 2012 entitled “Exploring the Earth’s Crust: History and Results of Controlled-Source Seismology” (C. Prodehl and W.D. Mooney, Geological Society of America Memoir 208, 2012, 764 pages.) I would never have imagined that my 1977 visit to the Geophysical Institute would have such a profound influence on my scientific career.



The author at age 61 (right) with Claus Prodehl (left) in 2012 in Menlo Park, California, presenting their book entitled “Exploring the Earth’s Crust: History and Results of Controlled-Source Seismology” (C. Prodehl and W.D. Mooney, Geological Society of America Memoir 208, 2012, 764 pages).

What has made the Geophysical Institute in Karlsruhe special? Why have so many successful national and international geophysical projects been created and completed by the Institute? Why have so many prominent scientists passed through this Institute?

There are several answers to these questions. The first and perhaps most important reason for success of the Institute is the pace and level of scientific interactions. People involved in seismic field data acquisition work with numerical modelers. Geophysicists are encouraged to work with petrologists, for example, in the mineralogical interpretation of upper mantle composition based on seismic velocity models. Everyone is encouraged to attend weekly seminars, which are held in a moderate-sized lecture hall that encourages discussion and debate. Equally important, participation in large-scale projects has always been encouraged. The Rhenish Massif and KRISP projects are two prominent examples. Later, I was pleased to find that the U.S. Geological Survey (USGS), had a very similar working environment.

I found that there were advantages to the German style of scientific culture as well. In the 1970’s in the United States, much of the geophysical research was carried out within a

Department of Geology. In such cases, the geophysics faculty consisted of three or four professors, each with about three graduate students and perhaps a post-doc. Thus, there were about a dozen people doing geophysical research. Much larger research groups existed only at the USGS and the major institutes, such as Lamont-Doherty Geological Observatory, Scripps Oceanographic Institution, and Woods Hole Oceanographic Institution. In keeping with the German scientific culture, the Geophysical Institute in 1976 had some forty or fifty faculty, research staff and graduate students. This provides a much richer scientific experience. My experience in Karlsruhe heavily influenced my decision to accept a job offer (extended to me by David P. Hill) from a large scientific organization, the USGS, where I have worked ever since.

What were some of the other benefits of my visit to the Geophysical Institute in 1977? There were several. Working in a foreign country provides a cultural immersion that cannot be duplicated in any other way. The historical background of a country is best appreciated by living in the country and experiencing the culture first-hand. This begins with personal interactions, but also includes the architecture, art, music, and food. Even the weather and how holidays, such as Fasching, are celebrated, play a role. There is a unique approach to life. Karlsruhe, being located in the German State of Baden-Württemberg, benefits from the charms of southern Germany and the proximity with France.

Even simple everyday matters are different, beginning with a morning handshake when first meeting a colleague, and the decision of when to use the formal "Sie" versus the informal "Du". Personal connections seem to be more deeply rooted in Germany, and I experienced a strong intellectual component to conversations. Issues are examined with a broad perspective and careful thought. I can remember having discussions about the creation of the American National Parks system, the curiously weak American coffee, our lack of gun control, and the outlandish size of American cars during the 1970's.

I found that the American personality and national character (admittedly a variable and ill-defined quality) complements the German one. We Americans tend to be informal, optimistic, lovers of small jokes, and not overly concerned with established tradition. Rules and restrictions are something to overcome, rather than actual limits. Perhaps this rule-breaking, innovative character is best typified by someone like the late Steve Jobs (1955-2011) of Apple Computer. At the same time, this brash and at times naïve character can lead to certain miscalculations. I discovered that Americans can learn much from the German capacity for historical analysis and introspection, and that Germans can learn from American optimism and innovation.

My new German acquaintances, both at the Institute and at my dormitory, extended much warmth and friendship. I had so much to learn, so many things to experience. High points included train rides along the Rhine River viewing the ancient castles and Lorelei; visits to the Kölner Dom and the Madonna mentioned in the Schubert Lieder; Sunday walks in the forest followed by cake and coffee; Friday nights at the Karlsruhe Opera to hear Die Walküre; getting warm in a neighborhood Kneipe and enjoying "Schnitzel Züricher Art"; Fasching in Elsass and Rottweil in the Schwarzwald; an organ concert at the Aachen Cathedral where Charlemagne (Karl der Grosse), Emperor of the Holy Roman Empire, is buried.

The life of an experimental scientist is a journey with many stopping points; it is filled with travel to distant locations, meetings with remarkable people, and periods of private, intense analysis of hard-won scientific data. My visit to the Geophysical Institute during 1977 was an important stopping point for me and had an immense influence on my later professional career. My visit to Germany also greatly expanded my cultural interests and awareness. Alexander von Humboldt remarked on the importance of travel in Kosmos (1845): "Die gefährlichste Weltanschauung ist die Weltanschauung derer, die die Welt nie angeschaut haben." (The most dangerous worldview is the worldview of those who have not viewed the world.) My time spent at the Geophysical Institute in Karlsruhe and the people I have met there have profoundly shaped my worldview. I expect that during the next fifty years, numerous foreign visitors will also benefit from their interactions with the staff of the Geophysical Institute in Karlsruhe.

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Edited by Claus Prodehl

Karlsruhe Institute of Technology (former Universität Karlsruhe (TH))

Abstract

In 1964 the Geophysical Institute was established as an independent research facility within the Faculty of Physics of the University of Karlsruhe. In the same year the subject "Geophysics" was recognized as an independent subject of education where students could finish their studies with diploma (today bachelor and master) and Ph.D. degrees. The authors of the individual Chapters of this book are all long-term members who, on the occasion of the 50th birthday of the Geophysical Institute in 2014, have summarized its history over the past 50 years from their point of view. The emphasis of this book is on its people, scientists, students, and technical personnel who have contributed to the success of research of the Institute. Besides some generalizing overviews, the major part of this book is devoted to the history of the main subjects of research in the personal view of the responsible long-term scientists involved, such as Seismicity and Seismic Networks, Active Seismology, Passive Seismology, Stress and Stress Release in the Lithosphere, Geothermics, Applied Geophysics, Strong Earthquakes, and the Black Forest Observatory, accompanied by detailed bibliographies. The final Chapter describes the Institute of today: its present main research and teaching directions as well as its technical facilities.

1. Introduction and Acknowledgments

Claus Prodehl and the Authors' Team

Geophysical phenomena were noticed by mankind as early as humans learned to observe their environments. Detailed geophysical research, however, did not start before the 1800s when physicists and geologists started to study the Earth's magnetic field and possible causes for earthquakes. Only by 1900, Geophysics was established as a special field of science, after in 1898 Emil Wiechert had been appointed the first professor in geophysics worldwide and the first Chair for Geophysics had been installed at Goettingen in Germany. The development of mobile geophysical equipment, e.g. Wiechert's mobile seismograph and its application on the study of the uppermost sedimentary layers by Mintrop, led to applied geophysics and to its first commercial successes in the 1930s. The systematic investigation of the Earth's crust and upper mantle, however, effectively started only after the end of World War II. Around the world many new geophysical university institutes and state institutions were founded. Also in Germany, in the 1950s a number of universities added a separate geophysical institute, often combined with meteorology or as subunits to physics departments. In Karlsruhe, it was in 1964, that the state of Baden-Wuerttemberg created a Chair for Geophysics at the University of Karlsruhe.

Geophysics has never become a mass subject, and the number of geophysical institutions and the number of geophysically oriented scientists in each country has always remained a limited number, but since its first days Geophysics has been international where scientists know each other around the world. This reflects also on the personnel of the Geophysical Institute at Karlsruhe. Many of its scientists have performed part of their research in foreign countries, and vice versa many guest scientists from around the world have visited Karlsruhe for longer time periods. For this reason we have written this history of the Geophysical Institute in English, which serves as the universal international language and is the basics of international understanding.

During their service as head of the Institute, Stephan Mueller (1964-1971), Karl Fuchs (1971-1997), and Friedemann Wenzel (1997 to present) on the Chair of General Geophysics as well as Peter Hubral (1983-2007) and Thomas Bohlen (2009 to present) on the Chair of Applied Geophysics have become worldwide known by their scientific achievements and merits. At the same time they have left great scientific freedom to their co-workers at their research work. But they have taken care that in spite of the manifold interests and activities of the individual scientists the general research direction of the Institute has remained uniform. This is, e.g., clearly demonstrated by the early research on graben systems, by the participation in priority programs of the German Research Foundation, by the three Collaborative Research Centers CRC 77 (Rock Mechanics), CRC 108 (Stress and Stress Release in the Lithosphere) and CRC 461 (Strong Earthquakes – a Challenge for Geoscientists and Civil Engineering), by the joint operations around KTB (Kontinentale Tief-Bohrung = Continental Superdeep Drillhole), the European Geotraverse or the International Lithosphere Program, by the foundation of the university consortium WIT (Wave Inversion Technology), or the initiation of CEDIM (CEnter for DIsaster Management and risk reduction technology), and by many other national and international projects.

This memoir is hitherto the only documentation on the research history of the Geophysical Institute Karlsruhe since its foundation. However, the reader will not find any statistics. Rather, our description of the history concentrates on details and scientific results of a huge number of research projects performed within the past 50 years. The various chapters were written by individual staff members of the Geophysical Institute. Nearly half of the authors are retired, but the majority is still in active service at the Institute or elsewhere. We do not claim to be complete. Rather, the single chapters represent the personal view of the individual authors.

We have subdivided the history into introductory chapters followed by more detailed descriptions of the main subjects of research. In Chapters 2 and 3 we start with overviews presented by Karl Fuchs. Chapter 4 by Helmut Wilhelm deals with the prehistory and the early history of the Institute. Chapter 5 is a summary of activities and an overview of the many scientists including guest scientists and technical personnel who have contributed to the success of research of the Institute. The listing may not be complete and we apologize to those we have forgotten to mention. Chapter 6 describes the activities of the research direction Applied Geophysics.

The following chapters deal with individual research directions: detailed descriptions of Seismicity and Seismic Networks, Active Seismology, Passive Seismology, Stress and Stress Release in the Lithosphere, Geothermics, the Black Forest Observatory, and Strong Earthquakes. The overall emphasis of these presentations is on people and their engagement in theory, experiments, and interpretations, but only a rough overview on scientific results is given. For detailed descriptions of scientific results and their implications the reader is referred to the detailed bibliographies which accompany these Chapters. The final Chapter describes the Institute and its main research directions as well as teaching activities of today.

Numbers in square brackets at the end of a reference in various Chapters refer to the corresponding number in the publication listings of the Geophysical Institute, ordered by numbers: (1) Publications of the Geophysical Institute from 1966 to 1984 (nos. 1-300), (2) Publications of the Geophysical Institute from 1984 to January 2014 (nos. 301 – 1411). This collection of publications of the Institute is not contained in the printed version, but will be available, besides the pdf-file of this Volume, on the www-site of the Institute as separate pdf-file.

We are grateful to our numerous supporters who contributed to the general history of activities and personnel, in particular to Gaby Bartman, Claudia Payne, and Kerstin Dick with their particular 'insiders' knowledge. Of great value for the more recent history were Ines Veile's Newsletters for the Alumni and her personal input. The cover results from a combination of two cover designs which were independently created by Martin Pontius and Ursula Heidbach. The authors are grateful to both of them for their efforts. Special thanks are also due to Sieglinde Prodehl for help in eliminating printing errors.

2. Expectations, Surprises, Serendipity – Scientific Achievements of the Geophysical Institute after the first 25 years

Presidential address on behalf of the 25th anniversary on 10 September 1989

Karl Fuchs

Introduction

Foundation

The Geophysical Institute was established at the Technische Hochschule Karlsruhe (later renamed into University of Karlsruhe (TH)), when on 10 September 1964 Stephan Mueller received the founding document signed by the Minister for Cultural Affairs of the state of Baden Württemberg, Prof. Hahn.

The members of the new institute spent their first months in two rooms of building no 36 on the western campus, measuring about 35 m^2. There were 1-2 students, taken care of by 1 professor, 3 scientists (including myself) and 1 secretary.

The foundation of the Geophysical Institute happened under favourable stars. It was founded beyond any tradition at the beginning of one of the most severe changes of the world's view of geoscientists. The first publications establishing plate tectonics had just recently appeared. – Furthermore the Institute was lucky to grow up within the Faculty of Physics which treated their "exotic" Institutes - and this was always meant positively – always with special pride and care. – Finally we were lucky to be established within the Upper Rhinegraben with its particular flavour. Not only physically, but also the geoscientific environment at the University of Karlsruhe fitted. Several institutes dealing with geology, geodesy, mineralogy, geography, and rock mechanics saw a common interest in joint research, though belonging to three different faculties. It was in these years that the "spirit of Karlsruhe" was born which was cited many times in later years. Henning Illies (Geology) and Stephan Mueller (Geophysics) were its masters.

Development

German universities faced difficult times, when in 1970 a critical situation approached the Institute which was only six years old. Stephan Mueller accepted an offer by the ETH at Zürich and die Faculty of Physics had to make a difficult decision, if it really wanted that this young plant continued to grow. Evidently the "spirit of geoscience of Karlsruhe" mentioned above had meanwhile also fascinated the Faculty of Physics, when it decided to reoccupy the position of a Professor for Geophysics.

1979 Gerhard Müller accepted a professorship at University of Frankfurt, and Helmut Wilhelm succeeded him in 1980. In 1987 the Faculty of Physics created a new chair for Applied Geophysics, which is held by Peter Hubral until today (1989).

Throughout the 25 years a particular specialty of the Institute is its cooperation with foreign research institutions worldwide and the regular short- and long-term visits of foreign earth scientists. This has essentially contributed to the fact that from the very beginning a fresh, world-open spirit existed in the Institute guiding the research work of the individual scientists.

Highlights 1964-1989

The history of the Institute is best described by its scientific investigations. I will try to find a red line through the past 25 years. I cannot be complete though I will do my best to view the events as objectively as possible.

Deep Seismic Sounding

Seismic low-velocity channels in the crust

A major theme of the Institute since its foundation was the investigation of the Earth's crust, in particular the detection of zones of reduced velocity within the continental crystalline crust. In two fundamental publications in 1966, Stephan Mueller and Mark Landisman had argued that these zones of reduced velocity do not only exist within the Earth's mantle, but that they also are present in the Earth's crust. They proved that low velocity zones in the crust are not singular phenomena, but exist worldwide on continents. In a way, this zone became a trade mark of the Institute. It was a challenge to find it and to understand its physical and petrologic causes. The first student in geophysics, G. Wolber, examined, in his master's thesis, the zone of reduced velocity in the Oberpfalz, where its existence may be tested nowadays (1989) by the continental deep drill hole.

Structure, velocities and anisotropy in the Earth's upper mantle

At the beginning of the 1970s deep seismic sounding started to explore the Earth beneath the crust. In cooperation with Paris, Karlsruhe and Zürich a window into the upper Earth's mantle was opened by means of a long-range seismic-refraction profile extending from the Bretagne to the Mediterranean Sea. Similar projects followed later by long-range profiles through Britain, Scandinavia, Israel and Jordan.

The greatest surprise was the observation of unexpectedly high velocities within a suite of alternating layers of high and low velocities. – Another surprise was that the velocity in the uppermost mantle increased more strongly with depth than was to be expected due to the influence of increasing pressure and temperature as known from laboratory investigations.

At the same time, when analyzing Southern German seismic refraction data, Dave Bamford discovered that the P-wave velocity in the uppermost mantle of Southern Germany is dependent on the azimuth of propagation direction. Both observations indicate elastic anisotropy of the uppermost mantle which may be understood as prime orientation of olivine crystals, i.e. as flow remnants of continental drift. The flow direction is N20°E; it is one of the known tectonic directions in Western Europe, the Upper Rhinegraben follows this direction.

Integrated reflection- / refraction seismics

It was for the very first time worldwide that during the course of pre-investigations for the location of an anticipated superdeep drill hole in the Black Forest two major tools for investigating the Earth's crust were applied: for the first time the seismic-refraction as well as the seismic-reflection method were applied along the same profile. The Earth's crust appears in a different seismic light when one explores the steep-angle or the wide-angle distance range. Both methods effectively complement each other. For example, low-velocity zones can better be seen at oblique incidence, strong reflections from the lower crust are better recognized in the steep-angle incidence range.

S-waves – petrologic composition

Also for the first time, during the pre-investigations of the Black Forest location S-wave observations were jointly interpreted with the P-wave data. It was a great surprise that whenever in the P-wave data strong reverberations from the laminated lower crust (15-27 km depth) were observed, in the corresponding well recorded S-wave field such reverberations did not exist. From this discrepancy in the P- and S-wave field depicting the lower crust, important limitations were the consequence concerning the interpretation of the petrologic composition of the lower crust.

This new image of the lower crust was tested by another novel steep-angle seismic-reflection experiment which, by its surprising results, raised some doubts. At special observations of the S-waves lower-crust reverberations were detected in the steep-angle incidence range which had been excluded based on the earlier observations. A possible explanation may be a strong anisotropy of the lower crust.

The seismological Rhinegraben Network

The seismological surveillance of the Rhinegraben and the investigation of the seismicity of this continental rift system is one of the main research activities of the Institute. The seismological Rhinegraben Network is being operated together with the University of Strasbourg and the ETH-Zürich. Permanent seismic stations transfer their data by telemetry to Karlsruhe and Strasbourg. Furthermore, digital mobile seismic stations were added. At Karlsruhe the data are being processed on-line.

One of the essential results of the seismicity investigations in the area in and around the Rhinegraben is a clear asymmetry of earthquakes in number and depth. The Black Forest shows more frequent and also deeper located earthquakes than the Vosges. In the southern Black Forest these events reach as deep as the crust-mantle boundary. The increased precision in locating nowadays also permits better fault plain solutions. They more and more clearly demonstrate that surprisingly detachment events occur in a region where one would expect horizontal displacements.

International Rhinegraben Research Group

Already in the 1970s the area of the Rhinegraben was the aim for seismic-refraction experiments in an international cooperation. At that time it already became evident that the nature of the crust-mantle boundary beneath the graben proper differs from that under the graben shoulders and that the crust beneath France is thicker than under Southern Germany. In the past year a French-German reflection experiment investigated the Rhinegraben along two traverses, a cooperation of DEKORP and ECORS.

Geoscientific Joint Observatory (BFO)

The **Geoscientific Joint Observatory** in the Heubach valley near Schiltach in the Black Forest is jointly being managed by the Universities Karlsruhe and Stuttgart and interdisciplinary cooperation is simultaneously being exerted by geophysicists and geodesists. One of the key fields at Schiltach is the analysis of long period surface waves and free oscillations of the Earth. The long-term recording with gravimeters allows high-precision spectral analyses of free modes. The Macquarie earthquake on 23 May 1989, for example, was recorded at Schiltach for a duration of 128 hours. This enabled a separation of modes. Unexpectedly, besides the expected spheroidal modes also toroidal modes occurred, in spite of the fact that toroidal modes cannot be observed by a gravimeter. Consequently a coupling of modes must have happened which converted a toroidal into a vertical displacement. The earthquake of Mexico on 19 September 1985 had such a small noise level that the fundamental mode ${}_0S_2$ could still be analysed with its longest period.

A further investigation with data of Schiltach tried to solve the question, in which manner rays propagate in a laterally heterogeneous Earth as it is known nowadays by seismic tomography. Simple calculations fail which assume a spherically symmetric Earth. Wolfgang Friederich has developed a method to calculate ray paths for surface waves in a laterally heterogeneous Earth. It is interesting that theses rays deviate from the great circle and that they furthermore depend on the kind of mode. There appear focussing and defocussing of rays, which differ from mode to mode. Using this ray method, synthetic seismograms of surface waves can be calculated for a laterally heterogeneous Earth and can be compared with the observed seismograms.

Numerical modelling

Wave propagation in heterogeneous media

The first synthetic seismogram for horizontally layered media with optional depth distribution of elastic modules and density was calculated by Karlsruhe in 1968 at the German Computer Center at Darmstadt, applying the reflectivity method. It was exciting to watch, after hours of calculation, the appearance of the head wave which finally was followed by the Whispering-Gallery wave. – Today (1989), on the VP400 the reflectivity program calculates within minutes what then on the IBM 7094 took several hours. Additionally Karl-Josef Sandmeier has coupled the reflectivity method with a Finite Difference algorithm, which now enables to calculate the wave propagation in laterally heterogeneous media, too. – A further important development deals with the modelling of wave propagation in anisotropic media. Also here it was possible, thanks to the availability of vector computers, that synthetic seismograms for realistic media can be calculated within minutes.

Research work concerning the Earth’s core

S-wave velocity in the inner Earth’s core. - Gerhard Müller reached an essential progress in the calculation of synthetic seismograms, when he added the so-called Flat-Earth Approximation into the reflectivity method which originally had been developed for horizontally layered media. By a transformation of velocity and radius respectively depth he was able to produce an artificial velocity-depth distribution which caused the reflectivity method to act as a ray would propagate within the spherical Earth. This enabled also that the reflectivity method could be applied on the diffraction at the core-mantle boundary. Particularly important was subsequently how, by modelling the amplitudes of the PKIKP phases, he could define the S-wave velocity in the inner Earth’s core to be within 3 and 4 km/s.

SFB 108 Stress and stress release in the lithosphere

In the past nine years (1980-1989) the research work of the Geophysical Institute concentrated more or less completely on the Collaborative Research Center 108 “Stress and stress release in the lithosphere“, a contribution of the Federal Republic Germany to the International Lithosphere Program (ILP). Causes and consequences of tectonic stresses are the main goals. Here only a few important themes will be discussed which are of special importance for the Geophysical Institute.

World Stress Map / European Stress Map

The Geophysical Institute has significantly contributed to the construction of the World Stress Map, which is a project of the International Lithosphere Program (ILP) under the heading of Mary-Lou Zoback (U.S. Geological Survey). Of fascinating interest for us was the European part of the World Stress Map. Western Europe is characterized by a unique trend of compressional stress, which favours the direction NW-SE.

Important for the future research direction is a comparison of most recent results of the data analysis of 6 Satellite-Laser-Ranging stations for Western Europe. Here the direction of maximal contraction in Western Europe results in 10°-20°E. This observation is remarkable for two reasons: data collected within 1 - 2 years can now be analyzed, i.e. for this time we can expect to detect deformations in an area as large as Western Europe. This means detection of tectonic deformations in real time (Real Time Tectonics). – Naturally it is possible that there are errors involved, and the geodesists are the last who deny this. Nevertheless it is allowed to question why the direction of maximal contraction is not identical with the direction of maximal compressional stress, as should be the case for an isotropic, elastic medium but that a discrepancy of 60° between the main axes of the stress and the strain tensor exist. Also it is curious, that the maximal contraction falls into the special tectonic direction N20°E, into the direction of the Rhinegraben. If the observation is real, one can imagine that it may contain information on the bloc structure of the lithosphere.

Seismicity and Deformation in the area of the Upper Rhinegraben

In the southern Black Forest, in the region of the Dinkelberg, a remarkable connection exists between the depth of earthquakes and geodetically determined recent crustal movements. It seems strange that the crust of this region, in which earthquakes occur as deep as the crust-mantle boundary, appears brittle, while the essential deformation occurs by creeping. Further north in contrary, where manifold observations indicate a well-defined ductile lower crust, the geodetic analysis of recent crustal movements define relatively stable areas.

Continental Rifting

At present (1989) preparations are starting for the international seismic experiment KRISP (Kenya Rift Seismic Experiment), to be carried out in the largest continental rift on Earth, in Kenya, East Africa. Teleseismic and seismic-refraction observations shall allow a view into the mantle of an active continental graben. In a pre-experiment in 1985, along a cross-profile through the graben, the existence of partial melt in the uppermost mantle could be interpreted from a discrepancy of traveltime anomalies and gravity

KTB Continental Deep Drilling

Pre-investigations

From the very beginning the Geophysical Institute in Karlsruhe was involved on pre-investigations at all four proposed locations of a super-deep drill hole. These were locations in the Hohenzollerngraben, Black Forest, Aachen, and Oberpfalz. The Institute participated, however, most intensively on the formulation of two proposals:

Hohenzollerngraben

The aim of this drill hole was to interpret the nature of a low-velocity zone in the region of Urach which might possibly be responsible for a concentration of stress and consequently for the occurrence of large earthquakes The proposal to locate the super-deep drill hole into thís area finally failed first. Possibly the idea to drill into a seismogenic zone can be revived in the future. After the idea to reach a depth record by a super-deep hole has been cancelled, it might be a good idea to propose this drill hole with a depth range of 5 – 7 km as a German contribution to the international decade for decreasing natural catastrophes (IDNDR).

Black Forest

It was in particular the pre-investigation of the Black Forest location which led to an unforeseen cooperation of all groups in the Geophysical Institute with the other geoscientific Institutes of the University of Karlsruhe and neighbouring universities which had never been that intensive before. There was hardly anybody who would anticipate how essential the geothermal measurements should become.

KTB-Oberpfalz

Geothermal investigations: One of the biggest surprises of pre-drilling for the main drilling in the Oberpfalz was: Here, 300°C will most probably be reached in the same depth of 10 km as was predicted for the Black Forest. This surprise had curious consequences:

- The scientists dealing with geothermics had to be strongly forced to make a prediction.
- The aims for the Oberpfalz-drilling were reduced.

Strangely the detection of 300°C at 10 km depth in the Oberpfalz was handled as a catastrophe. But, in contrary, this was the first successful surprise. Scientists had learned that within the upper 500m an essential transport of energy happened by mass transport, and not only by conduction. The temperature gradient here is being reduced by deducting water to the side.

Presently (1989) it is assumed that in unweathered crystalline basement heat is being mainly transported by heat transfer. Are we approaching the next big surprise? We expect new knowledge on mass transport from a combined interpretation of relevant experiments: Temperature-relaxation experiments, acoustic televiewer measurements of the borehole wall to determine stress, seismic-reflection- and VSP data, Acoustic-Log, as well as downhole measurements.

3D-Seismics

We (in 1989) expect decisive new knowledge on the nature of crystalline reflectors from the 3D-reflection seismics around the KTB-drill hole in the Oberpfalz. Integrated seismics, a combination of all seismic methods, will survey the surroundings of the deep drill hole and will allow to extrapolate the information gained from the drill hole data.

Stress measurements

One of the main aims of the KTB drill hole is a better understanding how the stress field changes with depth. Important hypotheses on the brittle – ductile conduct can be tested for the first time.

EGT (European GeoTraverse) and priority program "Lower Crust"

The European GeoTraverse, a project of the European Science Foundation, which is headed by Stephan Mueller was supported from the very beginning by active participation of the Geophysical Institute in Karlsruhe. Already in its pre-stage, at the FENNOLORA-experiment in Scandinavia, Karlsruhe had a leading position.

Future challenges for the geosciences

Scientific dreams

Having described the short history and presence of the Institute, we may question (in 1989) where the journey will lead.

A good friend uses new friends to surprise and test with the question: "Which are your scientific dreams?" Dreams demonstrate how far we succeed to look beyond the fences of the daily happenings and look for the frontiers of our science or if we have installed ourselves in the garden of self-content provinciality. Naturally financial restrictions are our daily bread. However, it becomes dangerous when because of these limitations our dreams dry up, too.

Consequently, what are the perspectives for the geosciences of the solid Earth for the future? Where are the frontiers of our science today (1989)? Necessarily the following is personally influenced. But I will try to include the experiences of the Institute in the last years in my view of the future.

Scientific goals: Lithosphere

An important goal of geosciences also in the future will be a better understanding of the continental lithosphere in its widest sense. There are a number of reasons.

The lithosphere

- offers us living space in widest sense: ground, nourishment, raw material
- at the same time it threatens us by natural catastrophes
- is the space where we can view the history of our planet at its earliest beginnings.

The special significance of the lithosphere is also expressed by a series of international programmes, which have been named for the next decade:

- The International Lithosphere Program (ILP)
- The International Geosphere-Biosphere-Program (IGBP), also called Program of Global Changes
- The Decade to avoid natural catastrophes (IDNDR)

In this context it is important to realize that the Third-World Countries, due to their location and due to the strongly increasing population, are threatened most strongly by such natural catastrophic events. It is astonishing how the Federal Republic lags behind. In the framework of foreign aid, the Scandinavian countries such as Finland and Sweden supply East Africa with a network of seismic stations. Similar attempts are undertaken by Italy for the Mediterranean area. Where is the contribution of the Federal Republic?

Future problems. - The exploration of the lithosphere has substantially changed our view of the uppermost 150 km of the solid Earth. At seismic-tomographic investigations we are interested in:

- not only structure and the physical properties, but also the chemical composition and its origin
- Transport of masses and energy on various space- / time scales
- Deformation, kinematics and forces; tectonics in real time (Real Time Tectonics)

Experiments

The seismic tomography of the Earth's mantle and the reflection-seismic penetration of the lithosphere deep into the mantle to depths of 100 km has demonstrated what can be achieved when applying modern observation and inversion techniques. On the other hand it turned out that the Lithosphere –Asthenosphere boundary, which is important for processes in the lithosphere, is located exactly at that depth where both methods reach their limits both in depth penetration and in accuracy. In spite of the fact that the Lithosphere –Asthenosphere boundary has many definitions, it is a fact that in this depth range the lithospheric plates glide over the remnants of the mantle, that here an interchange of mantle and lithospheric material happens, that here the causes for the break up of continents in rifting processing are located.

Transport processes. – It can be anticipated that the investigations in the continental deep drill hole in conjunction with geophysical surface measurements will also contribute to solve questions to processes occurring during transport of mass and energy in the crystalline Earth's crust.

Dynamics of the lithosphere. – It is expected that the combined application of geodetic satellite methods and stress measurements will essentially contribute to the understanding of deformation and stress transformation in the planet Earth.

Theory

A few themes may be addressed here which may keep us busy in the future:

- Wave propagation in heterogeneous media
- Inversion of 3D-seismic reflection data in crystalline basement
- Wave propagation around a pre-stressed borehole
- Strain and stress models in a cracked block-structured lithosphere.
- Heat transport in the lithosphere.

Europe and the Geosciences

When viewing the future of the Institute, definitely Europe and the year 1992 are important to be mentioned.

Projects

One of Europe's strength in geophysics is definitely the integrated seismics. We should not miss to remain up-to-date.

Also by its super-deep drill holes Europe has set its trademark.

An important European undertaking will be project EUROPROBE, which is being planned as a geotraverse from the Atlantic Ocean to the Ural mountains which traverses two deep drill holes. Not only scientifically it will become an exciting project, but for the first time it will offer the chance to collaborate with our East European colleagues in the field and in the laboratory, as we are used in the west since many years.

Participation on regional and global seismic networks (also in Third-World countries), together with Sweden, Finland, Italy, France.

Europe 1992

This Institute will also enter a Europe 1992. We have to think about how our university degrees shall look like in comparison to neighbouring countries. We will have to think about the length of studying, about recognizing examinations and about the employment chances. Is there a danger that leading positions in Europe may be occupied by younger candidates of British and French Elite-universities? Where in Europe will research centers be installed? Where will we have geosciences?

Conclusions

Today (1989) the Geophysical Institute consists of two chairs with three professors, 28 scientists and 18 technicians (VT), facing 152 students and building space of 2500 m^2.

The Geophysical Institute of the University of Karlsruhe was founded at a time of unrest in geosciences. In the last 25 years it has contributed to this development in several areas. Condition is a well expressed team spirit in addition to the individual freedom needed. We are proud of it. We are grateful to the German Research Society and the Federal Ministry for Science and Technology as well as to the Ministry for Science and Arts of the state of Baden-Württemberg, which strongly support our research. Condition for the success is last not least an open Faculty of Physics, the union of geoscientific Institutes at the University of Karlsruhe and the University proper which has confirmed the particular position of geosciences in a report of the Commission 2000.

The future of the Geophysical Institute within the Federal Republic, in Europe and in the World will be assured when we are able to keep this spirit and the international openness.

10 September 1989

3. Corner Stones

Karl Fuchs

3-1. Reflections on Stephan Mueller's Talents

Address at the opening of the 1st Stephan Mueller Conference
(slightly modified from Fuchs, 2002)

I have been asked to contribute with some informal personal impressions from the early time in Stephan Mueller's scientific career at Karlsruhe and before to the opening of this 1st Stephan Mueller conference. These times between 1959 and 1972 are unforgettable because I met a colleague, an advisor and, last not least, a friend. What did we learn from Stephan almost 40 years ago? What should we keep in mind as we try to master the future of Earth Sciences in Europe?

Out of many advises Stephan had a simple rule which I want to share with you. It may surprise you, he himself followed it almost 100%, and he transmitted it to his students and colleagues at Karlsruhe in the early 1960s: A good presentation has always to start with a seismogram (**Fig. 1-1**).

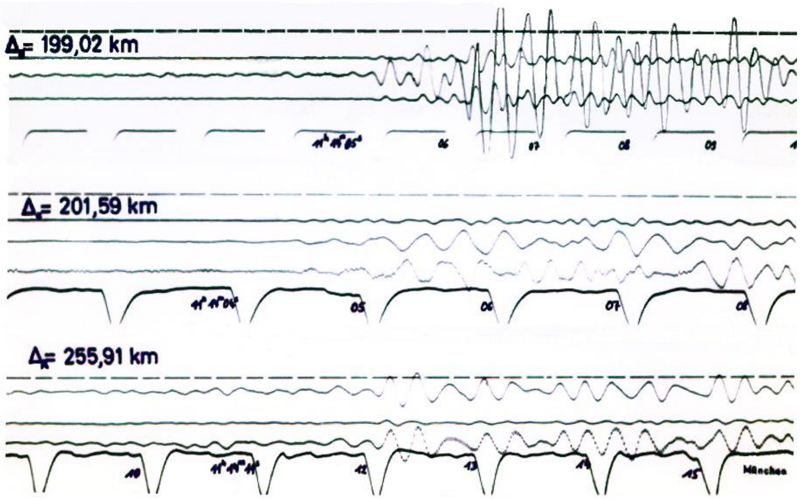

Fig. 1-1: Eschenlohe seismograms

Eschenlohe was the strongest shot point north of the Alps at that time (10-20 t instantaneous quarry blasts; unbelievable today). The recording instruments were still analogue and were a complete mixture of all possible types of instruments, as if out of the German Museum in Munich. Weak Pn forerunner and strong PmP supercritical reflection, at that time just barely recognized in its importance. A crew of two people was driving for 2–3 days to record a single seismogram.

Why do I follow Stephan's advice to start always with a seismogram? – Why am I telling this sentimental story about the Eschenlohe seismogram? It took me a while to understand the secret of the success of his recipe: A seismogram or seismogram section represents the complete data set, full of useful information, not just the picked arrival times and without the sophisticated bias of the interpreter expressed in the so called correlations. A model is always an abstraction from the observations and a poor, biased projection of the original data without its rich information content and - most important the surprises are in the data and not in the model.

We all know and appreciate Stephan's mastery in quantitative model building integrating various disciplines of seismology and geophysics; and yet, Stephan's research was data driven. What does this mean?

He was an arduous hunter of data (not just an archiver), because he was convinced that new ideas, surprises, the unexpected would only be encountered if we strive to conquer the unknown, the many terras incognitas.

Once at Karlsruhe I remarked to Stephan when he was heading for the next large field experiment that we should also take time for a more detailed analysis of the data which we had been compiling in the institute in a very short time. His answer: "Karl, when we are old we have all the time to analyse the data, now it is time to hunt for them!" New data were Stephan's life elixir! What happened to these new data?

There is a very important aspect of Stephan's scientific talents: he was not only a hunter, but also a master in storing data in his mind, searching for new connections and testing them, if necessary also by advanced quantitative modelling, but always with the powerful ability of the human mind for mental mapping through an enormous amount of data with incredible speed searching for connections in parallel in multidimensional phase diagrams in his mind.

On some occasions we could get a glimpse of what his mind was up to with the huge amount of fresh and "fossil" information (including that from literature!). At instances you could see him mental mapping, and to his friends he would allow a glimpse into his attempts to connect information, trying to enter even into the fourth dimension towards a picture of crustal evolution:

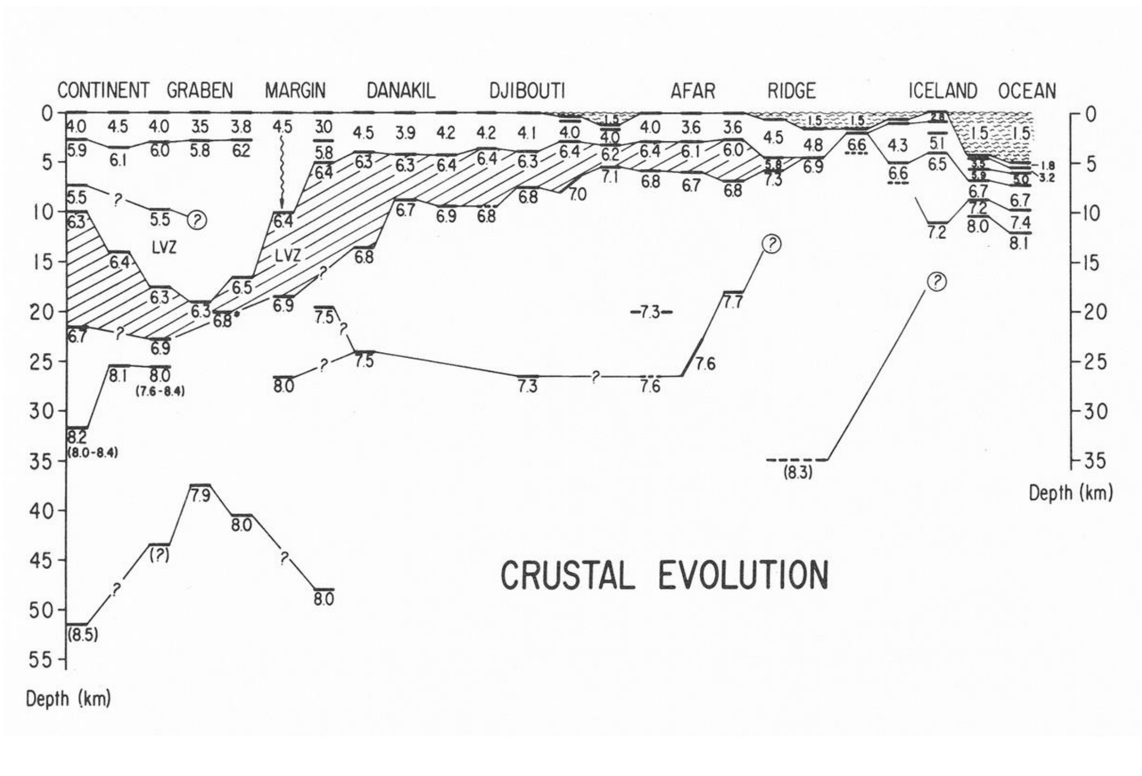

Fig. 1-2: Stephan Mueller's mental map of crustal evolution (from Mueller, 1978)

Stephan's mental map of Crustal Evolution (**Fig. 1-2**) first seen during the early 1970s, is highly relevant to this Conference. It also leads us to understand that Stephan was reaching from static models into the time domain. I know how much he was always eager to interact with the best of geologists like Henning Illies at Karlsruhe to widen static geophysical models as a Geophysicist into the fourth dimension of the Earth.

This is why Stephan was so intrigued and attracted by the new tools like GPS and the new mantle wide tomography. As in seismic exploration, observations are transformed into images of the Earth interior which allow direct access to the full range of information so directly as if you almost plan to drill into such a data set. This offers a new way to search for structure in data allowing mental connections to numerous Earth science data sets without loosing the freshness of the data.

There is another side to Stephan's talents. Three letters L V Z stand for low velocity zone; they signify the "sialic low velocity zone". Together with a typical velocity distribution both were very well known to Stephan's collaborators from Karlsruhe and Zurich and friends around the world.

The discovery of this low velocity zone in the mid 1960s is an excellent example of Stephan's ability to observe, to connect and to discover the unexpected. Two papers jointly published by Stephan Müller and Mark Landisman (Landisman and Mueller, 1966; Mueller and Landisman, 1966) demonstrate Stephan's mastery to connect widely separated data sets from all over continents as a basis for the test of the hypothesis of a continent-wide existence of a low velocity zone in the upper crust.

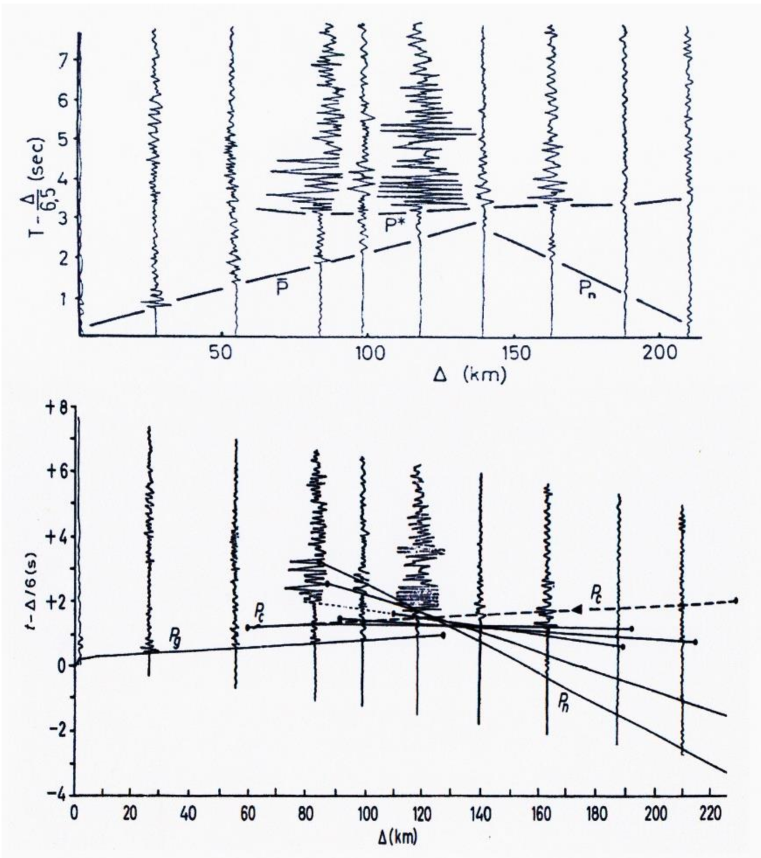

Fig. 1-3: Record section of the ESE profile of the blasts near Haslach in 1948
Top: Correlation of phases after Reich et al. (1948), **bottom:** Correlation by Landisman et al. (1966)

Please note: The reinterpretation by Stephan of the 1948 recorded profile Haslach published first by Reich et al. (**Fig. 1-3, top**), where he reinterprets phase P* of Reich et al. (1948) as Phase Pc (**Fig. 1-3, bottom**), results in a model with a low velocity zone beneath a high-velocity lid (Landisman and Mueller, 1966) the phase Pc being a strong reflection from the base of the LVZ (**Fig. 1-4**).

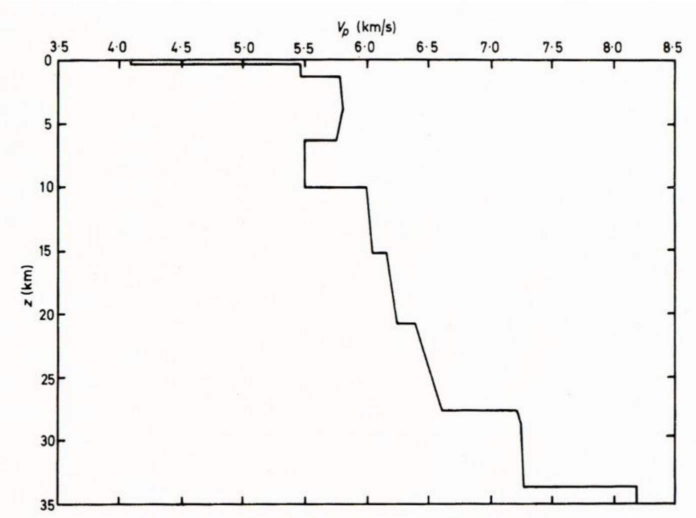

Fig. 1-4: Crust with low-velocity zone beneath a high-velocity lid (model of Landisman et al., 1966)

It was, however, NOT alone the reinterpretation of a single seismic profile, the famous 1948 Haslach explosion in S.-Germany, NOT a better error estimate, which would have convinced the seismic community: BUT it was the connection with two different seismic data sets: the newly recognised tool of vertical reflection information, and the world wide collection of Pc arrivals. In the same publication, Stephan presents a worldwide collection of seismograms showing evidence for the appearance of the phase Pc around the world (Mueller, 1978).

This still is and has always been a crucial problem, how to convince our fellow scientists, the scientific community of the data and of their connections which we have developed in our minds? There is no other way but to spell them out and to communicate them to the community.

Stephan and Mark had chosen a special way which was rather unusual in the seismic community at that time and even today. With our mathematical and physical education we tend to be easily satisfied by a robust model with drastically reduced rms errors obtained by fitting picked phases to calculated observations. But did we pick the right phases? Did we choose the right class of models?

Stephan let the readers share the relevant data set in his mind which convinced him of the existence of the Pc phase following the first arriving Pg, sometimes with quite strong amplitudes: from Heligoland explosion through Montana, Australia, Baltic Shield and other locations. - In a way, this is what is known as geological reasoning: “Look here and look there! How do you connect these observations? What is the connecting model?”

Two talents are very important in the exploration and understanding of this planet: first, new discoveries originate from the ability to recognize new patterns or surprizing structure in data and unexpected connections expressed as a testable hypothesis; and secondly, intuition and luck based on broad experience is the most important ingredient in the exploration of this world.

I do not want to become philosophical, Stephan was always very pragmatic. However, I have one concern: the growth of fast, powerful large memory computers provides us with enormous opportunities. We are fascinated by the huge and realistic amount of synthetic or calculated data of processes in complex 3D- and even 4D-models.

But, if we are not developing our ability to feed and store observed information into our minds and to operate on them, then we are endangering our ability to discover the unexpected. That could well mean that we are loosing track of the roots of our science, because, science is not living by dreams alone (our dreams reflect very much our present knowledge), but by the unexpected, by the surprise which we encounter in new observations and their connections.

This series of Stephan Mueller conferences is a very good chance that we continue in his spirit to master the future of Earth sciences in Europe. Stephan would say: let's do it!

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3-2. The reflectivity method – a success story

Presentation at Gerhard-Müller-Symposium in 2003 at Neustadt.
(slightly modified from Fuchs, 2004)

Opening

All who knew Gerhard would agree that he would not have liked this title! I am sure he even would not have liked the title of this symposium.

Nevertheless the academic marriage between two persons, each with its own abilities and its different characters and methods changed the world of DSS not only in the crust and lithosphere, even down to the inner core from the previous inversion of mainly travel times to that of the full wave field. It was very timely, spread like fire throughout the scientific community and therefore it was a success story! Gerhard, sorry to say so and you played a key role in this marriage! He would admit this!

Towards the Reflectivity Method

Two young scientists met during the 1960s, pursuing two different avenues to numerically synthesize wave propagation in realistic media. In the beginning they worked separately at different places. They had different and common forerunners and academic teachers (Table 1).

TABLE 1: FORERUNNERS

	Ray-Theoretical Method ***Gerhard Müller***	**Reflectivity Method** ***Karl Fuchs***	
Forerunners	Cagniard, 1932 Pekeris 1955, 1960 de Hoop, 1958 Cerveny, 1961 to 1966 and more Pekeris, Alterman, Abramovici, and Jarosch, 1965 Spencer, 1965 Bortfeld, 1964, 1967 Helmberger, 1968	Thompson, 1950 Haskell, 1953 Keilis-Borok, 1953 Brekhovskikh, 1960 Cerveny, 1961 Harkrider, 1964 Nuttli, 1964 Phinney, 1965 Cooley & Tukey, 1965: **FFT**	
Joint Forerunners (academic teachers)	Heinz Menzel & Otto Rosenbach, 1958: The influence of a layer complying with a linear velocity law on the shape of seismic pulses. Geoph. Prosp., 6: 408-432 *(both Mathematicians from Königsberg University, both formerly at PRAKLA;* *both at TU Clausthal (Bergakademie))*		

In 1969 they decided to join their efforts at the Geophysical Institute of Karlsruhe University. The time table (Table 2) of their cooperation shows how the fundaments were prepared separately and then within a very short time span the development of the reflectivity method was finalized. It became rapidly known throughout the Deep Seismic Sounding community and beyond.

TABLE 2: MERGING TWO DIFFERENT APPROACHES - TIME TABLE

	Ray-Theoretical Method **Gerhard Müller**	**Reflectivity Method** **Karl Fuchs**	
1963		Clausthal, PhD Thesis: Wave propagation in wedge-shaped media	1963
1964	Mainz, Diploma Thesis: Elastische **Kugelwellen und ihre Reflexion und Brechung an der ebenen Trennfläche zwischen zwei homogenen, isotropen Halbräumen**	St. Louis University**: P-waves transfer function for a system consisting of a point source in a layered medium**	1964
1965	Clausthal: Scientific Assistent	South West Center for Advanced Studies, Plano,Texas: **Plane wave reflectivity of layered medium**.	1965
1966	First personal contacts	**First personal contacts** at Geophysical Kolloquium Clausthal-Zellerfeld: KF: "Reflection seismic images of the earth crust and its boundaries"	**1966**
1967	"Theoretische Seismogramme für Punktquellen in geschichteten Medien" PhD Thesis, Clausthal		1967
1968	Theoretical Seismograms for some types of point-sources in layered media. Part I: Theory; Part II: Numerical Calculations. Z.Geophys. 34, 15 & 147.	1) Die Reflexion von Kugelwellen an inhomogenen Übergangszonen mit beliebiger Tiefenverteilung der elastischen Moduln und der Dichte. Habilitation Thesis, Karlsruhe, still with method of stationary phase. 2) Successful direct integration over angle of incidences Presentation at Symposium on Mathematical Geophysics, Tokyo/Kyoto: The Reflection of Spherical Waves from Transition Zones with Arbitrary Depth-dependent elastic Moduli and Density J. Physics Earth, 16, Special Issue, 1968	1968
1969	Clausthal, Gerhard moves to Karlsruhe	The method of stationary phase as a diagnostic aid in estimating the field pattern of body waves reflected from transition zones. Z. Geophys., 35, 431-435	1969
1969/ 1970	**Integration of** **layered overburden** **Influence of**	Ray theoretical part through on top of reflective zone, free surface	1969/ 1970
1970	Exact ray theory and its application to the reflection of elastic waves from vertically inhomogeneous media. Geophys. J.R.astr.Soc. 21, 261-	Visit to Ottawa/Mike Berry First application to Interpretation of system Grenville record sections with reflectivity method. ----------------------------- Program description and all commentaries translated from German into English.	1970
1971	**K. Fuchs** **Computation of Synthetic** **with the Reflectivity** **with Observations.**	**and G. Müller** **Seismograms** **Method and Comparison** **Geophys. J. R. astr. Soc. 23, 417-433**	**1971**
1971	IBM Watson Lab/ Lamont Doherty, Columbia University: Approximate treatment of elastic body waves in media with spherical symmetry. Geophys. J.R.astr.Soc. 23 . 435	The method of stationary phase applied to the reflection of spherical waves from transition zones with arbitrary depth-dependent elastic moduli and density. Z. Geophys. 37. 89-117	1971

1972	Development of **Flat Earth Approx**., Integration into Reflectivity Program Application to Inner Core Reflections		1972
1973	Amplitude studies of core phases. JGR, 78. 3469-3490		1973
1974	Karlsruhe, cumulative Habilitation Thesis: Flat Earth approximation and Inner Core Amplitudes		1974

What caused the success of the Reflectivity method?

OF COURSE, THE REFLECTIVITY METHOD WAS TIMELY IN THE SCIENTIFIC SCENERY!

But, lest we forget, let me take a few minutes to remind all of us about some historic background, which might otherwise become forgotten.

In Germany after World War II it was a coincidence of scientists with strategic thinking and willingness to cooperate, as well as the exciting development in the computer industry. All this generated a climate of research opportunities for the young generation. The leading generation of the post-war Geophysicists in Germany had a very clear primary focus: to generate a climate of cooperation between the many small Earth science institutes or departments in Germany and to return to international cooperation. They convinced the **Deutsche Forschungsgemeinschaft** (DFG) to install a series of large scale research programs in the Earth sciences: e.g. "Exploration of the Deep Structure of the Earth Crust in Central Europe" with a strong component of international cooperation.

In these early years the DFG (*Waldemar Heitz* and later *Franz Goerlich*) literally forced upon the Geophysical Institutes an institution which would today be called a Research Consortium (FKPE = Forschungskollegium Physik des Erdkörpers).

Heinz Menzel at Clausthal and *Otto Rosenbach* at Mainz belonged to the young driving forces in this cooperation of Earth Sciences including Geophysics institutions in Germany. They had both studied mathematics and physics at Königsberg University before and during the war. After the war they had begun their professional career with PRAKLA at Hannover in the exploration industry.

In seismology and DSS the other driving force were located in Stuttgart with *Wilhelm Hiller* and the even younger generation with international contacts to Lamont: *Hans Berckhemer* and *Stephan Müller*.

Gerhard Müller and Karl Fuchs profited directly from this stimulating spirit of national, international and interdisciplinary spirit prevailing throughout the western part of Germany.

The DSS-part of these programs generated the refraction/wide-angle reflection observations in high quality and growing and dense quantities. The young generation of scientists felt very soon, that the previous methods of interpretation, based primarily on travel times, were inadequate to the richness of information in the new data. This was the primary motivation for both Gerhard Müller and Karl Fuchs to start to develop methods to calculate synthetic seismograms.

The revolution in the computer industry was another timely incentive for both of us to achieve our ideas. In a very short time we went from machineries like ZUSE 23, IBM 1620 to IBM 7094, from punched tapes, punched cards to magnetic tapes, and in language from machine language, ALGOL to FORTRAN.

The coincidence of all these developments and circumstances were very fortunate. But all this is worthless if you do not meet the right persons to share your ideas and to work together.

The chemistry was alright (as one would say today). This was the basis for a very frank, sometimes controversial interaction.

Open unconditional international cooperation

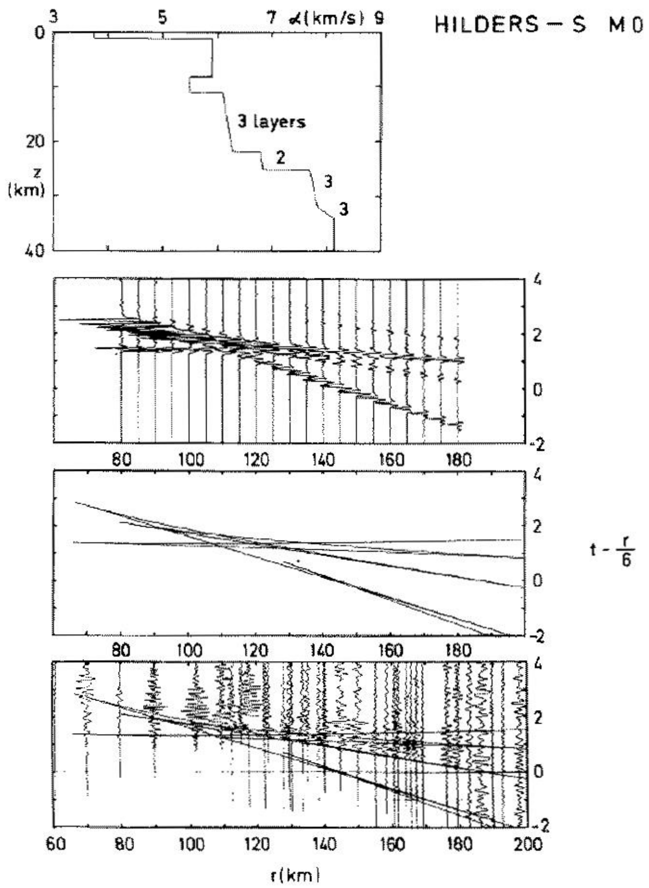

Fig. 2-1: Velocity-depth function, synthetic seismograms (vertical displacement), traveltime curves and traveltime curves overlain on the observed seismograms shown for the example of the profile from Hilders-S Only reflections from the bottom of the layers are included (from Müller and Fuchs, 1976, Fig. 3; see also Prodehl and Mooney, 2012, Fig. 6.2.5-04).

After our presentations on various conferences and workshops (Fuchs and Müller, 1971; Müller and Fuchs, 1976, **Fig. 2-1**) we received numerous requests for the FORTRAN code of our Reflectivity program. We both were determined from the beginning that we would share our program unconditionally with any reasonable request. This was not completely unselfish: we hoped and experienced that this free communication helped tremendously to detect hidden bugs, to improve the program and to develop new ideas.

Conclusions

This Academic Marriage had its up and downs. As in every marriage this happens and is the power of every successful marriage. The characters were clearly very different.

It was sheer luck for both of us to have met each other during this time. In spite of the difference in characters, the chemistry was alright and helped to overcome differences in opinion.

It was personally luck for Karl Fuchs, to have Gerhard Müller at Karlsruhe when he returned from Lamont. In his quiet, inconspicuous and yet ambitious manner he helped very much to keep Geophysics at Karlsruhe in the right balance between experiment and theory, between teaching and research.

When Gerhard went to start his new carrier on the Chair of "Mathematical Geophysics" at Frankfurt the marriage, after separation, converted into friendship between Karl and Gerhard, from SIE to DU. I still appreciate when Gerhard attended my 70 years symposium in April last year obviously with physical difficulties. He asked me on the stairs to go forward, he would follow. Now he went ahead!

Thanks Gerhard, for this fruitful Academic Marriage and Friendship!

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3-3. Geophysical Patterns - Traces of Deep Processes

Farewell Lecture, Faculty of Physics, Karlsruhe, 28. January 1998

It is in our nature, to see patterns, to identify regularities, to construct schemata in our minds.
There are many such empirical theories that connect together facts encountered in everyday life.
Murray Gell-Mann (1994)

Columbus Mistake:
He expected Indians and
missed the real discovery:
a new continent.

If you give up your DREAMS you will die!
(from: Flash Dance)

Science is not living by dreams, but by SURPRISE
V. Beloussov

To them who dare not do hope
the unexpected will never occur
Eva Heller

Abstract

Into the complex world of new scientific territory as in daily life we proceed by search for, recognizing and connecting of patterns even if we basically cannot explain them. Especially important are the unexpected surprising patters and their suspected connections. They allow us to make predictions whose eventual success give direction and motivation to explain the processes generating the patterns.

Introduction

If I look around here, I see essentially friendly faces.

To recognize a friendly face and to distinguish it from a hostile face is an exercise in pattern recognition. It belongs to our early childhood experiences and is vital to us. Such pattern recognition works without knowledge of laws and without scientific explanation.

For Murray Gell-Mann it is human nature to search for pattern in his complex environment and to connect them mutually by schemata.

The Earth is a complex system; its interior can be explored only indirectly from the Earth's surface. Even the deepest borehole is nothing but a tiny stitch. Processes within the Earth deform its surface in visible patters of continents and oceans, mountains and rifts. These processes are also perceptible in the patterns which are recognized by the Geophysicist in observations at the surface. These are anomalies of gravity and of the magnetic field, of heatflow and of propagation of seismic waves.

We learn from our tradition that scientific progress is only achieved if the generation of patterns and their connections receives a quantitative explanation. This, however, is only the ideal case.

In this lecture I would like to share with you an experience of a Geophysicist which fascinated me more and more from my time as a student to the present. Into the complex world of new scientific territory as in daily life we proceed by search for, recognizing and connecting of patterns even if we basically cannot explain them. Especially important are the unexpected surprising patters and their suspected connections. They allow us to make predictions whose eventual success give direction and motivation to explain the processes generating the patterns.

We fail to recognize the importance of pattern recognition, or even to conceal them bashfully. They have the flavour of the unscientific. Pattern recognition rarely, not to say never, finds its way into our text books. This situation I would like to explain by examples from the geosciences three scenarios:

A) Alfred Wegener's theory of continental drift: It is an example for a farsighted connection of patterns which was erroneously not accepted at his time because it was lacking a scientific explanation of the driving mechanism.

B) Exploration of the ocean floor: numerous connections, mutually confirming each other became accepted without a physical explanation of the driving mechanism of the oceanic and continental plates.

C) The structure of the lithosphere with the crust-mantle boundary as an example. A number of unexpected patterns, their connections, quantitative tests and open connections of patterns, i.e. connections in statu nascendi are the result from the last 25 years of research at the Geophysical Institute of Karlsruhe University.

A) Alfred Wegener's Continental Drift

Alfred Wegener was not the first to recognize the similarity of the coastlines of South America and Africa as a pattern and to propose a horizontal displacement of the two continents. His hypothesis first publicly reported in 1912 demonstrates Wegener's ability to recognize patterns beyond his own special discipline and to connect them: (1) the concept of isostasy or buoyancy of continental blocs together with (2) the distribution of topographic heights in a bipartite hypsometric curve demonstrated to him the basically different structure and composition of the oceanic and continental crust. Both observations were a stroke for the prevailing concepts for the generation of oceans. Oceans could not come about by the vertical collapse of continental crust. (3) Traces of ice ages in the Sahara and coal as tropical trace in Greenland were connected by Wegener as zones of paleo-climate on a past continent GONDWANALAND before its rupture and dispersion. He even could construct the position of the paleo equator of this continent. (4) Also the joint occurrence of certain kinds of fauna and flora in Africa, India and Antarctica did not require anymore the existence of collapsed land bridges between the continents.

With his theory of continental drift Wegener had not only to fight against the dominating fixistic geological models of his time allowing only vertical movements. He had also to defend his theory almost unanimously against the leading geophysicists. "Light-heartedly" he tried to give a physical explanation for the drift of the continents and also considered possible forces for the horizontal movements of the continents. He proposed qualitatively the "Polfluchtkraft" on a rotating Earth and the west drift due to the tidal friction of the moon. His strongest opponent became Sir Harold Jeffreys, one of the most recognized Geophysicists of his time. He became never tired to argue that the "Polfluchtkraft" was not sufficient to move the continents through the mantle of the Earth with its known viscosity.

Jeffreys committed a severe fallacy. From his correct refutation of the proposed physical explanation of the drift Jeffreys concluded erroneously on the inadmissibility of the connection "Continental Drift". As a consequence of Jeffrey's authority the discussion of continental drift among geophysicists was terminated for almost three decades.

B) Exploration of the Ocean Floor

The exploration of the ocean floor has been chosen as example for recognition and connection of numerous unexpected geophysical patterns. Only after two decades after the end of the Second World War the geosciences in almost all disciplines had been flooded by an unusual volume of observed data from the oceans, the terra incognita of that time.

Seafloor Spreading Hypothesis

From a number of weakly appearing patterns of observations the Harvard Geologist Harry Hess formulated in 1960 the hypothesis of the spreading by connecting such patterns from various disciplines of geosciences: (1) in the middle of the oceans the largest and unexpectedly high mountain chain of this planet was discovered by echo sounding during and immediately after the war. Its mean height above ocean floor is 4000 m. - (2) a continuous graben system was unexpectedly discovered on the ridge of the mountain chain, the ridge graben. - (3) Seismicity in the oceans is concentrated on this ridge graben. - (4) During deep seismic sounding surveys the oceanic crust was revealed as considerably thinner than the continental crust (10 km compared to 30-40 km). Wegener had already deduced this from the connection of the bimodal form of the hypsometric curve and the concept of isostasy; but now his pattern connection was verified by deep seismic sounding measurements. - (5) Rock specimens recovered from the ocean floor were never older than 200 Ma years. - (6) paleomagnetic measurements on magnetized rocks demonstrated that the location of the magnetic pole in the past was considerably different from its present position. This polar wandering occurred on different wander paths, e.g. in North America and in Europe.

Essentially these are the 6 observational patterns, which were connected by Hess to his seafloor spreading hypothesis. The main claims of his hypothesis are: (a) the ocean floor is much younger than the age of the continents, probably less than 200 Ma. - (b) The ocean floor is continuously produced by basaltic material that rises at the mid-ocean ridges. - (c) The ocean floor moves away from the ridges. - (d) At the deep sea grabens it returns into the Earth's mantle (marked by deep earthquakes). - (e) At the passive margins like in the Atlantic the growing ocean floor moves the continents.

From the connections of the six observed patterns a hypothesis resulted capable of predictions and which could be tested in many geoscience disciplines. It is remarkable that the polar wandering paths and therefore the relative horizontal motions of the continents were accepted without a quantitative explanation of the driving mechanism. In 1960 the Hess-hypothesis of seafloor spreading was not yet widely accepted. Further observational patterns were needed.

Patterns of geomagnetic measurements

One unexpected contribution from geomagnetics, the polar wandering, was mentioned already as pillar of the Hess-hypothesis. The surprises in this discipline of Geophysics were not yet at the end.

Geomagnetic time scale

During the derivation of the polar wandering in the middle of the 1950s scientists in geomagnetics observed to their surprise that half of their analyzed rock samples had an orientation reversed to the present orientation of the Earth's magnetic field. A debate arose about the origin of the reversed magnetizations. Did the polarity of the magnetic field of the Earth reverse at short time intervals or did the individual probes suffer a natural self reversal? American and Australian groups working on rock samples from different continents dated these samples with the K-Ar-method and noted that during certain time windows the probes on all continents had only one and in other intervals only the opposite polarization.

Since 1963 the pattern of a time scale of normal and reversed magnetizations started to crystallize out of the observational noise: the geomagnetic time scale for the last 4.5 million years of the Earth's history. The reversals of the Earth magnetic field were thus established. Even today we are far remote from a physical explanation of these reversals. This previously unknown pattern was discovered during magnetic measurements on continental rock samples. What is its relation to the exploration of the ocean floor?

Magnetic stripe patterns

Since 1957 the new proton resonance magnetometer allowed the fast and high resolution surveying of the Earth magnetic field from moving vessels in the oceans. Ron Mason, my Supervisor at Imperial College in London, returned from his research stays in the summers of California with whole tapestry of magnetic data. Ron belongs to that kind of scientists who gather by their curious persistence and fun in closing observational gaps with the most modern devices almost unintentionally an enormous volume of data in the shortest time. In the beginning Ron became unpopular with his "Water Bottle Magnetometer" dragged behind the stern of the ship because the measuring cable became frequently entangled in the ship's screw and since his measurement results at first sight appeared more boring than surprising. Then somebody had the idea to remove the well known long wavelength part of the Earth's magnetic field from the map, to obtain a view on the short wavelength signal. This is search for structure in data or pattern recognition (Bezdek, 1981). This filtered magnetic field appeared as a pronounced, never before observed pattern of stripes of positive and negative magnetic anomalies. The stripes had width of typically 20 to 100 km and continued over thousands of kilometers. Where they met tectonic fault zones the stripes were offset. At mid-ocean ridges they were parallel and symmetrical to the ridge axis.

Vine-Matthews Connection

Vine and Matthews at Cambridge/England succeeded in 1963 in a remarkable connection of these two newly discovered geophysical observational patterns: "Geomagnetic Time Scale" and "Magnetic Stripes" with the geological concept of seafloor spreading.

In the Hess-concept of seafloor spreading basalt rises at the mid-ocean ridges, cools and passes through the Curie temperature close to the ocean bottom. It then acquires a magnetisation with the orientation of the magnetic field prevailing at that time. Together with the ocean bottom blocks magnetized alternating in the rhythm of the geomagnetic time scale migrate away from the ridge, similar to a magnetized recording tape. Vine and Matthews (1963) could measure the velocity of the ocean floor by matching the observed anomalies to the geomagnetic time scale, at least for its duration of 4.5 million years. For the northern Atlantic they obtained a velocity of 1 cm/year or 10 km in 1 million years.

This is one of the most astounding examples of a multiple connection with mutual confirmation without a physical explanation of the two underlying processes: cause for the reversal of the Earth’s magnetic field and the driving mechanism for the motion of the ocean floor.

The connection could also be used for prediction. The observed pattern of magnetic stripes covered practically the whole ocean floor and not only the 50-100 km narrow zone around the crest of the ridges. This implied that the process of the magnetic field reversals is older than 4.5 million years and that the geomagnetic time scale had to be extrapolated. This extrapolation held until 180 Ma under the assumption of constant spreading velocity. The ocean floor could be mapped according to its age of generation at the mid-ocean ridges.

The age of the ocean floor could be determined from the sea surface without any kind of measurement at the seafloor. This enormous extrapolation over 180 Ma and across several thousands of kilometers surmounted by test of deep sea drilling, when the predicted age was confirmed from the drilled core of rock.

I want to discontinue the further avenue which led ultimately to the formulation of plate tectonics, thrilling as it is. There is no time today.

Retrospective

In the connections from Wegener through Hess and Vine & Matthews we have learned the following:

- The process of the spreading of the ocean floor could be measured quantitatively, although neither the cause for the driving mechanism nor for the reversals of the geomagnetic time scales were known;
- The connections of new pattern with other patterns to a net create predictions which can be tested;
- Patterns and their connections stabilize each other by successful prediction, even if the explanations of fundamental relationships are still missing;
- Important: a justified refutation of an attempted explanation, e.g. Wegener’s force model, does not refute the justification of a connection.

C) The Continental Crust-Mantle Boundary

I would like to introduce you now to recognition of patterns or their connections which have been applied by the Geophysical Institute at Karlsruhe during the past 25 years most intensively during the exploration of the continental Earth crust and its upper mantle. Deep seismic sounding and stress field determinations have been used. We will pursue this as we follow the development of our knowledge of the crust-mantle boundary.

During the past 20 years research in the Earth sciences has begun to focus on the continents. Here is the key to the early 90% of our planets history, - here is the coupling of the processes deep in the mantle to the tectonics in the crust near the Earth surface unexplained, - here are the essential resources on which our civilization is based and – here we suffer increasingly from natural catastrophes, e.g. from earthquakes and volcanic eruptions.

The Crust: Refraction Seismic Moho

The crust-mantle boundary is named after its discoverer, the Croatian geophysicist Andrei Mohorovičić. The name of this boundary is abbreviated as Moho. In 1909 Mohorovičić (1910) discovered during the investigation of the Agram earthquake weak early arrivals from the upper mantle. This pattern he recognized throughout Europe. This observation led him to deduce a sudden increase of the velocity of seismic waves at the transition from crust to mantle. The pattern of slow and fast arrivals, first seen during the Agram earthquake, stabilized because it was recognized shortly afterwards by other authors during other earthquakes. In fact it was soon recognized as a global pattern. The new definition of the crust-mantle boundary as a sudden increase of the velocity of seismic waves was also accepted by all other geoscience disciplines.

The connection of the individual seismograms happened in this early time of seismology by storing many hundreds of seismograms in the mental memory of the interpreter. This required long experience in handling seismograms. Today we are amazed by the courage of the early seismologists to recognize a jump of the velocities in their observational material

Today we are used to connect the individual seismograms in so-called record sections. Here the various phases can be followed with improved certainty and also more objectively. By this connection of seismograms we are able to recognize new patterns of seismic arrivals which could never have been revealed by the individual seismograms.

The Crust: Reflection Seismic Moho

At the end of the 1920s the new method of reflection seismic profiling at near vertical angle of incidence outstripped the classical method of refraction seismic during prospecting of sedimentary basins for oil deposits. Without this reflection seismic method we all would not drive a car. However, with all the success of this method, experts agreed until the late 1950s and further that it would not be applicable to the exploration of the crystalline part of the crust because of the expected negligible impedance contrasts or reflectivity.

In 1951 Junger from USA discovered during a routine reflection seismic survey by chance or accidentally intense patterns of seismic signals with travel times which he attributed to the reflection from the Moho. However, the new area of crustal investigations initiated by this discovery had to wait for almost 20 years. Leading seismologists from North America rejected the connection of the observed pattern with the crust-mantle boundary. Instead they tried to explain the signal as side-reflections from the topography. Here we observe again the conservative defense “because what ought not to be could not be”. This period of doubt was not terminated by new knowledge on the reflective properties of crystalline rocks but rather by the obstinacy of a data gatherer from the oil industry in Germany, Gerhard Dohr. He could reject with authority the alleged connection with side-reflections by new patterns in comprehensive observations. He asked seismic exploration teams under his responsibility to run their seismic paper recordings occasionally to the time of possible reflections from the Moho. The pattern in the resulting history frequency diagrams was surprising again: there were not only reflections from Moho but also at times of intracrustal discontinuities (Dohr, 1957, 1959).

It was the success of this tenacious pattern collection that motivated in the end Jack Oliver to start the COCORP (Consortium for Continental Reflection Profiling) project in the USA at the beginning of the 1970s (Oliver, 1986). The first continuously observed reflection sections from the crystalline crust revealed a previously not recognized, therefore surprising pattern of a transparent upper crust on top of a strongly reflective lower crust. The Moho was seen and defined as the lower border of the reflective lower crust, i.e. as the end of the reflective heterogeneities. The Earth’s mantle did practically not show any reflections below Moho.

Coincidence of Reflection and Refraction Moho

Both the seismic reflection and refraction method of deep seismic sounding were applied along the same profile during the pre-site survey for a possible location of a deep drill hole of the KTB project in the Black Forest in Germany. In **Figure 3-1** (upper part) the refraction depth model is displayed with the crust-mantle boundary (velocity jump 6.8/8.2 km/s). This boundary has been transferred into the reflection section (lower part of Figure 1).

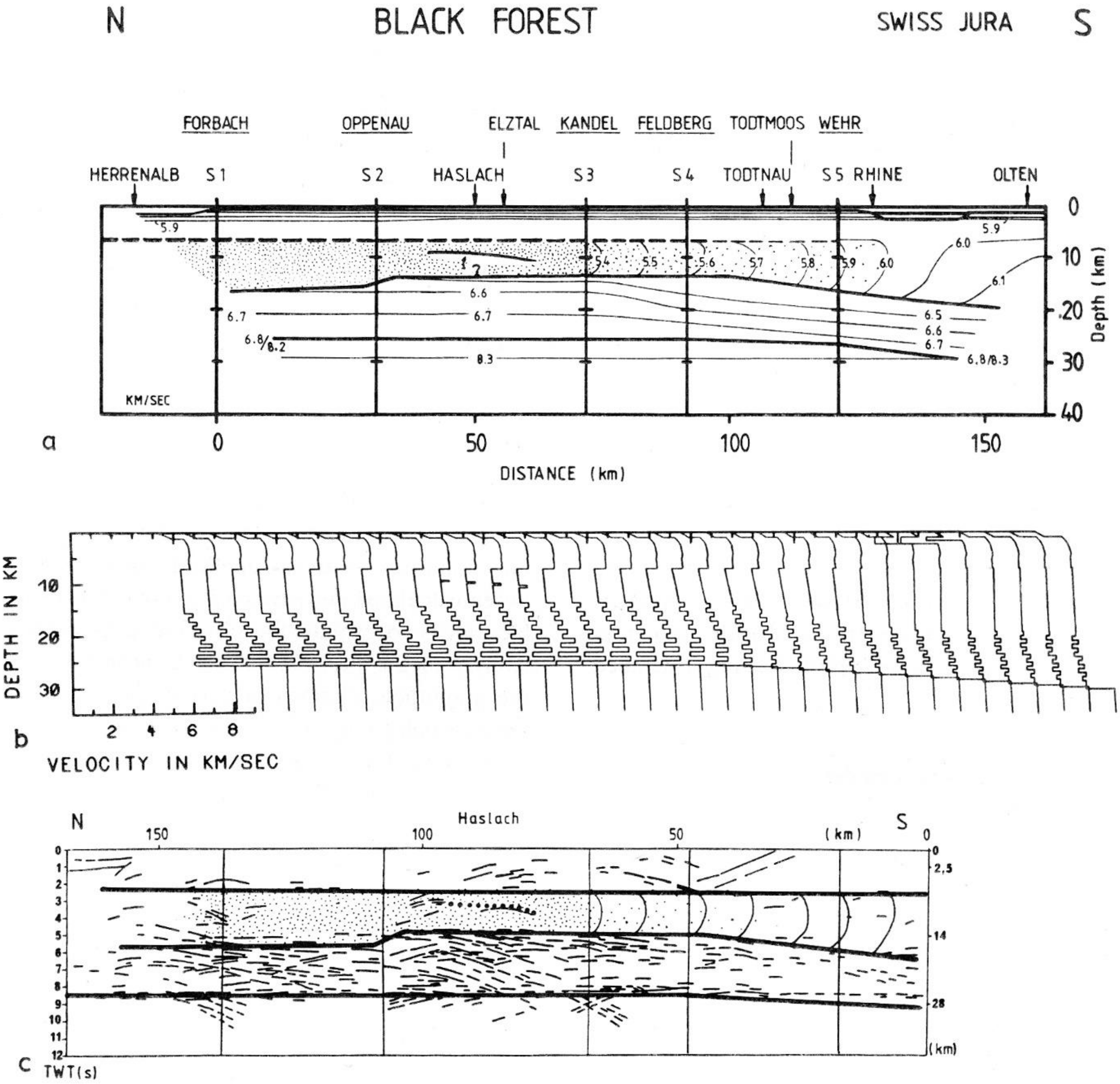

Fig. 3-1: Crustal model of the Black Forest (from Gajewski and Prodehl, 1987, Fig. 8; see also Prodehl and Mooney, 2012, Fig. 8.3.3-03). (a) Model with lines of equal velocity, derived from seismic-refraction data. (b) Velocity-depth sections along line S, derived from seismic-refraction data. (c) Line drawing of the seismic-reflection section along the Black Forest (simplified after Lueschen et al., 1987). Two-way travel times as calculated from model (a) are plotted as thick lines in (c).

It is the time section of the near-vertical reflection profile. The coincidence of the refraction M with the end of the reflections from the lower crust is obvious. It is also clear that there are no reflections from the mantle below Moho. Not only at this place in the Black Forest, but wherever both methods have been applied together along the same line, the coincidence of both Mohos became evident. For many years this coincidence of both depth-values for the Moho was considered as a mutual and satisfying confirmation of two independent sounding methods. The satisfaction was probably the reason why the obvious question did not arise, why the end of the lower crustal heterogeneities should coincide with the depth of the sudden velocity increase of the refraction-Moho. We are here confronted with an interesting phenomenon. The coincidence of the patterns, especially if expected, squelches the openness for surprises.

The disappearance of the near-vertical reflections below Moho was easily explained: the upper mantle is considered homogeneous and without structure, or this zone possesses strong inelastic damping of the seismic frequencies around 10 Hz. Both possibilities, although simple, turned out to be wrong. We all know the egg of Columbus as expression of a goal oriented surprising determination to solve a problem. Less known is that the goal oriented Columbus committed a remarkable, frequently duplicated and easily forgotten mistake, for short Columbus' mistake: "He found Indians, because he expected India, and therefore he missed the discovery of a new continent!"

At Karlsruhe we learnt during the past three years that the deep seismic sounding experts from all over the globe committed likewise Columbus' mistake at the Moho. We found only what we expected: the coincidence of the Moho depth as determined by two different methods. At the same time we missed the real discovery: a new property of the Moho - the change in structural scale. We became aware of the Columbus mistake by a newly observed pattern. At this time we succeeded to obtain from Moscow digitized versions of the seismic record sections observed from Peaceful Nuclear Explosions (PNE) in the former USSR during 1970-1990. With regard to the power of its explosions and therefore its depth penetration into the Earth's mantle these recordings are unique and surely not repeatable. They are seismic x-rays of the planet's interior to a depth of 800 km.

During his PhD thesis at Karlsruhe University Trond Ryberg (1993) of GFZ Potsdam discovered in these record sections from Russia quite unexpectedly a high-frequency scattering phase with 5-10 Hz dominant frequency. The phase propagated through the Earth mantle to distances of 3000 km. The high-frequency filtering was searching for structure in data or pattern recognition. This high-frequency pattern was found on all other PNE profiles. This scattering phase was attributed to a waveguide beneath Moho with schlieren-like fluctuations of the seismic wave velocities.

Change of the Structural Scale at Moho

This meant a collapse of the previous notions of the reflective properties of the upper mantle. In near-vertical incidence the upper mantle is transparent starting at Moho. At oblique, critical angle of incidence the same material transports the same frequencies like a light beam over thousands of kilometers. The Karlsruhe group (Enderle, 1998; Enderle et al., 1997) is about to find the way into these new patterns of fine structure. In his PhD thesis Enderle (1998) shows various examples of synthetic seismograms which belong to the structural model presented in the same figures below. In the far distance the high frequency scattering phase can be recognized. In contrast at small distances the reflections from the lower crust terminate at the M-discontinuity and the transparency of the schlieren-like structured upper mantle is obvious. From the numerical experiments carried out by Marc Tittgemeyer we are convinced, that there is a sudden change of the structural scale at the Moho (Tittgemeyer et al., 1996, Tittgemeyer, 1999; Fuchs et al., 2002). Since that time the Karlsruhe group is eager to hunt for new pattern in the upper mantle and their connections with other properties (**Fig. 3-2**).

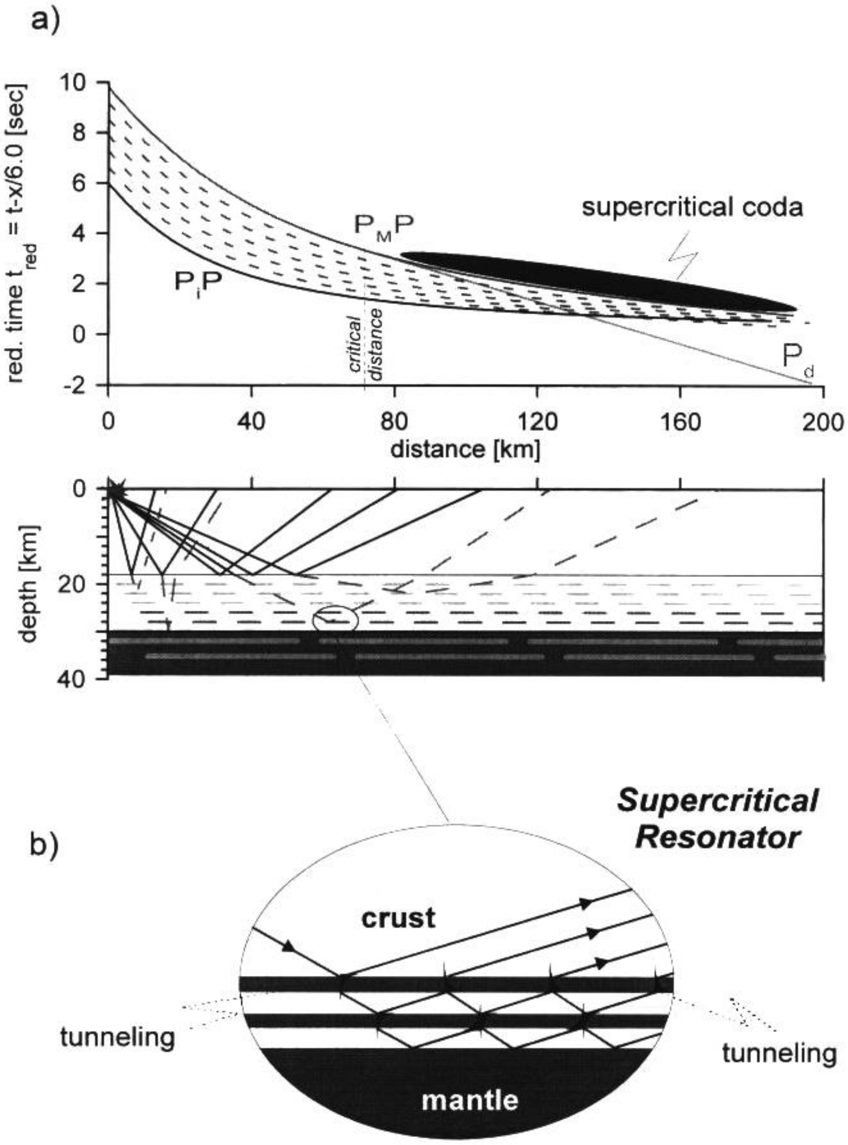

Fig. 3-2: Scattering of energy between PiP and PMP phases, caused by internal structure of the lower crust from 18-30 km model-depth, is followed by supercritical reverberations following PMP (supercritical coda), caused by internal structure of the topmost mantle below 30 km model-depth, which has a different scale of structural dimensions (from Enderle et al., 1997, Fig. 4a; see also Prodehl and Mooney, 2012, Fig. 9.2.2-12).

Worldwide P_n Mapping by Molnar and Oliver

Already in 1969 Molnar and Oliver derived a world map of a similar high-frequency phase from the observations at single stations. They realized that the phase propagates across continents and oceans. Its propagation is only interrupted at active plate-boundaries. Is it possible to obtain a denser sampling of this pattern with modern broadband stations? Then the waveguide found in Russia would be a world-wide phenomenon and also the change of scale at Moho.

Anisotropy of the Uppermost Mantle in Southern Germany

The dense network of seismic refraction profiles in southern Germany allowed for new pattern recognition from the numerous seismogram sections. A visitor from England, Dave Bamford, derived the azimuth dependence of seismic velocities and therefore the anisotropy of the upper mantle in southern Germany (Bamford, 1973). This anisotropy is achieved by a preferred orientation of the mineral olivine during mass transport in the upper mantle which must have reached close to Moho. From the seismic data the orientation of the olivine crystals and therefore the shear-direction of the viscous mantle flow could be estimated as N20°-30°E.

New questions arise:

- Is this mass flow, today or in the past of the Earth's history responsible for the formation of the schlieren in the waveguide of the upper mantle?

- How is this mass flow in the Earth's mantle coupled to the crust of the Earth? Numerical modelling by Veronika Wehrle (1998) has shown that the decoupling of crust and mantle produces a band of maximal deformation with a width of 3-4 km, directly above Moho.

Is this decoupling process the cause for the change in structural scale at Moho?

Reflection Pattern in the Rhinegraben and Decoupling of Crust and Mantle

In the southern Black Forest a strong band of reflections was found near the Moho during detailed reflection experiments (Lueschen et al., 1987). This could be the image of the mentioned decoupling process. But such patterns and their relation to the crust-mantle decoupling can only stabilize if they are observed elsewhere in similar geological situation.

World Map of Tectonic Stresses

How is the direction of mass flow connected to the direction of plate motion and how is it related to the direction of tectonic stress?

The World Stress Map of tectonic stresses, at which Birgit Müller (1993; Müller et al., 1993, 1997) worked already during the International Lithosphere Program, is now at the Heidelberg Academy of Science. This map shows that the direction of maximal horizontal stress in Western Europe points into the direction of plate motion. In Western Europe the resulting direction of maximal shear stress in the crustal stress field coincides with a certainty of 10° with the direction of mass flow in the upper mantle as deduced from the anisotropy analysis.

Are we allowed to connect these two patterns, direction of stress and of anisotropy? A similar density of anisotropy and stress data like in southern Germany is lacking in other parts of the world. Such a connection in status nascendi has to wait for further observations on other continents, also for geodetic deformation measurements.

P_mP World Map

We must proceed in the future to the next step of pattern connection from single seismogram sections to world maps. Such world maps would allow comparing patterns in seismogram sections more objectively than in the mental memory of interpreters. Uwe Enderle and Alex Goertz have started a digital world map in the internet of crustal refraction seismogram sections with clearly dominating P_mP reflections from the Moho.

Outlook

I have travelled with you almost through a century of pattern recognition in the geosciences. Into the complex world of new territory of science as in daily life we are groping our way by searching for, recognizing and connecting of patterns, even if we cannot explain them fundamentally. Very important are the unexpected patterns and their suspected connections. They permit predictions. Their ultimate success become signposts and challenge to the researchers to explain the processes which generate the pattern.

I hope that I succeeded to explain to you the role of pattern recognition and connection as traces of processes in the Earth's mantle: the motion of the ocean floor and the decoupling process of mantle flow at the Moho. Apart from a solid foundation in physics the ability and a readiness is required to gain knowledge beyond its own field of specialization. This allows recognizing patterns and the significance of their connection (following Wegener).

Of course, ultimately geophysics wants to arrive at quantitative detailed models of the Earth interior: prospecting, locating and measuring oil reservoirs, measuring and modelling the periods of the Earth's eigenvibrations, quantification of the earthquake risk, etc. Most of the really new discoveries occur when new patterns are recognized, connected and their predictions are verified.

A farewell lecture is suggestive to ask the question: which dreams have been realized or fulfilled? In 1984 after a visit to the deepest scientific borehole with 12 km depth, an international group of geoscientists exchanged toasts. Under the impression of a technical-scientific master piece and under the guidance of an experienced Tamada the toasts reached a high level. Two toasts remain in my memory:

- if you give up your DREAMS you will die !

I had proposed it as encouragement and incentive for the Russian colleagues. But then came the response by an outstanding Russian geologist:

- Science is not living by dreams but by SURPRISE.

I kept thinking about these two toasts ever since.

Expectations, hopes, dreams are important motivations for scientific work, and they should not be taken away from us, especially not in times of financial constraints. – But, as important is the openness for the unexpected and for the surprises. We could sum up: who does not dare to hope, to him the unexpected will never occur.

I want to extend my thanks to all with whom I could walk through this complex, wonderful world of unexpected geophysical patterns. Cornelia Fuchs deserves a special thank you. She caught the search for pattern in chaos in her patchwork quilt "The Earth is alive!" In this sense I would like to extend my best wishes to geophysics at Karlsruhe and especially to Friedemann Wenzel for luck during searching, recognizing, connecting, validating of patterns.

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4. Geophysics at Karlsruhe in the stress field between physics, geo-sciences and engineering sciences

Helmut Wilhelm

The roots of geophysics in Karlsruhe date back to the late 19th century. The earthquake of 24th January 1880 with its epicenter at about 20 km northwest of Karlsruhe caused some damages in nearby parishes. At the 6th February 1880 session of the Karlsruhe natural sciences federation, it was agreed on in the presence of the Grand Duke of Baden Friedrich, that an earthquake commission should be founded. This commission had to provide epicenter coordinates of all earthquakes happening in the Grand Duchy of Baden and to note all damages caused by them (Mälzer, 1993). It was the first earthquake survey organized in Germany. In 1886, the Association of Fatherland Natural sciences of the kingdom of Württemberg took this commission as an example by founding a similar commission on earthquake observation (Wielandt and Schick, 1997).

During the years 1884 -1887 Ernst von Rebeur-Paschwitz worked in Karlsruhe as scientific assistant at the Grand Duchy of Baden astronomical observatory on improving the horizontal pendulums which at that time were used to record the plumb-line changes caused by earth tides. In 1889 when working at the Geodetic Institute Potsdam, he was the first scientist who succeeded in recording a long distance earthquake, which had originated in Japan, with a horizontal pendulum. Mathäus Heid, the successor of Wilhelm Jordan at the Geodetic Institute of the Polytechnical School in Karlsruhe, in 1904 founded an earthquake observatory with stations on the Turmberg in Durlach and the Schlossberg in Freiburg. He was also engaged in earth surface surveying and gravity observation (Draheim, 1993).

In view of these roots it appeared natural to associate the chair of geophysics with the Geodetic Institute of the Technische Hochschule Karlsruhe, after its establishment in 1964. The Geodetic Institute was part of section 5 (structural engineering) of the faculty of natural sciences and humanities, the Mineralogical and Geological Institutes, as geo-institutes, were however, part of section 2 (chemistry). The Meteorological Institute, on the other hand, belonged to section 1 (mathematics and physics). Hence, the geo-sciences were distributed over three sections of the faculty of natural sciences and humanities, when the chair of geophysics was founded in 1964. Stephan Mueller decided to accept the offer to establish his chair in the section of physics and mathematics, because the scientific methods used in geophysics are mainly based on physical and mathematical methods. At the same time he was eager to care for intensive cooperations of his chair with the institutes for geology, mineralogy, geodesy and geography and he also promoted relations with the institute for rock mechanics, by establishing common geo-scientific projects which got funded by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG), thus creating the 'Karlsruhe spirit'. From the beginning, this cooperation was also established within international frameworks, in view of the fact that national borders are completely insignificant in the geo-sciences. Consequently, the DFG obtained many opportunities for supporting projects based on international cooperations in the geo-sciences, during the time following.

This development started with the DFG Priority Programme 'Geophysical exploration of the deep underground of Central Europe', in the course of which all geophysical institutes of the Federal Republic of Germany were supplied with refraction seismic instrumentation by the Volkswagenstiftung, even institutes which were mainly busy in non-seismic research, which then contributed to the national and international refraction seismic projects by providing students and scientists taking part in the seismic measurements. This DFG Priority Programme was the German contribution to the Upper Mantle Project, which had been agreed upon in 1960 by the International Union of Geodesy and Geophysics (IUGG).The first refraction seismic investigations of the Rhinegraben were performed within this program (Mueller et al., 1967).

The decision of Stephan Mueller to have his chair established in the section of physics and mathematics of the faculty of natural sciences and humanities was influenced by the consideration, that science branches which could improve their scientific efficiency and reputation by geophysical investigations would try to direct his research towards their specific aims and would like to strongly influence this research. Such a possible conflict of interest was not to be expected in the section of physics and mathematics within the faculty of physics, established in 1970. Therefore it is no wonder that all later trials of other faculties to incorporate the chair of geophysics, were in vain. Being a part of the faculty of physics was a guaranty of independence. On the other hand, it enabled him to design freely the contacts with all interested chairs of Karlsruhe University, and it also provided the basis for developing cooperations with chairs of the neighbouring universities of Stuttgart and Strasbourg, and to create common projects with other national and international research institutions. These projects were successful in the review process and became funded by DFG, as well as by other national or international research agencies.

By appointing Stephan Mueller, the Technical University Karlsruhe had decided to establish seismological research as the main research aim of its newly established chair of geophysics. However, other geophysical research fields, such as geomagnetism, gravimetry, and geothermics must also be included in the scientific education offered in a geophysics course, as well as the mathematical methods used in applied geophysics. These are especially important for the geo-sciences and engineering sciences and must be comprehended within the framework of their special geo-scientific and engineering applications. Under these circumstances a sound geophysics education was no longer effective as part of a pure physics diploma study-course. Hence, along with meteorology, geophysics was granted a diploma study- course of its own in 1969, which then was identical with the physics course until the pre-diploma examination, whereas afterwards, by reducing the theoretical physics courses, the spectrum of accepted courses could be extended.

This flexible arrangement helped to include all geo-scientific and engineering aspects in the geophysical education needed to provide excellent chances to geophysicists educated at Karlsruhe University for a later successful application in geo-scientific or engineering professions. With this diploma-study course in geophysics, Karlsruhe University became the only university south of the Main river in the FRG, except for the Ludwig-Maximilian University at Munich, where a diploma in geophysics could be obtained, and the Karlsruhe geophysics chair obtained a unique position compared to all other institutions offering a geophysics education in Baden-Württemberg. Therefore, the number of geophysics students increased so quickly that the faculty of physics had to realize that a second chair of geophysics was urgently needed, which should concentrate on applied geophysics. The faculty decided to create this chair by exchange with a chair which happened to become vacated at the Institute of experimental nuclear physics. In 1983, Peter Hubral was appointed as head of the new geophysics chair.

The state of the three chairs of geophysics, meteorology and crystallography as ‘exotics’ in the faculty of physics was partly a consequence of the strong relations of these research branches to other faculties of the university. These good connections probably also supported the application of Stephan Mueller as dean of the faculty of natural sciences I, which comprised the former section of physics and mathematics, in 1968/1969, and it was helpful for his plans to expand the number of scientific personnel of his chair.

When Karl Fuchs in 1972 received the appointment as successor to Stephan Mueller, who had accepted the geophysics chair of the ETH Zürich as successor to Fritz Gassmann, the cooperation of geophysics with the geo-sciences and engineering sciences at Karlsruhe

University was deepened and intensified again. This becomes obvious recalling the three Collaborative Research Centres (SFB), which were granted by DFG to Karlsruhe university in 1970 – 2007: i.e. SFB 77 (rock mechanics, 1970 -1977), SFB 108 (stress and stress release in the lithosphere, 1981- 1995), and SFB 461 (strong earthquakes, from geo-scientific basics to engineering applications, 1996-2007): Karl Fuchs became speaker of SFB 108. At the same time he achieved to become Chairman of the Commission of Coordinating Committee 5 (Structure and Composition of the Lithosphere) of IUGG, thus providing support for the external projects of these Research Centres by international scientific networks (see also the contributions of C. Prodehl and K.-P. Bonjer to this volume).

When Karl Fuchs became President of the Inter-Union Commission on the Lithosphere of the International Lithosphere Program (ILP), which was founded in 1980 by the International Council of Scientific Unions (ICSU), after a corresponding request by the International Union of Geological Sciences (IUGS) and by IUGG, he achieved to establish strong contacts with the federal ministry for Research and Technology. Enthused by the success of the Russian Deep Drilling Programme and the US World Stress Map Project (see the contribution of B. Müller to this volume), he succeeded in stimulating the funding of the expensive 450 M DM big geo-scientific project, the German Continental Deep Drilling Project (KTB) by the federal minister. Preparatory projects had already succeeded in getting funded by DFG within the frame of a KTB Priority Programme. A key aspect for the federal minister was the fascinating perspective that the German drilling industry would obtain an excellent chance to reach an impressive technological progress, which would result in achieving a prominent position among the internationally competing drilling companies. Therefore, a technical concept for a drilling rig installation was conceived, which would be able to drill a 14 km deep borehole (Chur et al., 1990).

After Karl Fuchs had become vice-president of the Inter-Union Commission of the Lithosphere in 1993, an International Continental Deep Drilling Program (ICDP) was founded in correspondence to the already existing International Ocean Deep Drilling Program (IODP), which, under the auspices of the Coordinating Committee 4 of ILP, was promoted by IUGS as well as by IUGG. The ICDP, for which Karl Fuchs continuously served as member of its Advisory Board evolved so successfully, that German research projects still got funding in 2012 within the frame of both international drilling programs by a corresponding DFG Priority Programme. As a consequence of the extraordinary engagement of Karl Fuchs in international scientific cooperation institutions, Alik Ismail-Zadeh was installed in 2007 at Karlsruhe Geophysical Institute as Secretary General of IUGG.

When I became C3-professor at the Geophysical Institute of Karlsruhe University (TH) in April 1980 as successor to Gerhard Müller, I was aware of the fact that I would be working at an institute which belonged to the faculty of physics. I was acquainted to this situation from my earlier education at the institute of geophysics of the University of Göttingen and my professional work at the institute of ocean sciences of the Christian-Albrecht University at Kiel. The special situation in Karlsruhe was that geophysics as well as meteorology and crystallography were considered as ‘exotics’ in the faculty. The amount of additional money which was collected for meteorological and geophysical projects from DFG soon induced acknowledgement in the physics faculty.

From my former engagement in earth tide research and my work in SFB 48 granted to University of Göttingen, Karl Fuchs as reviewer of this SFB noticed my work, so that afterwards he felt inclined to offer me the chance to contribute to the research on earth tides performed at the geo-scientific observatory of Schiltach, which was commonly supported by both universities Karlsruhe and Stuttgart (see the contribution of W. Zürn and T. Forbriger to this volume), and also expected a contribution from me to the planned SFB 108. Although I had already a permanent position as H3-professor at Kiel University, I decided to return to my geophysical roots and to accept the offered position at Karlsruhe University. Here a new research field, geothermics, which already Stephan Mueller had incorporated into his Rhinegraben research program, was waiting for me (Werner, 1970).

My investigations in this field started when we decided to participate in the pre-site KTB surveys of the German Continental Deep Drilling Program and to perform the planned geothermal measurements in the boreholes drilled in the Black Forest near the envisaged KTB site Haslach (Burkhardt et al. 1989, Wilhelm et al. 1989, Burkhardt et al. 1991). Practical and theoretical aspects arising during the geothermal KTB field studies and related problems were considered in the following years (Wilhelm, 1990, Stiefel et al. 1991, Wilhelm et al. 1994, Wilhelm 1994, Safanda & Wilhelm 1995, Wilhelm et al. 1995, Fielitz et al. 1999, Günzel & Wilhelm 2000, Wilhelm 2000, Wilhelm et al. 2000, Demetrescu et al. 2005, Demetrescu et al. 2007). Later we concentrated on geothermal investigations of impact structures such as Chicxulub and Chesapeake (Wilhelm et al. 2004, Popov et al. 2004, Wilhelm et al. 2005, Safanda et al. 2005, Safanda et al. 2006, Mayr et al. 2008, Safanda et al. 2009, Mayr et al. 2009, Heidinger et al. 2009, Wilhelm et al. 2013). In the following period we investigated the geothermal evolution of sub-salt hydro-carbon containing structures in the Precaspian basin (Ismail-Zadeh et al. 2008, Ismail-Zadeh et al. 2010).

The results of the preliminary geothermal KTB investigations performed at the last two locations Black Forest and Upper Palatinate remaining after a competitive review by DFG, showed differing temperature-depth predictions for the envisaged drilling depth of 14 km (Burkhardt et al., 1989, 'the deepest hole of the world'). In the official view this contributed essentially to the decision taken in 1986 that the Upper Palatinate won the competition, much against the presumptions of the combatants for the Black Forest, headed by Karl Fuchs. When, after the decision, an offer was proposed to drill at least a two km deep borehole at Haslach to enable an examination of the predicted results, he refused, arguing completely to the point that after the decision had been taken, it should be evident to concentrate on the location Upper Palatinate. There, the temperature of 270 °C predicted for the envisaged drilling depth 14 km (Burkhardt et al., 1989) was almost reached when drilling was finished at the depth of 9.1 km (Clauser et al., 1997).

In the final phase of SFB 77 an earthquake of magnitude 7.4 hit the Carpathian Mountains in the Vrancea region on 4th March 1977; 1500 people lost their lives and large costs by severe damages had to be deplored. This event and the 1986 and 1990 earthquakes in the Vrancea-region led to a revival of already long lasting scientific relations between Karlsruhe University and Romanian scientific institutions. A new SFB within the framework of the International Decade for Natural Disaster Reduction (IDNDR) was conceived to propel geo-scientific and geo-mechanic research including earthquake engineering applications (see the contribution of F. Wenzel to this volume). Due to the broad research aspects in engineering sciences of this SFB 461, new professional perspectives were opened for geophysicists educated at the two geophysics chairs of Karlsruhe University.

When the Faculty of physics granted a Fiebiger-professorship to geophysics, the chair got the privilege to appoint a successor to Karl Fuchs in advance of his retirement. When Friedemann Wenzel was appointed in 1996 as pre-elected successor to Karl Fuchs, the teaching capacity of the institute reached its maximum with four professors. With the retirement of Karl Fuchs in 1999 this capacity started to become strongly reduced. The strong relations of geophysics with the geo-sciences and the engineering sciences, which were a characteristic label of Karlsruhe University, were, however, not touched, due to the clamps created by SFB 461. And with the merger of the University with the Research Center Karlsruhe to establish the Karlsruhe Institute of Technology (KIT), new frames for scientific cooperations were created and successfully used.

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5. The people of the Geophysical Institute of the University of Karlruhe / Karlsruhe Institute of Technology

Claus Prodehl and Klaus-Peter Bonjer

The beginnings of the Geophysical Institute

The roots of the Karlsruhe Geophysical Institute lie at Stuttgart and Clausthal-Zellerfeld. In the early 1960s Hans Berckhemer und Stephan Mueller were assistant professors with Professor Wilhelm Hiller at the Geophysical Institute of the University of Stuttgart / State Earthquake Service (Landeserdbebendienst) Baden-Württemberg. Jörg Ansorge, Ursula Hägele and Dieter Seidl were physics students with geophysics as side subject and obtained the degree „ Diplom-Physiker", having written their diploma thesis at the Geophysical Institute. Also Dieter Emter, Dieter Mayer-Rosa and Walter Zürn finished their physics studies at Stuttgart, however, with metal physics as main subject. Only afterwards they changed their interest into geophysics. At the same time, Karl Fuchs served as assistant professor at the Geophysical Institute of the Mining Academy of Clausthal-Zellerfeld with Professor Heinz Menzel, while Klaus-Peter Bonjer started his geophysical career here as student.

When finally, in 1964, Stephan Mueller was appointed full professor for geophysics at the University of Karlsruhe, he was able to address scientists, whom he knew personally, and offer them a research position at the newly founded institute.

The scientists of the 1960s and 1970s

The first scientists who started at Karlsruhe were Jörg Ansorge, Dieter Seidl, Karl Fuchs, Klaus-Peter Bonjer, and Ursula Hägele. As location for the new institute, the University offered Building no 42 of the former military complex at Hertzstrasse. However, before the reconstruction of this building was finished, the scientists had to arrange themselves in a flat of a multi-story residential premise, opposite their future location. The first scientists had to fulfil a multitude of tasks. The reconstruction of the future institute's building had to be supervised. A master plan for the study of geophysics at Karlsruhe had to be created. Geophysical field and lab experiments for geophysics students had to be organized and set up. Instruments for new funded research projects had to be bought, tested and installed. Last not least planning and active work for a geophysical underground observatory had to be organized and supervised which was planned to be installed in a former silver mine in the central Black Forest, located in the Heubach valley close to Schiltach. Jörg Ansorge was made responsible for the construction work both at the new institute's building and at the site of the future observatory.

Stephan Mueller was also responsible for the reconstruction and operation of the Gräfenberg Array near Erlangen. This seismological array had been installed by the U.S. Army in the late 1940s as part of a worldwide seismic survey in a remote area of the Franconian Jura to monitor the testing of nuclear weapons of the Eastern Bloc states, but which in the 1960s was no more needed by the U.S. army and had therefore been transferred to the community of German geophysical institutions. The first scientific director, Johannes Kopietz, was, for the first years, officially employed by the University of Karlsruhe. In the course of the reconstruction first installations at Gräfenberg were performed by Jörg Ansorge, Dieter Seidl and Klaus-Peter Bonjer.

One of the first field projects of Stephan Mueller at Karlsruhe was the continuation of an investigation of the dispersion and absorption of surface waves in order to deduce the structure of the crust and upper mantle in the South German Triangle. Dieter Seidl became the responsible scientist for this project, together with a young diploma student Horst Reichenbach. For this purpose a long-period seismic network between the Taunus Observatory and the Po Valley area was operated for several years.

During the following years new scientists joined the Karlsruhe Institute. The first master thesis in Geophysics was performed by G. Wolber, a student who finished with a physics master's degree for teachers. During the international seismic exploration of the Alps in 1966 with a central shotpoint at Lac Nègre in the Western Alps, for the first time the new MARS-66-instrumentation came into use. It was still in a test phase and was supervised by Erhard Wielandt, who during his employment from 1965 to 1968 at the company Lennartz at Tübingen was essentially responsible for the development of this equipment. In 1968 Erhard Wielandt moved to Karlsruhe to join the Institute as Ph.D. student. Here he developed some instrumentation for the permanent recording of seismic data. Also in 1968, following a visit of Stephan Mueller to Nairobi, Jürgen Wohlenberg, who had worked as seismologist in Africa for several years, came to Karlsruhe for a year, before he moved to Berlin. Together with Klaus Bonjer, some research work on the structure of the East African rift system using surface waves was completed. For some time, Reinhard Fröhlich was responsible for geoelectric work, he left the Institute in 1969 to accept a teaching position at the state university at Rolla, Missouri. Another non-seismic project in the late 1960s and early 1970s was a systematic magnetic and gravimetric campaign in the Kaiserstuhl volcano supported by scientists of the Geology and Geodesy Institutes. It started as students' fieldwork and was finished by a diploma thesis of Sonja Faber, who was the first full geophysics student at Karlsruhe.

In 1969 Dieter Mayer-Rosa could be hired, having finished his Ph.D. work at Stuttgart. He followed Ursula Hägele as scientist responsible for seismology. In the same year Gerhard Müller moved from Clausthal-Zellerfeld to Karlsruhe. He took care in particular in an efficient organization of teaching geophysics. Scientifically he continued his work on the development of the reflectivity method and, now in cooperation with Karl Fuchs, the calculation of synthetic seismograms. Both Gerhard Müller and Karl Fuchs had independently worked on the development of the theory which they now could terminate together and start its practical application. The resulting program for the calculation of synthetic seismograms on the basis of the reflectivity method was to become one of the worldwide mostly used programs in the interpretation of seismic data. Finally, in September 1969 Claus Prodehl joined the Institute. He had obtained his Ph.D. in 1965 at Munich and had, from 1967 to 1969, worked as Visiting Scientist at the U.S. Geological Survey in Menlo Park, California, where he had reinterpreted crustal seismic data and developed a new crustal model for the western United States.

The year 1971 brought essential changes which ended in a large segmentation and nearly threatened the existence of the Institute. Stephan Mueller was offered a unique position at the ETH Zurich, as successor of Professor Fritz Gassmann at the Institute for Geophysics of the ETH and as director of the Swiss Seismological Survey. This position offered immense chances, because he could reoccupy the major part of existing and new positions by himself. An intensive discussion with all scientists at the Karlsruhe Institute followed with the consequence that almost half of all scientists decided to follow Stephan Mueller to Zurich. Herbert Harcke, Dieter Mayer-Rosa, Erhard Wielandt and Dietrich Werner (recently graduated in geophysics as Diplom-Geophysiker). Jörg Ansorge followed a year later in 1972. Dieter Seidl moved to the Seismological Central Observatory Erlangen. Fortunately the Faculty of Physics decided to keep the Geophysical Institute as independent research facility and appointed Karl Fuchs as professor for geophysics and director of the Institute. Furthermore the existing scientific fixed positions were granted which were held by Klaus-Peter Bonjer, Gerhard Müller and Claus Prodehl.

Another fixed position could be occupied one year later by appointing Werner Kaminski, who at Hamburg University had developed a program package to digitize seismic data and plot them as record sections, which he transferred to Karlsruhe to the new Raytheon Computer. This system was in particular determined to process the telemetry data of the seismological Rhinegraben network in real time. It created the basis for a capable data processing facility for future large seismic projects.

In 1974 Walter Zürn could be hired as the Karlsruhe based geophysical scientist of the Black Forest Observatory Schiltach. After study and Ph.D. work at Stuttgart he had moved for four years to Los Angeles to the University of California (UCLA). During this time he was appointed scientific leader for one year at the Amundsen-Scott-South Pole Station of the USA. To honour his merits, in 1976 the 1515 m high Zürn Peak was named after him.

In the early 1970s, Rainer Blum (1970), Günter Bock (1971), Christoph Gelbke (1971), Rainer Kind (1972), Gheorghe Merkler (1972), Dave Bamford (1973) and Sonja Faber (1974) joined the Institute. Rainer Blum, Günter Bock and Gheorghe Merkler worked on a new project on induced seismicity which had been initiated by Stephan Mueller and which was now continued by installing seismological arrays at hydroelectric reservoirs in the Austrian and Swiss Alps and in the Romanian Carpathians. Christoph Gelbke worked with Klaus Bonjer on seismology of the Rhinegraben, Rainer Kind and Dave Bamford worked on long-range seismic refraction projects. Sonja Faber was the first full student in geophysics, after her diploma in 1974 she started her PhD work on the long-range seismic data LISPB.

They all worked on the basis of temporary appointments which allowed maintaining a position for maximum of 5 years. The funding came from research projects such as the Rhinegraben project, Induced Seismicity and seismic refraction projects. At the same time, in the early 1970s, Karl-Otto Millahn and Horst Stöckl held temporary assistant positions.

Later in the 1970s many other scientists were employed in the Institute on Third-Party Projects such as Jürgen Fertig (industry project), Manfred Koch, Gerhard Sattel (EG-Geothermics-Project Rhinegraben), Martin Jentsch (EG-Geothermics-Project Urach), Bertram Perathoner (DFG Israel), Susan Raikes, Walter Mooney and Jim Mechie (DFG priority program Rhenish Shield).

Gerhard Müller continued his development on the reflectivity method now to be applied for seismological data covering the whole earth (flat-earth approximation), supported for some time by Rainer Kind. In 1979 Gerhard Müller was appointed full professor at the University of Frankfurt. He was followed in 1980 by Helmut Wilhelm.

Scientists at the time of the Collaborative Research Centers 108 and 461 (1981-2007)

When the geoscientific Collaborative Research Center 108 “Stress and stress release in the lithosphere” (Sonderforschungsbereich = SFB 108) was established at the University of Karlsruhe in 1981, funded by the German Research Association, the Geophysical Institute faced new challenges, because Karl Fuchs served as “Speaker” and the administration of the SFB 108 was established at the Institute. The establishment of the SFB 108 was especially fruitful for the Institute, as all scientists on fixed positions could be persuaded to cooperate actively in the SFB 108. Most of them initiated their own subprojects and were able to maintain them successfully for at least nine years or even to its end in 1995.

This concerns the following subprojects: A4 “Seismicity as access to anomalies of stress in the lithosphere in space and time” (leader Klaus-Peter Bonjer), A7 “Drillhole-Geophysics” (leader Gerhard Sattel, later Birgit Müller), B1 “Structure, deformation and physical properties of the lithosphere imaging deep stress fields” (leaders Karl Fuchs and Claus Prodehl), B2 „Inversion of geophysical data – model computations” (leader Helmut Wilhelm), B5 “The roots of mobile continental plate regions from the dispersion of ultra-long period surface waves" (leader Walter Zürn), C4 "Structure of the lithosphere under the Afro-Arabian rift system" (leader Claus Prodehl) and Z "Central Administration" (leaders Claus Prodehl and temporary business directors, subsequently Peter Blümling, Ulrich Achauer and Joachim Ritter). The scientific and administrative activities required the temporary employment of numerous new scientific and technical staff members the costs of which were almost exclusively covered by the funding resources of the SFB 108. In 1990 the SFB 108 was rearranged and the project areas A and B were transferred into a new project area D. This caused a partial renumbering of subprojects. A4 became D6, A7 became D4, B1 became D8 (with changed leadership Peter Hubral and Claus Prodehl), B5 became D9. Project area C with subproject C4 and project area and subproject Z remained unchanged.

National and international projects took place, where the research work of the SFB 108 provided major support. The International Lithosphere Project (ILP) was headed for some time by Karl Fuchs for which purpose he was released from his official duties by the University of Karlsruhe. The World Stress Map Project of the Heidelberg Academy of Sciences achieved major support by the investigations of subproject A7. During the planning and performance phases of the German Deep-Drilling Project (KTB) the Karlsruhe Institute was active with pre-investigations in the Hohenzollerngraben and Black Forest and subsequent research projects in and around the final location of the super-deep drillhole in the Oberpfalz during and after the drilling phase. Active participation of the SFB 108 supported finally the German DEKORP (long-range seismic-reflection profiling) program and the international European GeoTraverse (EGT) program. The individual scientific activities (experiments, theory, data interpretation and references) will be presented in detail in the following Chapters.

Business directors of the SFB 108 became exclusively scientists who had obtained their diploma at the Geophysical Institute of Karlsruhe and who, besides their voluminous tasks as business directors, were now involved in ambitious own research projects leading to their promotion by obtaining their Ph.D. degree. The first business director was Peter Blümling. He founded the working group "Drillhole Geophysics" which was later continued by Birgit Müller (subprojects A7 and Z). After promotion he left the Institute, and Ulrich Achauer took over the position of the business director. He introduced and started the research direction "teleseismic tomography" (subprojects B1/D8 and Z). He was followed in 1991 by Joachim Ritter who continued the teleseismic tomography research direction (subprojects C4 and Z).

As mentioned above, numerous scientists were temporarily employed in the geophysical SFB 108 subprojects, who either were Ph.D. students or worked as full-time scientists. Without claiming completeness, besides the business directors just mentioned, these were (subproject in brackets): Beate Aichroth (D8), R. Apel (D4), Ioanna Apopei (A4), Bernd Blankenbach (C2), Thorsten Dahm (D6), Helmut Echtler (D8), Sonja Faber (A4 / D6), Thomas Fehlhaber (B5), Christine Fichler (B5), Kurt Finkbeiner (B2), Wolfgang Friederich (B5 / D9), Martin Fritzsche (D8), Dirk Gajewski (B1/D8), Andreas Glahn (D8 und C4), Michael Grünewald (B5), Heinz Häge (B2), Klaus Jäger (B2), Karl Koch (A4), Manfred Koch (B2), Gabi Laske (D9), Ewald Lüschen (D8), Larry Mastin (D4), Gunther Mayer (D8), Jim Mechie (B1/C4), Birgit Müller (D4), Wolfgang Ott (A7), Thomas Plenefisch (D6), Michaela Rizescu (D6 / IDNDR), Paul Rydelek (D9), Thomas Schneider (A7), Raimund Stangl (B1/D8), Gerald Stoll (C4 / D8), Gerhard Zink (A7), C. Williams (D4), Hermann Zeyen (D8).

Additional scientists employed on temporary basis by the university or in third-party projects were amongst others: Christoph Baumann, Uwe Kästner, Volker Mayer, Birgit Müller, Jürgen Neuberg, Kwasi Preko, Trond Ryberg, Karl-Josef Sandmeier, Gerhard Sattel, Günther Schroth, Andreas Stiefel, Friedemann Wenzel and Ruedi Widmer.

When the SFB 108 finally ended in 1995, new plans were made to create a new research program which should involve not only geosciences, but to a major degree also scientists of engineering faculties. So, in 1996, under leading efforts of the Geophysical Institute, a new Collaborative Research Center ”Strong Earthquakes – a Challenge for Geoscientists and Civil Engineering” (Sonderforschungsbereich 1562, later renamed into SFB 461) was established at the University of Karlsruhe. It involved both geoscientific (research areas A and B) and civil engineering (research areas B and C) themes. Friedemann Wenzel became Speaker for the first years. Also here, besides Friedemann Wenzel, all other permanently employed scientists of the Institute were involved: Klaus-Peter Bonjer, Karl Fuchs, Peter Hubral, Werner Kaminski, Claus Prodehl, Joachim Ritter, and Helmut Wilhelm. Also for the SFB 1562 / 461 the administration was established at the Geophysical Institute where it remained nearly to the end of the SFB in 2007.

The Institute participated with five subprojects: A1 “Deep seismic exploration above the Vrancea subduction zone” (project leaders Peter Hubral and Claus Prodehl, from 1997 Claus Prodehl and Werner Fielitz, from 2002 Joachim Ritter and Werner Fielitz, from 2005 Joachim Ritter and Thomas Forbriger), A2 “Seismic tomography of the Carpathian arc” (until 2001, leaders Friedemann Wenzel and Karl Fuchs), A4 “Geothermal field, fluid regime, and tectonics along a NW-SE profile through the Carpathians” (until 2001, leaders Helmut Wilhelm und Gerhard Eisbacher), A6 “Recent stress field and geodynamics” (since 2002, leader Birgit Müller, from 2005 Oliver Heidbach and Birgit Müller), A7 “Prognosis of ground movement during strong earthquakes” (since 2005, leader Friedemann Wenzel), B2 “Stress transfer in the collisional subduction zone of southeastern Europe” (until 2001, leaders Birgit Müller und Doris Stüben), B3 “Seismogenic potential of the Vrancea subduction zone – quantification of source and local effects during strong earthquakes” (leader Klaus-Peter Bonjer, from 2005 Friedemann Wenzel), Z2 “Central Administration” (leaders Claus Prodehl, from 2002 Joachim Ritter and Friedemann Wenzel).

Business directors became again scientists of the Geophysical Institute who, besides their voluminous administrative tasks, undertook their own research projects finishing with a Ph.D. degree. The first business director was Joachim Ritter who soon left for Göttingen and was followed by Olaf Novak (subprojects B3 and Z). One after the other followed Michael Martin (subprojects A2 und Z2) und Maren Böse (subprojcts B3 und Z2). For the last three months of SFB 461 Ulrike Sturm (Institut für Photogrammetrie und Fernerkundung) became responsible for its administration.

Also from the funding resources of the SFB 461, numerous scientists were temporarily employed in the geophysical subprojects, who either were Ph.D. students or worked as full-time scientists. Without claiming completeness, besides the business directors just mentioned, these were (subproject in brackets): Martin Brudy (B2), Tobias Diehl (A1), Linda Driad (B3), Uwe Enderle (A1), Ellen Gottschämmer (A7), Jörn Groos (A1), Franz Hauser (A1), Stefan Hettel (A6), Andreas Hippel (A1), Frank Lorenz (A2), Michael Martin (A2), Gunther Mayer (A1), Joachim Miksat (A2/A7), M.C. Oncescu (B3), Adrien Oth (A7), Steffen Ragg (B2), Gunda Reuschke (A3), Thomas Schler (A2), Olivier Sebe (A1),Vladimir Sokolov (A6/B3), Blanka Sperner (A6), Sabine Spindler (B6), Henriette Sudhaus (A1), Veronika Wehrle (B2), Wolfgang Wirth (B3), Andreas Wüstefeld (A6), Julia Ziehm(A1).

Additional scientists employed on temporary basis by the university or in third-party projects during and after the time of the SFB 461 were amongst others: Johannes Altmann, Julia Bartlakowski, Thies Buchmann, Peter Conolly, Andreas Eckert, Matthias Gölke, Ellen Gottschämmer, Oliver Heidbach, Philipp Heidinger, Tobias Hergert, Alik Ismail-Zadeh, Martin Itzin, Martin Karrenbach, Nina Köhler, Daniel Kurfeß, Michael Landes, Birgit Müller, Tobias Müller, EIke-Marie Nolte, Linus Passas, Gwendolyn Peters, Hanna-Maria Rumpel, Rachmat Sule, Mark Tittgemeyer, Tanja Titzschkau, Britta Wawerzinek, Christian Weidle, Fabian Wenzlau, Ruedi Widmer.

Second Geophysics Chair Applied Geophysics

In 1983 the Ministry for Cultural Affairs agreed to establish a second geophysics chair at the Geophysical Institute, the Chair for Applied Geophysics. Peter Hubral was appointed full professor and started to build up a working force in the same year. One of his first co-workers was Martin Tygel. The first Ph.D. students were of substantial help to establish the working group of this division, concentrating particularly on research connected with the German continental drilling project KTB. Claudia Kerner headed the second-large project on absorption and other mechanisms in wave propagation in the 1990s. Many other successful and internationally recognized projects followed. The three most important co-workers were Ewald Lüschen, Walter Söllner and Xiao-Ping Li. They were fully paid from Third-Party projects and supervised diploma as well as Ph.D. students.

Peter Hubral assured that always external fundings for payment of his Ph.D. students were available, furthermore he took care that many guest scientists stayed at Karlsruhe for longer periods to cooperate with his students, such as renowned scientists from Brazil, Russia, Norway, USA, Great Britain, Australia, Israel, and last not least Germany. In 1991 Serge A. Shapiro came to Karlsruhe and worked here from 1991-1997 and received his habilitation. During this time he received an Alexander-von-Humboldt and a Heisenberg fellowship. When he finally left to take over a professorship for Applied Geophysics at the Geological School of the Polytechnic Institute in Nancy, France, in 1997, and became full professor of Geophysics at the Free University at Berlin in 1999, he kept his close relationship to Karlsruhe by founding, together with Peter Hubral, the university consortium WIT (Wave Inversion Technology). One of the latest co-workers was Jürgen Mann, who stayed at the Institute beyond the time when Peter Hubral retired in 2007.

The working force of the division Applied Geophysics from 1983 to 2007 consisted mainly of Ph.D. students, such as Iain Bush, Steffen Bergler, Erik Duveneck, Robert Essenreiter, Stephan Gelinsky, Norbert Gold, Christian Hanitzsch, Zeno Heilmann, Thomas Hertweck, German Höcht, Hans Huck, Makky S. Jaya, Christoph Jäger, Uwe Kästner, Andreas Kirchner, Tilman Klüver, Ingo Koglin, Guido Kneib, Gerd Liebhardt, Jürgen Mann, Alexander Müller, Jörg Müller, Thilo Müller, Tobias Müller, Tamara Prokovskaja, Matthias Riede, Thomas Rühl, Joerg Schleicher, Petra Schruth, Miriam Spinner, Kai-Uwe Vieth, Markus von Steht, Ulrich Werner, Martin Widmaier, Jörg Zaske, Yonghai Zhang and Holger Zien. Several Ph.D. students received international prizes for their excellent research work. In addition 70 diploma students passed successfully their exams between 1983 and 2007.

The Geophysical Institute today

Karl Fuchs became emeritus in 1997. Werner Kaminski retired from active service in 2000, Claus Prodehl in 2001, Walter Zürn in 2002, Helmut Wilhelm in 2004 and Klaus-Peter Bonjer and Peter Hubral in 2005.

In 1996 Friedemann Wenzel started by the installation of a Fiebiger professorship at Karlsruhe and took over the Chair for General Geophysics in 1997. The position of Helmut Wilhelm was returned to the Faculty of Physics, the position Academic Director of Claus Prodehl was changed from a permanent into a temporary assistant position. In 2002 Joachim Ritter returned to Karlsruhe, in 2005 his temporary employment became permanent. Ellen Gottschämmer is member of the Institute since 1996 (permanent since 2013), and is responsible for various administrative tasks in teaching and research, in particular for student and publicity affairs and cooperation with high schools.

The Chair for Applied Geophysics, established in 1983, became vacant in 2006, when Peter Hubral officially retired. However, together with Jürgen Mann, he took care of his Ph.D. students until 2007. Finally the Chair was adopted by Thomas Bohlen in 2009.

The Geoscientific Joint Observatory of the Karlsruhe Institute for Technology (KIT) and the University of Stuttgart is administered since 1971 by both institutions. The staff members are based at the Geophysical and Geodetic Institutes of KIT as well at the University of Stuttgart. Since 2002 Thomas Forbiger is the geophysics representative of Karlsruhe.

Today (summer term 2013) the following scientists are temporarily employed on KIT or Third-Party positions: Andreas Barth (Research and Teaching), James Daniell (Ph.D. candidate), Anja Diez (Ph.D. candidate), Simone Dunkl (Ph.D. candidate), Jörn Groos (Research scientist), Lisa Groos (Ph.D. candidate), Sven Heider (Ph.D. candidate), Tobias Horstmann (Ph.D. candidate), Stefan Jetschny (Research scientist), Bijan Khazai (Research scientist), Tina Kunz-Plapp (Research scientist), André Kurzmann (Research scientist), Sandra Laskowski (Research scientist), Christopher Power (Bachelor, Research), Anna Przebindoska (Ph.D. candidate), Martin Schäfer (Ph.D. candidate), Vladimir Sokolov (Research scientist), Ines Veile (Ph.D. candidate).

Long-term Guest Scientists at the Geophysical Institute

The research work at the Geophysical Institute was strongly supported by long-term and short-term visits from scientists of well-known scientific institutions around the world. Most of them were supported by stipendia or other sources independent from Karlsruhe research project fundings.

The following listing of guest scientists, who stayed at least a few weeks at Karlsruhe, relies on memories of the present-day active and retired members of the Institute, and therefore may not be complete.

<u>Guest scientists of the section General Geophysics since 1964</u>

Prof. Leon Knopoff, University of California at Los Angeles (12 months 1966-1967)
Prof. Mark Landisman (several months, 1966-67)
Prof. Dr. Maruyama, Japan (12 months, 1968-1969)
Dr. John Schlue, University of California at Los Angeles (12 months 1968-69)
Dr. Leon Steinmetz, IPG Paris (two weeks, 1969)
Prof. A.E. Süßtrunk, Baden, Schweiz (several months, around 1970)
Dr. Victor Sousa-Moreira, Meteorological Survey of Portugal, Lisbon (several 1-month visits 1970-73)
Dr. Weichert, Yellowknife Array-Dominion Observatory, Ottawa (12 months, early 1970s)
Prof. Alsop, IBM Research Institute, New York (early 1970s)
Dr. Michael Berry, Dominion Observatory, Ottawa, Canada (12 months, early 1970s)
Dr. Albert Stein, Niedersächs. Landesamt für Bodenforschung (6 months 1970)
Prof. Zvi Ben Avraham, (University of Tel Aviv, Israel (several 2 week visits late 1970s)
Dr. Alfred Hirn, IPG Parsi (several visits in 1970 to 1976)
Dr. Martine Sapin, IPG Paris (1 month 1972)
Dr. David Bamford, University of Birmingham, U.K. (12 months 1973-74)
Dr. Keith Nunn, University of Birmingham, U.K. (1 month 1974)
Dr. Jean-Bernard Edel, University of Strasbourg (6 months 1973-74)
Dr. Heinz Miller, München (1 month 1975)
Dr. Walter Mooney, University of Wisconsin, Madison (6 months 1976) and U.S. Geological Survey (several one-week-visits)
Prof. Avihu Ginzburg, University of Tel Aviv, Israel (several 2-week visits 1978)
Calle Lund, University of Uppsala, Sweden (1 month 1979)
Prof. Max Wyss, Colorado School of Mines, Boulder, Colorado (12 months, 1978-79)

Prof. Carl Kisslinger, Colorado School of Mines, Boulder, Colorado (12 months, 1979, Humboldt fellowship; three months 1986, Humboldt reinvitation)
Prof. Brian Jacob, Dublin Institute for Advanced Studies, Ireland (3 months DAAD-stipendium and other two-week visits, 1980s)
Dr. Zuhair El Isa, University of Jordan, Amman, Jordan (2 months 1984)
Prof. David Chapman, University of Utah, Salt Lake City (2 weeks, early 1980s)
Prof. John Ebel, Boston College, Weston Observatory (12 months, August 1986-August 1987)
V.G. Krishna, Heiderabad, India (6 months, 1980s)
Q.Z. Yan, Beijing, China (several months 1987-88)
Prof. Mark Zoback, Stanford University (12 months, Humboldt fellowship, 1988-89)
Dr. Mary-Lou Zoback, U.S. Geological Survey (12 months, 1988-89)
Dr. Jay Zucca, U.S. Geological Survey (6 months 1988-89)
Dr. Mary Andrews, U.S. Geological Survey (3 months 1988-89)
Dr. Peter K.H. Maguire, University of Leicester, U.K. (1 month 1990)
Dr. Trond Ryberg, GeoForschungsZentrum Potsdam (several months 1990)
Prof. Stefan Sobolev, GeoForschungsZentrum Potsdam (early 1990s)
Dr. Edwin Dindi, University of Nairobi, Kenya (3 months 1991)
Prof. Zeng Rongsheng, Bejing, China (2 weeks)
Dr. Jan Safanda (Leiter des Departments of Geothermics der Akademie der Wissenschaften, Tschechien) (1 Monat, Humboldt-Stipendium)
Prof. John Ebel, Boston College, Weston Observatory (1 month, July 1996)
Dr. Ouiza Hadiouche, Institut de Physique du Globe, Paris (1.5 years)
Dr. Fred F. Pollitz, Dept. Terrestrial Magnetism,Carnegie Institution, Washington (1 year)
Professor Friedrich Busse, IGPP, UCLA (1 year)
Dr. Gabriele Marquart, Frankfurt
Prof. Harro Schmeling (Guest Lecturer during long-term release of Prof. Karl Fuchs)
Prof. Ulrich Christensen (Guest Lecturer during long-term release of Prof. Karl Fuchs)
Dr. Victor Raileanu, National Institute for Earth Physics, Bucharest, Romania (several 4-weeks-visits 1998-2003)
Dr. Andrej Bala, National Institute for Earth Physics, Bucharest, Romania (several one-week visits 2000-2008)
Dr. Stefan F. Balan, National Institute for Earth Physics, Bucharest, Romania (2-week visits 2007-2008)
Prof. Zvi Ben Avraham, (University of Tel Aviv, Israel (several months 2008)
Prof. Norman Harthill, Colorado School of Mines, Boulder, Colorado
Dr. Rebecca Harrington (5 years 2008-2013, Humboldt Foundation scholarship and Young Investigator, Group Leader)
Dr. Prantik Mandal, National Geophysical Research Institute, Hyderabad, India (2 months 2012)
Prof. Hing-Ho Tsang, Univesity of Hong Kong, China (6 months 2013)
Dr. Christopher Burton, Global Earthquake Model (GEM) at Pavia, Italy (3 months 2013)
Mr. Ganesh Kumar Jimee, National Society for Earthquake Technology, Nepal (2 months 2013, Karlsruhe House of Young Scientist Visiting Research Scholarship)
Dr. Dipok Kumar Bora, Diphu Government College, Assam, India (1 month, DAAD scholarship)
Prof. Katsu Goda, University of Bristol (1 year 2013-2014, Humboldt scholarship)

Guest scientists of the section of Applied Geophysics since 1983

Prof. Martin Tygel, IMECC / UNICAMP, Campinas, Brazil (Alexander-von-Humboldt-Stiftung, several long-term visits)

Prof. Ru Shan Wu, University of Santa Cruz, California (6 months)
Dr. R. Gerhard Pratt, today Professor at Department Chair, Imperial College, University of London
Prof. Serge Shapiro, Russia (Alexander-von-Humboldt-Stiftung)
Dr. Tijmen Moser (Netherlands)
Dr Boris Gurevich, Russia, today: Head of Department, Curtin University, Australia
Dr. Sven Treitel, USA
Prof. Enders Robinson, USA
Dr. Boris Gelchinsky, Israel
Prof. Norm Bleistein, USA
Prof. Bjørn Ursin, Norway
Dr. Mikhail Popov, Leningrad University, Russia

Guest scientists from Brazil: Prof. Rogério de Godoy, Prof. Reynam Pestana, Prof. German Garabito, Prof. Edson Sampaio, Prof. Marco Bothelho and Prof. Lourenildo Leite
Prof. Dr. Ru-Shan Wu, UCSC, USA
Prof. Dr. Sergey Goldin, IGIG, Novosibirsk, Russia
Prof. Dr. Lourenildo Leite, UFPa, Belem, Brasilien
Prof. Dr. João Carlos Cruz , UFPa, Belem, Brasilien
Dr. Huazhong Wang, Tongji University, 1999

Prof. Dr. Jianguo Sun, Jilin University, Chanchun, VR China
Prof. Edson E.S. Sampaio, UFBa/PPPG, Salvador-Bahia
Prof. Marco A. Botelho, UFBa/PPPG, Salvador-Bahia
Prof. Rogerio C. de Godoy, PPPG, UFBA, Salvador-Bahia (1994)
Dr. Ludek Klimes, Charles Universität, Prag
Dr. Petr Bulant, Charles Universität, Prag

Publications

Since its beginning the directors and leading scientists of the Institute have assured that the results of research work was properly published, in particular in peer-reviewed journals and books. The long list of publications of the Institute from 1964 to the end of 2012 approaches the number of 1400.

The strong motivation of Ph.D. students at any time essentially contributes to a great deal of these publications. The publication list of the Institute therefore includes also the Ph.D. theses accomplished within this time by students of the Geophysical Institute. We have extracted the Ph.D. theses accomplished during research work at the Geophysical Institute and have listed them by year of completion in **Supplement 1** of this Chapter.

On the other hand the unified efforts of members of the Institute is also visible in a large number of book publications in which members of the Institute were involved as Authors or Co-Authors as well as Editors or Co-Editors. We have listed these summary publications in **Supplement 2**. Also this list is ordered by year of publication.

In both supplements numbers in square brackets at the end of a reference refer to the corresponding number in the publication listings of the Geophysical Institute, ordered by numbers: (1) Publications of the Geophysical Institute until 1984 (nos. 1-300), (2) Publications of the Geophysical Institute since 1984 (starting with no. 301).

The Secretariat

An institution having scientific ambitions cannot survive without a capable and well maintained secretariat. From the very beginning the acting directors of the Geophysical Institute have taken care that a competent team of secretaries was available to support the efforts of the scientific employees. Due to their quiet, knowledgeable and sympathizing manner the secretaries took care of a very harmonic and personal climate in the Institute.

For the first years of the Institute there was only one secretary, Mrs. Steidel. When she left in 1969, Mrs. Mukai became the chief secretary, supported by Mrs. Stühlen on a Third-Party position. Anneliese Hoinkis first took over the Third-Party position, but soon followed Mrs. Mukai as chief secretary. Due to the intensive research activities of the Institute and its scientists, the secretaries' clerical work and obligations became larger and larger which called for additional personnel in the secretariat. Various clerical staff members who were paid from Third-Party sources helped to take care of the manifold typing tasks, such as Mrs. Lüdecke or Heidi Gadau. In particular Ingid Hörnchen became, for many years, the most important helper of the chief secretary to deal with the numerous typing and administrative tasks which the scientists asked for. Ingrid Hörnchen left in 1979 and followed Gerhard Müller to become his chief secretary at Frankfurt University. When Anneliese Hoinkis left the Institute in 1976, for a few years Mrs. Lohrengel and thereafter Mrs. di Pillo took over the position of the chief secretary, until in 1981 Gaby Bartman could be hired on this position. Already in her first year, the secretariat was faced by the transition from typewriter to work on the PC. The introduction of the PC into the secretaries' office allowed managing major additional tasks which arose when the SFB 108 was installed at the University in 1981 with its administration at the Geophysical Institute.

As a consequence of the installation of a second Chair or Applied Geophysics at the Institute, also a second permanent secretary's position was involved. Silvia Stühlert started on this position. She was followed by Claudia Payne who administers her tasks with enormous personal enthusiasm and engagement until today. Gaby Bartman retired in June 2013 and is followed by Kerstin Dick.

Already in 1969 the financial affairs were separated from the tasks of the chief secretary and a new position was obtained to deal with the accurate administration of the university funds and the numerous additional Third-Party fundings. In the beginning this task had been one of many others for Anneliese Hoinkis, when she started on a Third-Party position. But when she became chief secretary, Mrs. Michael was hired who remained at the Institute until she retired in the beginning of the 1980s. Her tasks were taken over for a short time by Agnes Warth and finally by Monika Hebben who managed the Institute's university and Third-Party funds until her retirement in 2012. Nowadays Marina Dewes is responsible for the financial affairs.

In 2014, when the Geophysical Institute celebrates its 50 years existence, a competent three-ladies-team takes care of the administrative requirements of the Institute: Kerstin Dick and Claudia Payne in the secretariat and Marina Dewes as financial expert.

When in 1981 the administration of the SFB 108 was installed at the Geophysical Institute, also an additional position was necessary to administer the funding of all individual subprojects, which involved the cooperation of all university institutes in geosciences, belonging to three different faculties. Silvia Bachman could be hired for this voluminous task. She not only administered the funding of the SFB 108 until its end in 1994, but she also continued to take care of the funding of the subsequent SFB 461 which ran from 1996 to 2007 and covered institutes from three faculties. When the SFB 461 ended, Silvia Bachman had reached the age for retirement.

The Technicians

For an institution with experimental work, in the 1960s a well equipped mechanical workshop was a necessity. Günter Volk was hired as head of this workshop. His main task was to develop, construct and service recording systems for seismological instrumentation. Having obtained the craftsman master's degree in mechanics, he was able to lead and teach apprentices. Various apprentices, after having served a three-years term of learning at the Institute, successfully passed their final examinations as fellow craftsmen.

In the 1960s also a photo lab belonged to the basic installation of the Geophysical Institute. When the corresponding skilled lady, Mrs. Baumgarten, geb. Meier, left in the early 1970s, her position was transferred to the electronic lab and the photo lab was closed. In later years, nevertheless, its installation was extremely useful when Petra Scheil-Illich, within the frame of the SFB 108, for a number of years was responsible for the preparation of numerous drawings, slides and other photographic tasks.

From the very beginning Stephan Mueller took care that the Institute received an excellent electronic shop. The first leader of this unit, the E lab, was Herbert Buggle. The next one was W. Schnerr, who in particular accompanied seismic-refraction experiments in Portugal and finally decided to accept an offer of the Meteorological Office at Lisbon. Additionally Werner Nold, fellow in electronics, was employed in the E lab. He remained at the Institute for many years, until he was offered a leading position at another electronic laboratory on the western campus of the University. Furthermore Matthias Diestl was a long-year member of the E lab in the 1970s.

Around 1971-72 Otto Gothe became the leading electronic engineer. He was a particular friend of seismic-refraction field experiments and took care of a thorough servicing and casing of the sensible instrumentation, so that the equipment was able to survive the rough field work. When he joined for the first time one of the many experiments in France, he had studied with particular interest the mechanical clocks of the French equipment which allowed to leave an instrumentation unoccupied in the field and have it recording seismic events at pre-given times. Soon, he had equipped the Karlsruhe and Stuttgart seismic-refraction MARS-66 stations with such clocks. Otto Gothe left the Institute in the early 1980s, having reached his age of retirement. Also Manfred Rittershofer joined the E lab in the 1970s. He remained here until he retired at the end of the 1990s. He supported in particular the investigations for induced seismicity in the Swiss and Austrian Alps and in the Romanian Carpathians and he took care of a successful installation and smooth performance of the seismic networks in the Rhinegraben and in Romania.

Hans Stecker was the next leader of the E lab. He accompanied field excursions for the supervision of dams in Romania and seismic-refraction experiments. In particular he took care of the manifold seismic field equipment during the major seismic and seismological experimental work in the Rhenish Massif in 1979.

With Dipl.-Ing. (FH) Heinz Hoffmann, for the first time an engineer could be hired who had obtained his engineering degree at a special engineering school (FH) which nowadays compares to a university degree. From 1980 onwards he supervised the Rhinegraben seismic network, he accompanied field expeditions into Romania and numerous seismic-refraction field experiments such as in Ireland in 1982, in particular, however, seismic-refraction expeditions to Jordan (1984) and to Kenya (1985 to 1990). Together with the leading electronic engineers of the E labs at the Universities of Berlin, Frankfurt and Hamburg he worked on the development of new digital seismic equipment for seismic-refraction fieldwork. However, the cooperation was extremely complex, furthermore major funding for a large number of instruments could not be obtained at the time being. Consequently no company could be persuaded to take over a further industrial development. Only the foundation of the GFZ Potsdam after 1989 delivered a sufficient large financial basis to take care of nation-wide digital seismic equipment in large numbers in the early 1990s which then was bought from U.S. companies. During the time of Heinz Hoffmann, also Werner Fischer, Horst Laske, Andreas Reimann, Andreas Ruf and Matthias Schoch were employed as members of the E-Laboratory.

Since the beginning of the 1990s Werner Scherer is heading the E lab. Due to his engagement the installation of a powerful network in Romania could be accomplished in the frame of the SFB 461 “Strong Earthquakes”. His engagement also was essential during the fieldwork of the teleseimic projects KRISP 93/94 and Kapverden. He was in particular engaged in the technical installation and performance of the Karlsruhe Broadband Array (KABBA) with installations at Bucharest, Romania, in Norway, Luxembourg and in the Upper Rhine Graben. Today he is being supported by Hartmut Thomas.

To realize seismic supervision of real-time recording, in 1981 Dipl-Ing (FH) Hans-Peter Bluhm was hired. In the frame of the Hochschulbauförderungsgesetz (law to regulate funding of universities) in 1984 the HP 1000/A600 computer allowing real-time data management could be bought. The time critical real-time processing as well as the offline processing of digital data of mobile earthquake stations (PCM 5000, PCM 5800) was solved by H-P. Bluhm. These pieces of work were the basis for the following teleseismic experiments and their data handling. H-P Bluhm started also to install a Work-Station pool at the Institute. After H-P Bluhm left, Dipl.-Inform. (FH) Petra Knopf overtook the position as system engineer for the meanwhile enlarged IT-infrastructure. The increasing use of PCs made it necessary to employ an additional technician, Peter Dausch, for their servicing. After he left, Thomas Nadolny was transferred from the E lab into that position.

For the data collections and proper transfer of earthquake data of the Rhinegraben network to the German earthquake bulletin, first Doris Wagner was responsible. When computer-based collection of the telemetric stations and the seismic networks were introduced, Dipl-Ing. (FH) Rainer Plokarz became responsible for data processing and management and was supported by Doris Wagner. In 1994 the earthquake service Baden-Württemberg was founded and the seismic networks of the Rhinegraben area were transferred to the Geologic State Survey at Freiburg. Since then Doris Wagner took over service of the Institute’s library. After her retirement Rainer Plokarz took over also this duty in addition to his various other tasks for SFB 461 projects. So he also took over the data management of KABBA, supported by Jörn Gross who took particularly care of real-time acquisition and the systematic data preparation.

Supplement 1: Ph.D. and Habilitation theses with geophysical background based on research work at Karlsruhe

Numbers in square brackets behind a reference refer to the corresponding number in the publication listings of GPI

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6. Applied Geophysics from 1983 to 2007

Peter Hubral and Jürgen Mann

In 1983 the Ministry of Education and Cultural Affairs Baden Württemberg authorized the installation of a second professorship at the GPI, the Chair for Applied Geophysics. The reason for the approval was directly related to the Continental Deep Drilling Program (KTB) which was imminent at the time. The Program was planned to be the largest geoscientific research project in Germany, it took place from 1987 to 1995.

Professor Karl Fuchs was directly involved in the project's planning stage. His professional competence and rhetoric qualities have persuaded his colleagues at the Faculty of Physics that a vast amount of seismic measurements would come up which could only be handled by an Applied Geophysicist with experience in data processing, analysis and interpretation. Thus, the Faculty of Physics approved the request and the position was announced.

Peter Hubral was offered professorship for this newly created chair in 1983. After his transfer from Bundesanstalt für Geowissenschaften und Rohstoffe Hannover to Karlsruhe, he began to establish a new working group together with Ph.D. candidates, especially considering that there were no permanent positions for researchers allocated to the chair.

Thomas Rühl, Reinhard Lengeling, Holger Zien, Guido Kneib, Hans Huck und Jörg Schleicher were among the first Ph.D. Students. They contributed immensely to building a working group, carrying out the KTB-Project as well as other research projects that followed. During this time, Peter Hubral received some support from Professor Martin Tygel (IMECC/UNICAMP, Campinas, Brazil), who had cooperated with him in Hannover as research fellow of the Alexander-von-Humboldt-Foundation (AvH) and who began to visit the GPI on a regular basis.

Later on, this cooperation brought Jörg Schleicher a one-year AvH Feodor-Lynen Scholarship with a research visit to Campinas and eventually a professorship at IMECC UNICAMP. Hans Huck was also able to visit Campinas at the time. Unfortunately, he broke off his Ph.D. studies to take on an impressive career in the publishing and media sector.

As soon as the KTB Project started in 1987, many intensive cooperations with national and international research teams were initiated. The primary topics were seismic data processing and analysis of wide-angle refraction measurements as well as 2D and 3D reflection-seismic measurements and VSP borehole measurements at great depths in the surroundings of the KTB location. Extensive measurement-data was available, from which an increasingly differentiated seismic image of the underground could be made. The most significant employees at the time were Dr. Ewald Lüschen, Dr. Walter Söllner and Dr. Xiao-Ping Li. They held full research positions and also co-supervised degree candidates and Ph.D. Students.

Peter Hubral was constantly busy with securing research funds from third parties to support his Ph.D. Students, so that up to 10 young researchers could be employed with part-time positions in best times.

The second-largest project was undertaken in the 90's. It was efficiently funded by the EU and headed by Dr. Claudia Kerner. The research work was performed in cooperation with researchers from Imperial College and Birkbeck College, London. The topic was in most part the theoretical investigation of seismic absorption- and spreading mechanisms during wave propagation in random media. Dr. Kerner was able to enlist the competent help of Professor Ru Shan Wu (University of Santa Cruz, California) who stayed at the GPI for six months. Dr. R.

Gerhard *Pratt* (today: Professor & Department *Chair* at *Imperial College*, University of *London*) also visited the GPI for a longer period of time.

It was always important for Peter Hubral to have his students cooperate with renowned guest scientists. He was successful to invite, in addition to Martin Tygel, also Dr. Tijmen Jan Moser (Holland) and Professor Serge Shapiro (Russia) as AvH-research fellows. During his time in Karlsruhe, Serge Shapiro wrote his habilitation thesis. This was also the time when Dr Boris Gurevich from Russia (today: Head of Department, Curtin University, Australia) worked on a poroelasticity-project at the GPI. Prestigious AvH prize winners followed in the 90's: Dr. Sven Treitel (USA), Professor Enders Robinson (USA), Dr. Boris Gelchinsky (Israel) and Professor Norman Bleistein (USA).

Due to excellent contacts to Brazil, where Peter Hubral spent some time as guest professor before and after he became professor at the GPI, there were many Brazilian geophysicists who visited the GPI throughout the years. Those were, for example: Professors Rogério de Godoy, Reynam Pestana, German Garabito, Edson Sampaio, Marco Bothelho und Lourenildo Leite.

Professor Bjørn Ursin from Norway was also a regular guest at the GPI. The Mathematician Professor Dr. Mikhail Popov (St. Petersburg Department of V.A. Steklov Institute of Mathematics of the Russian Academy of Sciences, Russia) was another guest scientist who frequently visited the GPI (partially supported by the GPI). He had obtained international recognition for his research on ray seismics. Throughout the years Professor Sergey Goldin (Russia) was also a very welcome visitor and always a long-lasting source of inspiration for Peter Hubral and his team.

Ray-seismics and seismic imaging methods, in particular with true amplitude preservation, were always important main research topics at the Applied Geophysics group in Karlsruhe. Four international workshops on this subject took place in Karlsruhe and at the Lufthansa Training Center in Seeheim (Bergstraße). These events were efficiently co-organized by Claudia Payne.

After the KTB Project ended many more research projects were carried out. There was another EU-funded project on „*Seismic Imaging“.* In particular, the DFG Collaborative Research Center on „*Non-Destructive Testing“* in cooperation with University of Stuttgart should be mentioned. Serge Shapiro was deeply involved in this project and supervised several Ph.D. candidates.

During the beginning of the 90's Peter Hubral turned towards industrially funded research projects. In 1997 the Wave Inversion Technology (WIT) Consortium was founded in cooperation with Martin Tygel in Seeheim. The consortium has been funded exclusively and to this day by oil- and exploration companies. The main research topics have been accurate and efficient target-oriented seismic modelling, imaging, and inversion using elastic and acoustic methods.

One of the most outstanding scientific achievements of WIT research was the development of the Common-Reflection-Surface (CRS) Stack Technology. Its theoretical foundations were formulated during the start of the 80's by Professor Bortfeld (Clausthal), however, they could not be implemented at the time due to the lack of data processing capacity.

The idea worked so that the number of sponsors climbed up to 15 at best times. The working group Applied Geophysics of University of Hamburg led by Professor Dirk Gajewski joined WIT, as well as the research group of Professor Serge Shapiro from the FU Berlin (temporarily).

The following researchers were employed during the time 1983 to 2007 (most of them were Ph.D. candidates): Iain Bush, Steffen Bergler, Erik Duveneck, Robert Essenreiter, Stephan Gelinsky, Norbert Gold, Christian Hanitzsch, Zeno Heilmann, Thomas Hertweck, German

Höcht (he coined the expression CRS), Hans Huck, Makky S. Jaya, Christoph Jäger, Uwe Kästner, Andreas Kirchner, Tilman Klüver, Ingo Koglin, Guido Kneib, Gerd Liebhardt, Jürgen Mann, Alexander Müller, Jörg Müller, Thilo Müller, Tobias Müller, Tamara Prokovskaja, Matthias Riede, Thomas Rühl, Joerg Schleicher, Petra Schruth, Miriam Spinner, Kai-Uwe Vieth, Markus von Steht, Ulrich Werner, Martin Widmaier, Jörg Zaske, Yonghai Zhang und Holger Zien. Also in the time 1983-2007 approximately 70 graduate students completed their studies in the Applied Geophysics group.

Several Ph.D. candidates and researchers have received international awards for their research activities. In 1998 Jörg Schleicher was awarded the *J. Clarence Karcher Award* of the Society of Exploration Geophysicists (SEG). In 1999 Thilo Müller received the *van Weelden Award* from the European Association of Geoscientists & Engineers (EAGE). In 2002 Yonghai Zhang received the *Loránd Eötvös Award* of the EAGE together with Steffen Bergler and *Peter Hubral.*

During the years before Peter Hubral's retirement, many Ph.D. candidates and graduate students were co-supervised by his long-term employee Jürgen Mann who kept the connection to the different WIT-groups alive after 2007 and continued to offer his know-how to WIT's industrial partners.

In 2006 the direction of the WIT-Consortium was transferred to Prof. Dirk Gajewski at the University of Hamburg while Professor Shapiro founded his own Consortium.

A colloquium to honor Peter Hubral entitled „Making Waves about Seismics“ took place in 2007 in the Karlsruhe Castle (Gartensaal). Many former Ph.D. candidates and scientists who had met Peter Hubral in his scientific career participated in this event.

Today, the WIT-Consortium comprises of a global network of working groups. These are: the applied geophysics group at the University of Hamburg, the mathematical-geophysical group at Campinas University, Brazil and the Geophysical Institute at the Karlsruhe Institute of Technology. Associated members are: The Geophysical Institute at University of Pará in Belém, Brazil, NORSAR Kjeller, Norway and the Fraunhofer ITWM in Kaiserslautern.

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7. Seismic networks in the Upper Rhinegraben and in the Vrancea (Romania) focal zone: Contributions of the Geophysical Institute to the earthquake services of Baden-Wuerttemberg and Romania

Klaus-Peter Bonjer

The seismic real-time surveillance of the Upper Rhinegraben was one of the important objectives when the Geophysical Institute of Karlsruhe University (GPI) was founded by Stephan Mueller (Fig.1) in 1964. A real-time data transfer from the remote high-sensitivity seismic sensors to the datacenter in the GPI could only be realized by radio telemetry (Fig. 2) due to the technical capabilities and the postal regulations at that time. Because radio waves do not stop at national borders, it was technically possible to connect the telemetric networks of the GPI, the Institute de Physique du Globe, Strasbourg (IPG), and the Swiss Earthquake Service, Zuerich, (SEDZ). These networks had been implemented and developed in the late 1960s and early 1970s. However, the use of stationary telemetry systems, and in particular cross-border telemetry, was not really legal in Germany, since the approved licenses were only valid for so-called mobile stations. Fortunately, the intervention of the European Council with the ministries for postal issues in the capitals Bonn and Paris was successful in allowing the legal transmission of these data in 1980. After years of struggle, the efforts of Karl Fuchs (Fig.1), who had succeeded St. Mueller at the GPI, of A. Roche, E. Peterschmitt and Michel Cara, all at IPG, and of St. Mueller, who had left GPI to become head of the Geophysical Institute at the ETH-

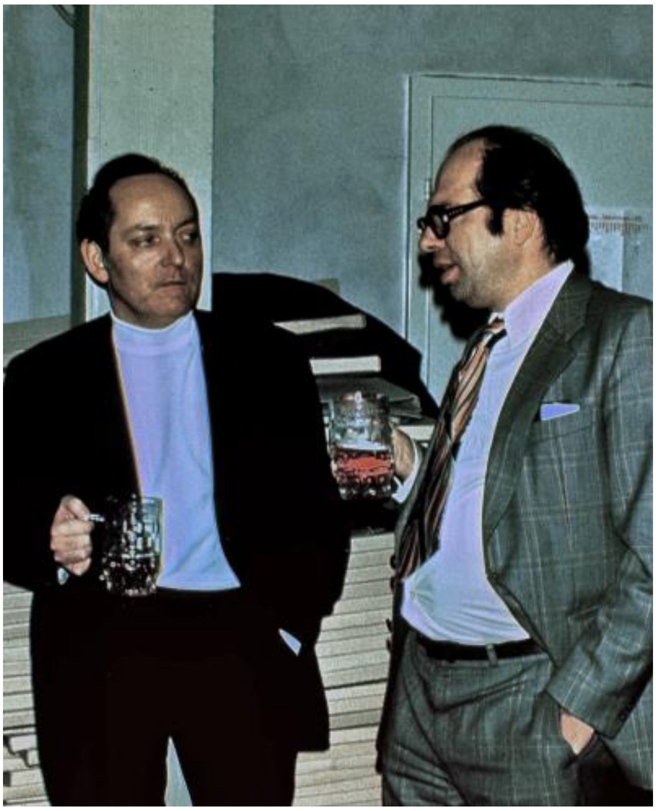


Fig. 1: Stephan Mueller and Karl Fuchs at a Ph.D. celebration on January 1976 (GPI-archive).

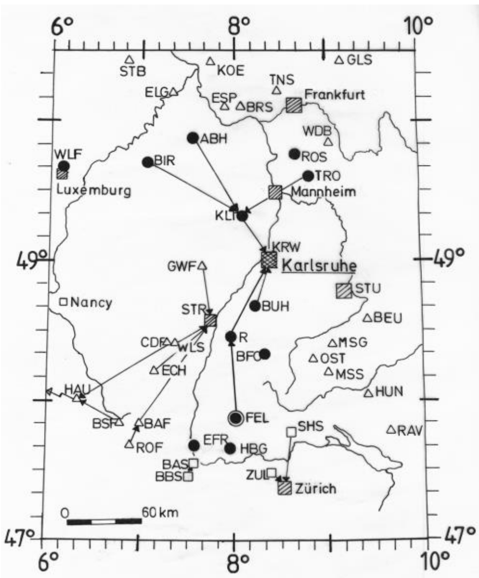


Fig. 2: Position map of the telemetry lines of the seismic networks of the university institutes in Karlsruhe and Strasbourg. The station at the Feldberg (FEL) acted as a relay for the Swiss station Blauen (BBS). To enable reception in Strasbourg and in Karlsruhe, an additional relay at the Hornisgrinde (R) was necessary. Station Buehlerhoehe (BUH) was equipped with two antennae. One was directed towards Strasbourg, a second towards Karlsruhe. The data of the French stations ROF and BAF (later replaced by LOM and MOF) as well as WLS were received in Strasbourg and Karlsruhe without additional technical measures. In the northern Rhinegraben, station Kalmit (KLT) acted as relay for the northern stations Birkenfeld (BIR), Alteburg (ABH), and Tromm (TRO).

Zuerich and director of the SEDZ, led to the legal implementation of directional radio links for the continuous real-time transfer, in particular across national borders, of the seismic data from the Upper Rhinegraben for use by all three institutes.

In parallel with the installation of the telemetry lines, time-signal receivers, a time encoder and decoder, DC-amplifiers and ink-recorders were developed and manufactured in the labs of the GPI (Fig. 3). These components enabled the acquisition of analog seismic data

Fig. 3: Components of a stand-alone station. All instruments were manufactured in the labs of the GPI, with the Geotech S-13 seismometer.

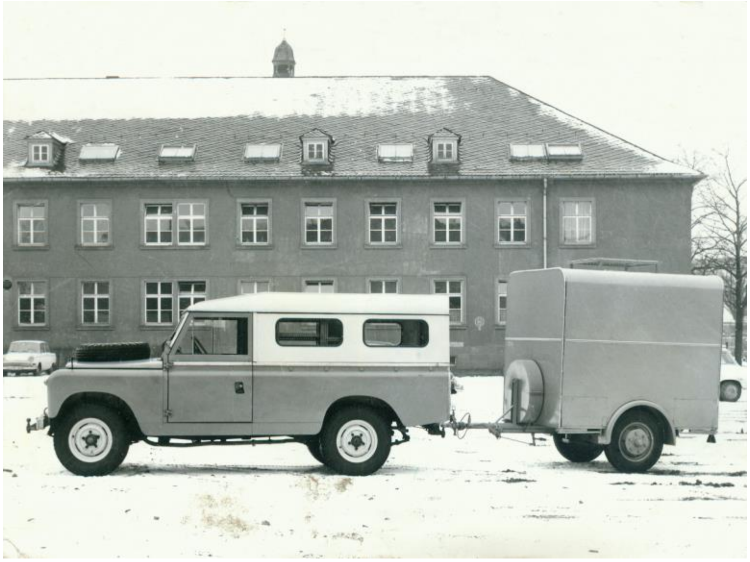


Fig. 4: The mobile station, assembled by the GPI. Long-duration tape recorder and ink monitor, timing unit, filters, and amplifiers, and buffered batteries were arranged in the trailer.

in the Rhinegraben area (Fig. 5), at large water reservoirs in the Alps like the Austrian lake Schlegeis and the Swiss lake Emosson, and at several large lakes in the Romanian Carpathian Mountains. The idea for the development and manufacturing of seismic instrumentation by the Geophysical Institute was initiated by a 3-year research program for the development of a 'mobile station' (more precisely: a mobile observatory, see Fig. 4) financed by the 'Deutsche

Fig. 5: The ink-monitors (Volk-Schreiber) in the 'telemetry-room'.

Fig. 6: The coupled Hewlett-Packard (HP-1000) A600/A900 computers and the SAS-Decoder of the Lennartz Company.

Forschungsgemeinschaft' (German Research Association or DFG), starting in 1966 (Bonjer and Mueller, 1971). The investigation of the performance of seismic instrumentation, in particular by longterm testing of the amplifiers and the re-calibration of the commercially available seismic sensors, accumulated expertise in the operation and repair of such equipment, which was the basis for the participation in several different priority programs of the DFG during the first decade of the institute. The first practical experience with the digital recording technique was acquired with a **P**ulse-**C**ode-**M**odulation (PCM)-5000 system, manufactured by the Lennartz Company in Tuebingen. That system was first used at the Swiss reservoir Emosson as part of a GPI project of the Collaborate Research Center 77 (SFB 77-Felsmechanik) from 1977 to 1978. In January 1979, a modified and upgraded Emosson system was installed at the seismic station Feldberg (FEL) in the southern Black Forrest (Durst, 1981). This installation and the development of data processing routines for the institute-owned Raytheon computer by Werner Kaminski mark the beginning of the processing of digital earthquake recordings at the Geophysical Institute. Installations of directional radio lines enabled stable data-transmission from the Karlsruhe seismic stations BUH, KLT, FEL, TRO, ABH, BIR and LIM (see figure 2) as well as the reception of data from the French stations in the Jura (ROF/LOM) and Vosges Mountains (BAF/MOF and WLS). The Swiss station BBS was recorded via station FEL. However, it soon turned out that the Raytheon hardware was not sufficiently capable of performing simultaneously the real-time digitization of all these continuous seismic data streams, the online seismic event detection, arrival-time picking and the archiving of the events. An additional issue that required computer support was the offline processing of the event-based data from 6 Lennartz PCM-5000 earthquake stations in Romania (Fig. 33) and 13 Lennartz PCM-5800 stations in the southern Rhinegraben (Fig. 9). In 1984, we implemented two coupled real-time HP-1000 computers (A600 and A900) and a Lennartz SAS-5000 system, linked to the A900 (Fig. 6), to

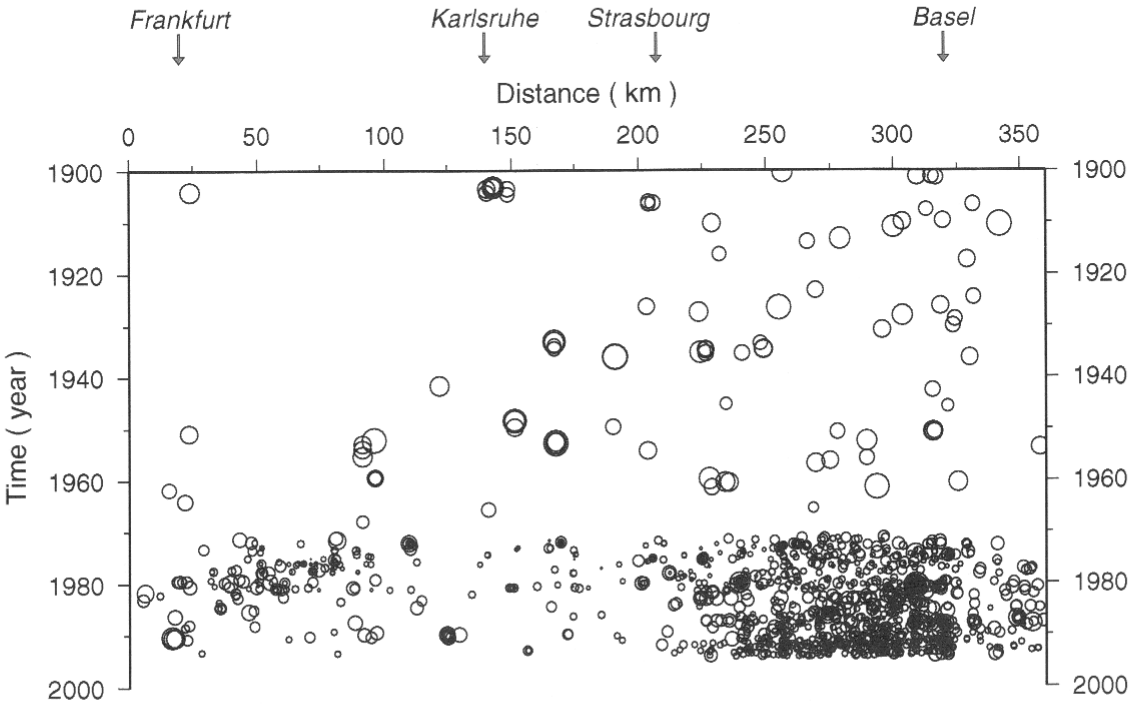


Fig. 7: The seismic activity in the Upper Rhinegraben between Frankfurt and Basel for the years 1900-1979. The rather abrupt increase of the seismic activity around 1971/72 is the result of the implementation of the high-gain networks of the GPI, the French networks in the Vosges Mountains and the Swiss networks in the southern end of the Rhinegraben.

carry out all of these tasks in an efficient manner. To make this system work, quite a number of software programs had to be written to control the interaction of the three computers and to run the data-transfer code, the format conversion programs and the seismological processing software. Hans-Peter Bluhm, the newly hired system-engineer, expertly accomplished this complex task. Several additional people supported the primary GPI scientists and engineers during the course of the development of this integrated system. In particular, the special

contributions of Heinz Hoffmann from our Electronic Lab, colleagues from the Swiss Earthquake Survey in Zuerich, and Ioanna Apopei (GPI) must be acknowledged, especially in the early phases when the system was being developed, tested and first implemented. The funds for purchasing the hardware for this project were provided by the ‘Hochschulbau-Foerderungsprogramm’ of the state Baden-Wuerttemberg, the Collaborative Research Center (SFB) 108 ‘Stress and Stress Release of the Lithosphere’, the VW-Foundation, and the Federal Ministry of Science and Technology, Bonn, through the International Bureau of the Nuclear Center, Karlsruhe.

The growing amount of collected seismic data (see, e.g., Fig. 7, 8) by the GPI required ever more automated processing systems for efficient data management. The necessary improvements were provided by H.-P. Bluhm. He introduced a database system, originally one that he had developed for chemical analysis, to implement an event association scheme

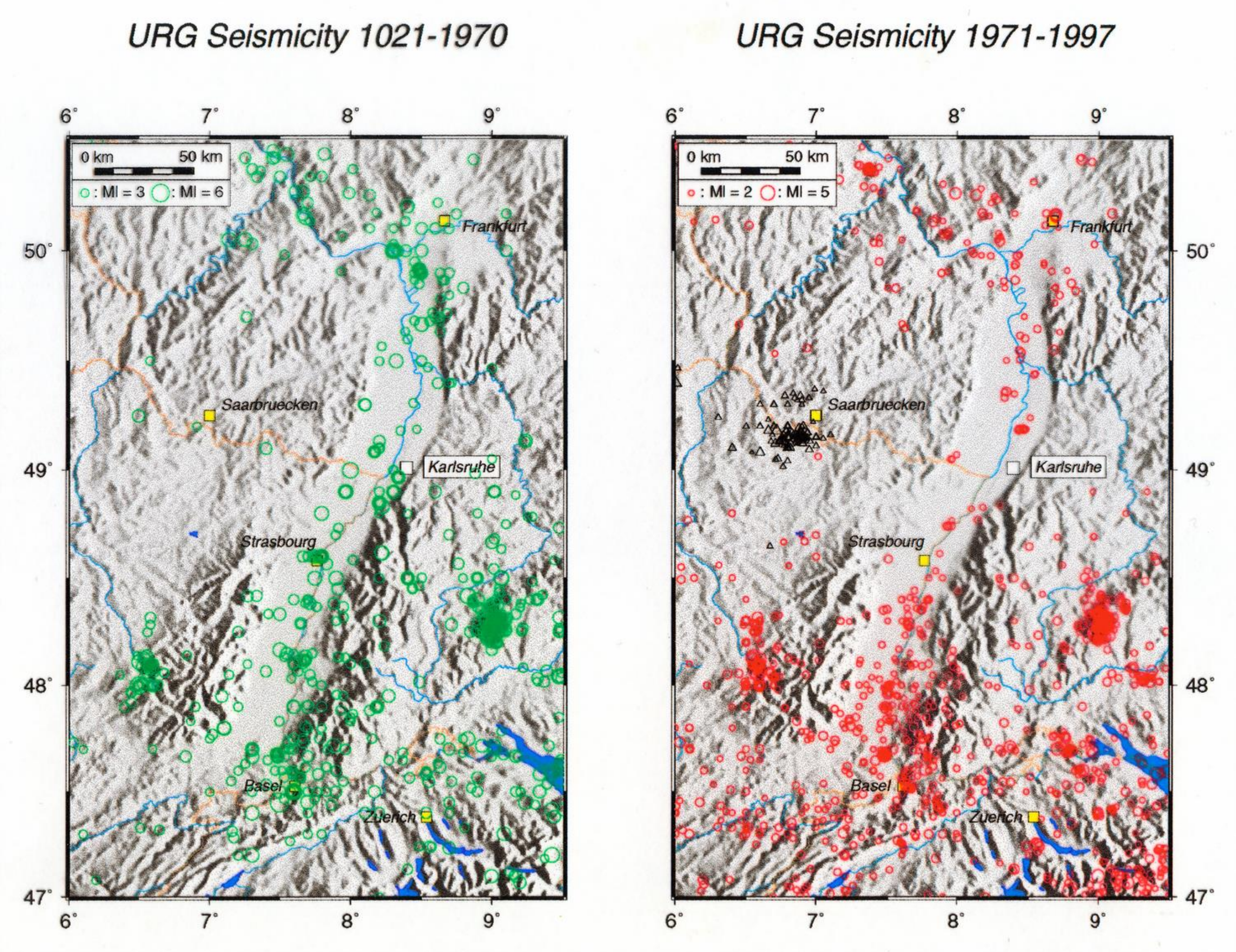


Fig. 8: The seismicity of the Upper Rhinegraben from 1021-1997: Period 1021-1970 (left figure; data are from an earlier version of the catalog of Leydecker, 2011); period 1971- 1997 (right figure; data are from the nrift35-file of Bonjer, 1979). Note the similarity of the distribution of ‘felt’ and (mostly) microearthquakes. About 25 years are seen to be sufficient to discover the significant epicentral patterns in the Upper Rhinegraben area.

that used all seismic channel arrival-time picks, and this enabled the automatic determinations of earthquake localizations. The database was implemented on a HP workstation, which had been made available through a special program (‘WAP-Programm’) of the Faculty of Physics. This first HP-workstation of the institute facilitated the straightforward and fast use of internationally approved seismic analysis programs for Unix-Platforms, such as SAC. The successful combination of the data-acquisition, format-conversion and data pre-processing codes on the HP-1000 A600 and A900 systems as well as the database-controlled processing of the relevant seismological information continued until the early 1990s when the performance of the A900 became unstable. Fortunately, in 1993 a PC-controlled acquisition and processing system of the seismic telemetry and PCM data had been implemented by Lani Oncescu and Mihaela Rizescu (Oncescu et al., 1996) and was running in parallel with the HP-systems, thus minimizing the loss of data. The great advantage of the newer PC-based system (SAP, see Oncescu et al., 1996) was the real-time hypocenter and magnitude determination as well as the dissemination of the determinations by email in near real-time. This data acquisition and processing system became, together with the real-time telemetry, the nucleus for the newly created earthquake survey of Baden-Wuerttemberg in 1993. A separate implementation of the SAP-system was installed by Mihaela Rizescu at the 'Erdbebenstation Bensberg' of the University of Cologne.

The acquisition and installation of the 'Karlsruhe' earthquake stations in the Rhinegraben area had been enabled by several different funding sources: appointment funds of Stephan Mueller, institute budgets, DFG projects, appointment funds of Karl Fuchs, the DFG priority program 'Plateau Uplift', the VW-Foundation, and the SFB 108. Unfortunately, the diversity of funding sources for the 'Karlsruhe' stations meant that funding for the project fluctuated with time. In the early 1990s the announced discontinuation of the funds of the SFB and the lack of financial support from the GPI and the University threatened the cessation of the operation of the 'Karlsruhe' seismic networks and, therefore, the end of the cross-border seismic surveillance of the Upper Rhinegraben on December 31, 1992. To avoid the closing of the Rhinegraben networks of the GPI, in 1990 the search began for an institution that was willing and capable to overtake the operation of the networks. In the search for a long-term source of funding, the GPI contacted the DFG as well as the Federal Agency for Geosciences and Natural Resources, Hannover. These attempts were not successful. However, a first informal meeting of GPI members Klaus-Peter Bonjer, Sonja Faber and Hans-Peter Bluhm with R. Schweizer of the 'Geologisches Landesamt' (GLA) of Baden-Wuerttemberg in Karlsruhe revealed a mutual interest in the transfer of the seismic services and responsibilities to a partner with more stable funding. The concept for a future state seismological service, the 'Landeserdbebendienst' (LED), was presented at a follow-up visit of K.-P. Bonjer and H.-P. Bluhm at the GLA in Freiburg on January 16, 1991. The next steps towards a realization were discussed and decided on during this meeting. What followed was a long, painstaking and time-consuming process to convince the state government of Baden-Wuerttemberg of the importance of the newly proposed seismological service. Unfortunately, these efforts were strongly hindered by a change of the state government, which took place on June 11, 1992.

During the years 1991-1992 the University of Karlsruhe, through the state Ministry of Science and Research (MSR), and the Geological Survey of Baden-Wuerttemberg (GLA) had made repeatedly submissions to the state Ministry of Commerce (MW), Stuttgart, to avoid the closure of the Karlsruhe networks and to implement a seismic survey at the GLA. However, the combined attempts were without success. Also, written appeals from the heads of the seismic services of the Rhinegraben bordering countries Switzerland and France (Dieter Mayer-Rosa, SEDZ; Michel Cara, IPG Strasbourg; Bernard Massignon, LDG Paris-Bruyer) to prevent a shutdown of the data of the Karlsruhe network received no response from the State Government. In the end, the initiation of the implementation of an earthquake survey at the GLA in Freiburg was achieved through public pressure on the Ministry of Commerce (MW) by announcing to the media the shutdown of the real-time seismic monitoring system. This was accomplished by calling a press conference on December 22, 1992 at the 'Gastdozentenhaus' of the University Karlsruhe (see Appendices 1-3). The public pronouncement was agreed on and supported by the chancellor of the University. Although the press conference was a beginning, additional efforts by the MSR, the University of Karlsruhe, the GPI, and the DFG as well as by the seismic surveys of the neighboring countries were necessary for further progress. Finally, on April 26, 1993, the Council of Ministers of the State Government of Baden-Wuerttemberg decided to transfer the earthquake services from the universities of Karlsruhe and Stuttgart to the Geological Survey in Freiburg by June 1, 1993. As agreed on, the transfer of the responsibilities for maintaining the telemetry-network and the PCM-5800-stations took place on March 31, 1994. This transfer included the responsibility for the data interpretation and the dissemination of the seismic data to the national and international datacenters. An earlier handing over was not possible because of the lacking infrastructure at the GLA at that time. The uninterrupted real-time seismic surveillance of the Upper Rhinegraben area was ensured by two actions:

1. The DFG unblocked the partly frozen financing of the subproject D6 of the SFB 108 (project leader K.-P. Bonjer) for 1993.
2. The GLA Freiburg financed the operation of the networks for the time period of January 1 to March 31, 1994.

By April 1, 1994 the newly created earthquake service at the GLA Freiburg took over the operation of the seismic networks, the processing and analyses of the seismic recordings and the dissemination of the data to the national datacenter at the Central Observatory Graefenberg.

Timeline of the installation of the seismic surveillance networks in the Upper Rhinegraben area and in Romania

Upper Rhinegraben

I. Telemetry stations (FM-telemetry and frequency modulated seismic channels):

BUH (Buehlerhoehe, Black Forest): February 1967 (tests started in autumn 1966)
KLT (Kalmit, Palatinate): January 1971
FEL (Feldberg, Southern Black Forest): April 1971
TRO (Tromm, Odenwald): November 1972
BBS (Blauen, Switzerland via Feldberg): June 1974
ABH (Alteburg, Hunsrueck-Soonwald): November 1975
BIR (Birkenfeld-Ruppelstein, Hunsrueck): November 1976
LIM (Kaiserstuhl/Limburg via WLS in the Vosges Mountains): Summer 1987

First sites for a seismic real-time surveillance system in the Upper Rhinegraben area (Buehlerhoehe, Feldberg, Kalmit, and Tromm) were selected by the founder of the Geophysical Institute (GPI), Stephan Mueller. The installation of the stations Buehlerhoehe and Kalmit were performed by Stephan Mueller, Joerg Ansorge, Dieter Seidl, Dieter Mayer-Rosa, K.-P. Bonjer, Werner Nold, and Guenter Volk. The following people were involved in the installation of the stations FEL, TRO, ABH, BIR, BBS, LIM and the relay-station at the Hornisgrinde (middle Black Forrest) as well as in the modification of the new directional radio links: K.-P. Bonjer (project leader), Manfred Rittershofer, W. Schnerr, Werner Nold, Matthias Diestl, Otto Gothe, H. Stecker, in particular Heinz Hoffmann, as well as Horst Laske, Richard Lohmann, and Michael Wagner.

1969: Development and implementation of a computer-based yearly seismic bulletin by Dieter Mayer-Rosa for the station Buehlerhoehe (BUH) and the station of the Geodetic Institute (KRL). The bulletins of the years 1966 and 1967 were the first computer-based seismic bulletins of a seismic station in Germany. The computer code was then used at the Central Observatory Graefenberg for the yearly data compilations of the German seismic stations. The first joint bulletin was edited for the year 1969 (Aichele and Mayer-Rosa. 1971).

II. Digital stations:

November 28-30, 1978: Installation of a Lennartz 8-channel-PCM-5000 station at the FEL site by Helmut Durst and Eiko Raekers (diploma-thesis Durst, 1981).

1980-1983: Testing of 6 PCM-5000 stations at sites in Basel, Efringen, Feldberg, Buehlerhoehe, and Karlsruhe. These stations were provided by the Federal Ministry for Sciences and Technology (BMFT), Bonn, for the scientific cooperation with Romania (see in Fig. 33 the position map of the PCM-5000 installations).

SFB 108 stations in the southern Rhinegraben-Black-Forest area

A total of 13 Lennartz PCM-5800 with three-component seismic sensors were acquired within the subproject D6 and installed permanently for the duration of the project (Fig. 9). A

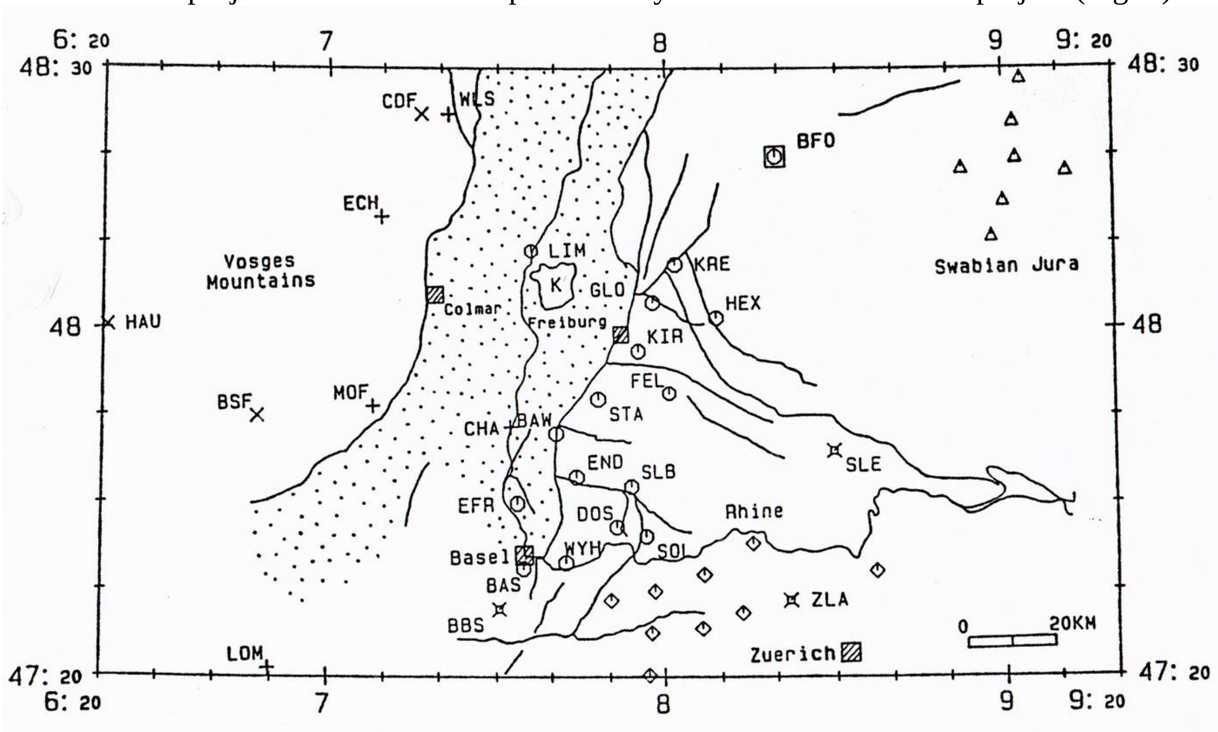


Fig. 9: Map of the earthquake stations in the southern Rhinegraben area: CRC 108-B3 PCM-5800 stations (circles), Nagra telemetry-network (diamonds), Swabian-Jura network of the Institute of Geophysics Stuttgart (triangles) as well as the French telemetry networks in the Vosges Mountains and the telemetry stations of the SEDZ.

few stations had to be moved for various reasons during the project. Throughout the years, quite a number of colleagues, seismologists, geologists and petrologists visited the different geological station locations and seismic installations (e.g. Fig. 10).

The timeline of the installations was as follows:
1984: BAS, EFR, END, FEL, SOL
1985: STA (24.5.), BUH (26.7.), SLB (7.8.), BRE (15.11.), GLO (21.11.)
1986: BFO (23.7.), LIM (28.11.)
1987: WYH (14.4.), KIR (16.12.)
1988: DOS (17.2.), HEX (25.5.), BAW (1.9.)
1990: KRE (17.10.)

(The PCM-5800 station of the Schiltach Black-Forest Observatory (BFO) was purchased from the budget of the Observatory.)

Fig. 10: Visitors of the PCM-station Schlechtbach (SLB) in the southernmost Black Forest. From left to right: John Ebel, Boston College-Weston Observatory; Carl Kisslinger, CIRES, Boulder, and K.-P. Bonjer, GPI. The station SLB was installed 20 m deep in the granite of a former well-room (Brunnenstube).

Romania

The following research work of the Geophysical Institute, University of Karlsruhe, in Romania is reported here:

- Induced seismicity: the seismic surveillance of the large water reservoirs in the Carpathian Mountains of Romania;
- The Vrancea earthquake of March 4, 1977: the aftershock campaign;
- The digital acquisition of the Vrancea earthquake activity and the first studies of the source- and site-effects of intermediate-depth Vrancea earthquakes;
- The installation of the digital strong-motion network within the subproject B3 of the CRC 461.

The seismic surveillance of the large reservoirs in the Romanian Carpathian Mountains

The hazard of great water reservoirs from earthquakes that are induced by the impoundment and continuous operation of some reservoirs is an acute safety risk. Because of the experience of strong earthquakes that were apparently induced by the filling of large reservoirs, in March 1973 UNESCO recommended the seismic surveillance of all great reservoirs. As part of the March 1973 recommendations, UNESCO included instructions about how the seismic surveillance should be carried out.

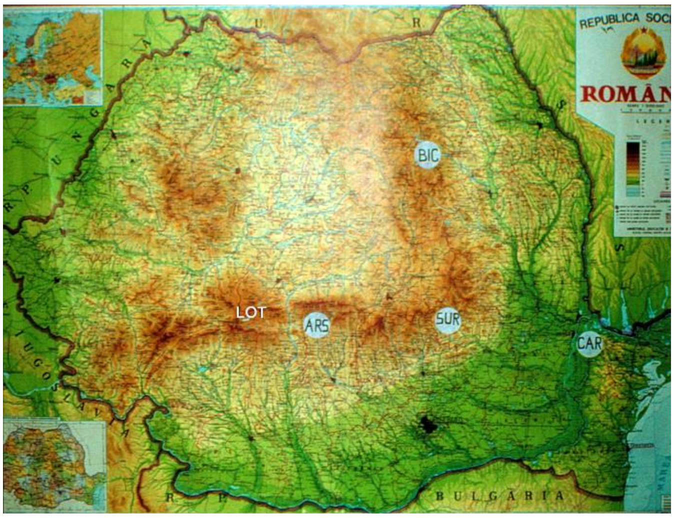


Fig. 11: Position map of the first installations of seismic stations by the GPI at great Romanian reservoirs: Bicaz (BIC), Lotru (LOT), and Vidraru-Arges (ARS).

Based on these recommendations, on June 19, 1974 in Bucharest the Geophysical Institute of Karlsruhe University (GPI) and the Romanian Institute of Hydroenergetic Studies and Designs (ISPH), Bucharest, reached a cooperative agreement to monitor any possible induced seismicity at the great water reservoirs in the Romanian Carpathian Mountains. The specific goal of this seismic monitoring was to detect changes in the local earthquake activity caused by the construction and the operation of such reservoirs. At the meeting where this project was initiated the following people participated:

From the GPI: Karl Fuchs (chair of the GPI, leader of the project on induced seismicity of the SFB-77-Rock Mechanics), Rainer Blum (GPI/SFB-77) and Klaus-Peter Bonjer (GPI);
From the ISPH: Constantin Budeanu (technical director), Constantin Privighetorita (head of the geology department), Traian Moldoveanu (member of the department of geophysics), Gheorghe Merkler (member of the geo-department of the ISPH and visiting scientist at the GPI).

The Izvorul Muntelui-Bicaz and Vidra-Lotru reservoirs:

November 1974: According to the cooperative agreement of June 19, 1974, two analog seismic stations were permanently installed (Fig. 11). One was positioned at the base of the gravity dam of the lake Izvorul Muntelui-Bicaz (BIC, see Fig. 12) and the second one at the abutment area of the rock-fill dam of the Vidra-Lotru reservoir (LOT).

Participants of the GPI: Guenter Bock (head of the German team; SFB-77), Klaus-Peter Bonjer (seismologist-in-charge), Manfred Rittershofer (electronic technician).
Participants of the ISPH: Traian Moldoveanu (head of the Romanian team), Victor Dumitrescu (electronic technician), several additional technicians and drivers, and Gheorghe Merkler (geologist; visiting scientist at GPI).
Financing: Resources of the GPI and ISPH.

Fig. 12: The first seismic station was installed at the greatest Romanian reservoir Bicaz, following the cooperative agreement between the GPI and the ISPH. The station was installed at the base of the gravity dam. The photo shows the installation team: Guenter Bock, K.-P. Bonjer, Manfred Rittershofer (all GPI), and Victor (Bebe) Dumitrescu and Gheorghe Merkler (not seen because of taking the photo) after successful startup of the station BIC.

The Vidraru-Arges reservoir:

April 1975: The permanent installation of an analog seismic station (ARS) in the area of the eastern abutment of the arch dam (Fig. 13) was performed by the scientists and technicians of the GPI and ISPH. This installation was pushed forward after an accident in the operation of the reservoir, which had led to a rapid, total emptying. The financing of the construction work and of the instruments was enabled by the ISPH, the power company Arges, the SFB-77, and the GPI.

April 29 – Mai 24, 1976: A seismic survey was conducted in order to find the optimal positions for three telemetry stations for the hypocenter determination of the earthquakes in the immediate vicinity of the lake.

Participants GPI: Guenter Bock (responsible leader of GPI team), Klaus-Peter Bonjer (team leader during second half of the survey), members of the electronic lab.
Participants ISPH: Traian Moldoveanu (responsible leader of ISPH team), several technicians and drivers, and Gheorghe Merkler (geologist; visiting scientist at GPI).

November 1976: Members of the GPI (Guenter Bock (team leader), H. Stecker and M. Diestl (electronic lab)) and of the ISPH (Traian Moldoveanu (team leader), and several technicians and drivers) installed the telemetry station TE1 at the end of the reservoir and TE2 and TE3 at both sides of the reservoir as well as receivers and monitoring instruments at the central station ARS (see, e.g., Nourescu et al., 1979; Moldoveanu et al., 2010). With the exception of the sensors, all components were manufactured in the electronic and mechanical labs of the GPI. Financing was made possible with funds from the BMFT, Bonn, within the scientific and technical cooperation agreement with Romania. First results of the seismic surveillance of the great reservoirs as well as of the impact of the big Vrancea Earthquake of March 4, 1977 on the seismicity pattern in the lake areas were presented by Nourescu et al. (1979).

Fig. 13: The double curvature arch dam Vidraru-Arges. The station ARS was installed in the area of the eastern abutment (left side) of the dam. The red VW-Bus of the GPI is parked at the left side of the dam.

The Vrancea, Romania, earthquake of March 4, 1977

(see e.g. Fuchs et al., 1979; Mueller et al., 1978; Radu et al., 1979)

On March 4, 1977 (Figures 14, 15), an Mw=7.5 earthquake occurred at intermediate depth in the Vrancea zone of the southeastern Carpathian Mountains. The earthquake caused considerable damage country wide (Fig. 16) and in particular in the capital city of Bucharest (see the photo show). More than 1500 casualties resulted due to the earthquake.

The German government donated three seismic telemetry stations to the Romanian government as part of its humanitarian aid program. That donation initiated the set-up of a country-wide system for the real-time surveillance of the seismic activity across the Romanian territory. The stations were composed of seismic sensors, transmitters and receivers, as well as associated monitors with a radio-controlled (DCF) timing unit.

Fig. 14: The clock at the hotel Athene Palace stopped at the time of the arrival of the strong motion phases of the March 4, 1977 earthquake. The photo was taken by Karl Fuchs on March 8, 1977.

The telemetry stations were installed and maintained by a team from the GPI (Klaus-Peter Bonjer, responsible team leader; Guenter Bock (deputy team leader); R. Broetz (Geophysical Institute, University of Frankfurt); Bruce Cassels, Juergen Fertig, Karl Fuchs, Martin Jentsch, Manfred Rittershofer, Gerhard Sattel, Wolfgang Schott, Guenter Schroth, Horst Stoeckl, Rainer Wenderoth) together with the Romanian colleagues Traian Moldoveanu, Gheorghe Merkler, Victor Dumitrescu, Gabriel Tudorache (all from ISPH), and Radu Dumitrescu (Central Institute of Physics, Magurele) at appropriate sites in Sinaia (southern Carpathian Mountains), Carcaliu (western Dobrodgea), and Istrita (southeastern Carpathian Mountains Bend). The seismic data streams were recorded continuously with the 'Volk-paper-recorders' (see the photo show) at the Faculty of Physics at the Nuclear Center in Bucharest Magurele (CSEN). For the first time the seismic activity of Romania could be monitored in real-time at a center, where a 24-hour service enabled the communication of near real-time information to the responsible authorities in case of an earthquake above a defined level. This was the beginning of a seismic real-time information system for the Romanian Government and the public, but, of course, in a still rudimental form.

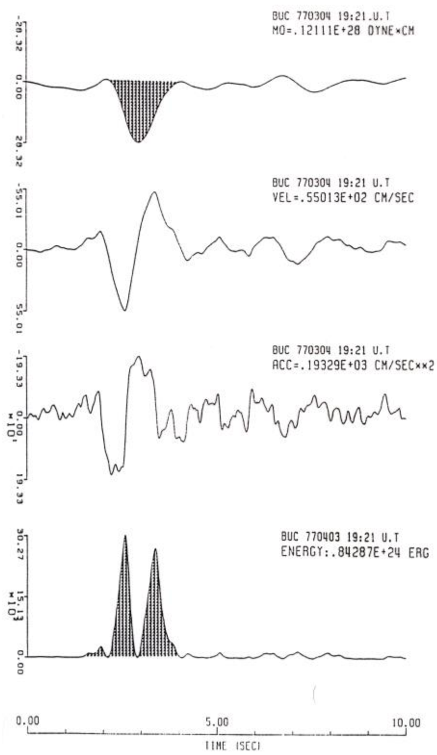


Fig. 15: The Vrancea earthquake of March 4, 1977: The INCERC SMAC-B recording processed by Bonjer and Apopei (1991).

Immediately after the 1977 earthquake a rapid installation of the GPI mobile earthquake stations was deemed necessary to monitor the early aftershock pattern as completely as possible. This was needed to map the extent of the source area and to learn more about the redistribution of the stresses in the focal area due to the earthquake faulting. The installation and the servicing of these mobile stations were made possible during the state of emergency in the first two weeks after the earthquake by the use of helicopters of the Romanian government (figures 17, 18, 19). The Center for Physics of the Earth and Seismology (CFPS), at Bucharest-Magurele, an institute of the CSEN, supported the operation of the mobile stations through the efforts of Ioana Apopei and additional members of staff and students of the Faculty of Physics until the end of the campaign in June 1977.

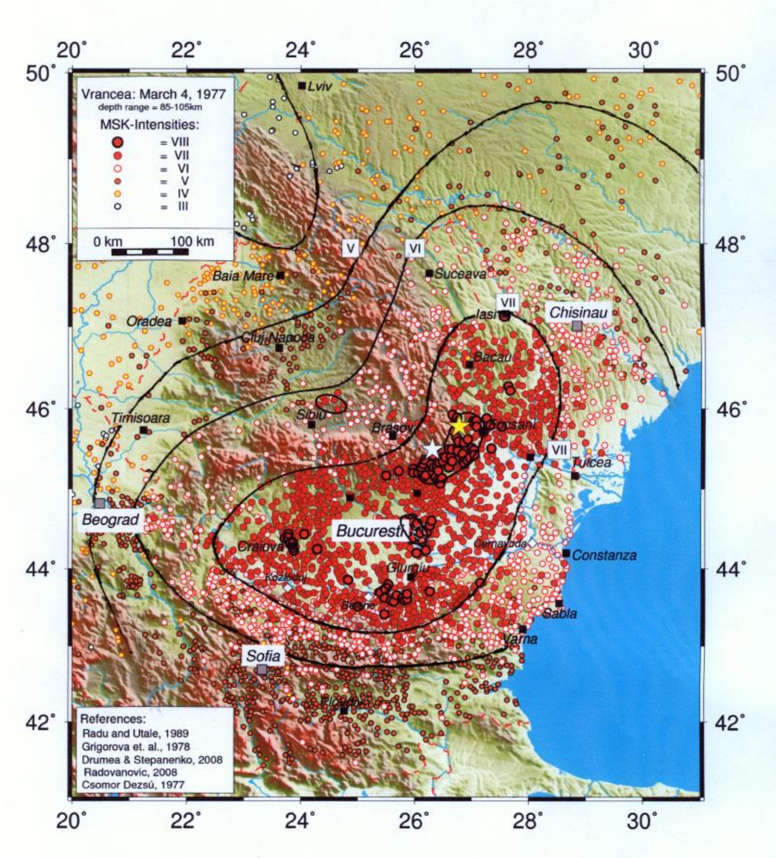


Fig. 16: Unified macroseismic map of the Vrancea March 4, 1977 earthquake (Bonjer, 2012). Stars: yellow: rupture initiation; white: rupture stopping area.

Doris Wagner (GPI) joined the team for the second half of the campaign and organized the readings of the records and a proper archiving of the recorded data. Peter Zeil (Geophysical Institute, University of Munich) installed temporarily two Lennartz PCM-5000 stations of the Munich institute at the

The aftershock campaign:

Fig. 17: Helicopter transport of the installation and service teams to the mobile stations. The photo shows the landing site at Carcaliu.

Fig. 18: Karl Fuchs on the flight to Prisaca, the rupture initiation area.

epicenter areas of Prisaca and Gura Teghii (see Fig. 16). Furthermore, he prepared two PCM-5000 stations, together with the staff of the CFPS, for the implementation at the central observatory of the CFPS in Muntele Rosu (Cheia) and in Focsani. These two stations were also a donation of the German government.

Results of the aftershock campaign were presented by representatives of the GPI and the CFPS, in particular by Karl Fuchs, at national and international conferences. A summary of the results and a presentation of a new model of the Vrancea earthquake scenario (Fig. 20) were published by Fuchs et al. (1979).

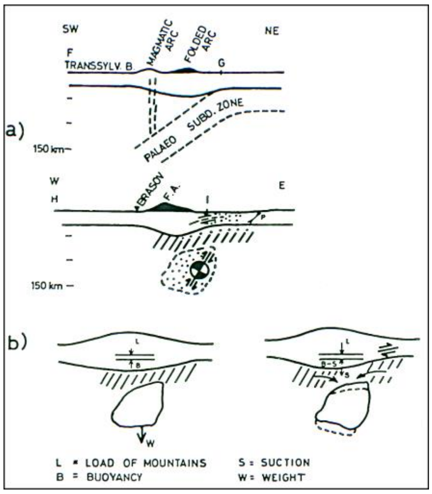


Fig. 19: The aftershock campaign: Karl Fuchs at the epicenter area in Prisaca, in the south-eastern Carpathian Mountains.

Fig. 20: Karl Fuchs 'Suction Model' of the Vrancea earthquake scenario.

The means for purchasing the instruments and for financing the campaign were provided by the German government through the Federal Ministry of Science and Technology (BMFT), the Federal Ministry of the Interior (BMI), and the Romanian government through the National Councils for Science and Technology (CNST), and Nuclear Energy (CSEN) as well as by the Ministry for Electrical Energy (MEE).

Photo show of the aftermath of the Vrancea earthquake of March 4, 1977:

Examples of the damages in Bucharest and in the country site:

Bloc Nestor in the center of Bucharest: photo taken from hotel Athene Palace on March 8, 1977.

Bucharest: Bv. Balcescu (March 7, 1977)

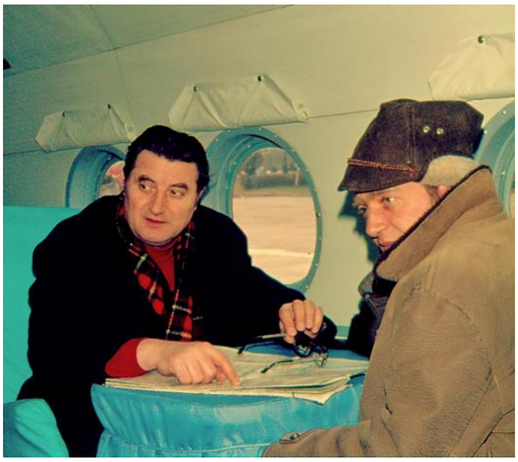
Bucharest: Piata Rosetti (March 7, 1977)

Bucharest: Bv. Balcescu (March 7, 1977): Faculty of Architecture, Restaurant Dunarea, and the Biserica Enei, which was demolished on purpose during cleanup after the March 4, 1977 Vrancea event.

Area of the stopping of the rupture process: Damage in **Buzau** (left figure) and in **Nehoiu** (right figure). Differences in the damage pattern as a function of site-effects or construction or workmanship?

Examples from the aftershock survey:

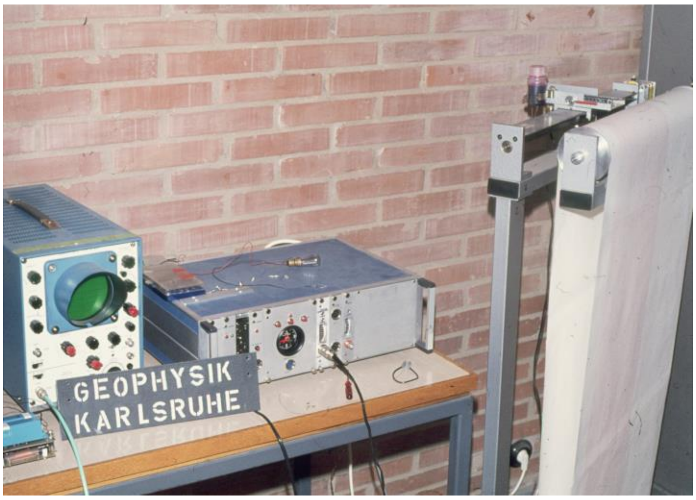
Targu Ocna: Site search with government helicopter. Instruction of the service team.



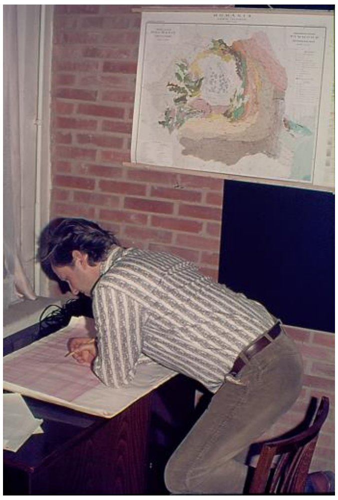
Two weeks of state of emergency followed the earthquake. During this time cross-country flights with government helicopters facilitated the site search, the installation and maintenance of the seismic stations. The secret services of the ministry of the Interior and Foreign Affairs always participated in these missions.

The Karlsruhe teams which served the local station operators: W. Schott, G. Sattel, M. Knecht, H. Stoeckl, M. Jentsch, G. Schroth (left figure); W. Schott, R. Wenderoth, B. Cassel and staff of the hotel-restaurant Magurele. This hotel hosted the German teams during the 3.5 months lasting aftershock survey (right figure).

Arrival of the instruments donated by the German Government in Magurele: Ion Cornea, director of the CFPS; H. Lennartz (Tuebingen), K.-P. Bonjer.



Headquarter in Magurele: Recording unit of the first long distance seismic telemetry-line in Romania from Sinaia, southern Carpathian Mountains, to Bucharest-Magurele.



Record analysis: **H. Stoeckl**

W. Schott

Instrument control and repair: **G. Sattel**

After-work meeting at the headquarter in Magurele: A. Apostol (CFPS), V. Dumitrescu and T. Moldoveanu (both ISPH), D. Wagner (GPI), R. Dumitrescu (ICF).

Mid June 1977: Celebration of the end of the survey with a banquet at the restaurant Magurele.

Spring 1978: Installation of high-gain seismic stations at the reservoirs Oasa-Sebes (southern Carpathian Mountains) and Fintinelle (Apusen Mountains) by ISPH and GPI technicians. The financial means for the instruments and the campaign were provided by the Romanian companies of the reservoirs and the hydro-electrical power plants.

September 8 -27, 1978:

Installation of a local seismic high-gain telemetry station at Surduc-Paltinis (SUR) in the south-eastern Carpathian Mountains and an analog station in a small gallery at the water reservoir Dragan (DRA) in the north-eastern Apusen Mountains as well as the calibration of the station at the Fintinelle reservoir by GPI and ISPH teams were all accomplished.

Participants GPI: K.-P. Bonjer (team leader), Hans Stecker (head of the electronic lab) and Wolfgang Epp (diploma student);
Participants ISPH: T. Moldoveanu (team leader), V. Dumitrescu, technicians and drivers.
The financing of the instruments, the constructions and the costs for the campaign were taken over by the BMFT, the Romanian power companies, and the ISPH.

July 25 – November 4, 1979: The Surduc Survey

The purpose of the survey was to detect seismically active faults in the vicinity of the reservoirs Siriu and Surduc on the southeastern edge of the Carpathian Mountains, which coincides roughly with the epicentral area of the Vrancea intermediate depth earthquakes (Fig. 21). At that time both reservoirs were still under construction.

After assembly of the GPI and the ISPH teams at the Romanian border at Oradea, the seismic stations at the reservoirs at Dragan, Oasa-Sebes and Vidraru-Arges were inspected, repaired and re-calibrated. During a stop in Bucharest final details of the scheduled 3-months campaign were decided on. The survey started in the first days of August with the installation of a temporary seismic telemetry-network (stations SIR1, PAL, GUR; Fig. 21) in the closer vicinity of the reservoirs. Furthermore, ten seismic mobile stations were deployed around the central station in Paltinis at distances of about 30 to 70 km (Fig. 21). In addition, two 4-component Lennartz PCM-5000 units were installed in the school building of Paltinis, which was used as a headquarter during the survey (Fig. 22, 23). One PCM-station was used for the digital recording of the data from the three telemetered stations and the second for the data from a three-component accelerometer, which was installed in the yard of the school. The fourth channel on each instrument recorded the data of the telemetry station SUR and was used as a trigger for the PCM's. Furthermore,

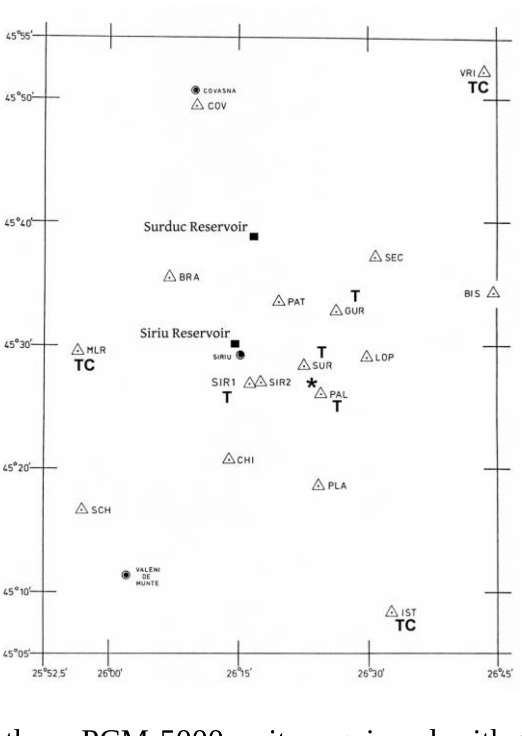


Fig. 21: Position map of the Surduc survey (Jung, 1983). The star shows the headquarter of the campaign: the school in Paltinis. The PCM-5000 locations BIC, CAR, and ARS are shown in Fig. 11.

three PCM-5000 units, equipped with three-component medium-period seismometers, were installed temporarily at the reservoirs Vidraru-Arges (ARS) and Izvorul Muntelui-Bicaz (BIC) as well as in the Dobrodgea at the site of the telemetry-station Carcaliu (CAR=CFR).

These three stations formed a triangle (Fig. 11) around the target area and were intended to record unclipped stronger shocks from local sources and from the Vrancea focal area (see,

Fig. 22: The daily breakfast in the school yard: S. Raikes, D. Wagner, H. Durst, T. Moldoveanu, P. Waegerle, P. Jung, H. Laske, Ion Scolaru, V. Stoian, and I. Dragomir (from left).

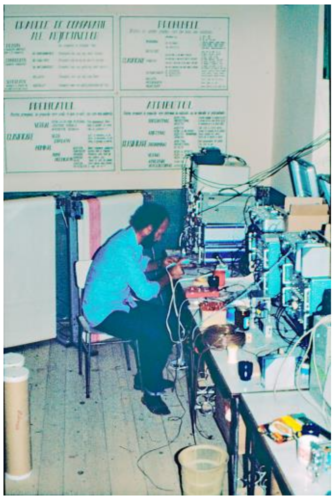


Fig. 23: The headquarter in the school: M. Rittershofer at work.

e.g., Jung, 1983). The financing of the expenses of this campaign was provided by the BMFT through the International Bureau of the Nuclear Center, Karlsruhe, and the Romanian Ministry for Electrical Energy (MEE) through the ISPH, Bucharest.

Participants GPI: K.-P. Bonjer (team leader), Sue Raikes and Eiko Raekers (both served as proxy in the absence of the team leader), Manfred Rittershofer, Manfred Koch, Helmut Durst, Peter Jung, Peter Waegerle, Horst Laske, Doris Wagner and Guenter Volk;
Participants ISPH: T. Moldoveanu (team leader), Victor Dumitrescu, Vasile Stoian, Ion Scolaru, Anatol Sisman, Ion Dragomir (all technicians), and drivers from the ISPH car pool.

Crash-landing of the Swissair DC-8 in Athens

October 7, 1979: Following an invitation from the Chinese Academy of Sciences, on October 7, 1979 the first German seismological delegation (with Karl Fuchs as group leader) began a trip to China. K.-P. Bonjer was one of the members of the delegation. He had left the running of the Surduc campaign in order to participate in the trip to China. At a stopover in Athens the DC-8 of Swissair (flight SR 316), upon which they traveled,

Fig 24: The Swissair DC 8 in Athens on October 8, 1979: the morning after the crash. (The photo is scanned from a Greek newspaper).

suffered a crash-landing (Fig. 24). The German delegation survived the crash without greater injuries. However, 15 casualties resulted from this accident. This visit of the German delegation to China was cancelled due to the crash and was postponed until March 1981.

Upgrade of the seismic station Surduc-Paltinis

July, 1980: Based on the experience obtained during the operation of the Lennartz PCM-5000 in the Rhinegraben and during the 1979 Surduc survey, the first 4-channel PCM-5000 was permanently installed in Paltinis in July, 1980 (Fig. 25). Three channels were used to record the outputs of medium period seismometers (one vertical and two horizontal components). The fourth channel was used for a low-gain vertical component, attenuated by a factor 400 (Jung, 1983).

Fig. 25: Installation work at the seismometer hut (Vizuina Lupuli = Wulfs hut) in Paltinis. From left: P. Jung, H. Laske, H. Hoffmann, and H. Durst.

Participants GPI: K.-P. Bonjer (team leader), Heinz Hoffmann and Horst Laske (both from the electronic lab), Helmut Durst and Peter Jung (diploma students);
Participants ISPH: T. Moldoveanu (team leader), I. Apopei (seismologist), V. Dumitrescu (technician), and technical staff of ISPH.

The micro-seismic survey at the Vidraru-Arges reservoir

April – May, 1982: The purpose of this survey was the determination of high-precision hypocenters of the earthquakes and their focal mechanisms in the immediate vicinity of the reservoir in order to elucidate the effects of lake level changes on the seismic activity. The lake-level changes are a result of the seasonal operation of the reservoir (Nourescu, 1979; Moldoveanu, 2002; Moldoveanu et al., 2010).

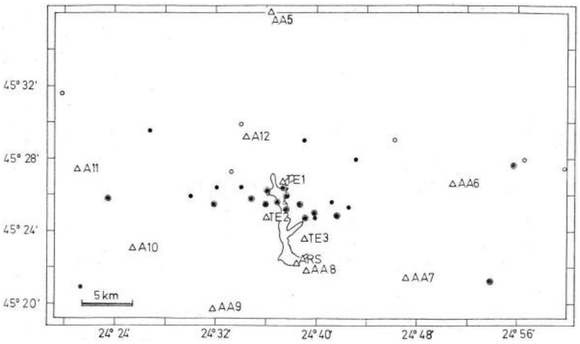


Fig. 26: Position map of the Vidraru-Arges survey: ARS = permanent station in the eastern abutment of the dam; T1, T2, T3 = permanently installed telemetry stations (see the survey report of November 1976); A* = mobile stations. Located events are shown by circles.

The position of the 9 mobile stations (station AA1 is situated in Sambata, north and outside of figure 26) were selected based on a simulation of a focal mechanism comparable to the composite fault plane solution of about 22 events in the reservoir area (Nourescu et al., 1979). In addition, a PCM-5000 was installed during the survey at the central station ARS (Fig. 27). After the completion of the survey the six Geotech Portacorders, which were provided by the BMFT, as well as the clones, manufactured by the labs of the GPI, were transferred to the partner institute, the ISPH. The joint investigations on induced seismicity, which had been initiated in June 1974, ended with this survey.

Fig. 27: Lunch break at the central station ARS. From left: M. Rittershofer, H. Hoffmann, and M. Wagner.

Participants GPI: K.-P. Bonjer (team leader), Heinz Hoffmann, Manfred Rittershofer and Horst Laske (all electronic lab), Richard Lohmann, Peter

Waegerle, Michael Wagner and Dieter Peritsch (diploma students); Participants ISPH: T. Moldoveanu (team leader), Ioanna Apopei (seismologist), Victor Dumitrescu, Vasile Stoian, Ion Scolaru, Anatol Sisman, Ion Dragomir (all technicians), and drivers from the ISPH car pool.

First steps towards a continuous, digital acquisition of the Vrancea earthquake activity with three-component seismometers:

May, 1982: Immediately after the seismic survey at the Vidraru-Arges reservoir, the PCM-5000 that was used during the survey was installed at the Bucharest Observatory ‘Cutitul de Argint’ (Fig. 28). The purpose of the installation was to obtain a quantitative comparison of the historic strong Vrancea earthquake records from the 1t-Mainka seismograph with parallel recording by modern instrumentation. The Mainka seismograph was used routinely for the event recording and magnitude determinations over decades. The parallel recording was considered necessary to prove a presumed deficit in the 5.5-6.5 magnitude range of the Vrancea earthquakes.

Fig. 28: The seismic observatory ‘Cutitul de Argint’, Bucharest: Installation of a 4-channel PCM-5000 with a vertical 2s Geotech S-13, and two 5s horizontal KMI SH1s.

It was hoped to clarify whether or not that deficit is due to an effect of the calibration of the recording instrument or to the particular seismogenic processes in the Vrancea source. For Vrancea earthquakes with intensities greater than I=4-5 the Mainka seismograph showed weakly damped, monochromatic oscillations. Such oscillations were not seen on the PCM recordings and therefore were considered as parasitic rather than as actual earthquake signals. We confirmed this artificial effect on the Mainka seismograph by manually exciting its spring suspension and observing the astaticity of the seismometer mass.

First digital site-response studies in Romania

Spring 1984: The investigation of site responses in Romania were intensified in 1984 with the installation of three more PCM-stations that were all provided by the BMFT within the framework of the governmental cooperation with Romania; they had been tested and up-graded during surveys in the Rhinegraben area and in Romania. Furthermore, the two stations that had been donated by Germany within the human aid program after the 1977 event were reinstalled as well - after being checked and upgraded in Karlsruhe (Fig. 29 a, b). All of these stations had three-component data streams from medium period seismometers as well as a low-gain fourth channel. After the 1984-campaign, the

Fig. 29a: Coffee break during installation work at the telemetry station Carcaliu, northern Dobrodgea. V. Dumitrescu, U. Fischer, A. Gruber, and V. Stoian.

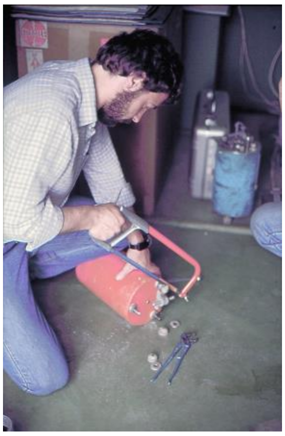


Fig. 29b: A. Gruber fights with a corroded Geotech at Muntele Rosu (MLR).

following sites were equipped with these instruments: Surduc-Paltinis (SUR), Cutitul de Argint (BUC), Bacau (BAC), Carcaliu (CAR=CFR), Focsani (FOC) Muntele Rosu (MLR), and Medias (MED). First results were published by Bonjer and Apopei (1991).

Participants GPI: K.-P. Bonjer (team leader), Uwe Fischer (electronic technician), and Andreas Gruber (diploma student);
Participants ISPH: T. Moldoveanu (Team leader), V. Dumitrescu and V. Stoian.

Ten years cooperation GPI-ISPH: 1974 -1984

Autumn 1984: On the occasion of the tenth anniversary of the GPI-ISPH cooperation, the ISPH organized a symposium in Bucharest to celebrate this event. The Federal Ministry of Science and Technology, Bonn, was represented by Baroness von Schoenburg (IB-Karlsruhe) and a delegate from the German Embassy in Bucharest. K.-P. Bonjer (GPI) gave two presentations about the joint work. Members of the ISPH as well as of the CFPS and other state institutes contributed with presentations to the symposium. Following the symposium, a field trip through the southern Carpathian Mountains and Transylvania, including a visit to the PCM-stations in Surduc-Paltinis (SUR), in Medias (MED) and at the Vidraru-Arges reservoir (ARS), was organized (Fig. 30). During this trip K.-P. Bonjer and V. Dumitrescu performed servicing and re-calibrations at the stations SUR, MED and ARS.

Fig. 30: Visitors at the central station ARS of the Vidraru-Arges network. From left: K.-P. Bonjer (GPI), Mrs. Stanuca, A. Stanuca (deputy director, ISPH Bucharest), Baroness Schoenburg (International Bureau, Nuclear Center Karlsruhe), a woman interpreter, Cornelius Radu (head of the National Seismic Service of Romania, CFPS Magurele), Traian Moldoveanu (Geotechnical Department of the ISPH, Bucharest).

Meeting of the Mixed German-Romanian Governmental Commission on Science and Technology in 1985:

Beginning in 1976, the scientific cooperation of the GPI and the ISPH was accompanied and financially supported by the German and Romanian governments within the framework of the Mixed Commission on Science and Technology (MC). This commission was the body where the joint seismological projects had to be approved. Such an approval was made only at the more or less regular meetings of the MC. This was a mandatory prerequisite for receiving financial funding by the ministries or governmental agencies.

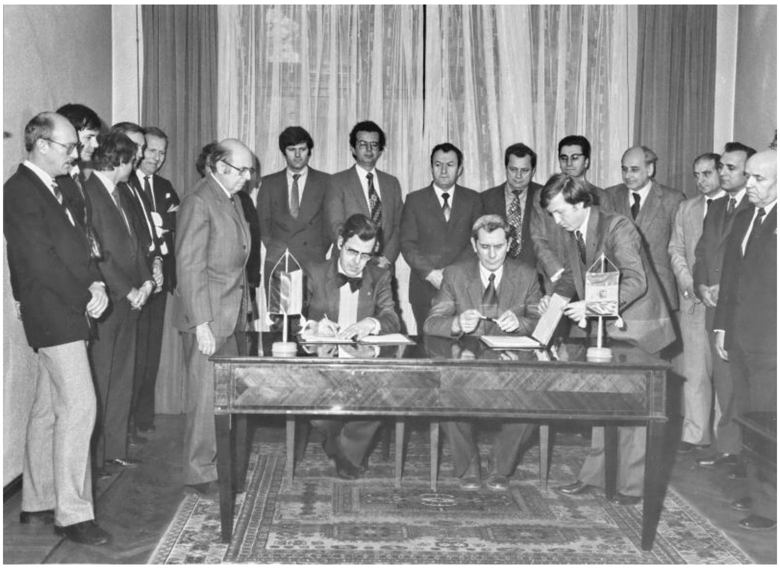


Fig. 31: Signing of the memorandum at the Ministry of Science and Technology (CNST) in Bucharest. The German delegation stands on the left side and the Romanian delegation on the right side. The German delegation was headed by MD Losch. The secretary of the German delegation, von Arnim, is left of MD Losch; the secretary of the Romanian delegation, M. Sbirna, is right of the Romanian leader. In the middle of the back row Prof. Dr. Ursu, the vice-president of the CNST is seen. K.-P. Bonjer (second from left) and A. Cosma, ISPH (second from right), participated in this meeting as experts in the field of seismology.

At the 1985 meeting of the Mixed Governmental Commission in Bucharest (Fig. 31), a memorandum on the cooperation in the field of seismology and seismic hazard was initialed between the GPI and the Center of Physics of the Earth and Seismology (CFPS), Bucharest-Magurele, in addition to the continued contacts to the ISPH. Unfortunately, the GPI-CFPS agreement was never signed. Therefore, the cooperation of the GPI with the CFPS remained very limited. The seismological activities of the GPI in Romania were continued primarily with the ISPH. However, the situation changed considerably after the political change in Romania in December 1989.

Campaign during November 3-20, 1986:

After the August 31, 1986 Vrancea Mw=7.2 earthquake, a GPI team left by car for Romania to collect the PCM-recordings and to perform a re-calibration of the stations SUR, MLR, FOC, BAC, CAR (CFR), and BUC (Fig. 28). After finishing the service tour, a playback station for the recordings was installed at the Lab of the ISPH, enabling them direct access to the data. This was particularly important for a rapid evaluation of the proper functioning of the acquisition instruments and in case of malfunctioning to allow for immediate repair.

Participants GPI: Manfred Rittershofer (technician, team leader), Klaus Zimmermanns and Richard Lohmann (both diploma students);
Participants ISPH: Traian Moldoveanu (team leader), Victor Dumitrescu (technician).

The aftershock campaign following the May 1990 Vrancea earthquakes:
June 1 – mid July, 1990:

Immediately after the Mw=6.9 Vrancea earthquake of May 30 and the strong Mw=6.4 aftershock of May 31 K.-P. Bonjer and Hans-Peter Bluhm went to Bucharest by plane to install a Lennartz PCM-5800 in downtown Bucharest in cooperation with colleagues from the National Institute for Earth Physics (NIEP), the former CFPS. At the same time, a second group (Klaus Zimmermanns, Markus Rudolf, and W. Burkhardt, all diploma students) started by car with 5 more PCM-5800 stations on board. The mission was made possible because the project leaders of the IDNDR-project (**I**nternational **D**ecade of **N**atural **D**isaster **R**eduction) of Karlsruhe University had chosen Romania as the target area just a few days before these earthquakes happened.

The purpose of this survey was the quantification of site-effects in downtown Bucharest using the Vrancea aftershocks. Furthermore, this trip would allow PCM-records of the mainshocks to be collected. Regrettably, only station SUR (see e.g. Fig. 32) and BUC were operating when the May events occurred. In order to compare weak and strong ground motions at the same sites, those sites that had recorded the Vrancea earthquakes of 1977 (INCERC), 1986 (INCERC, ISPH, and NIEP-Magurele), and 1990 (INCERC, ISPH, and NIEP-Magurele) on the analog Japanese SMAC-B and the Kinemetrics SMA1-accelerometers were preferentially selected for the deployment. Additional stations were installed at Calderusani (station of the Geodynamic Institute of the Academy, about 30 km north of Bucharest) and, south of Bucharest near the river Danube, in buildings of the municipalities of Giurgiu and Turnu Severin. Calderusani was considered as the reference station for the site-effect analyses. The survey was conducted in cooperation with the staff of the ISPH.

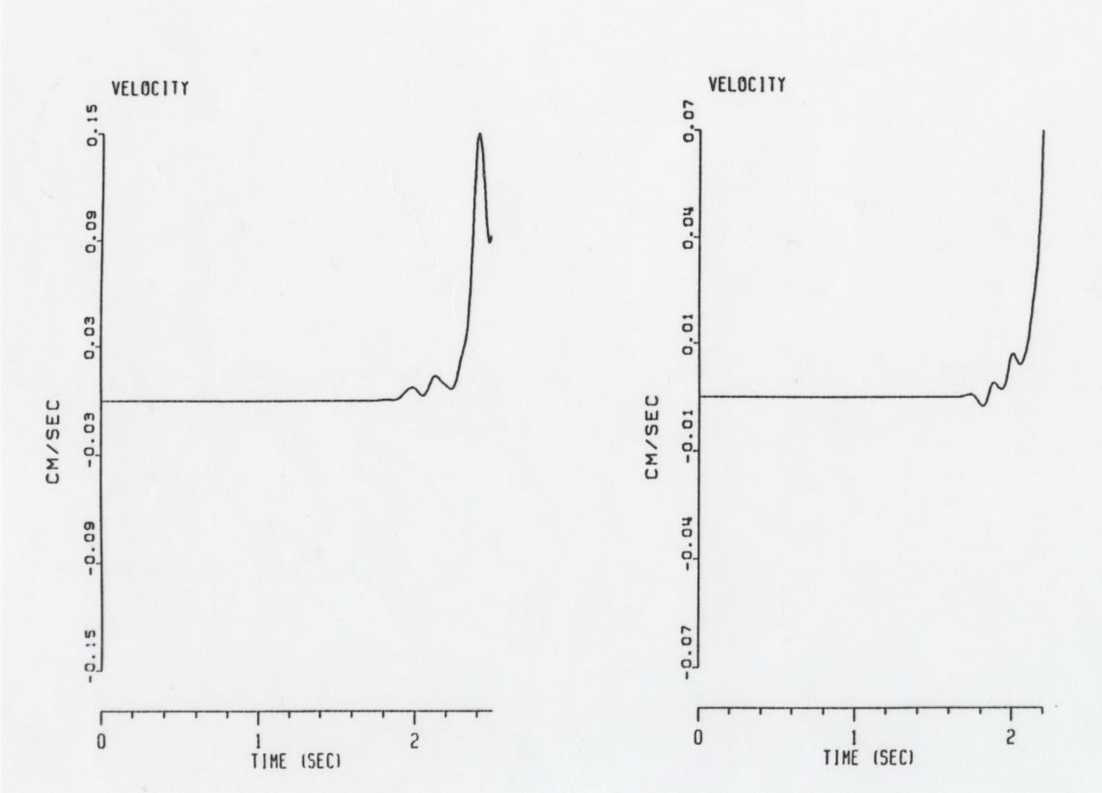


Fig. 32: SUR (see Fig. 33) velocity-recordings of the vertical component of the initial phases of the strong Vrancea earthquakes of August 1986 and May 1990. Note the oscillatory character of the onset. It remains still open whether or not this is due to the source processes or to structural effects at the sources or along the propagation paths.

K. Zimmermanns, M. Rudolf, and W. Burkhardt capably performed the servicing of the stations during this campaign, and they returned the instruments afterwards to Karlsruhe. First results were presented at the ESC-meeting in Barcelona in September 1990 (Zimmermanns et al., 1990) and later analyses were published by Bonjer and Apopei (1991) and Oncescu et al. (1999).

Participants GPI: K.-P. Bonjer (team leader, seismologist in charge), H.-P. Bluhm (system engineer), K. Zimmermanns, M. Rudolf, and W. Burkhardt (all diploma students);

Participants ISPH: T. Moldoveanu, and V. Dumitrescu;

Participant NIEP: M. C. Oncescu (head of the Romanian national seismic network)

Financing: Without a significant financial contribution of the International Bureau of the Nuclear Center of Karlsruhe the aftershock campaign would not have been possible. The Romanian partner ISPH paid the costs of the overnight stays and daily expenses in Romania of the German team.

The seismology project within the Karlsruhe University IDNDR activities: Spring 1991 and September 4-16, 1991

The IDNDR-project of the University of Karlsruhe was supported by the 'Landesforschungsplan' of the state government of Baden-Wuerttemberg in the early 1990s. Within this framework all PCM-5000 stations, which had been installed in 1984, were completely checked and refurbished at the manufacturer Lennartz in Tuebingen during spring 1991. After repair and calibration the instruments were reinstalled at their original locations (Fig. 33) during a campaign in September 4-16, 1991. Furthermore, an absolute timing unit with GPS control was installed at the NIEP data center in Magurele in order to make the data of the NIEP telemetry network compatible with the global seismic data. Until this time the network had been running only with a local time code, which was daily calibrated against a radio-time signal.

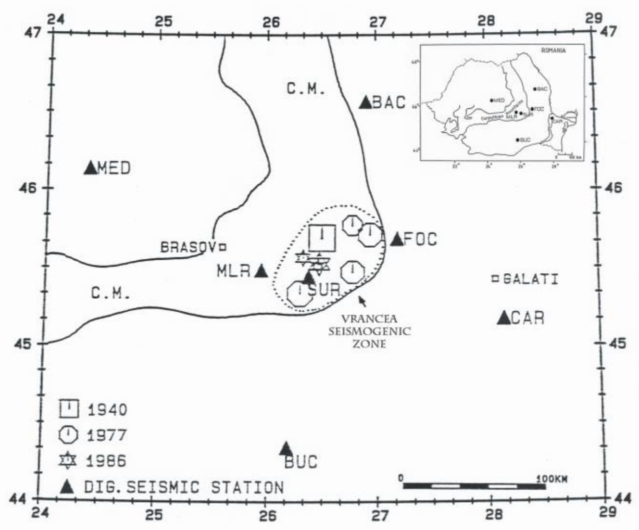


Fig. 33: Position map of the PCM-5000 sites.

Participants GPI: K.-P. Bonjer (team leader), Werner Scherer (head of the electronic lab), and Thomas Plenefisch (diploma student); Participants NIEP: M. C. Oncescu (head of the Romanian national seismic network, visiting scientist at GPI), Constantin (Viorel) Ionescu (head of the electronic lab).

The Pre-CRC-461 Phase

Survey October 25 – November 5, 1995: In anticipation of the already approved **C**ollaborative **R**esearch **C**enter 461 (CRC 461) 'Strong Earthquakes: A Challenge for Geosciences and Civil Engineering' the University of Karlsruhe financed the purchase of six Kinemetrics K2-data-loggers with external standard 2g-accelerometers. A mixed GPI-NIEP team (Thomas Nadolny, Peter Dausch and Viorel Ionescu) installed these instruments in Birlad, Carcaliu, Covasna, and Istrita as well as on the top and in the basement of a multi-story building in Bucharest-Magurele. The installation in the tall building was due to a request from the engineering projects in order to take a step towards the observation of the soil-building interaction. In early October, NIEP experts installed three NIEP owned K2's with internal accelerometers and different measuring ranges in Focsani, Vrincioia, and Muntele Rosu. According to a pre-order agreement with Kinemetrics all GPI accelerometers were to be exchanged with the new EpiSensors as soon as they became available. The NIEP accelerometers were included into this agreement.

The K2-Accelerometer-Network of the Subproject B3 within the CRC 461:

The Seismogenic Potential of the Vrancea Subduction Zone: Quantification of Source- and Site-Effects of Strong Earthquakes (principal investigator K.-P. Bonjer)

Strong earthquakes in the Vrancea focal zone have caused a high toll of casualties and extensive damage over the past centuries. Four major Vrancea earthquakes occurred with moment magnitudes between Mw=6.9 and 7.7 in the last century (see, e.g., Oncescu and Bonjer, 1997). The activity of this seismic zone is dominated by events of intermediate depth. Weak and strong earthquakes accumulate in a small zone beneath the southeastern Carpathian Mountains. This zone is confined to an area of only 20 x 60 km^2. The focal depths range from

60 to 180 km within an almost vertical column, but a few events also have been found down to depths of about 220 km. The high moment release rate and the stationary position of the seismogenic source were the main reasons to choose Vrancea as the target area for the Karlsruhe University IDNDR project as well as for the following CRC 461 (see, e.g., Wenzel and Schmitt, this volume).

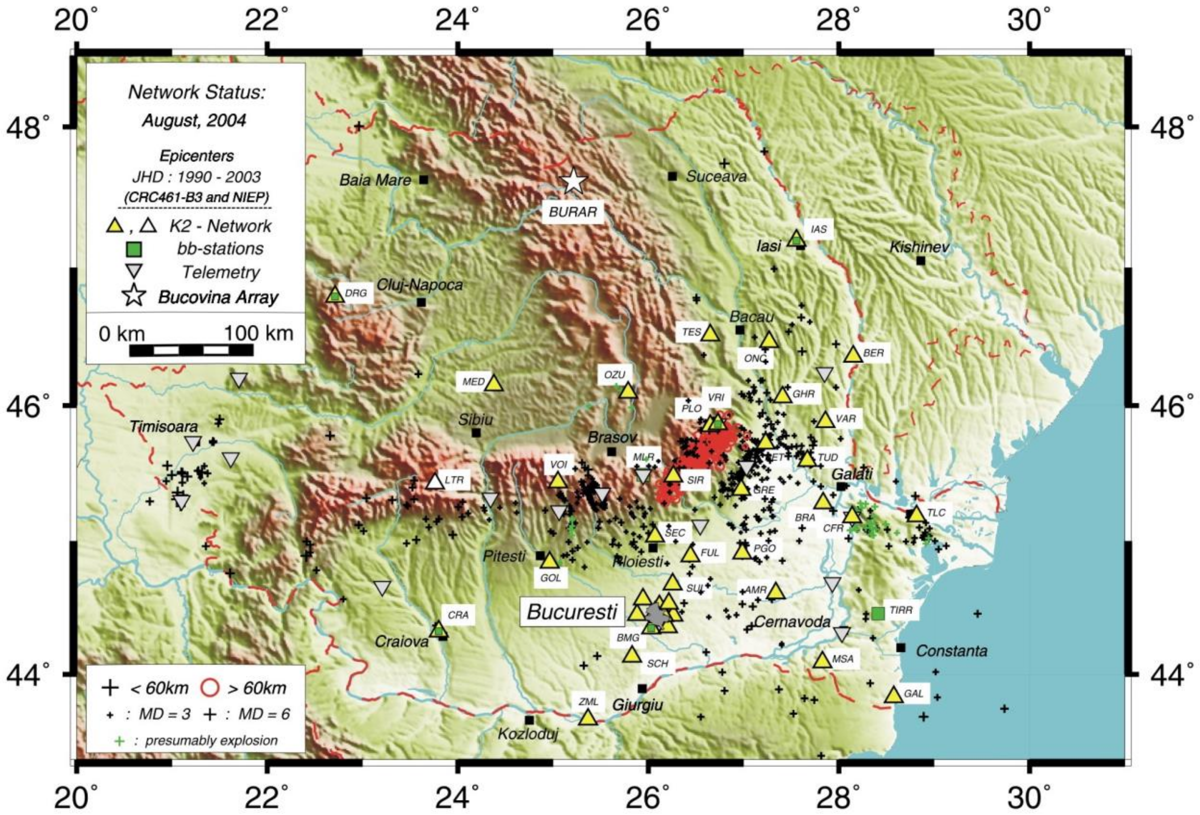


Fig. 34: Position map of the CRC 461- and NIEP K2-accelerometer stations (status of August 2004).

The main objectives of subproject B3 were:

--mapping the fine structure of the seismogenic zone of the Vrancea focal area;

--determining the site effects of different soil and rock conditions, in particular in the capital Bucharest;

--adapting the shakemap philosophy to the Vrancea source;

--developing the proper tools for the state-of-the-art construction of the hazard-maps for strong, past Vrancea earthquakes and for a suite of so-called scenario earthquakes.

The ultimate goal of these investigations was to provide usable information for the mitigation of the impact of future strong earthquakes on the communities in Romania and in the bordering countries. ***To achieve these tasks, a state-of-the-art seismic network was deemed mandatory.***

Monitoring of weak and strong ground motion:

A total of 43 Kinemetrics (KMI) K2-Altus stations were deployed by the GPI-NIEP teams at varying (81) locations during October 1996 until September 2004 (Fig. 34, 35). The free-field stations consisted of three-component EpiSensor sets and three-component velocity sensors of broad-band, medium and short-period types. In addition to the free field installations in the subproject B3, installations for the civil engineering projects also were performed:

Fig. 35: The Japanese analog SMAC-B accelerometer at the INCERC site (in the central background). This accelerometer was the single near-source instrument that recorded the Vrancea March 4, 77 event unclipped (see, e.g., Fig. 15). On the left side the digital K2 datalogger and the forced balance KMI-accelerometer FBA-23 are seen. Furthermore, in the background: on the left side is a KMI-SMA1 analog instrument and on the right the INCERC Wilmot-seismoscope is visible. The velocity sensors of the K2-station, the (red) S-13 and a part of the SH1, are recognizable in the very right part.

July 2, 1998: Instrumentation of a ‘test-building’ at the INCERC ground, which had been requested by J. Eibl for the subproject C1/C2 (Fig. 36 a, b, c). This task was performed by K.-P. Bonjer (scientist in charge), with the electronic specialists W. Scherer (GPI), and G. Chircea (NIEP). Six three-component EpiSensors were installed in the test-building, three in the basement and three in an up-side-down configuration beneath the roof (see Fig. 36 b). The free-field instrumentation consisted of a three-component EpiSensor and a three-component

a) **b)** **c)**

Fig. 36: The test-building at the INCERC-site (a). The roof is decoupled by Elastomer-buffers from the basement. The six three-component KMI FBA-23 accelerometers are at the basement and (upside down) under the roof (b). The two 12-channel K2-datalogger (c) record the 3 basement, and the 3 roof accelerometers as well as the three-component nearly free-field Episensor and the Mark Products velocity-sensor installed in the cellar of the neighboring building (see (a)).

Fig. 37: Instrumentation of a standard 11-story building at the Bv. Stefan cel Mare in Bucharest. The arrow indicates the position of the installation (left figure). Installation of the Episensor under the roof (upside down) and the K2 (right figure).

short-period velocity sensor. The roof of the building was an inverted pendulum, suspended by Elastomer dampers, simulating a multi-story building. The test-building was designed within the subproject C1/C2. The construction was supervised by M. Baur (C1/C2) and members of the INCERC.

May 8, 2001: Installation of three three-component EpiSensors was carried out in the eleventh floor of a standard Bucharest multi-story building in the Bv. Stefan cel Mare

Fig. 38: Briefing at the top of the multy-story building: M. Bayraktarli (project C1/C2), Dan Lungu (owner of the flat, see Fig. 37), INCERC member, K.-P. Bonjer (left figure). The center Episensor is still without thermal protection. The ceramic isolators of the feet are visible (right figure).

(Figures 37, 38). The building had already been registered from the point of view of structural dynamics by the Technical University of Bucharest (UTCB) and the INCERC. Therefore, the response of the building in strong earthquake shaking could be computed. It was anticipated that the future K2-recordings would proof of the correctness of the response computations and could lead to improvements in the theoretical model of the building, if necessary. The installation of the seismic instrumentation was performed by K.-P. Bonjer (scientist in charge) and the electronic specialists W. Scherer (GPI), and G. Chircea (NIEP).

The CRC-UTCB/INCERC boreholes at INCERC site

At the occasion of an expert meeting at INCERC in 2001, the installation of an accelerometer in the 200 m deep hole was presented by UTCB-INCERC, Geotec S.A., and Faculty of Geology and Geophysics (University of Bucharest) representatives (Fig. 39). Due to some

Fig. 39: The attempts to create a reference for the test-building responses: **The Prelude.**
Presentation of the 200 m borehole at the INCERC site: (left figure) the experts; (right figure) emotions: **peace** (Eibl), **happiness** (Lungu), **skepticism** (Bonjer). In the front the borehole mouth with the instrument cable.

problems with the deeper part of the borehole, the accelerometers had to be installed at a depth of only about 160 m by the INCERC specialists. It was decided at that meeting to drill an additional borehole of 100 m and to install ***oriented*** a three-component Kinematics borehole-accelerometer by the CRC.

The instrumentation of the 100 m deep borehole

October 29, 2002: The installation of a Kinematrics three-component borehole accelerometer took place in the 100 m deep borehole on the INCERC site (Fig. 40) for the subproject C1/C2 (Eibl/Stempniewski). The costs were overtaken by INCERC/UTCB, because the 200 m borehole was paid for by the CRC 461.
Participants GPI: K.-P. Bonjer (scientist in charge), Werner Scherer, and Manfred Rittershofer (both from the electronic lab), and George Chircea (electronic technician) from NIEP.

Fig. 40: The 100 m borehole at INCERC site: the Karlsruhe installation:
The team (left figure): Werner Scherer (GPI), George Chircea (NIEP), and Manfred Rittershofer (GPI). (Right figure): the waterproofed box protecting the borehole mouth, and the power supply.

The Early Warning System in Plostina, southeastern Carpathian Mountains

May 26, 2003: The purchase, calibration, and installation of a Kinemetrics three-component borehole KMI-accelerometer in a 50 m deep borehole as well as of a three-component EpiSensor and a short-period seismometer at the Early Warning Site **Plostina** (Fig. 41) was conducted in support of subproject A2 (F. Wenzel). The installation was performed by K.-P. Bonjer (scientist in charge), Werner Scherer (head of the electronic lab GPI), and George Chircea (electronic technician) from NIEP.

Fig. 41: The Early Warning Site Plostina in the center of the southeastern bend of the Carpathian Mountains: the main building and the instrument hut with borehole, K2-datalogger, Episensor, and Mark Products sensor.

October 2004:
A last joint service tour of the GPI-NIEP team (K.-P. Bonjer (project leader B3), Julia Bartlakowski (PhD student at GPI), Werner Scherer (head of the electronic lab at the GPI) and George Chircea (electronic technician, NIEP)) was combined with a documentation of every station of the K2-network (Fig. 42). This was a prerequisite for the transfer of all B3 stations to the responsibility of NIEP, the principal partner institution during the course of the project.
This K2-network was an important step towards a modern national network to acquire three-component weak and strong motion data, especially of Vrancea earthquakes.

Fig. 42: (left figure) Station Vrincioia where a final inventory is taken: W. Scherer (GPI), G. Chircea (NIEP), and Julia Bartlakowski (GPI); (right figure) headquarter of the Romanian National Seismic Survey in Magurele-Bucharest: V. Pirvu, B. Grecu, W. Scherer, C. Ionescu (head of the Romanian National Seismic Survey), J. Bartlakowski, G. Chircea, and K.-P. Bonjer (from left to right).

Reaching his retirement age, K.-P. Bonjer left the University Karlsruhe on December 31, 2004. The CRC-subproject B3 was continued by F. Wenzel but with new objectives.

Epilog

In meritorious recognition of the scientific cooperation of the GPI with Romania, and in

Fig. 43: Ceremony at the Faculty of Physics of Bucharest University: K.-P. Bonjer gives his presentation on ‘Some contributions to the estimation of the seismic hazard caused by deep Vrancea Earthquakes’; the audience during the presentation: First row: Traian Moldoveanu (General manager Geotec Consultant); Corneliu Dinu (Dean of the Faculty of Geology and Geophysics, University Bucharest (FGG)); Gheorghe Marmureanu (General Director of NIEP, and principal partner of project B3 of the CRC 461). Second row: Victor Mocanu (FGG), Laurentiu Munteanu (NIEP). Third row: A. Constantin (NIEP); Dumitru Enescu (former General Director of NIEP); C. Cuciuc.

particular with the collaborative research centers on ‘Rock Mechanics’ and ‘Strong Earthquakes’, the Faculty of Geology and Geophysics of Bucharest University awarded Karl Fuchs and Friedemann Wenzel the title of ***Professoris Honoris Causa*** on March 11, 2002 resp. on January 15, 2001. On October 15, 2004 the Faculty of Physics of Bucharest University awarded K.-P. Bonjer this title as well (Fig. 43).

Acknowledgments:

The continuous support of the general directors of the National Institute for Earth Physics (NIEP), Dumitru Enescu and Gheorghe Marmureanu, was essential for the activities within the project B3. I am also grateful to Cornelius Dinu, Dan Lungu, Traian Moldoveanu and Victor Mocanu for supporting or facilitating the site selection search as well as the execution of the borehole drilling projects and downhole measurements. The following colleagues have contributed significantly to the technical works within B3 during October, 1996 until September, 2004: GPI: **Werner Scherer**, Manfred Rittershofer, Markus Treml, and Thomas Nadolny; NIEP: Constantin Ionescu, and in particular **George Chircea**, Viorel Pirvu, and Stefan Tataru.

I am grateful to John Ebel for polishing my English and for valuable suggestions which improved the manuscript considerably.

The Earthquake of October 27, 2004: a Farewell Greeting from Vrancea

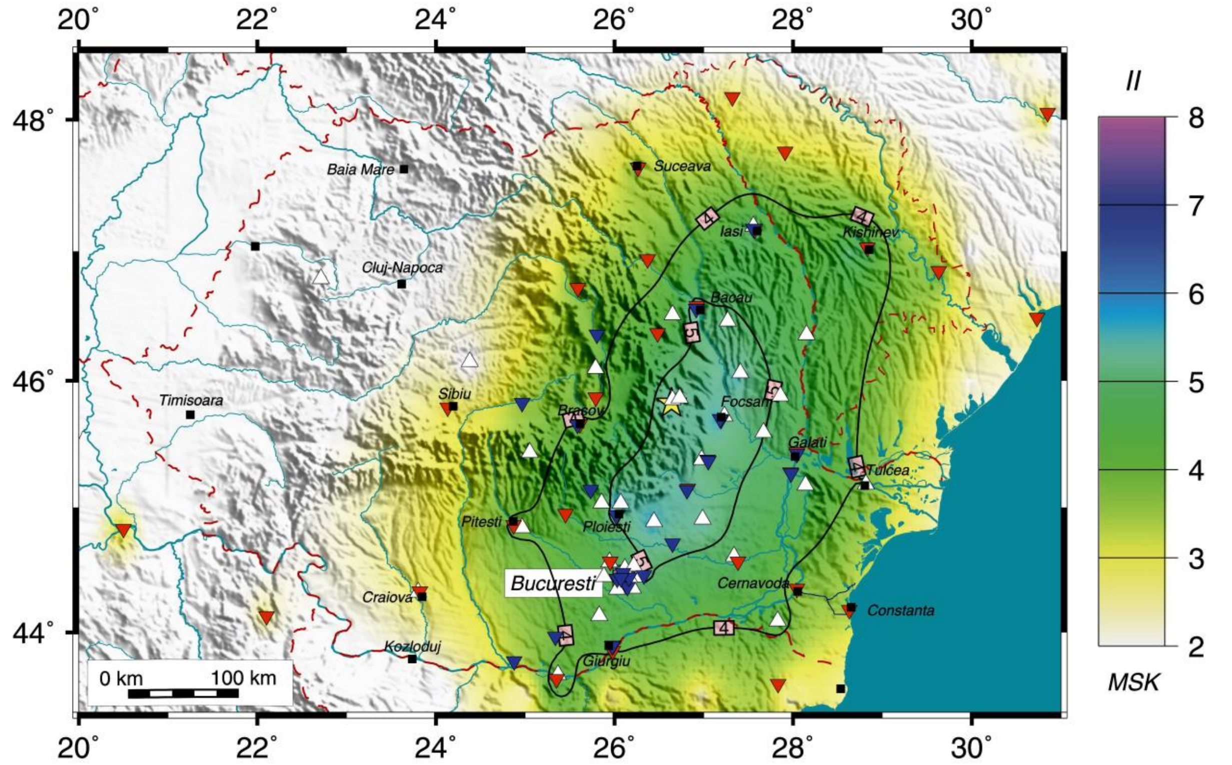


Fig. 44: Shakemap of the Vrancea Mw=5.8 earthquake of October 27, 2004 (Bonjer et al., 2008; Bonjer, 2012): The intensities (II) are determined from accelerograms (white triangles: CRC-NIEP K2-data; blue triangles: INCERC-UTCB data) and from the observed intensities from the Community Internet Intensity Map data (Wald et al., 1999).

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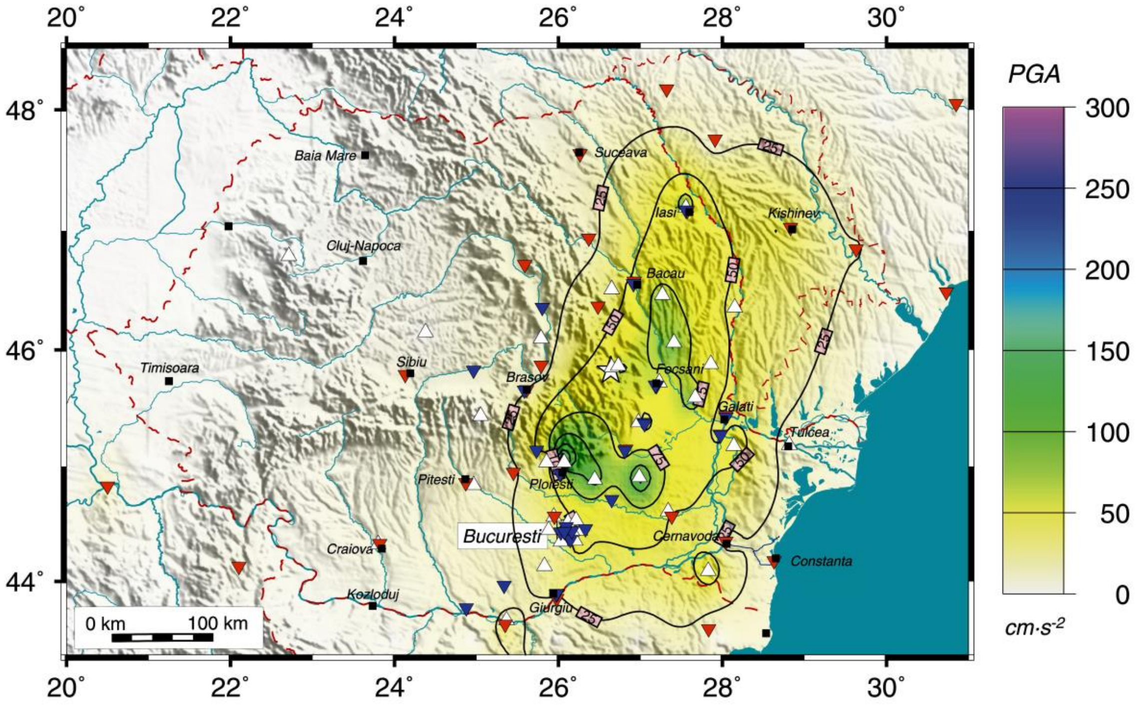

Fig. 45: PGA-Shakemap of the October 27, 2004 event: Observed peak ground accelerations (white and blue triangles), and computed PGA's (red triangles) (Bonjer et al., 2008; Bonjer, 2012) on the basis of the observed intensities from the Community Internet Intensity Map (Wald et al., 1999).

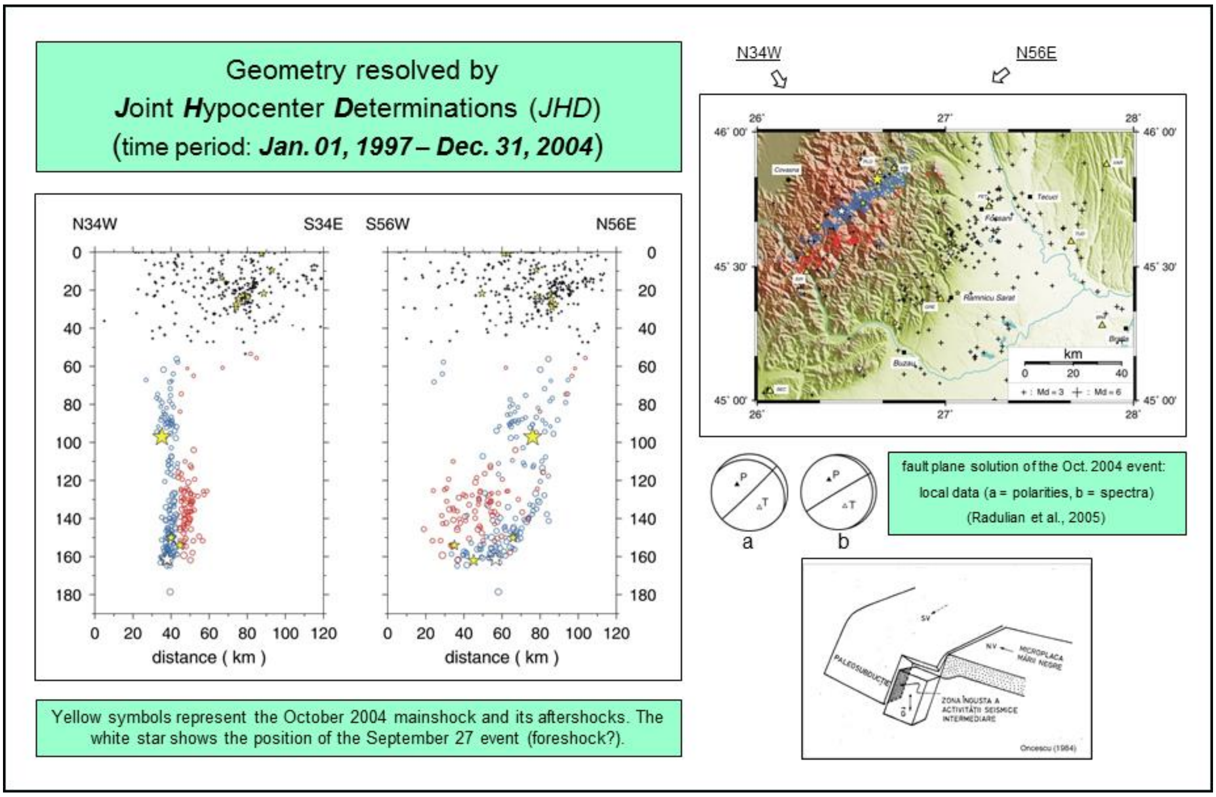

Fig. 46: The Vrancea Source Scenario: The fine structure of the source: the double Wadati- Benioff Zone (see, e.g., Bonjer et al., 2008; Bonjer, 2012; Oncescu, 1984; Radulian et al., 2007)

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The list of references is far from complete. However, it is the intention to give an impression of the variety of the scientific investigations that were tackled using the collected data.

The following diploma and PhD theses were performed as well with the network data. Also this list might not be complete.

Rhinegraben

Diploma Theses: J. Barsch, H. Durst, B. Gilg, A. Gruber, W. Haberecht, K. Koch, W. Lippert, T. Plenefisch, D. Raupach, M. Rudolf, T. Schler, T. Schroer (passed away before finishing), M. Weber, R. Wenderoth, J. Wössner

PhD Theses: T. Dahm, C. Gelbke, T. Plenefisch

Romania

Diploma Theses: D. Eul, B. Grecu, P. Jung, K. Zimmermanns (not completed because of break-off of the studies)

PhD Theses: B. Grecu, C. Ionescu, M. Koch, T. Moldoveanu, A. Oth, M. Popa, M. Rizescu, W. Wirth

Appendix I

GEOPHYSIKALISCHES INSTITUT
UNIVERSITÄT FRIDERICIANA KARLSRUHE
Hertzstraße 16 Bau 42 7500 Karlsruhe 21
Telefon: (0721)-608 4493 * Telefax: (0721) 71173 * Telex: 7825740 GEOK D

Herrn
Minister Dr. D. Spöri
Ministerium für Wirtschaft, Mittelstand
und Technologie Baden-Württemberg
Theodor-Heuss-Straße 4

7000 STUTTGART 10

18. Dezember 1992 Bo/gb

Betr.: Erdbebenüberwachung im Oberrheingraben

Bezug: Mein Schreiben vom 12.11.1992; Vorlage des Geologischen Landesamtes (GLA) Freiburg zur Vereinheitlichung des Landeserdbebendienstes vom 5.2.1992

Sehr geehrter Herr Minister,

ich setze Sie hiermit in Kenntnis, daß ich die Einstellung der seismischen Überwachung der Region Oberrhein durch Abschalten des seismischen Überwachungssystems der Universität Karlsruhe zum 31. Dezember 1992 verfügt habe, falls seitens der Landesregierung - bis zu diesem Zeitpunkt - keine Reaktion auf den in meinem Schreiben dargelegten Vorschlag zur Aufrechterhlatung dieses Netzes erfolgt.

Diese Entscheidung und ihre Konsequenzen für die Region Oberrhein werden auf einer Pressekonferenz am Dienstag, den 22. Dezember 1992, 11.00 Uhr, im Dürerzimmer des Gastdozentenhauses der Universität Karlsruhe, Engesserstraße, erläutert.

Mit freundlichen Grüßen

Karl Fuchs

Professor Dr. Karl Fuchs

Kopie:

Minister für Wissenschaft und Forschung
Minister des Inneren
Umweltminister
Deutsche Forschungsgemeinschaft

Referat: Katastrophenschutz der Regierungspräsidien Karlsruhe, Freiburg
Referat Katastrophenschutz der Stadt Karlsruhe
Referat Katastrophenschutz der Stadt Mainz
Polizeipräsidium Karlsruhe

Appendix II

SENDER :Ministerbuero ;18-12-92 ; 16:54 ; STS-Buero, WM→ 49 721 71173;# 2

WIRTSCHAFTSMINISTERIUM
BADEN-WÜRTTEMBERG
Der Ministerialdirektor

Herrn
Prof.Dr. Karl Fuchs
Universität Fridericiana Karlsruhe
Geophysikal.Institut
Hertzstr. 16 , Bau 42
7500 Karlsruhe 21

Betr.: Erdbebenüberwachung im Oberrheingraben.

Sehr geehrter Herr Prof. Fuchs,

in Namen des Herrn Ministers bedanke ich mich für Ihre Anfrage vom 18. Dezember 1992. Hierzu kann ich Ihnen mitteilen, daß ich heute die Grundsatzentscheidung getroffen habe, dem Ministerrat vorzuschlagen, daß der badische und württembergische Teil des Erdbebendienstes auf das Geologische Landesamt Baden-Württemberg übertragen wird.
In diesen Gesamtrahmen für das Land wird auch das Erdbebennetz im Oberrheingraben eingebunden.

In einer Kabinettsvorlage wird das Wirtschaftsministerium auch Vorschläge zur Finanzierung und Personalausstattung des Landeserdbebendienstes machen. Einzelheiten sind noch mit dem berührten Ministerium fürWissenschaft und Forschung abzustimmen.

Mit freundlichen Grüßen

Anschrift: 7000 Stuttgart 10, Postfach 10 34 51
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Telex 7 23 931 wmbws d

Presse*INFORMATION*
*Universität Fridericiana Karlsruhe (TH)
Pressestelle
75 Karlsruhe, Kaiserstraße 12
Postfach 6380, Telefon (0721) 6082089*

Nr. 71/92 21. Dezember 1992 - H/mht

ERDBEBENÜBERWACHUNG DES OBERRHEINGRABENS WIRD FORTGESETZ

PRESSEKONFERENZ ABGESAGT!

Der Minister für Wirtschaft, Mittelstand und Technologie Baden-Württemberg hat dem Geophysikalischen Institut der Universität Karlsruhe fernschriftlich seine Absicht signalisiert, die Erdbebenüberwachung der Region Oberrheingraben fortzusetzen. Die für den 22. Dezember 1992 vormittags um 11 Uhr im Dürersaal des Gastdozentenhauses der Fridericiana angekündigte Pressekonferenz wird aufgrund dieser neuen Sachlage abgesagt. Wir bitten der Redaktion wegen der kurzen Frist dafür um Verständnis.

Am 18.12.1992 um 16:54 Uhr erreichte das Geophysikalische Institut folgendes Fernschreiben aus dem Ministerium:

> *'Im Namen des Herrn Ministers bedanke ich mich für Ihre Anfrage vom 18. Dezember 1992. Hierzu kann ich Ihnen mitteilen, daß ich heute die Grundsatzentscheidung getroffen habe, dem Ministerrat vorzuschlagen, daß der badische und württembergische Teil des Erdbebendienstes auf das Geologische Landesamt Baden-Württemberg übertragen wird.*
> *In diesem Gesamtrahmen für das Land wird auch das Erdbebennetz im Oberrheingraben eingebunden.*
> *In einer Kabinettsvorlage wird das Wirtschaftsministerium auch Vorschläge zur Finanzierung und Personalausstattung des Landeserdbebendienstes machen. Einzelheiten sind noch mit dem berührten Ministerium für Wissenschaft und Forschung abzustimmen.*
> *gez. Peter Bogusch, Ministerialdirektor '*

Um Schaden abzuwenden, wurde telefonisch vereinbart, das seismische Überwachungsnetz ab 1.Januar 1993 zu Lasten des Landes Baden-Württembergs zunächst unter der jetzigen Verantwortung und Organisation des Geophysikalischen Instituts fortzubetreiben bis der Kabinettsbeschluß vorliegt.

Bei der Rücknahme der Abschalt-Verfügung geht das Geophysikalische Institut davon aus, daß das Kabinett bald den nötigen Beschluß faßt und alle Beteiligten in enger Zusammenarbeit die Übergabe des seismischen Regio Meßnetzes an das Geologische Landesamt Baden-Württemberg vollziehen.

Das Geophysikalische Institut der Universität Karlsruhe wird auch weiterhin an der wissenschaftlichen Bearbeitung der seismischen Meßdaten mitwirken.

Wir gehen davon aus, daß das Land Baden-Württemberg die Presse weiter informieren wird.
Für nähere Auskünfte notieren Sie bitte folgende Verbindung:
Professor Dr. Karl Fuchs: Telephon: 0721-608-4493; Fax: 0721-71173; E-mail: bi72@dkauni2.bitnet

8. The lithosphere of the Earth and controlled-source seismology – a personal challenge for students, technicians and scientists

Claus Prodehl

0. Summary

One of the central research themes of the Geophysical Institute of Karlsruhe (GPI) from 1964 to 2001 was the investigation of the Earth's crust and upper mantle by controlled source seismology. Both experiments and development of theory were important corner stones. Following the foundation of the Geophysical Institute in 1964, one of the first undertakings of Professor Stephan Mueller was the organization of a systematic investigation of the Earth's crust by seismic methods, both passive, by surface wave investigations and by the establishment of the Rhinegraben seismic network (see Chapter by Klaus-Peter Bonjer), and active, by controlled source experiments using quarry blasts.

The 1970s saw the continuation of the Rhinegraben research, now under the direction of Professor Karl Fuchs. The research was extended to the entire Central European Rift System by organizing joint controlled-source experiments in cooperation with French scientists culminating in two large experiments covering the Rhinegraben and the Rhônegraben and its Variscan environments, Black Forest and Vosges as well as Central Massif of France, using borehole shots organized by scientists of the University of Paris. In cooperation with the Meteorological Survey of Portugal, a series of seismic experiments in 1970-73 covered the Variscan areas of southern and central Portugal, using marine shots. Furthermore, Karlsruhe participated in a seismic expedition to Namibia in 1975, investigating the deep structure under the Damara orogen and adjacent Kalahari craton.

The highlight of the 1970s, however, was the systematic investigation of the upper 100 km of the European lithosphere by long-range seismic profiles of 1000-2000 km length. Sea shots were organized and their efficiency was optimized by using an optimum depth for the charges. In addition, crustal control was assured by intermediate borehole shots. The first successful experiment was a 1000 km long profile through France in 1971, followed by a second experiment in 1973, resulting in the detection of fine structure of the lower lithosphere beneath Moho. An offshore shot off western Scotland recorded in 1972 on profiles along the Rhônegraben and along the Bavarian Forest in 1972 allowed an even deeper view in the Earth's lower lithosphere. Other long-range profiles followed through Britain (LISPB 1974), along the axis of the Alps (ALP 1975), along the Rhenish Massif and Ardennes in 1979, and finally, a 2000 km long profile along Scandinavia (FENNOLORA 1979) allowed to view a reflection from the 20° discontinuity, the mantle transition zone at 400 km depth.

During the 1980s, the crustal research of the Geophysical Institute concentrated on two major areas: Seismic refraction and reflection experiments in Southern Germany supported scientific deep drilling projects and added to the realization of the European GeoTraverse. A second major research goal was the Afro-Arabian rift system.

Already in 1978 Karlsruhe organized seismic-refraction profiling in the Urach area, within the frame of an interdisciplinary geothermal deep drilling project. When KTB (continental deep drilling) came into discussion in the early 1980s, Karlsruhe supported pre-investigations of two proposed sites in the Hohenzollerngraben and the Black Forest by a sophisticated seismic refraction network (Black Zollern-Forest 1984), combined with the first joint seismic reflection and refraction experiment along the axis of the Black Forest. Further to the east, Southern Germany was covered by a network of seismic refraction profiles radiating from the troop training area Wildflecken in 1982 as well as by the European GeoTraverse. The seismic refraction investigation of the central part of the European GeoTraverse crossing Germany, Switzerland and northern Italy along a line from Kiel to

Genova was carried out under the supervision of the Karlsruhe Institute in 1986. In 1988 Karlsruhe was a leading partner at the realization of two major seismic reflection surveys crossing the southern and the northern Rhinegraben. Also in the framework of the European Geotraverse, in 1989 the project ILIHA (Iberian LIthosphere Heterogeneity and Anisotropy), a three-dimensional lithospheric profile on the Iberian Peninsula, was carried out with strong Karlsruhe participation, both in the field and in the interpretation.

Seismic work of Karlsruhe scientists in the Afro-Arabian rift system started in 1977 with a seismic refraction campaign in Israel with the main goal to investigate the deep structure of the Jordan – Dead Sea Transform. It was continued by a second project in Jordan in 1984, both in close cooperation with the University of Hamburg and with the University of Tel Aviv respectively the University of Amman. In 1985 the research direction of the Special Collaborative Program 108 (SFB 108) was shifted to the East African rift in Kenya, and in close cooperation with British and U.S. scientists a major seismic expedition with seismic refraction and teleseismic observations was successfully launched along the axis of the rift valley in Kenya (KRISP 1985). Also in the 1980s, a close cooperation with DIAS, the Dublin Institute for Advanced Studies, started with a joint project in 1982 along the first Irish seismic refraction line, ICSSP (Irish Caledonian Suture Seismic Project). Furthermore, in 1979 Karlsruhe and Zurich participated with MARS seismic refraction stations in a seismic investigation of the Yellowstone Park and adjacent Eastern Snake River Plain.

In the 1990s Karlsruhe was a leading partner in several large controlled source seismic campaigns. In 1990-91 the southern Rhinegraben was again investigated with seismic reflection profiles in the Dinkelberg area and wide-angle observations undershooting the Rhinegraben by recording quarry blasts in the southern Black Forest and Vosges. In 1995, in cooperation with GFZ Potsdam, the investigation of the crust of Southeastern Germany was the goal of project GRANU-95 centered around the Saxonian Granulite Mountains. Another joint project with GFZ Potsdam was carried out in Ireland in the frame of the EU project VARNET in 1996, a geophysical investigation of the Variscan Front in Ireland with seismic and magnetotelluric experiments.

The investigation of the East African rift culminated in two large seismic refraction expeditions, KRISP 90 and KRISP 93-94. Both projects involved major teleseismic campaigns and sophisticated seismic refraction profiling with shots organized by experts of the participating universities and the U.S. Geological Survey in Lake Turkana, Lake Baringo and Lake Victoria and in boreholes in between as well as with one shot fired by the Kenyan navy in the Indian Ocean. Profile lengths of 400 km and beyond allowed to reveal not only the crustal structure, but, in combination with the teleseismic observations, also allowed a detailed view into the lower lithosphere.

In 1999 Karlsruhe participated in two major North American campaigns. With major DFG funding Karlsruhe supported the CDROM project (Continental Dynamics – Rocky Mountains), an interdisciplinary large-scale project of 14 U.S. universities, and was responsible for the seismic refraction observation of the central part of the 1000 km long geotraverse along the Southern Rocky Mountains The second project was LARSE II (Los Angeles Region Seismic Experiment), where Karlsruhe participated together with GFZ Potsdam.

Finally, within the frame of the Collaborative Research Center 461 (CRC 461) ”Strong Earthquakes - a Challenge for Geosciences and Civil Engineering” at the University of Karlsruhe, and in close cooperation with the National Institute for Earth Physics at Bucharest, in 1999 and 2001 two long-range seismic refraction profiles were observed crossing the southeastern Carpathians in N-S as well as in W-E direction and crossing each other within the seismogenic Vrancea zone.

1. Early history

In the late 1950s and early 1960s Hans Berckhemer and Stephan Mueller were assistant professors under the heading of Professor Wilhelm Hiller at the Landeserdbebendienst of Baden-Württemberg at Stuttgart. In this time Jörg Ansorge started as student and finished with a diploma thesis in physics, having chosen geophysics as side-subject. At the same time Karl Fuchs was assistent professor at the Technical University at Clausthal-Zellerfeld, which was headed by Professor Heinz Menzel, and worked on theoretical and model-seismic problems.

In 1956 and 1958 Madame Yvonne Labrouste and Professor Hans Closs had organized a large-scale international seismic-refraction investigation of the Western Alps. In particular during the interpretation of the data, Stephan Mueller and Karl Fuchs got to know each other very well. Together with Eli Peterschmitt from Strasbourg, Albert Stein from Hannover and Klaus Strobach from Hamburg they established an interpretation group which they named FUMUEPESTE (Fuchs et al., 1963).

In the framework of a priority program of the German Research Society „Geophysical exploration of crustal structure in central Europe“ quarry blasts were systematically used as energy sources for seismic-refraction measurements. This program led to a close cooperation of scientists and students of all German geophysical universities and research institutions which worked on seismic and seismological problems. The scientific exchange of knowledge was in particular prompted by symposia which were organized in one-year intervals from 1961 to 1964. This enabled also Ph.D. and diploma students, who worked on interpretations of seismic-reflection and –refraction data like Jörg Ansorge from Stuttgart or Claus Prodehl from Munich for example, to get in close personal contact with professors and advanced scientists of other institutions in Germany, such as Stephan Mueller or Karl Fuchs.

When Stephan Mueller in 1964 became professor for Geophysics at the newly founded Geophysical Institute at the University of Karlsruhe, he was able to address scientists who were specially interested in research in general seismology and in controlled-source seismology, as Stephan Mueller had decided that the physics of the Earth’s interior was to become the main research subject of the new Geophysical Institute. Seismology, applied seismics and geothermics (e.g., Werner, 1970) became the main research fields, while magnetic und geoelectric investigation methods only were taught in the cause of lectures. Gravimetric research remained in the frame of the Geodetic Institute.

The Central European and the Afro-Arabian rift systems became the focus of major research projects of the Institute. Both are major rift systems of the Earth: the Central European rift system reaches from the Hessian depression and Lower Rhine embayment through the Rhenish Massif into the Upper Rhinegraben and from there through the Saône- und Rhônegraben to the Mediterranean Sea; the Afro-Arabian rift system reaches from the Levant in Lebanon through Dead Sea and Red Sea into East Africa as far south as Malawi. A second focus of the Institute’s research was the study of fine structure of the subcrustal lithosphere and asthenosphere. Both research fields involved major fieldwork and expeditions which in most cases comprised almost exclusively seismic-refraction measurements on profiles with several 100 to more than 1000 km length, but from the 1980s to present also involved large-scale teleseismic projects. The seismic-refraction fieldwork usually required much more personnel than was available at the Institute with its small number of scientists with permanent and temporary positions. Rather, the experiments were only possible because many students, technicians and scientists from other research fields and from other German research institutions participated which often required absence from home for several weeks. Success was granted to practically all expeditions, mainly due to the fact that each individual participant involved himself with greatest effort, joy and care, hereby not minding major personal inconveniences.

In the following the major seismic-refraction projects of the Institute will be described in some detail and also some of the seismic-reflection and teleseismic projects will be briefly mentioned. This contribution focuses less on the data interpretation and scientific conclusions, but more on technical details and occasional problems during the fieldwork. Also the participants from Karlsruhe will be named as far as they are still known to the author today. For results, the corresponding publications may be referred to.

2. The Central European Rift System

2-1. Early quarry blast observations around the Rhinegraben

The first major project, which Stephan Mueller undertook immediately, after having accepted his call to Karlsruhe as professor, was, in close connection with the head of the Geological department Henning Illies and his co-workers, the coordination of geoscientific research in the Rhinegraben. In cooperation with the Geological State Office of Baden-Württemberg and the colleagues Eli Peterschmitt and J.P. Rothé from Strasbourg University, in 1966 the first Rhinegraben symposium was held at Wiesloch, which in fact was a collection of knowledge on the state of the art and initiated an intensive interdisciplinary research activity (Rothé and Sauer, 1967, Mueller et al., 1967).

Part of this project was a study of the Earth's crust and upper mantle by surface waves. Under the direction of Stephan Mueller, Dieter Seidl, together with a young diploma student Horst Reichenbach, continued the investigation of the dispersion and absorption of surface waves in order to deduce the structure of the crust and upper mantle in the South German Triangle. For this purpose a long-period seismic network between the Taunus Observatory and the Po Valley area was operated for several years (Seidl et al., 1966, 1970a, b; Seidl, 1971).

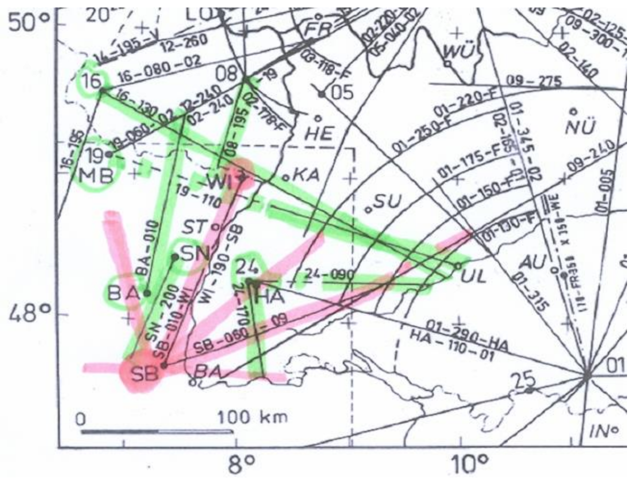


Fig. 2-01: Location of seismic-refraction profiles in the Rhinegraben and its surroundings until 1972 (green: quarry blast profiles, red: project 1972).

Fig. 2-02: Claus Prodehl with recording equipment of Munich in the Rhinegraben 1966.

At the time when the Karlsruhe Geophysical Institute was founded, in fact none of the seismic-refraction profiles of the priority program of the German Research Society „Geophysical exploration of crustal structure in central Europe", where quarry blasts were systematically used as energy sources for seismic-refraction measurements, yielded information on the deep structure of the Rhinegraben. Only now quarries with suitable series of blasts were looked for which enabled to ‚undershoot' the Rhinegraben. In 1966 the first measurements could be realized using blasts at quarries near Taben Rodt at the southwestern border of the Hunsrück (no 16 in **Fig. 2-01**) and near Merlebach in Lorraine (MB in **Fig. 2-01**) to establish profiles crossing the Rhinegraben.

Already in 1968, at the second international rift symposium at Karlsruhe, a first report on seismic studies in the Rhinegraben could be presented (Illies and Mueller, 1970; Ansorge et al., 1970; Mueller et al., 1973a). The theory on the Rhinegraben rift cushion was born here.

After the successful start of crustal studies of the Rhinegraben with the aid of quarry blasts at Taben Rodt und Merlebach in 1966, fieldwork continued with additional recordings of blasts at these and additional quarries in the Vosges mountains (Col de Bagenelles and Saint Nabor, BA, SN in **Fig. 2-01**) and in the Black Forest (Steinach, no. 24 in **Fig. 2-01**), until finally by the initiative of Alfred Hirn and Leon Steinmetz of Paris a more detailed crustal study could be undertaken by organizing specially arranged borehole explosions in Alsace (red lines in **Fig. 2-01**).

2-2. MARS-66 and ASFA

While in 1966 only the heterogenic self-built stations of the participating institutions were available (see, e.g., **Fig. 2-02**), soon afterwards the Institute was able to obtain a substantial number of the recently newly developed type MARS-66 (Magnetic tape Apparatus for Refraction Seismic; Berckhemer, 1970). MARS-66 consisted of four parts: 3 seismometers (either 3 vertical seismometers or 1 vertical and 2 horizontal seismometers), a frequency modulator, a tape recorder and a time signal receiver (**Fig. 2-03, Fig. 2-04**). As seismometers the geophones FS60, developed in the early 1960s by Hans Berckhemer and built by the company Stroppe, were available which, by changing the positions of the stands, could be used both as vertical and horizontal components. For measurements with three vertical seismometers cable drums were looked for which could carry up to 500 m long two-thread telephone cables. People were not very happy when they had to roll out and in 1 km of cable.

Fig. 2-03: Recording unit MARS 66. Left: modulator, center: tape recorder and T75A time receiver, right: seismometer box.

Fig. 2-04: Recording unit MARS 66 equipped with a mechanical clock (upper right). Upper left: T75A time-signal receiver, middle left: modulator, lower left: tape recorder. FS-60 seismometers in the background to the right.

An initial purchase of 40 MARS-66-stations had been enabled by a grant of the Volkswagen-Stiftung to the FKPE (Forschungs-Kollegium für die Physik des Erdkörpers), which distributed these stations in equal numbers to all interested geophysical research institutions in Western Germany: the universities of Berlin, Clausthal-Zellerfeld, Göttingen, Hamburg, Karlsruhe, Kiel, München, Münster und Stuttgart und State Geological Survey of Lower Saxony at Hannover (NLfB).

Initially, Mr. Schröder from NLfB Hannover continued to organize the recording of quarry blasts as he had done before the MARS-66 equipment became available. However, when gradually the more active institutions started to organize their own projects for which they needed the whole MARS-66 instrument pool, a working group ASFA (Arbeitsgruppe für Seismische Feldmessungen und Auswertung) was founded by the FKPE which met regularly at the annual meetings of the German Geophysical Society to discuss the need of instrumentation and personnel and decide on priorities when necessary (Giese et al., 1976). From the early 1970s to 2000 Claus Prodehl headed this group.

Fig. 2-05: French MARS equipment.

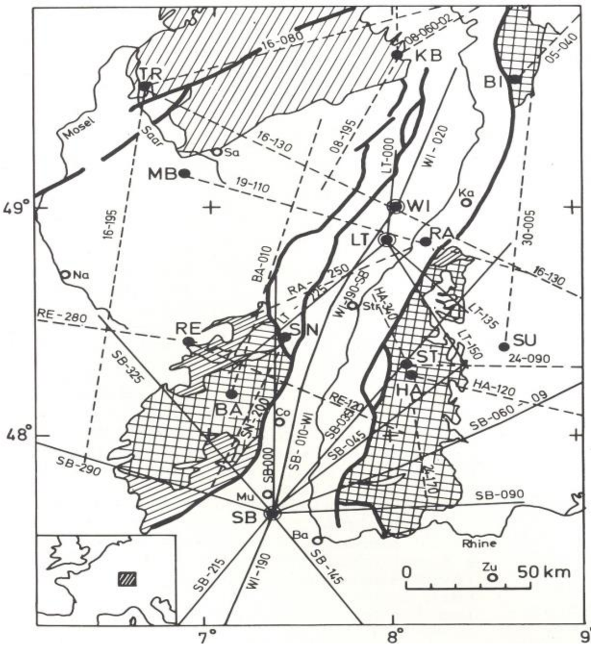


Fig. 2-06: Location of the 1972 project (full lines) and quarry blast profiles until 1972 (dashed lines) (from Prodehl et al., 1976a, Fig. 3; Prodehl and Mooney, 2012, Fig. 7.2.2-01).

Leon Steinmetz and Alfred Hirn of the Institut de Physique du Globe of the University of Paris had visited the Karlsruhe Institute in 1968 to explore the new MARS-66 equipment. They had obtained a considerable amount of funding for a large-scale research seismic project of the Earth's crust. The MARS equipment convinced them, and subsequently Paris bought 30 stations from the Lennartz Company. With this investment of Paris a long-lasting cooperation started between Karlsruhe and Paris. In order to be able to run more than one station by one man, the French engineers added a mechanical clock to their new MARS stations which enabled switching on and off at given times (**Fig. 2-05**). Otto Gothe from Karlsruhe overtook the idea of a clock for the Karlsruhe and Stuttgart equipment.

2-3. Fieldwork and theory interaction

On the basis of the wordwide accumulated quantity of crustal seismic data, Stephan Mueller and Mark Landisman were able to demonstrate evidence for a world-wide existing crustal low-velocity zone (Mueller and Landisman, 1965, 1966). They also argued that this concept might bring crustal seismic-refraction and -reflection data into better agreement, as proved from examples from Southern Germany and elsewhere (Fuchs and Landisman, 1966a, b; Fuchs et al., 1967; Landisman and Mueller, 1966, 1970; Landisman et al., 1976; Mueller and Landisman, 1971).

Stimulated by the wealth of data obtained particularly during the 1960s, new methodologies were developed, most of them in close cooperation with or as a consequence of the numerous high-quality data obtained by DSS (deep seismic sounding) field work. The DFG priority program "Geophysical Investigation of Crustal Structure in Central Europe" had generated refraction/wide-angle reflection observations of high quality and growing and dense quantities. At the beginning of the 1960s, the young generation of scientists, such as Peter Giese at Munich, Rolf Meissner at Frankfurt, Karl Fuchs at Clausthal, Gerhard Müller at Mainz, and others felt very soon, that the previous methods of interpretation, based primarily on travel times, were inadequate to the richness of information in the new data.

The new computer technology, available since the mid-1960s, enabled sophisticated traveltime routines by programming the formulas for multi-layered structures, so that models could be checked by recalculating the theoretical travel times and comparing them with the observations. When Karl Fuchs arrived at Karlsruhe, it was one of his first undertakings to create such a powerful computer program on the local university computer (Fuchs and Landisman, 1966a, b).

Gerhard Müller and Karl Fuchs were not satisfied with travel time calculations alone, but started to develop methods to calculate synthetic seismograms. A first approach was published by Karl Fuchs in 1968 (Fuchs, 1968). Initially K. Fuchs and G. Müller, working separately and independently at different places and having different and common forerunners and academic teachers, developed the basic ideas for the reflectivity method (e.g., Fuchs, 1966a, b, 1968, 1969a, b, c, 1970, 1971); Müller, 1970, 1971a, b, 1973), which successfully enabled the calculation of the dynamics of the seismic wave field, i.e. amplitudes, frequency contents and reverberations. Subsequently they jointly programmed and published the method in joint papers (Fuchs and Müller, 1971; Müller and Fuchs, 1976; Müller and Mueller, 1979) which for the first time allowed the computation of whole synthetic seismograms allowing more severe testing of crustal models (for details see Fuchs (2004) and **Chapter 3** by Karl Fuchs).

Throughout the 1970s, the interpretations of the many seismic-refraction experiments concerning the crust and upper mantle were mainly performed using traveltime routines for which many different computer programs had been developed over the years. In addition, the reflectivity method published by Fuchs and Müller (1971) was applied all over the world (Fuchs, 2004). There is hardly an interpretation published during the 1970s in which the model has not been checked and verified by calculating synthetic seismograms and comparing them with the main observed phases. Braile and Smith (1975) published a whole series of synthetic record sections calculated for typical crustal models.

However, a serious drawback of this methodology was that a horizontally homogeneous layered structure was required. Several, and not always successful attempts were undertaken to overcome this problem. For example, Brian Kennett, amongst others, modified the reflectivity method to allow slight variations in structure on the shot side (Kennett, 1974, 1983).

The problem of laterally homogeneous structures was only solved when the first ray tracing approaches were published. A breakthrough of this approach was made when Červený and co-authors published their book and later results on ray theory (Červený et al., 1977). A corresponding computer program for ray tracing had been prepared and made available for all interested users around the world, before it was finally published by Červený and Pšenčik (1984). This procedure would become the major interpretation tool of the following decades. Červený's method and the computer routines developed on its basis also allowed to compute synthetic seismograms. Dirk Gajewski, when interpreting the "Black Zollern Forest" seismic refraction data, made intensive use of Pšenčik's routine, worked on its more simplified application for seismic refraction data, and in close cooperation with Ivan Pšenčik worked on the development and application of the theory on the computation of ray synthetic seismograms for three-dimensional structures (Gajewsky, 1987; Gajewsky and Pšenčik, 1986, 1987).

2-4. The Rhône- and Rhinegraben experiments of 1972

After a successful first cooperative campaign of a long-range profile through France in 1971 (see next chapter), in June 1972 a joint experiment of Paris and Karlsruhe established a network of reversed seismic-refraction lines along the flanks of the Rhônegraben, organized by Alfred Hirn. During the Rhônegraben experiment the international working force of French and German institutions was joined by Swiss and Portuguese participants and their equipment (Sapin and Hirn, 1974; Michel, 1978; Prodehl et al., 1992, 1995). This survey did not only consist of a reversed profile along the rift axis, but also supplied reversed lines along the flanks to the west in the Massif Central and to the east in the sub-Alpine region. Furthermore intermediate shots were added in the middle of all lines, and transverse profiles across the Rhône valley were arranged. The data in the southern Rhône Valley was further complemented by the crustal data of the NW-SE long-range profile of 1971. The data were interpreted and published by our Paris colleagues (Sapin and Hirn, 1974, Michel, 1978). Most of the data were presented as record sections and are reproduced in ***Appendix A2*** (pages 38-48) of Prodehl and Mooney (2012).

This project was followed by a similar active experiment in the Rhinegraben in September 1972, this time jointly organized by Alfred Hirn, Eli Peterschmitt, Jean-Bernard Edel, Jörg Ansorge, and Claus Prodehl. As the liability problem for self-organized borehole explosions could not be clarified for the German side, borehole explosions were solely arranged on the French side in Alsace, with the southernmost shotpoint being located near Steinbrunn (SB in **Fig. 2-06)**, in the border region between the Rhinegraben and the Swiss Jura, and the northernmost shotpoint being close to the French-German border near Wissembourg (WI in **Fig. 2-06)**. Besides a reversed line in the graben proper, the Rhinegraben project produced a series of non-reversed fan-like profiles in various azimuths across the flanks of the graben in France and in Germany. For the shotpoints the French team under Eli Peterschmitt and Alfred Hirn was responsible, the recording sites were jointly organized by Karlsruhe and Strasbourg at the headquarter at Strasbourg.

First results of this active project could not yet be reported during the third international rift symposium at Karlsruhe in April 1972, but could be included in the subsequent publication of this symposium (Illies and Fuchs, 1974; Rhinegraben Research Group, 1974). A more detailed interpretation which included all hitherto recorded quarry blast profiles was subsequently performed by Jean-Bernard Edel, who, by the aid of a French grant, spent half a year at Karlsruhe. The data showed profound differences of phases to be correlated under the graben and under the flanks. As a result of the extended data set, the idea of a high-velocity lower-crust rift cushion was abandoned and replaced by a transitional crust-mantle boundary centered under the rift. Under the graben flanks the Moho appeared as a first-order discontinuity. The new data furthermore evidenced a broad warping in an upward direction of the Moho by up to 5 km and a normal P_n velocity of about 8 km/s (**Fig. 2-07**, Edel et al., 1975**;** Prodehl, 1981; Prodehl and Mooney, 2012; Prodehl et al., 1975a, 1976a, 1992, 1995). The interpretation of Edel et al. (1975) incorporated both old and new data, which were all published in small-scale format. The data of the graben profile were later reinterpreted by Jay Zucca (1984) from the U.S. Geological Survey who spent some time at Karlsruhe as Visiting Scientist.

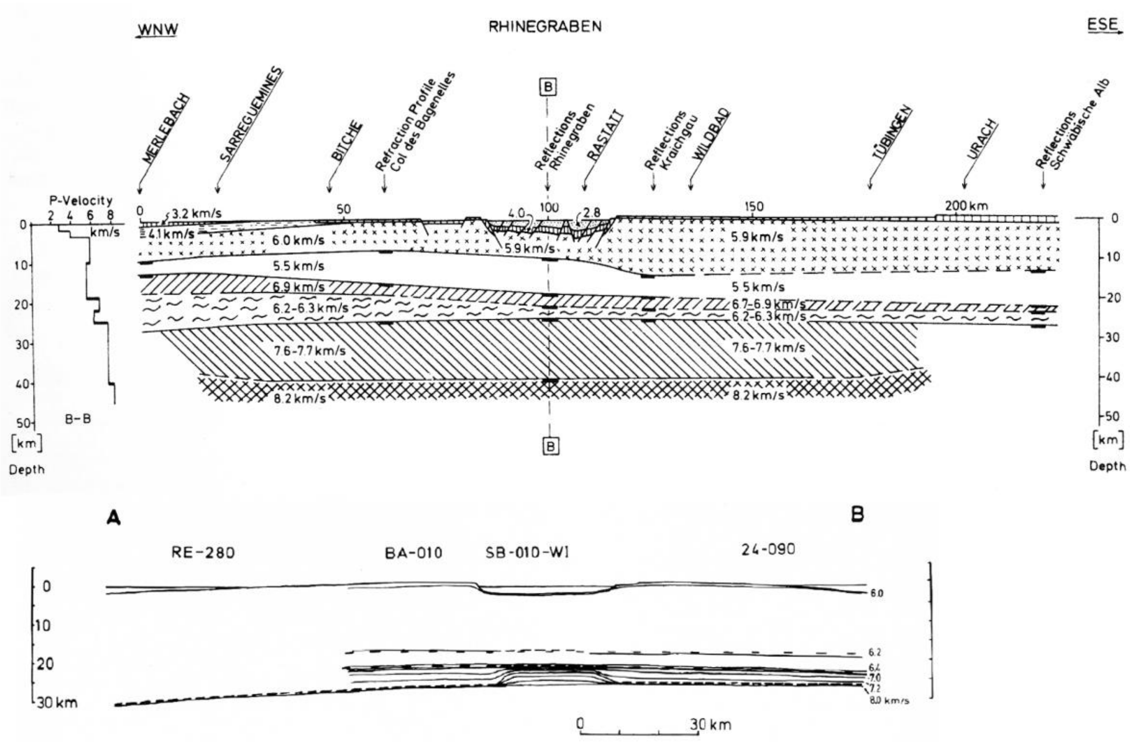


Fig. 2-07: Crustal cross sections through the central part of the Rhinegraben area (from Prodehl et al., 1976, Figs. 6 and 14; Prodehl and Mooney, 2012, Fig. 7.2.2-03). **Top:** The depth range of 25-40 km is interpreted as a rift cushion, i.e. a high-velocity lower crust after Mueller et al. (1973a). **Bottom:** The Moho rises gradually from 30 km west of the graben to about 25 km east of the graben, but becomes a transitional gradient zone under the graben proper, with its top upwarping to less than 25 km depth, after Edel et al., 1975). Thin lines show equal velocity contours, interval is 0.2 km/s.

2-5. Uppermost-mantle anisotropy in Southern Germany

In 1973 David Bamford from Birmingham received a grant to work for one year at the University of Karlsruhe. His goal was to investigate the large amount of P_n data recorded by the dense network of quarry blast and other seismic-refraction profiles in Southern Germany, applying the time-term method. This project resulted in an unexpected finding, namely a large continental anisotropy of more than 3% in the uppermost mantle, with the fast velocity in the NNE direction and the slow velocity in the WNW direction (Bamford; 1973, **Fig. 2-08**).

David Bamford's results stimulated Karl Fuchs to discuss the impact of the seismic uppermost-mantle anisotropy with respect to the petrological composition of the subcrustal mantle material (Fuchs, 1975, 1977) and to construct his famous "anvil" model (Fuchs, 1983, **Fig. 2-09**).

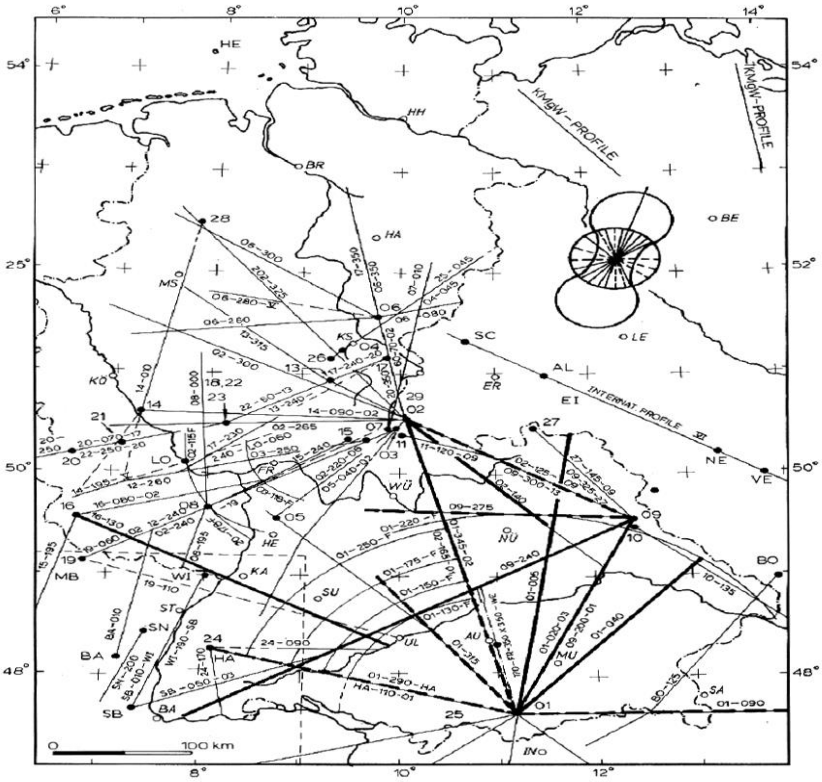


Fig. 2-08: Azimuthal distribution of P_n/P_MP amplitude ratios on a location map of all seismic-refraction profiles in western Germany (from Fuchs, 1983, Fig. 12). Thick solid lines: ratios = 1, thick dashed lines, ratios < 1. These amplitude ratios are projected into Bamford's (1973) velocity distribution plotted to the right above. The large-amplitude sector is centered around Bamford's fast direction, the small amplitudes around the slow one (see also Prodehl and Mooney, 2012, Fig. 7.2.4-01).

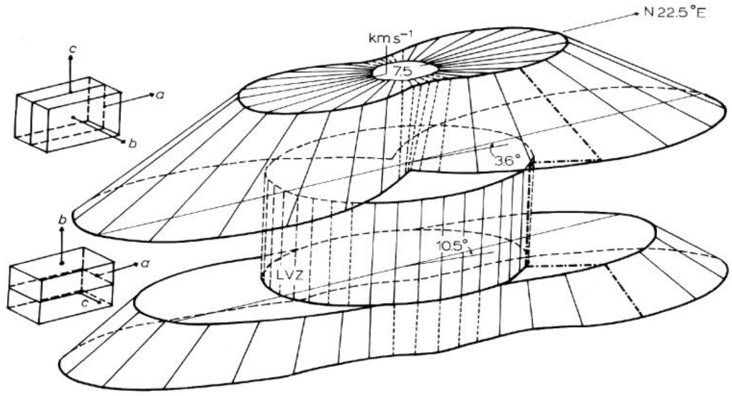


Fig. 2-09: Three-dimensional "anvil" model of Fuchs (1983) showing the continental anisotropic velocity-depth distribution in the uppermost mantle under southern Germany found by Bamford's (1973) time-term analysis (Fuchs, 1983, Fig.13; see also Prodehl and Mooney, 2012, Fig. 7.2.4-02).

Some years later, Dave Bamford, in cooperation with his Karlsruhe colleagues, extended his research to other continental areas where rather dense networks of seismic profiles existed. In Northern England and in the Eastern United States the uppermost mantle appeared to be isotropic within the limits of measurement error. However, a similar result as that for southern Germany emerged from the crustal data of the western United States collected by Claus Prodehl (1970a, b, 1979). Here a similarly large anisotropy of about 3% was found, with its high velocity direction 70-80° east of north, parallel to the spreading direction of the Basin and Range province (Bamford et al., 1979).

Both the amount and the direction were very similar to results found for the Pacific Ocean off California (Raitt et al., 1971; Fuchs, 1975, 1977). This coincidence led to the conclusion that this anisotropy is present as a consequence of the subduction of oceanic lithosphere beneath the western United States during Mesozoic times **(Fig. 2-10**).

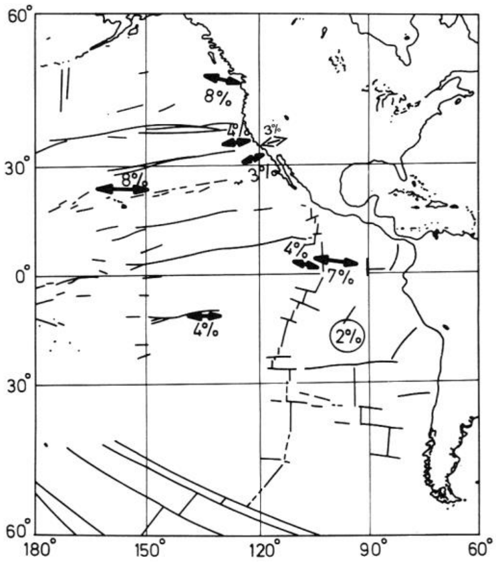


Fig. 2-10: Anisotropy of uppermost-mantle velocity extending from Western North America into the Pacific Ocean (from Bamford et al., 1979, Fig. 17; Prodehl and Mooney, 2012, Fig. 7.2.4-03).

2-6. The geothermal project Urach

The sudden shortage in oil in 1973 had raised a general interest for alternative energy sources. Consequently, the focus was also directed on geothermal energy. In Germany, the FKPE established a working group „Geothermics“, whose task was to look for areas where chances for an exploration of geothermal energy could be investigated. In western Germany two areas seemed to be promising for a geothermal investigation: the Rhinegraben and the area of the so-called “Swabian Volcano” near Urach, east of Stuttgart, where a geothermal anomaly reaching temperatures of 130-140°C at 3 km depth had been mapped. Independently, the city of Urach had established a local working group with the aim to plan for a geothermal drillhole in order to gain geothermal water for heating purposes. It took some time, until the two working groups decided to cooperate. 13 specialists’ subgroups were formed which combined their efforts with the final goal to drill a geothermal hole around Urach: geology, hydrology, mineralogy, geochemistry, geothermics, magnetotellurics, magnetics, gravimetry, seismology, refraction seismics, reflection seismics, microseismics, and rock mechanics. A special program of the European Community offered a possibility to obtain financial support (Haenel, 1982). Drilling at the Urach geothermal research drillhole started in 1977 and was terminated in 1980, having reached a depth of 3334m.

Karlsruhe und Stuttgart (Claus Prodehl and Dieter Emter) designed a seismic-refraction program with two goals: to compile a depth contour map of the surface of the crystalline basement beneath the surroundings of Urach and to explore the structure of the Earth’s crust down to Moho (Jentsch et al., 1980, 1982, Prodehl et al., 1982). For this purpose it was decided to reoccupy part of the Rhinegraben profile SB-060-09 of 1972 which ran along the Swabian Jura (**Fig. 2-06,** see subchapter 2-4**,** Rhinegraben Research Group, 1972; Edel et al., 1975) and plan for two shotpoints in the Urach area (U1 and U2 in **Fig. 2-11**), 30 km apart. At the same time these additional shots should be recorded along several unreversed short profiles in various directions (**Fig. 2-11**).

While the necessary approvals for shotpoint U2 could be obtained without problems, the procedure for shotpoint U1 seemed to be even easier, because it was planned to be located within the borders of the troop training area Münsingen which at this time was used for shooting exercises of the French army. The contrary was the case: a long burocratic fight developed between the French administration of the troop training area, the Bundesliegenamt which officially owned the area, and the University of Karlsruhe. The procedure finally filled a thick folder with 200 pages of paper. This folder became one of the half-year research reports to the European Community.

However, with the permission to carry out the explosion with the aid of a small private company, the liability problem was not yet solved. A special investigation of specialists of the NLfB (Niedersächsisches Landesamt für Bodenforschung) had stated that no damage was to be expected. But was the state of Baden-Württemberg ready to take care of unforeseen problems which were caused by research activities of state employees like professors of a state university? A long discussion between Karl Fuchs as head of the Geophysical Institute and the chancellor of the University of Karlsruhe clarified this question in a positive sense.

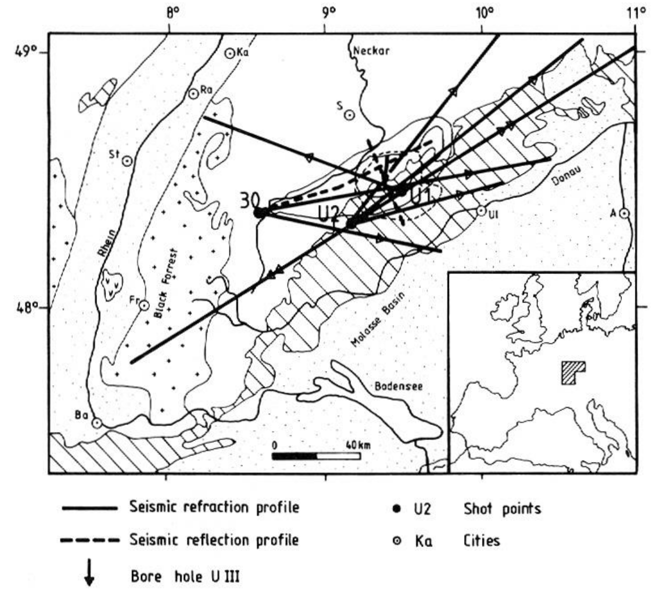


Fig. 2-11: Seismic profiles of 1978 in the Urach area (from Gajewski and Prodehl, 1985, Fig. 1; Prodehl and Mooney, 2012, Fig. 7.2.5-02).

Fig. 2-12 Swabian Jura (Hohenneuffen).

The financial handling of the project was also unusual and connected with certain personal financial risks for the responsible researcher causing him to obtain special personal liability insurance. While research costs funded by the German Research Society were covered by 100% and were made available beforehand, the European Community would reimburse only 50% after the bills were submitted and approved. On the other hand indirect costs like salaries of university employees, rent of university rooms, use of university computers, etc. would also be partially reimbursed. Consequently, firstly the cashier of the University had to be convinced to prepay the bills out of other funds and secondly the project leader had to estimate the indirect costs in a realistic way that at the end the sum of the reimbursed amounts would cover all actual costs. It was not obvious that at the end it worked with a small surplus for the Geophysical Institute.

Having overcome all legal and financial problems, the fieldwork could be carried out successfully. Furthermore the Geophysical Institute of the University of Kiel under the heading of Professor Meissner, in cooperation with Karlsruhe, organized the recording of a 27 km long seismic-reflection line in the foreland of the Swabian Jura, including a short cross line across the borehole location (dashed lines in **Fig. 2-11**) and some piggy-back refraction observations of up to 100 km distance (Bartelsen et al., 1982). Applying the time term method on the seismic-refraction data, a depth contour map of the basement resulted (Jentsch et al., 1980, 1982; Jentsch and Bamford, 1982; Prodehl et al., 1982), while the long-range data were interpreted and published three years later (Gajewski and Prodehl, 1985).

In 1985-1987 a teleseismic and petrological investigation of the Urach area follwed which was jointly planned and carried out by Andreas Glahn, Ulrich Achauer of Karlsruhe and Peter M. Sachs of Stuttgart (Glahn et al., 1992; Glahn, 1993; for more details see Chapter 9-2-4 of tis volume).

3. The European Rift System in the framework of KTB, EGT and SFB 108

3-1. Wildflecken 1982

Following a cooperation of Karlsruhe with Mr. Goos of the German army in the late 1970s (see subchapter 4-6), the Institute one day was asked to record a series of test explosions at the troop training area Wildflecken / Rhön and to measure their environmental impact. As the explosions were scheduled for a time interval of several days, the unforeseen chance arose to record a series of crustal profiles across Southern Germany. Due to the good relationship between the seismically active German Geophysical Institutes, a large number of seismic refraction stations could be mobilized on short notice and distributed along seven profiles directed fan-like from Wildflecken from a NW-SE profile towards the Bavarian Forest to a NE-SW directed line towards the Black Forest (profiles no. 4 in **Fig. 3-02**). It was arranged that the charges increased from day to day so that the stations could systematically move from day to day towards larger distance ranges. The project was coordinated by Dirk Gajewski und Claus Prodehl, the data preparation was executed by Beate Aichroth, Wolfgang Friederich, Thomas Faulhaber, and Uwe Kästner under the direction of Werner Kaminski. The interpretation served Stephan Zeis for his diploma thesis and was subsequently published in Tectonophysics (Zeis et al., 1990).

3-2. KTB Black Forest 1984 (seismic refraction and reflection experiments)

When German geoscientists in the beginning of the 1980s started discussing about a geoscientific continental super-deep drillhole (KTB) in Germany, naturally it was discussed where such a drillhole would best be located. Four sites seemed suitable positions: the Aachen transfer fault, the Black Forest, the Hohenzollerngraben with its strange strong seismic events, and the Oberpfalz near the Czech border. Karlsruhe was especially interested in the two Southwest German locations: the Black Forest and the Hohenzollerngraben, and planned for corresponding pre-site surveys in the form of seismic crustal investigations. A special application to DFG ensured funding for a seismic refraction profile along the axis of the Black Forest (Gajewski and Prodehl, 1987, **Fig. 3-01**). The existing Collaborative Research Center 108 (SFB 108) at Karlsruhe enabled to extend the seismic investigation of the Black Forest by adding two refraction lines, one in the strike direction of the Hohenzollerngraben and one in the strike direction of the Swabian Jura. For the Jura line already data from the 1972 Rhinegraben and the 1978 Urach experiments (profile SB-060-09, see **Fig. 2-06**) existed (Gajewski et al., 1987a, b).

The resulting project was named "Black Zollern Forest" (network no. 5 in **Fig. 3-02**). While the project was being planned, the KTB plans were focussed and the site selection was re-examined and subsequently limited on two sites only: Black Forest and Oberpfalz. For the Black Forest a location for a possible deep drillhole was determined near Haslach. This enabled planning of more detailed seismic pre-investigations by seismic-reflection profiling, consisting of a 170 km long line parallel to the refraction line and two short cross lines intersecting each other around Haslach. Furthermore a seismic-reflection line was recorded along the Badenweiler-Lenzkirch fault zone. Thus, a total of 345 „reflection kilometers" resulted (Lueschen, 1985, 1987; Lueschen et al., 1987). Responsible for the organization and realization of the active reflection-seismic fieldwork were Ewald Lueschen and coworkers such as Dieter Menges, Thomas Rühl, Karl-Josef Sandmeier, and others. For the seismic-refraction project in summer 1984, Dirk Gajewski und Claus Prodehl were responsible for the organization, under active cooperation during the fieldwork by Beate Aichroth, Heinz Hoffmann, Klaus Joehnk, Jürgen Neuberg, Raimund Stangl, Walter Zürn, and others.

By an unexpected mishappening the project became a subject of public interest. One of the recording stations which had been hidden at a remote site in the forest had disappeared. The responsible scientist Raimund Stangl informed a local newspaper agency and spent a day with a newspaper reporter explaining the project in all details. Subsequently a full page of the local newspaper was devoted as a search add accompanied by a two-page report describing purpose and activities of the project in detail with many photographs of geophysicists in action. However, the lost equipment did not show up. Only one year later a man hiking through the forest found the equipment close to but not exactly at the original site. It was still functioning, proving the high quality of the MARS-66 system.

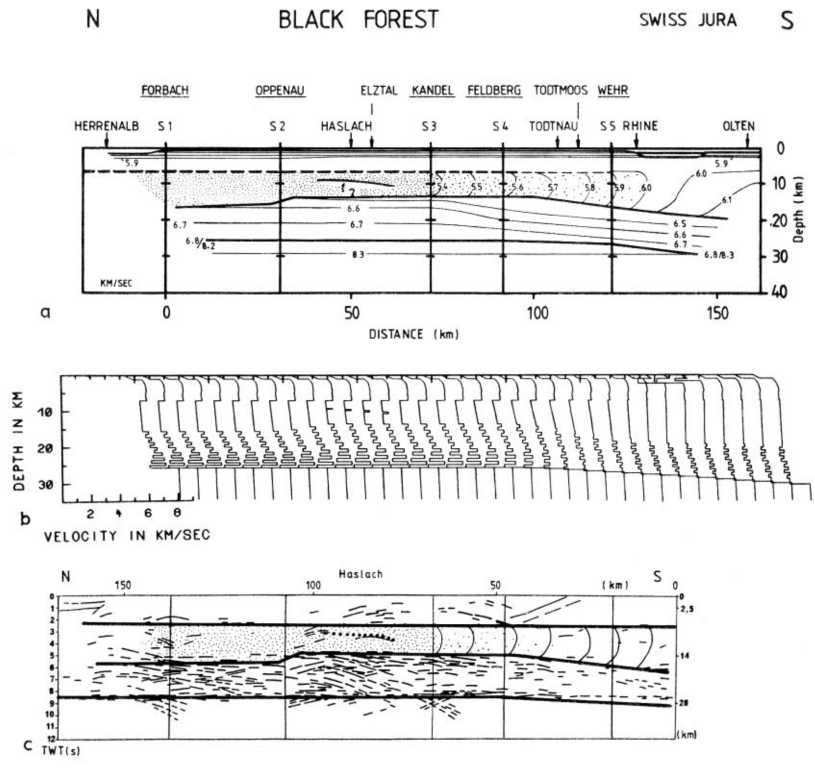


Fig. 3-01: Combined refraction and reflection seismic surveys in the Black Forest (from Gajewski and Prodehl, 1987, Fig. 8; Prodehl and Mooney, 2012, Fig. 8.3.3-03). **(a)** Model with lines of equal velocity, derived from seismic-refraction data. **(b)** Velocity-depth sections, derived from refraction data. **(c)** Line drawing of the seismic-reflection section along the Black Forest (simplified after Lüschen et al., 1987). Two-way travel times as calculated from model (a) are plotted as thick lines in (c).

The data preparation was mainly the task of Dirk Gajewski, Uwe Kästner, Stephan Zeis and H. Fischer, supervised by Werner Kaminski. Dirk Gajewski acted as principle scientist for the interpretation (Gajewski and Prodehl, 1987; Gajewski et al., 1987a, b). Anton Krammer interpreted the recorded shear-wave data in his diploma thesis. At the supervision of this work, Steve Holbrook was greatly involved, who, on leave from the U.S. Geological Survey, spent a year as guest scientist at Karlsruhe (Holbrook et al., 1987, 1988). The joint investigation of reflection and refraction data showed some interesting results. The upper crust of the reflection sections was little reflective which coincided with a low-velocity zone derived from the refraction data. In contrast the lower crust of the reflection sections was highly reflective which in the wide-angle distance range of the refraction data corresponded to a strong coda of high-amplitude P_MP-reflections. It was interpreted as a laminated lower crust, i.e. a sequence of subsequent thin high- and low-velocity layers. The refraction-seismic Moho correlated in depth with the lower termination of the high-amplitude reflections in the reflection seismic sections (**Fig. 3-01,** Fuchs et al., 1987a; Gajewski, 1989; Lüschen et al., 1989; Sandmeier and Wenzel, 1990; Lüschen, 1990; Prodehl et al., 1992, 1995).

At the closing session judging on the optimal location for a superdeep drillhole in Germany the location „Black Forest“ was abandoned and the location „Oberpfalz“ chosen as the favourite site. Drilling started on 18 September 1987 (Emmermann and Wohlenberg, 1989; Fuchs, 1990; Lueschen et al., 1990, 1991, 1996).

3-3. The European Geo-Traverse (EGT)

The idea of a geophysical European Geotraverse was essentially created at Zurich by Stephan Mueller, who served as chairman of the project for more than a decade, from 1980 to 1992, being assisted by Jörg Ansorge and the EGT secretaries D.A. Galson and Roy Freeman and being supported by the European Science Foundation (Blundell et al., 1992, Freeman, and Mueller, 1992). Its backbone was a seismic-refraction project subdivided into a northern segment, covering Scandinavia and the Baltic Sea (FENNOLORA 1979, already performed (see subchapter 4-7), POLAR in Finland, and EUGENO-South around the Baltic Sea), a central segment (EUGEMI = EUropean GEotraverse Mitte), covering Germany, Alps, and northern Italy, and a southern segment comprising Ligurian Sea – Corsica – Sardinia – Thyrrenian Sea – Tunesia.

Karlsruhe participated in 1983 in the southern segment and in 1984 in EUGENO-S, but was one of the principle investigators for the northern segment in 1979 (Prodehl and Kaminski, 1984; Guggisberg et al., 1991) and the central segment in 1986 (Aichroth and Prodehl, 1990; Aichroth et al., 1992). The seismic refraction line of the central segment ran from Genova in the south to Kiel in the north (green line on the EGT map in **Fig. 3-02**). While the search for shotpoints and their realization for the Alpine part were organized by Zurich, the shotpoints in Italy were taken care of by Milano, and Karlsruhe was responsible for the German shotpoints (Giese and Prodehl, 1986).

At the northern end, the German Navy could be interested to organize an underwater shot in German waters of the Baltic Sea. Within the North German Plain a shotpoint could be arranged to be carried out by the German Army in a troop training area in the Lüneburger Heide, for which Roland Vees of Clausthal overtook the organizational details. Again, a large shot of the German Army could be arranged at the troop training area Wildflecken.

For the remaining shotpoints the commercial company PRAKLA was hired for the drilling of shotholes, and Dr. Jürgen Wieck of Neckartailfingen was hired to organize and carry out the borehole explosions. For all non-military shotpoints in Germany the Niedersächsische Landesamt für Bodenforschung had delivered an expertise which certified that the vibrations caused by the borehole explosions would not cause any damages to adjacent buildings and structures (e.g., Behnke, 1988). In total 30 shots were fired and successfully recorded at 850 recording sites. All sites had been explored prior to the main field campaign.

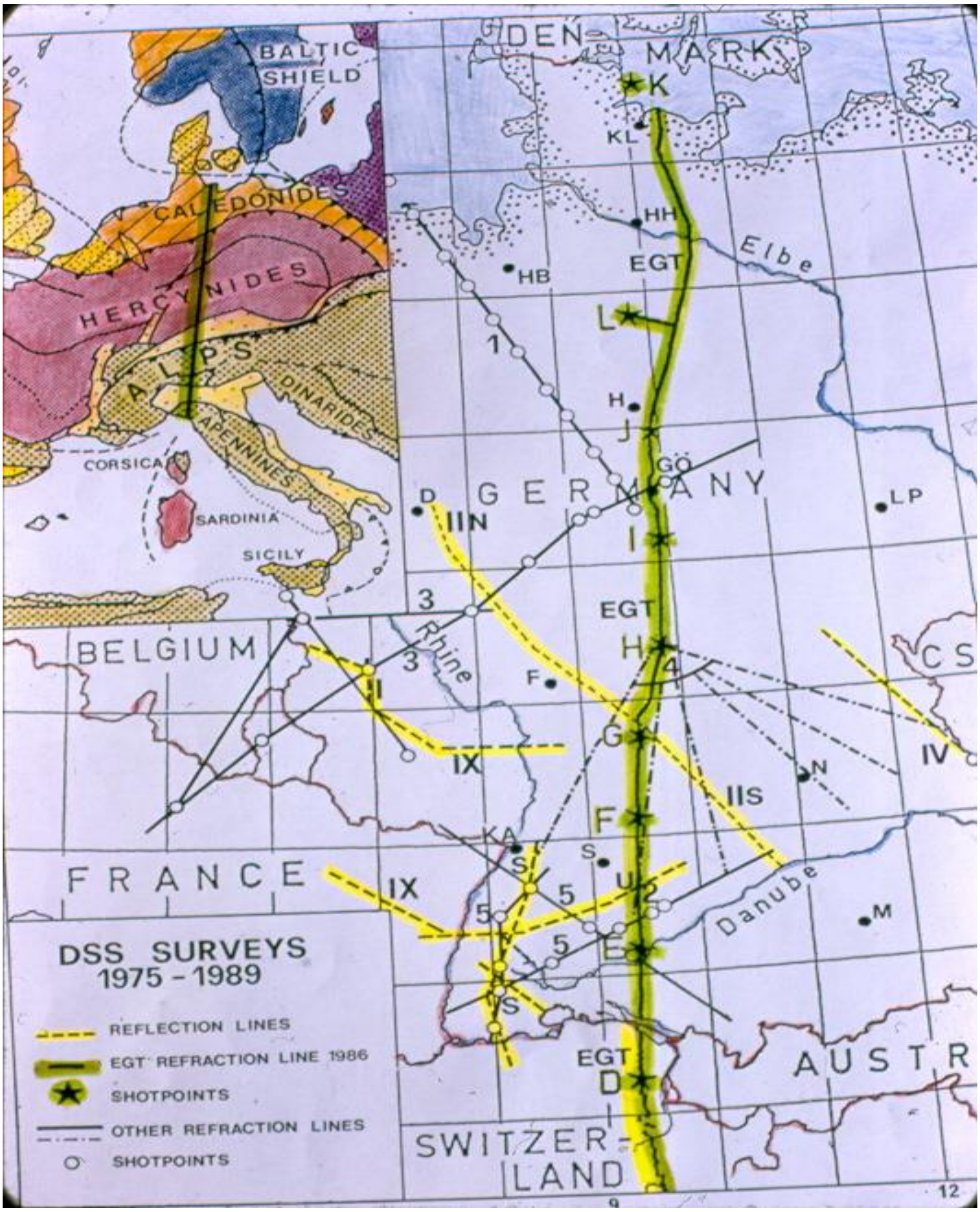


Fig. 3-02: Seismic profiles 1975-1989 around the European Geotraverse (after Prodehl and Aichroth, 1992, Fig. 1; Prodehl and Mooney, 2012, Fig. 8.3.4-08).

Beate Aichroth was the principle scientist and was, together with Claus Prodehl, responsible for organization and following data preparation and interpretation. Her chief assistant was Joachim Ritter, at that time geophysics student in his third semester. Because of the length of the central section (1200 km), it was subdivided into three segments which were successively occupied by recording stations. Consequently the headquarters was moved three times. The first headquarter site was the Albergo Pavese within the northern Apennines. The owners of the small guesthouse spoke Italian only, but there was a very friendly agreement that their local telephone was mainly used for the EGT communication, because each observer team had been instructed to telephone regularly to keep up to date with the shot schedule. The second and third headquarters for the operations in Germany were successively installed at Bretzfeld near Heilbronn and Bockenem south of Hildesheim. Here, the Headquarters personnel also took care of the shot operations, i.e. for the communication with the shooting teams and the recording of the shot instants. For recording, 202 MARS-66 instruments, a British Geostore and 20 Irish stations, all analogue, and 6 Finnish digital stations had been acquired. In total 200 participants from Denmark, Germany, Finland, France, Great Britain, Ireland, Italy, Spain, Sweden, and Switzerland were in the field.

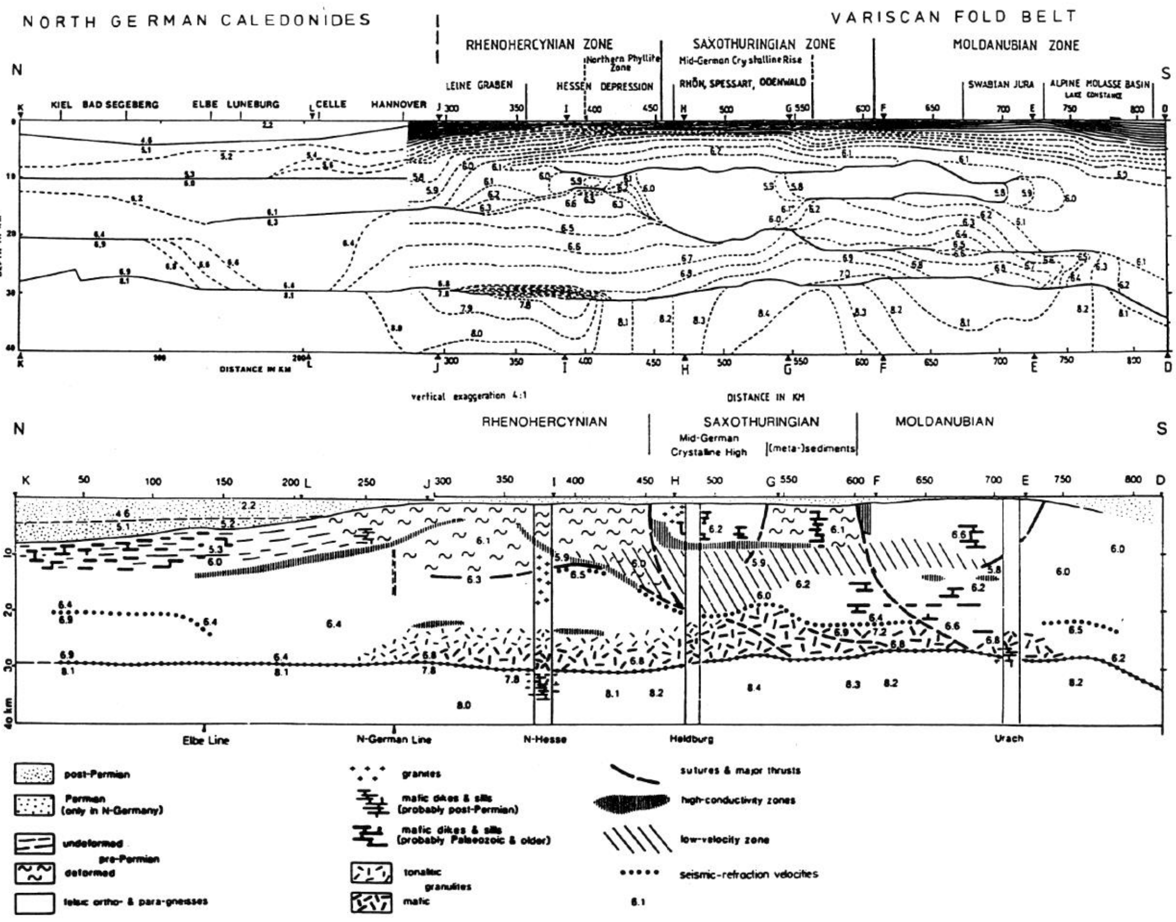


Fig. 3-03: Crustal cross section of the EGT central segment from the Baltic Sea to Lake Constance (from Prodehl and Aichroth, 1992, Fig. 3; Prodehl and Mooney, 2012, Fig. 8.3.4-09). Depth versus distance is exaggerated by 4:1. **Upper part:** Seismic velocity model. **Lower part:** Petrological interpretation.

At the data preparation and digitalization Beate Aichroth and Werner Kaminski were helped by J. Feddersen, O. Hoppe, and Joachim Ritter. For the data interpretation under the heading of Beate Aichroth and Claus Prodehl a special seismic workshop was held from 27 February to 4 March 1989 at Karlsruhe, Germany, and the results were subsequently published in Tectonophysics (EUGEMI Working Group, 1990; Aichroth et al., 1992). An interdisciplinary EGT Study Center from 25 March to 5 April 1989 at Rauischholzhausen near Giessen, Germany, served in particular to interpret the seismic model of the central segment of the EGT, leading to its petrological interpretation shown in **Fig. 3-03** (Aichroth and Prodehl, 1990; Prodehl and Giese, 1990; Aichroth et al., 1992; Prodehl and Aichroth, 1992).

3-4. Teleseismics in the Rhinegraben

During 1988-1989 in the area of the southern Rhinegraben between Karlsruhe and Basel a temporary network of seismological stations was installed which recorded a series of teleseismic events. The Karlsruhe project leader was Andreas Glahn (Glahn and Granet, 1992, Glahn et al., 1993; for more details see Chapter 9-2-6 of this volume).

3-5. Seismic reflection profiles in the Rhinegraben

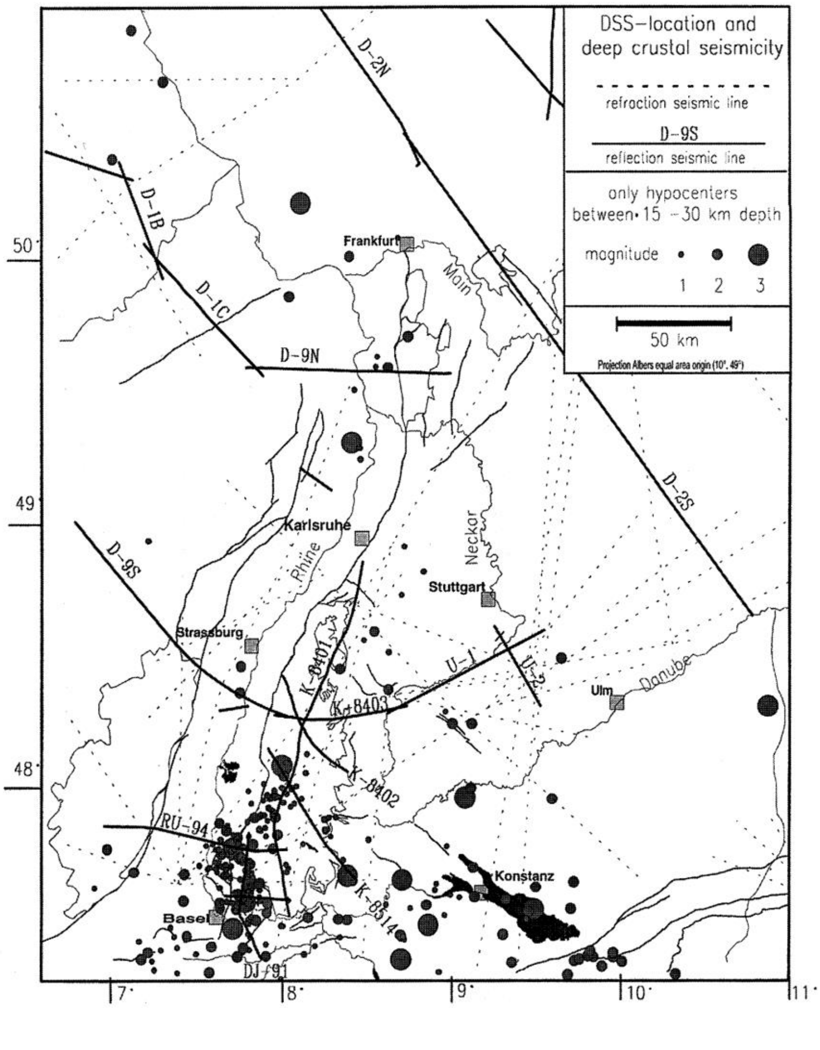


Fig. 3-04: Seismic-reflection lines and seismicity in the Rhinegraben (from Mayer et al., 1997; see also Prodehl and Mooney, 2012, Fig. 9.2.2-06).

In close cooperation with ECORS, in 1988 DEKORP recorded two seismic-reflection profiles across the Rhinegraben, both in NW-SE direction (**Fig. 3-04**). The southern profile started in the Lorraine basin, crossed the northern Vosges and the southern Rhinegraben near Selestat south of Strasbourg and terminated in the central Black Forest. In order to assure sufficient energy for recording lower crust information, in addition to the Vibroseis measurements some borehole explosions were arranged. The northern profile ran from the Saar-Nahe basin across the northern Rhinegraben into the Odenwald. Here, for lack of funding, borehole shots had to be omitted and only Vibroseis came into use. The principal Karlsruhe investigator was Friedemann Wenzel, assisted by Ewald Lueschen and others (Brun et al., 1991, 1992; Wenzel et al., 1991; Prodehl et al., 1992, 1995).

3-6. Dinkelberg and southernmost Rhinegraben

In 1990 Helmut Echtler was temporarily employed in project D8 of the SFB 108. He initiated a special project in the southernmost Rhinegraben and adjacent eastern flank, the Dinkelberg. In 1990 and 1991, two seismic-reflection profiles were recorded between the southernmost Black Forest and the Rhinegraben, traversing the Dinkelberg (Echtler et al., 1994, **Fig. 3-04**).

In this area the strongest seismicity of the entire Rhinegraben had been observed (Faber et al., 1994; Bonjer, 1997; Plenefisch and Bonjer, 1997; Chapter 7 of this volume) and special investigation of seismological upper-mantle phases had been carried out (Plenefisch et al., 1994). Furthermore, in 1994 undershooting of the southern Rhinegraben was carried out by recording wide-angle seismic reflections from lower crust and Moho. For this purpose seismic stations were placed on outcropping rocks in the Vosges and Black Forest which recorded quarry blasts and borehole explosions from the opposite sides of the Rhinegraben in Vosges and Black Forest (Mayer et al., 1997).

Summaries of all active seismic experiments in the entire European Cenozoic rift system (Fuchs et al., 1997a; Prodehl et al., 1992, 1995) were compiled for a symposium on the Geodynamics of Rifting (Ziegler, 1992) as well as in the framework of CREST (Continental Rifts: Evolution, Structure, Tectonics, edited by Olsen (1995).

3-7. Seismic refraction and teleseismic observations in the French Massif Central

The fruitful cooperation between Karlsruhe and Paris over many years enabled a new joint project in 1992, a renewed investigation of the Central European rift system in the region of the French Massif Central. The project had two seismic components: a passive teleseismic project and an active controlled-source seismic part.

From 1991 to 1992, for half a year a temporary network of seismological stations was installed which, together with the permanent French network, recorded teleseismic events (dots in **Fig. 3-05**). From Karlsruhe, Ulrich Achauer and Gerald Stoll were the responsible scientists. From the recorded data a three-dimensional velocity model to a depth of 180 km could be established. It showed lateral heterogeneities in the upper 60 km of the lithosphere which allowed astonishingly well correlations between the volcanic provinces (black areas in **Fig. 3-05**) and the observed negative velocity anomalies (Granet et al., 1995; Ritter et al., 1997, 1998; for more details see Chapter 9-2-7 of this volume).

As in Germany and France modern equipment for seismic refraction work was not available, the U.S. instrument pool of PASSCAL could be borrowed. This pool comprised 150 cassette recorders (SGR – one-component-stations, **Fig. 3-06** to **Fig. 3-08,** Murphy et al., 1993) including a modern mobile computer for digital data preparation (**Fig. 3-09**) and personnel of PASSCAL and the University of Texas at El Paso under the heading of Marcos Alvarez. The equipment was shipped from U.S.A. to the observatory of Garchy where the European participants were instructed and trained (**Fig. 3-06** and **Fig. 3-08**) by the American colleagues.

105 out of the 150 stations were installed along a 230 km long west-east profile through

the neogene volcanic field at the southern end of the Limagnegraben, the remaining 45 stations were distributed along a second parallel west-east profile 70 km further north without, however, placing stations in the graben proper (lines in **Fig. 3-05**). Seven borehole shots, four along the southern profile, three along the northern line, were recorded simultaneously on both profiles (stars in **Fig. 3-05**). Thus, in addition to the in-line observations, fan-like P_MP-phases at critical distance ranges could be gained from the shots along the other profile.

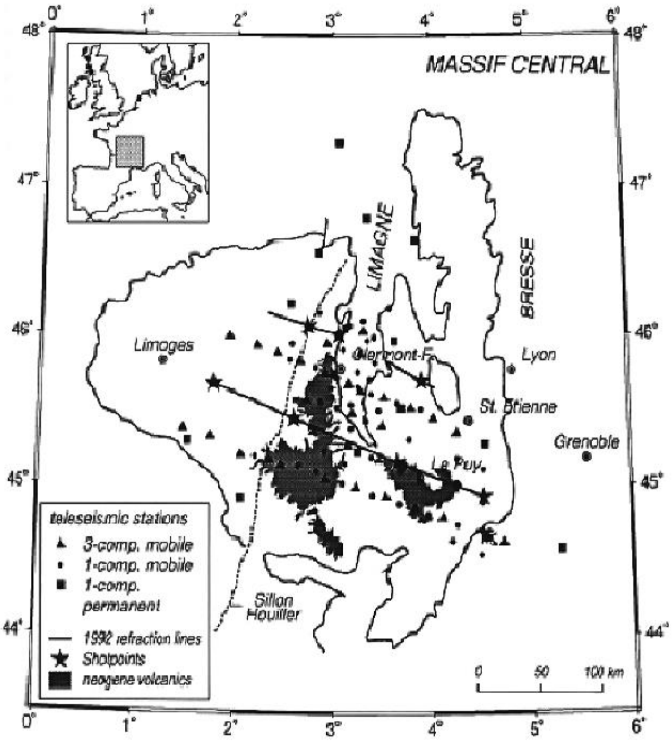


Fig. 3-05: Limagnegraben 1992: location of teleseismic stations and seismic refraction lines (stars = shotpoints) (from Prodehl et al., 1995, Fig. 4-4; Prodehl and Mooney, 2012, Fig. 9.2.2-09).

Fig. 3-06: Huddle Test of the SGR

Fig. 3-07: PASSCAL's SGR at Garchy. **Fig. 3-08:** Equipment test. **Fig. 3-09:** Mobile computer of PASSCAL.

During a couple of days following the field work the data were digitized by Marcos Alvarez on the mobile PASSCAL field computer at the French headquarters in Clermont-Ferrand, stored on a computer tape and handed over to the European organizers. From

Karlsruhe, Uwe Enderle, Werner Kaminski, Uwe Kästner, Michael Landes, Jim Mechie, Thomas Nadolny, Mark Tittgemeyer, Veronika Wehrle, and Claus Prodehl participated in the field work. The interpretation was carried out at Karlsruhe by Olaf Novak and Michael Landes under the supervision of Hermann Zeyen. Moho depths varied between 25 km underneath the Limagnegraben and 30 km underneath the surrounding Massif Central (Prodehl et al., 1995; Zeyen et al., 1997; **Fig. 3-10**).

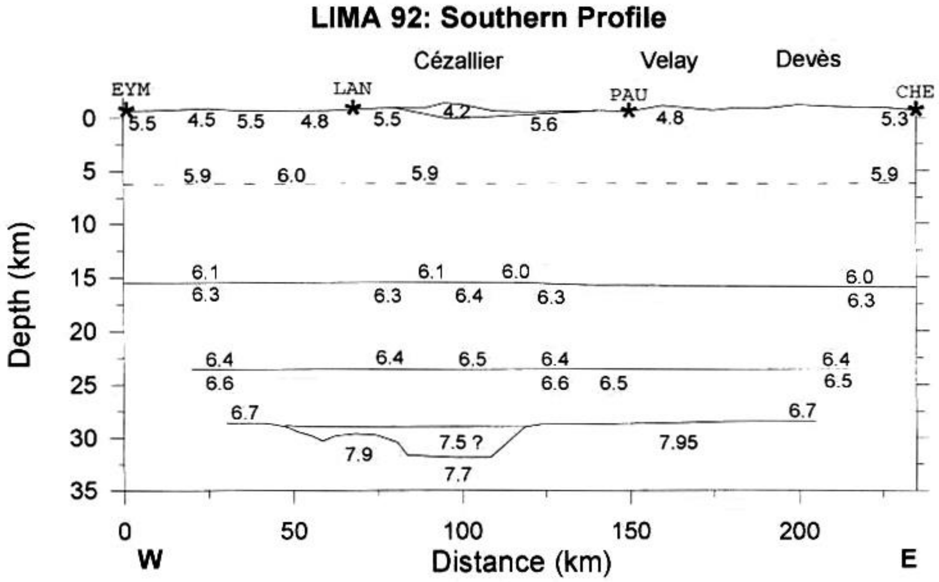


Fig. 3-10: Crustal cross section through the neogene volcanic fields of Cantal (south of Clermont Ferrand) and le Deves (around Le Puy) and the southern end of the Limagne graben in between (from Zeyen et al., 1997, Fig. 7; Prodehl and Mooney, 2012, Fig. 9.2.2-11).

4. Exploring the subcrustal lithosphere – long-range profiles of 1000 km and more

Though many seismic-refraction profiles observed in the 1960s reached recording distances of several hundred kilometers, the fine structure of the P_n phase had barely been noticed. A first report on systematic amplitude variations of the P_n phase was published in 1966 by a Soviet scientist (Ryaboi, 1966). Ansorge (Ansorge and Mueller, 1971; Ansorge, 1975) took up this idea and started to investigate the long-range observations of the Lake Superior experiments in North America (Early Rise experiment) and compared them with data recorded in the past 25 years in central and northern Europe with distances ranging from 400 to 2200 km (Heligoland-South 1947, Lac de l'Eychauda 1963, Norway 1965, Lac Nėgre 1966, Folkestone 1967, Trans-Scandinavian Profile 1969, quarry blast observations at Böhmischbruck, Germany 1960-71). He found that a similar fine structure described by Ryaboi (1966) for the P_n phase could also be seen in these sparse data which indicated that a rather complex structure in the uppermost mantle down to 120 km depth was to be expected (Ansorge, 1975).

4-1. France 1971

So, the idea was born to systematically plan for an experiment out to 1000 km in Western Europe to be placed within a tectonically unique surrounding. Experience from the Early Rise project, where 5-ton underwater shots had been recorded to distances of up to 3000 km, and the theoretical investigations of Wielandt (1972, 1975) had shown that underwater shooting of relatively small depth charges (1000-3000 kg) at optimal water depths would produce sufficient energy to be recorded across a profile of possibly up to 1000 km length.

Several discussions between Stephan Mueller, Jörg Ansorge, Karl Fuchs and the French colleagues Leon Steinmetz and Alfred Hirn resulted finally in the idea to plan a profile diagonally through France from the Bretagne across the Massif Central to the Mediterranean coast being located mainly on Variscan rocks (**Fig. 4-01**). Such a line should almost fulfil the requirement of a tectonically homogeneous subsurface and would furthermore offer the chance to work with sufficiently large offshore shots at both ends. In order to exclude or at least control disturbing effects by crustal anomalies, the recording sites should be placed as far as possible on outcropping Variscan rocks. Furthermore borehole shotpoints on land were added every 300 km.

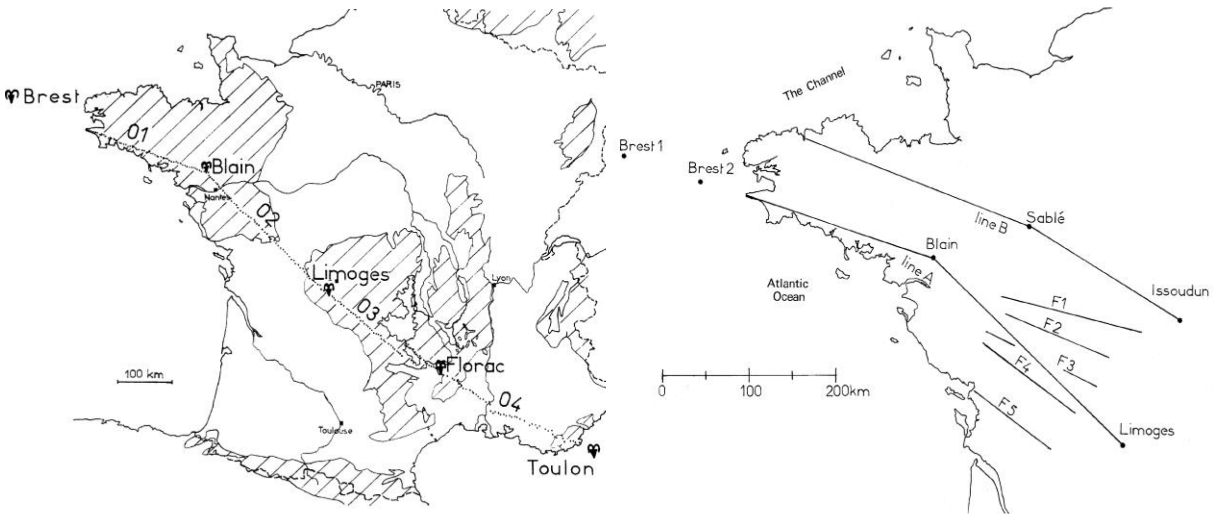


Fig. 4-01: Long-range lines through France**: left:** 1971 location map, **right:** long-range lines of 1973 (from Sapin and Prodehl, 1973, Fig. 1 and Hirn et al., 1975, Fig. 1; Prodehl and Mooney, 2012, Figs. 7.2.1-01 and -4).

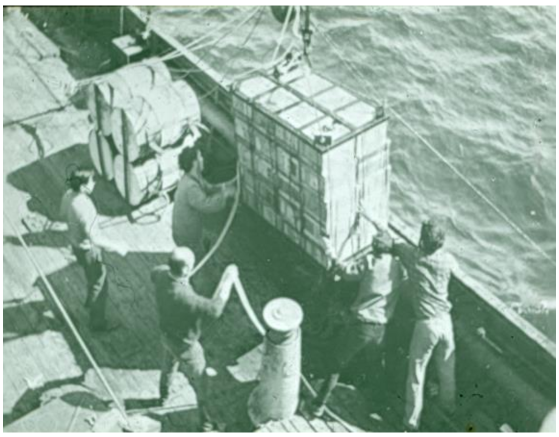


Fig. 4-02: One-ton charge off Brest in 1971.

Fig. 4-03: Meeting of participant at headquarter Florac in 1971.

The size of the underwater charges off Brest and off Toulon were minimized to 1 ton explosives (**Fig. 4-02**) and detonated at „optimal depth" making use of the effect of the bubble pulse following the theoretical calculations of Erhard Wielandt. The project was successfully carried out in the summer of 1971. Only the shots off Toulon did not provide the energy hoped for, due to extremely bad weather conditions (Groupe Grands Profils Sismiques and

German Research Group for Explosions Seismology, 1972).

To secure data quality, the field headquarters of this and the following projects had to fulfil several tasks: A 24h telephone service served for a continuous communication between shooting crews and headquarters as well as between recording crews and headquarters. Furthermore the tape recordings were collected after each major shot series and played back immediately in the headquarters in order to control the functionality of the recording instruments and to enable a repetition of observations if necessary. In addition, the field playbacks were assembled to preliminary record sections which allowed a first glance on possible results.

In the headquarters of the 1971 project Stephan Mueller and Leon Steinmetz were responsible for the local communication, Alfred Hirn and Claus Prodehl were busy collecting tapes, and Karl Fuchs pasted the first preliminary record sections. Playbacks were carried out by the undergraduate student Friedemann Wenzel and the technician Matthias Diestl. Recording crews came from Paris, Strasbourg, Lissabon, Zürich, Clausthal-Zellerfeld, Hamburg, Hannover, Karlsruhe, Kiel, München, and Münster. Field participants from Karlsruhe were Rainer Blum, Sonja Faber, and Karl-Otto Millahn (partly seen in **Fig. 4-03**).

The interpretation was primarily carried out by Martine Sapin and Claus Prodehl for the crust and by Rainer Kind, Alfred Hirn and Karl Fuchs for the subcrustal lithosphere. Moho depths averaged around 30 km (Sapin and Prodehl, 1973). As expected, the P_n–phase was not a continuous phase reaching to several 100 km distance as hitherto interpreted for long seismic-refraction and seismological data, but disappeared beyond 300 km, while at larger distances slightly delayed phases consisted of several branches which the authors interpreted as reflections from subcrustal discontinuities between 50 and 80 km depth (Hirn et al., 1972, 1973; **Fig. 4-04, Fig. 4-08**). Rainer Kind has reinterpreted the long-range data and has proposed a more refined model of the lower lithosphere (Kind, 1974a, b; **Fig. 4-08**).

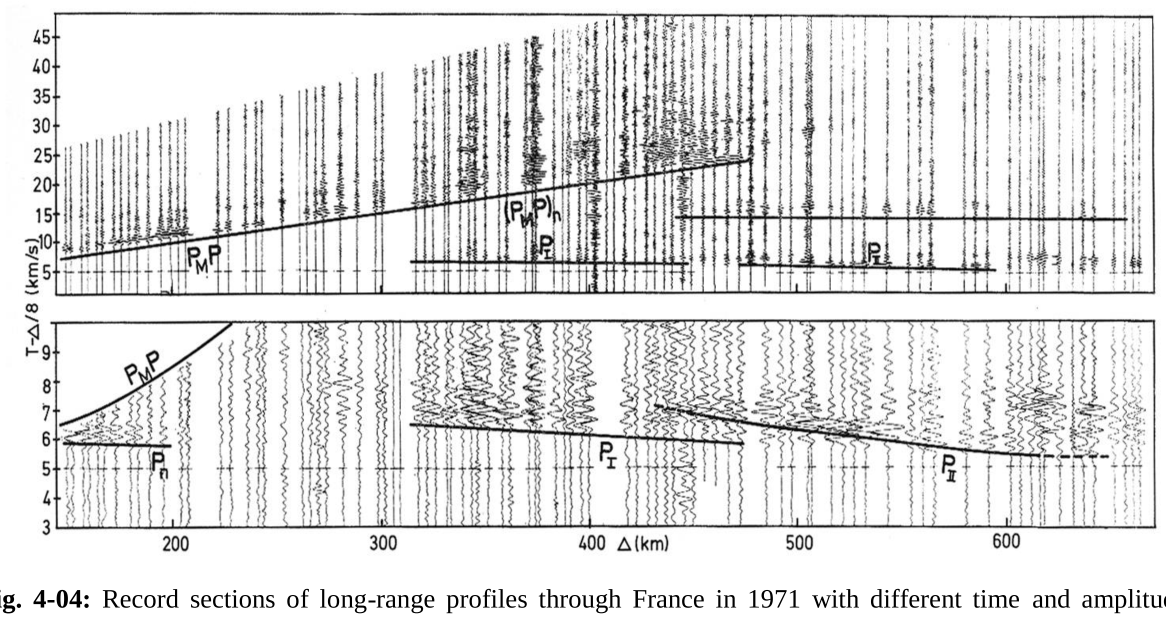


Fig. 4-04: Record sections of long-range profiles through France in 1971 with different time and amplitude scales (from Hirn et al., 1973, Fig. 3; Prodehl and Mooney, 2012, Fig. 7.2.1-03). P_MP reflection from Moho, P_n refracted head wave guided at Moho, P_I, P_{II} reflections from subcrustal interfaces at 55 km resp. 80 km depth. The lower section shows a clear separation of P_I and P_{II}, which is not clearly visible in the upper section.

4-2. 10-ton shot off northwestern Scotland 1972

In 1972 the long range observations were extended to 1500 km distance. Following a

10-ton explosion off Scotland which had been arranged by P.L. Willmore and Brian Jacob and was successfully recorded by all permanent seismological stations throughout Europe (Jacob and Willmore, 1972), Brian Jacob organized a second 10-ton shot off the coast of western Scotland which was timed such that it could be recorded during the Rhônegraben project by the full MARS pool of French, German and Portuguese stations.

Fig. 4-05: France 1971-73. Headquarters of 1972 at Pont d'Isère during the Rhônegraben experiment.

For this purpose all stations had been rearranged along a line extending from the northern end of the Massif Central to the delta of the Rhône river over a distance range from 900 to 1500 km (Steinmetz et al., 1974). **Fig. 4-05** presents a view of the headquarters in France where the crustal and upper-mantle projects were coordinated, communication with shotpoints and recording crews assured, tapes collected and playbacks made for quality control. In addition, Klaus-Peter Bonjer and Rainer Kind had mobilized all other German stations which were not involved in the Rhônegraben experiment and placed them along a NW-SE line in the Bavarian Forest between 800 and 1400 km distance (Bonjer et al., 1974). Bad-weather conditions delayed the shot by almost one week, but finally the 10-ton charge was successfully detonated and recorded along the two profiles. Steinmetz et al. (1974) deduced a model to the base of the asthenosphere at 200 km depth (see velocity-depth section 74S4 in **Fig. 4-08**).

4-3. France 1973

In order to verify the existence of subcrustal reflections P_I, P_{II} etc. and to exclude the possibility that local crustal heterogeneities caused the offset of first arrivals beyond 320 km recording distance, on the initiative of Alfred Hirn in 1973, again in cooperation of Paris and Karlsruhe, a control experiment was organized (**Fig. 4-01**). The first 650 km of the 1971 profile were reoccupied and the shotpoint in the Atlantic Ocean was shifted by 50 km. In addition, around the main profile several fan lines were arranged for the distance range of 450-650 km where the subcrustal reflections P_I, P_{II} had been recorded in 1971 and another 1-

ton shot was fired at the same position as in the 1971 experiment (shotpoint Brest 1 in **Fig. 4-01**).

This was the second project where the mechanical clocks of Otto Gothe helped to reduce the required Karlsruhe personnel. Furthermore a second 500 km long line with shotpoints at Issoudun and Sablé was recorded 100 km north of and parallel to the 1971 line. Unfortunately, the underwater shot at the northwestern end failed (Hirn et al., 1975; **Fig. 4-01**), but the shotpoint Issoudun **(Fig. 4-01**) carried sufficient energy along the whole line of 500 km length.

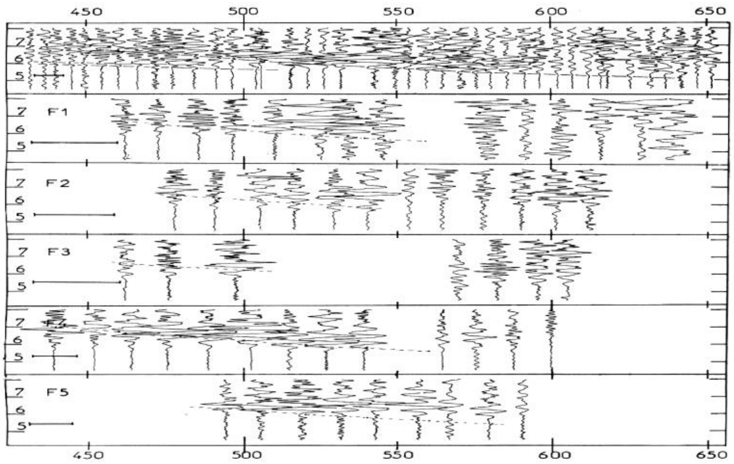


Fig. 4-06: Observed data on the main profile Brest 1 (1971) and fan profiles F1 to F5 obtained in 1973 from a shot at the same position Brest 1 (from Hirn et al., 1975, Fig. 4; Prodehl and Mooney, 2012, Fig. 7.2.1-05). Reduction velocity is 8 km/s. The dotted line on each section indicates the travel time curve correlated for P_{II} on Brest 1, line A (top section). Overall magnifications are uniform for all traces in one section, but note its variation from one section to another (0.5 µ/s amplitude bar in lower left corner).

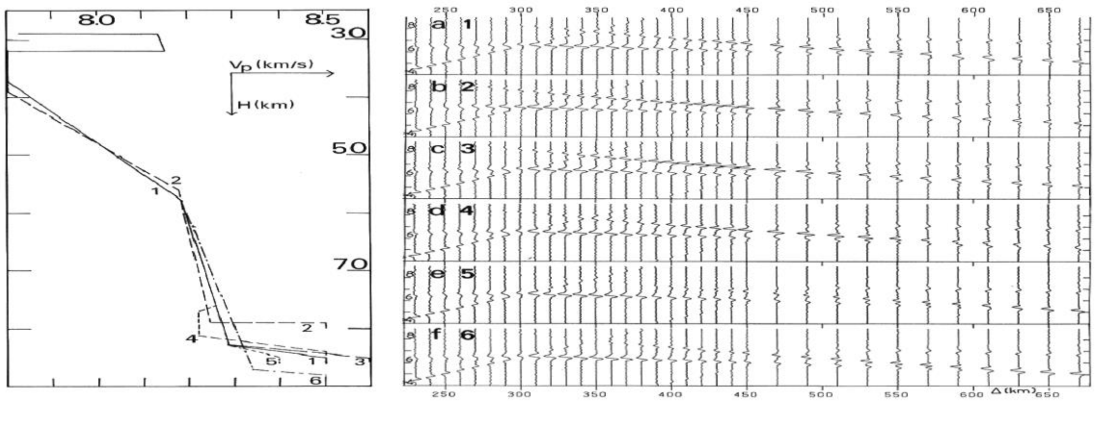


Fig. 4-07: Left: Velocity-depth models, corresponding to the long-range profiles in western France, show small possible variations in velocity resp. depth for slightly varying recording positions (from Hirn et al., Fig. 7). **Right:** Synthetic record sections in the P_I, P_{II} distance range computed by the reflectivity method for the models to the left (from Hirn et al., 1975, Fig. 8; see also Prodehl and Mooney, 2012, Fig. 7.2.1-06).

The interpretation proved that the classical „P_n-phase“ in reality was a sequence of P_n recorded to about 300 km and slightly delayed reflections from the subcrustal lithosphere at larger distances (**Fig. 4-06**). The modelling for all fan profiles resulted in a similar depth-velocity function with subcrustal discontinuities at 50 and 80 km depth (**Fig. 4-07,** Hirn et al., 1975). Prodehl has compiled the various models of fine structure of the lower lithosphere down to 150 km depth obtained by Ansorge (Ansorge and Mueller, 1971, Ansorge, 1975) for earlier long-range data in Europe and for the French long-range experiments (**Fig. 4-08;** Prodehl et al., 1976b, 1984).

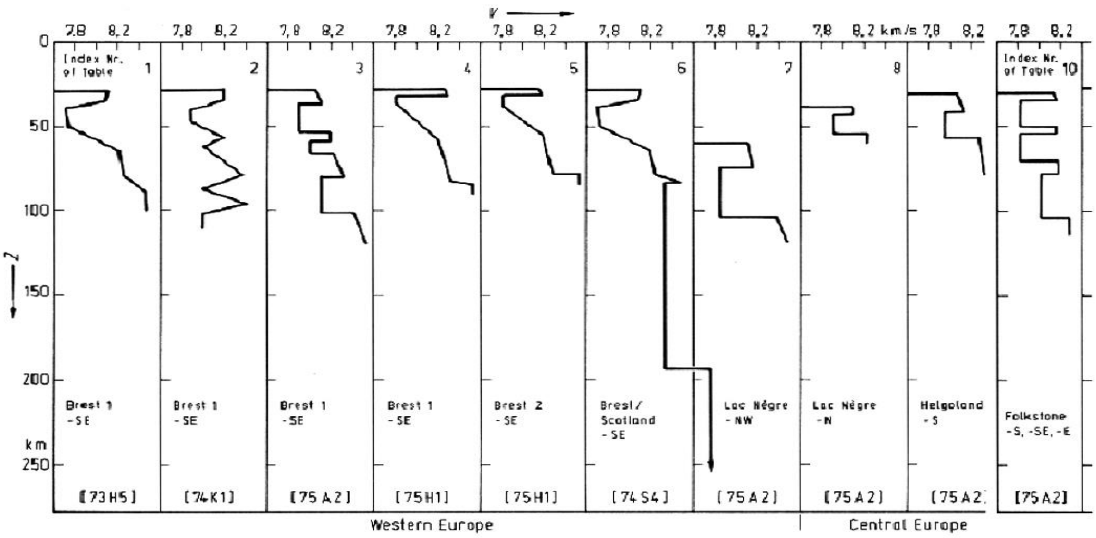


Fig. 4-08: Velocity-depth models of the subcrustal lithosphere in Western Europe for profiles recorded until 1973 (from Prodehl, 1984, Fig. 15; Prodehl and Mooney, 2012, Fig. 7.2.1-07). 73H5: Hirn et al., 1973, 74K1: Kind, 1974a, 75A2: Ansorge, 1975, 75H1: Hirn et al., 1975, 74S4: Steinmetz et al., 1974.

4-4. LISPB 1974

The publications met high interest in the geoscientific community and initiated follow-up experiments in other parts of Europe. A one-year research visit of David Bamford from Birmingham at Karlsruhe, which originally had served for a detailed interpretation of P_n-phases in southern Germany as described in detail in subchapter 2-5, became the nucleus of a fruitful British – German cooperation which immediately became visible in the planning of a second European long-range profile to be carried out along the axis of the British Isles. In a unique cooperation all seismically active British and German institutions concentrated their pools of seismic stations for the recording of a long-range profile extending from the south coast of Britain to the north coast of Scotland (LISPB – LIthospheric Seismic Profile through Britain). On the British side the leading scientists were David Bamford, Keith Nunn, Roy King, and Don Griffiths of the University of Birmingham, as well as Brian Jacob and P. Willmore of the British Geological Survey at Edinburgh, while on the German side the project leaders were Karl Fuchs and Claus Prodehl.

In order to avoid the crossing of the industrial areas of southern and central England, the southern part of the profile was shifted to the west as a N-S line though Wales. The central and northern part of the line was also arranged in N-S direction, but shifted by 80 km to the east (**Fig. 4-09**).

A key problem, when planning the underwater shots, was the limited water depth for optimal-depth shooting off the northern and southern ends of the line. Brian Jacob, then scientist at Edinburgh, had long before thought about to optimize effectiveness of underwater shots and had carried out trial experiments in a small lake of Scotland to see how seismic charges could be most efficiently detonated at shallower water depths, making use of the optimum depth which is directly dependent on the charge size. He found that splitting a charge into small units to be detonated simultaneously resulted in a much smaller optimum depth than would be necessary for a single larger charge (Jacob, 1975). As a result 3 - 9 units of 200 kg were assigned for the northern offshore shots and 4 to 6 units for the southern offshore shots which would be equivalent to unit charges of up to 5000 kg (**Fig. 4-10**). The concept was successfully applied. Similar as in France, several intermediate shotpoints on land with borehole explosions were arranged for crustal control (Bamford et al., 1975, 1976). An earthquake in western Scotland (KEQ in **Fig. 4-10**) happened during a recording window and added additional useful data (Kaminski et al., 1976).

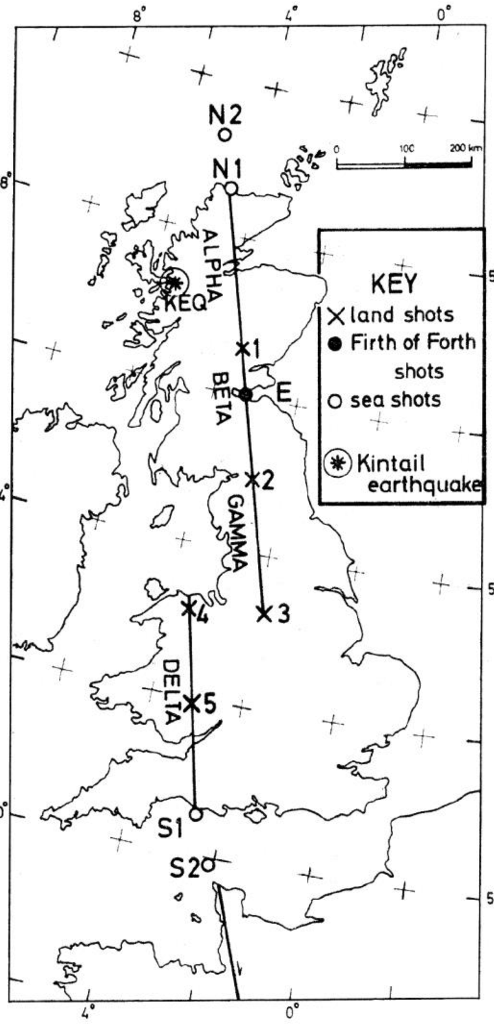


Fig. 4-09: LISPB 1974 location map (from Bamford et al., 1976, Fig. 1; Prodehl and Mooney, 2012, Fig. 7.2.4-05).

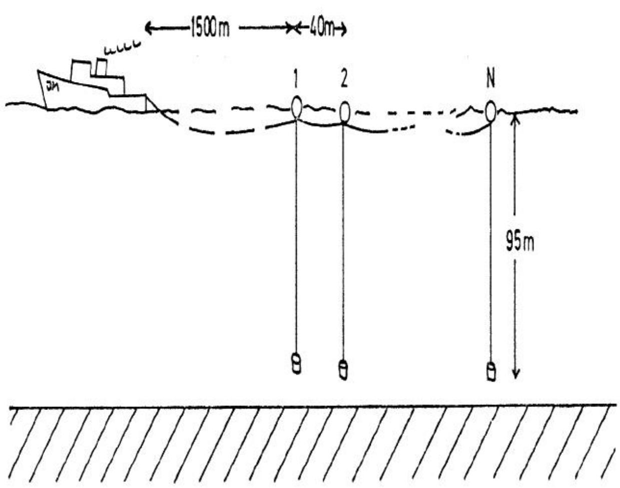


Fig. 4-10: Scheme of sea shots with split charges (from Bamford et al., 1976; Fig. 4; Prodehl and Mooney, 2012, Fig. 7.2.4-04).

The organization of the project was similar to that in France. A moving headquarter served for continuous communications and tape collection (Claus Prodehl and British colleagues) and their play back for quality control and preliminary mounting of record sections (Karl Fuchs). Participants from Karlsruhe in the field were Rainer Blum, Matthias Diestl, Sonja Faber, Christoph Gelbke, Otto Gothe, Ismail Haggag, Ingrid Hörnchen und Heinz Otto, Werner Kaminski, Rainer Kind, Georg Merkler, Manfred Rittershofer and Klaus Schulz. In total, 107 persons from 22 universities and 6 state institutions in Germany and Great Britain were actively involved in the project (**Fig. 4-11**). Four ships were used to carry out the underwater explosions at sea.

Most of the vehicles were VW-buses of German institutions; furthermore landrovers and similar cars were provided by British universities or rented from a company in Scotland. In a few cases the left-hand traffic caused some orientation problems when the German driver changed from field tracks and narrow roads with negligible traffic to main roads. For example, on a one-lane road in Scotland one of the German drivers when approaching the top of a hill suddenly faced another car. Instinctively the driver turned to the right. Fortunately the opponent did the same, because he came from Belgium.

Fig. 4-11 LISPB 1974**:** General meeting of the observers before the beginning of fieldwork at Birmingham.

Thanks to the mechanical clocks of Otto Gothe, half of the Karlsruhe stations could be left in the field unmanned. However, at a time when Irish bomb attacks threatened the British public, this was not unproblematic. For example, one of the British observers also was responsible for such an unmanned station and had left it at a hidden place at a castle. People heard the clock ticks and alarmed the police. Only because Dave Bamford and Claus Prodehl were able to reach the site in a hurry which was already attended by a large number of police surrounding the site in respectful distance, they could avoid that the MARS-station was detonated by a police removal crew. At another site a courageous boy had grapped the seismograph and thrown off into a bush.

For the interpretation of the crustal data the British colleagues were primarily responsible (**Fig. 4-12, top;** Bamford et al., 1977, 1978; Assumpcao and Bamford, 1978; Maguire et al., 2011), while the upper-mantle data were investigated by Sonja Faber and extensively discussed in her Ph.D. thesis and subsequent publications (**Fig. 4-12, bottom;** Faber, 1978; Faber and Bamford, 1979, 1981).

As in the French long-range profiles, mantle phases could be correlated on several parts of the line from different shotpoints. The model proposed by Faber (1978) and Faber and Bamford (1979) showed two high-velocity layers with velocities near 8.15 and 8.4 km/s embedded in an upper mantle ranging from 28 to 85 km depth where the background velocity gradually increased from near 7.95 to near 8.25 km/s (**Fig. 4-12, bottom**). The model was similar to the previously obtained model in France, except for the crust-mantle transition north of the Moine Thrust. The strong velocity contrast of the French model immediately below the Moho, consisting of a high-velocity lid underlain by a distinct velocity inversion, was missing in Britain. Also, some lateral variations of the sub-crustal structure could be determined which are evidently related to gross geological variations beneath northern Britain (Faber and Bamford, 1981).

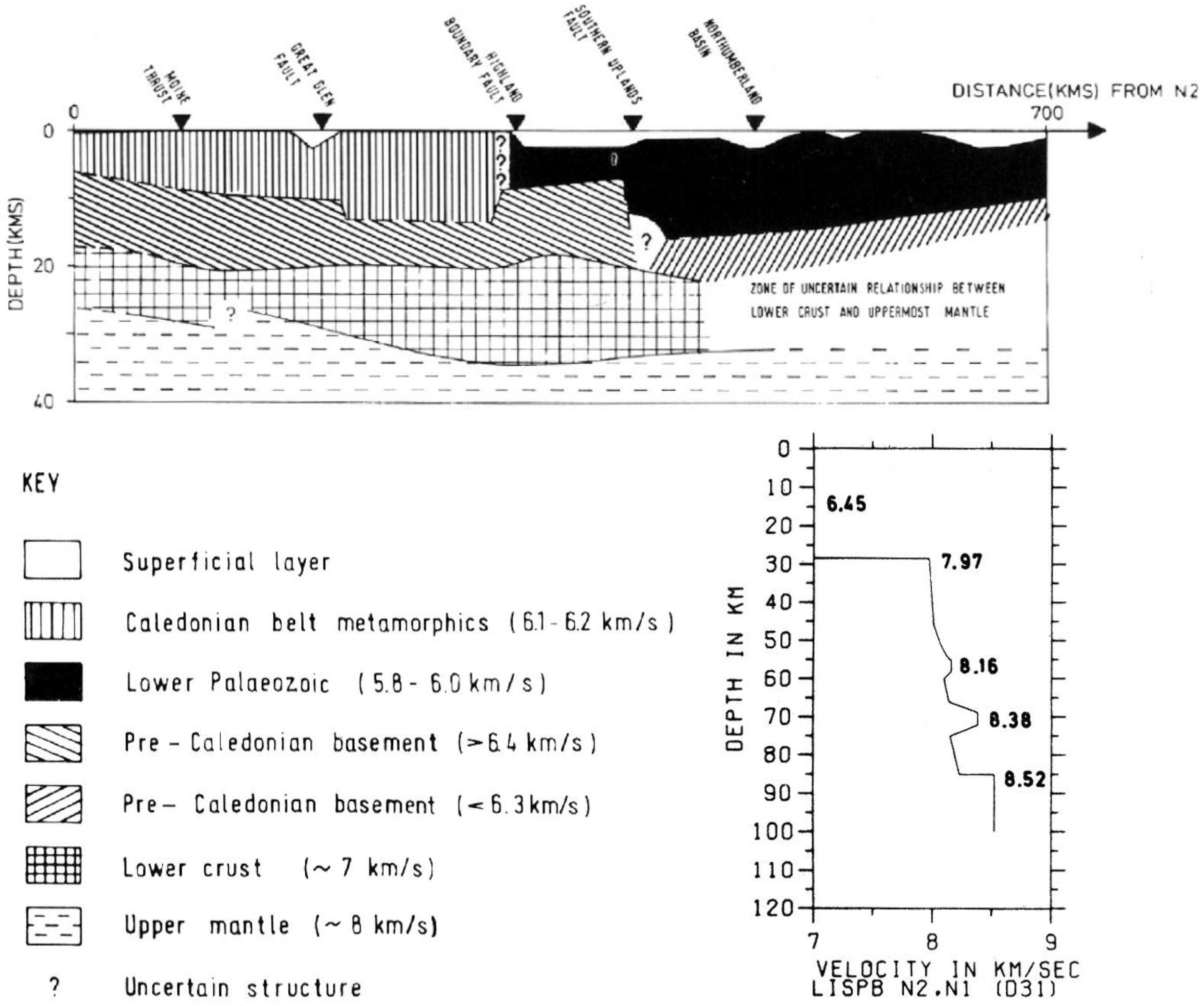


Fig. 4.12: Top: Crustal cross section of LISPB 1974 (from Bamford et al., 1978, Fig. 15). **Bottom:** Schematic cross section of subcrustal reflections (from Faber, 1978, Fig. 10.4; see also Prodehl and Mooney, 2012, Fig. 7.2.4-06).

4-5. Long-range profile ALP 1975

Based on a project study of Claus Prodehl, in 1975 a long-range profile was organized which ran along the axis of the Alps, starting in the Western Alps in France, crossed the Central Alps in Switzerland and Austria, and ended in Hungary where the Hungarian colleagues had organized a large borehole shot (**Fig. 4-13**). Karlsruhe was involved in the DFG application and provided personnel during the field project, but the organization and data interpretation was primarily in the hands of the scientists of Munich and Zurich (Alpine Explosion Seismology Group, 1976). At a later stage, in 1989, Jim Mechie supervised a Chinese student in a reinterpretation of the whole set of data (Yan and Mechie, 1989).

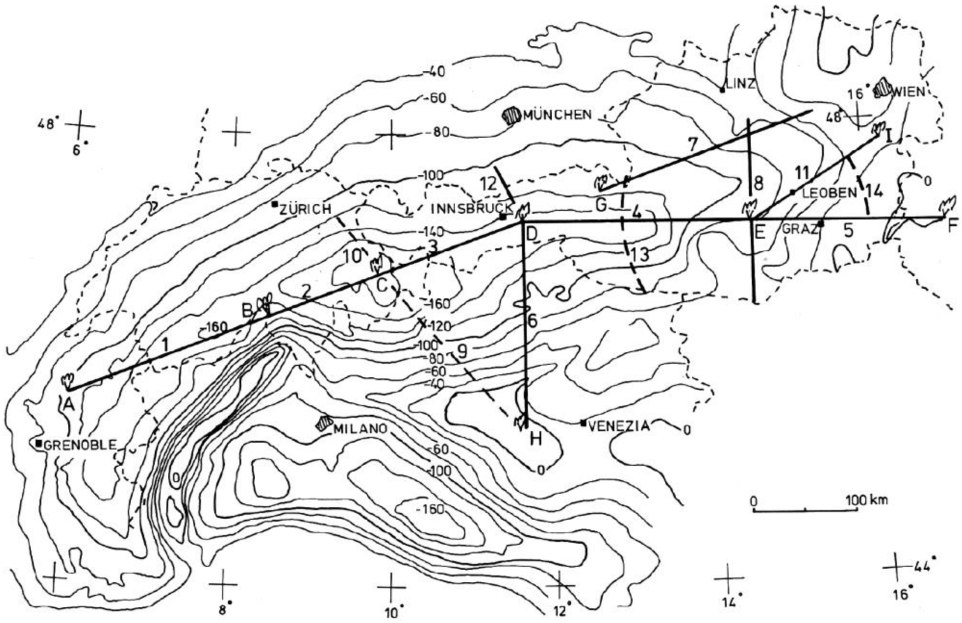


Fig. 4-13: Simplified gravity map of the Alps and the location of ALP75 (from Alpine Explosion Seismology Group, 1976, Fig. 2; see also Prodehl and Mooney, 2012, Fig. 7.2.4-08).

4-6. A long-range profile through the Rhenish Massif

From 1976 to 1982 the German Research Society funded a geoscientific priority program „Plateau Uplift - The Rhenish Massif - A Case History“. It was coordinated by Professor Henning Illies from the Geological Institute of the University of Karlsruhe. The state of the art and preliminary results were regularly reported at annual symposia organized by the German Research Society (Illies et al., 1979; Illies and Fuchs, 1983) and finally published in a special volume (Fuchs et al., 1983).

The Karlsruhe Geophysical Institute participated with a seismological program organized by Klaus-Peter Bonjer and Susan Raikes (Raikes and Bonjer, 1983; for more details see Chapter 9-2-1 of this volume) and a large-scale seismic-refraction project, organized by Claus Prodehl who was successively assisted by David Bamford, Walter Mooney and Jim Mechie (Mechie et al., 1982, 1983).

In 1976 Walter D. Mooney, at that time Ph.D. student of Bob Meyer at the University of Wisconsin, worked together with Claus Prodehl for half a year as guest scientist at Karlsruhe (see his contribution in Chapter 5). Due to his open mind he managed to attract the interest and help of a major number of diploma students. His task was to reinterpret existing seismic refraction data which covered the area of the Rhenish Massif. A key result was that under areas covered by Tertiary to recent volcanism the crustal structure was anomalous and the Moho was disrupted (Mooney and Prodehl, 1978, **Fig. 4-14**). Consequently, when planning the main project, these regions with anomalous crustal structure were avoided.

The fieldwork of the main project took place in May 1979. It consisted of a 600 km long line through Germany, Luxembourg, and northeastern France and extended from the Harz Mountains through the Rhenish Massif and Ardennes into the Paris Basin of northern France and ended south of Reims (**Fig. 4-15**, see also no.3 in **Fig. 3-02**). In addition, two side profiles, up to 170 km long, were planned from Aachen towards the southwest through the Ardennes of eastern Belgium and towards the east into the volcanic area of the Vogelsberg (Mechie et al., 1983).

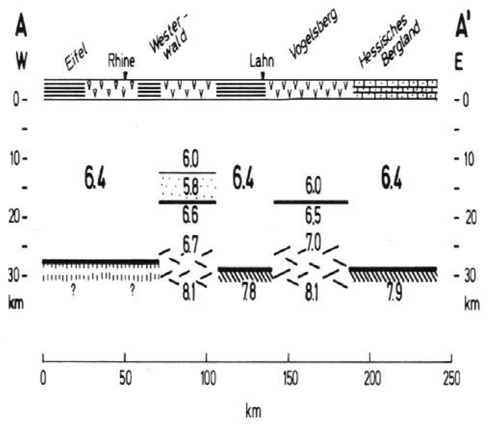


Fig. 4-14: Anomalous crust under volcanic areas (from Mooney and Prodehl, 1978, Fig. 17; Prodehl and Mooney, 2012, Fig. 7.2.6-02).

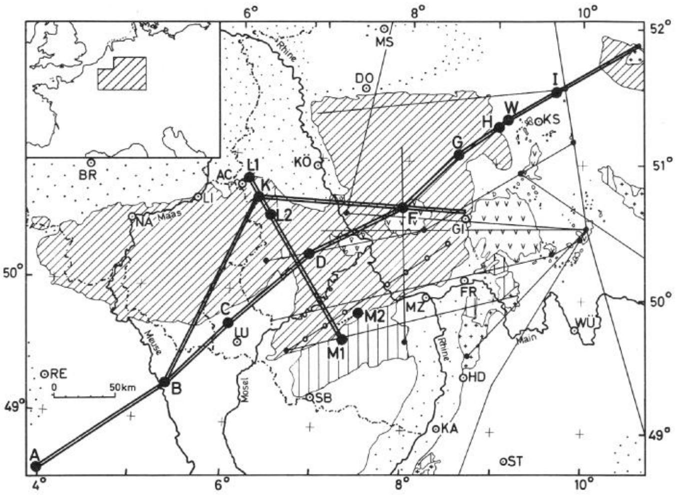


Fig. 4-15: Rhenish Massif – location of seismic profiles. Thin lines: pre-1978, thick lines: projects 1978-79 (from Mechie et al., 1983, Fig. 1; Prodehl and Mooney, 2012, Fig. 7.2.6-01).

The Geotraverse Rhenoherzynikum of 1978 (Meissner et al., 1983) served as the third side profile towards the SSE (**Fig. 4-15**). In a first step, in 1978 a reversed N-S directed profile could be recorded between Aachen (shotpoint series L1-L2) and Baumholder (shotpoint M1). By accident an unusual strong event had been recorded prior to 1978 at the seismological network operated by Karlsruhe around the Rhinegraben. Klaus Bonjer identified this event as a quarry blast within the troop training area Baumholder (location M1 in **Fig. 4-15**). The subsequent personal contact to the army geologist Mr. Goos started a fruitful cooperation for future use of army test explosions for scientific investigations. In summer 1978 Karlsruhe was asked for an expert opinion on vibration effects of a series of test explosions. Besides recording the explosions in the near-distance surroundings, a 100 km long seismic-refraction profile could be established directed northwards towards Aachen. Shortly afterwards in the same year, within the frame of the the project Geotraverse Rhenoherzynikum ((Meissner et al., 1980), Professor Meissner organized a seismic-reflection survey south of Aachen in order to map the subsurface trace of the so-called Aachen-transform. The shots of this survey were used for wide-angle seismic refraction observations to reverse the Baumholder line.

For the 600 km long main line several shotpoints were prepared. The easternmost shotpoint was located in the Hessen depression near the quarry Adelebsen (I in **Fig. 4-15**). W is the location of the troop training area Wildflecken where Mr. Goos arranged a special test explosion for our project. Shotpoints H, G, and F were placed at remote positions in the Westerwald. A shotpoint near Koblenz had to be abandoned due to threatening legal problems. West of the Rhine a suitable site could be found near Daun in the Eifel (location D). Further west Jean A. Flick offered to provide a location within Luxembourg (location C) which technical realization was overtaken by Roland Vees of Clausthal (Prodehl and Faber, 2002). It was the beginning of a long-lasting cooperation between the Clausthal Geophysical Institute and the Laboratoire souterrain de géodynamique de Walferdange, Luxembourg. In France Alfred Hirn organized the two shotpoints B and A. Furthermore one of the seismic-reflection shot sites of 1978 near Aachen could be revived (site K) enabling reverse shooting of the two side lines through the Ardennes towards site B and through the Westerwald towards site F north of the Vogelsberg (**Fig. 4-15**).

The preparation of the shotpoints faced several unexpected problems. First, to enable the official permissioning process by the state mining offices to carry out major borehole explosions, an agreement had to be obtained with the higher-rank mining office (Oberbergamt) Clausthal to get entitled searching for a mineral which was of no interest for any mining industry, but which needed our seismic project to be explored. In the end Karl Fuchs and Claus Prodehl became directors of a 500 km long and 1 km wide geothermal mining area. Furthermore, for all non-military shotpoints in Germany the Niedersächsische Landesamt für Bodenforschung had delivered an expertise which certified that the vibrations caused by the borehole explosions would not cause any damages to adjacent buildings and structures (Behnke, 1970, 1979).

The second problem arose when we tried to hire the British company for drilling and shooting which had successfully worked for the LISPB 1974 project and which had offered the most economical price. In order to obtain the permission by the mining offices, these offices required a police document for the shooting operators. However, the British police would not issue any document stating that the shooting operators were no criminals. So, the opposing German and British laws caused the fact that British shooting operators could not obtain permission to work in Germany. This contradicted European Community law which promised job permissions for any citizen in any occupation throughout the Community. The problem was finally solved by posing it to the German Foreign Ministry. Though no criminal action was involved the international police force could be asked for help. Its application to the British police for a statement could not be denied. Having solved these burocratic problems, the project could go on without any further difficulties.

135 persons were involved during the main phase. It included the participation of all German institutions with instrumentation and personnel, furthermore recording crews came from Switzerland (ETH Zurich), from France (University of Paris), Britain (Birmingham, East Anglia, Leicester, Swansea), Austria (Vienna), Sweden (University of Uppsala) and Portugal (Meteorological Service, Lisbon). From Karlsruhe participated in the field Peter Blümling, Matthias Diestl, Sonja Faber, Jürgen Fertig, Karl and Carsten Fuchs, Dirk Gajewski, Ingrid Hörnchen, Martin Jentsch, Werner Kaminski, Ewald Lüschen, Gheorghe Merkler, Claus Prodehl, Manfred Rittershofer, Raimund Stangl, Hans Stecker, and Günter Volk.

For the interpretation Jim Mechie could be hired. Originally he had been recommended by Roy King at Birmingham to work within Klaus-Peter Bonjer's seismological working group, but Jim Mechie's real interest was seismic-refraction. Quickly a close friendship developed between him and Werner Kaminski, who was involved in the digital data preparation.

The interpretation resulted in a quite unusual structure of the crust-mantle transition zone along the Rhenish Massif. The new data showed very few P_n arrivals and, but not in all cases, very strong secondary arrival phases. In particular, on the eastern half of the main line, under the Eifel and Westerwald, the secondary arrivals indicated the existence of two phases mixed into each other. It was interpreted as a Moho lid, at 30 km depth overlying an approximately 5-7 km thick low-velocity zone where the velocity drastically decreases and then gradually increases to 8.4 km/s or more below 35 km depth (**Fig. 4-16**).

As the long-range line did not cross the volcanic area of the Westerwald, the disrupted Moho of Mooney and Prodehl (1978) did not show up in the new model. West of the Eifel, under the Ardennes, this Moho lid had disappeared, as well as much of the intracrustal structure, modeled elsewhere, and only the lower velocity boundary, at 37 km depth, appeared as a deep-reaching transition between the crust and mantle. A normal crust, with a sharp Moho at 30 km depth, appears again under the Paris Basin (Mechie et al., 1983). A slightly differing interpretation was proposed by Giese et al. (1983).

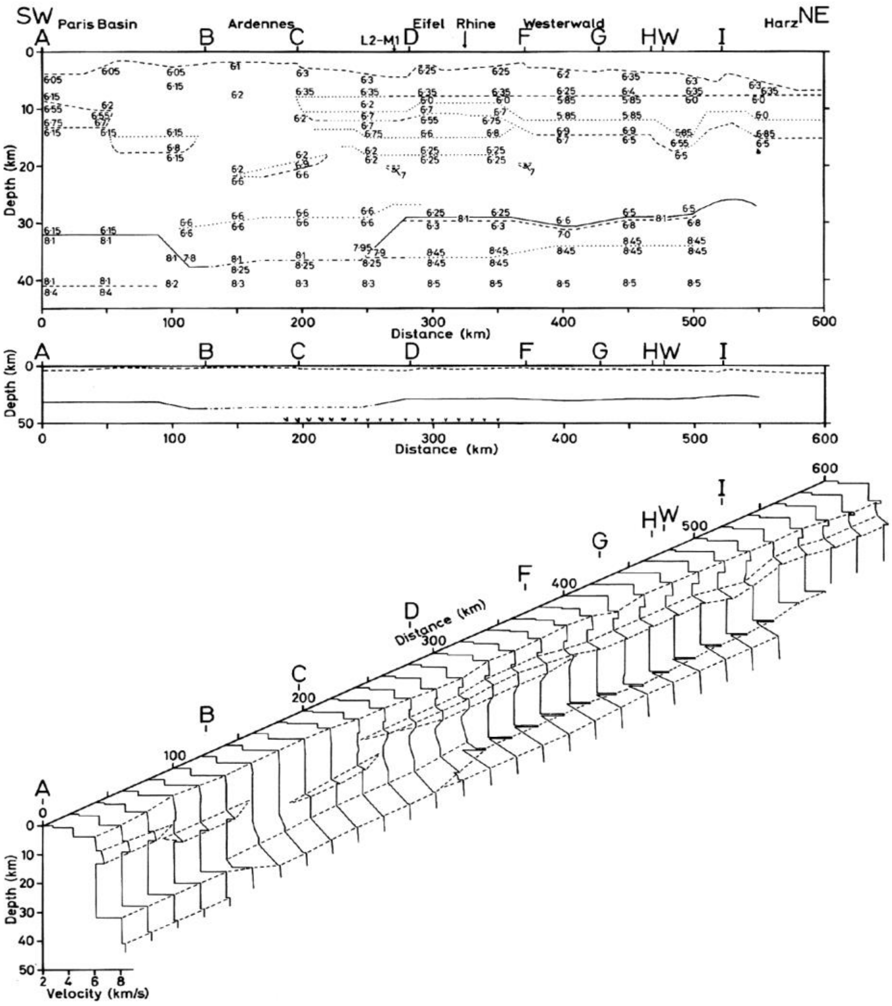


Fig. 4-16: Crustal cross section and velocity-depth functions along the main line of the Rhenish Massif project (from Mechie et al., 1983, Fig. 4; Prodehl and Mooney, 2012, Fig. 7.2.6-04).

As mentioned above, the Karlsruhe Geophysical Institute participated in the DFG priority program also with a seismological program. Klaus-Peter Bonjer had collected data of teleseismic events from all seismological permanent stations in and around the Rhenish Massif and he had been able to hire Susan Raikes who had worked on a similar interpretation of seismological data in Southern California (Raikes and Hadley, 1979) to interpret the teleseismic data in terms of depth structure of the lower lithosphere (Raikes, 1980; Raikes and Bonjer, 1983).

4-7. FENNOLORA 1979

The geological map of Europe (**Fig. 4-17**) shows all long-range profiles recorded up to the end of 1976. In addition to the profiles described above in subsections **4-1** to **4-5**, a long-range profile from the Western Alps across the Apennines in central Italy was recorded in 1966 from a single shotpoint Lac Nègre (Morelli et al., 1977). Another line extended northwards from Lac Nègre towards the Rhinegraben. It was included in Jörg Ansorge's early research of pre-1971 long-range observations (Ansorge and Mueller, 1971; Ansorge, 1975). The long-range profile along the Swabian Jura in Southern Germany was recorded during the Rhinegraben project of 1972 (profile SB-060-09). In 1972 the long-range profile 'Blue Road' crossed Scandinavia (Hirschleber et al., 1975, Lund, 1979).

Fig. 4-17: Long-range profiles in Europe until 1976.

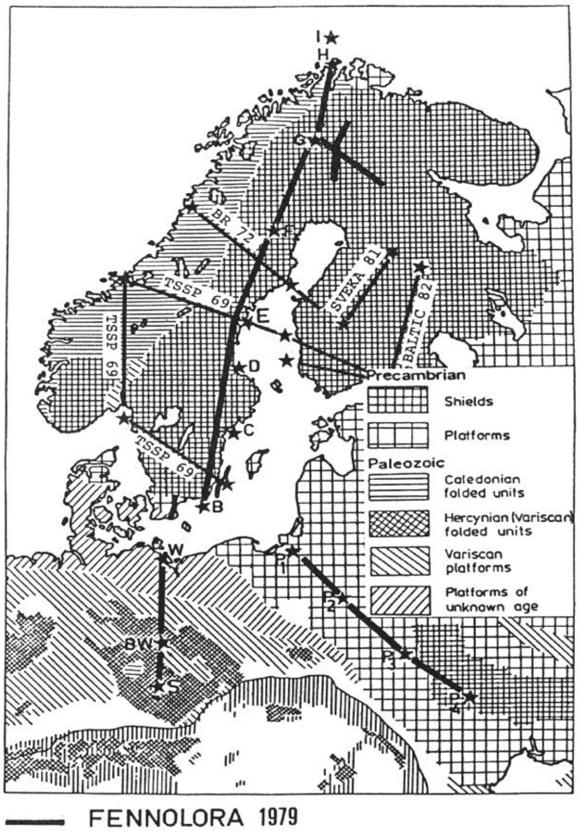


Fig. 4-18: FENNOscandian LOng RAnge profile 1979 (from Guggisberg et al., 1991, Fig. 1; Prodehl and Mooney, 2012, Fig. 7.2.6-05).

Fig. 4-19: Playback Center at Martsbo.

Fig. 4-20: Calle Lund at FENNOLORA Headquarters Kramfors.

Highpoint and final project of long-range profiles organized by Karlsruhe was FENNOLORA (FENNOscandian LOng RAnge), which also was carried out in 1979, but which aimed for a much deeper penetration of the upper mantle than any previous long-range profile. One of the goals of FENNOLORA was to reach the mantle transition zone at 400 km depth named by seismologists the 20° discontinuity. Therefore observation distances were laid out to almost 2000 km between shotpoints off the North Cape, and off the southern coast of Sweden (**Fig. 4-18**).

In parallel, a series of intermediate shots, most of them detonated by the Swedish Navy in the Baltic Sea close to the shore of Sweden as well as a shotpoint on land in northwestern Finland served to obtain all necessary details of crustal and uppermost mantle structure. Responsible for the recording sites and personnel, communication, tape collection and data control were Jörg Ansorge, Calle Lund and Claus Prodehl (**Fig. 4-19** and **Fig. 4-20**).

The FENNOLORA shots were also recorded on two lines to the south through eastern Germany, and to the SE on a line through Poland and the Ukraine (**Fig. 4-18**). Furthermore, the map shows profiles in Finland, which were recorded in 1981 and 1982, in the framework of the European Geotraverse as was mentioned in subchapter 3-3.

The interpretation of the crustal data was published by Prodehl and Kaminski (1984) and Guggisberg et al. (1991). The long-range data were interpreted in parallel both by Beat Guggisberg at ETH Zurich (Guggisberg and Berthelsen, 1987) and by Raimund Stangl at Karlsruhe (Stangl, 1990; Hauser and Stangl, 1990). Of particular interest was a phase recorded at 1650-1900 km distance which Karl Fuchs recognized as a reflection from the top of the mantle transition zone (**Fig. 4-21 left**). A corresponding model (**Fig. 4-21 right**) showed a rather complicated velocity-depth structure with the mantle-transition zone at its base at 400 km depth, which agreed with models obtained from other seismological data (Fuchs et al., 1987b).

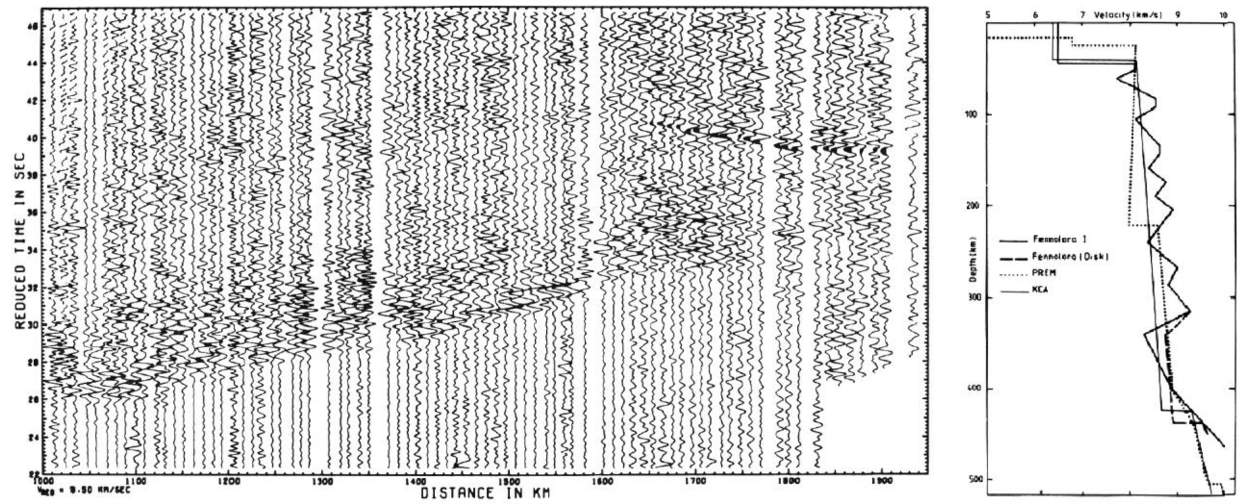


Fig. 4-21: Left: Record section of the Fennolora profile, shotpoint I, distance range 1000-1950 km, reduction velocity 9.5 km/s. A later phase near 40 sec reduced traveltime at 1650 and 1900 km is interpreted as reflection from the mantle transition zone (from Fuchs et al., 1987b, Fig. 5). **Right:** Preliminary velocity-depth function deduced from the data of shotpoint I, in comparison with other earth models based on seismological data (from Fuchs et al., 1987b, Fig. 6; Prodehl and Mooney, 2012, Fig. 7.2.6-09).

In a review of world-wide controlled-source seismic crustal and upper-mantle studies, Claus Prodehl (1984) has collected and redrawn all subcrustal lithospheric velocity-depth functions in figures and tables, published until 1983 (see also various discussions by Karl Fuchs and others (Fuchs and Vinnik, 1982; Fuchs, 1986; Fuchs et al., 1987b; Fuchs and Froideveaux, 1987).

4-8. Three-dimensional lithospheric observations on the British Isles

In 1987, a 2-ton explosive source was fired in the North Sea off Scotland and was recorded in southeastern Ireland on the so-called BB 1987 profile oriented in SSW direction (Bean and Jacob; 1990, Jacob et al., 1991). Combined with the far distant shots of the CSSP project recorded along the ICSSP line in Ireland (see subchapter 6-1), a long-range line of about 600 km length resulted. Together with the LISPB observations (Faber and Bamford, 1979), three long-range and intersecting refraction profiles resulted in Ireland and Britain providing velocity-depth information of the lower lithosphere along different azimuths. The observation that upper-mantle velocities were different for the CSSP and LISPB profiles, and that P-wave velocities of 8.6 km/s at 85 km depth were well in excess of the predicted isotropic velocities of 7.85 km/s (taking 80% olivine, 20% pyroxene and a calculated geotherm for the region), led Bean and Jacob (1990) to the conclusion that seismic anisotropy should be present in the lithospheric mantle.

4-9. ILIHA, a three-dimensional lithospheric project

In the framework of the European Geotraverse the project ILIHA (Iberian LIthosphere Heterogeneity and Anisotropy), a three-dimensional lithospheric profile system, was planned on the Iberian Peninsula. This tectonically relatively homogeneous region was the only place where long-range profiles of at least 600-800 km length could be arranged in various directions which would intersect each other at a central point and thus study velocity anomalies and possible anisotropy in the lower lithosphere (**Fig. 4-22**). The planning of this project ILIHA had started in 1984, but could only be funded and realized in 1989 (Mezcua and Carreno, 1993, ILIHA DSS Group, 1993a, b).

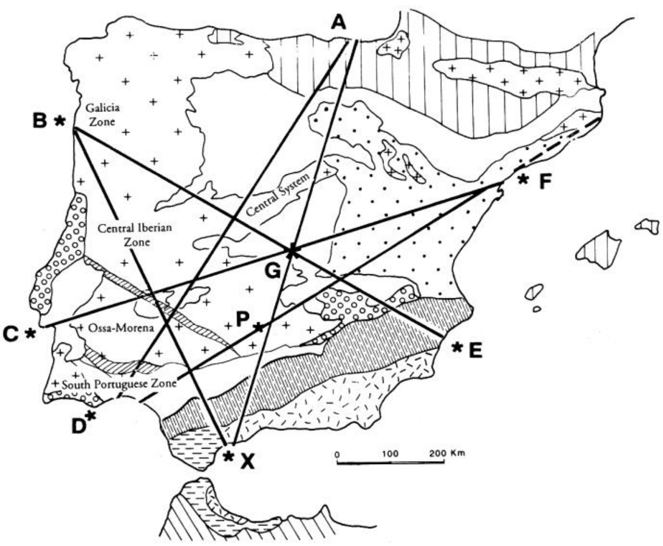


Fig. 4-22: Location of ILIHA long-range profiles (from. ILIHA DSS Group, 1993, Fig. 1; Prodehl and Mooney, 2012, Fig. 8.3.4-18):

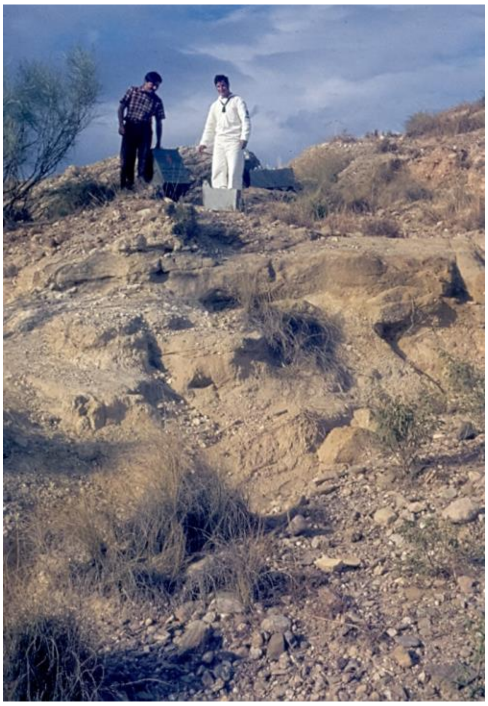


Fig. 4-23: Karlsruhe MARS-66 stations in Spain.

140 stations were used to record simultaneously along four reversed and two non-reversed long-range profiles (**Fig. 4-22**), most of them MARS-66 stations (**Fig. 4-23**). The long-range profiles crossed each other in central Spain at various points of intersection. Underwater shots with charges of 500-1000 kg were fired by the Spanish and Portuguese Navies in the surrounding Atlantic Ocean and Mediterranean Sea, furthermore two land shots could be arranged in the interior of the Iberian Peninsula (P and G in **Fig. 4-22**). The participation of Karlsruhe was organized by Hermann Zeyen, in the data preparation and interpretation Robert Arlitt, Regina Patzwahl and Hermann Zeyen were involved, including own publications (Arlitt et al., 1993, ILIHA DSS Group, 1993a, b). The interpretation of the long-range data (**Fig. 4-24**) resulted in lateral heterogeneities of the fine structure of the lower lithosphere. The authors comment on possible anisotropy in the upper mantle between 57 and 67 km depth, but discuss also an alternating explanation.

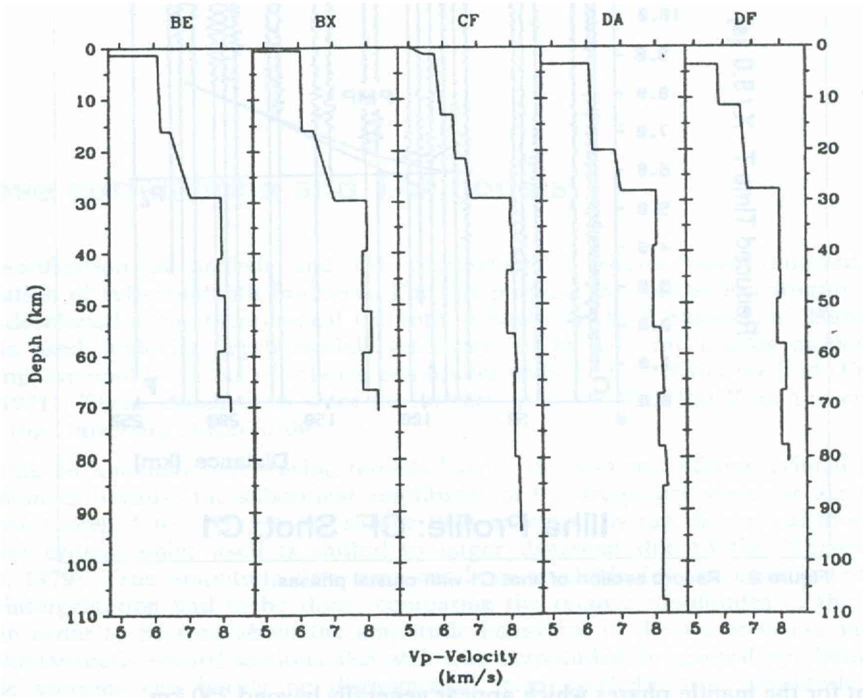


Fig. 4-24: 1-D velocity-depth models for the long-range profiles of ILIHA (from Arlitt et al., 1993, Fig. 8).

4-10. A new view of the lower lithosphere

Over the years doubts arose how realistic a model might be proposing alternating low- and high-velocity layers in the upper mantle down to 400 km depth as shown in **Fig. 4-21**. In cooperation of Karl Fuchs with Uwe Enderle, Mark Tittgemyer, and Martin Itzin a new image of crust and mantle, with changing scales of structure (**Fig. 4-25**), was proposed (Enderle, 1998; Enderle et al., 1997; Tittgemeyer et al., 1996, 1999, 2000).

The deep-seismic sounding observations of the early 1990s had gathered a great wealth of new high-quality and dense data sets. A critical review of the then utilized interpretation procedures led Karl Fuchs and co-workers to a new view of the dynamic properties of seismic wave propagation through the crust-mantle transition. In various papers (e.g., Tittgemeyer et al., 1996; Enderle et al., 1997), the wave propagation was tested by modelling the scattering in the upper mantle and by comparing the resulting synthetic seismograms with observed record sections. The abrupt termination of near-vertical reflections at the Moho and the coincident presence of a strong supercritical P_MP reflection coda in record sections of continental seismic wide-angle refraction experiments led to the vision of a hitherto unrecognized property of the crust-mantle boundary and a new picture of the lithosphere. It was proposed (Enderle et al., 1997) that the Moho formed a sandwiched mix of crust-mantle material between the lower crust and uppermost mantle in combination with a stepwise increase in mean velocity, and that at Moho level a significant change occurred in the scale of the structural dimensions and of velocity variance (**Fig. 4-25**).

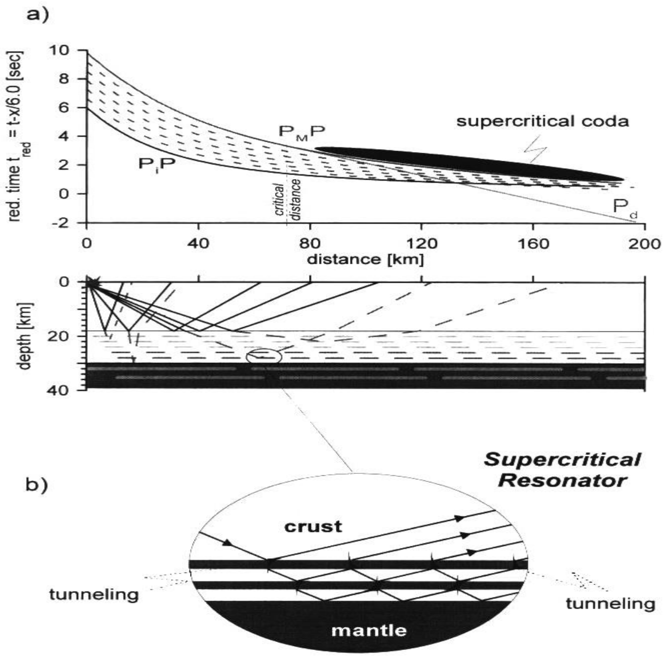


Fig. 4-25: Scattering of energy between PiP and P_MP phases, caused by internal structure of the lower crust from 18-30 km model-depth, is followed by supercritical reverberations following P_MP (supercritical coda), caused by internal structure of the topmost mantle below 30 km model-depth, which has a different scale of structural dimensions (from Enderle et al., 1997, Fig. 4a; Prodehl and Mooney, 2012, Fig. 9.2.2-12).

4-11. EUROPROBE and PNE data

To a great deal initiated by Karl Fuchs, EUROPROBE started in 1990 (Fuchs, 1992). Its basic idea was to bring East and West European scientists together for future cooperations. It was a promise which by Russian and German scientists was immediately agreed upon.

The third period of Russian deep seismic sounding (DSS) investigations had started at the end of the 1970s and continued through the 1980s. This seismic research included three-component magnetic recordings of shots of varying sizes recorded by up to 300 stations on profiles with 2500-3000 km length (**Fig. 4-26**). Two types of energy sources were used. Chemical explosions with charges up to 5000 kg loaded in a series of boreholes 100-150 m apart allowed recording distances of 300-400 km. For distances up to 3000 km so-called "industrial" (nuclear) explosions were specially arranged for these investigations (later named PNE – peaceful nuclear explosions, dots in **Fig. 4-26**). Two to four of such shots, spaced 1000-1500 km apart, were arranged on several profiles (**Fig. 4-26**). The long-range profiles allowed in particular to record reflections from the transition zone between upper and lower mantle. Most of its data were reprocessed and reinterpreted in the 1990s by several authors (e.g., Mechie et al., 1993; Ryberg, 1993; Ryberg et al., 1995, 1996, 1997, 1998; Wenzel and

Ryberg, 1995) to mention only those interpretations with Karlsruhe participation. A data example from the "Quartz" profile is shown in **Fig. 4-27**.

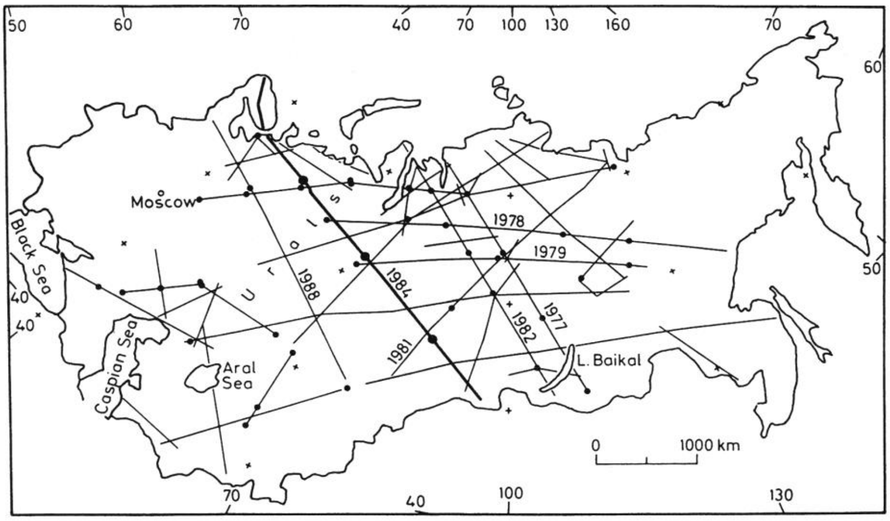


Fig. 4-26: Location map of long-range deep seismic sounding profiles in the USSR using PNE (dots - peaceful nuclear explosions) as energy sources for distance ranges of several 1000 km (from Mechie et al., 1993, Fig. 1; see also Prodehl and Mooney, 2012, Fig. 8.4-02).

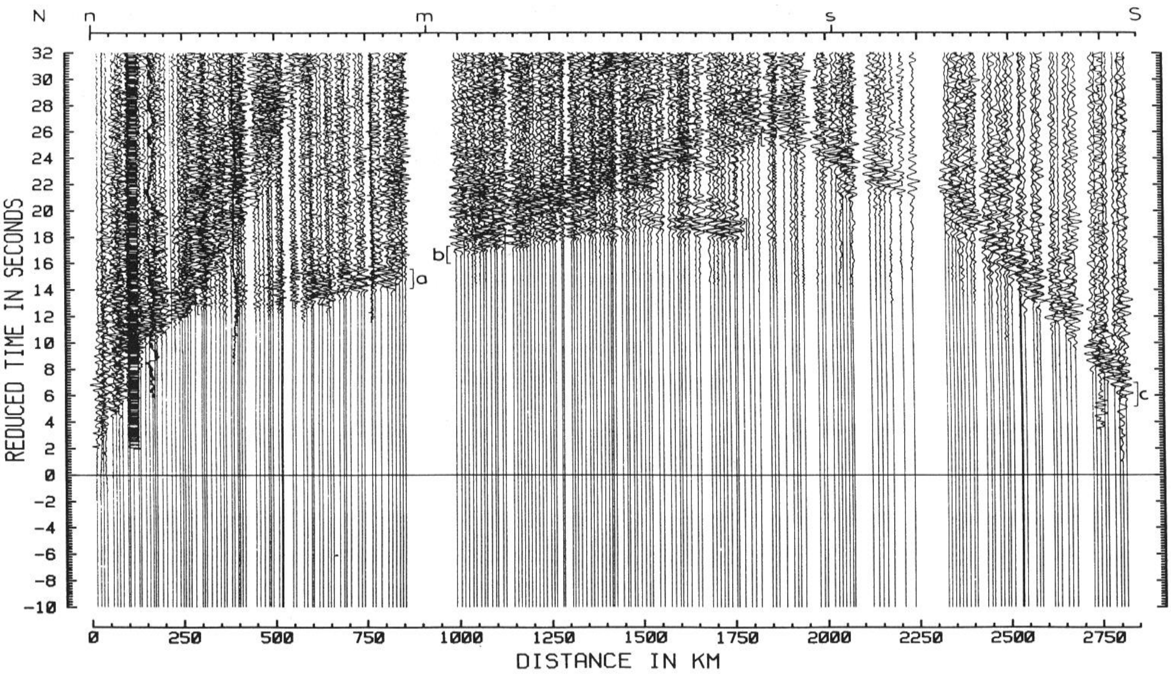


Fig. 4-27: Data example of the super long deep seismic sounding profile "Quartz" in the USSR observed in 1984 (thick line in **Fig. 4-26**) (from Mechie et al., 1993, Fig. 3b; see also Prodehl and Mooney, 2012, Fig. 8.4-03).

An immediate result of EUROPROPE was the agreement on a joint field experiment in Russia. When in 1991 an approximately 3000 km long deep seismic sounding profile, named GRANIT, was recorded by Russian scientists from eastern Ukraine to the West Siberian basin (Juhlin et al., 1996), a sub-experiment, aiming for a detailed anisotropy investigation was arranged. It was one of several sub-experiments of the project GRANIT and was a large-scale seismic anisotropy experiment, carried out in 1991 across the Voronesh Massif, named ASTRA (**Fig. 4-28**, left). It consisted of 280 km long seismic-refraction profiles, which crossed each other in a central point. The ASTRA experiment was characterized by observations with dense multi-azimuthal more-component recordings in the near-vertical incidence to wide-angle distance range. This recording scheme (**Fig. 4-28**, right) allowed investigating a 5 million km^2 large block for signs of rock anisotropy, including shear-wave birefringence and azimuthal dependency (Lueschen, 1992).

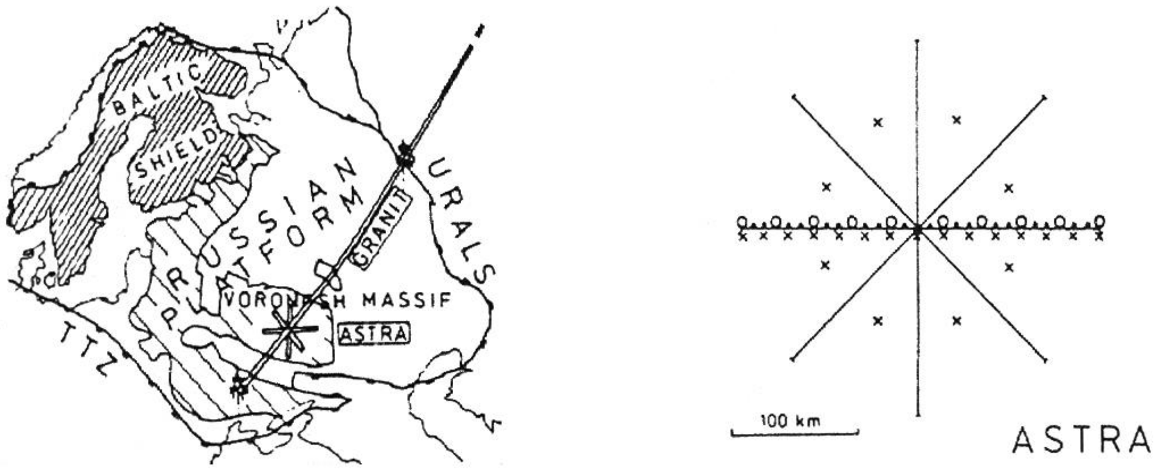


Fig. 4-28: Left: Location of the ASTRA sub-experiment (from (Lueschen, 1992; see also Prodehl and Mooney, 2012, Fig. 9.3-17). **Right:** Observation scheme. Crosses are borehole shots with 200-300 kg charges, 20 km apart. Circles are 48-channel digital recording instruments of type < Progress >, which were spaced 30 km apart. Dots are 3-component analogue recording devices, which were 10 km apart.

The size of the borehole shots ranged between 200-300 kg. For recording the following devices were available: five 48-channel “Progress“ systems and ten 3-component analog stations plus two digital PDAS from GFZ Potsdam. The operation shown in **Fig. 4-28** was planned to be repeated for each line. However, for logistic reasons, only half of the experiment could finally be realized. Unfortunately, results of this project were never published in the international literature.

5. The Portuguese adventure

Initiated by the personal contact of Stephan Mueller to Professor A.S. Mendes of the Serviço Meteorologico Nacional at Lisbon, Portugal, in 1970 a German – Portuguese cooperative program for seismic studies in Portugal could be started (**Fig. 5-01**).

Using the Karlsruhe MARS equipment, which number was later enlarged by MARS stations which the Serviço Meteorologico Nacional bought for its own purposes, a first reversed seismic-refraction profile could be recorded through southern Portugal. Participants from Karlsruhe were Stephan Mueller, Jörg Ansorge, Herbert Harcke, Dieter Mayer-Rosa (**Fig. 5-02**), Gerhard Greiner, Werner Nolt, Claus Prodehl, Horst Reichenbach, Dietrich Werner, and Erhard Wielandt, the Portuguese coordinator was Victor Souza Moreira. Shotpoints were underwater explosions of the Portuguese navy. The first recordings were made in July 1970 from shots off the Atlantic coast near Sines south of Lisbon, the reversed observations were delayed until December 1970 using offshore explosions off Fuzeta near Faro at the southern coast of Portugal (**Fig. 5-01**; Mueller et al., 1973b).

A second reversed profile could be established in 1971 in the west of Portugal north of Lisbon (**Fig. 5-03, Fig. 5-04**) using underwater explosions off Cabo Raso (west of Lisbon) and off Nazaré (a fishermen's village 100 km to the north). Finally, a third 300 km long, non-reversed profile was recorded in 1972 in SW – NE direction from a shotpoint off Sagres at the southwestern corner of Portugal. All shotpoints were at sea, which was enabled by the cooperation with a Portuguese navy vessel and a shooting crew of the German navy (Mueller et al., 1973b, 1974; Prodehl et al., 1975b; Moreira et al., 1977; Prodehl and Mooney, 2012).

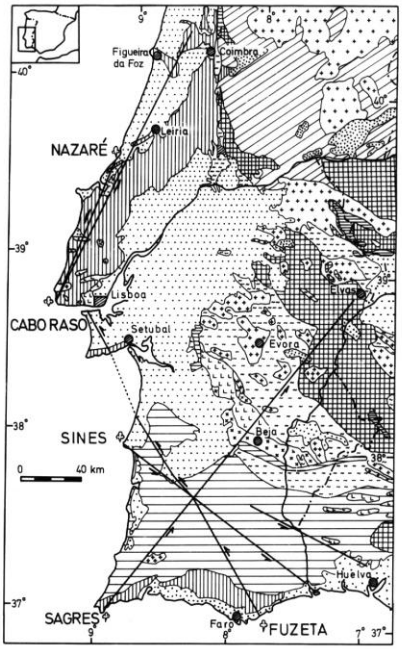


Fig. 5-01: Profiles in Portugal 1970-72 (from Prodehl et al., 1975, Fig. 1; Prodehl and Mooney, 2012, Fig. 7.2.3-01).

Fig. 5-02: Herbert Harcke, Jörg Ansorge, Dieter Mayer-Rosa and Stephan Mueller at Sines 1970.

Fig. 5-03: Difficult approach of a recording location.

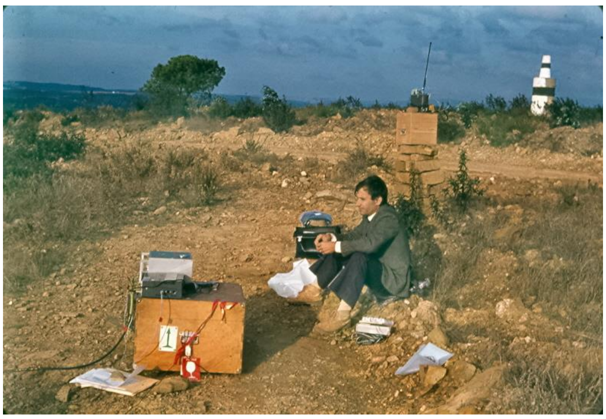


Fig. 5-04: Dieter Mayer-Rosa watches a recording.

While for the first experiment people and stations had to face a long-lasting transport by cars through France and Spain, from December 1970 onwards air transport by the German army was enabled. To support the Portuguese navy in handling the large underwater charges, a specialist of the German navy could be hired. In reverse the German navy could test the behaviour of some of their bulky underwater equipment during large explosions. For the transportation of this equipment as well as of the Karlsruhe stations and personnel the regular flights of the German army from Cologne to Beija could be used. The danger of handling explosives became apparent at one of the shots. The electric cable between charge, suspended underneath a buoy, and the shooting vessel had been caught by the ship's propeller causing that the charge did not remain in position, but was dragged at close distance to the ship. The charge was detonated when the ship had reached a reasonable distance from the buoy which normally would have indicated the position of the charge. Fortunately there was still a minimal distance between charge and ship. Nevertheless the ship was heavily shaken, but did not suffer damage.

The data were digitized in 1971 at Hamburg by Werner Kaminski, who had developed a digitizing system at the University of Hamburg. For the interpretation of the first Portuguese data, Erhard Wielandt developed a computer program package which enabled to produce the first digital record sections at Karlsruhe. All record sections were re-published by Prodehl and Mooney (2012, *Appendix A2, pages 54 and 55*). Crustal thickness along most profiles ranged around 35 km.

In 1974, Karlsruhe participated at the first deep seismic sounding experiment in southern Spain. A 450 km long profile crossed the area of the Betic Cordillera between Cartagena in the east and Cadiz in the west, with shotpoints both at sea and on land. The main organizers of this and following Spanish projects were Zurich and Spanish institutions. The interpretation resulted in drastically varying crustal thickness, from near 25 km near the southeastern coast at Cartagena and near the southern coast near Adra to as much as 39 km under the central Cordillera (Working Group for Deep Seismic Sounding in Spain 1974-1975, 1977; Banda and Ansorge, 1980; Prodehl and Mooney, 2012).

6. The Caledonian Suture Zone – Dublin and Karlsruhe cooperations in Ireland

6-1. Irish Caledonian Suture Seismic Project (ICSSP) 1982

During the annual meeting of the European Geophysical Society in spring 1982, Brian Jacob reported on a British project of Professor Martin Bott to arrange for a series of underwater explosions in the North Sea and in the Irish Sea to be recorded along a cross profile through northern England. The aim was to study the crustal structure of the suture zone between Laurentia in the north and East-Avalonia in the south (CSSP = Caledonian Suture Seismic Project). This news created the idea, together with Karlsruhe to plan for a first seismic-refraction profile through Ireland (**Fig. 6-01**).

The 250 km long profile was chosen such that it would follow the postulated border between Variscides and Caledonides in Ireland and was therefore named ICSSP (Irish Caledonian Suture Seismic Project).

Martin Bott was ready to plan for additional large shots in the Irish Sea near the Irish coast. So a total of 31 shots in the Irish Sea became available for the Irish project. Brian Jacob organized two reversing shots at the mouth of the Shannon River and in the adjacent Atlantic Ocean close to the Irish coast. These were small dispersed (50-100 kg) offshore shots (one at optimum depth) from which seismic energy was recorded at distances of almost 200 km.

Furthermore Brian Jacob found a quarry in the west of Ireland along the line in which timed explosions could be arranged. With 23 instruments of DIAS (Dublin Institute for Advanced Studies) and Karlsruhe and the Irish networks DNET und KNET with 5 telemetry stations a mean station interval of 10 km could be realized. Moving the mobile stations in between the first recording sites on the following day and by repeating all shots, a mean interval of 5 km was finally obtained (Jacob et al., 1985).

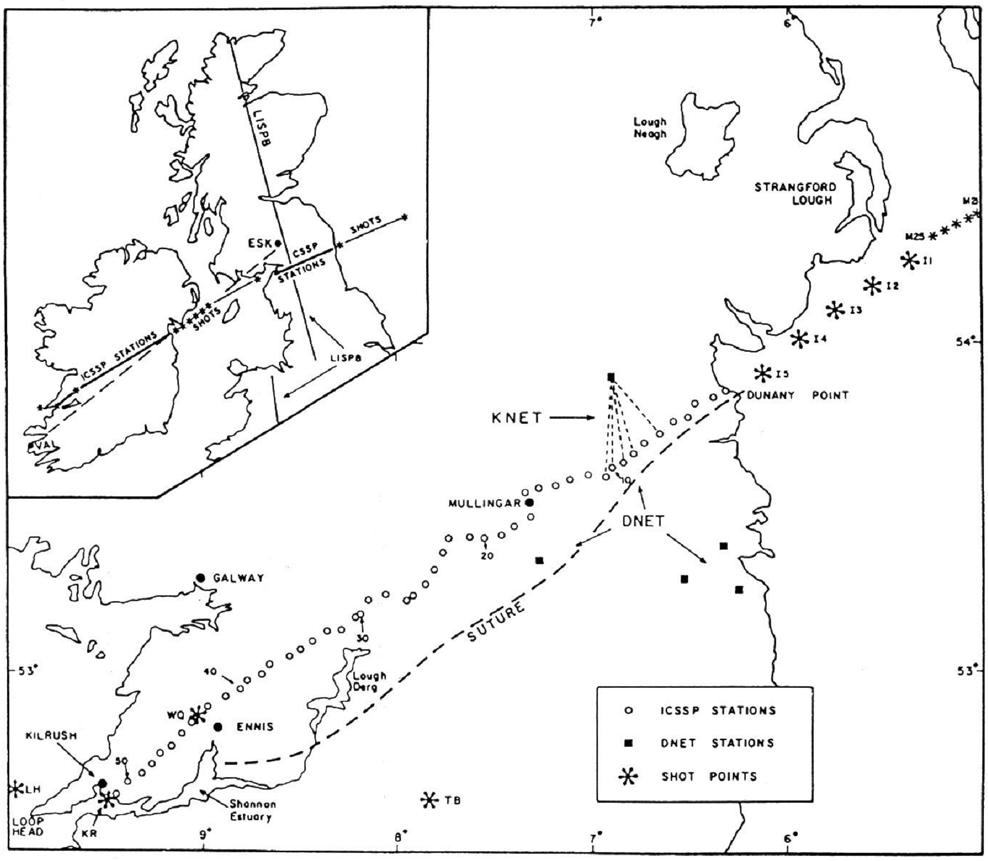


Fig. 6-01: Upper left: Location of the British CSSP project (also shown is the LISPB-1974 line). **Main map:** Location of shotpoints and recording sites of the ICSSP project (from Jacob et al., 1985, Fig. 1; Prodehl and Mooney, 2012, Fig. 8.3.2-03).

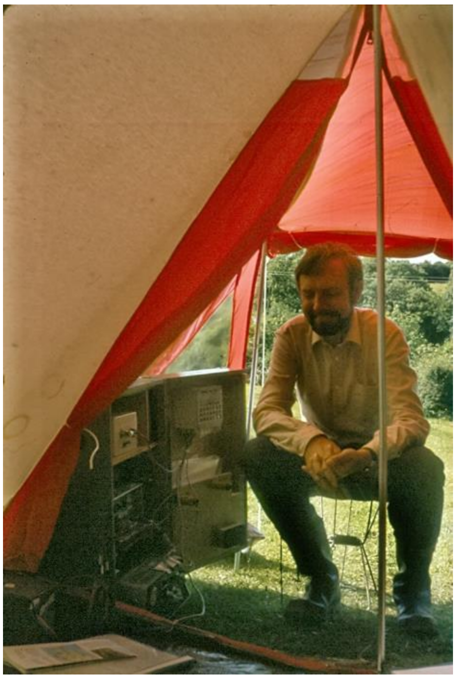


Fig. 6-02: The green island Ireland: Exposed basement rock inmidst farmland.

Fig. 6-03: Continuous recording at a mixed-weather day.

Fig. 6-04: Cows – unforeseen noise producers.

Fig. 6-05: Music by tin whistle deviates disturbing guests.

The fieldwork was carried out in summer 1982 (**Fig. 6-02** to **Fig. 6-05**). All sites had been pre-investigated and permissioned, because most sites were on private grounds, often inmidst farmland with grazing animals where quite often basement rocks cropped out.

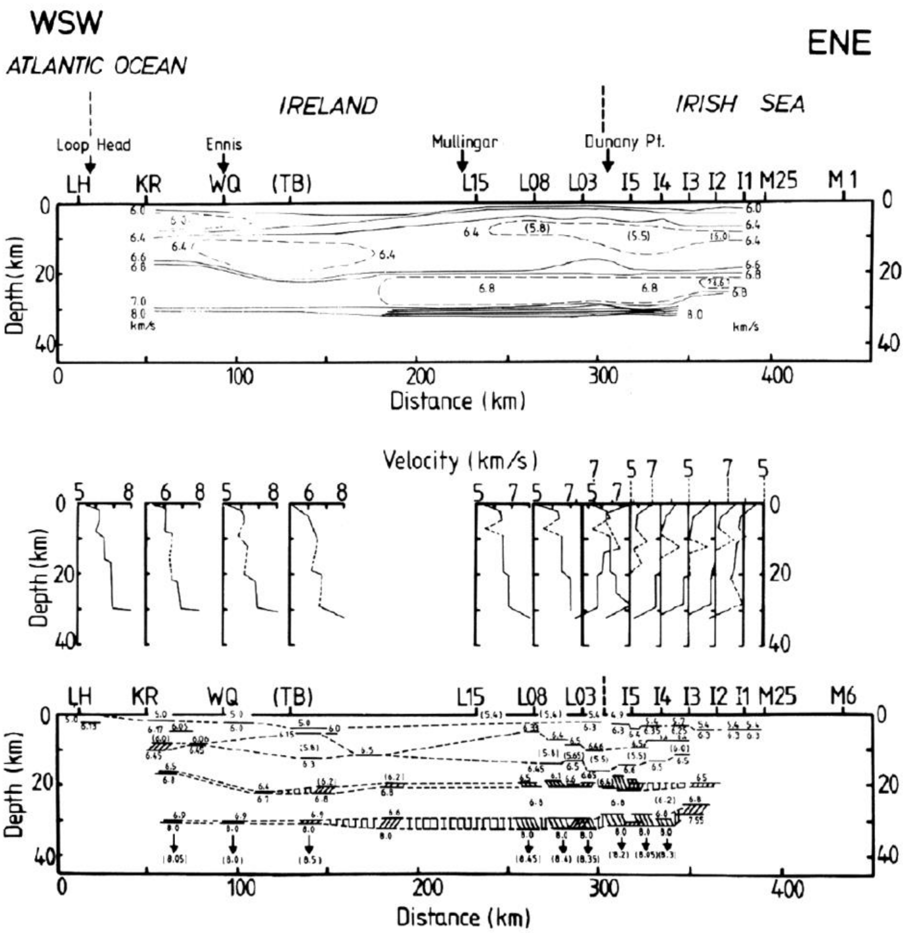


Fig. 6-06: Crustal cross section resulting from the ICSSP project of 1982 (from Jacob et al., 1985, Fig. 8; Prodehl and Mooney, 2012, Fig. 8.3.2-04). **Upper part:** Cross section with lines of equal velocity, **middle part:** 1-D velocity-depth functions, **lower part:** Position of zones where crustal reflected phases originate.

Recording was scheduled for two full days, and recording times were 15 minute-windows starting every full hour during which time intervals the ships were allowed to fire the shots. The grazing animals were not really convenient, because especially cows are curious and love seismometers. A relatively successful trial to deviate the interest of cows and persuade them to turn away from the seismometers was to play the tin whistle (**Fig. 6-05**). The continuous recording at continuous rain caused several technical problems which had to be solved during the remaining 45 minutes between the shot windows. Sometimes damages could not be solved on the spot. Fortunately the roads were relatively empty for fast driving geophysicists. Participants from Karlsruhe and Schiltach were: Dieter Emter, Christine Fichler, Dirk Gajewski, Heinz Hoffmann, Jürgen Neuberg, and Claus and Sieglinde Prodehl.

The data were digitized at Karlsruhe on the Raytheon 500 and plotted as record sections by Werner Kaminski and Brian Jacob. The latter one had obtained funding from the German Academic Exchange Service (DAAD) to spend several months at Karlsruhe. The interpretation resulted in an average Moho depth of 32 km and showed that the characteristics of the Moho changes gradually from a sharp boundary in the west to a 3-4 km wide crust-mantle transition zone in the east (**Fig. 6-06**, Jacob et al., 1985).

6-2. GEOTWIN and COOLE 1985

In 1985 the "Caledonian Onshore-Offshore Lithospheric Experiment" (COOLE) was organized. It consisted of two separate seismic refraction studies carried out onshore and offshore southern Ireland. The onshore part consisted of a 280 km long N-S profile stretching from the southern coastline across the Irish Midlands up to Donegal Bay (Lowe and Jacob, 1989). A total of 6 shots was recorded by 59 seismic receivers deployed at about 3 km spacing. The profile was approximately perpendicular to the ICSSP profile of 1982 and the proposed surface trace of the suture zone. The main objectives of this project were to investigate the crustal structure across the suture zone and to provide seismic control for the very dense gravity data onshore Ireland. The participation of Karlsruhe was enabled by a program of the European Communuty, in which Brian Jacob and Claus Prodehl received funding by a scientific cooperation contract named GEOTWIN (“To develop and install inversion techniques suitable for seismic refraction data with an emphasis on Ireland and the neighbouring continental margin”).

In 1987, a 2-ton explosive source which was fired in the North Sea off Scotland was recorded in southeastern Ireland on the so-called BB 1987 profile oriented in SSW direction (Bean and Jacob; 1990, Jacob et al., 1991), resulting in a long-range line of about 600 km length when combined with the far distant shots of the CSSP project recorded along the ICSSP line in Ireland. Together with the LISPB observations (Faber and Bamford, 1979), three long-range and intersecting refraction profiles resulted in Ireland and Britain. The velocity-depth structure of the lower lithosphere sampled along different azimuths let Bean and Jacob (1990) conclude that seismic anisotropy should be present in the lithospheric mantle (see subchapter 4-8).

6-3. VARNET 96, a geophysical investigation of the Variscan Front in Ireland

In 1995-1997 a 3-year project started with seismic, seismological and magnetotelluric studies with the goal to investigate the Varsican Front in western Ireland, the border zone between the Variscan and Caledonian terranes. The project was named VARNET (VARiscan front NETwork) and was funded by the European Community. It had five partner institutions from Ireland, Germany and Denmark. The seismic part was operated by Brian Jacob and Claus Prodehl and was carried out in 1996. Two profiles were planned in the southwest of Ireland perpendicular to the strike direction of the Variscan Front (**Fig. 6-07**). The 170 recording stations were analogue DIAS-equipment, but for the majority digital equipment (PDAS and RefTek from GFZ Potsdam (**Fig. 6-08**), EDL from DIAS Dublin and MARS-88 from Copenhagen).

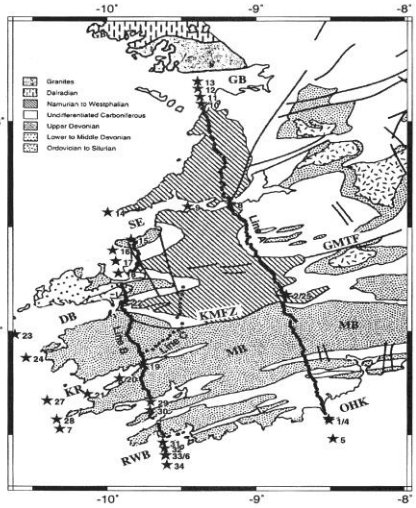


Fig. 6-07: Seismic profiles of VARNET 96 (from Landes et al. 1990, Fig.1; Prodehl and Mooney, 2012, Fig. 9.2.1-01).

Fig. 6-08: PDAS-station of GFZ Potsdam in Ireland.

The western profile was 100 km long and crossed several peninsulas and sea bights which enabled to arrange for an optimal shotpoint density with underwater shots which could be recorded by closeby networks of land stations with a small station separation. By arranging for a series of shots at both ends with increasing offsets, a profile length of 140 km was obtained. The eastern profile was planned to be 200 km long, with a series of sea shots on both ends with increasing offsets, two shots in the Shannon delta, and four shots in a water-filled quarry in the center of the line. In a first deployment all 170 stations were distributed along the eastern line with 1 km average station separation. At the second deployment 38 stations remained on the eastern line, 112 stations were deployed on the western line, and the remainder of 20 stations occupied a short, 40 km long, profile between the two main lines. Amongst the numerous participants from DIAS Dublin, GFZ Potsdam and GPI Karlsruhe were Uwe Enderle, Ellen Gottschämmer, Michael Landes, Olaf Novak, Claus Prodehl, Hanna-Maria Rumpel, Sabine Sindler, and Marc Tittgemeyer.

During this experiment, a total of 34 shots was recorded. The shotpoint geometry was designed to allow for both inline and offline fan shot recordings on the profiles to extend the 2-D interpretation of the inline data to three dimensions. All sea shots were set off from an Irish research vessel. The charges were 25 or 2 x 25 kg, shot depths ranged between 5 and 64 m, depending on the depth to the sea bottom.

The first step of data preparation was executed at the home institutions Dublin, Copenhagen and Potsdam, and in a second step combined with the program package Pro MAX and transferred from SEG-Y-Format into the SeismicHandler Q-Format. The multi coverage of the recording lines as well as the multifold fan observations due to the geometry of the shots allowed well constrained modelling. Both in-line modelling and a 3-D interpretation were enabled (Masson et al., 1998; Abramovitz et al., 1999; Landes et al., 2000, 2003, 2004b). **Fig. 6-09** presents the cross sections for two main lines.

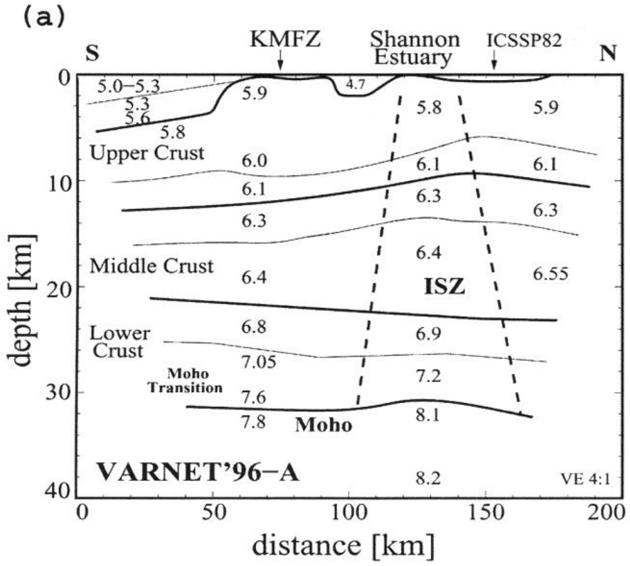


Fig. 6-09: Crustal structure underneath southwestern Ireland (from Landes et al., 2005, Fig. 6; Prodehl and Mooney, 2012, Fig. 9.2.1-02).

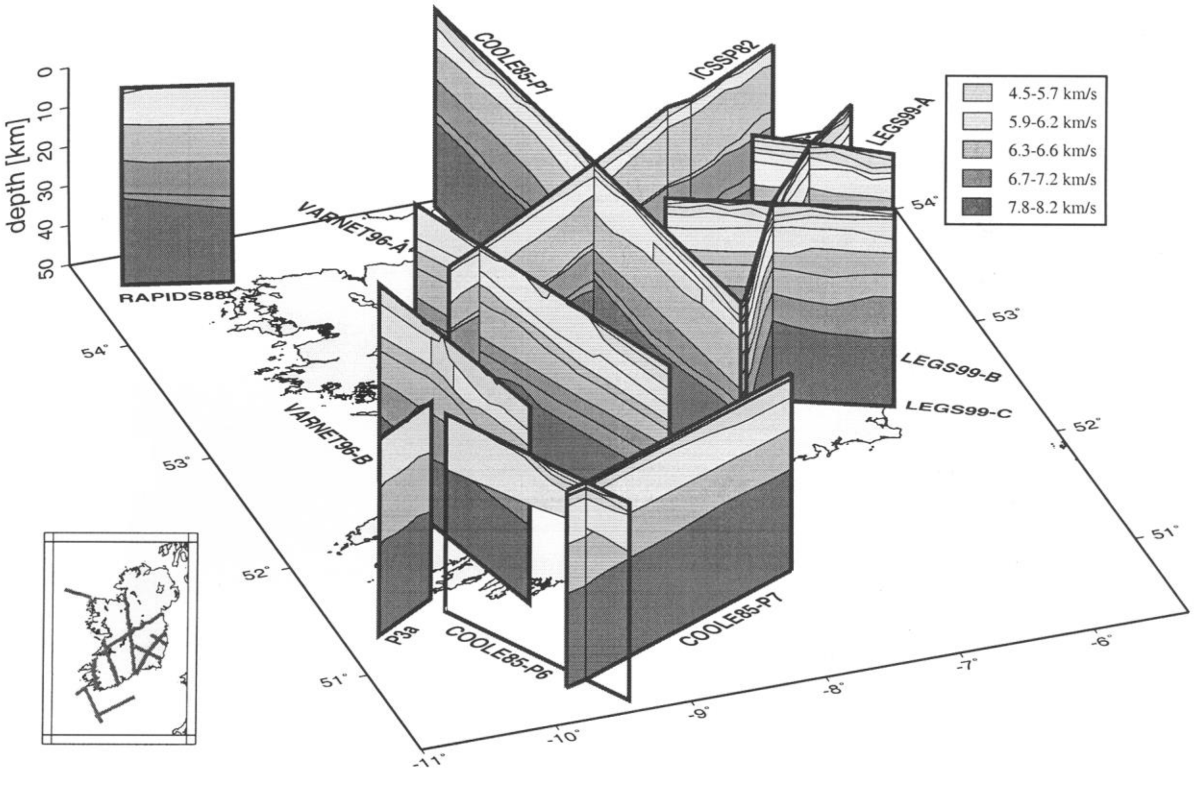


Fig. 6-10: Crustal structure underneath Ireland and adjacent seas (from Landes et al., 2005, Fig. 8; Prodehl and Mooney, 2012, Fig. 9.2.1-04).

Landes et al. (2005) compiled all crustal investigations in Ireland and the surrounding seas into three-dimensional block diagrams. The review of Landes et al. (2005) also includes seismic-tomography studies, the first of which was an outcome of the Varnet-96 program, as mentioned above, when some earthquakes and a nuclear event had also been recorded during the recording windows set for the controlled-source seismic experiment. These data could be used to model the probable trace of the Iapetus suture in the upper mantle just south of the Shannon river estuary between 30 and 110 km depth (Masson et al., 1999).

6-4. Irish Seismological Lithospheric Experiment (ISLE)

In 2002 and 2003 a specially designed Irish Seismological Lithospheric Experiment (ISLE) was undertaken, to investigate the nature and tectonic history of the deep lithospheric and asthenospheric structure of the Iapetus Suture Zone (Landes et al., 2004c, 2005, 2006, 2007; for more details see Chapter 9-3-2).

7. The first African adventure – Southwest Africa (Namibia)

From 1969 to 1980 the geoscientific Special Collaborative Program 48 „Evolution, composition and distinctive characteristics of the Earth's crust, particularly in geosynclinal regions" was launched by the German Research Society at the University of Goettingen. Particular goals were the Rhenish Massif and the Damara Orogen in Southwest Africa. Chairman was Professor Henno Martin. As the Geophysical Institute at Goettingen had abandoned since long its seismological department, no scientist was available who was able and willing to organize a deep-seismic sounding project, in particular in a remote area such as Southwest Africa. Therefore Professor Martin addressed Hans Berckhemer at Frankfurt, who agreed to help out after having secured the support of Clausthal and Karlsruhe.

By his personal connections of Hans Berckhemer to the director of the University of Witwatersrand at Johannesburg, South Africa, a joint seismic program could be planned and initiated. Here Rod W. Green had developed an instrumentation which allowed carrying out one-man seismic-refraction surveys (Green, 1973). He would install his recording devices (BPI) and let them run in a continuous mode for up to a week, and in between he would organize shotpoints, load them and detonate the charges whenever ready. This worked very well for small-scale surveys.

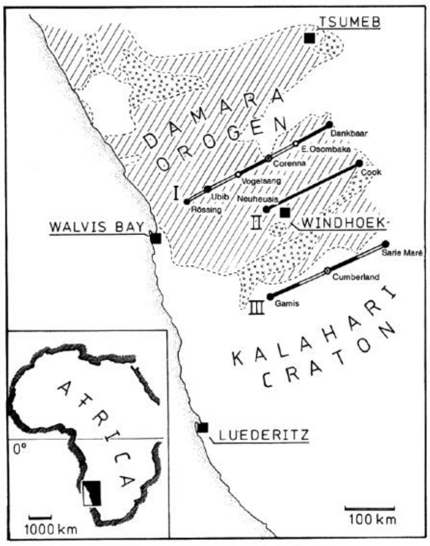


Fig. 7-01: Seismic profiles in SW Africa (from Baier et al., 1983, Fig. 1; Prodehl and Mooney, 2012, Fig. 7.7.2-01).

Fig. 7-02: MARS-66 on profile I in the Damara-Orogen, Southwest Africa.

In close cooperation with Rod Green an extensive seismic-refraction program could be launched in Southwest Africa (**Fig. 7-01**). The operation comprised three parallel, SW-NE directed, profiles through the Damara Orogen and the adjacent Kalahari craton.

Before the field work could be started, the local organization was overtaken by Roland Vees (Clausthal) and Claus Prodehl. Each profile was planned to be 220-350 km long with shotpoints at each end and a few intermediate shotpoints. With exception of the westernmost shot of the northern profile I, which was a commercial mine blast, all shots were drillhole shots arranged by teams of the participating institutions. For the drilling work of the boreholes a special team was engaged. The shotpoint organization and detonation of the charges was carried out by Rod Green and Roland Vees. The institute of Frankfurt installed a special radio station at Tsumeb which transmitted a suitable time signal. 15 MARS-stations (**Fig. 7-02** and **Fig. 7-03**) and 15 South African self-recording long-term stations enabled to obtain a mean station interval of 5 km (Baier et al., 1983).

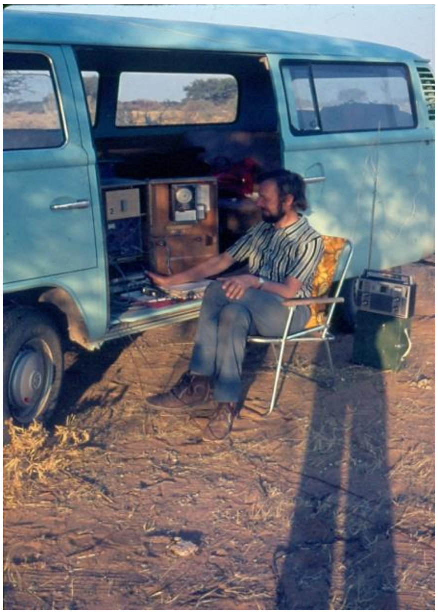


Fig. 7-03: Claus Prodehl at a recording site.

Fig. 7-04: Camp of Profile III in Southwest Africa.

Along each profile several mobile field camps were established (**Fig. 7-04**) which were equipped with a special communication system to guarantee connection between shotpoints and field stations. For example, external help was required if vehicles got stuck in sand. Occasionally „victims“ had to suffer. In one case two cameras „died“ under the wheels of a heavy truck which pulled one of the VW buses out of a sandy river bed. In spite of the fact that local inhabitants were rarely seen, some of the 50 m long cables disappeared. Not only theft caused losses, cables were also favourites of strong animals’ teeth.

Unforeseen delays at the preparation of the shotpoints caused that the time for the European participants ran out. Therefore only profiles I and III could be completed. A data example is shown in **Fig. 7-05**. However, Profile II could be completed later thanks to Rod Green’s technique to run self-sustained stations for more than a week, before a tape change was required, and such to enable recording a seismic-refraction profile by one man. Rod Green would first install his 15 recording stations in a day and then, with the aid of the drilling personnel, would drill and shoot as many shots as he could accomplish in the remaining time of one week. He repeated this system several times until profile II was completed as it had been planned beforehand.

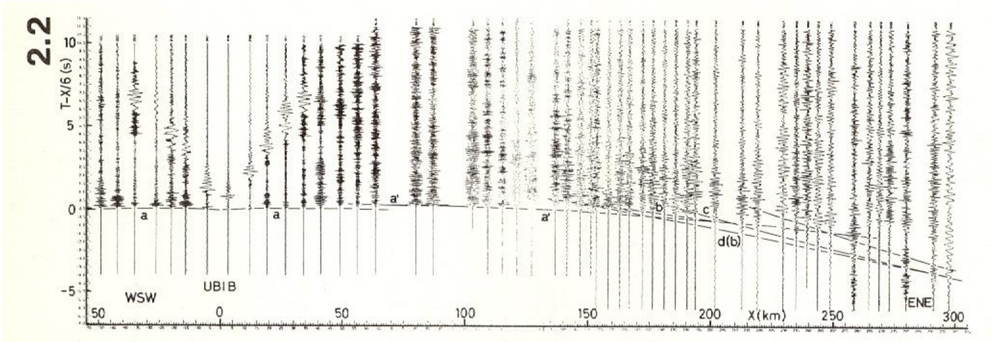


Fig. 7-05: Record section of shotpoint Ubib on profile I in the Damara Orogen (from Baier et al., 1983, Fig. 1; Prodehl and Mooney, 2012, Fig. 7.7.2-02).

A major part of the interpretation of the data was carried out at Clausthal by two diploma students (Christian Grimsel and Dirk Gajewski) under the supervision of Roland Vees and with the support of Claus Prodehl during a longer research visit. In contrary to other Gondwana regions where 40 km crust had been found, both for the Damara orogen (**Fig. 7-06** and **Fig. 7-07**) and for the Kalahari craton crustal thicknesses of 45-50 km resulted (**Fig. 7-07**, Baier et al., 1983).

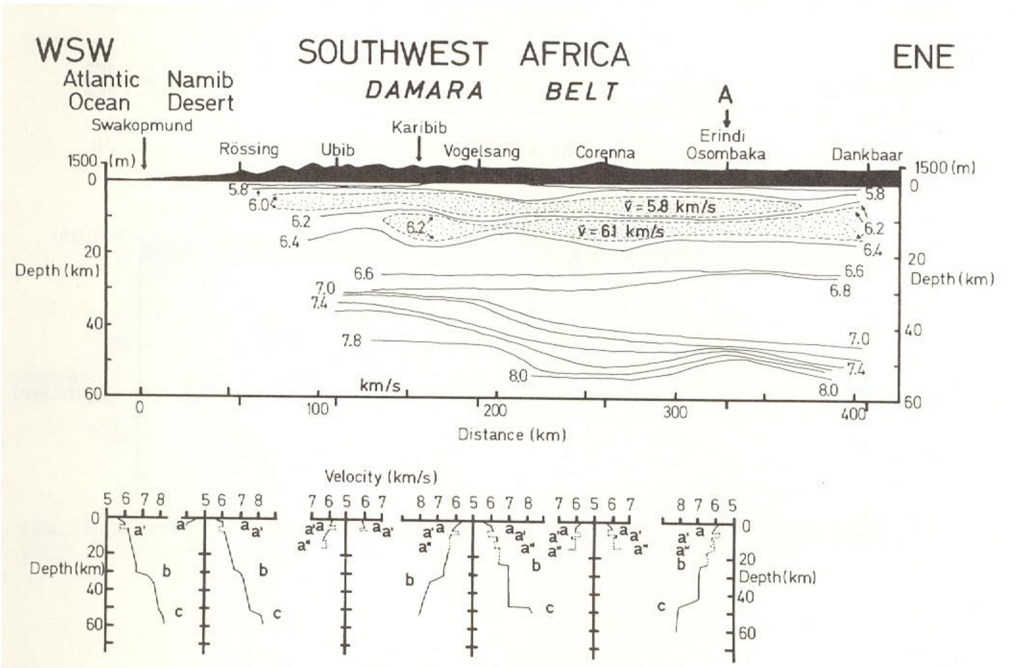


Fig. 7-06: Crustal cross section of profile I (Rössing to Dankbaar). Contour interval of lines of equal velocity (upper part) is 0.2 km/s. Surface altitude versus depth is exaggerated 3:1, depth versus horizontal distance 2:1. At each shotpoint depth z = 0 corresponds to the respective surface altitude above sea level. In the corresponding velocity-depth functions (lower part), the position of velocity 5 km/s corresponds with the position of the shotpoint in the crustal cross section above (from Baier et al., 1983, Fig. 3.1).

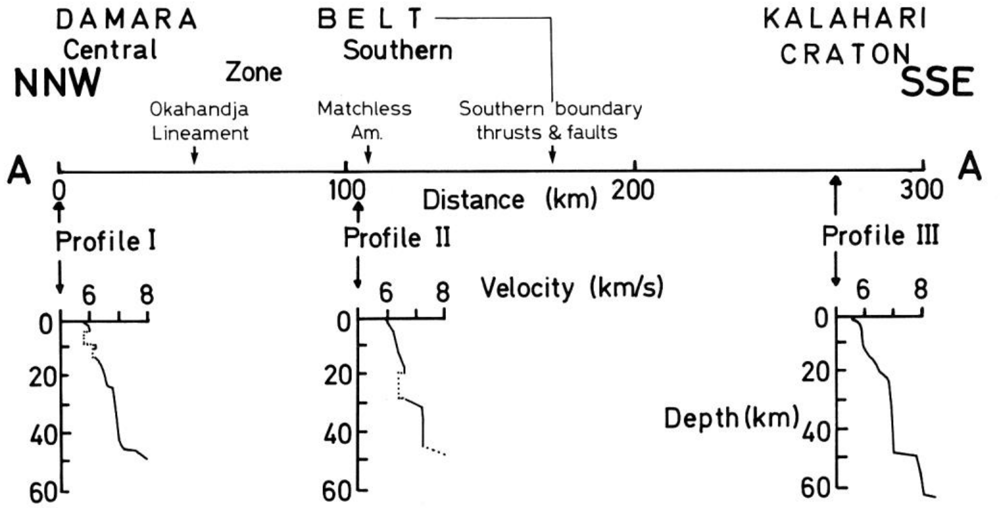


Fig. 7-07: Velocity-depth sections through the Damara orogen and adjacent Kalahari craton, approximately 380 km NNE of the Atlantic coast (from Baier et al., 1983, Fig. 4; Prodehl and Mooney, 2012, Fig. 7.7.2-03).

8. The Afro-Arabian Rift System

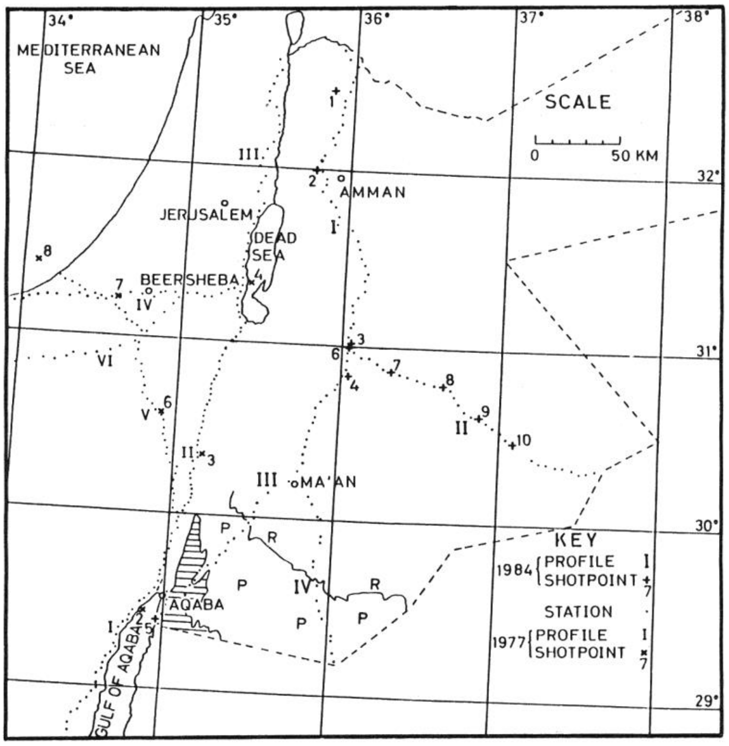
8-1. Early work in the East African Rift of Kenya

In the late 1960s Jürgen Wohlenberg had worked at IRSAC, a Belgian seismological observatory at Kiwu, Congo, and at the University of Nairobi, before he came as visiting scientist to Karlsruhe in 1968 for one year. Together with Klaus Bonjer they interpreted the existing seismological data to derive a crustal model for the East African rift from spectral response ratios of long-period body waves (Bonjer et al., 1970; Wohlenberg, 1975).

8-2. The Dead Sea rift seen from Israel in 1977

In May 1977, Jannis Makris of the University Hamburg and Karl Fuchs and Claus Prodehl travelled to Tel Aviv in order to explore the feasibility of a seismic project in the Dead Sea rift. In particular, the Dead Sea seemed to be a perfect location for a shotpoint. A few months later funding by the German Research Society was assured and the project could start. Several profiles were planned and realized which covered the whole of Israel between Mediterranean Sea, Dead Sea and the Lake of Tiberias. No shot could be realized in Lake Tiberias, but all other profiles were reversed. Along the rift axis along Wadi Arava and the Gulf of Aqaba a long-range profile was established extending from the Dead Sea to the south tip of Sinai Peninsula. Recording distances along most of the lines were up to 240 km, but along the rift a maximum distance of 400 km could be reached, due to the optimal damming of the shots in the Dead Sea (**Fig. 8-01**, Ginzburg et al., 1979a, b).

Unexpected happenings and problems gave the project a special touch. It had been agreed that all field teams would consist of an Israeli and a German participant. Surprisingly there were not enough students available at Tel Aviv so that additional technically trained people were looked for by newspaper adds. For training purposes a small test shot was fired in the Mediterranean near Holon (**Fig. 8-03** and **Fig. 8-04**). When teaching the Israeli participants, it turned out that some of them did not have technical experience at all. Rather they served as a kind of police group.



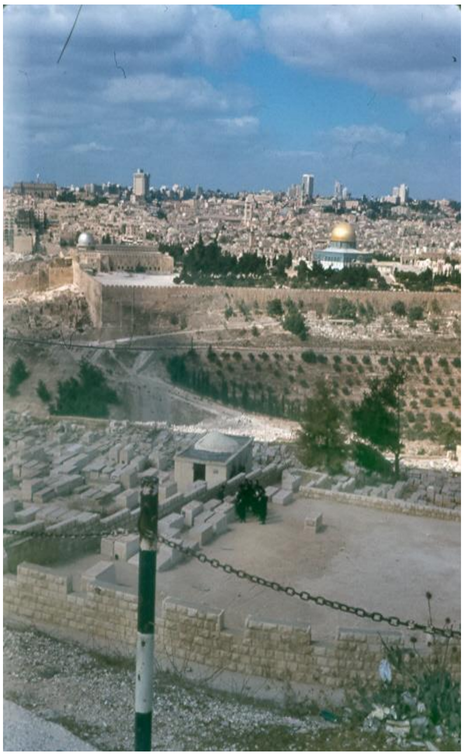


Fig. 8-01: Seismic profiles in the Dead Sea rift of 1977 + 1982 (from El Isa et al., 1987a, Fig. 1; Prodehl and Mooney, 2012, Fig. 8.6.1-01).

Fig. 8-02: Jerusalem 1977.

Fig. 8-03: Israel 1977- test shot near Holon.

Fig. 8-04: Israel 1977- MARS-66 at the Mediterranean.

While a series of shots could be organized without any problems in the Dead Sea (**Fig. 8-05**), which due to its salt content was ideal for energy distribution, the northern shotpoint in the Gulf of Aqaba near Coral Island (**Fig. 8-06**) caused some legal problems, but the problems could finally be solved in an urgently scheduled court session. An unexpected heavy rain shower caused some irritations because it drained the hotel complex near Eilat which consisted of tents only and which served as head- and living quarter for all participants during part of the time. Furthermore it seemed to serve as headquarters for an Israeli mafia group whose members turned out to be quite aggressive, but could be calmed down by our Israeli companions.

In spite of any problems, the project was a full success. From Karlsruhe Otto Gothe, Matthias Grünewald, Heinz Haege, Werner Kaminski, Georg Merkler, Bertram Perathoner and Manfred Rittershofer were in the field besides other participants from Berlin, Hamburg and Tel Aviv, while Karl Fuchs and Claus Prodehl together with Israeli and Hamburg colleagues managed the organization in the mobile headquarters.

Fig. 8-05: Shotpoint Dead Sea during the 1977 project.

Fig. 8-06: Shotpoint of 1977 in the Gulf of Aqaba near Coral Island off Sinai.

A fast data preparation and interpretation was carried out by Bertram Perathoner at Karlsruhe, urged for and accelerated by several visits of Avihu Ginzburg at Hamburg and Karlsruhe. Already one year after the fieldwork results could be reported upon at a symposium on the Dead Sea Rift at Jerusalem (Freund and Garfunkel, 1981; Ginzburg et al., 1981; Perathoner et al., 1981). Furthermore in quick succession two publications were launched in the Journal of Geophysical Research of 1979 (Ginzburg et al., 1979a, b). The data suggested a transition zone between the lower crust and the upper mantle which evidently was restricted to the rift area proper. The crust thickened from 20 km near the Mediterranean coast to about 30 km under the rift. The side profiles indicated a further crustal thickening towards 40 km under the Sinai peninsula. **Fig. 8-11** shows a west-east crustal section through the southern Dead Sea rift from the Mediterranean coast into Jordan.

Under the impression of the technical problems and achievements of the shotpoint organizations for which on the Israeli side Uri Amitai was responsible, Karl Fuchs composed the following song which was finally sung at the farewell-party after the Dead Sea Seismic Refraction Experiment.

Uri fit the battle of Jericho

Refrain: Uri fit the battle of Jericho
and the waves came thundering down

1.) The Dead Sea proved as the hot spot
of seismic efficiency;
the waves they travelled quite a lot
to the farthest distant sea. Refrain: . . .

2.) To stations at lake Kinerett
and along Gulf of Eilat
the Air Force sent the radio time
from the Ebel crystal clock Refrain: . . .

3.) The basement was thrown into light;
look, how old Moho cried
since seismic waves arrived down there
where formerly was night. Refrain: . . .

4.) No judge, no court, no rain, no flew,
no sandstorm nor vibration,
no tired cars, no tired crew
could stop the operation. Refrain: . . .
5.) The shots went off; the tapes came back
all whistling loud and clear.
If you remember a playback
it still sounds in your ear:
Uri fit the battle of Jericho
and the waves came thundering down.
Jerusalem, 27.4.1977 Karl Fuchs

8-3. The Dead Sea rift seen from Jordan in 1984

Seven years later, in 1984, due to good contacts of Jannis Makris to Arabian scientists, the possibility arose to continue the Dead Sea rift research on its eastern side in Jordan. This time our partner was Zuhair El Isa of the University of Jordan in Amman, from Germany again Hamburg and Karlsruhe cooperated, with additional support by recording crews from Clausthal and Frankfurt. Also this project offered a few unforeseen surprises for the participants which required much optimism and patience of the German participants. From Karlsruhe Beate Aichroth, H.J. Bayer, Dirk Gajewski, Heinz Hoffmann, Klaus Joehnk, Horst Laske, Jürgen Neuberg, Raimund Stangl, Michael Wagner, and Karl Zippelt participated. Their enthusiasm helped the project leaders and led to a successful end.

Fig. 8-07 Explosion in the Wadi Elabyad phosphate mine.

Fig. 8-08 Field camp along pofile II, Jordan 1984**.**

Parallel to the rift profile of 1977, a long-range profile was organized in the 1984 experiment in north-south direction along the eastern flank of the rift passing the cities of Amman and Maán (lines I, III and IV in **Fig. 8-01**) with land shotpoints (1 to 4, **Fig. 8-07**) and an underwater shotpoint in the Gulf of Aqaba (no. 5 in **Fig. 8-01**) providing energy up to 200 km offsets (El Isa et al., 1986, 1987a). A third profile II of 170 km length was recorded to the east of the main line. Here, to obtain information on the near-surface structure, in addition to large shots at shotpoint 3, several small shots (6 to 10 in **Fig. 8-01**) were detonated in shallow drill holes providing energy up to 30 km offset. In total 28 shots, of which 3 were underwater shots, were recorded by 20 mobile seismic stations of type MARS-66 (**Fig. 8-08** and **Fig. 8-10,** for instrumental details see subchapter 2-2), recording three components of ground motion and an external time signal of radio Moscow, all frequency modulated, on single-track analogue magnetic tape.

Fig. 8-09 One of many viaducts of the Hedschas railway.

Fig. 8-10 MARS-66 station in Wadi Rum (profile III).

Station spacing was in average 5 km along the main lines I, III and IV and 1-2 km along line II. The recording sites had been explored and carefully described by Jim Mechie during an extraordinary pre-excursion one month before the project. One of the problems arose that the available detailed maps had been printed at British colonial times and did not contain the modern main road connecting Amman and Aqaba. However, it did contain the trace of the Hedschas railway which had been completed before World War I. For many sites the numerous viaducts of this railway became the main orientation in the else featureless desert country (**Fig. 8-09**). For example it would read: "Turn off the main road at km XXX, drive to 10-arch viaduct of the Hedschas railway, cross it under the second arch from left and continue for 0.6 km in direction 275°." The site in nowhere was a larger rock which had been marked by a number in red colour. Out of 80 sites only 2 sites could not be relocated. At the end of the seismic project, Karl Zippelt of the Karlsruhe Geodetic Institute determined the coordinates of all sites by a geodetic survey.

The organization of suitable shotpoints was another miracle. For the main line I (**Fig. 8-01**) north of Amman borehole explosions could be arranged at two sites (shot sites 1 and 2 in **Fig. 8-01**). At the center of the line, Jim Mechie had found a phosphate mine where for mining purposes regularly large explosions were carried out (shotpoint 3 in **Fig. 8-01**). Jim Mechie would visit the responsible German engineer at his lunch time shortly prior to days, when an explosion was probably due, and persuaded him to detonate the charges at a prefixed time. One of the recording crews would then enter the quarry and time the explosion (**Fig. 8-07**). Jannis Makris took care that the Jordanian navy could be persuaded to organize a shotpoint in the Gulf of Aqaba at the southern end of line III (shotpoint 5 in **Fig. 8-01**). Dirk Gajewski undertook the task to time the explosions on board of the navy ship, but evidently during its manoeuvring he suffered some frightening moments. For the side profile II which ran in southeasterly direction towards the Saudi Arabian border, the phosphate mine served as its unreversed shotpoint. To obtain some near-surface informations, Jannis Makris had hired some strong Jordanian workers with shovels to dig holes at five sites along the line with 30 km intervals (6-10 along line II in **Fig. 8-01**), in which small charges could be detonated. As mentioned above, these charges could be recorded to a distance of 30 km.

Unfortunately the money transfer by Jordanian banks did not work as a first organizing team had found out when arriving at Amman. Therefore, cash money had to be supplied by the university cashier of Karlsruhe on very short notice and to be carried by the following crews in several bundles of 10,000 DM each. The import of the equipment into Jordan required the help of a Jordanian university customs specialist who distributed money here and there. This was the only time in the Karlsruhe involvement of projects in remote countries that "special fees" had to be paid.

The next problem was that, with two exceptions, there were no suitable rental cars available. Instead, local owners of pick-ups were hired to transport one observer with his equipment, usually two or three MARS-66 stations. To keep these drivers and avoid their run-away, their regular payment was paid in small amounts every second or third day and in addition an equal amount had to be added for „acknowledgment of their good service" whatever our Jordanian partner regarded as proper payment. Due to the fact that Jordanian banks had proved not to be reliable, the German project leader had to carry large amounts of cash in his pockets. Fortunately, never any security problem occurred, but the more car tire problems happened. Most drivers had no desert experience and drove like hell. Carrying spare tires was evidently equal to burning money. Only by threatening that payment would be refused if recording sites could not be reached in time due to tire problems, finally the truck owners agreed to buy spare tires. In general the hired drivers developed no interest in the project. Using the drivers as occasional helpers proved to be a vane wish. As soon as the final recording site was reached the driver would only care to cook himself a pot of tea. It was nevertheless amazing how in the plant-less desert he would find enough wood for a fire to boil his water. Only in very few cases the German crew boss was offered a cup of tea.

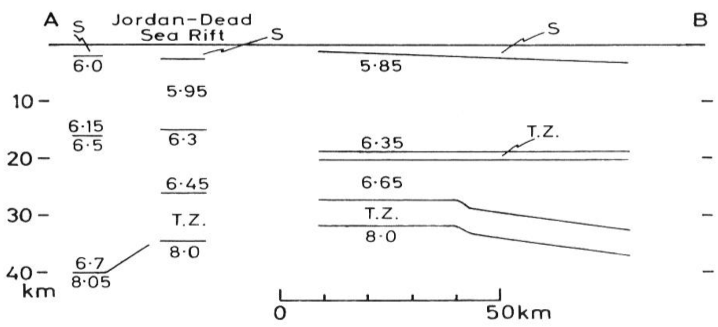


Fig. 8-11: Crustal cross section across the southern Jordan-Dead Sea rift (from El Isa et al., 1987a, Fig. 13; Prodehl and Mooney, 2012, Fig. 8.6.1-03).

The data preparation and interpretation was carried out at Karlsruhe and was essentially accomplished by Jim Mechie with occasional support by Zuhair El-Isa. Subsequently the results were combined with those of Ginzburg et al. (1979b) and a west-east crustal cross section through the Jordan-Dead Sea rift and its flanks was compiled (**Fig. 8-11**). The main result was that under the rift proper crustal thickness is about 30 km and that, different from the western flank, the elevated crust under the rift proper extends eastwards for at least 40 km away from the rift underneath the eastern flank and only then gradually starts to thicken towards the thick Arabian Shield crust (El Isa et al., 1987a; Prodehl, 1987; Mechie and Prodehl, 1988). Also the shear-wave data were interpreted and subsequently published. The upper crust including sediments has a Poisson´s ratio of 0.25 except in northwestern Jordan where it gets as high as 0.32. The lower crust has a higher Poisson´s ratio of 0.29 to 0.32 for which the authors have offered two possibilities, either the lower crust possesses high feldspar and low quartz content or fluid phases exist in the form of penny-shaped inclusions (El Isa et al., 1987b, 1990).

8-4. U.S. Geological Survey profile in Saudi Arabia

In 1978 a long-range profile was realized which traversed the Arabian Shield of Saudi Arabia over a distance of nearly 1000 km from the southern Red Sea to the neighborhood of Riad (**Fig. 8-12**). This survey was carried out by the U.S. Geological Survey (USGS), using for the first time the newly built mobile array of 100 cassette recorders mentioned above which had been designed by J.H. Healy and co-workers (Murphy, 1988, see **Fig. 3-6** to **Fig. 3-9** in subchapter 3-7). In total, 100 portable seismographs were available; they were successively deployed in each of five 200-km recording spreads. A portable computer center, including field playback, digitizer, and plotting system, was moved along the profile to provide rapid feedback of data quality and content, and to allow for preliminary assessment of scientific results as the experiment progressed (Mooney et al., 1985).

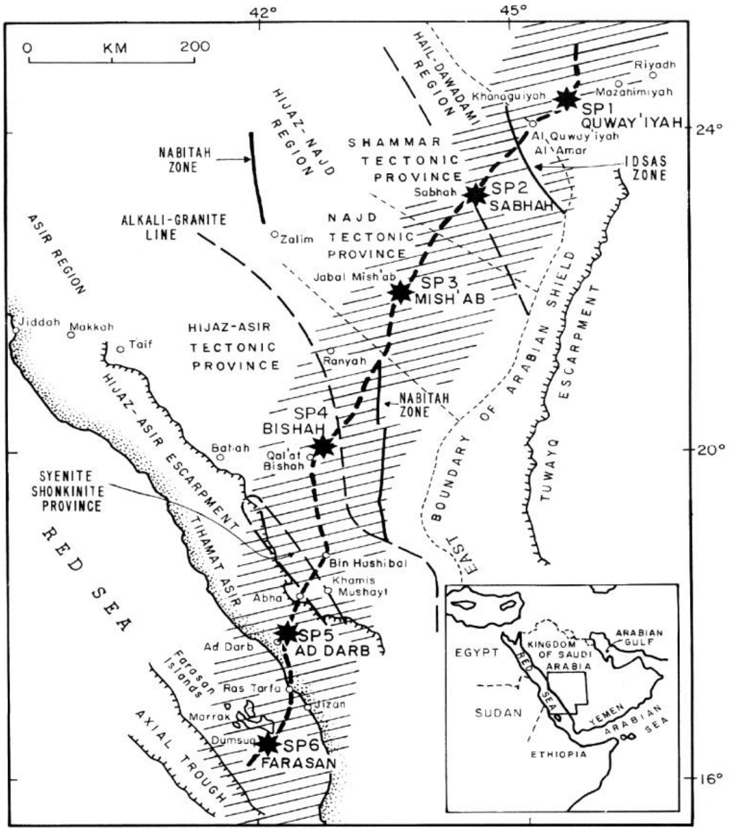


Fig. 8-12: Location map of the seismic refraction survey of 1978 in Saudi Arabia (from Mooney et al., 1985, Fig. 1; Prodehl and Mooney, 2012, Fig. 7.5.2-04).

The data was of extremely good quality (**Fig. 8-13**, see also Prodehl and Mooney, 2012, *Appendix A2*, pages 86-88, *Appendix A7-6-2* and *A7-6-3*), and was, in the course of a seismic workshop (Mooney and Prodehl, 1984), interpreted by several other authors, including Claus Prodehl and Jim Mechie from Karlsruhe (Prodehl, 1985, Mechie et al., 1986).

The overall structure (**Fig. 8-14**) shows a rather uniform 40 km thick crust under the Arabian Shield, which thins more or less abruptly west of the escarpment under the coastal plain to less than 10 km in the Red Sea (Mooney et al., 1985; Mechie et al., 1986).

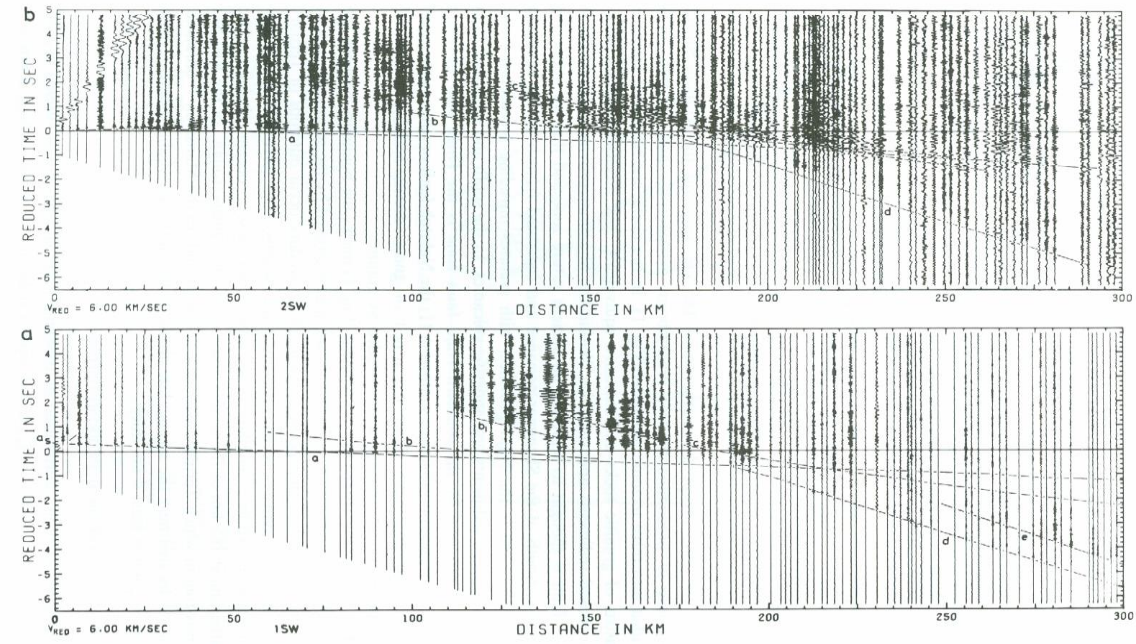


Fig. 8-13: Band-pass filtered record sections with correlated phases for **(a)** shotpoint 1 SW (true amplitudes) and **(b)** shotpoint 2-SW (normalized amplitudes). Reduction velocity = 6 km/s (from Mechie et al., 1986, Fig. 3).

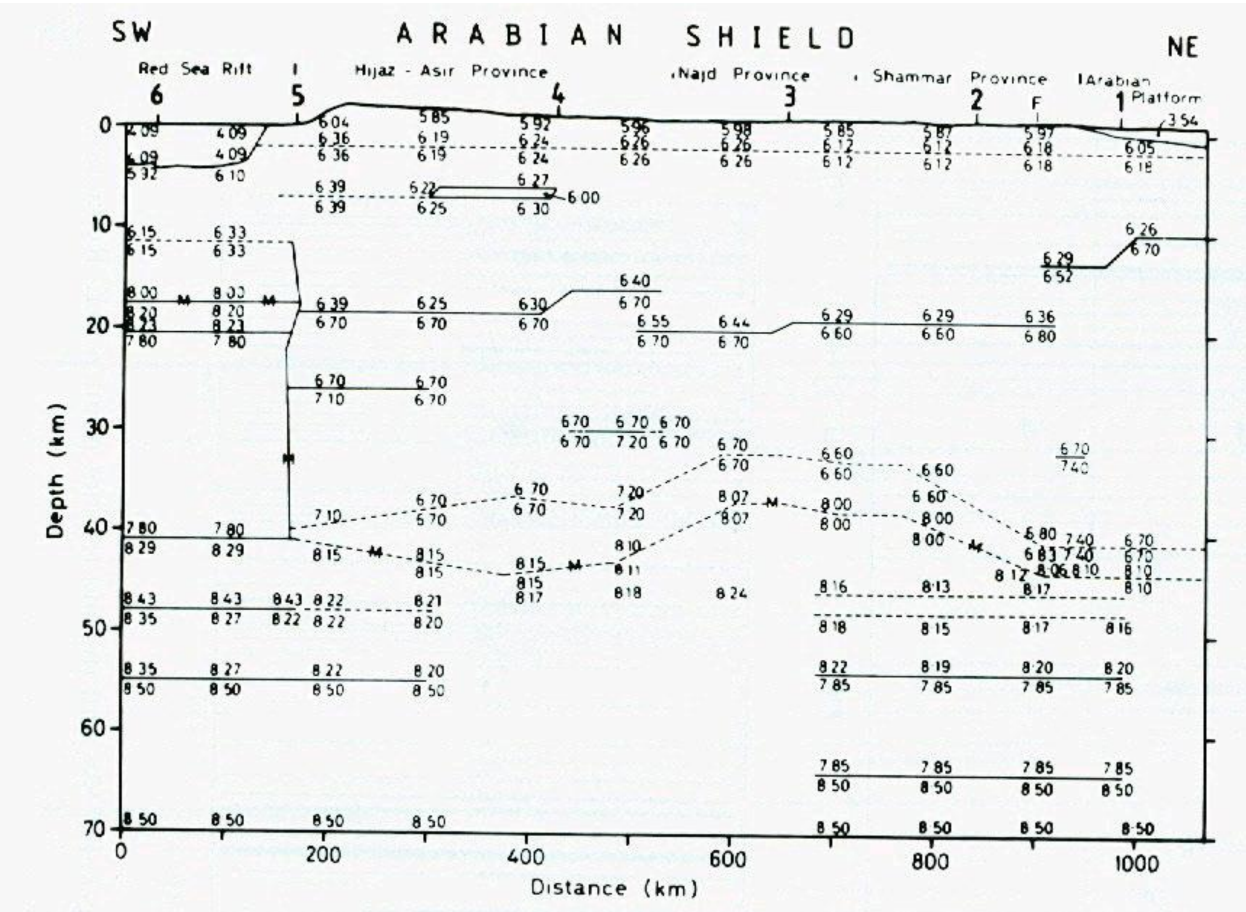


Fig. 8-14: Cross section through the Arabian Shield from the Red Sea to Riad (from Mechie et al., 1986, Fig. 4).

In the framework of the SFB 108, the available seismic results on deep structure of the Dead Sea rift environment were compiled by Bayer et al. (1989) and those of the Red Sea were compiled by W. Voggenreiter and Jim Mechie. Their compilation included also the above mentioned long-range profile through the Arabian Shield of Saudi Arabia (Voggenreiter et al., 1988; Mechie and Prodehl, 1988; Prodehl et al., 1997a).

9. The East African rift system in Kenya - KRISP

9-1. Introduction

The original plan of SFB 108 "Stress and stress release in the lithosphere" had foreseen detailed studies in the Afro-Arabian rift. In particular for 1984 -1986, additional seismic-refraction measurements were planned to add to the USGS data of 1978 (see above, subchapter 8-3) and to obtain more detailed crustal information in the border region between Red Sea and Arabian Shield.

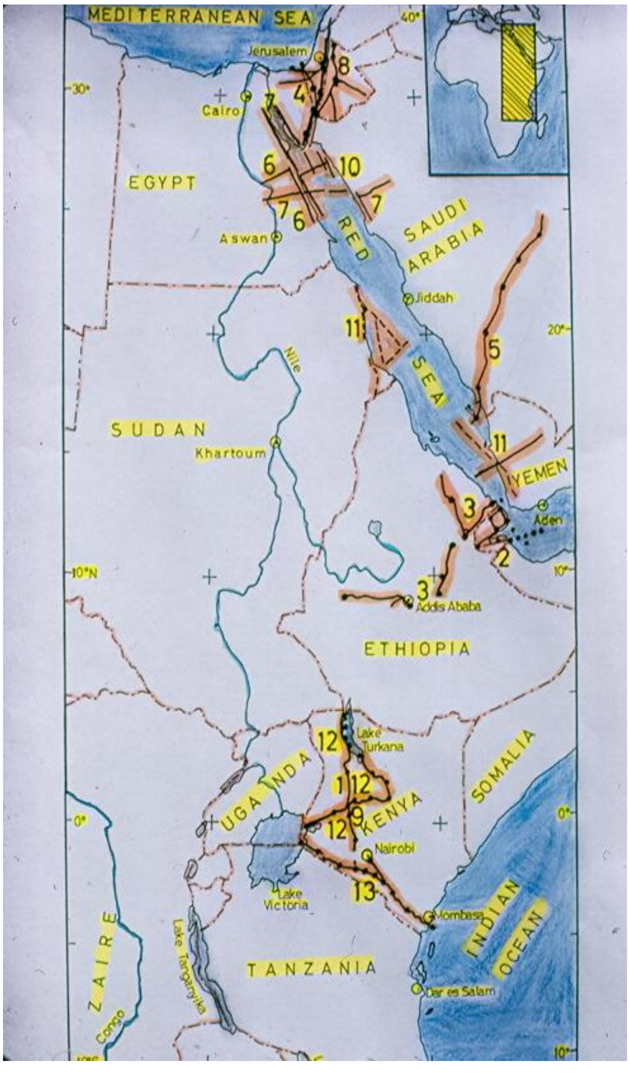


Fig. 9-01: Seismic refraction lines recorded in the Afro-Arabian Rift System in 1969-1994 (after Prodehl et al., 1997a, Fig. 1).

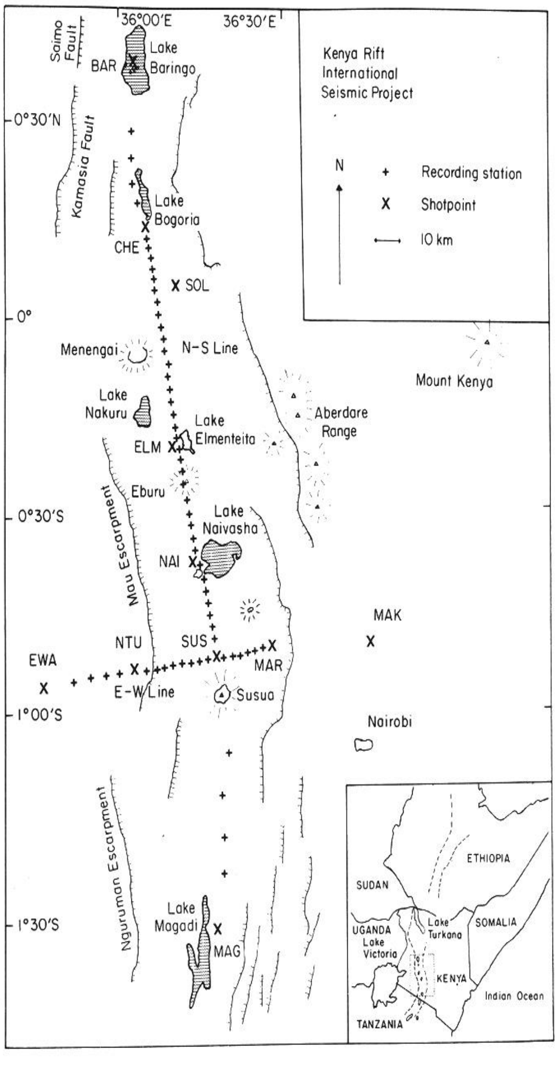


Fig. 9-02: KRISP 85 in the East African rift of Kenya (from KRISP Working Group, 1987, Fig. 1; Prodehl and Mooney, 2012, Fig. 8.6.2-01).

Unfortunately the attempt failed to get into contact with interested Saudi Arabian geophysicists. Therefore it was decided to re-direct the priority of future research of the SFB

108 into the East African Rift of Kenya. Up to date mainly British geoscientists from Birmingham and Leicester had carried out seismic and seismological investigations of the rift in Kenya. But also Stephan Mueller during his time at Karlsruhe had visited the Kenya rift in 1970 and had supported the seismological research of Jürgen Wohlenberg. In 1984, a first step towards Kenya had been made by a feasibility study of Karl Fuchs, Henning Illies, Claus Prodehl und Jürgen Wohlenberg in the report volume of the SFB 108 for 1981-1983, summarizing the state of art on crustal and upper mantle structure of the East African Rift in Kenya. In 1984, Aftab Khan from Leicester, Randy Keller from El Paso, and Ken Olsen from Los Alamos visited Karlsruhe during the time of the Black Forest project and discussed in detail the chances for a joint large-scale seismic project in Kenya: KRISP (Kenya Rift International Seismic Project).

Fig. 9-01 shows all seismic lines recorded within the Afro-Arabian Rift until 1994 (Prodehl et al., 1997a), including the KRISP projects 85, 90 and 93-94, which will be described below.

9-2. KRISP 85

The first phase of KRISP started in 1985 as a joint project of the Universities of Birmingham (Roy King and Don Griffiths) and Leicester (Aftab Khan and Peter Maguire) in England, the Purdue University (Larry Braile), Stanford University (George Thompson) and University of Texas at El Paso (Randy Keller) in the USA, and the University of Karlsruhe (Claus Prodehl, Jim Mechie, and Karl Fuchs) in Germany.

Fig. 9-03: Don Griffith's raft to lower seismic charges.

Fig. 9-04 KRISP 85: 1-to shot in Lake Baringo.

The project consisted of two seismic-refraction profiles within the graben proper (**Fig. 9-02**). Along the N-S directed line underwater shots in lakes were recorded from Lake Baringo (**Fig. 9-03** and **Fig. 9-04**), Lake Bogoria and Lake Naivasha. Along the cross profile borehole shots were recorded. On the German side Ulrich Achauer, Heinz Hoffmann, Horst Laske, Jim Mechie, Norbert Ochmann, Claus Prodehl, Rolf Stellrecht and Jürgen Wohlenberg participated with MARS-66 stations in the field (**Fig. 9-05** and **Fig. 9-06**). In order to protect unmanned stations in the field from curious locals and thieves, the chiefs of the neighbouring settlements were visited. As a result, often young local men could be hired who would guard the sites day and night (**Fig. 9-06**). Being afraid of wild animals, these brave men might build a fence from thorny bushes and then disappear. The data were published first in Nature (KRISP Working Group, 1987) and served as a realistic basis to plan for a second phase: KRISP 90. It turned out that only the underwater shots along the longitudinal profile delivered enough energy to observe phases from the deeper crust (KRISP Working Group, 1987; Henry et al., 1989, 1990).

Fig. 9-05: Heinz Hoffmann with MARS-66-playback system.

Fig. 9-06: British Geostore outer station.

Parallel to the main seismic refraction profile temporary long-time recording seismological stations were installed along a 400 km long West-East profile with the aim to record far-distance natural events (sites marked by triangles in **Fig. 9-07**). The equipment came from UCLA (University of California at Los Angeles), Wisconsin and Karlsruhe. The interpretation of the teleseismic data resulted in a clear traveltime anomaly within the rift proper (Dahlheim et al., 1989; Achauer, 1990, 1992; Achauer et al., 1992; for more details see Chapter 9-2-5-1 of this volume).

9-3. KRISP 90

The results of KRISP 85 were promising for the organizers to plan a second phase of KRISP with seismic-refraction and teleseismic observations covering the whole Kenya rift (KRISP Working Party, 1991).

In 1987 a team of experts undertook a two-weeks excursion along the rift from Lake Turkana to Lake Magadi and along the flanks of the rift in order to explore the feasibility such as the availability of suitable trucks and 4-wheel drive vehicles for transportation of explosives and recording stations as well as the possible location and accessibility of possible shotpoints and profiles. However, in the beginning the support and cooperation of influential geophysicists at Nairobi was little encouraging and endangered the permission process at the local authorities. The problem was finally attacked by a longer visit of Karl Fuchs and Claus Prodehl at Nairobi where in close cooperation with the German Embassy a project study was written addressing the Kenyan colleagues and authorities which very sudden solved the permission problems (Fuchs and Prodehl, 1990).

At another pre-excursion, Karlsruhe scientists and technicians explored the wireless communication and tested a promising radio system with wide distance ranges which was later used to keep connection between shotpoints, observer camps and a mobile central headquarter. Doris Zola offered her service and her house at Nairobi to install a permanent system for communication and she served as local agent for the times of pre-investigations and the main experiment. In return the European crews brought special food for endangered baby elephants at Nairobi National Park where Doris Zola served as unpaid helper.

Serious problems were caused by the unreliability of locally available vehicles (**Fig. 9-09** to **Fig. 9-12**). Frequent flat tires due to the little served tar and dirt roads were the minor problems. More severe was when a driver on downhill roads was outrun by one of his own wheels. There was no doubt that modern 4-wheel drive vehicles of Toyota and other companies were more comfortable than the old-fashioned landrovers. But at one of the preexcursions when crossing a sandy river bed only at one out of four Toyota vehicles the 4-wheel drive system functioned. This was not promising. It also soon turned out that nearly all small garages in the countryside were able to handle any kind of repair of landrovers but were helpless if a sophisticated modern vehicle stranded. Even the chassis of a landrover which broke in nowhere could be melded together by local mechanics.

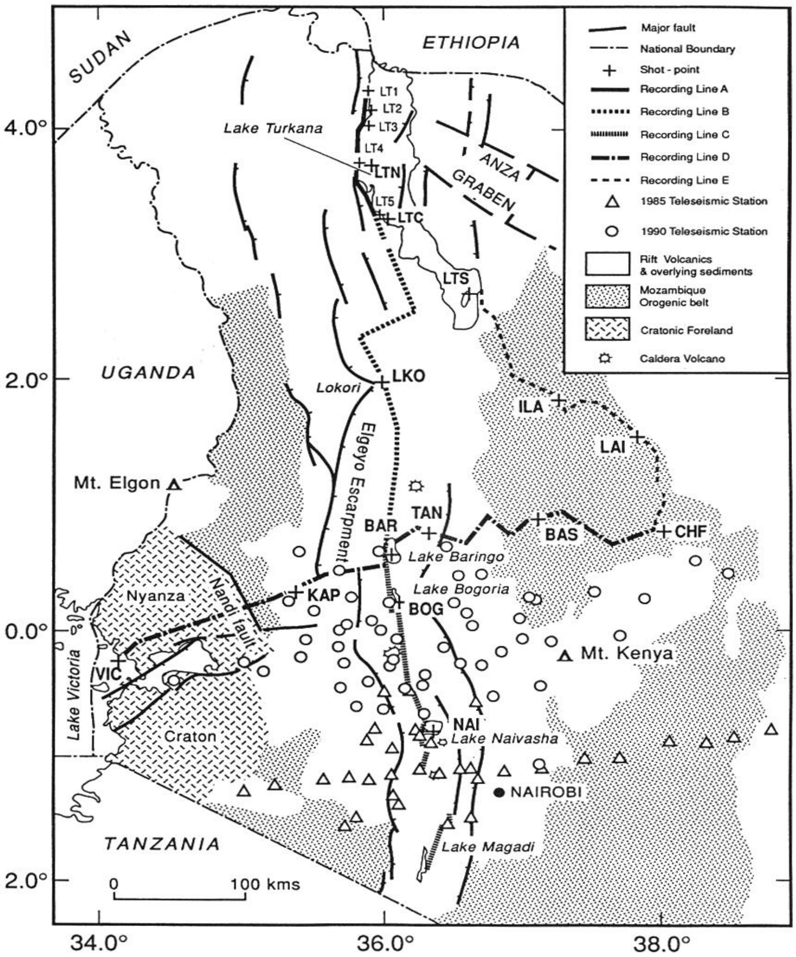


Fig. 9-07: KRISP 90 location map showing the seismic refraction / wide-angle reflection lines and the configuration of the teleseismic networks in 1985 and 1989-1990 (from Keller et al., 1994b, Fig. 1; Prodehl and Mooney, 2012, Fig. 9.5.1-01). The 1985 refraction lines extended from Lake Baringo to Lake Magadi and across the rift valley south of Lake Naivasha, parallel to the 1985 teleseismic cross line (white triangles).

Finally, in 1990 KRISP 90 could start (**Fig. 9-07**, (Prodehl et al., 1994a, b). A teleseismic network of seismological long-time recording stations spanned graben and flanks of the southern Kenya rift (Achauer and KRISP Working Group, 1994; Ritter and Achauer, 1994, for details see Chapter 9-2-5-2 of this volume). Along the axis of the graben a 550 km long seismic-refraction profile was planned extending from the northern end of Lake Turkana via Lake Baringo to Lake Naivasha (Mechie et al., 1994a; Keller et al., 1994a, b), a 450 km long cross profile extended from Lake Victoria via Lake Baringo to the Ewaso-Ngiro river in the east (Braile et al., 1994), and a 400 km long profile covered the eastern flank in NW-SE direction from the southeastern part of Lake Turkana to the Ewaso Ngiro river (Prodehl et al., 1994c).

Fig. 9-08: Ca.200 SGR stations in Nairobi before field work.

Fig. 9-09: Mixed fleet of vehicles for KRISP-90.

Fig. 9-10: Vehicle problems.

Fig. 9-11: Repair service.

Fig. 9-12: Difficult river crossing.

Fig. 9-13: Right of way for big animals.

Fig. 9-14: KRISP 90 huddle test at Lake Turkana.

As far as possible shots were planned as underwater shots in lakes (**Fig. 9-15** and **Fig. 9-16**), else as drillhole shots (**Fig. 9-17**). 206 SGR one-component recording stations from USA (Murphy et al., 1993) were available (**Fig. 9-08, Fig. 9-14, Fig. 9-18**) enabling an average station separation of 2 km.

In total 34 shots were detonated at 19 shotpoints with charges ranging from 100 to 2000 kg. All explosions were planned, prepared and carried out by experts of Birmingham and Leicester (Don Griffiths and others), of Dublin (Brian Jacob), of the U.S. Geological Survey (Ed Criley and others), of the University of Clausthal (Roland Vees and co-workers), and of Karlsruhe (Dirk Gajewski and Christian Grosse). All lake shots produced excellent recordings, limited in the rift to 400 km offsets and on the flanks to 450 km. Also the borehole shots, except LKO, provided suitable energy to at least 250 km distance. In total, 1063 recording sites were occupied. All sites had been located beforehand in pre-site surveys with many positions being determined by GPS measurements.

Fig. 9-15: Boat for Lake Turkana underwater shot.

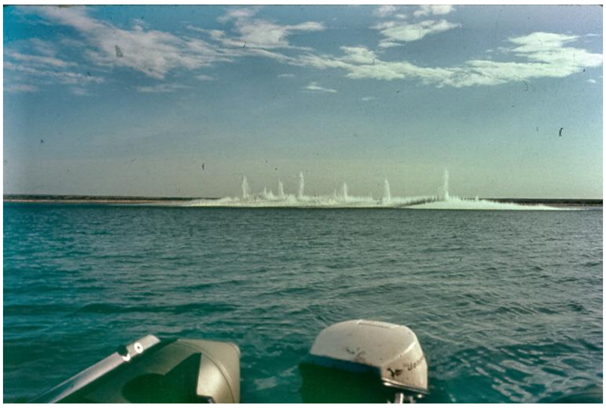


Fig. 9-16: KRISP 90 underwater shot in Lake Turkana.

Fig. 9-17 Preparing a KRISP-90 borehole shot.

Fig. 9-18: One of 200 SGRs in the field.

72 scientists divided their tasks in self-sustaining recording and shooting parties and technical services at a mobile headquarters where batteries were recharged, instruments repaired and tapes collected to be transported to a temporary processing center at Egerton University near Nakuru. Participants in the field from Karlsruhe were: Beate Aichroth, Uwe Enderle, Dirk Gajewski, Christian Grosse, Heinz Hoffmann, Klaus Joehnk, Werner Kaminski, Uwe Kästner, Jim Mechie, Jürgen Oberbeck, Claus Prodehl, Matthias Schoch, and Raimund Stangl.

Life in lonely areas of Africa is not without risk. The following stories may serve as examples. At Lake Baringo hippopotami step on land at night and graze on the surrounding meadows including those of the lodge which are arranged between the huts for overnight guests. One of the KRISP participants when walking from the restaurant to his hut unfortunately and unknowingly stepped between a mother hippo and its baby. The mother hippo attacked immediately. Such attacks usually are deadly. The KRISP person was only saved because he was close to a door of a hut whose inhabitants immediately opened the door and dragged him inside. However, he was dangerously wounded. He was immediately transported to the Nairobi hospital and from there, always in flat-lying position, was flown back to Europe. He completely recovered.

Also, shot experts were met by unforeseen risks when handling and detonating explosives. In Lake Turkana a charge which fortunately was very small drifted unseen underneath the rubber boat. When it was detonated, the man in charge was thrown 10 m high into the air and then landed hard but safely in water.

A specialty of Lake Turkana is that in some areas in the early morning hours strong waves develop which only calm down near noon time. As, however, the careful preparation of an underwater shot requires much time, the shot team did not dare to wait until the waves calmed down and, against the warning of the locals, started their voyage by rubber boat. But the waves were too strong for the boat, the boat capsized, and its contents disappeared in the water. The crew could turn over the boat, but only half of the gasoline could be saved. This was not enough to return safely to the shore. As also the radio equipment had gone lost, nobody on land had any idea that the shot team was drifting on the lake. Fortunately, a few locals were present who predicted where the drifting boat would reach the shore, approximately 40 km further north. The rescue team drove northward to that position and luckily around midnight the drifting boat reached the shore at the predicted position and could be safely collected by the search team. Later on, all those happenings decorated a KRISP 90 T-shirt.

In order to assure a joint interpretation of the data (KRISP Working Group, 1991), several workshops were organized where the results of the individual interpretation teams were discussed and unified and prepared for publication in a special volume of Tectonophysics (Prodehl et al., 1994a). It included the results of the teleseismic (Ritter and Achauer, 1994) and other geoscientific investigations (Mechie et al., 1994b) in the Kenya rift. A main result was that the crustal thickness of 35 km beneath the Kenya dome and the adjacent Lake Naivasha region decreased to as little as 20 km under Lake Turkana. Beneath the flanks adjacent to the Kenya dome the crust appeared to be 40 km thick and the upper-mantle velocities increased from 7.7.km/s in the rift to 8.1 km/s outside of the graben proper.

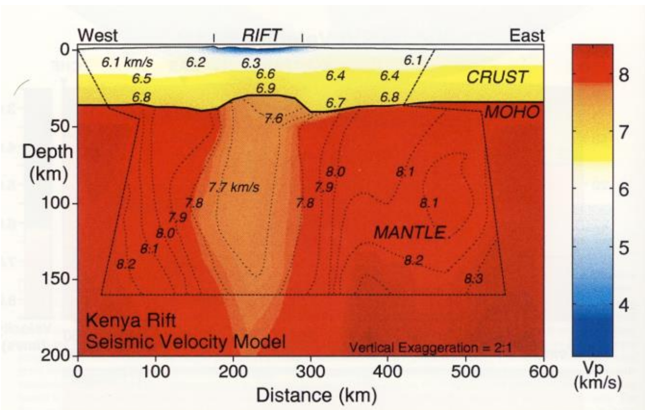


Fig. 9-19: Model of the lithosphere under the Kenya rift based on teleseismic and seismic-refraction data (from Braile et al., 1995, Fig. 5-3).

Fig. 9-20: KRISP seismic-refraction profiles.

Last but not least, during the active phase of KRISP 90, the teleseismic array also recorded all shots. The data were used to interpret the P-wave first arrivals in order to determine lateral crustal inhomogeneities with a three-dimensional approach. Several high-velocity bodies found within the crust were attributed to possible mafic cumulates or magma chambers, which evolved during the major magmatic episodes and which are typical indicators for an active rift (Keller et al., 1994b; Ritter and Achauer, 1994).

In a subsequent summary on the deep structure of the East African rift system, the teleseismic velocity perturbations in the upper mantle from 40 to 160 km depth, which had been published as relative velocity variations in %, had been combined with the seismic-refraction cross section of Braile et al. (1994) and converted into absolute velocities (Braile et al., 1995, **Fig. 9-19**).

9-4. KRISP 93-94

The continuation of the deep structure of the Kenya rift southwards had remained an open question from KRISP 90. Therefore, beginning in 1993 and continuing into early 1995, the KRISP Working Group began a new series of multidisciplinary field investigations in the rift in southern Kenya (KRISP Working Group, 1995a; Prodehl et al., 1997b). The research program involved six experimental efforts: (1) a teleseismic survey of the area of the Chyulu Hills located on the eastern flank of the rift, about 100 km to the southeast of Lake Magadi (Ritter et al., 1995**;** Ritter and Kaspar, 1997; Kaspar and Ritter, 1997a, b; Chapter 9-2-5-3 of this volume), (2) a seismic refraction / wide-angle reflection survey across southern Kenya extending from the Indian Ocean near Mombasa to Lake Victoria (**Fig. 9-20**), (3) the installation of a temporary seismological network in southern Kenya, (4) a local earthquake recording survey around Lake Magadi which was continued in 1997 and 1998 (Ibs-von Seht et al., 2001), (5) a detailed gravity survey along the active-source seismic lines (Birt et al., 1997), and (6) a magnetotelluric study at selected sites along the same seismic lines (Simpson et al., 1997).

The teleseismic investigation of the neovolcanic Chyulu Hills was successfully performed in 1993 (for details see Chapter 9-2-5-3 of this volume). However, difficulties due to theft and other problems with the local people caused headaches to our Kenyan colleagues. Consequently they managed to use a visit of President Moi to the Magadi area for a public advertising campaign in the Kenyan television.

The influence of our Kenyan partners enabled that the project could be demonstrated by the leading scientists to President Moi which later on was shown in the Kenyan television program (**Fig. 9-21** to **Fig. 9-24**).

The immediate Presidential support proved to be very positive for the following fieldwork of the KRISP 94 seismic-refraction program. Nevertheless near Mombasa some equipment disappeared. Immediately Jim Mechie visited several villages and talked intensively to the elders. It did not take long, and the equipment mysteriously re-appeared.

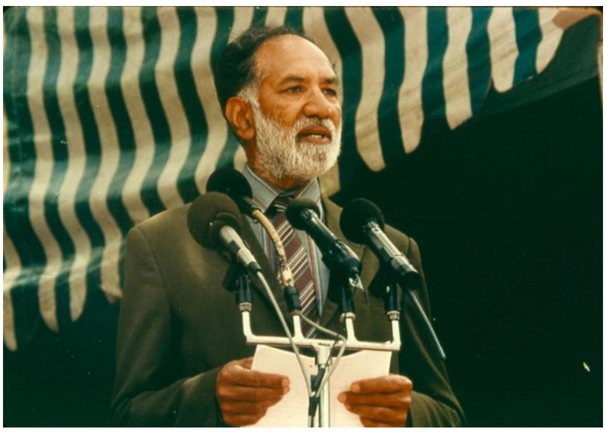


Fig. 9-21: Presentation of KRISP by Aftab Khan at the Magadi visit of President Moi.

Fig. 9-22 Briefing of President Moi by KRISP scientists Raimund Stangl and Claus Prodehl.

Fig. 9-23: Presidential visit at Magadi: school classes.

Fig. 9-24: Presidential visit: Masai in local costumes.

One of the goals of the seismic refraction / wide-angle reflection survey KRISP 94 was to obtain an 850 km long profile across southern Kenya extending from Lake Turkana to the Indian Ocean at Mombasa. It was realized by establishing two profiles which were in fact two deployments. Line F, the 430 km long eastern line, extended from the eastern flank of the rift near Magadi to the Indian Ocean near Mombasa (**Fig. 9-20**).

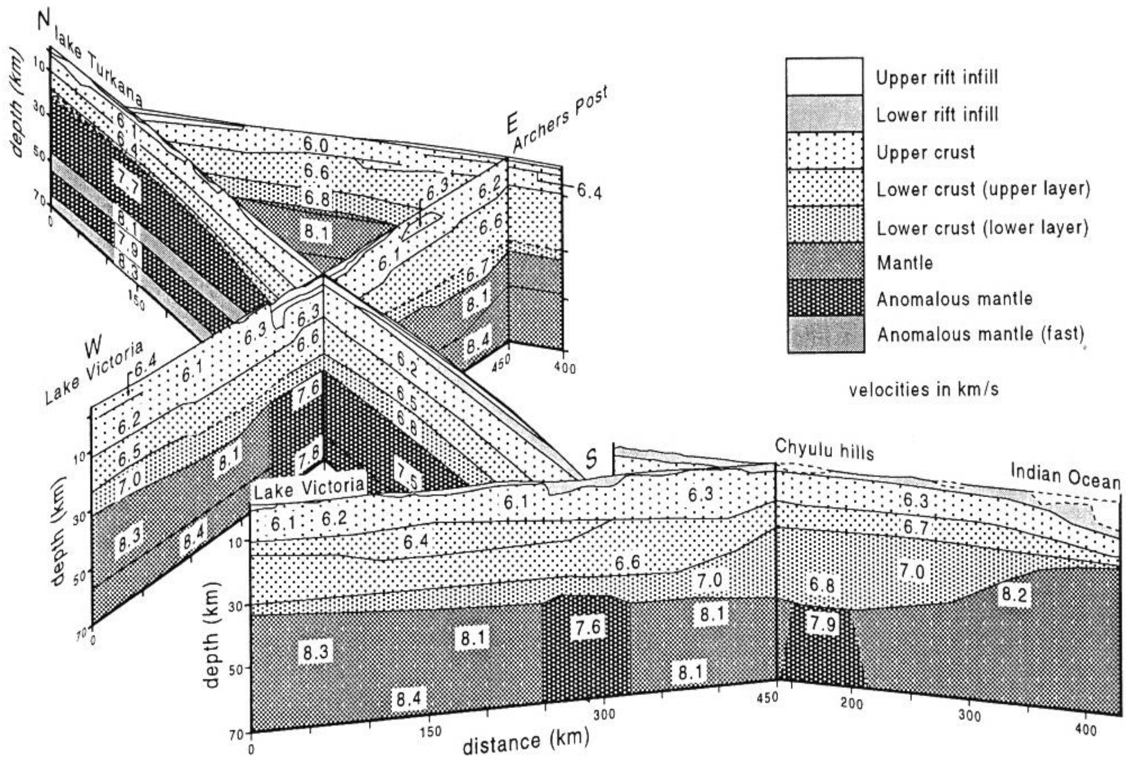


Fig. 9-25: KRISP 90/94 fence diagram showing crustal and upper mantle structure of the Kenya rift from Lake Turkana to Lake Magadi and beneath the neighbouring flanks from Lake Victoria to the Indian Ocean (from Khan et al., 1999, Fig. 4; Prodehl and Mooney, 2012, Fig. 9.5.1-08).

Line G, the 420 km long western line, extended from the northwestern end of the Chyulu Hills across the southern rift and the game park Masai Mara to Lake Victoria near the border of Kenya and Tanzania. In total 10 borehole shots were fired with charges from 450 to 2080 kg, loaded in one or two boreholes. At the ends underwater shots, where the charge was subdivided into smaller, separated units, could be arranged. Two shots in Lake Victoria had total charges of 900 kg each. In the Indian Ocean, using the support by a Kenyan Navy vessel, only one small charge of 300 kg could be fired. The second shot failed due to ever-lasting shortage in gasoline of the vessel. Furthermore two quarry blasts with 1000 kg charges near Kibini could be timed in accordance with the layout of the two lines and fired without delays between detonators.

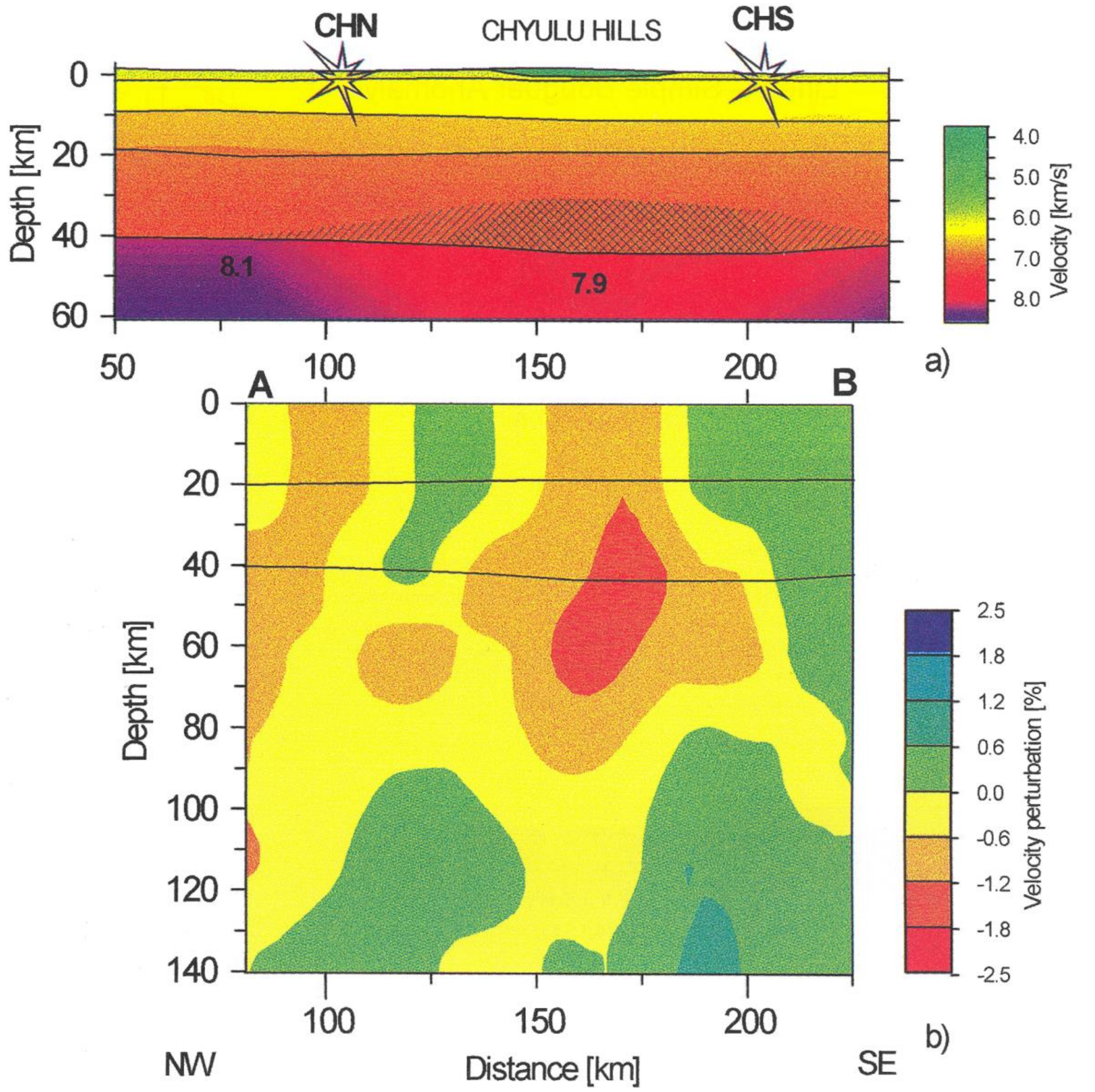


Fig. 9-26: Crust and upper mantle structure underneath the Chyulu Hills volcanic field (from Novak et al., 1997b, Fig. 7; Prodehl and Mooney, 2012, Fig. 9.5.1-09). **a)** Part of the crustal model along line F of Novak et al. (1997a), **b)** cross section through the teleseismic tomography model of Ritter and Kaspar (1997).

In total 15 shots were recorded by 202 stations. 167 were RefTek 3-component instruments, the remainder consisted of 1-component SGR equipment. Participants from Karlsruhe in the field were Uwe Enderle, Dirk Gajewski, Werner Kaminski, Jim Mechie, Olaf

Novak, Claus Prodehl, and Raimund Stangl. Following the successful KRISP 90 procedure, for the interpretation again workshops were organized (KRISP Working Group, 1995b) and the results were jointly presented at meetings (e.g., Mechie et al., 1996) and jointly published in a special volume of Tectonophysics (Fuchs et al., 1997b: Prodehl et al., 1997a, b; Novak et al., 1997a, b; Mechie et a., 1997). A synthesis of the results of the entire KRISP research is shown in **Fig. 9-25. Fig. 9-26** shows the combination of the seismic refraction crustal and the teleseismic mantle models (Novak et al., 1997b).

10. GRANU-95, seismic studies around the Saxonian Granulite Mountains

Following the re-unification of Germany of 1990, in 1992 a new priority program of the German Research Society "Orogenic processes - their quantification and simulation at the example of the Variscides" was started (Franke et al., 2000). One of the highlights was the investigation of the so-called Saxonian Granulite Mountains (SGM in **Fig. 10-01,** Sächsisches Granulitgebirge), a metamorphic core complex within the Saxothuringian section of the Variscides (see inlet of **Fig. 10-01**) which was known by its Bouguer anomaly (**Fig. 10-02**). It is located 50-100 km north of the seismic-reflection line MVE-90 which had targeted the Erzgebirge.

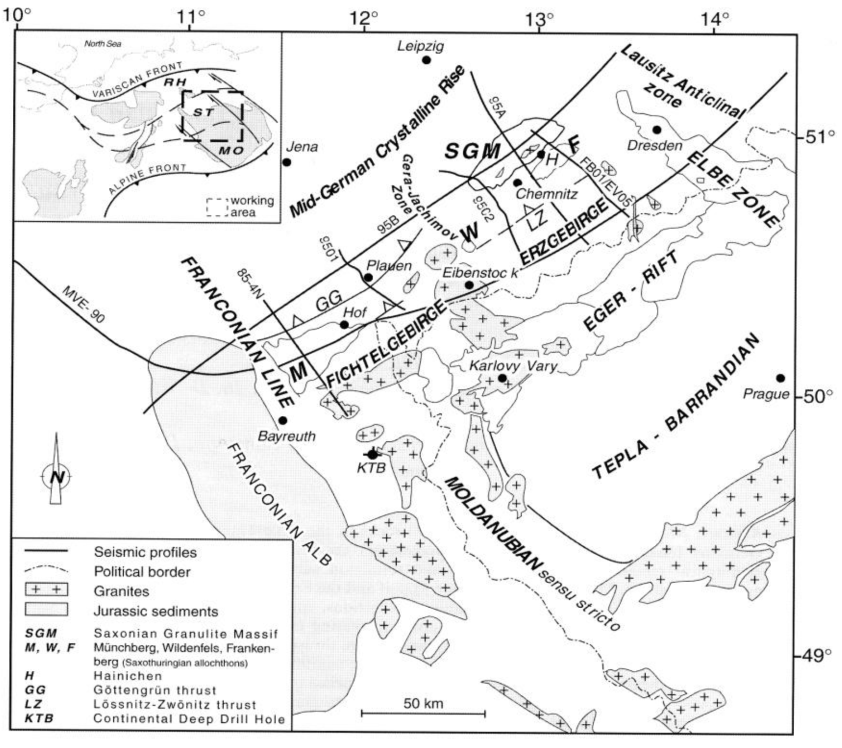


Fig. 10-01: Location of the seismic profiles MVE-90 + GRANU-95 (from Krawzyk et al., 2000, Fig.1; Prodehl and Mooney, 2012, Fig. 9.2.2-01).

Named "The lithosphere of the Saxothuringicum, a geological and geophysical anomaly of the Variscan orogeny", a seismic investigation by Karlsruhe and GFZ Potsdam was planned in 1993 and carried out in 1995 (lines 95A and 95B in **Fig. 10-01**), aiming to unravel the crustal structure underneath the Saxonian Granulite Mountains metamorphic core complex

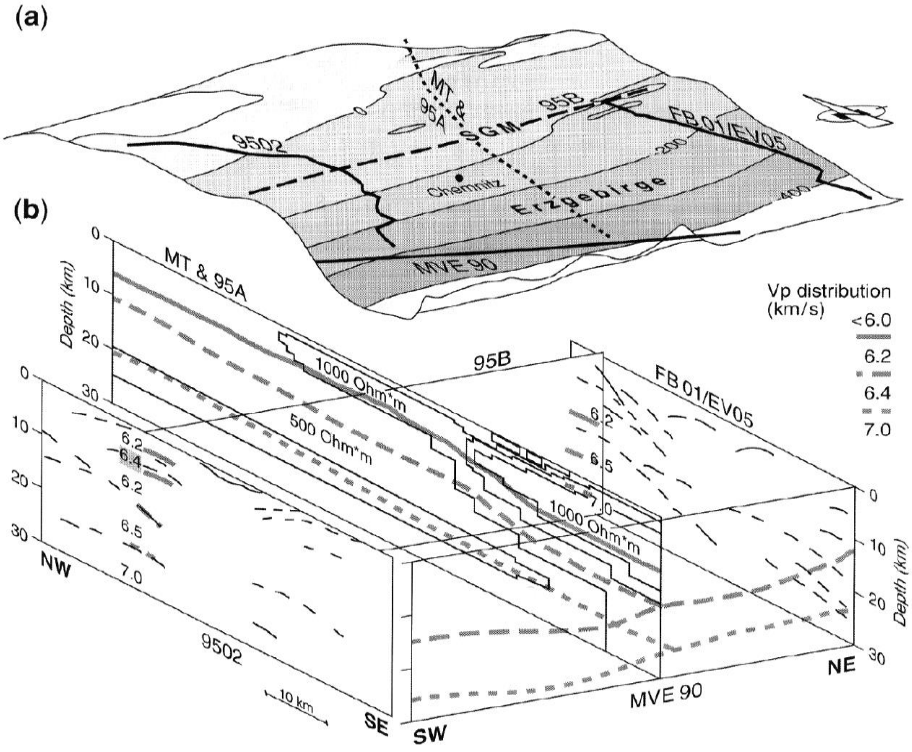


Fig. 10-02: Bouguer anomalies and reflectors in the region Erzgebirge and Sächsisches Granulitgebirge (from Krawzyk et al., 2000, Fig.6; Prodehl and Mooney, 2012, Fig. 9.2.2-03).

The seismic-refraction project involved a 260 km long NE-SW profile and a 90 km long cross profile in NW-SE direction, using 140 recording stations (**Fig. 10-03** to **Fig. 10-05**) and two deployments. In the first deployment stations were installed along the short cross line 95A, running from Leipzig to the Czech border, and along the perpendicular line around the crossing point (part of line 95B), and 4 borehole shots along the cross profile were recorded. In the second deployment each second station of the cross profile was removed and shifted to the main NW-SE line 95B, which extended over a length of 260 km from north of Dresden, Saxony, to Bamberg, Bavaria, and 8 shots, more or less equally spaced along the NE-SW line, were recorded.



Fig. 10-03: GFZ-stations before the field project. **Fig. 10-04** and **Fig. 10-05:** Training of field personnel.

In the framework of DEKORP, in addition two short reflection profiles (lines 9501 and 9502 in **Fig. 10-01**) were organized and funded which ran perpendicular to the main seismic refraction line 95B, one crossed the center of the metamorphic core complex, the other one crossed the main line further southwest. The project also involved magnetotelluric measurements.

The largest basement velocities (up to 6.5 km/s) were not found underneath the Saxonian Granulite Mountains, but were found at 4-5 km depth shifted by 70 km towards southwest. Also, southwest of the region with exposed granulites, a highly reflective zone at 1.5 s TWT beneath the reflection lines corresponded well with the top of the high-velocity zone at about 4 km depth under the main refraction line. In this region high velocities of 6.5-6.6.km/s were also seen at 15-17 km depth (Enderle, 1998; Enderle et al., 1998a, b; DEKORP and OROGENIC PROCESSES Working Groups, 1999; Krawczyk et al., 2000). A lower crust with 7 km/s between 24 and 30 km depth could be well established. **Fig. 10-02** gives a composite picture of seismic reflection boundaries, magnetotelluric anomalies, and Bouguer gravity, **Fig. 10-06** shows the detailed seismic-refraction model of Enderle (1998).

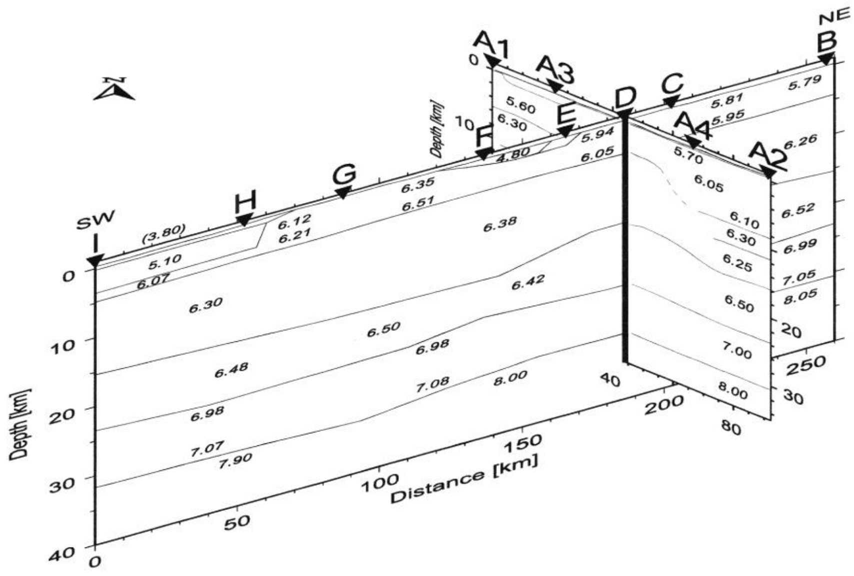


Fig. 10-06: 3D-model of the seismic-refraction project GRANU-95 (from Enderle, 1998, Fig. 2.28; Prodehl and Mooney, 2012, Fig. 9.2.2-02).

11. U.S. – European projects in North America

11-1. Ties of the Geophysical Institute Karlsruhe to North American institutions

Strong ties to North American institutions existed since the very beginning of the Institute. Having obtained his diploma and Ph.D. degrees at Stuttgart, Stephan Mueller had spent some time at the Lamont Geological Observatory at Palisades, New York, and had obtained a Master's degree from the Columbia University. Furthermore he, as well as Karl Fuchs, before coming to Karlsruhe, had spent some time at the Southwest Center for Advanced Studies at Dallas, Texas, where both worked closely together with Mark Landisman (Fuchs and Landisman, 1966a, b; Fuchs et al., 1967; Mueller and Landisman, 1965, 1966; Landisman and Mueller, 1966; Landisman et al., 1976). Vice versa, Leon Knopoff from U.C.L.A. (University of California at Los Angeles) was one of the first guest scientists who spent his sabbatical at the Karlsruhe Geophysical Institute in the mid-1960s (Knopoff et al., 1966; Seidl et al., 1966, 1970a; Berry et al., 1967, 1968). Furthermore Mark Landisman came for longer periods to Karlsruhe. Claus Prodehl, on recommendation of Stephan Mueller, had spent two years at the Seismological Branch of the U.S. Geological Survey at Menlo Park, California (Prodehl, 1970a, b, 1971, 1976, 1979), before he became a member of the Institute in 1969. Mike Berry and Karl Fuchs vice versa spent sabbaticals at Karlsruhe resp. at Ottawa, Canada (Berry and Fuchs, 1973). In 1971, 1973 and 1976 Claus Prodehl spent several weeks at the U.S. Geological Survey at Menlo Park and continued his research of the late 1960s (Prodehl, 1977; Prodehl and Pakiser, 1980). His data collection on U.S. Geological Survey investigations in the Rocky Mountains / Great Plains and the Appalachians served also for some diploma theses (Haggag, 1974; Schlittenhardt, 1979; Prodehl et al., 1984) and, following Bamford's P_n-studies (Bamford, 1973), for a worldwide anisotropy investigation (Bamford et al., 1979), and he arranged a research visit of Peter Blümling to Menlo Park to interpret jointly near-earthquake and refraction data in terms of crustal structure beneath the San Andreas fault system south of San Francisco (Blümling and Prodehl, 1983). Vice versa, Walter Mooney from the University of Wisconsin spent half a year at Karlsruhe to interpret pre-1979 seismic-refraction data recorded in the area of the Rhenish Massif (subchapter 4-6 and Welcome Address, this volume; Mooney and Prodehl, 1978).

The close contact of Karlsruhe and Zurich scientists to North American scientists finally led to a cooperation in the Yellowstone Park – eastern Snake River experiments of 1978 and 1980 (subchapter 11-2), where MARS-equipment supplied by Karlsruhe and Zurich played a fundamental role in the success of the fieldwork. Furthermore, the development of the U.S.G.S. cassette recorder system (Murphy, 1988) by J.H. Healy at Menlo Park, California, and its successful test in the field in 1978 in Saudi Arabia under most severe field conditions had been strongly influenced by Jack Healy's close connection to Claus Prodehl and his visits to Europe where he had seen the successful story of the MARS-66 equipment. The cooperation continued when Walter Mooney was employed by the U.S. Geological Survey at Menlo Park, California, and became responsible for the seismic refraction operations of the seismology branch (see, e.g., subchapter 8-4, Mooney and Prodehl, 1984). For example, in the 1980s Jay Zucca and Steve Holbrook came as visiting scientists to Karlsruhe, Jay Zucca (1984) reworked the 1972 Rhinegraben data, while Steve Holbrook was partly responsible for the interpretation of the "Black Zollernwald" shear wave data (Holbrook et al., 1987, 1988). Based on Claus Prodehl's intensive studies of USGS seismic refraction data (Prodehl, 1979, Prodehl and Pakiser, 1980), in 1987 Lou Pakiser and Walter Mooney (U.S.G.S.) invited him to write the Chapter on the Rocky Mountains ((Prodehl and Lipman, 1989) in their summary volume "Geophysical Framework of the Continental United States" (Pakiser and Mooney, 1989).

In the late 1980s and 1990s several Karlsruhe students and scientists joined North American field projects to become acquainted with the US seismic equipment. The cooperation reached its peak in the following joint KRISP projects in Kenya (subchapter 9) and also enabled a seismic-refraction project in the Central Massif of France in 1993 (subchapter 3-7) at times when modern German equipment was not yet available. Similar, the success of the large-scale seismic-refraction project VRANCEA-2001 (subchapter 12-2) was enabled by the joint use of German and US recording equipment. Vice versa, German funding and equipment helped substantially to support the two 1999 North American projects CD-ROM (subchapter 11-3**,** e.g., Rumpel, 2003; Prodehl et al., 2005; Rumpel et al., 2005) and LARSE-II (subchapter 11-4, Fuis et al., 2003; Lutter et al., 2004). Finally, on the basis of their long-year cooperation, Walter Mooney and Claus Prodehl compiled summaries on explosion seismic studies around the world (Mooney et al., 2002; Prodehl and Mooney, 2012).

11-2. North American – European project: Yellowstone Park – Snake River Plain

Following a request by Bob Smith of the University of Utah, USA, in 1978 and 1980 Karlsruhe and Zürich participated on two projects to study the crustal structure beneath the

Yellowstone Park and the adjacent Eastern Snake River Plain (**Fig. 11-01**). It was a joint project of Bob Smith of the University of Utah in Salt Lake City and Larry Braile of the Purdue University in Indiana. Except for the U.S. Geological Survey, in the 1960s and 1970s in the United States little interest had been shown on crustal structure research and subsequently modern instrumentation had neither been developed nor purchased. For major crustal projects therefore equipment was not available. Various universities owned only small numbers on mobile seismic stations for long-term temporary recordings of earthquakes.

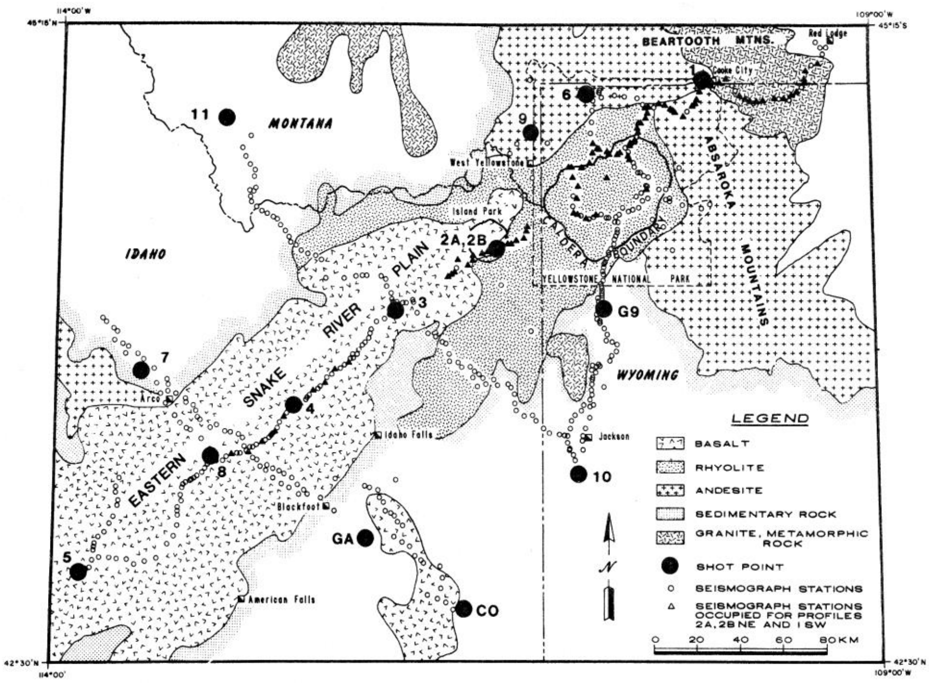


Fig. 11-01: 1978-80 seismic refraction observations in the Yellowstone – Snake River plain (from Braile et al., 1982, Fig. 1; Prodehl and Mooney, 2012, Fig. 7.4.1-03).

The European participation was organized by Stephan Mueller and Jörg Ansorge from Zurich and Claus Prodehl from Karlsruhe. Other Karlsruhe participants in the field were Martin Jentsch and Manfred Rittershofer. In total 20 MARS stations were shipped from Europe by air to Chicago and then transported by our American colleagues by trucks to Salt Lake City. During the field work of 1978 shots and stations were distributed spatially throughout the Yellowstone Park (**Fig. 11-02**), while in the Eastern Snake River Plain shots and stations (**Fig. 11-03**) were arranged along a long-range profile (**Fig. 11-01**).

In total fifteen shots were recorded that provided coverage to distances of 300 km (**Fig. 11-01**). Except for a few mishappenings the project could be carried out as planned, even a sudden snow storm did not cause any delays, which brought the traffic to a complete still stand, but transformed the Yellowstone Park into a white dream world with steam clouds here and there arising from the geysers.

In 1980 the data of 1978 were supplemented (**Fig. 11-04** and **Fig. 11-05**). The MARS stations were flown by helicopter into inaccessible areas of the Yellowstone Park, other stations were carried by horses.

Fig. 11-02: MARS 66 in snow-covered Yellowstone Park, September 1978.

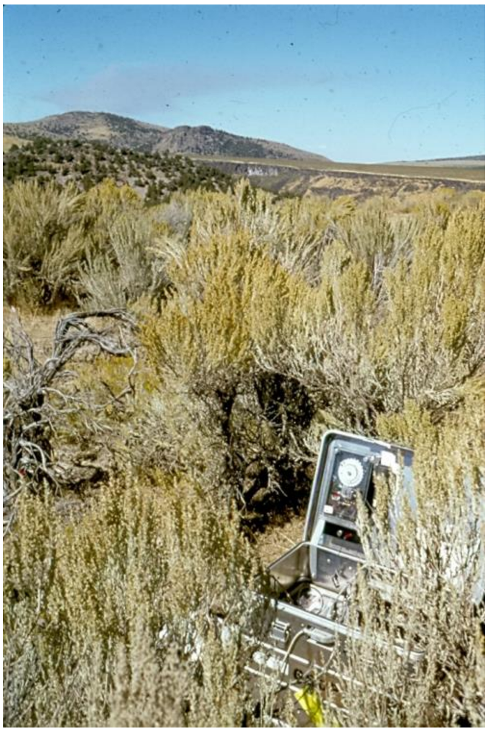


Fig. 11-03: Snake River Plain lava field.

Fig. 11-04 Y-SRP 1980 Project: Equipment test.

Fig. 11-05: Waiting for test shot at Fish Creek Reservoir.

Due to the complexity of recording stations the data preparation was a difficult task and was coordinated and carried out at Karlsruhe by Werner Kaminski. Most of the data showed extremely clear wide-angle reflections, both in the eastern Snake River Plain and in the Yellowstone Park area. The interpretation showed for the upper 10 km of the crust strong lateral heterogeneities, probably reflecting the effects of a major lithospheric anomaly, which is evidenced by large volumes of volcanic rocks, and the systematic progression of the silicic volcanism along the eastern Snake River Plain to its present position beneath Yellowstone. The intermediate and lower crustal layers proved to be more homogeneous, and the total crustal thickness underneath the Island Park – Yellowstone Plateau – Beartooth Mountains was about 43 km, which increased slightly into the Snake River Plain to the southwest (**Fig. 11-06**). The results were published by several papers in Journal of Geophysical Research (Braile et al., 1982; Smith et al., 1982).

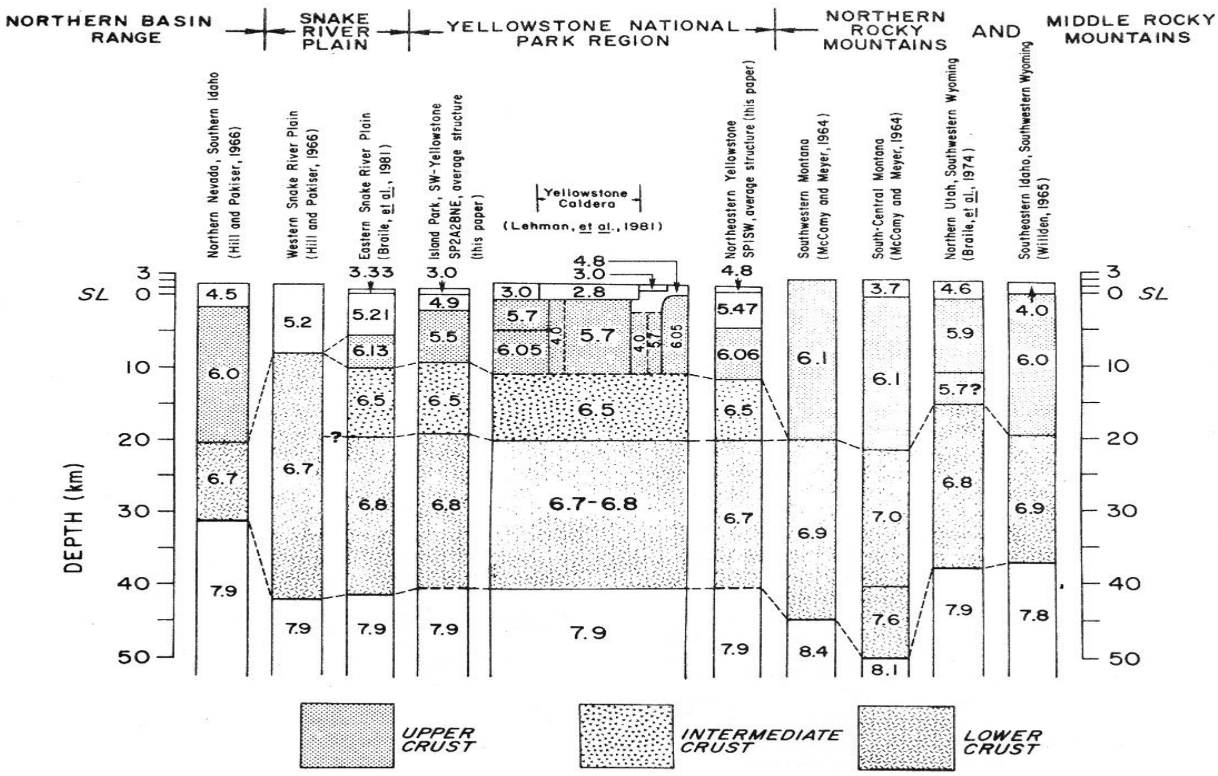


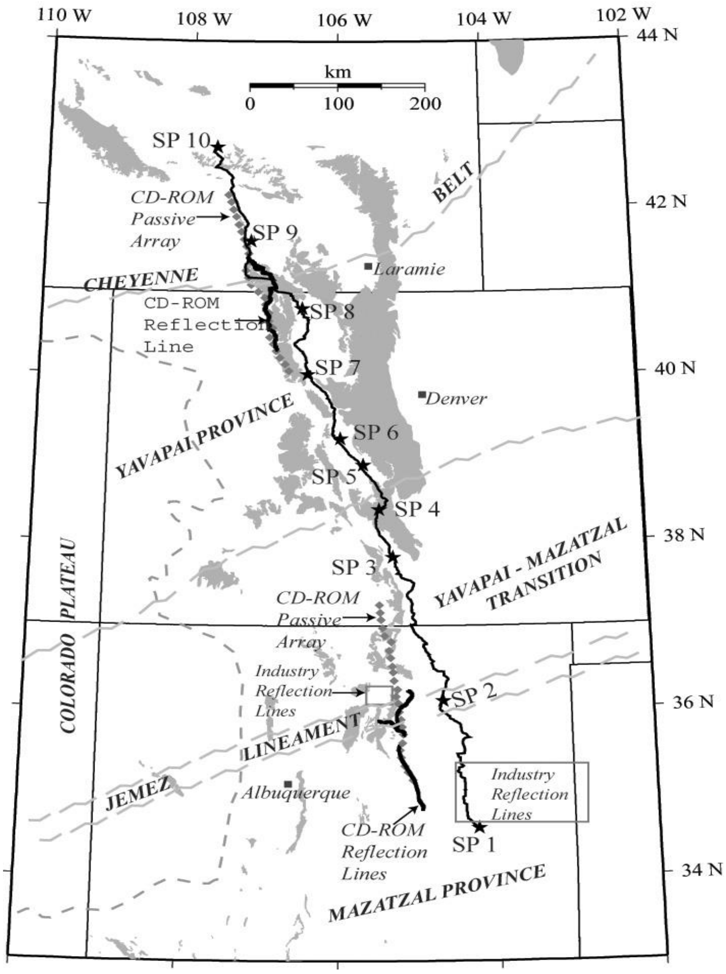
Fig. 11-06: Generalized P wave crustal model for the Yellowstone – Snake River plain survey (from Smith et al., 1982, Fig. 8; Prodehl and Mooney, 2012, Fig. 7.4.1-06).

11-3. Seismic-refraction profiling in the Southern Rocky Mountains (CD-ROM)

In spite of great geologic interest and abundant natural resources, relatively little was known about the crust and upper mantle structure of the Rocky Mountains until the 1990s. Summaries of early surveys, all prior to 1980, had been published in 1989 (e.g., Prodehl and Lipman, 1989). It was only in the 1990s, that three major seismic projects were undertaken (for details see Prodehl and Mooney, 2012), one of them being CD-ROM with a seismic-refraction program which involved Karlsruhe as partner.

In 1995 fourteen U.S. universities jointly created the interdisciplinary research project CD-ROM (Continental Dynamics – Rocky Mountains) with the aim to study crust and upper mantle of the Southern Rocky Mountains along a 1000 km long Geotraverse extending from Wyoming to New Mexico (**Fig. 11-07**). Its main aim was to study the Proterozoic assembly of southwestern North America which has been overprinted by Phanerozoic orogenic processes such as the Ancestral Rocky Mountain orogeny, the Laramide orogeny, and the formation of the Rio Grande rift. Involved were tectonics, structural geology, regional geophysics, geochemistry, geochronology, xenolith studies, seismology and active seismics (Karlstrom, 1998, 1999, Karlstrom and Keller, 2005). Following a first workshop in 1995, the project was funded from 1997 to 2002 by the National Science Foundation. The seismic investigations in particular comprised passive-source seismic studies and two active-source experiments, consisting of seismic reflection profiling and a 950 km long seismic refraction profile (Karlstrom and Keller, 2005).

In July 1997 Claus Prodehl was informed by Randy Keller, that another workshop was planned at Laramie, Wyoming, for the beginning of August 1997 in order to discuss the state of knowledge (e.g., Prodehl et al., 2005), and plan for details of large-scale teleseismic as well as seismic-refraction and -reflection campaigns. Accidentally the date of the workshop coincided with the first days of a vaccation trip of Claus Prodehl to the western U.S.A. enabling his participation on that workshop. During the workshop it turned out that the available funding resources did not allow a complete coverage of the refraction line by steep-angle reflection seismics. Therefore it was decided to limit the seismic-reflection campaign on two separate lines in the northern and the southern part of the Geotraverse. Subsequently Claus Prodehl wrote a research application to the German Research Society to support the seismic CD-ROM part by funding the participation of Karlsruhe with personnel (salary for a Ph.D. student and travel costs) and contribution to the shotpoints. The goal was to increase the number of shotpoints as well as the number of recording sites in the central 550 km long section (**Fig. 11-07** and **Fig. 11-09**) which was not covered by reflection seismics.



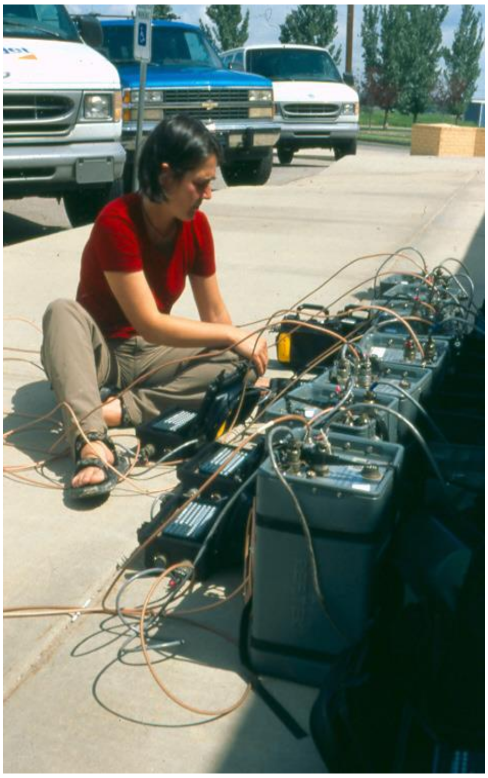


Fig. 11-07: Seismic profiles in the Southern Rocky Mountains (from Rumpel et al., 2005, Fig.1; Prodehl and Mooney, 2012, Fig. 9.4.2-27).

Fig. 11-08: Bärbel Traub testing PASSCAL-RefTeks for CD-ROM-99 fieldwork.

The seismic-refraction project was carried out in July 1999. In total 600 seismic recording stations were available: 450 Texans, (RefTek-1-componente stations which had been developed in cooperation of UTEP (University of Texas at El Paso) and the company RefTek, and 150 3-component RefTeks of the PASSCAL equipment pool at Socorro, New Mexico (**Fig. 11-08** and **Fig. 11-10**).

For the preparation of the logistics of the 950 km long seismic-refraction profile, Hanna-Maria Rumpel of Karlsruhe spent several months before the field experiment at El Paso where she, together with Cathy Snelson, worked on the detailed planning, explored location of shotpoints and recording sites in advance in the field, and prepared the necessary paper work for the field crews. It was decided to occupy the southern and northern sections, which were also to be covered by steep-angle reflection measurements, by crews of El Paso with 450 one-component „Texans“, resulting in an 800 m mean station interval and two deployments, the first one for the southern, the second one for the northern section. For the central part the Karlsruhe personnel was responsible, equipped with 150 three-component stations supplied by PASSCAL at Socorro. During the first deployment every second site was occupied, resulting in a station interval of 1600 m, in the second deployment the stations were moved into the gaps so that in the end also for the central part a station interval of 800 m resulted. At the shotpoints at the outer ends of the 950 km long line shots were fired twice, also at all shotpoints at the ends and within the central section. To handle the logistics of the 550 km long central section a local headquarter was installed at Cañon City, Colorado. Here also technical personnel of PASSCAL were located under the supervision of Marcos Alvarez. From Karlsruhe the following participants were in the field: Franz Hauser, Sonja Hofmann, Alexander Gerst, Philipp Heidinger, Uli Micksch, Werner und Ange Kaminski, Claus und Sieglinde Prodehl, Hanna-Maria Rumpel, Barbara Schechinger, Bärbel Traub, and Andreas Wüstefeld. They formed 10 observer teams, each being responsible for 15 RefTek stations. Except for two the German observers were accompanied by a local partner from El Paso.

Fig. 11-09 Rocky Mountains near Denver.

Fig. 11-10: RefTek 3-component-station.

The seismic-reflection campaigns of the southern and northern sections were planned independent from the seismic-refraction work and were executed at a later time.

The data preparation was jointly carried out by Cathy Snelson and Hanna-Maria Rumpel at El Paso. The interpretation was accomplished jointly in parts, but also individual, being for both scientists part of their Ph.D. thesis work at El Paso (Cathy Snelson, 2001) and at Karlsruhe (Hanna-Maria Rumpel, 2003). For the following book publication the tasks were officially subdivided into upper – middle crust and lower crust – upper mantle (Continental Dynamics of the Rocky Mountains Working Group, 2002; Karlstrom et al., 2005; Keller et al., 2005; Prodehl et al., 2005; Rumpel et al., 2005; Snelson et al., 2005).

Crustal thickness varied substantially along the entire line (**Fig. 11-11**). Moho depth is near 50 km at the northern end, increases gradually towards the south and reaches a maximum depth of about 57 km underneath the North and South Parks east of the Front Range in central Colorado, where the Colorado Mineral belt traverses the Southern Rocky Mountains. A local Moho high of about 50 km was interpreted under the Wet Mountains, followed by a crustal thickness increase of about 5 km around shotpoint 3 where the line enters the Great Plains. Southwards from here Moho depth decreases gradually to near 40 km depth at the southern end of the line.

While the northern and southern sections which included seismic-reflection investigations concentrated on the two major suture zones of the Proterozoic assembly of southwestern North America, the Cheyenne belt in southern Wyoming / northern Colorado and the Jemez lineament in north-central New Mexico, the central Proterozoic boundary, coinciding with the present-day Colorado Mineral belt, had been covered by the more densely recorded central section of the seismic-refraction profile (**Fig. 11-07**).

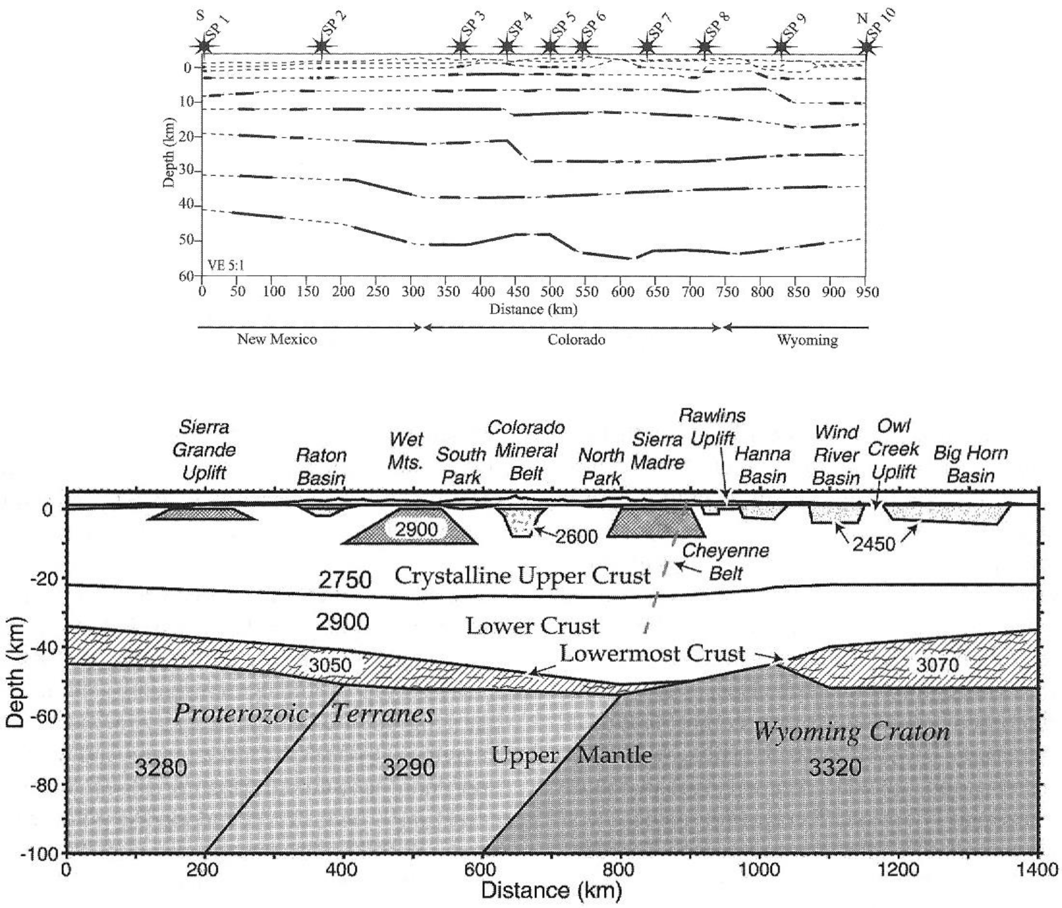


Fig. 11-11: Interpretation of the CD-ROM seismic-refraction data (from Snelson et al., 2005, Fig. 11c and Fig.12d; Prodehl and Mooney, 2012, Fig. 9.4.2-29). **Top:** Model based on first arrivals and wide-angle reflections (from Snelson et al., 2005, Fig. 11c). **Bottom:** 2.5-D density model along the CD-ROM transect. The distance scale corresponds to that of the seismic model (from Snelson et al., 2005, Fig.12d).

11-4. LARSE II (Los Angeles Regional Seismic Experiment)

In the framework of the priority program „ICDP" of the German Research Society, in 1997 Claus Prodehl and Trond Ryberg had applied for a participation on U.S. projects investigating the surroundings of the San Andreas fault zone with seismic-refraction experiments both at Los Angeles (LARSE) and in the Parkfield – Cholame section. For logistic reasons the projects were later separated. Trond Ryberg had already been involved in the interpretation of the seismic-refraction data of project LARSE I (Los Angeles Region Seismic Experiment), which had extended from the Pacific Ocean through the Los Angeles basin and the San Gabriel Mountains into the Mojave desert and had been carried out in 1994 (e.g., Ryberg and Fuis, 1998). Following the Northridge event of 1994, another detailed land survey (LARSE II) was added further to the west in 1999 (line 2 in **Fig. 11-12**).

The field work on LARSE II was carried out in October 1999. The line started at Santa Monica, crossed the Santa Monica Mountains and the San Fernando Valley, which had been the center of two large earthquakes of 1971 and 1994, traversed the Santa Susanna Mountains and the Transverse Range and ended in the western Mojave Desert. In total 93 boreholes of differing depth ranges had been drilled and loaded with charges between 2.5 and 2000 kg, depending on the local conditions, which ranged from school yards or city parks within densely populated city areas to lonely desert locations. A large number of participating institutions with a total of 57 participants enabled the installation of 1385 seismic stations, using five different types of equipment (**Fig. 11-13**). One-and three-component stations were distributed such that along the 150 km long line a station separation of 100 m was obtained. Only at the northern end in the Mojave Desert the station separation was successively increased.

Fig. 11-12: Location of LARSE I (1991) and II (1999) (Fuis et al., 2003, Fig. 1; Prodehl and Mooney, 2012, Fig. 9.4.2-19).

Fig. 11-13 More than 1000 recording stations waiting in a deserted Supermarket hall.

The German crews of Karlsruhe / Potsdam were responsible for the coverage of the northernmost section in the Susanna Mountains and the Mojave Desert. This area was crossed by the San Andreas Fault, but offered a very difficult terrain due to its steep topography (**Fig. 11-14** to **Fig. 11-18**)

As the location of seismometers should follow a rather strict straight line, the flexible 6-channel stations of GFZ Potsdam were best suited, because cables and seismometers could be carried and laid out across steep hills and valleys which could not be managed by any car, and such fulfilling the requirement of seismometer separations of 100 m. Only the central station had to be along an accessible road. Participants in the field were Julia Bartlakowski, Steffen Bergler, Franz Hauser, Ingo Koglin, Claus Prodehl, and Jochen Woessner from Karlsruhe and Karl Otto, Trond Ryberg, Albrecht Schulze, and Michael Weber from Potsdam.

Fig. 11-14 and **Fig. 11-15:** GFZ-6-channel stations with 6 vertical seismometers being connected to the central station by long cables are being deployed in difficult terrain in the Susanna Mountains north of Los Angeles.

Fig. 11-16 to **Fig. 11-18:** GFZ-6-channel stations at LARSE II north of Los Angeles and in the Mojave Desert.

The data interpretation was primarily coordinated by Gary Fuis and Trond Ryberg (Fuis et al., 2003; Ryberg et al., 2004). Tomographic modeling of the first arrival data of line 2 (Lutter et al., 2004) produced a similar model for line 2 as for line 1. Along line 2 prominent zones of dipping reflectors, which were superimposed onto the tomographic model, could be correlated. The most prominent feature is a north-dipping reflective zone which extends downward from near the hypocenter of the 1971 San Fernando earthquake at about 13 km depth (brown circle in **Fig. 11-19**) to about 30 km depth in the vicinity of the San Andreas fault in the central Transverse Ranges. A fainter south-dipping reflective zone extends from the 1994 Northridge hypocenter at about 16 km depth (blue circle in **Fig. 11-19**) to 20 km depth beneath the Santa Monica Mountains. These reflective bands could be correlated with aftershock series of the 1971 San Fernando and the 1994 Northridge earthquakes (brown and blue dots, respectively, in **Fig. 11-19**), which were projected from a zone 10 km east of line 2 (Fuis et al., 2001, 2003; Ryberg et al., 2004).

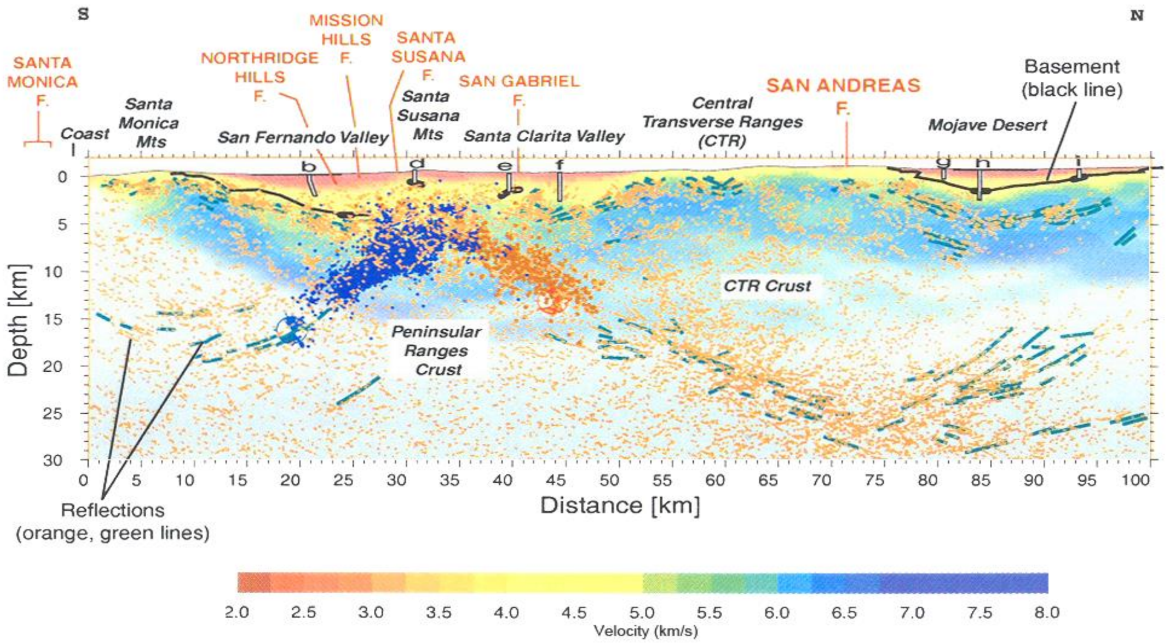


Fig. 11-19: Tomographic velocity model and superimposed line drawings of CMP data along LARSE line 2 (from Ryberg et al., 2004, Fig. 11; Prodehl and Mooney, 2012, Fig. 9.4.2-22). Internal report, based on Fuis et al. (2001, 2003).

11-5. Upper crustal seismic profile at SAFOD, central California

The Parkfield project mentioned above which had been separated from the LARSE-II project subsequently was followed up further by Trond Ryberg. In the framework of the SAFOD drillhole (San Andreas Fault Observatory at Depth) into the San Andreas fault near Parkfield, California (a tiny place with a population of 37 located in scarcely inhabited farm land half way between Los Angeles und San Francisco), in 2003 a 46 km long profile could be recorded (**Fig. 11-21,** Ryberg et al., 2005) with 62 shots (0.5-1.0 km separation) and 912 seismometers with 25-50 m separation.

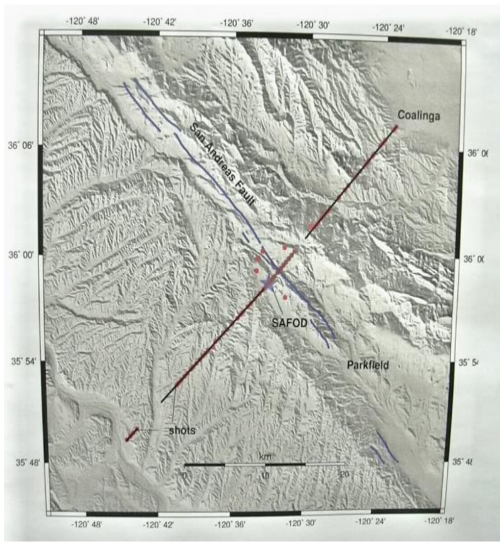


Fig. 11-20: Parkfield, center of several M=8 earthquakes.

Fig. 11-21: SADOD seismic line (from Ryberg et al., 2005).

12. Seismic crustal investigations in the Carpathians of Romania (Vrancea)

The Vrancea Zone at the southeastern edge of the Romanian Carpathians is characterized by the occurrence of unusually deep and strong earthquakes (**Fig. 12-01**). Seismic-refraction studies and a large-scale tomography study of southeastern Romania were part of an interdisciplinary research program, carried out by the Collaborative Research Center 461 (CRC 461) "Strong Earthquakes - a Challenge for Geosciences and Civil Engineering" at the University of Karlsruhe (Germany) and the Romanian Group for Vrancea Strong Earthquakes (RGVE) at the Romanian Academy in Bucharest (e.g., Wenzel, 1997; Wenzel et al., 1998, 1999; Sperner et al., 2001, 2004; Ritter et al., 2005).

A major teleseismic project was undertaken in 1999, when continuously recording stations were distributed throughout Carpathians and foreland of southeastern Romania (Martin et al., 2005, 2006; for more details see Chapters 7 and 9-3-1).

Two major active-source seismic refraction experiments were carried out in the eastern Carpathians of Romania in 1999 and 2001 (**Fig. 12-01**) as a contribution to this research program (Prodehl et al., 2000; Hauser et al., 2001, 2007). They were designed to study the crustal and uppermost mantle structure to a depth of about 70 km underneath the Vrancea epicentral region and were jointly performed by the Geophysical and Geological Institutes of the University of Karlsruhe (Germany), the National Institute for Earth Physics in Bucharest (Romania) and the University of Bucharest (Romania).

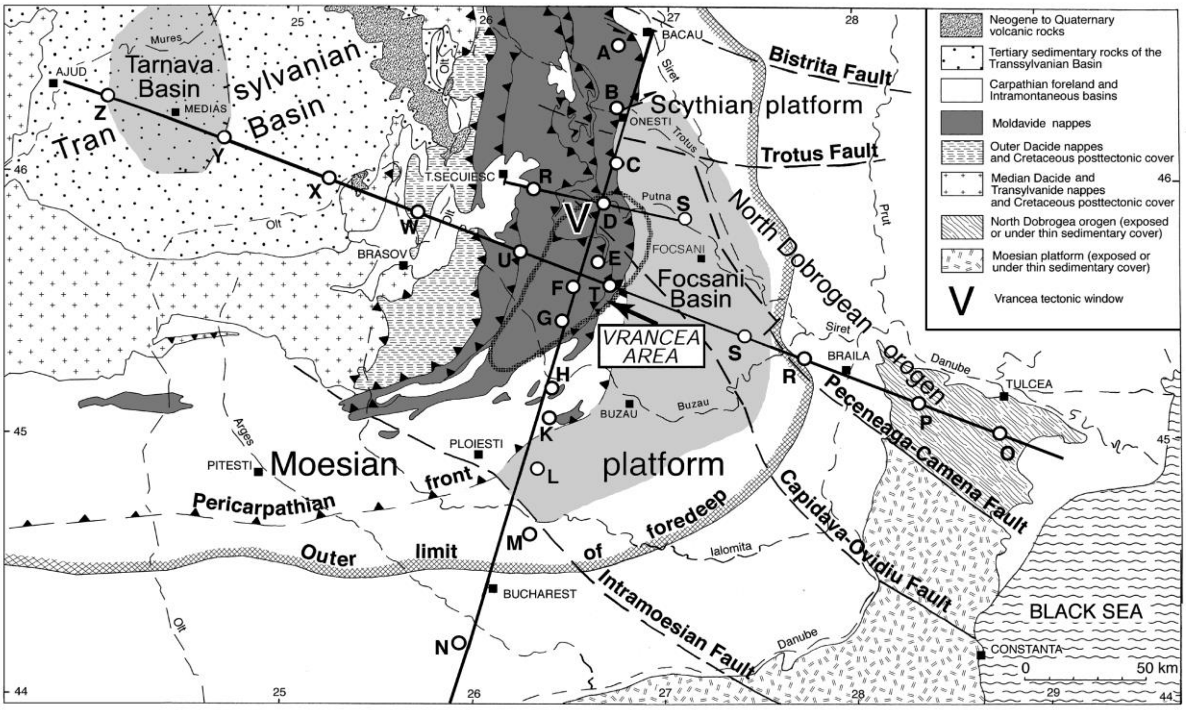


Fig. 12-01: Location map of seismic-refraction VRANCEA profiles 1999 (N-S line) and 2001 (W-E line) through the seismogenic Vrancea zone in the eastern Carpathians of Romania (from Hauser et al., 2002; Prodehl and Mooney, 2012, Fig. 9.2.4-11). V = Vrancea seismogenic zone with strong intermediate-depth earthquakes between 70 and 160 km depth.

12-1. VRANCEA-1999

Planning for the first profile through the Vrancea zone started in 1996, it was realized in 1999. It was 300 km long line and ran from Bacau in the eastern Carpathians to the Bulgarian border south of Bucharest traversing the Vrancea epicentral region in NNE – SSW direction (**Fig. 12-01**). The Romanian partner was Victor Raileanu at the National Institute for Earth Physics at Bucharest. Both for the preparation of necessary permits and the execution of shots the company Prospectiuni was hired. However, all shotpoint sites had to be located in advance by the responsible scientists. For security reasons also for each recording site a cellar or shed on a guarded property had to be found in advance requiring several one- to two-week field excursions by the organizers.

In May 1999 the preparations were ready and the field work could start. 130 recording stations and ten shot sites were placed along the main north-south profile. Simultaneously ten stations and two shot sites were occupied along a short perpendicular profile along the east-west running Putna valley. In total borehole explosions with charges of 300 and 900 kg were carried out at 7 shotpoints in the Carpathians and 5 shotpoints in the Romanian plain between Danube and Carpathians. The spacing of shotpoints ranged from 12 - 30 km, with an average of 22 km. Mean station interval was 2 km. The major part of the equipment came from GFZ Potsdam, additional equipment including personnel from the University of Leicester. From Karlsruhe ten participants were in the field: Sandra Bourguignon, Alex Goertz, Franz Hauser, Philipp Heidinger, Christoph Jäger, Ingo Koglin, Claus Prodehl, Hannes Raue, Hanna-Maria Rumpel, and Christian Weidle (Hauser et al., 2000, 2001, 2002; Raileanu et al., 2004, 2005).

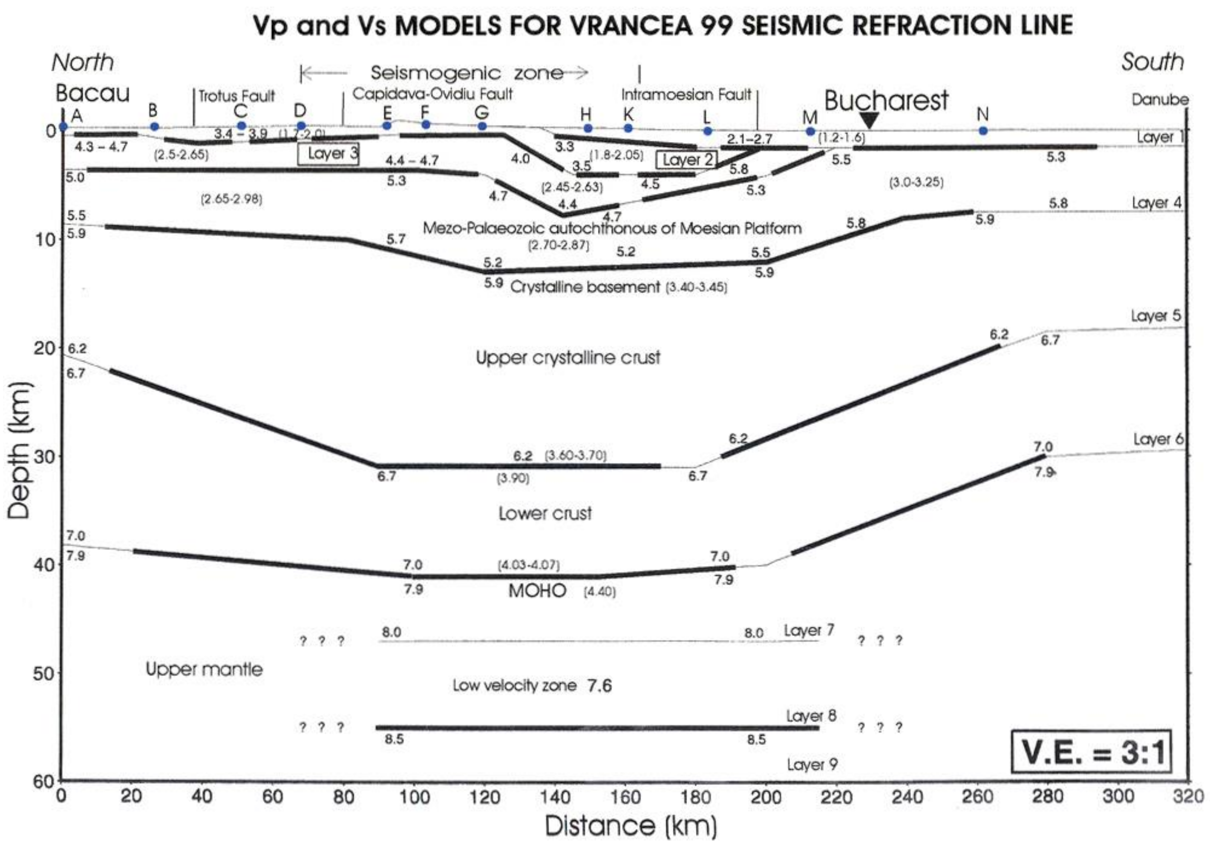


Fig. 12-02: Crustal P-wave cross section along the north-south profile VRANCEA 1999 (from Hauser et al., 2001, Fig. 9; Prodehl and Mooney, 2012, Fig. 9.2.4-13). Velocities in brackets are corresponding S-velocities.

Data and other technical details were compiled in a data report (Hauser et al., 2000; see also Appendix A9-1-5 of Prodehl and Mooney, 2012). Franz Hauser and Victor Raileanu were the principal investigators for the interpretation of the seismic refraction P-wave data (Hauser et al., 2001; Raileanu et al., 2004) and have also investigated the S-waves (Raileanu et al., 2005).

The P-wave interpretation (**Fig. 12-02**) showed up to 10 km thick sedimentary sequences. Both the sedimentary and crystalline upper-crustal layers appeared to thicken underneath the seismogenic Vrancea zone and the adjacent southern margin of the Carpathians. As a result, the intra-crustal discontinuity varies strongly in depth, between 18 km at both ends of the line and 31 km at its center. Strong wide-angle P_MP reflections indicated the existence of a first-order Moho, the depth of which also varies from 30 km near the southern end of the line to 41 km near the center and to 39 km near the northern end. Within the uppermost mantle a low velocity zone was interpreted from a reflection, named P_LP, which defined the bottom of this low velocity layer at a depth of 55 km (Hauser et al., 2001; Raileanu et al., 2004). The data also showed reasonable appearance of S-waves, which were incorporated into the P-wave model (corresponding velocities are shown in brackets in **Fig. 12-02**), and Poisson's ratios were calculated for the individual crustal layers (Raileanu et al., 2004, 2005). **Fig. 12-03** presents the interpreted geological section underlain by the intermediate depth earthquakes of the Vrancea zone after Oncescu et al. (1999) projected onto this cross section.

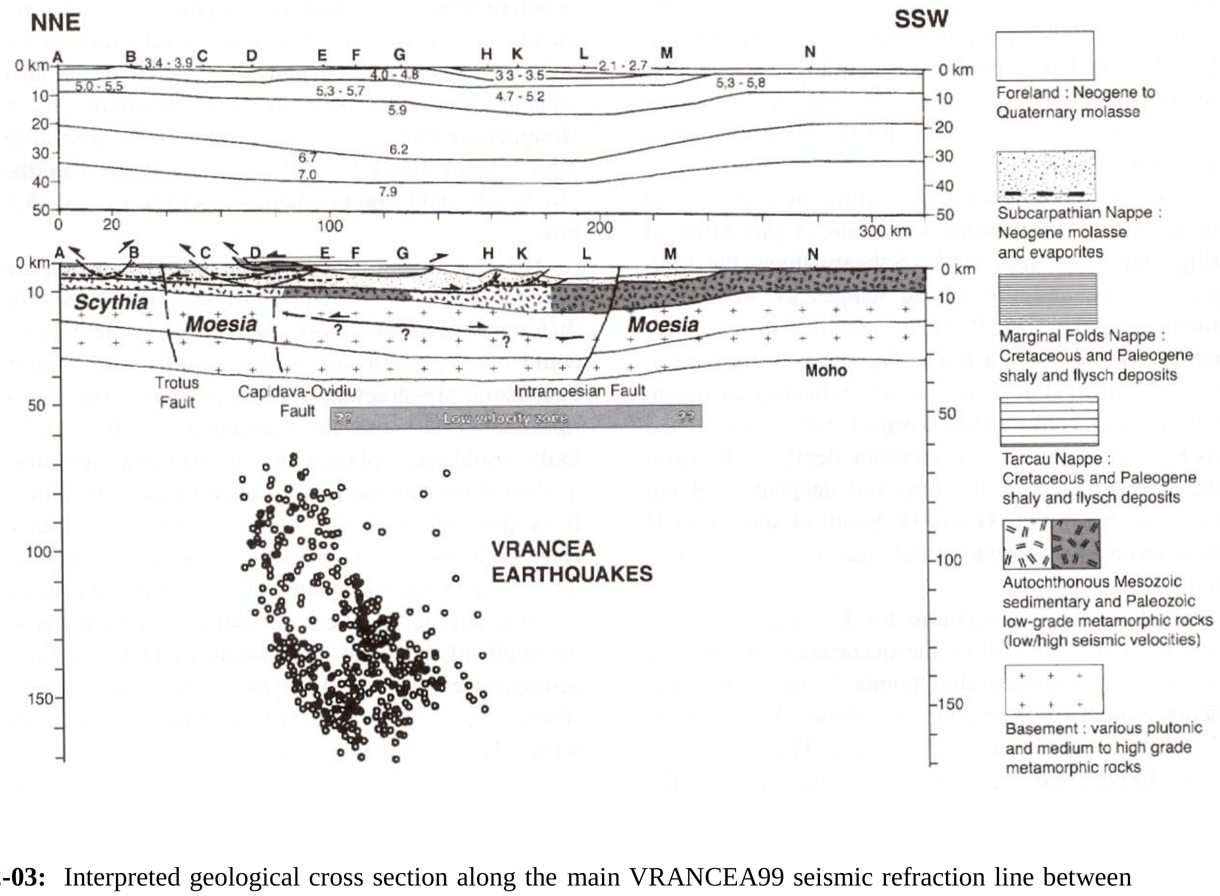


Fig. 12-03: Interpreted geological cross section along the main VRANCEA99 seismic refraction line between Bacau and Bucharest (from Hauser et al., 2001, Fig. 10). Circles represent the foci of the intermediate depth earthquakes of the Vrancea zone after Oncescu et al. (1999) projected into this cross section.

12-2. VRANCEA-2001

Funding for a second seismic-refraction field campaign was included in the application of the Collaborative Research Center 461 (CRC 461) "Strong Earthquakes - a Challenge for Geosciences and Civil Engineering" at the University of Karlsruhe for 2000-2002 which was proved and acknowledged in March 1999, before the field work of May 1999 had been carried out. VRANCEA-2001 was a 700 km long WNW – ESE trending seismic refraction line in Romania with a short extension into Hungary (Hauser et al., 2002, 2007). The main, 450 km long, part started near Ajud in western Transylvania, crossed Transylvania, Carpathians and Focsani-foreland and ended in the North Dobrogea Mountains bordering the Black Sea, hereby crossing the VRANCEA-1999 profile within the Vrancea-Zone in WNW-ESE direction (**Fig. 12-01**).

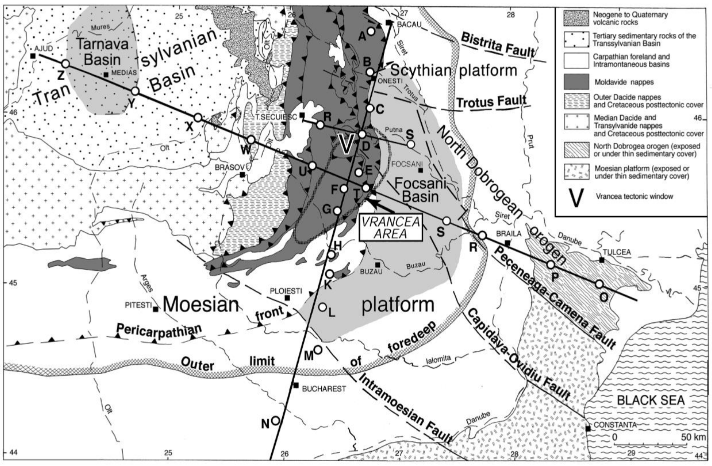


Fig. 12-04: Location of the seismic-refraction lines VRANCEA 1999 + 2001.

Fig. 12-05: Hanna-Maria Rumpel recording a shot instant.

Fig. 12-06: Shotpoint investigation in the Carpathians.

Fig. 12-07: Shotpoint investigation in the Foreland.

The experiment was jointly performed by research institutes and universities of Germany, Romania, the Netherlands and the United States. They included the University of Karlsruhe and the GeoForschungsZentrum Potsdam, Germany, the Free University of Amsterdam, Netherlands, the National Institute for Earth Physics and the University of Bucharest, Romania, and the Universities of El Paso and South Carolina, USA.

The project was enabled by recruiting a total of 790 seismic recording stations, provided by the equipment pools of GFZ Potsdam (3-component REFTEK and PDAS stations) and by the University of El Paso and PASSCAL, USA (TEXAN 1-component stations **Fig. 12-08** and **Fig. 12-09**). Of these stations the small 640 one-component geophones (Texan type) were mostly deployed in the open field outside of localities, while, for safety reasons, the 150 three-components geophones (REFTEK and PDAS type) were deployed in guarded properties within towns and villages.

Fig. 12-08: Equipment: 15 „Texans" in a box for transportation.

Fig. 12-09: „Texan" – RefTek-1-component station.

Fig. 12-10: 70 VRANCEA-2001 participants from Germany, Netherland, USA, and Romania.

The project was carried out in August and September 2001 (Hauser et al., 2002, 2007). Ten large drill hole shots with 300 - 1500 kg charges (O to Z in **Fig. 12-01** and **Fig. 12-04**) were fired in Romania between the town of Aiud at the western margin of the Transylvanian Basin and the Black Sea (**Fig. 12-05** to **Fig. 12-07**) which resulted in an average shotpoint spacing of 40 km. To the west an additional shot (500 kg) was fired in Hungary. These shots generated 11 seismogram sections each with almost 800 traces. The spacing of the geophones was variable. It was around 1 km from the Black Sea to Aiud (ca. 450 km length), 6 km from Aiud to Oradea (Romanian-Hungarian border) and about 2 km on the Hungarian territory. Between shotpoints T and U the geophones were deployed at a spacing of 100 m (Landes et al., 2004b; Panea et al., 2005).

In total more than 70 participants were involved in the VRANCEA-2001 fieldwork: its majority coming from Karlsruhe and Bucharest, others came from Potsdam, Amsterdam and El Paso. From Karlsruhe were: Bettina Allmann, Tim Boelsen, David Bribach, Anne Chudziak, Fabian Domes, Frank Eichelhardt, Sabrina Ernst, Manuel Gehrig, Alex Goertz, Franz Hauser, Philipp Heidinger, Ingo Koglin, Michael Landes, Ricardo Maerz, Holger Maier, Martin Maier, Karsten Mueller, Adrien Oth, Ulrike Plattner, Claus Prodehl, Hannes Raue, Teresa Reinwald, Hanna-Maria Rumpel, Andreas Sabellek, Werner Scherer, Rachmat Sule, and Markus von Steht (**Fig. 12-10**).

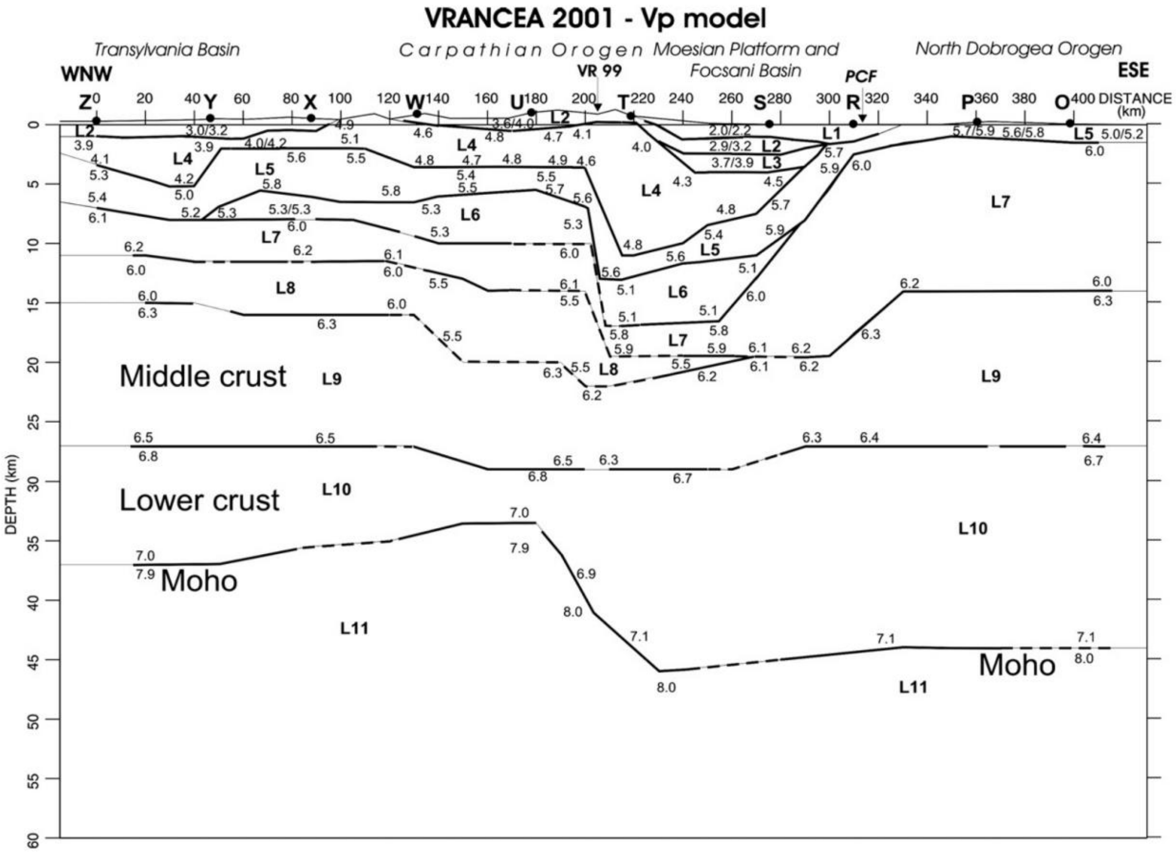


Fig. 12-11: Crustal P-wave cross section of the west-east profile VRANCEA 2001 (from Hauser et al., 2007, Fig. 11; Prodehl and Mooney, 2012, Fig. 9.2.4-15).

The data interpretation for the eastern 450 km long segment indicated a multi-layered structure with variable thicknesses and velocities. The sedimentary stack comprised up to 6 layers (L1-L6 in **Fig. 12-11**) with seismic velocities of 2.0 - 5.9 km/s and reached a maximum thickness of more than 15 km within the Focsani Basin area. The underlying crystalline crust (L7-L10 in **Fig. 12-11**) showed considerable thickness variations in total as well as in its individual subdivisions. The model (**Fig. 12-11**) shows the lateral velocity structure of these blocks along the seismic line which remained almost constant with about 6.0 km/s along the basement top and with 7.0 km/s above the Moho. Under the Transylvanian basin the crust appeared to be 34 km thick with low velocity zones in its uppermost 15 km. Under the Carpathians the Moho deepens to beyond 41 km, reaching 46 km under the Focsani basin. However, the crystalline crust does not exceed 25 km in thickness and is covered by up to 15 km of sedimentary rocks. The North Dobrogea crust reaches a thickness of about 43 km and was interpreted as thick Eastern European crust overthrusted by a thin 1 - 2 km thick wedge of the North Dobrogea Orogen (Hauser et al., 2007).

Landes et al. (2004) have compiled data and other technical details in a data report. (see also data examples in Hauser et al., 2007; Prodehl and Mooney, 2012: Appendix A9-1-5). Franz Hauser and Victor Raileanu were again the principal investigators for the interpretation of the seismic refraction P-wave data (Hauser et al. 2007). The two seismic-refraction campaigns and the teleseismic tomography survey of 1999 (Wenzel et al., 1998; Martin et al., 2005, 2006) produced a wealth of data, concentrating on the Vrancea zone proper and allowed Michael Landes to perform a three-dimensional tomographic interpretation of the crustal data, which results were presented in contour maps at various depth levels (Landes et al., 2004a).

12-3. DACIA-PLAN

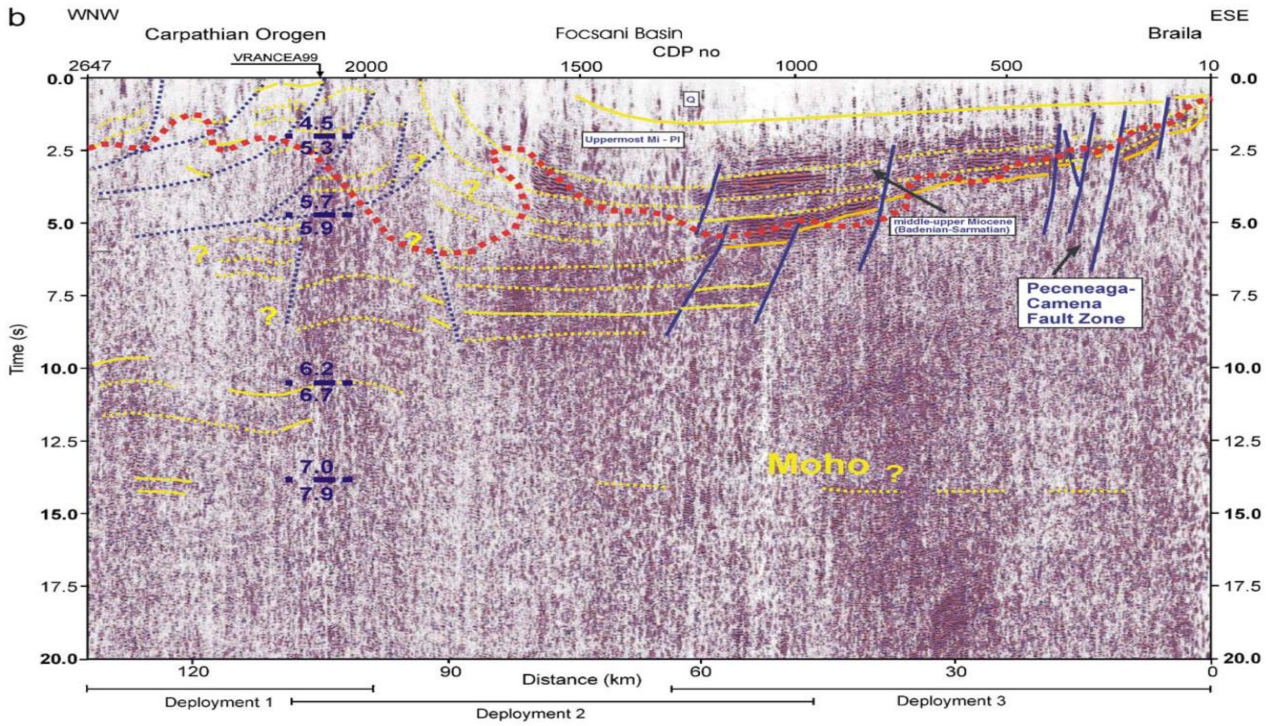


Fig. 12-12: Interpreted time seismic section of the DACIA PLAN seismic survey (from Panea et al., 2005, Fig. 10b; Prodehl and Mooney, 2012, Fig. 10.2.3-06). Dark blue velocity interfaces are from the VRANCEA-1999 model of Hauser et al. (2001), red dashed interface represents the 5.0 km/s velocity contour of the tomographic model of Bocin et al. (2005), blue and yellow lines – geological interpretation of the seismic-reflection data.

The VRANCEA-2001 project (Hauser et al., 2002, 2007) also included a near-vertical incidence seismic reflection part. Between shotpoints T and U the geophones had been deployed at a spacing of 100 m. Immediately following the seismic refraction work of VRANCEA-2001, two more deployments, using all available 640 one-component geophones (TEXAN type), were again laid out at 100 m spacing along the VRANCEA-2001 refraction line to the east of shotpoint T, traversing most of the Focsani basin, and shots were fired every 1 km. This additional seismic-reflection program was enabled by the project DACIA PLAN (Danube And Carpathian Integrated Action on Process in the Lithosphere And Neotectonics). I. Panea (Panea et al., 2005) processed the data and published a first interpretation (**Fig. 12-12**).

13. Closing remarks and acknowledgments

Scientists and students of Karlsruhe have participated on many other projects as well, which have been undertaken by other German research institutions such as Berlin, Hamburg, Kiel or München, as well as in other seismic projects in the U.S., organized by the U.S. Geological Survey. In our review of seismic projects we have restrained ourselves on projects for which Karlsruhe was a co-responsible partner in planning, execution and data interpretation. Considering the manifold difficulties and problems which are connected with fieldwork we can be happy that at none of the Karlsruhe seismic-refraction projects a major accident happened, fortunately the hippo-attack at KRISP-90 did not cause lasting damage.

With the end of active service of Karl Fuchs and Claus Prodehl, the time of active large-scale seismic-refraction experiments has terminated. The priority in research has changed to the method of teleseismic traveltime tomography, which in the mid-1980s was applied by Karlsruhe scientists under the direction of Ulrich Achauer for the first time in Kenya and in the Rhinegraben. The teleseismic experiments which record for several months local and teleseismic events with long-term recordings at temporarily fixed sites nowadays request for a similar amount of equipment as did seismic-refraction campaigns, but can be accomplished with considerably less personnel. However, due to long recording times and regularly necessary repair services the costs of an experiment may nevertheless be substantial, as may be judged when reading the contributions on teleseismic projects by Joachim Ritter (Chapter 9 of this volume).

The research work presented in this report would not have been possible without the help of the numerous members and students of all research fields of the Geophysical Institute (GPI) as well as from other institutions worldwide. As far as still known to me, the Karlsruhe participants in the individual field projects and data preparations were named. I apologize for unavoidable omissions.

All of the scientific figures (location maps, record sections, crustal and upper-mantle cross sections) were obtained from GPI's research projects. The majority of these figures had recently been digitally prepared and modified where necessary and subsequently re-published by Prodehl and Mooney (2012). The author acknowdges the permission by the Geological Society of America (GSA) to re-use the figures for this report.

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9. Experimental Seismology in Karlsruhe: Passive Field Experiments and Their Main Results

Joachim Ritter

9.1 Introduction

Passive-source or passive seismology is based on the observation of seismic signals which are not specifically and actively generated during an experiment. Such signals comprise mainly earthquake waves but also volcanic tremor or the continuous background noise induced by weather phenomena, ocean waves, traffic, machines or other human activities. Thus during a passive field experiment one listens carefully into the Earth with sensitive seismometers and waits for useable signals. Typically, the aim is to discover signals of low- to high-amplitude, about 1 nm to 10 cm ground displacement, over a wide frequency range of about 0.01-100 Hz. Lower or higher frequencies are observed in special observatories or laboratories (see also Zürn, this volume). During passive experiments several seismometers are placed as network or array in a target area to study local seismicity, deep structure or other properties. The Geophysical Institute in Karlsruhe (GPI) was involved in many international projects in which different research institutions shared their instrumental facilities to achieve ambitious experiments at geoscientifically interesting regions on Earth. Also experiments done solely by GPI were planned, realised and interpreted. State of the art instrumentation was acquired and existing instruments were replaced as new technologies were available.

Many passive experiments were conducted in the framework of major research projects funded by the Deutsche Forschungsgemeinschaft (DFG), such as the Special Priority Program (SPP) on Uplift in the Rhenish Shield, the Collaborative Research Centre (CRC) 108 on *Stress and Stress Release in the Lithosphere* and CRC 461 *Strong Earthquakes: A Challenge for Geosciences and Civil Engineering*. Between the years 1978 and 2000 3-D imaging of structures in the Earth's crust and upper mantle was the main goal: Teleseismic tomography was applied for example in Germany, Romania, France and Kenya. These studies complemented active-source seismic refraction studies and were jointly interpreted with tectonic and petrological collaborations. During this period especially Lennartz PCM 5800 recorders were purchased together with 1 s and 5 s seismometers and Ulrich Achauer played a leading role for establishing teleseismic studies at GPI. He organised the acquisition of instruments and worked as guest scientist at the USGS in Menlo Park to get familiar with teleseismic tomography. Uli Achauer built up the Karlsruhe teleseismic working group and supervised the following project leaders Andreas Glahn, Gerald Stoll and Joachim Ritter who conducted several sucessful projects.

In 2002 experimental seismology was systematically expanded at GPI by Friedemann Wenzel. Using his appointment funds he acquired 31 autonomously recording broadband stations which form the core of the KArlsruhe BroadBand Array (KABBA). Coincidently he prompted the return of Joachim Ritter to Karlsruhe and established with a permanent position for passive experimental seismology. Using KABBA data, tomography was complemented by other methods in order to better use the full information contained in broadband recordings. Converted phases (*P-to-S* and *S-to-P*) were used to image discontinuities inside the Earth. Splitting of shear waves was studied to analyse anisotropy and seismic noise was used to apply seismic interferometry and to analyse time-varying properties. The analysis of induced seismicity was started as it became a newly available source near to Karlsruhe. Today (2014) KABBA comprises 42 broadband stations and an open waveform archive (partly in real time), which was installed by Jörn Groos, and is included in international archives by internet connection and the WebDC and EIDA (European Integrated Data Archive) initiatives.

Experimental broadband seismology was also included in the teaching curriculum. There are special courses on seismological instruments by Thomas Forbriger and on data analyses of teleseismic and local earthquake phases including tomography and array techniques by Joachim Ritter. The KABBA instruments and waveform recordings were used for PhD, master and bachelor theses (see list at KABBA Homepage www.gpi.kit.edu/KABBA.php). In the following the passive field experiments by GPI and their main achievements are described. Details can be found in the cited references.

9.2 Early Field Projects and PCM-Era

9.2.1 Rhenish Schield, Central Europe

During the SPP on vertical crustal movements the ACH tomography by Aki et al. (1977) was applied for the first time in Europe. Klaus-Peter Bonjer and Susan Raikes analysed P-wave recordings of teleseismic phases from 55 temporary and permanent stations together with bulletin listings from eight permanent stations (Fig. 9.1). They determined travel time residuals which are the difference between observed and theoretical travel times of the analysed phases in the seismograms. Based on these travel time residuals Susan Raikes and Klaus-Peter Bonjer calculated a 3-D model of seismic velocity perturbations relative to a background model. Their model represents anomalies in the upper mantle underneath the station network and it displays a clear body with a reduction of the *P*-wave velocity (about -4%) as shown in Fig. 9.1. This anomaly was linked to the recent uplift in the region and for the first time Raikes & Bonjer (1983) connected the image of deep processes in the mantle to the volcanism at the surface in the Eifel area. This finding was an important basis for the Eifel Plume project and its field experiment in 1997/98.

Raikes S., 1980. Teleseismic evidence for velocity heterogeneity beneath the Rhenish Massif. J. Geophys., 48, 80-83.

Raikes S. & Bonjer K.P., 1983. Large-scale mantle heterogeneity beneath the Rhenish Massif and its vicinity from teleseismic P-residuals measurements. In Fuchs, K. et al. (editors), Plateau Uplift, The Rhenish Shield - A Case History, Springer Verlag (Berlin), 315-331.

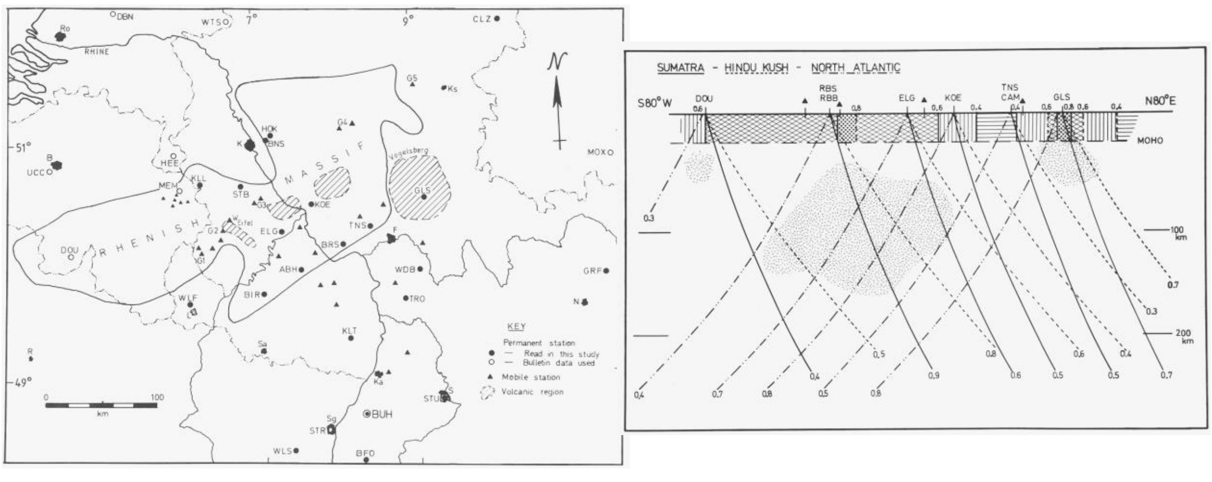


Fig. 9.1: Left: recording network in the Rhenish Shield (indicated by solid line) and surrounding regions, the different symbols indicate different types of recording stations. Right: East-west cross section through the Rhenish Shield. The displayed ray paths of teleseismic waves to selected stations (with station code) display the experimental layout and numbers give observed travel time residuals in seconds (solid lines: ray paths of a Sumatra earthquake, dashed lines: ray paths of a North Atlantic earthquake). Inside the shaded region the seismic velocity is reduced (from Raikes, 1980).

9.2.2 Volcanoes in the western USA

Scientists from GPI stayed with the US Geological Survey in Menlo Park, California, to study the technique of teleseismic analysis and tomography. There the working group of H. M. Iyer had recorded teleseismic earthquakes along several profiles across volcanoes in the western USA. The aims were to better understand the depth range of magmatic processes and eventually to use geothermal heat. John Evans' programme for the 3-D inversion of travel times was refined continuously and used by the USGS and Karlsruhe groups (Evans & Achauer, 1993). Ulrich Achauer (now University of Strasbourg) was involved in the tomography studies of the Mono Crater volcanic field in eastern California and the Newberry shield volcano in the Cascades in Oregon. In 1993 und 1994 Joachim Ritter was also guest scientist in Menlo Park and analysed a dataset which was recorded at Medicine Lake volcano, the other large shield volcano at the eastern margin of the Cascades in California. There a high-velocity anomaly was recovered which was interpreted as cooled pathway of the magma ascend down to more than 100 km depth. In addition, it was demonstrated that there is a regional east-west change of the physical properties of the upper mantle.

Achauer, U., Greene, L., Evans, J.R. & Iyer, H.M., 1986. Nature of the magma chamber underlying the Mono Craters area, eastern California, as determined from teleseismic travel time residuals. J. Geophys., 91, 13.873-13.891.

Achauer, U., Evans, J.R. & Stauber, D.A., 1988. High resolution seismic tomography of compressional wave velocity structure at Newberry Volcano, Oregon Cascade Range. J. Geophys. Res., 93, 10.135-10.147.

Evans, J.R. & Achauer, U., 1993. Teleseismic velocity tomography using the ACH method: theory and application to continental-scale studies. In Iyer, M.H & Hirahara, K. (eds.) Seismic Tomography: Theory and Practice, Chapman & Hall, London, 319-360.

Iyer, H.M., Evans, J.R., Dawson, P.B., Stauber, D.A. & Achauer, U., 1990. Differences in magma storage in different volcanic environments as revealed by seismic tomography: I. Silicic volcanic centers and subduction-related volcanoes. In: Ryan, M.P. (editor) Magma Transport and Storage, J. Wiley, 293-317.

Ritter, J.R.R. & Evans, J.R., 1997. Deep structure of Medicine Lake Volcano, California. In: Fuchs, K., Altherr, R., Müller, B., and Prodehl, C. (editors), Stress and stress release in the lithosphere. Tectonophysics, 275, 221-242.

9.2.3 Vrancea, Romania

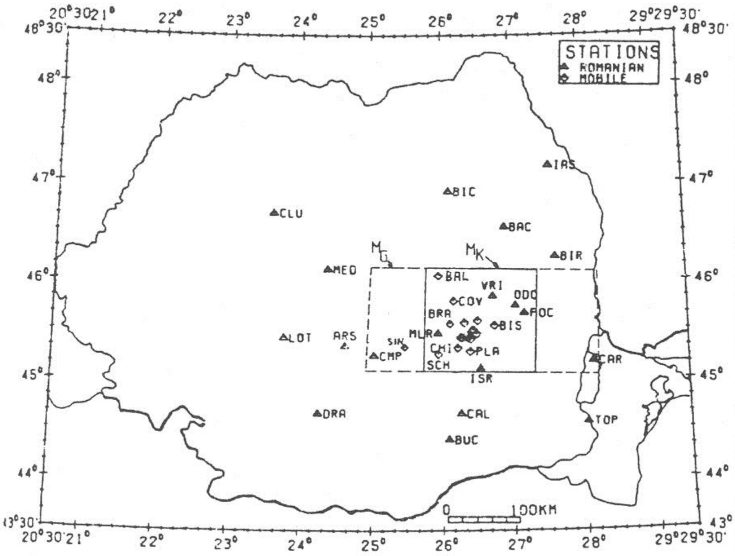
Since 1974 there was and still is a close relationship of GPI with Romania, especially the National Institute of Earth Physics in Bucharest (see also contribution by Klaus-Peter Bonjer). Within the framework of the CRC 108 on stress in the lithosphere, Manfred Koch (now Kassel University) applied seismic tomography to the subduction system underneath Vrancea where strong earthquakes occur frequently. He used and further developed the inversion technique of Aki & Lee (JGR, 1976). Thus it was possible to calculate simultaneously the 3-D seismic structure together with precise hypocenters (SSH method). This method allowed the use of sources inside the inversion volume (the Vrancea earthquakes). Manfred Koch used the ISC-bulletin listings and the listings of the 1979 survey arrival times (see Bonjer, this volume) and he calculated the 3-D velocity structure underneath the Vrancea region (Koch, 1985a). In this way he contributed to the detection of the subduction zone which was imaged as high velocity anomaly (Fig. 9.2) as found also by Oncescu (1984).

Koch, M., 1982. Seismicity and structural investigations of the Romanian Vrancea region: evidence for azimuthal variations of P-wave velocity and Poisson's ratio. Tectonophysics, 90, 91-115.

Koch, M., 1983. Die Bestimmung lateraler Geschwindigkeitsinhomogenitäten aus der linearen und nichtlinearen Inversion tele- und lokalseismischer Laufzeiten – Anwendung auf die seismische Zone Vrancea, Rumänien. Dissertation, Universität Karlsruhe (TH), Department of Physics, 256 p.

Koch, M., 1985a. Nonlinear inversion of local seismic traveltimes for the simultaneous determination of the 3-D velocity structure and hypocenters - application to the seismic zone Vrancea. J. Geophys., 56, 160-173.

Koch, M., 1985b. A numerical study on the determination of the 3-D structure of the lithosphere by linear and non-linear inversion of teleseismic travel times. Geophys. J.R. astr. Soc., 80, 73-93.



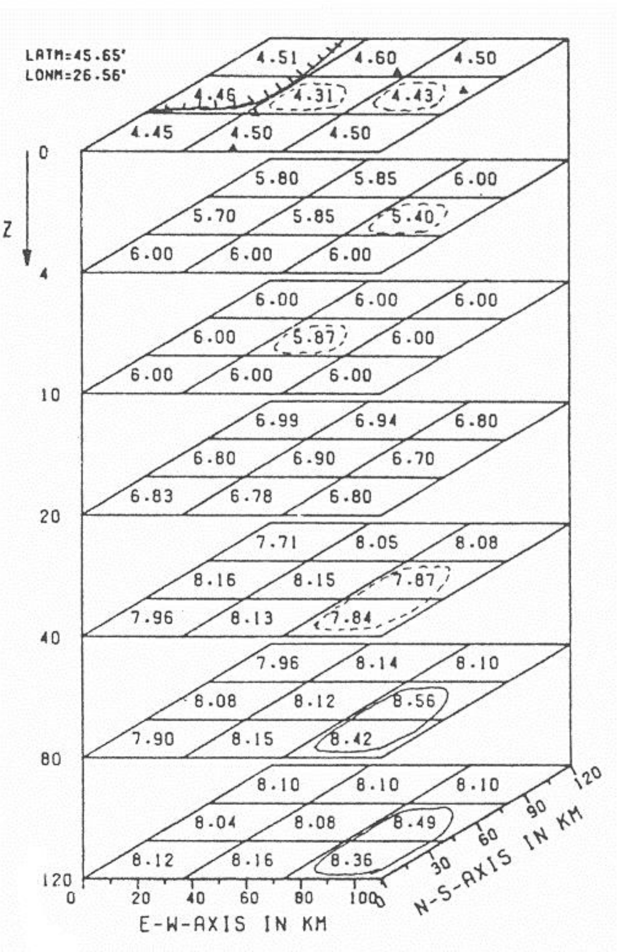


Fig. 9.2: Left: Seismic station network in Romania for the tomography of Koch (1985a). Right: 3-D model with the P-wave velocity (in km/s) down to 120 km depth. The area of relatively high velocity (solid line) corresponds to the Vrancea subduction zone (after Koch, dissertation, 1983).

9.2.4 Urach volcanic field

In spring 1983 the first Lennartz electronic PCM 5800 recorders were delivered to GPI. These instruments were purchased with funding by the CRC 108 programme „stress and stress release in the lithosphere“. The goal of this investment was to be able to study experimentally the lithosphere asthenosphere system. In total nine PCM 5800 recorders (pulse code modulation) could be purchased which recorded digitally with 12-bit coding (plus the possibility for gain-ranging) on magnetic tape (8-40 MByte capacity depending on tape velocity). As sensors vertical seismometers Geotech S-13 (eigenperiod 2 s) and horizontal seismometers Kinemetrics SH-1 (eigenperiod 5 s) were bought. Due to the low data storage capacity, a trigger mode was used for recording and the teleseismice P- und S-waves were stored in an about 20-minutes long time window. The tapes were then playbacked with a Revox tape recorder and processed with the micro-computing system SAS 68000 by Lennartz electronic and the Hewlett-Packard 1000 system.

The teleseismic experiment in the Miocene Urach-Kirchheimer volcanic field (SE Germany) was the first one which was conducted with the Karlsruhe PCM 5800 stations. Around Urach (Fig. 9.3), in the region of the Swabian Alb and its foreland towards Stuttgart, about 350 maar diatremes were formed some 11-17 Ma B.P. The volcanic conduits can still be found nowadays, because they resisted partly erosion. In the same region there is a positive geothermal anomaly at the surface. The goal of the Urach project (Fig. 9.3) was to search for relations between this geothermal anomaly, the past magmatic processes and structural anomalies in the crust and upper mantle. Between 1984 and 1987 the nine recording stations were installed at 21 sites in an area of 70 km E-W and 40 km N-S extension (Fig. 9.3).

Recording was done in triggered mode with 50 samples per second on tapes which could store 20-30 events (often false triggers). Each week the tapes had to be replaced. The waveforms were analysed by Andreas Glahn (now Zürich) und Ulrich Achauer. They determined 3-D tomographic models with P-wave velocity (*vp*) perturbations down to 100 km depth. The main result was an anomaly with a reduction of *vp* by 3% to 4% which was interpreted in collaboration with Peter Sachs (then University of Stuttgart) who did petrological studies at the same time. The *vp* anomaly was attributed to the Miocene magmatic processes and the increased heat flow (Glahn et al., 1992).

Achauer, U., 1986. Teleseismische Untersuchung der Geschwindigkeitsstruktur im Bereich der geothermischen Anomalie Urach. Berichtsband SFB 108 für die Jahre 1984-1986, 421-441.

Glahn, A., 1993. Untersuchungen zur 3D-Struktur der Lithosphäre mittels teleseismischer P- und S-Wellen am Beispiel der geothermischen Anomalie Urach, SW-Deutschland. Dissertation, Universität Karlsruhe (TH), Department of Physics, 184 p.

Glahn, A., Sachs, P.M. & Achauer, U., 1992. A teleseismic and petrological study of the crust and upper mantle beneath the geothermal anomaly Urach / SW-Germany. Phys. Earth Planet. Interiors., 69, 176-206.

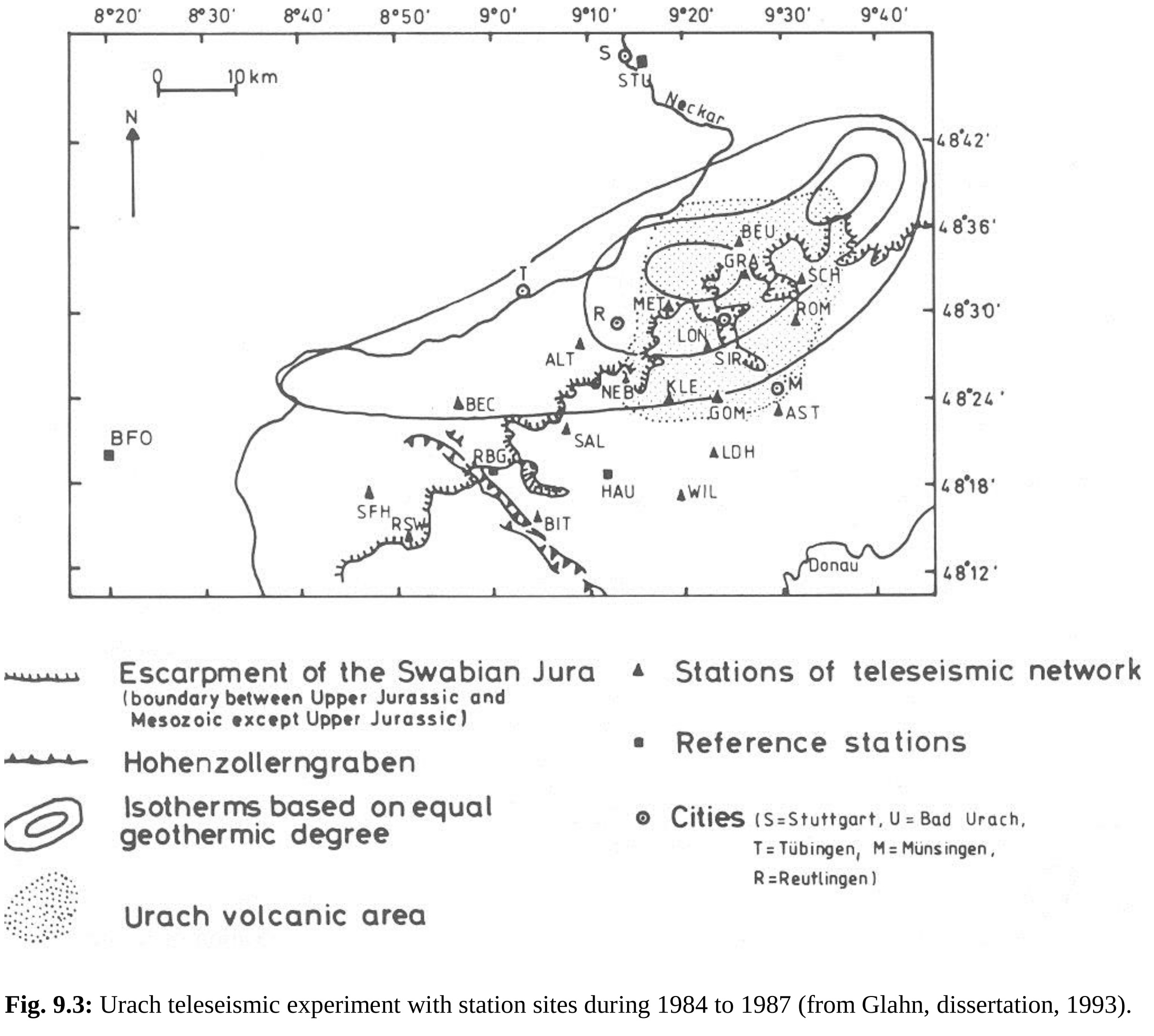


Fig. 9.3: Urach teleseismic experiment with station sites during 1984 to 1987 (from Glahn, dissertation, 1993).

9.2.5 Kenya

9.2.5.1 KRISP‘85

The availability of the Karlsruhe PCM 5800 recorders opened the door for the active contribution to international experiments. One focus was the Kenya Rift which was a major research goal within CRC 108 on stress in the lithosphere. In Kenya active continental breakup (rifting) can be studied in a favourable and fascinating environment. The Karlsruhe teleseismic group was involved in the three experiments of the Kenya Rift International Seismic Project (KRISP). A first experiment, KRISP’85, was conducted in 1985 in collaboration with the University of California, Los Angeles (UCLA, Paul Davis), logistical support was provided by the University of Nairobi (J.-B. Patel). Altogether 19 recording stations were installed along a 600 km long profile across the Kenya Rift and its shoulders at 1° southern latitude (Fig. 9.4). The average station distance was about 30 km. The recording time was nearly four months between September and December 1985. The maintenance of the stations was quite laborious, because they had to be visited each 3-5 days. Most roads were in a bad condition and complicated the fieldwork. As time base a signal by radio Moscow was used which could be recorded by the three Karlsruhe stations. Most stations from the USA had to be synchronized with a mobile clock during the station visits. Thus time keeping and limited data storage required regular station maintenance.

The analysis of the KRISP’85 dataset resulted in the discovery of a clear travel time delay for teleseismic waves of up to two seconds in the area of the rift which was an obvious hint for a significant reduction of the seismic velocity. This anomaly was interpreted as upwelling of the asthenosphere underneath the Kenya Rift which drives the separation of the lithospheric plates (Dahlheim et al., 1989).

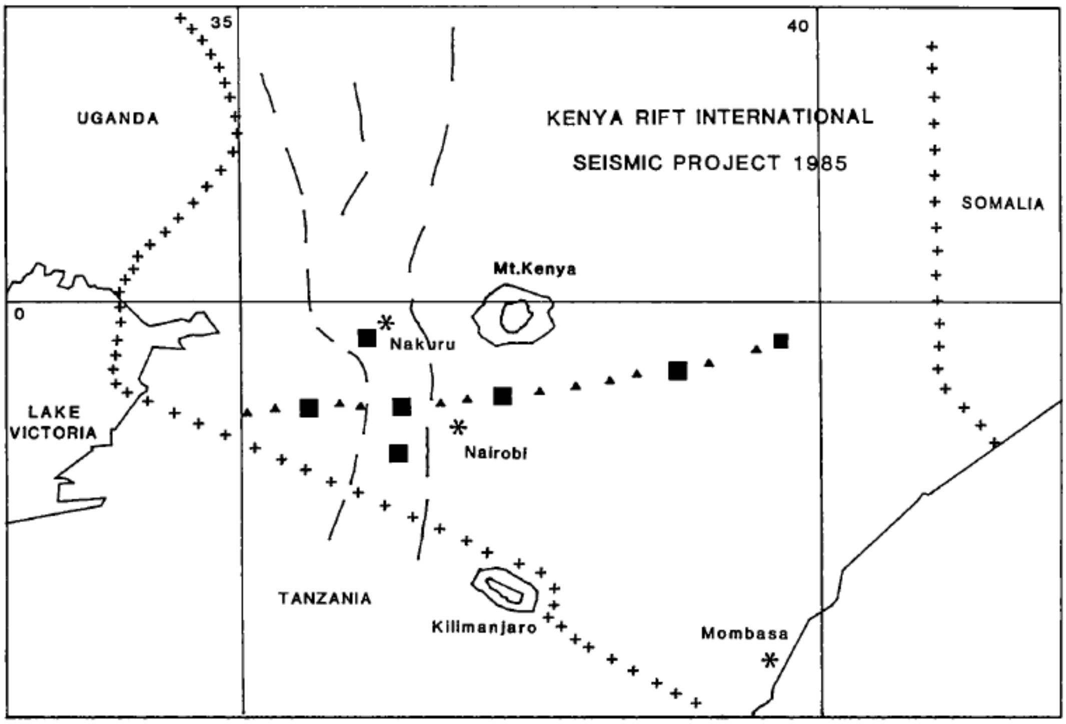


Fig. 9.4: Station map of the KRISP’85 experiment. The dashed lines indicate the position of the Kenya Rift, a major zone of continental breakup. Triangles show 1 s one-component stations, squares show 5 s three-component stations (Achauer, dissertation, 1990).

At the same time in autumn 1985, when the linear GPI / UCLA experiment was running, the University of Wisconsin in Madison operated a 2-D station network of 100 km by 110 km inside the rift at about 1°S in the centre of the Kenya Dome. This is an impressive region: if one approaches the rift from east, e.g. from Nairobi, the rift flanks are nearly 1000 m high along steeply dipping faults. At the bottom of the rift floor at Lake Naivasha the elevation is still 1800 m above sea level. The recordings of the 19 stations of the Wisconsin network and five nearby stations of the GPI / UCLA network were the observational basis for a 3-D tomography study. Its results were published in Nature (Green et al., 1991) and these display the narrow updoming of the asthenosphere underneath the Kenya Rift.

9.2.5.2 KRISP‘89/90

Based on the experience from KRISP’85 a major teleseismic experiment, KRISP‘89/90, was planned and conducted in the central Kenya Rift to complement seismic refraction measurements (Prodehl et al., 1994). Within KRISP‘89/90 a large station network of 200 km N-S and 500 km E-W extension was installed in autumn 1989 (Fig. 9.6). Ulrich Achauer coordinated this joint experiment of the universities of Karlsruhe, Los Angeles and Madison. GPI was responsible for 17 Lennartz PCM 5800 stations from Karlsruhe, Aachen and Munich. UCLA was running 19 stations and Madison took care of 29 stations. As field headquarter a very comfortable villa was rented in Nakuru at the base of the Menengai volcano. The large living room was data centre, lounge and dining room for the Kenyan-American-German field crew (Fig. 9.5). During the maintenance tours two tragic car accidents occurred: Robert Meyer (Wisconsin) was fatally injured when a car with a Kenya colleague deviated from the road. Another car crashed during a transit from Nakuru to Nairobi with a Karlsruhe crew. Four severely injured had to be brought back by plane to Germany. The rough field conditions also caused typical breakdowns which can happen on a daily basis in the African bushes: complete breakdowns of cars, punctures and even overnight stays in lion territory.

Fig. 9.5: Field headquarter of the KRISP’89/90 experiment in Nakuru. Left: villa at the flank of the Menengai volcano, right: living room with playback centre for field tapes.

In case of minor and major problems the research group could always rely on the extraordinary and cordial support by Doris Zola in Nairobi. As project secretary Doris provided her house, including a huge avocado tree, as central point for KRISP. Her two dogs complemented each other perfectly: one was deaf, the other was blind. Doris was also a volunteer with the David Sheldrick Wildlife Trust at the outskirts of the Nairobi National Park which takes care of orphan elephants and other wild orphan animals. The KRISP participants got a very close insight and memorable encounters with baby elephants and other exotic baby animals.

KRISP89/90 was a remarkable scientific success. Numerous teleseismic events could be recorded for the following data analysis. Besides logistical challenges, a main problem was the time signal for the synchronization of the recorders. The transmitting site for the OMEGA radio navigation system on La Reunion Island often failed and caused many extra visits to the station sites. However, the data quality was excellent for the circumstances. The crustal model obtained along the seismic refraction lines was supplemented with a 3-D mantle model. The upwelling of the asthenosphere underneath the Kenya was clearly imaged in three dimensions (Achauer & The KRISP Teleseismic Working Group, 1994). In addition, the powerful shots of the seismic refraction experiment were recorded at the teleseismic network. During the shooting campaign the station density was increased in the centre close to Lake Bogoria with six brand-new Lennartz electronic MARS-88 stations from Copenhagen (Fig. 9.6). More recordings were provided by the network of the University of Leicester which was installed around Lake Baringo. All recordings together were used to determine a 3-D crustal *vp* model. It contained distinct high seismic velocity anomalies which were interpreted as magmatic intrusions related to the main volcanic centres (Ritter & Achauer, 1994).

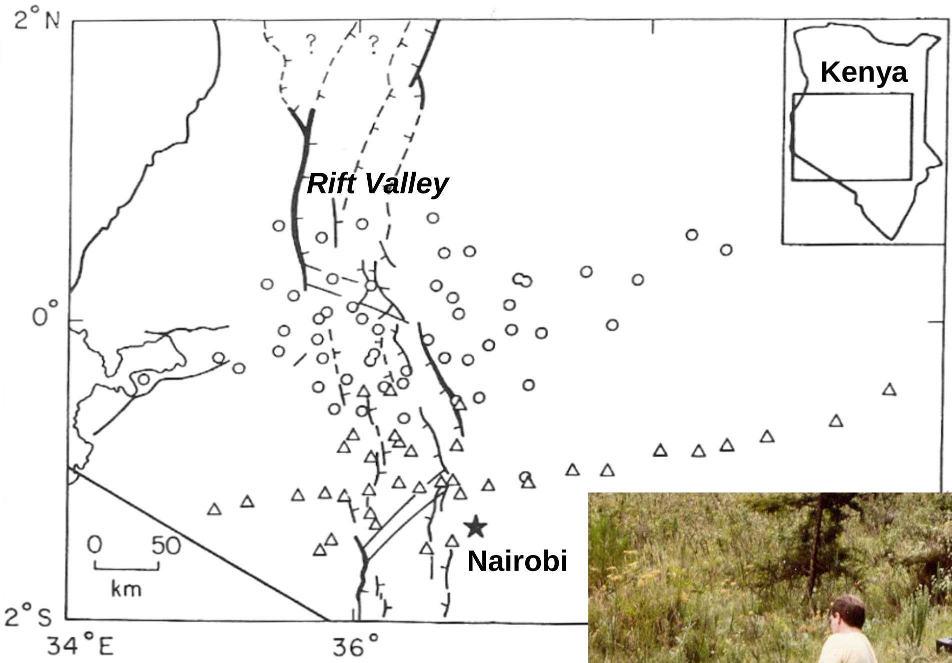


Fig. 9.6: Top: Map of teleseismic KRISP85 (triangles) and KRISP89/90 (circles) recording sites. Right: huddle test with the MARS-88 recorders on the rim of the Menengai crater in January 1990.

Within the collaboration between GPI and the University of Nairobi a lecturer for geophysics was sent to Nairobi. This lecturer position was financed by the DAAD (German Academic Exchange Service) and Raimund Stangl (now retired in Munich) moved to Kenya in 1991. At the same time a Kenyan seismic network was acquired with the help of GTZ (German Technical Cooperation). This network included five Lennartz electronic MARS88 recorders with Lennartz 1 s seismometers, computers and an off-road vehicle. The Kenyan president, Daniel arap Moi, announced the implementation of this network during the IASPEI General Assembly in Nairobi in August 1990. A delegation of six scientists from GPI attended the IASEPI assembly (Fig. 9.7). During an international reception in the residence of the German Embassador, Karl Fuchs explained the importance of the Kenyan-German scientific cooperation and especially the seismic monitoring network during a lively address.

THE STANDARD, Friday, August 24, 1990. 11

National News

Tremors: Govt to set up monitoring system — Moi

By Nelson Oslemo

THE Government is in the process of establishing a national seismological network to enable Kenyans to monitor occurrences of earthquakes and their effects, President Daniel arap Moi announced yesterday.

This would provide a complementary and comprehensive view of natural hazards and the disaster they could cause, he said. "We believe that through these efforts, we may provide a forum for interchange of data, ideas and techniques, as well as stimulate new global collaborative research into understanding hazards and combating disasters," said the President during the opening of a one-week Regional Seismological Assembly in Africa at the Kenyatta International Conference Centre (KICC), Nairobi.

In a speech read for him by the Minister for Environment and Natural Resources, Dr Njoroge Mungai, President Moi also called upon other governments of the world towards greater security against natural disasters.

"Let all governments participate actively in disaster reduction by educating and training their citizens to increase awareness by enhancing social preparedness and by integrating disaster-consciousness into their development programmes," he said.

President Moi recalled that over the past 10 years, 80,000 people had died in the world, 8,000 of them in Africa, from "violent earthquakes, vicious volcanic eruptions, landslides and furious storms."

Related economic loss was collosal and could easily reverse development trends of small economies, he noted. Said the President: "When looking at the loss of life globally resulting from natural disasters, the temptation is to think that the loss of life in Africa is negligible and, therefore, the mitigating measures necessary to reduce the effects of natural disasters should be given low priority."

Within this year alone, said the President, Africa had experienced some very strong earthquakes, and Kenya had not been spared. Several parts of Kenya had been rocked by earth tremors which had caused a lot of anxiety among the people of epicentral areas, he added.

President Moi said it was important that Kenyans understood dangers posed by natural disasters such as volcanic eruptions which could increase toxic gases in the soil and the atmosphere, thereby adversely affecting agriculture on which the country depended.

"In Kenya, we have taken significant steps to deal with these problems, and more will be done to combat the negative effects of these natural hazards.

"To this end, the Government, through the Ministry of Environment and Natural Resources, is already working on the establishment of a national seismological network which will enable us to monitor and understand the nature and distribution of earthquakes with a view to proper development planning and mitigation of the adverse effects of these natural hazards.

"The basic concept which we are pursuing is to build on the numerous national efforts in place, and to provide a complementary and comprehensive view of natural hazards and the disaster they can cause," said the President.

He told the assembly, being attended by scientists from Africa and the world, to provide answers or solutions to:

- Earthquakes prediction and measures to be taken in order to mitigate the effect of earthquakes and estimate seismic risk of various regions of the world,
- Delineation of major active faults under the concept of neotectonics as an aid in recognising areas where strong earthquakes occur.

Some of the assembly participants during the opening ceremony yesterday.

Fig. 9.7: Newspaper clipping reporting on the IASPEI General Assembly in Nairobi in 1990. The following KRISP scientists are displayed from left to right: Aftab Khan (Leicester), Joachim Ritter, Verney Green (Madison), Raimund Stangl, James (Jim) Mechie and Claus Prodehl.

9.2.5.3 KRISP‘93

During the final phase of the CRC 108 (1993-1995) a volcanic field in Kenya was a major research focus for joint geophysical, petrological and tectonic studies. The Chyulu Hills are a Quaternary volcanic field with the latest eruption at Shaitani volcano in 1855. They are located in SE Kenya at the foothills of the Kilimanjaro volcanic complex (Fig. 9.10). The petrology group of Prof. Rainer Altherr (now Heidelberg) had discovered xenoliths which had been transport upwards from different depths of up to 120 km, the inferred local depth of the lithosphere-asthenosphere boundary. These crustal and upper mantle xenoliths allowed the determination of the modal composition of the complete lithospheric column as well as ambient pressure and temperature conditions. Thus the Chyulu Hills were a perfect site to calibrate seismic velocity and petrological quantities. The GPI initiated international long-range seismic refraction and teleseismic experiments in SE Kenya (Prodehl et al., 1997).

The KRISP‘93 teleseismic experiment was coordinated by Joachim Ritter as collaboration between the universities of Karlsruhe, Nairobi (Raimund Stangl) and Leicester (Peter Maguire & Paul Denton). In summer 1994 a network was installed in and around the Chyulu Hills. Altogether 31 temporary stations were deployed including 10 PCM 5800 from Karlsruhe, 4 PCM 5800 from Aachen, 12 PDAS-100 recorders from Leicester and five Lennartz MARS88 from Nairobi. In Nairobi the houses of Raimund Stangl and Doris Zola were meeting points and coordination centres. As field headquarter the guest house of an agricultural research centre was rented near Kiboko (Fig. 9.8, close to shot point CHN). Communication was done via radio to Doris Zola in Nairobi. Jürgen Oberbeck from the computing centre of the Universität Karlsruhe (TH) provided technical assistance with the radio equipment and his humorous way always helped to have a good mood within the team. As there were only few Lennartz GPS recorders available at that time, our chief technician Werner Scherer tried to broadcast our own DCF77-type time signal (a standard German time signal). In the field headquarter the output of a GPS-recorder was converted into the DCF77-code and then broadcasted several times a day. At the recording sites the time signal should be received with Sony radios and transferred via the cable of the earphones to the PCM 5800 recorders. To the difficult conditions for radio wave propagation near the equator, there was only a partial success with receiving this time signal. However, as there was a Sony radio at each station, it was possible to receive Germany news including Bundesliga soccer reports at each site during the maintenance work.

Fig. 9.8: Headquarter of the KRISP’93 experiment in Kiboko. Left: preparation of metal drums for recording sites (see also Fig. 9.9). The drums were later buried and fixed into a massive concrete base at the recording sites (in the centre: Raimund Stangl with local helpers). Right: office with radio communication and Jürgen Oberbeck studying a manual and Raimund Stangl fixing a computing problem.

Fig. 9.9: Test installation in the Chyulu Hills. Different sensors and their recorders were run in parallel mode to compare response functions (red: Geotech S13, black: Kinemetrics SH-1, blue: Lennartz electronic 1 s)

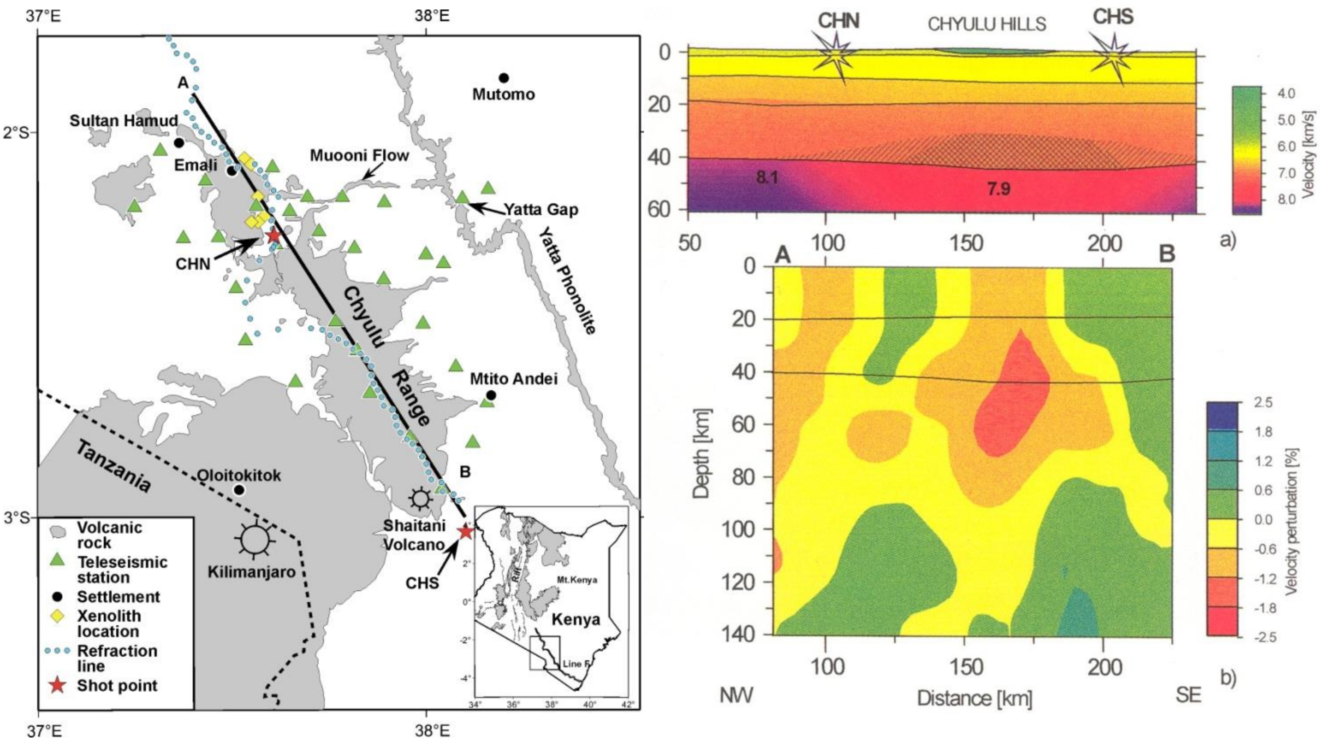


Fig. 9.10: Recording network (left) and model (right) of the KRISP'93 experiment in the Chyulu Hills. The models show seismic P-wave velocity combined from seismic refraction (top) and teleseismic (bottom) modelling (from Novak et al., 1997). CHN and CHS are refraction shot points (after Ritter, dissertation, 1996).

The field work in the Chyulu Hills had to be stopped after two months instead of eight months due to severe security problems. The economic problems of the country and the availability of weapons (partly due to the civil war in neighbouring Somalia) caused daily shootings and robbery in the region. E.g. during one station maintenance trip Friederike Lange (now Ritter) found a shot and robbed local politician by the roadside and brought him to a nearby hospital. After the experiment had run for some weeks, there was vandalism and theft at about ten stations. Our local station guards were armed only with sticks and long knives (pangas), but sometimes they were attacked with pistols and had to flee. Mostly batteries and solar panels were stolen, but four stations were completely destroyed. Even so the chief of the Kenya Police intervened and there were diplomatic effort by Karl Fuchs, who flew in from Karlsruhe and discussed the problem with the German Embassy, the situation could not be calmed down. However, not only criminals caused problems, a scorpion put the project leader out of action in a painful way for a short time.

Despite the short recording time and the described problems, the measurements provided important insights on the deep structure of the Chyulu Hills volcanic field. The tomography model (Fig. 9.10, right) revealed the magma production in the asthenosphere (Ritter & Kaspar, 1997) and by analysing converted phases the Moho and Conrad discontinuities could be mapped in 2-D as well as alleged magma chambers could be localised (Kaspar & Ritter, 1998). The results by all CRC 108 groups working in the Chyulu Hills were synthesised and published in an interdisciplinary publication (Novak et al., 1997) which proved the successful concept of the CRC 108 in an exemplary way.

Achauer, U., 1990. Das Lithosphären-Asthenosphärensystem unter dem Ostafrikanischen Rift, Kenia. Dissertation, Universität Karlsruhe (TH), Department of Physics, 173 p.

Achauer, U., 1992. A study of the Kenya rift using delay-time tomography analysis and gravity modeling. Tectonophysics, 209, 197-208.

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Achauer, U., Maguire, P.K.H., Mechie, J., Green, W.V. & KRISP Working Group, 1992. Some remarks on the structure and geodynamics of the Kenya rift. In: Ziegler, P.A. (ed). Proc. Geodynamycs of Rifting, Vol. II. Case History Studies on Rifts: North and South America and Africa, Tectonophysics, Vol. 213, 257-268.

Achauer, U. & the KRISP-Teleseismic Working Group, 1994. New ideas on the Kenya rift based on the inversion of the combined dataset of the 1985 and 1989/1990 seismic tomography experiments. Tectonophysics, 236, 305-330.

Dahlheim, H.-A., Davis, P. & Achauer, U., 1989. Teleseismic investigation of the East African Rift - Kenya. J. Afr. Earth Sci., 8, 461-470.

Green, W.V., Achauer, U. & Meyer, R.P., 1991. A three-dimensional seismic image of the crust and upper mantle beneath the Kenya rift. Nature, Vol. 354, 199-203.

Kaspar, T. & Ritter, J.R.R., 1997. On the use of later teleseismic arrivals in ACH-tomography with an application in SE-Kenya, Geophys. Res. Lett., 24, 1827-1830.

Kaspar, T. & Ritter, J.R.R., 1998. P-SV conversions of teleseismic waves beneath the Chyulu Hills volcanic field, Kenya. Geophys. Res. Lett., 25, 559-562.

Keller, G.R., Prodehl, C., Mechie, J., Fuchs, K., Khan, M.A., Maguire, P.K.H., Mooney, W.D., Achauer, U., Davis, P.M., Meyer, R.P., Braile, L.W., Nyambok, I.O. & Thompson, G.A., 1994. The East african rift system in the light of KRISP 90. In: Crustal and Upper Mantle Structure of the Kenya Rift. Prodehl, C., Keller, G.R. & Khan, M.A. (eds.), Tectonophysics, 236, 465-483.

Novak, O., Ritter, J.R.R., Altherr, R., Byrne, G.F., Sobolev, S.V., Garasic, V., Kluge, C., Kaspar, T. & Fuchs, K., 1997. An integrated model for the deep structure of the Chyulu Hills volcanic field, Kenya. In: Fuchs, K., Altherr, R., Müller, B., and Prodehl, C. (eds), Stress and stress release in the lithosphere. Tectonophysics, 278, 187-209.

Prodehl, C., Mechie, J., Achauer, U., Keller, G.R., Khan, M.A., Mooney, W.D., Gaciri, S.J. & Obel, J.D., 1994. The KRISP 90 seismic experiment - a technical review. In: Crustal and Upper Mantle Structure of the Kenya Rift. Prodehl, C., Keller, G.R. & Khan, M.A. (eds.), Tectonophysics, 236, 33-60.

Prodehl, C., Ritter, J.R.R., Mechie, J., Keller, G.R., Khan, M.A., Jacob, B. Fuchs, K., Nyambok, I.O., Obel, J.D. & Riaroh, D., 1997. The KRISP 94 lithospheric investigation of southern Kenya - the experiments and their main results. In: Fuchs, K., Altherr, R., Müller, B., and Prodehl, C. (eds), Stress and stress release in the lithosphere. Tectonophysics, 278, 121-147.

Ritter, J.R.R., 1996. Experimentelle Bestimmung lithosphärischer Strukturen unter temporären Stationsnetzwerken mit der Hilfe teleseismischer Wellen. Dissertation, Universität Karlsruhe (TH), Department of Physics, 215 p.

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Ritter, J.R.R. & Kaspar, T., 1997. A tomography study of the Chyulu Hills, Kenya. In: Fuchs, K., Altherr, R., Müller, B., and Prodehl, C. (eds), Stress and stress release in the lithosphere. Tectonophysics, 278, 149-169.

9.2.6 Southern Upper Rhine Graben

The study of continental rifting within CRC 108 was also done in the home area of GPI, the Upper Rhine Graben. Within a co-operation between the universities in Karlsruhe (Andreas Glahn, Ulrich Achauer), Strasbourg (Michel Granet) and Los Angeles (Paul Davis and Phil Slack) an international project to study the deep structure of the Upper Rhine Graben was initiated. From November 1988 to Mai 1989 68 temporary recording stations were placed along two lines and on a central 2-D network between Freiburg in the south and Strasbourg in the north. Additionally, the permanent networks of the universities of Karlsruhe and Strasbourg, which monitored the local seismicity, could be used (Fig. 9.11).

The 3-D tomography model, which resulted from the analysis of these measurements, contains only a very weak anomaly in P-wave velocity in the lithosphere which strikes along the graben axis. Below, in the upper mantle down to 130 km depth, only faint velocity perturbations with east-west direction were found. These results could not confirm earlier models for the rifting of the Upper Rhine Graben which hypothesized a doming of the asthenosphere below the graben (Glahn et al., 1993).

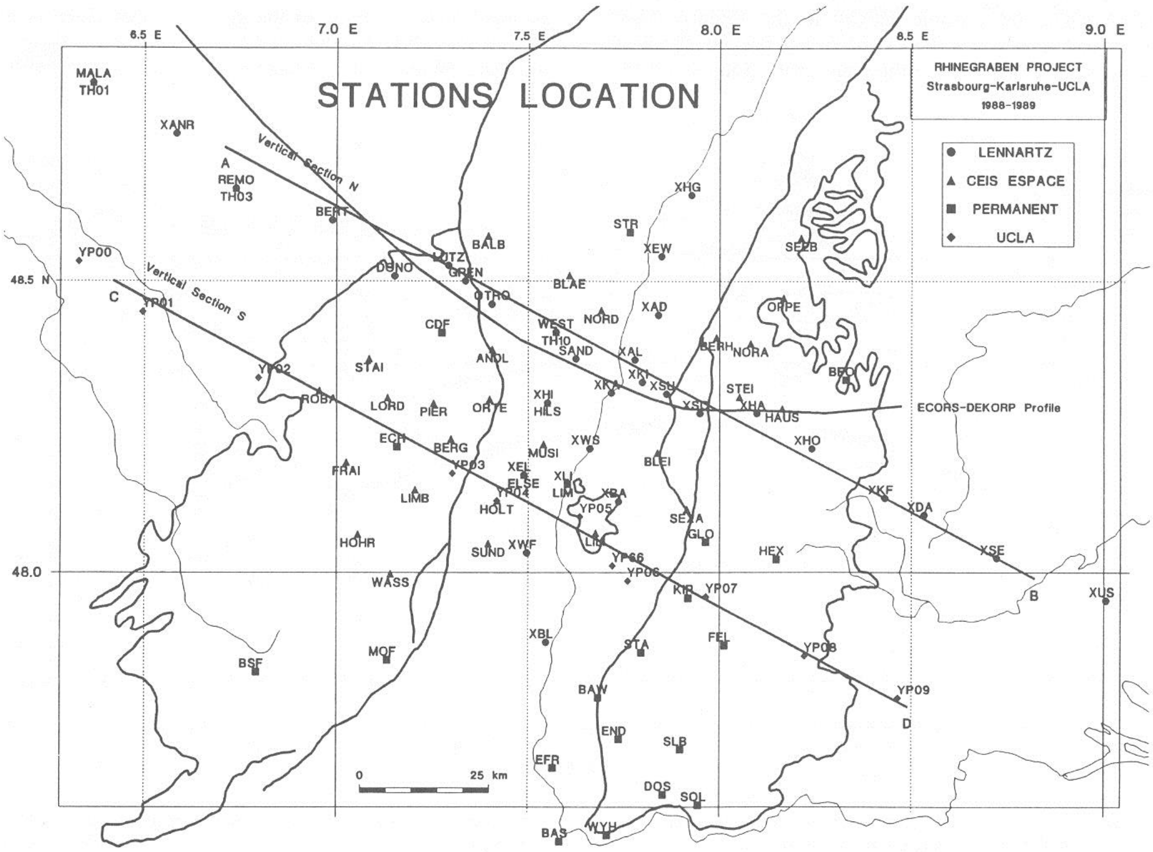

Fig. 9.11: Network with temporary and permanent stations in the southern Upper Rhine Graben region in 1988/89 (SFB-Berichtsband, 1991).

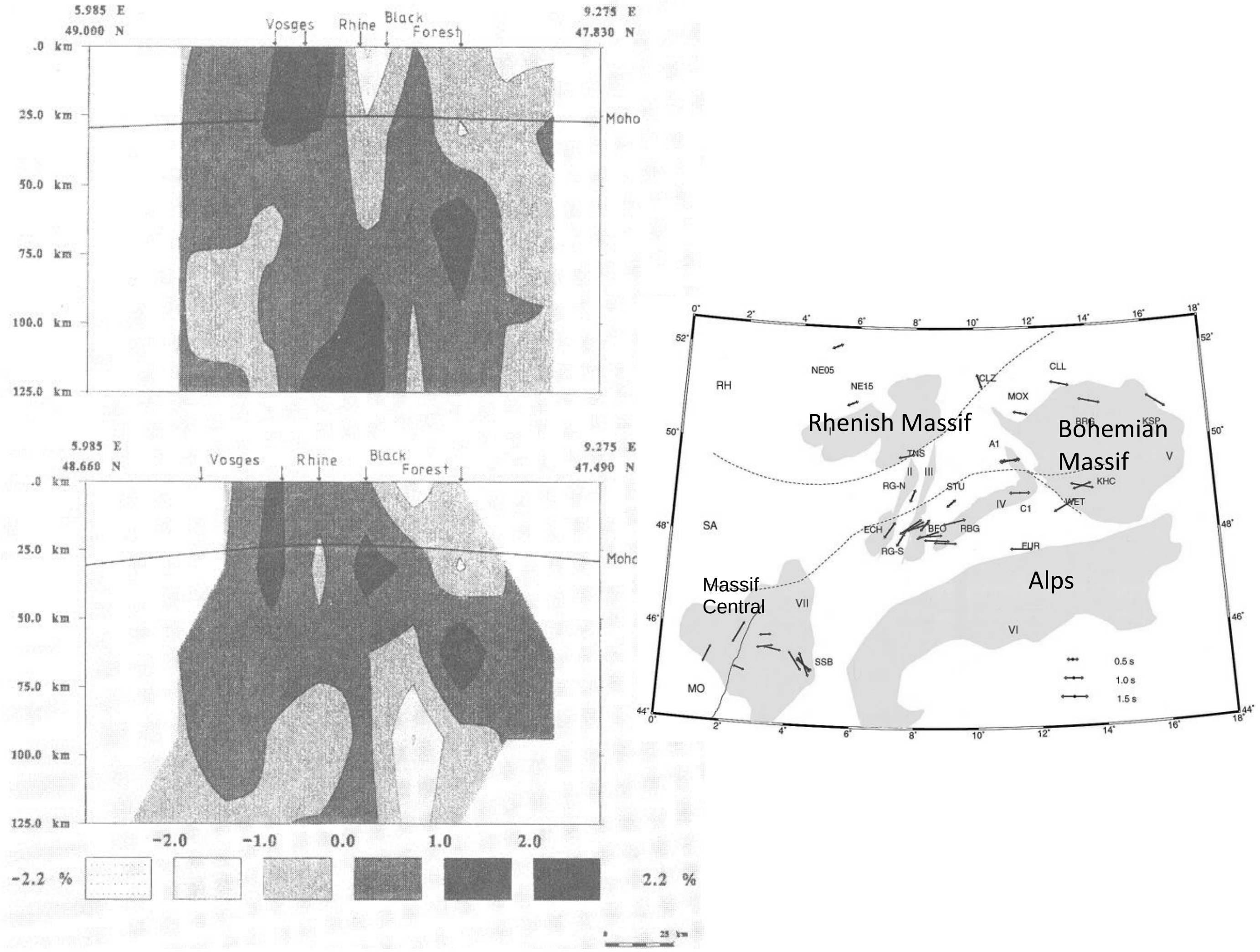

Fig. 9.12: Left: vertical cross sections through the 3-D model with perturbations of the P-wave velocity underneath the southern Upper Rhine Graben (for position of the sections see map in Fig. 9.11 from SFB Berichtsband 1991). Right: collection of fast polarisation directions of SKS splitting measurements in several regions of Central Europe. Mountain areas are indicated in grey, modified after Granet et al. (1998).

Andreas Glahn was the first at GPI to analyse anisotropy with SKS wave spitting. Earlier, David Bamford and Karl Fuchs used seismic refraction measurements to recover anisotropy in the uppermost mantle underneath South Germany and Karl Fuchs developed the anvil model of depth dependent anisotropy. In his PhD thesis Andreas Glahn determined the fast polarisation direction of SKS phases and the delay time between the fast and slow SKS phase arrivals. Besides the dataset from the Upper Rhine Graben he included also the waveforms of the Urach experiment. The results were published in his PhD thesis and later combined with a SKS analysis from the Massif Central experiment (see below). A joint publication of all results by Granet et al. (1998) presented the fast polarisation directions for Central Europe which shows preferred mineral fabrics in the upper mantle.

Glahn, A. & Granet, M., 1992. 3-D structure of the lithosphere beneath the southern Rhine Graben area. In: Ziegler, P.A. (ed), Proc. Geodynamics of Rifting Symposium. Tectonophysics, 208, 149-158.

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Granet, M., Glahn, A. & Achauer, U., 1998. Anisotropic measurements in the Rhinegraben area and the French Massif Central: geodynamic implications. Pure appl. geophys., 151, 333-364.

Prodehl, C., Müller, St., Glahn, A., Gutscher, M.A. & Haak, V., 1992. Lithospheric cross sections of the European Cenozoic Rift System (ECRIS). In: Ziegler, P.A. (ed)., Proc. Geodynamics of Rifting Symposium, Tectonophysics, 208, 113-138.

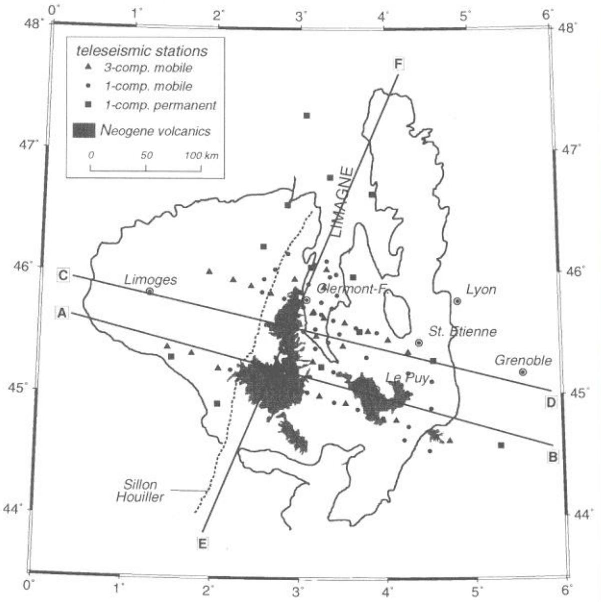
9.2.7 Massif Central

The Massif Central in France is a perfect region to study basic geoscientific questions related to rifting processes, volcanism, plume dynamics or Variscan mountain building. Around and in the Limagne Graben, a Cenozoic continental rift at the east side of the Massif Central, seismic refraction and passive teleseismic experiments were done within CRC 108 and collaborations with French colleagues. Mainly west and south of the Limagne Graben, there are Neogene volcanic fields such as the Velay, Mont Dore, Devès, Cantal, Chaine des Puys and others. Mantle xenoliths from these magmatic activities were collected and analysed by the Karlsruhe petrology group of Rainer Altherr. Their results included information on the composition and ambient temperature of the lithosphere asthenosphere system. The seismological models should be correlated with these petrological results and combined to an integrated model of the geodynamic evolution of the region.

The teleseismic experiment consisted of an 150 km (NS) by 300 km (EW) wide station network with 79 temporary and 14 permanent recording sites (Fig. 9.13). This field experiment was a French-German cooperation and the observation period was between October 1991 and May 1992. As head quarter a huge flat was rented in Clermont-Ferrand. The instruments were provided by the universities of Karlsruhe, Munich, Aachen, Paris und Grenoble and the Karlsruhe group was responsible for the 36 Lennartz PCM 5800 stations. The German project leader was Gerald Stoll (now IT consultant with Lufthansa).

The 3-D model with variations of the seismic P-wave velocity (*vp*) reached down to 180 km depth (Granet et al., 1995). It shows a deep reaching anomaly of reduced *vp* (5%-10%) below the volcanic fields. This anomaly was interpreted as region with increased temperature (+300°C relative to the surrounding upper mantle) and it was denoted as small mantle plume (Granet et al., 1995). Mantle plumes consist of hot mantle material which is upwelling due to its reduced density. Near to the Earth’s surface decompressional melting produces magmatic melts which ultimately feed the volcanoes. In this way the volcanic fields developed in the area of the Massif Central. A seismic anomaly related with the Limagne Graben could not be detected. The interdisciplinary studies of the CRC 108 on the Massif Central were summarised in Sobolev et al. (1996 & 1997). In a later study by Barth et al. (2007) more data from permanent stations and an improved tomography method was applied. In this way the mantle plume could be recovered as deep as 300 km as region with reduced *vp*.

The teleseismic waveforms from the Massif Central contained high frequency, reverberating signals, which reminded Karl Fuchs of reverberations from the lower crust known from active-source seismic experiments (Ritter et al., 1997). Joachim Ritter studied these signals systematically and developed a method to study teleseismic wavefield fluctuations together with Serge Shapiro (now Berlin). This method allowed us to determine the main parameters of a medium describing randomly distributed heterogeneities in the lithosphere (Ritter et al., 1998). Afterwards, this new approach was also successfully applied in other regions, e.g. the Fränkische Alb below the Gräfenberg array (Rothert & Ritter, 2000) the Baltic Shield (Hock et al., 2004) and the Chinese Lanzhou array (Shen & Ritter, 2010. Small-scale heterogeneities below the Lanzhou CTBTO seismic array, from seismic wavefield fluctuations, J. Seismology, 14, 481-493) .



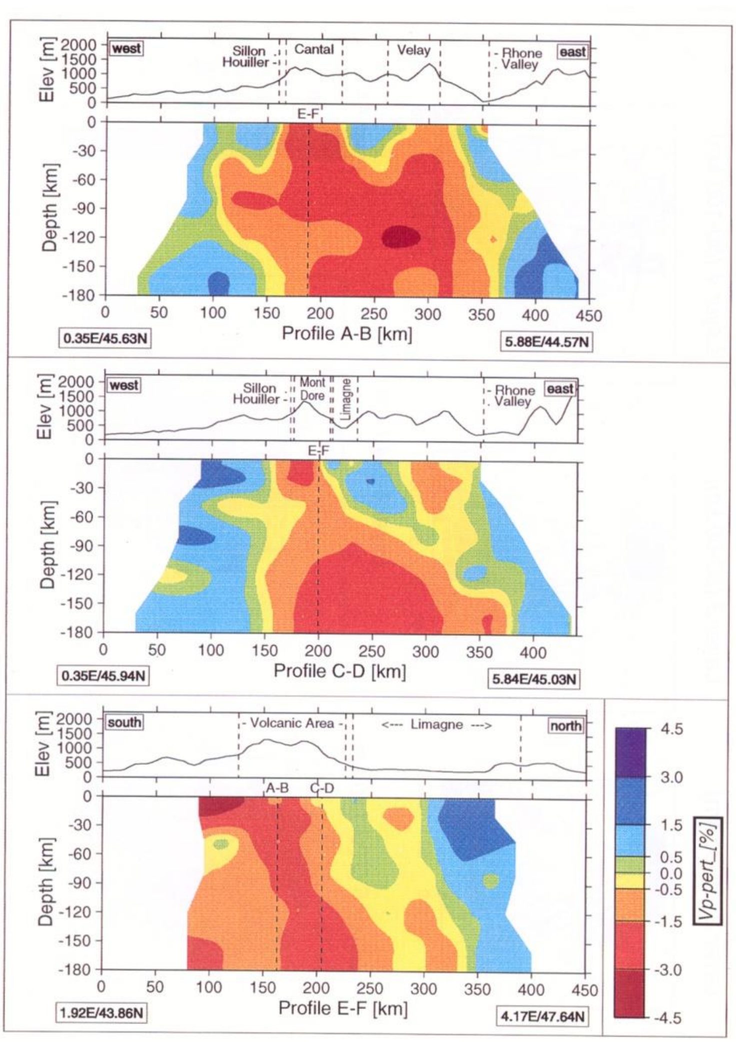


Fig. 9.13: Left: teleseismic network around the Massif Central with position of the cross sections. Right: vertical cross section through the 3-D velocity model with P-wave velocity variations (Δvp) down to 180 km depth. The reduction of vp is interpreted as signature of a mantle plume (from Granet et al., 1995).

Barth, A., Jordan, M. & Ritter, J.R.R., 2007. Crustal and upper mantle structure of the French Massif Central plume. In: Ritter, J.R.R. and Christensen, U.R. (eds.), Mantle Plumes – A Multidisciplinary Approach, Springer Verlag, Heidelberg, 159-184.

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Hock, S., Rothert, E., Ritter, J.R.R. & Korn, M., 2004. Mapping random lithospheric heterogeneities from the Baltic Shield to the Massif Central, France, Geophys. J. Int., 157, 251-264.

Ritter, J.R.R., Mai, P.M., Stoll, G. & Fuchs, K., 1997. Scattering of teleseismic waves in the lower crust. Observations in the Massif Central, France, Phys. Earth Planet. Interiors, Special Issue: Stochastic Seismology (eds. H. Sato, M. Korn & F. Scherbaum), 104, 127-146.

Ritter, J.R.R., Shapiro, S.A. & Schechinger, B., 1998. Scattering parameters in the lithosphere below the Massif Central, France from teleseismic wavefield records. Geophys. J. Int., 134, 187-198.

Rothert, E. & J.R.R. Ritter, 2000. Small-scale heterogeneities below the Gräfenberg array, Germany from seismic wavefield fluctuations of Hindu Kush events, Geophys. J. Int., 140, 175-184.

Shen X. & Ritter, J.R.R., 2010. Small-scale heterogeneities below the Lanzhou CTBTO seismic array, from seismic wavefield fluctuations, J. Seismology, 14, 481-493.

Sobolev, S., Zeyen, H., Stoll, G., Werling, F., Altherr, R. & Fuchs, K., 1996. Upper mantle temperatures from teleseismic tomography of French Massif Central including effects of composition, mineral reactions, anharmonicity, anelasticity and partial melt. Earth Planet. Sci. Lett., 139, 147-163.

Sobolev, S.V., Zeyen, H., Granet, M., Stoll, G., Achauer, U., Bauer, C., Werling, F., Altherr, R. & Fuchs, K., 1997. Upper mantle temperatures and lithosphere-asthenosphere system beneath the French Massif Central constrained by seismic, gravity, petrologic and thermal observations. In: Fuchs, K., Altherr, R., Müller, B., and Prodehl, C., (eds.) Stress and stress release in the lithosphere, Tectonophysics, 275, 143-164.

9.3 Experiments with stations of the GFZ Geophysical Instrument Pool Potsdam

The installation of the Geophysical Instrument Pool Potsdam (GIPP) at the GeoForschungsZentrum Potsdam (GFZ), including the provision of these instruments for experiments by external users allowed the GPI scientists to conduct teleseismic measurements with a large number of modern digital instruments. Using these instruments it was possible to record in continuous mode instead of triggered mode. The broadband sensors also allowed us to observe a wide frequency band of about 0.01-50 Hz of the seismic wavefields.

9.3.1 Romania

Within the framework of the CRC 461 *Strong Earthquakes*, which was funded between 1996 and 2007, several international experiments were done in Romania under the coordination by the Universität Karlsruhe (TH). The teleseismic experiment CALIXTO99 (Carpathian Lithosphere X Tomography) was intended to image the geometry of the the subducting slab underneath the Carpathians. Together with the cooperation partners of the National Institute for Earth Physics Bucharest (M. Radulian), the University of Bucharest (V. Mocanu), the University of Strasbourg (U. Achauer), the ETH Zürich (E. Kissling) and the University of Milano (G. Mussacio) Frank Lorenz and Michael Martin organized and headed CALIXTO99. The recordings of the national Romanian network and the strong motion network, which had been installed by Klaus-Peter Bonjer and his group (see Bonjer, this volume), were also integrated. In this way up to 110 temporary and 49 permanent stations recorded teleseismic events between May and November 1999. The Karlsruhe team was responsible for the 80 mobile stations borrowed from GIPP. The maintenance of the network across the Carpathian Arc required a big logistical effort which was coordinated by a temporary data centre in Bucharest. Afterwards the many different station types and their various data formats required another effort for pre-processing to produce a homogeneous dataset.

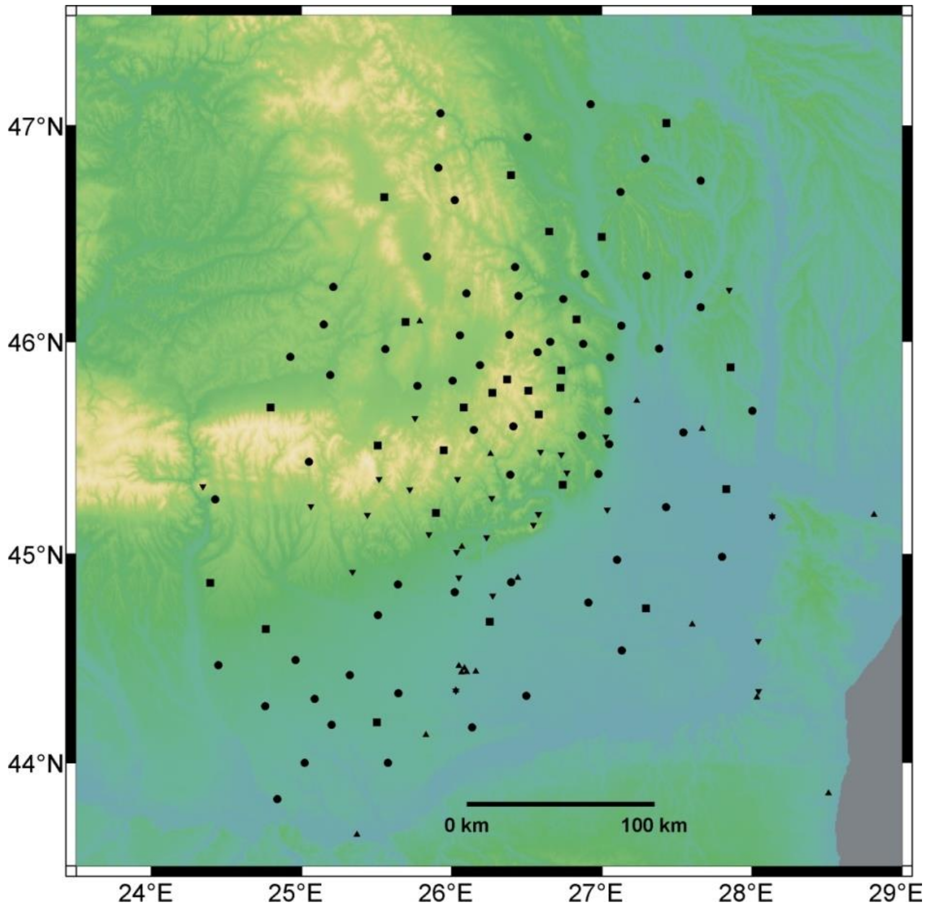

Fig. 9.14: CALIXTO'99 network across the Carpathian Arc. Squares: temporary broadband stations, circles: temporary short-period stations, triangles: permanent stations.

The 3-D tomography models (Martin et al., 2006; Weidle et al., 2005) display a zone of increased seismic velocity in which the hypocentres of the strong Vrancea earthquakes are located (Fig. 9.15). This zone is interpreted as subducting lithospheric plate and can be traced to about 350-370 km depth with the CALITXO dataset. With the addition of a global dataset the subduction zone can be imaged even deeper than 400 km (Weidle et al., 2005). The crust-mantle boundary (Moho) was also imaged in 3-D with the CALIXTO recordings. P-wave receiver functions were determined and analysed by Diehl & Ritter (2005). These results together with the seismic refraction models (see Prodehl this volume) were combined into a new Moho map for the region (Martin et al., 2005). By chance teleseismic events were recorded along the seismic refraction lines with their dense station spacing (VRANCEA99 and VRANCEA2001, see Prodehl, this volume). These recordings were used to study variations of seismic attenuation which can be correlated with the main tectonic units (Sudhaus & Ritter, 2005). Another passive experiment was conducted in 2003/2004 in Bucharest with KABBA instruments (see below).

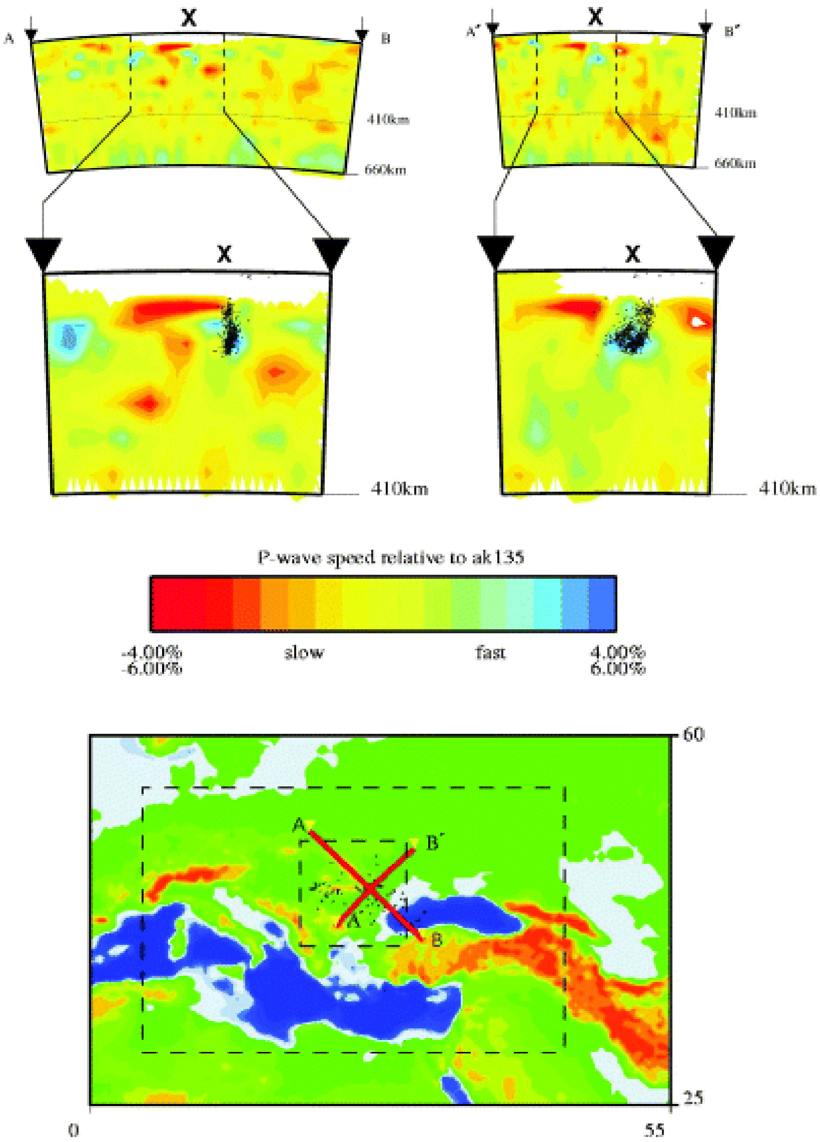

Fig. 9.15: Models with P-wave velocity perturbations (Δvp) south-eastern Europe. The top panels show Δvp down to 660 km depth at regional scale (A-B and A'-B'), the panels in the middle are enlargements down to 410 km in the Vrancea region. X is the crossing point of the profiles (Weidle, dissertation, 2005).

Diehl, T., Ritter, J.R.R. and CALIXTO Group, 2005. The crustal structure beneath southeastern Romania from teleseismic receiver functions, Geophys. J. Int., 163, 238-251.

Lorenz, F.P., 2000. Optimierung mehrdimensionaler Inversionsrechnungen zur Anpassung von Laufzeiten elastischer Wellen. Dissertation, Universität Karlsruhe (TH), Department of Physics.

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Martin M., J.R.R. Ritter and the CALIXTO working group, 2005. High-resolution teleseismic body wave tomography beneath SE-Romania (I): Implications for 3D vs. 1D crustal correction strategies with a new crustal velocity model. Geophys. J. Int. 162, 448-460.

Martin, M., Wenzel, F. and the CALIXTO working group, 2006. High-resolution teleseismic body wave tomography beneath SE-Romania (II): Imaging of a slab detachment scenario. Geophys. J. Int., 164, 579-595.

Sperner,B., Lorenz, F.P., Bonjer, K.-P., Hettel, S., Müller, B. & Wenzel, F., 2001. Slab break-off – Abrupt cut or gradual detachment? New insights from the Vrancea region (SE-Carpathians, Romania). Terra Nova, 13, 172-179.

Sudhaus, H. & Ritter, J.R.R., 2005. High-resolution measurement of the seismic attenuation across the Vrancea region, Romania. Geophys. Res. Lett., 32, L10301, 1-4.

Weidle, C., 2005. The velocity structure of Earth's upper mantle beneath the Eastern Carpathians – Implications from traveltime inversion and amplitude analysis. Dissertation, Universität Karlsruhe (TH), Department of Physics, 145 p.

Weidle, Ch., Widiyantoro, S. & CALIXTO Working Group, 2005. Improving depth resolution of teleseismic tomography by simultaneous inversion of teleseismic and global P-wave traveltime data – application to the Vrancea region in Southeastern Europe. Geophys. J. Int., 162, 811-823.

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9.3.2 Ireland

There is a longstanding close relationship between GPI and the Dublin Institute of Advanced Studies (DIAS) mainly based on joint seismic refraction projects (see Prodehl, this volume). In 2002 GPI was invited to participate in an experiment to study the deep structure of Ireland, especially the Iapetus Suture Zone and the lithosphere-asthenosphere system below it. GPI was funded with a DFG grant to support the Irish Seismological Lithospheric Experiment (ISLE). Michael Landes coordinated together with Joachim Ritter the contribution by Karlsruhe. In southern and central Ireland Michael Landes installed eight PDAS-100 recorders with Mark 1 s seismometers provided by GIPP. Together with the 15 mobile broadband stations of DIAS and four permanent stations in total there was network of 27 stations (Landes et al., 2004 and Fig. 9.16).

Cows proved to be a major local source of seismic noise during the measurements which was partly due to the fact that many stations were deployed on remote farms. During the experiment all previous existing models for the Irish lithosphere are gathered and integrated into a new joint model (Landes et al., 2005). Using the ISLE recordings teleseismic P-wave receiver functions were calculated for mapping the Moho (Landes et al., 2006). The lithosphere-asthenosphere boundary (LAB) underneath Ireland was mapped for the first time based on S-wave receiver functions. The LAB topography shows a systematic thinning of the lithosphere from south to north underneath Ireland. This was interpreted with thermal erosion of the lithosphere during the opening of the North Atlantic and the magmatism related to the Iceland plume (Landes et al., 2007). A tomography study with the ISLE dataset revealed a reduction of the *P*-wave velocity which could be also explained with an upwarping of the asthenosphere in the northern part of Ireland (Wawerzinek et al., 2008).

Do, V.C., Readman, P.W., O'Reilly, B.M. & Landes, M., 2006. Shear-wave splitting observations across southwest Ireland. Geophys. Res. Lett., 33, L03309.

Landes, M., Ritter, J.R.R., Do, V.C., Readman, P.W. & O'Reilly, B.M., 2004. Passive teleseismic experiment explores the deep subsurface of Southern Ireland. Eos Trans. Am. Geophys. Union, 85, 337-341.

Landes, M., Ritter, J.R.R., Readman, P.W. & O'Reilly, B.M., 2005. A review of the Irish crustal structure and signatures from the Caledonian and Variscan Orogenies. Terra Nova, 17, 111-120.

Landes, M., Ritter, J.R.R., O'Reilly, B.M.O., Readman,P.W. & Do, V.C., 2006. A N-S receiver function profile across the Variscides and Caledonides in SW Ireland. Geophys. J. Int., 166, 814-824.

Landes, M., Ritter, J.R.R. & Readman, P.W., 2007. Proto-Iceland plume caused thinning of Irish lithosphere. Earth & Planetary Sci. Lett., 225, 32-40.

Wawerzinek, B., Ritter, J.R.R., Jordan, M. & Landes, M., 2008. An upper mantle upwelling underneath Ireland revealed from non linear tomography. Geophys. J. Int., 175, 253-268.

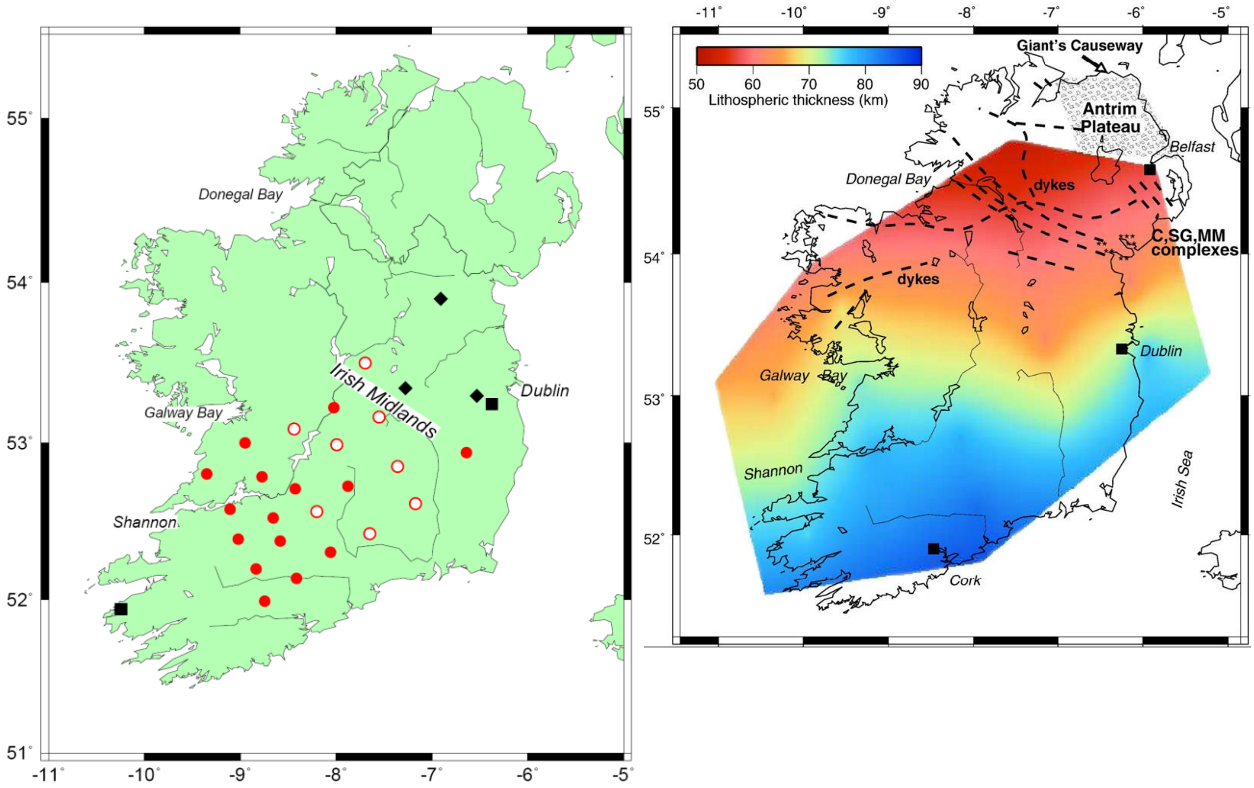
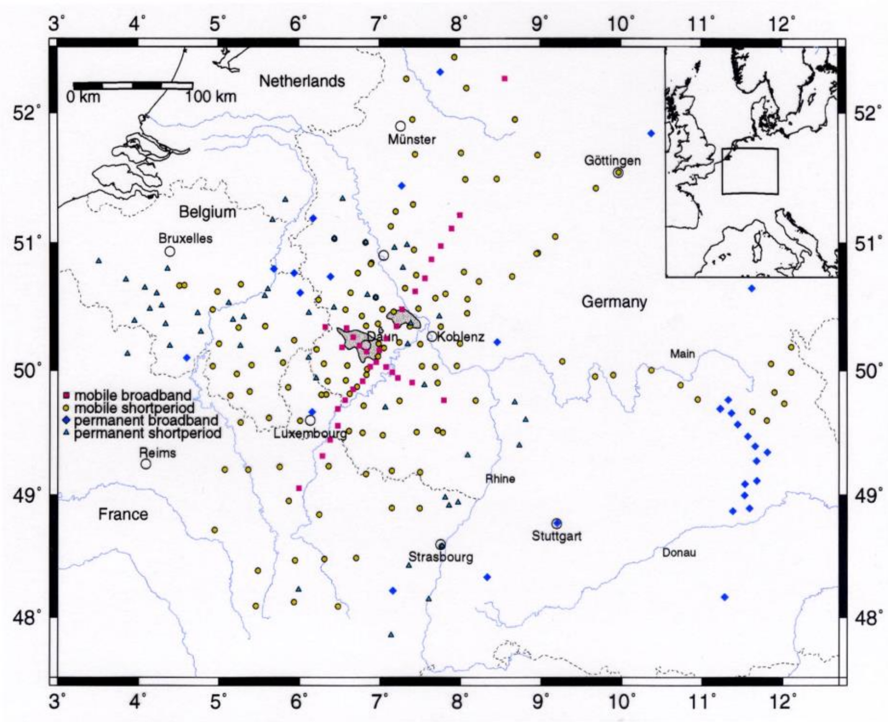


Fig. 9.16: Left: Map of Ireland with the station sites of the ISLE experiment, black squares and diamonds indicate permanent broadband and short-period stations, red and white circle indicate mobile broadband and short-period stations. Right: Map of the lithospheric thickness and Tertiary volcanic structures in the northern of Ireland (after Landes et al., 2007).

9.3.3 Eifel

The Eifel region is a mountain area in the western part of Germany which was volcanically active since the past 600,000 years. The latest eruptions occurred only 12,200 years and 10,800 years ago, volcanic gas emission is still ongoing and future eruptions can be expected. The study of the magma source in the upper mantle underneath the Eifel started with a major field experiment from Nov. 1997 to June 1998 under the guidance of the University of Göttingen and the participation of many student helpers from Karlsruhe. More than 150 short-period and broadband temporary stations were deployed between 90 permanent stations to achieve a homogeneous network; about 90 instruments were provided by the GIPP. The main result was an upper mantle plume as source for the volcanism (Ritter, 2007). After 2002 the dataset was available in Karlsruhe and new studies concentrated on the upwarp of the asthenosphere in connection with the plume head which had been proposed by the Göttingen group. Jan Mathar studied the surface waves which were recorded at the 41 broadband temporary and permanent stations in the wider region. In cooperation with Wolfgang Friederich (previously Karlsruhe, now Bochum) dispersions curves and 1-D shear wave velocity profiles were determined from Rayleigh waves (Mathar et al., 2007) and Love waves (Mathar et al., 2006). These models contain a velocity reduction at about 50-60 km depth. Similar results had been found before and later using KABBA data and they imply a significant upwarp of the lithosphere-asthenosphere boundary. In this way, the model of the first teleseismic experiment in the Rhenish Shield (see above) was confirmed and refined due to the increased resolution of the Eifel plume experiment. Under the assumption of petrophysical constraints the seismological model of the Eifel Plume was interpreted and the mass transport in mantle was estimated (Ritter, 2005 and Fig. 9.17). This calculation resulted in a minor buoyancy flux of about 50 kg/s (Fig. 9.17) and a mass flux of 300 million tons per year.



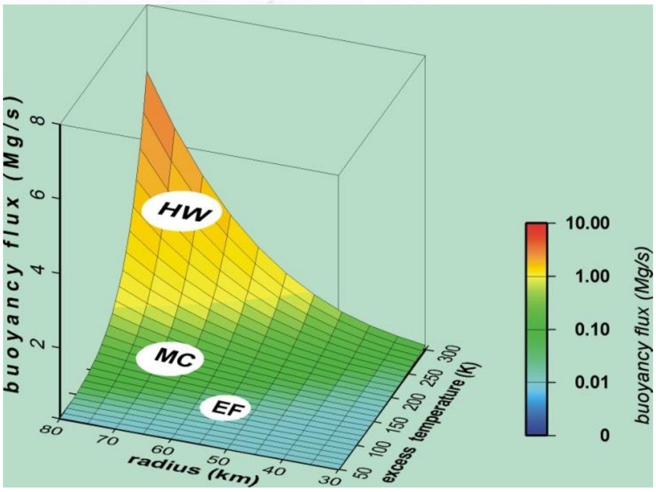


Fig. 9.17: Top: station network of the Eifel Plume project 1997/98; right: estimation of the buoyancy flux of mantle plumes HW: Hawaii, MC: Massif Central, EF: Eifel following Ritter (2005).

Mathar, J.P., Ritter, J.R.R. & Friederich, W., 2006. Surface waves image the top of the Eifel plume. Geophys. J. Int., 164, 377-382.

Mathar, J., Friederich, W. & Ritter, J.R.R., 2007. Rayleigh wave dispersion in the Eifel region. In: Ritter, J.R.R. & Christensen, U.R. (eds.), Mantle Plumes – A Multidisciplinary Approach, Springer Verlag, Heidelberg, 417-437.

Ritter, J.R.R., 2005. Small-scale mantle plumes: Imaging and geodynamic aspects. In: Wenzel, F., Perspectives in Modern Seismology, Lecture Notes in Earth Sciences, 105, Spinger-Verlag, Heidelberg, 69-94.

Ritter, J.R.R., 2007. The seismic signature of the Eifel plume. In: Ritter, J.R.R. & Christensen, U.R. (eds.), Mantle Plumes – A Multidisciplinary Approach, Springer Verlag, Heidelberg, 379-404.

Ritter, J.R.R., Mathar, J., Jordan, M. & Gabriel, G., 2007. Gravity observations in the Western Rhenish Massif and forward modelling of the Eifel plume Bouguer anomaly. In: Ritter, J.R.R. & Christensen, U.R. (eds.), Mantle Plumes – A Multidisciplinary Approach, Springer Verlag, Heidelberg, 465-476.

9.3.4 Cape Verde

The Cape Verde Islands form a volcanic archipelago in the Atlantic Ocean in front of the west coast of Africa. The ocean bottom is at nearly 4000 m depth and the volcanoes reach up to nearly 2900 m above sea level (Pico de Fogo volcano, last eruption in 1995). The enormous amount of magmatic melt is explained with a mantle plume. In 2002 a group of German and Portuguese seismologists started an initiative to study this plume in details. The plan included a dedicated amphibious field experiment with land and ocean bottom seismometers. Following problems with funding in Germany, the field work could only start after the Portuguese funding was granted to Graca Silvera (University of Lisbon) and the partner in Cape Verde (Instituto Superior de Educacao) supported the project. The German collaborators GFZ Potsdam, Universität Karlsruhe (TH) and University of Frankfurt contributed with internal funds and in this way the COBO Project (Cape Verde's Origin from Broadband Observations) could finally be realized in 2007. Between November 2007 and September 2008 39 broadband stations from the GIPP recorded on nine islands of the Cape Verdes. The station deployment was assisted by Werner Scherer who did two trips to the Cape Verdes, of which the first one was very relaxed because the delivery of the instruments was delayed.

The recordings were archived at the GFZ Potsdam and then analysed by the project partners. Julian Eisenbeis studied the travel time residuals of the teleseismic P-phases at the GPI and applied the finite frequency methodology together with Karin Sigloch (LMU Munich). As measurements could be done only on the islands the station coverage was not enough to image a seismic contrast between the plume and the surrounding mantle. Thus a clear anomaly due to the Cape Verde plume could not be recovered but the travel time variations indicate lateral heterogeneities related to the magmatic processes within the archipelago.

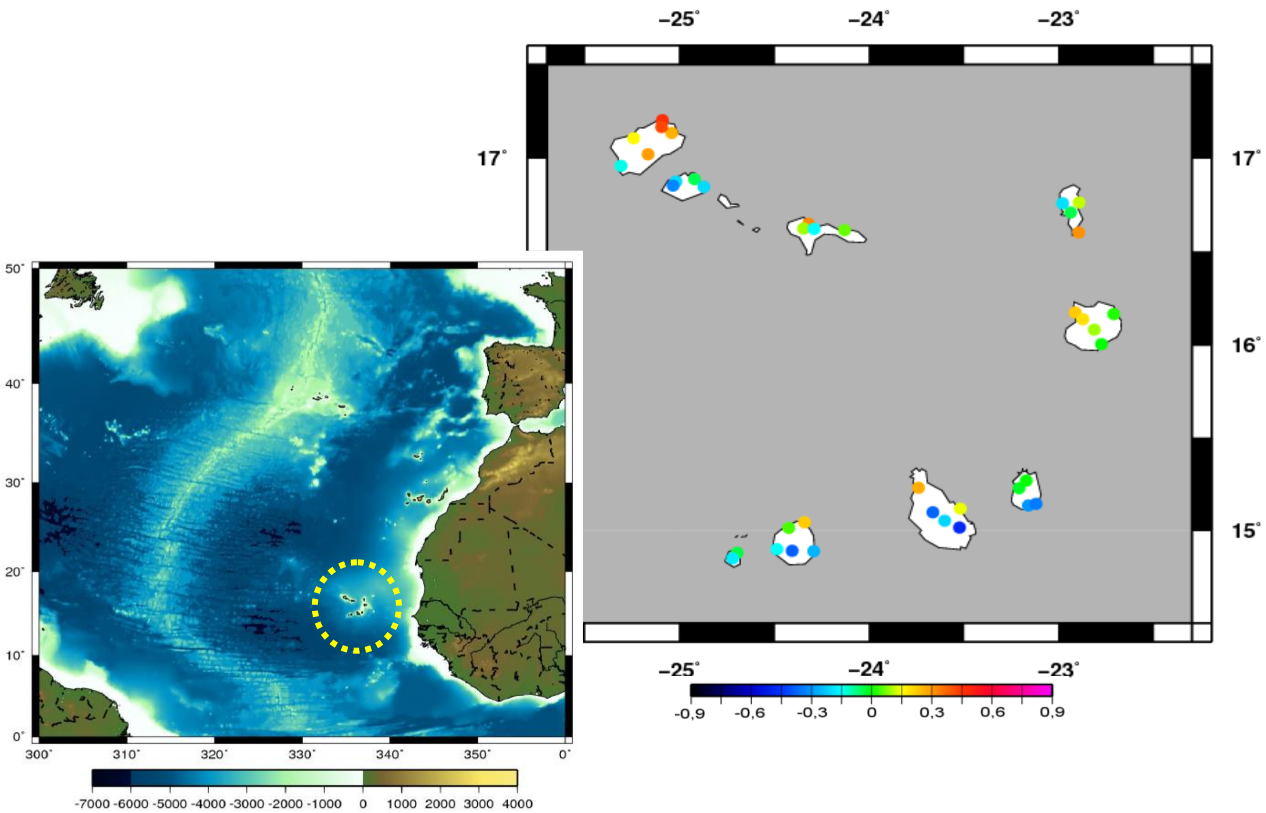


Fig. 9.18: Left: map of the Central Atlantic with the Cape Verde Islands (yellow circle). Right: station deployment of the COBO experiment 2007/08. The colour code displays travel time residuals in seconds for the earthquake source region South Sandwich Islands (wave incidence from south) (courtesy of J. Eisenbeis).

9.4 KABBA Experiments

The availability and operation of one's own instruments is a crucial premise for innovative and successful experimental seismology. If there are own instruments available, these can be deployed rapidly in areas where a current scientific question is a burning issue. The duration of an experiment with own stations is not limited and one does not need to consider instrument reservations by other scientists. This point is quite important, as for example teleseismic experiments require increasingly longer observation times (2-3 years) to better record wavefields from rare backazimuth regions as well as low-amplitude signals such as mode converted phases. Another point is that own instruments can be used to buy one into a major experiment in which instruments and data are shared between institutions.

GPI recognised these advantages and Friedemann Wenzel used his appointment funds to acquired 31 mobile broadband stations as basis for the KArlsruhe BroadBand Array (KABBA). As recording unit the Earthdata Logger PR24 (EDL) with a 24-bit digitizer was chosen which was also used at GIPP and thus could be easily deployed in joint projects. Broadband sensors were chosen to record a wide frequency band which allows many aspects of seismological research. The first sensors were six Geotech KS-2000 (0.05-100 s free period) and 21 Streckeisen STS-2 (0.05-120 s). Three Güralp sensors (0.05-30 s) were already available at GPI. Tobias Diehl, Petra Knopf, Rainer Plokarz, Joachim Ritter, Werner Scherer und Hartmut Thomas were involved in the technical implementation of KABBA and the KABBA datacentre. Many components were delivered in parts and numerous cables, plugs, boxes etc. had to be configurated and assembled. The organization of the data processing was also of importance because continuous data acquisition was planned. With a sampling rate of 50-100 data points per second a yearly data volume of one terrabyte could be expected for processing and archiving. Thus many codes had to be written, implemented and tested for an automation of the data processing.

The first test of KABBA was performed in a large barracks building of the Bundeswehr (German army) in Huchenfeld near Pforzheim (Fig. 9.19). All KABBA stations were installed and recorded simultaneously for two months in summer 2003. Minor malfunctions of the instrument configuration were identified and eliminated as well as the operators were trained with the handling of the instruments. Another output was the calibration of the recorded ground amplitudes before the first installation in Bucharest.

Since 2002, eleven additional KABBA stations were acquired in the framework of different projects. The sensors were chosen according to the requirements of the specific project aims: three Lennartz LE-3D 5 s (0.05-5 s), three Lennartz LE-3D lite (0.01-1 s), two Lennartz BH (borehole) (0.01-1 s) und three Nanometrics Compact (0,01-120 s). Following an initiative of Friedemann Wenzel real-time data transmission was started in 2007. After several tests data transmission by mobile phone technology was identified as a stable solution. One of the first tests was done with a provider from Turkey and a recorder in the electronic laboratory at GPI. The data were transferred to Turkey via mobile phone and internet and then back to Germany into the intranet of the university where we could observe the waveforms in near real time on a computer screen. Such real time recordings were later used for several projects, see below. In February 2012 the first KABBA borehole observatory with a Lennartz seismometer (BH, 1 s) was installed near Landau, the second followed in September 2013. These recordings were transmitted to the KABBA datacentre where Jörn Groos installed the *SeisComP3* system with *arclink* (GFZ development) Potsdam) including an online *miniSEED* archive with external data access at http://gpikabba.gpi.kit.edu/ .

Fig. 9.19: Top: first test measurements with the KArlsruhe BroadBand Array near Huchenfeld, Pforzheim (from left: T. Diehl, J. Ritter & J. Mathar). Different sensor types can be seen (red: Geotech KS-2000, green: Streckeisen STS-2, blue: Lennartz 5 s, silver: Güralp 40T). Bottom: Orientation and installation of a Lennartz borehole seismometer near Landau (Fig. 9.29) with W. Walker.

9.4.1 Bucharest

The first major experiment using KABBA instruments was done in Bucharest, the capital of Romania within the CRC 461 on "*Strong Earthquakes*". The URS project (URban Seismology) was pioneering because for the first time a broadband network was installed in a major city despite the expected high noise level. Instead of carefully selecting quiet (low noise level) sites at remote places far from settlements, the instruments were running for 10 months inside a lively city (Fig. 9.20). This experimental setting was necessary because Bucharest is endangered by the strong earthquakes of the Vrancea Zone and local properties affecting wave amplitudes should be studied. The recording sites were selected by the cooperation partner Stefan Balan from the National Institute for Earth Physics (NIEP). The URS network (Fig. 9.20) was installed by the GPI (PI Joachim Ritter with Tobias Diehl, Jan Mathar and Werner Scherer,) together with scientists and technicians from NIEP in October 2003. The URS network recorded numerous small Vrancea earthquakes and many teleseismic events until August 2004 (Ritter et al., 2005). There were no significant stations failures but some minor local misunderstanding. E.g. at one site, the STS-2 seismometer was displaced without locking it by the people living in house as they decided suddenly that they would need the place themselves. At another site the STS-2 was put onto a box to prevent it from possible water on the ground.

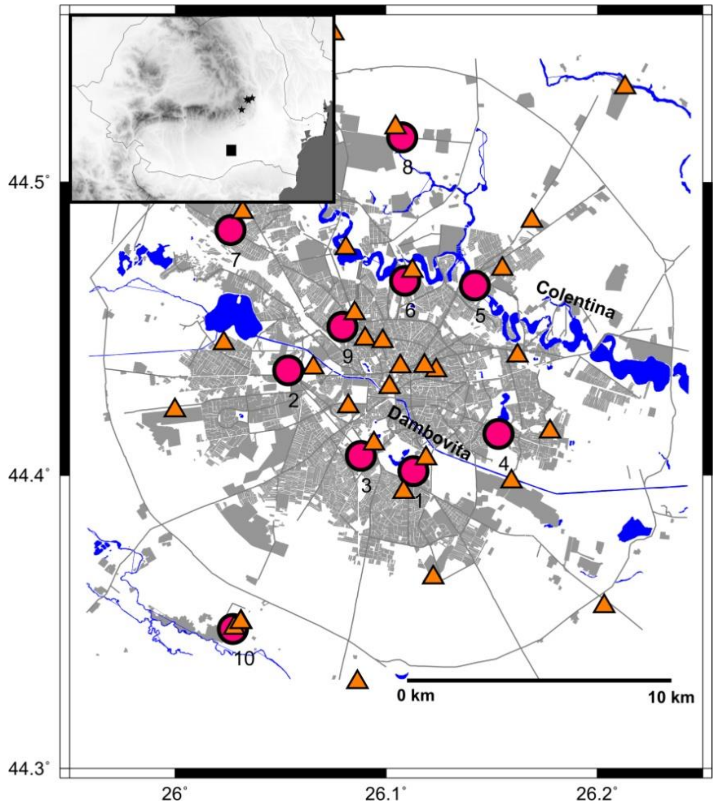


Fig. 9.20: Experimental layout for Bucharest urban projects: orange triangles indicate sites of the URS network (2003/04), red circles are locations of boreholes drilled within a NATO-funded project.

URS was a great success and the recordings were analysed with various techniques covering broad scientific aspects. The site effects for wave amplitude amplification which control the intensity of the earthquake waves were determined using the concept of phantom sites (Bartlakowski et al., 2006). The broadband recordings were also used to study the amplitude variation over a wide frequency band of 0.14-8.6 Hz. This analysis revealed interference effects in the inclined sedimentary layers (Sudhaus & Ritter, 2009). Of special interesting was the identification and quantification of the seismic background noise in the city of Bucharest. Daily and weekly cycles of the noise intensity were found which look like the heartbeat of a city (Fig. 9.21). Jörn Groos developed a statistical method to quantitatively describe noise recordings (Groos & Ritter, 2009) and he received the *Werner von Siemens Exzellenz Award* 2007 and the *Best Student Paper Award* 2010 of *Geophysical Journal International*. The large-scale shear wave velocity (*vs*) structure underneath Bucharest was determined using surface waves (Sèbe et al., 2009). In addition shallow seismic refraction profiles were measured in parks in Bucharest (von Steht et al., 2009) in order to determine vs_{30} (*vs* in the upper 30 m depth as described in the EUROCODE). Furthermore, funding was provided through a *NATO Science for Peace Project* which was done together with NIEP to drill ten 50 m deep boreholes for geotechnical measurements and a vertical seismic profiling analysis (Bala et al., 2009 & 2010).

Bala, A., Balan, S.F., Ritter, J. & Hannich, D., 2009. Seismic site effect modelling based on in situ borehole measurements in Bucharest, Romania, in: Schanz, T. and Iankov, R. (eds.), Coupled site and soil-structure interaction effects with applications to seismic risk mitigation, NATO Science for Peace and Security Series C: Environmental Security, Springer, 101-111.

Bala, A., Hannich, D., Ritter, J.R.R. & Ciugudean-Toma, V., 2011. Geological and geophysical model of the Quaternary layers based on in situ measurements in Bucharest. Rom. Rep. Phys., 63, 250-274.

Bartlakowski, J., Wenzel, F., Radulian, M., Ritter, J.R.R. & Wirth, W., 2006. Urban shakemap methodology for Bucharest, Geophys. Res. Lett., 33, L14310.

Groos, J.C., 2010. Broadband Seismic Noise: Classification and Green's Function Estimation. Dissertation, Karlsruhe Institute of Technology, Department of Physics, 154 pp

Groos, J. & Ritter, J.R.R., 2009. Time domain classification and quantification of seismic noise in an urban environment. Geophys. J. Int., 179, 1213-1231.

Ritter, J.R.R., Balan, S.F., Bonjer, K.-P., Diehl, T., Forbriger, T., Mărmureanu, G., Wenzel, F. & Wirth, W., 2005. Broadband urban seismology in the Bucharest metropolitan area. Seism. Res. Lett., 76, 573-579.

Sèbe, O., Forbriger, T. & Ritter, J.R.R., 2009. The shear wave velocity underneath Bucharest city, Romania, derived from surface waves, Geophys. J. Int., 176, 965-979.

Sudhaus, H. & Ritter, J.R.R., 2009. Broadband frequency-dependent amplification of seismic waves across Bucharest, Romania, J. Seismology, 13, 479-497.

von Steht, M., Jaskolla, B. & Ritter, J.R.R., 2008. Shallow shear wave velocity in a City: A study in Bucharest, Romania, Nat. Hazards Earth Syst. Sci., 8, 1299-1307.

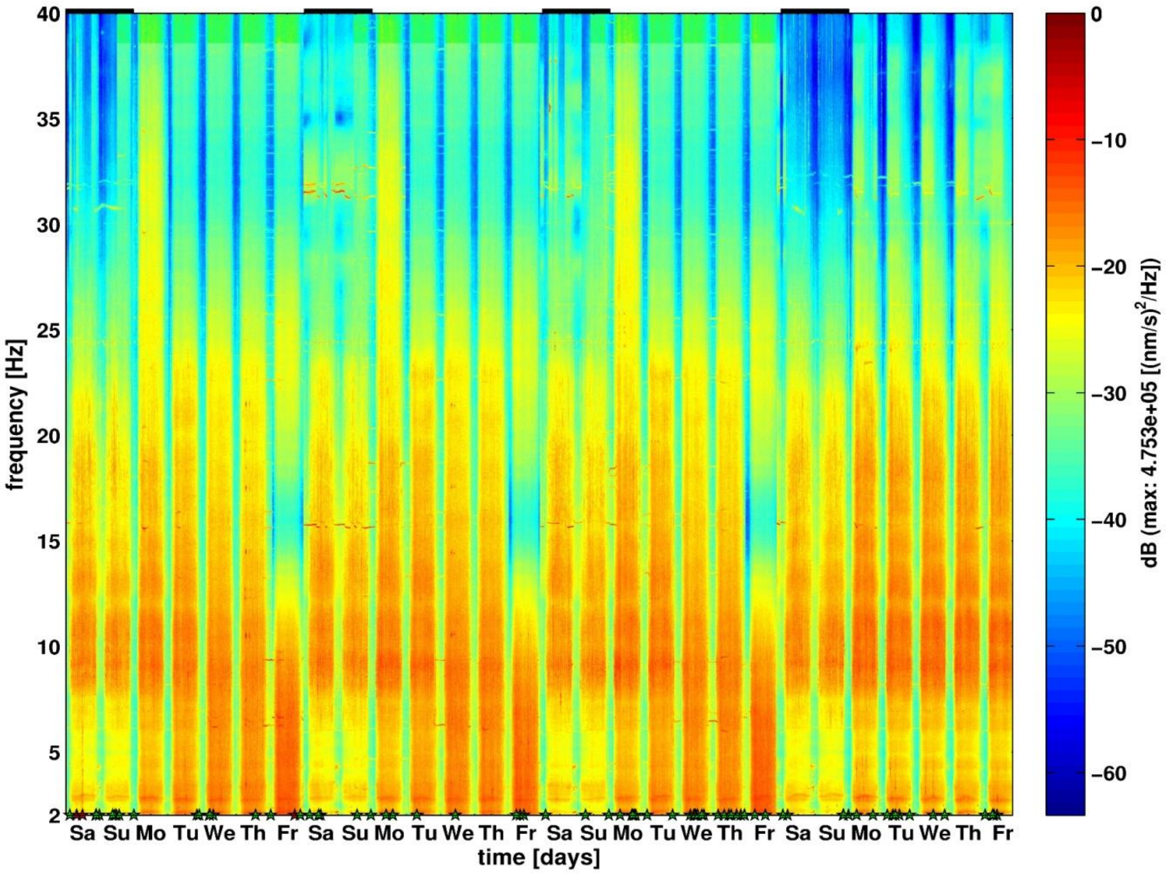


Fig. 9.21: Spectrogramme of a site in Bucharest, the capital of Romania, with the power spectral density in decibel for four weeks: there is a daily and a weekly rhythm of the background seismic noise. Thick bars at the top indicate weekends, stars at the bottom local and teleseismic events (courtesy of J. Groos).

9.4.2 Upper Rhine Graben

In autumn 2004 a field experiment was planned to study the deep structure of the Upper Rhine Graben (TIefenstruktur des Mittleren Oberrheingrabens, TIMO). The concept was to use broadband recordings and modern waveform analysis methods for a continental rifting study (Ritter et al., 2008). Two recording lines were equipped with KABBA stations (Fig. 9.22): an E-W station line from Stuttgart to Walferdange (Luxembourg) including the permanent stations STU und WLF. A second SW to NE station line was running from Bad Bergzabern to the Odenwald Mountains (Fig. 9.22). Recording was done from December 2004 until May 2006 and it included the great Sumatra earthquake on Christmas 2004 (Mw = 9.1) which was observed with half of the network which was already in place.

The data analysis was done with several methods. Applying array techniques, teleseismic wavefronts were analysed with respect to their travel time, backazimuth and slowness; however, no deep reaching seismic velocity anomaly was resolved (Kirschner et al., 2011). A splitting analysis of SKS-phases did also not indicate an anomaly in anisotropy related with the graben (Wagner & Ritter, 2013). *S*-to-*P* converted waves were analysed with the receiver function method to characterize seismic discontinuities such as the crust-mantle boundary (Moho) and lithosphere-asthenosphere boundary (LAB). This study confirmed earlier seismic refraction results with a relatively flat Moho at 27-30 km depth. *S-P* conversions at delay times of 6.5-10.5 s (Fig. 9.23) were interpreted as signals from the LAB (Seiberlich et al., 2013). The LAB below the Upper Rhine Graben was found at a depth of about 60 km. Towards east below the Swabian Alb, the LAB dips downwards to nearly 80 km depth. Interestingly, below the volcanic Eifel region a very shallow LAB at only 41 km depth was discovered, in agreement with other measurements based on the Eifel Plume project (see above).

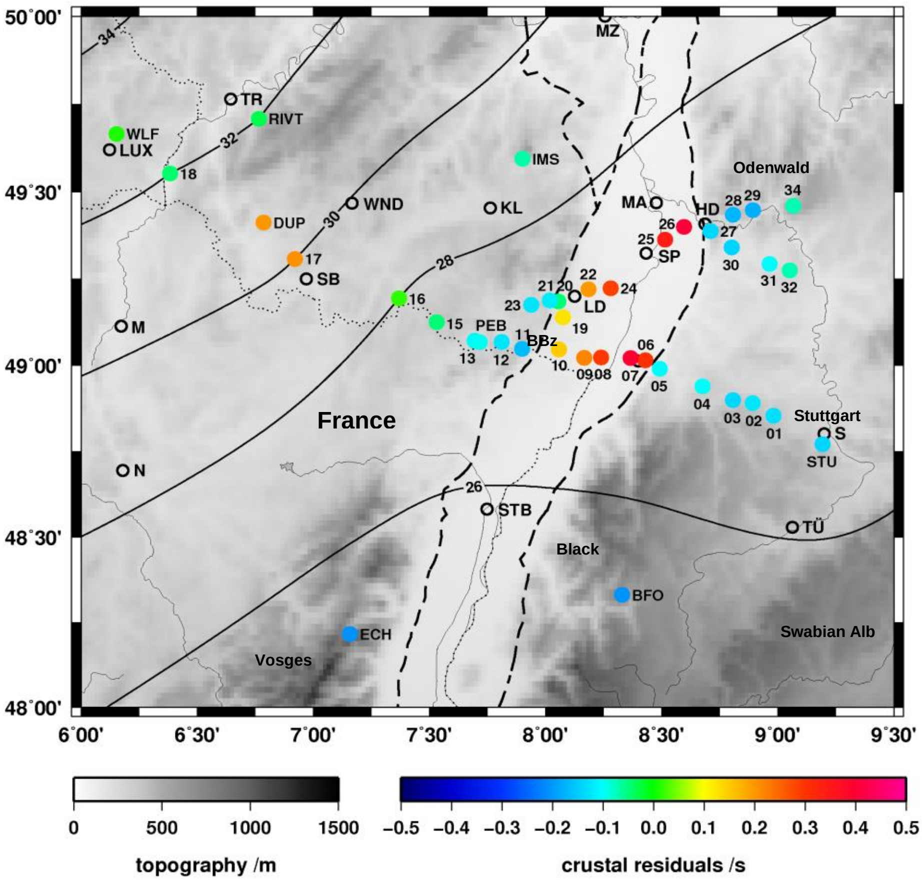


Fig.9.22: Station map of the TIMO experiment (2004-2006). The colours indicate average travel time residuals for P-waves due to variations in crustal structure and thickness. Contour lines show known crustal thickness.

Some weak local events events ($M_L < 3$) in the Upper Rhine Graben near Heidelberg and Speyer were recorded and analysed. These events were put together with previous events to compile the seismicity of the Central Upper Rhine Graben (Fig. 9.23). A surprising result was the occurrence of normal faulting in lower crust underneath the Speyer area. This finding indicates current rifting activity down to the lower crust (Ritter et al., 2009a).

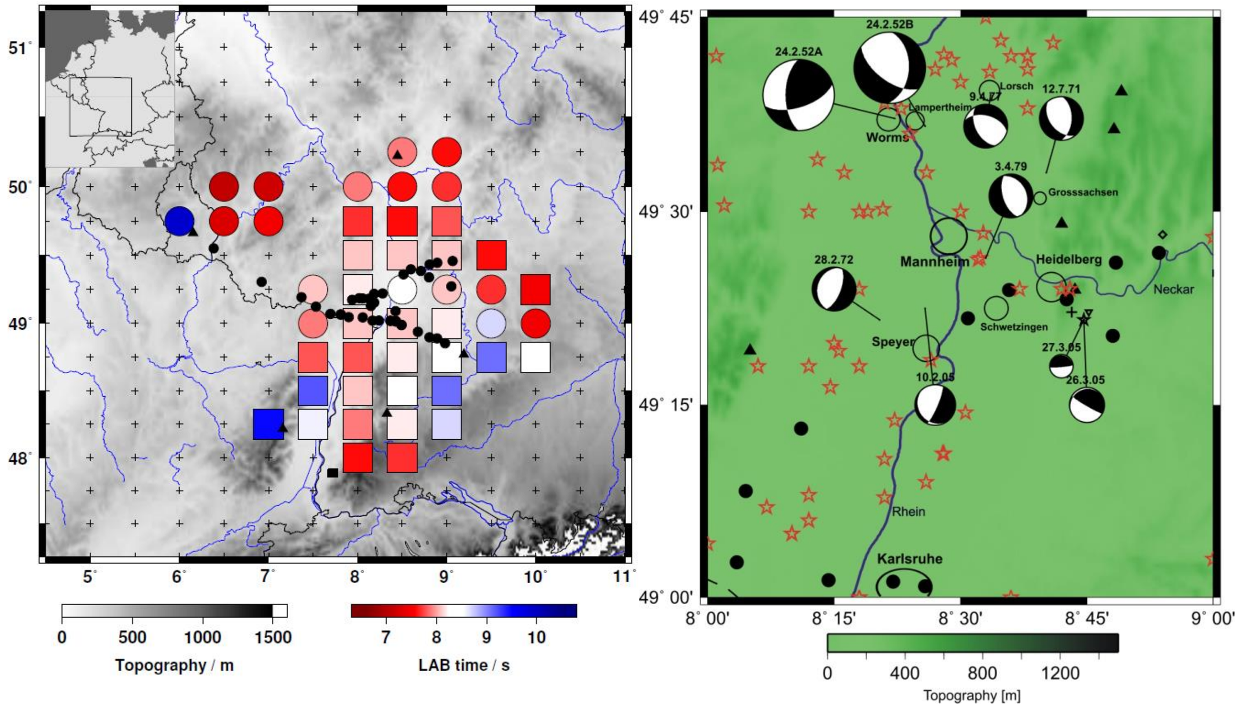


Fig. 9.23: Left: map with delay times of a negative amplitude phase in S-wave receiver functions. This phase is interpreted to be generated the lithosphere-asthenosphere boundary and increasing delay time can be explained with increasing LAB depth (depth in kilometres about 8 times the delay time in seconds). Numbers indicate common conversion points (after Seiberlich et al., 2013). Right: summary of the seismicity between Karlsruhe and Speyer in the Central Upper Rhine Graben; red stars are instrumentally recorded earthquakes (1973-1997) and fault plane solutions up to year 2005 displayed (after Ritter et al., 2009a).

Two TIMO stations, TMO07 in the basement of the GPI main building and TMO44 in Durlach (a suburb east of Karlsruhe), have been installed in a nearly permanent way. Thus quasi long-term measurements are available for specific studies as well as there are recordings to characterise events close to Karlsruhe, e.g. for outreach activities. During winter storm Kyrill in January 2007 the recordings at TMO44 were used to describe the ground motion behaviour during the passage of a storm front (Ritter & Groos, 2007). Systematic studies on the influence of weather phenomena on the seismic background motion were done during the METSEIS project. In collaboration with the KIT Institute of Meteorology and Climate Research (Christian Hauck, now Fribourg) four KABBA stations were installed close to meteorological stations between May 2007 and May 2008 within a KIT Start-Up-Budget project (Fig. 9.24). In addition data from four permanent broadband stations (BFO, STU, TNS and WLF) were included which are close to stations of the Deutscher Wetterdienst (DWD, Germany's National Meteorological Service) which provided time series of different meteorological parameters such as wind, air pressure, precipitation etc. The data analysis gained quantitative insight into the relationships between ground motion, wind and near-surface site conditions (Ritter et al., 2009b).

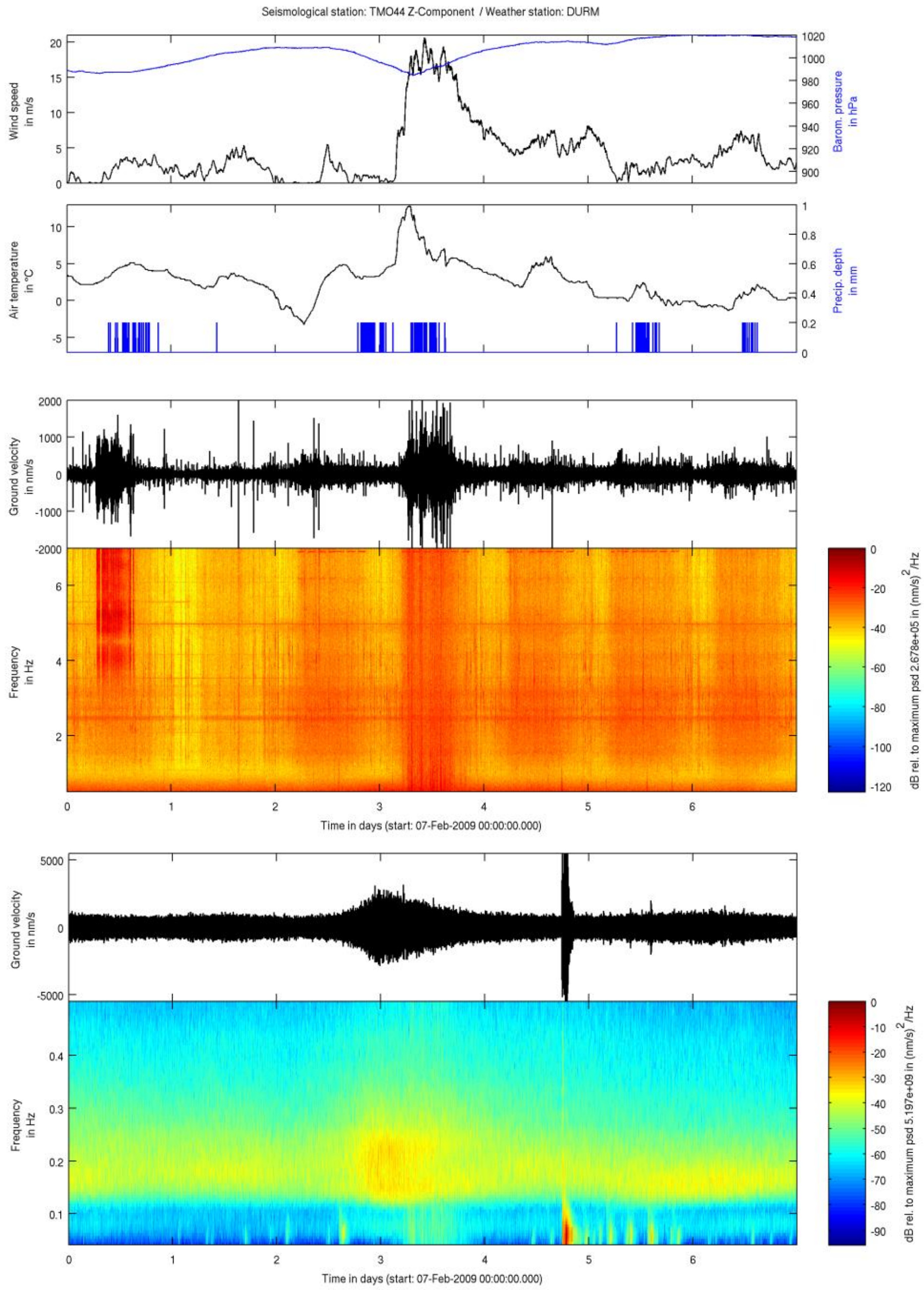


Fig. 9.24: Weather parameters (top 1: wind velocity & air pressure, top 2: temperature & precipitation) and seismic recordings (centre 1-7 Hz, bottom 0.03-0.5 Hz) in Durlach (Ritter et al., 2009b) between 7th and 13th February 2009. During the passage of a depression front on 9th/10th February the background seismic noise is clearly amplified. On 11th February there are the waves of a Kepulauan Talaud islands (Indonesia) earthquake (Mw = 7.2) which are well observed at low frequencies (<0.1 Hz).

In the town Staufen im Breisgau, in the Southern Upper Rhine Graben, the ground started to rise due to defective drill holes in autumn 2007. Water had come in contact with dry anhydrite at 60-70 m depth and it started to swell due to chemical reactions. This swelling resulted in uplift rates of up to 11 mm/month causing severe damage (2013: about 50 million EURO damage and still reduced uplift rates after countermeasures). The high deformation rates exceed natural processes by far and thus the KIT institutes involved in geophysics, geodesy and geology started a joint monitoring project and received a KIT Start-Up Budget grant. It was expected that the ductile deformation at depth may cause fracture in the overlying competent sandstone layers; the aim of the geophysics programme was to search for related micro-earthquakes. A network called URS2 (URban Seismology 2) of eight KABBA stations was designed and recorded between May 2008 and May 2009 in Staufen (Fig. 9.25). In addition mini-arrays were deployed for one night when an active source (SISSY) was fired at several sites to study the seismic velocity structure. This active part was quite successful whereas micro-earthquakes were not observed. This was probably due to the high noise level inside the town. Later, the URS2 data were used for studying the deeper structure of the Upper Rhine Graben (receiver functions, SKS splitting)

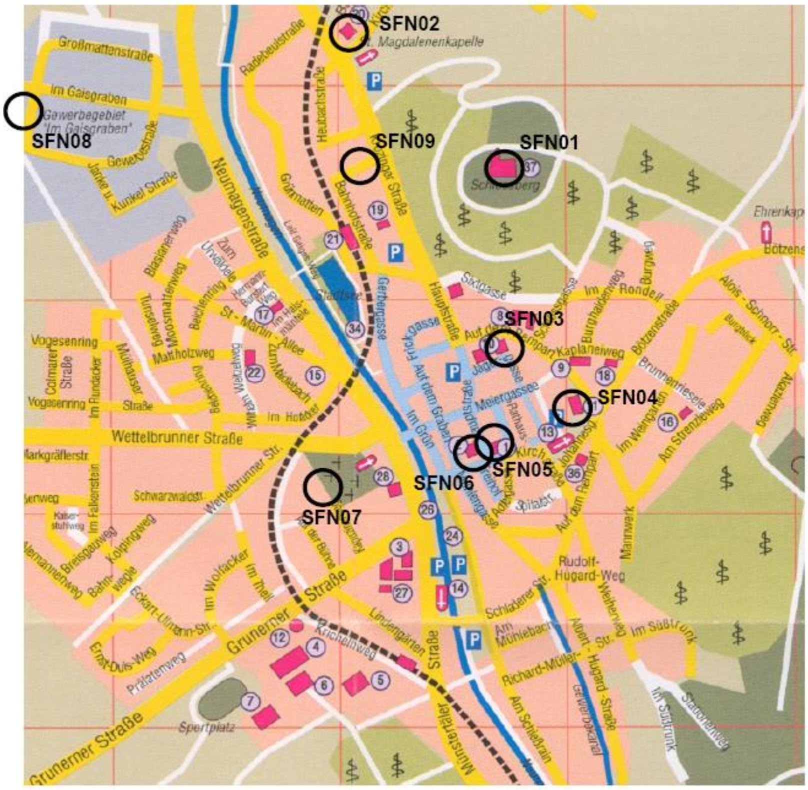


Fig. 9.25: Station map of the URS2 experiment (2008/09) inside the town of Staufen im Breisgau, Southern Upper Rhine Graben. The main uplift was at stations SFN06 and SFN05 in the centre.

Baumann, T., Ritter, J. and Köhler, A., 2010. Seismological signal classification in an urban environment using self-organizing maps. European Seismological Commission, 32nd General Assembly, Montpellier, France, Abstracts, 262.

Kirschner, S., Ritter, J.R.R. & Wawerzinek, B., 2011. Teleseismic wave front field anomalies at a continental rift: no mantle anomaly below the Central Upper Rhine Graben, Geophys. J. Int., 186, 447-461.

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Ritter, J.R.R., Thun, J., Groos, J., Wenzel, F. & Hauck, C., 2009b. METSEIS: An experiment to quantify meteorological and seismological interactions. In: Sens-Schönfelder, C., Ritter, J., Wegler, U. and Große, C. (eds.), 2009. Noise and diffuse wavefields, Mitt. d. Deut. Geophys. Gesell., Sonderband II/2009, 101-106.

Seiberlich, C.K., Wawerzinek, B. & Ritter, J.R.R., 2013. Topography of the lithosphere-asthenosphere boundary below the Upper Rhine Graben Rift and volcanic Eifel region, Central Europe. Tectonophysics, 603, 222-236.

Wagner, M. & Ritter, J.R.R., 2008. Fault plane solutions for small earthquakes in SW Germany: Merzig, 17. Aug. 2007 and Osthofen, 13. Dec. 2007, Geotect. Res., 95/1, 180-183.

Wagner, M. & Ritter, J.R.R., 2013. Asthenospheric flow below SW Germany derived from high-resolution SKS anisotropy measurements, Tectonophysics, in revision.

Fig. 9.26: Station SFN02, URS2 experiment in Staufen im Breisgau. Left: installation of a GPS antenna. Right: recording box and STS-2 seismometer (inside the blue box for thermal insulation) in a historic cellar.

9.4.3 Norway

In spring 2006 there was a request for KABBA instruments for an experiment in Southern Norway. Christian Weidle (currently Kiel), who did his diploma and PhD studies in Karlsruhe, was working as a postdoc with Valerie Maupin in Oslo. They studied the upper mantle structure of Northern Europe using surface waves. Since the origin of the presently high topography of the Palaeozoic Southern Scandinavian Mountains was unclear, they proposed to start a seismological broadband experiment. After a meeting in Oslo in June 2006 with interested seismologists from Denmark (N. Balling, H. Thybo), Germany (J. Ritter) and Norway (J.-I. Falleide, V. Maupin, J. Schweitzer & C. Weidle), a field experiment was born without a funded project: Karlsruhe provided instruments and personnel, Oslo and NORSAR provided personnel, infrastructure and some financial support and Denmark also provided financial support. The experiment was called MAGNUS (MAntle InvestiGations of Norwegian Uplift Structures, Magnus is also the name of the Norwegian prince born in 2005). In September 2006 the installation of MAGNUS started with 30 KABBA stations in a 500 km NS by 500 km EW region. In addition ten permanent stations were included (Fig. 9.27). Station servicing was laborious, because a lot of driving was necessary to cross mountains and fjords, and driving was hampered by strict speed limits with high fines. Christian Weidle organized the field work and the first data processing (Weidle et al., 2010).

During the MAGNUS experiment the TOPO-EUROPE initiative driven by Sierd Cloetingh (Utrecht) was implemented. When the European Science Foundation (ESF) finally asked for proposals for TOPO-EUROPE (then an ESF EUROCORE programme), the MAGNUS team was well prepared to submit an application for a Collaborative Research Project (CRP). Based on the already identified research questions (mainly related to the uplift mechanisms of the Scandinavian Mountains) and the fieldwork with an excellent dataset, the MAGNUS group applied successfully for funding of the data analysis as well as additional active-source experiments. In Karlsruhe Britta Wawerzinek (currently Hannover) was in charge of the data processing and analysis of the teleseismic *S*-wavefield which she summarised in her dissertation. The partners in Oslo, Copenhagen, Aarhus and Kjeller analysed the teleseismic *P*-waves and surface waves as well as local seismic phases. In this way the MAGNUS data were used extensively and geodynamic studies accompanied the seismological research (Maupin et al., 2013).

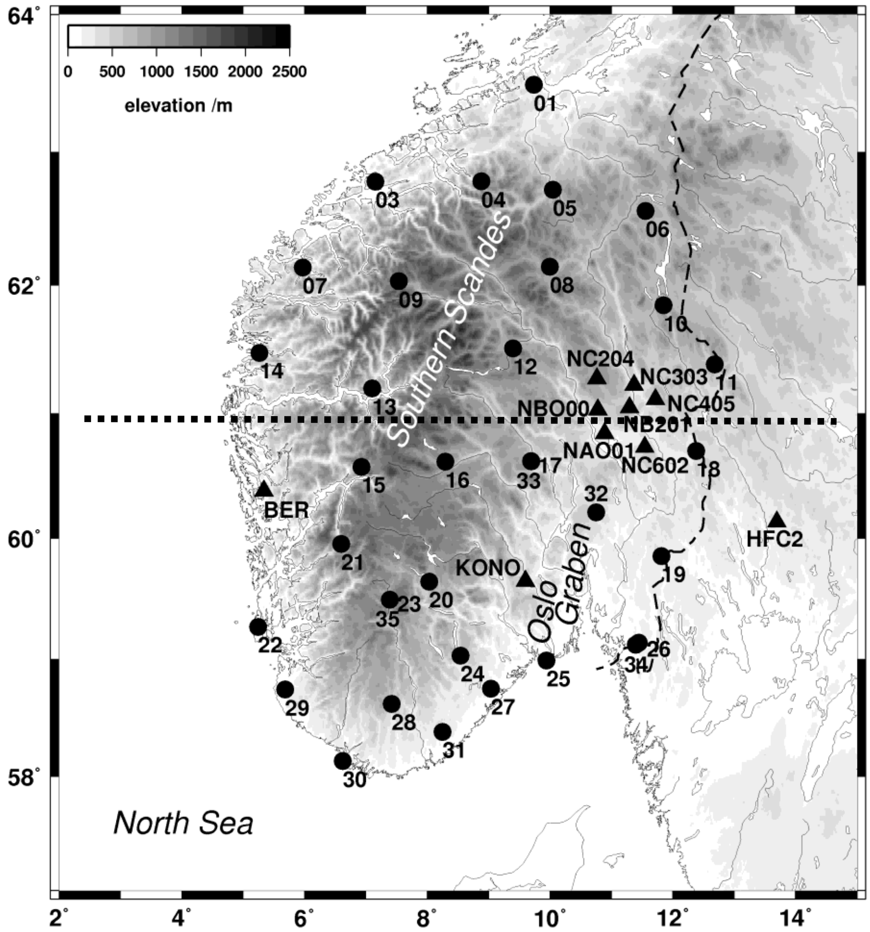


Fig. 9.27: Stations map of the MAGNUS experiment (2006/08). KABBA stations are indicated by dots and numbers, permanent broadband stations are indicated by triangles and their official station codes (NORSAR stations begin with N). The dotted line indicates the position of the cross-section in Fig. 9.28.

S-wave travel time residuals were calculated with respect to a standard Earth model. The residuals were characterised by a systematic delay for waves that propagated through the upper mantle underneath the Scandinavian Mountains. The tomography model contains an anomaly of relatively reduced shear wave velocity underneath the mountain area in the west compared to the Baltic Shield in the east of the station network (Fig. 9.28). Interestingly, another low-velocity anomaly was found in the lower part of the upper mantle at 270-410 km depth (Wawerzinek et al., 2013) which coincides with a depression of the 410 km discontinuity discovered by the colleagues from Copenhagen using *P*-wave receiver functions. The analysis of the *S*-wave receiver functions by Britta Wawerzinek (2012) provided a 3-D model for the Moho topography. However, but no unique model for the lithosphere-asthenosphere boundary (LAB) was found, because several upper mantle discontinuities were imaged with the *S*-wave receiver functions (Maupin et al., 2013). The splitting analysis of the SKS phases resulted in a complex anisotropic structure underneath Norway (Roy & Ritter, 2013); simple anisotropic one-layer models cannot explain the results of the data analysis and possibly the lithospheric fabric was reworked during the Caledonian orogeny as well as asthenospheric flow.

Maupin, V., Agostini, A., Artemieva, I., Balling, N., Beekman, F., Ebbing, J., England, R.W., Frassetto, A., Gradmann, S., Jacobsen, B.H., Köhler, A., Kvarven, T., Medhus, A.B., Mjelde, R., Ritter, J., Sokoutis, D., Stratford, W., Thybo, H., Wawerzinek, B. & Weidle, C., 2013. The deep structure of the Scandes and its relation to tectonic history and present-day topography, Tectonophysics, 602, 15-37.

Roy, C. & Ritter, C., 2013. Complex deep seismic anisotropy below the Scandinavian Mountains. Journal of Seismology, 17, 361-384.

Wawerzinek, B., 2012. Untersuchung der elastischen Scherwellenstruktur unter dem Südskandinavischen Gebirge. Dissertation, Karlsruhe Institute of Technology, Department of Physics, 194 p.

Wawerzinek, B., Ritter, J.R.R. & Roy, C., 2013. New constraints on the 3-D shear wave velocity structure of the upper mantle underneath Southern Scandinavia revealed from non-linear tomography. Tectonophysics, 602, 38-54.

Weidle, C., Maupin, Ritter, J., Kværna, T., Schweitzer, J., Balling, N., Thybo, H., Faleide, J.I. & Wenzel, F., 2010. MAGNUS – a seismological broadband experiment to resolve crustal and upper mantle structure beneath the southern Scandes mountains in Norway, Seism. Res. Lett., 81, 76-84.

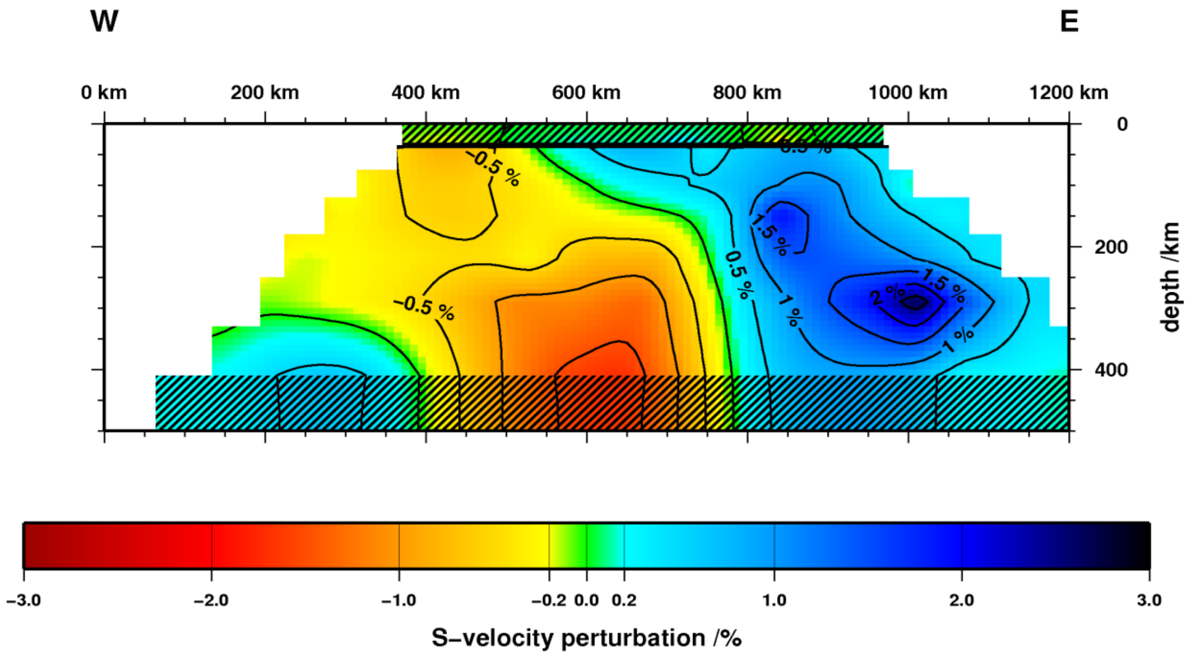


Fig. 9.28: East-west cross section through the 3-D tomography model with shear wave velocity (*vs*) perturbations (for approximate position see Fig. 9.27). There is a clear steeply eastward dipping transition with low *vs* in the west (Phanerozoic lithosphere) and higher *vs* in the east (Baltic Shield lithosphere). This velocity contrast continues subvertically into the upper mantle (after Wawerzinek, 2012).

9.4.4 LuxBB

In summer 2009 a cooperation was started with the European Centre for Geodynamics and Seismology (ECGS) in Walferdange, Luxembourg. At ECGS Adrien Oth, who did his diploma and PhD studies in Karlsruhe, is responsible for the seismological research. Because Luxembourg is close to the Eifel region (see Fig. 9.17) short-period recordings were done already in 1997/98 within the Eifel Plume project. However, as broadband observations were missing, GPI and ECGS installed a network with 5-6 KABBA stations in Luxembourg to measure teleseismic wave propagation from east through the Eifel Plume. In addition, local seismicity is observed and Luxembourgish stations will be added for this GPI-ECGS co-operation. The measurements are currently still under way and there are not yet any results.

9.4.5 Landau and Insheim

In summer 2009 GPI was approached by the Geological Survey of Rhineland-Palatinate (LGB-RP) to assist with seismic monitoring during a stimulation test at a geothermal reservoir near Insheim (Fig. 9.29), about 40 km northwest of Karlsruhe. In the beginning of July 2009, five broadband stations were installed around Insheim which is located south of Landau – the start of the TIMO2 project. At first nothing fancy happened but teleseismic waves could be recorded for future studies on the deep structure of the Upper Rhine Graben. Hence the PI from GPI went on summer holidays on Saturday, 15th August. Just after one hour on the highway, the radio programme was interrupted and breaking news was reported on an earthquake in Landau ("*according to several calls from radio listeners, the town of Landau was shaken by an earthquake*"). The disapproving glance of the PI's wife avoided a spontaneous return to the institute. Instead, only the news reports were intensively followed up and numerous phone calls were made between the involved collaborators. Anyway, the TIMO2 installation was one of the few seismological experiments in which recording stations were installed *before* an earthquake occurred. Later the waveforms recorded with the TIMO2 network were crucial to determine the precise hypocentre of the earthquake which caused a lot of trouble and became a serious political issue.

The induced seismicity at Landau provoked a lot of public interest and pressure on politicians and authorities. Especially seismological expertise as well as appropriate data were required to better assess the situation and rethink countermeasures (Ritter, 2011). As induced seismic events occurred at several locations, several German seismologists started initiatives to study induced seismicity and advise authorities and companies. Friedemann Wenzel proposed to start a FKPE working group on Induced Seismicity which had its first official meeting in Karlsruhe in June 2010. Joachim Ritter organized a subgroup that worked on recommendations for monitoring induced seismic events (Baisch et al., 2012).

The ministry of economics in Mainz funded the continuation of the TIMO2 measurements with the KABBA stations (Fig. 9.29) as well as the analysis of these recordings and previous recordings to evaluate the local natural background seismicity. Katrin Plenkers (now GMuG company Bad Nauheim) used cross-correlation techniques to detect seismic events in the TIMO dataset of 2004-2006 when KABBA stations were recording in the Landau region by chance. She detected some hundred events ($M_L < 1$) related to the stimulation phase of the Landau geothermal project (Fig. 9.30 and Plenkers et al., 2013). This analysis demonstrated the use of properly archived data as well as the operation of very sensitive observatories such as BFO (see Zürn, this volume), because only BFO recordings were suitable to estimate the magnitude of the stimulation events. The TIMO2 network was used to study the local noise conditions (Groos & Ritter, 2010).

A project proposal was submitted by several German institutions to the Federal Ministry for Environment. The funding resulted in the MAGS project (microseismic activity of geothermal systems) and then Jörn Groos coordinated the TIMO2 activities. The network around Landau and Insheim was expanded and the data of several stations were transmitted in real time to the involved project partners. Two borehole stations were installed in cooperation with local partners and these provided waveform recordings with a very low noise level.

The TIMO2 data were extensively studied to better understand the upper crustal structure and the mechanisms of the seismicity in the area of Landau and Insheim. Cross-correlation techniques were applied to detect the seismic events in the high-noise environment of the Upper Rhine Graben. Based on waveform similarities, event clusters were identified by Michael Grund who was awarded with the KIT Research Student Award. The event clusters indicate reoccurring ruptures at specific fault locations (Fig. 9.31). The hypocenters were determined in absolute position (about 300-500 m precision) and in relative position using double difference techniques (Fig. 9.31) what clearly outlines the rupture planes. Fault plane

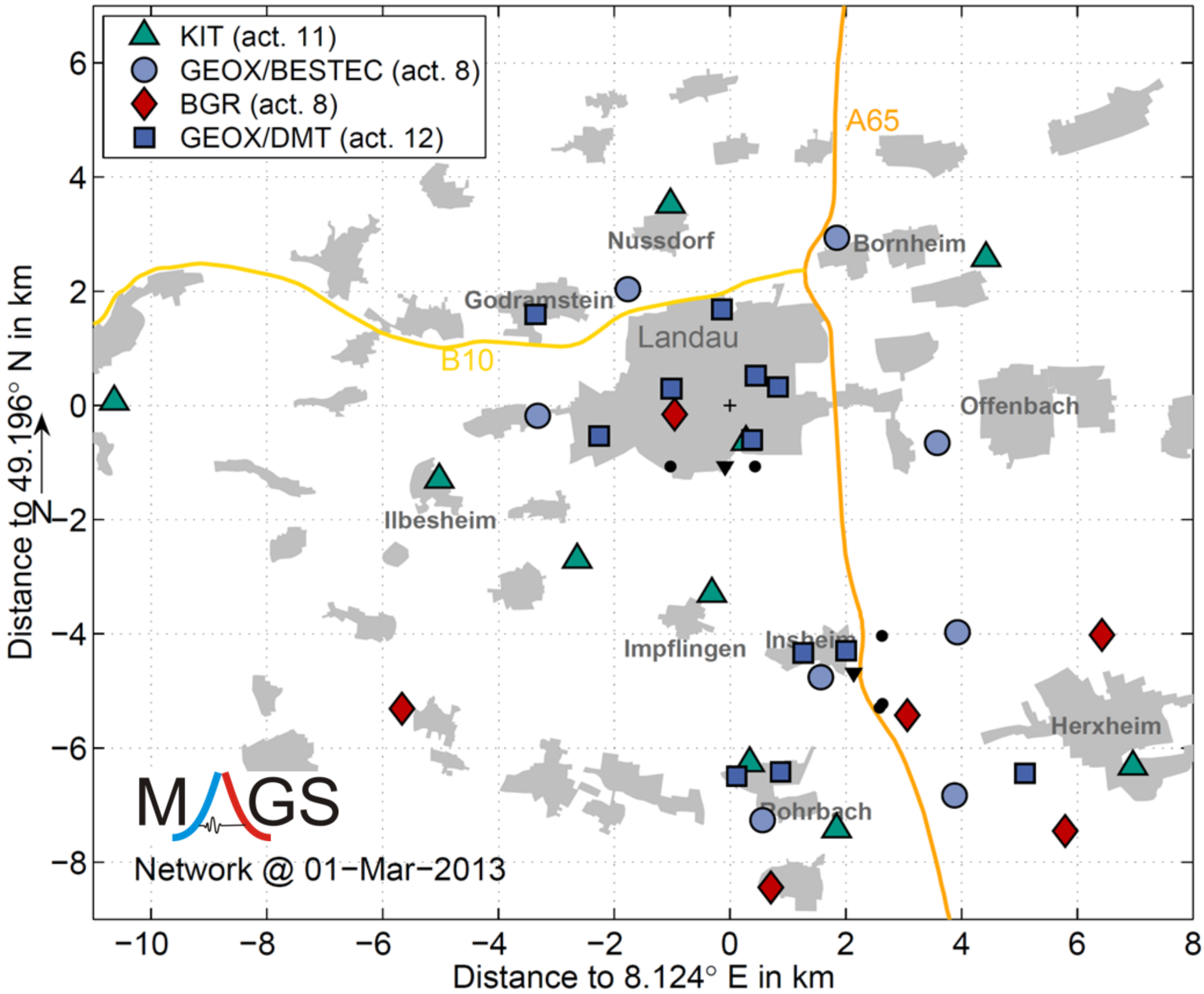


Fig. 9.29: Map displaying the TIMO2 / MAGS station sites from different operators around Landau and Insheim. Black inverted triangles represent geothermal power plants, black dots are the landing points of the drill holes at about 2.5-3.5 km depth.

solutions indicated a mainly normal faulting and strike slip mechanism of possibly reactivated faults (by infiltration of reinjected water) related to the development of the Upper Rhine Graben. Measurements of seismic anisotropy with polarized shear waves also support a model of NNW-SSE oriented, fluid-filled cracks in the uppermost crust. Seismic noise analysis and interferometry was used to characterize local wave propagation conditions within the TIMO2 network (Stein et al., 2012).

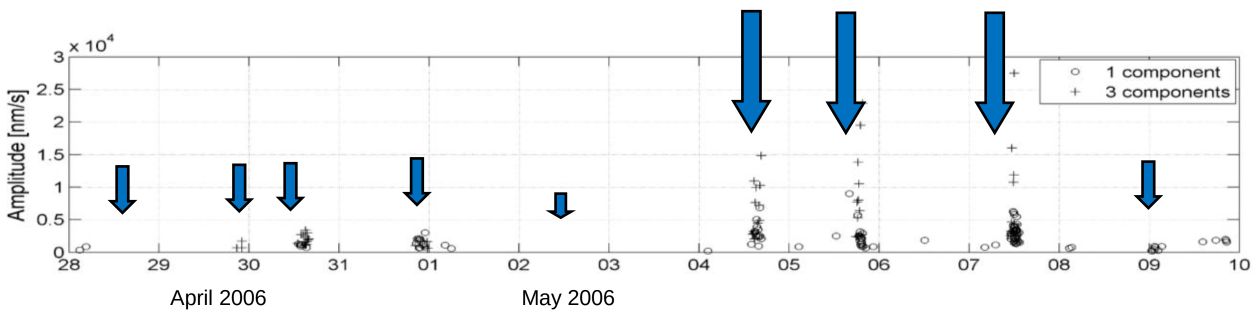


Fig. 9.30: Occurrence of seismic events ($M_L < 1$, see amplitude scale) in the TIMO dataset at stations near Landau. Arrows indicate fluid injection periods with length about proportional to injection rate (modified after Plenkers et al., 2013).

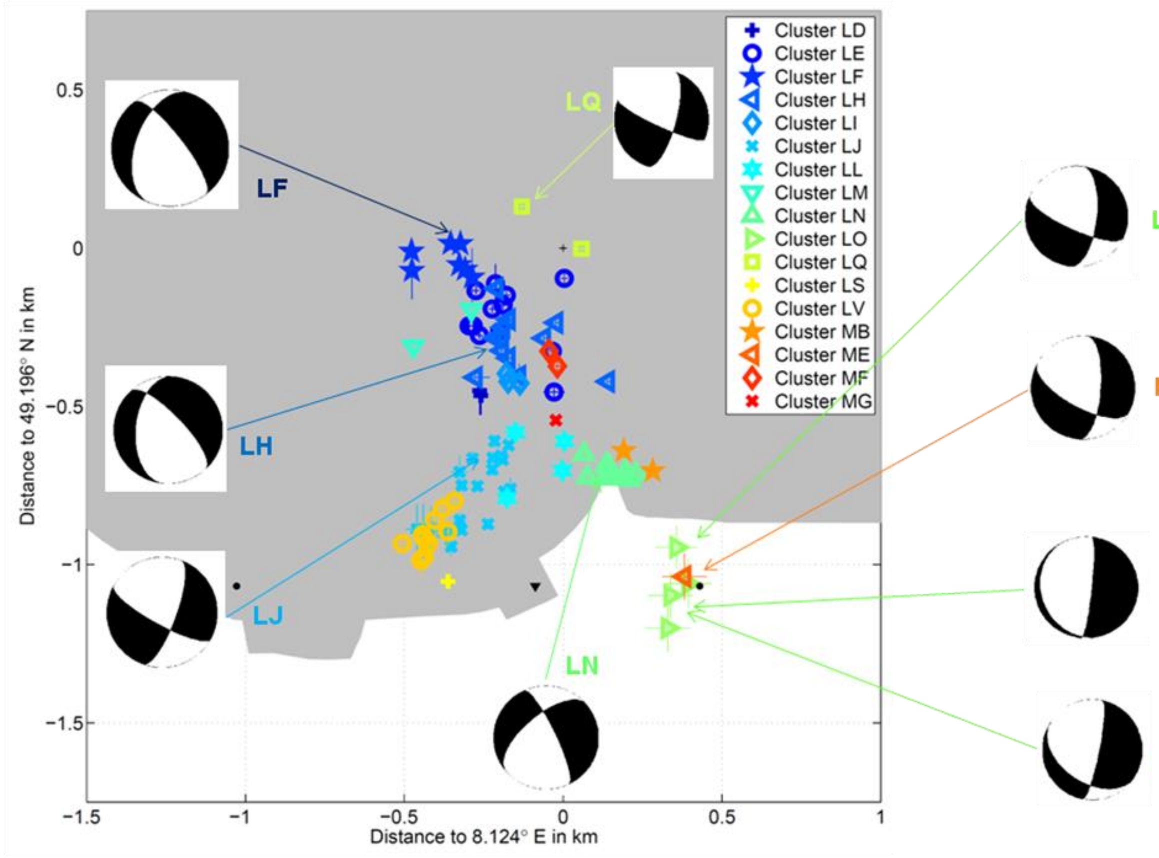


Fig. 9.31: Results of the seismic event analysis ($M_L < 2.7$) below Landau (grey area corresponds to the town area of Landau). Colours indicate events with a very high waveform correlation which are merged in clusters. Fault plane solutions imply a normal to strike slip faulting regime. Figure courtesy of Laura Gassner, Jörn Groos, Michael Grund, Joachim Ritter and Jens Zeiß.

Baisch, S., Fritschen, R., Groos, J., Kraft, T., Plenefisch, T., Plenkers, K., Ritter, J., & Wassermann, J., 2012. Empfehlungen zur Überwachung induzierter Seismizität – Positionspapier des FKPE, Mitteil. Deut. Geophys. Gesell., 3/2012, 17-31.

Groos, J. & Ritter, J.R.R., 2010. Seismic noise: A challenge and opportunity for seismological monitoring in densely populated areas. In: Ritter, J. & Oth, A. (Eds.), Induced Seismicity, Cahiers du Centre Européen de Géodynamique et de Séismologie, 30, 87-97.

Plenkers, K., Ritter, J.R.R. & Schindler, M., 2013. Low signal-to-noise event detection based on waveform stacking and cross correlation: application to a stimulation experiment, J. Seismology, 17, 27-49.

Ritter, J.R.R., 2011a. Konzeptionelle Ansätze zur Überwachung induzierter Seismizität im Oberrheingraben, Rheinland-Pfalz, Mainzer geowiss. Mitt., 39, 157-176.

Ritter, J.R.R., 2011b. Urbane Seismologie am Beispiel der aktuellen seismischen Ereignisse unter Landau, Südpfalz. 12. D-A-CH Tagung, Erdbeben und Baudynamik, ISBN 3-930108-11-9, 113-119.

Stein, F., Groos, J.C. & Ritter, J.R.R., 2012. Seismic interferometry at the TIMO2-network, Germany. In: Schmidt, A., Sens-Schönfelder, C., Hadziioannou, J., Wegler, U. & Niederleithinger, E. (eds.). Noise and Diffuse Wavefields, Mitt. d. Deut. Geophys. Gesell., Sonderband IV/2012, 86-87.

9.4.6 Parkfield

Parkfield is located in the central, creeping segment of the San Andreas Fault in California. In 2009 Rebecca Harrington (now McGill University) received funding for a KIT Young Investor Group which she used to undertake the PERMIT project (Parkfield Experiment to Record MIcroseismicity and Tremor). The goals were to study fracture processes and especially seismic tremor at the San Andreas Fault (Horstmann et al., 2013). Together with the University of California in Riverside (Elizabeth Cochran, now USGS Pasadena) a field experiment near Cholame, SE of Parkfield, was planned and organised (Fig. 9.32). Thirteen KABBA stations were installed in the grasslands in May 2010 and recorded up to July 2011. The dataset was completed with ten permanent stations of the Parkfield experiment. Although the temporary KABBA stations were installed in well-designed vaults with a concrete base and barbed wire, there were attacks by cattle (besides big spiders and rattle snakes) which were also a significant noise source. One STS-2 survived a hardness test when a cow felt onto it (Fig. 9.32). During PERMIT some small local events were recorded, however, more importantly were successful recordings of tremor signals which were identified and located by Tobias Horstmann during his PhD work.

Horstmann, T., 2013. Analysis of tremor at the San Andreas Fault at Parkfield. Dissertation, Karlsruhe Institute of Technology, Department of Physics, 95 p.

Horstmann, T., Harrington, R.M. & Cochran, E.S., 2013. Semiautomated tremor detection using a combined cross-correlation and neural network approach. J. geophys, Res., 118, 4827–4846.

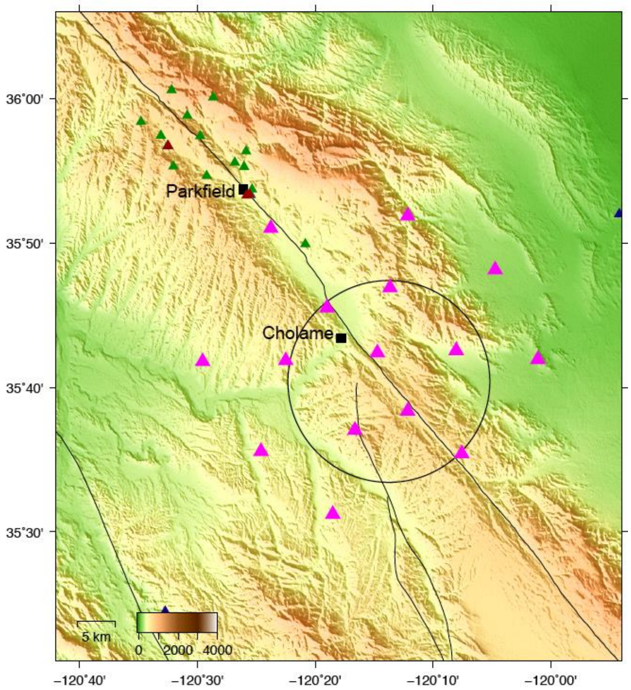


Fig. 9.32: Top: location and station sites of the PERMIT experiment near Cholame, California. Purple triangles are KABBA stations, green triangles are permanent stations. Black lines indicate faults related to the San Andreas Fault system. Right: Recording station before and after an attack by cows. Note the upside down recorder box and the trampled seismometer vault (courtesy W. Scherer & E. Cochran).

10. Stress and stress release in the lithosphere – Geothermics and borehole geophysics

for sustainable use of the underground and geodynamic understanding

Birgit Müller and Oliver Heidbach

with contributions by **Tobias Hergert and Frank Schilling**

Abstract

Safe and environmentally compatible exploration and production of underground energy resources and the description of geodynamic processes such as earthquakes require a detailed quantitative understanding of the state of stress in the Earth´s crust. This needs a compilation of stress information in time and space by natural as well as anthropogenic processes. With responsible application of knowledge about the relations between fluid pressure and mechanical stress, hazard in mining can be reduced, the efficiency of underground utilization will be enhanced and the influence on the living environment is minimized. Tectonic stresses that form our planet are ultimately linked to volcanism, plate tectonics and earthquakes. The researcher Karl Fuchs at the Geophysical Institute of the University of Karlsruhe (now KIT) initiated numerous projects in that context on national and international scales which led to a new understanding of processes. This knowledge is today's basis for modern reservoir management and safely use of the underground for a reliable and economical future energy supply. Moreover, it contributes to systematic earthquake and tsunami risk reduction as has been foreseen in the essay of Karl Fuchs on the 1755 Lisbon and 2004 Aceh earthquakes.

1. Introduction

In a common sense *stress* is mostly understood as a feeling of strain. Thus, stress is perceived mostly in a negative way when man is under extreme pressure with panic exhaustion, high blood pressure or conflict and political tension. Moreover, the German translation of stress is "Spannung", which is used as equivalent to electrical voltages as well as human excitement, which can lead to misunderstandings. In a geological sense stress is related to strain of rocks, but even in scientific literature there is some confusion about some of the stress definitions. Terry Engelder has described that in 1994 in EOS in his essay "Deviatoric stressitis: A virus infecting the Earth science community" in a humorous style. Thus, stress is not an easy term. The geomechanical stresses in the Earth´s crust are of great relevance for geodynamic processes that generate our landscape such as plate tectonics, orogeny, volcanism and earthquakes or cause catastrophes such as the strong motion earthquakes generating tsunamis responsible for hundreds and thousands of casualties such as in Lisbon 1755 or Banda Aceh in 2004 (Fuchs, 2009). In that context geomechanical stresses have found broad acceptance.

The necessity to deal with stress in the framework of effective and safe energy exploitation is less known in the public, but also relevant. E.g., seismicity occurring as a consequence of hydraulic stimulation in the Basel geothermal project led to project abandonment. Seismicity in the gas fields of the Netherlands started after about 10 years of production (van Eck et al. 2006). Furthermore, there is an intense public concern about shale gas production using hydraulic fracturing that can also result in induced seismic events.

A wide spectrum of use of the underground for energy supply is under debate: efficient use of hydrocarbons in combination with a reduction of the CO_2 emissions into the atmosphere by underground storage of CO_2, Enhanced oil Recovery (EOR), Enhanced Gas Recovery (EGR) using hydraulic fracturing technology, shale gas and coal bed methane exploration . The further development of hydropower reservoirs is limited, but is an important contribution for base load supply. The underground storage of gas in caverns and abandoned gas reservoirs requires a good knowledge about geomechanical stresses and is an important contribution to stable energy supply. For the efficient use of geothermal energy and for EGS systems at depth geomechanics is an important issue in terms of safety and economics.

How stresses in the Earth´s crust influence modern life also indirectly was experienced by the strong earthquake at the Japanese coastline in April 2011 that led to political shut-down of power plants in Germany - located more or less on the other side of the globe. A number of system components of the Fukushima nuclear power plant could not withstand peak ground accelerations from the earthquake in combination with a tsunami wave which finally led to nuclear meltdown in several reactors. This strong earthquake is basically a consequence of the movement of tectonic plates where especially at convergent plate boundaries strain and stress build up, which will be released in form of seismicity when the crustal strength is exceeded. Aside from well-established probabilistic methods for seismic hazard assessment which are based on statistical analysis of (mostly incomplete) earthquake catalogues, there are geomechanical approaches to understand the earthquake process of strong motion earthquakes and to perform numerical simulations in advance. For this approach the mechanical stresses and their changes with time are required to quantify these processes.

A wide spectrum of research activities of the Geophysical Institute, initiated by Karl Fuchs dealt with the processes involved in reservoir exploitation. During about 20 years the scientific base for the understanding of the process has been founded by the creation of a fundamental stress database within the framework of the World Stress Map (WSM) project. The WSM project was initiated in 1985 as a task force under the leadership of Mary Lou Zoback during Karl Fuchs´ time as president of the International Lithosphere Program (ILP) of the IUGG and IUGS. Applying this stress database, important findings for the interpretation of geodynamic processes on a continental scale but also for the optimized and safe production of hydrocarbons on reservoir scale have been established. Karl Fuchs intensified research on strong motion earthquakes especially after the tsunami generating earthquake in December 2004 in Indonesia (Fuchs, 2009).

Here, we describe the activities of crustal stress research taking place in the last 40-50 years, without claim of completeness. We want to highlight the contribution of scientific investigation of reservoir geomechanics for the current discussion on safe energy supply and climate protection. We sketch the state of the art of research and give a future perspective on the potential of geomechanical-numerical 2D to 3D modeling especially for strong earthquake understanding and hazard assessment. We will first start with the definition of the stress terminology used in this essay and then focus on the research for reservoir geomechanics and geodynamic processes along with earthquake generation – a field of research for which Karl Fuchs motivated generations of geophysicists and settled a solid base in the Geophysical Institute of the University of Karlsruhe (now KIT).

2. Stress in the Earth´s crust

Stress is a field quantity which we cannot sense such as temperature or velocities. Whereas temperature at any location can be described by a scalar and velocity by a vector, the stress has to be described by a second-order tensor, thus a 3x3 matrix with nine components. Due to conservation of momentum, the stress tensor is symmetric, thus there are only six independent components of the stress tensor. For a symmetric tensor it is always possible to find a principal coordinate system, for which only the diagonal elements of the matrix remain and the stress state can be described by three eigenvectors. Those are the principal stresses, which can be visualized by a stress ellipsoid (Fig. 1). The difference between the magnitudes of the largest and the minimum principal stress is called differential stress.

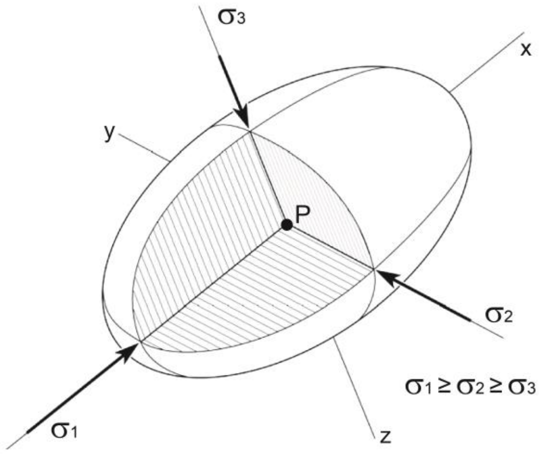


Fig. 1: Lamé stress ellipsoid. The three principal stresses (Eigenvectors) σ_1, σ_2 and σ_3 of the symmetrical stress tensor σ_{ij} describe the state of stress at a point P.

Under the assumption that in the Earth´s crust the vertical stress resulting from the gravitational load is one of the principal stresses – which is only valid directly at the surface under the assumption of the absence of shear stresses e.g. induced by winds – the state of stress can be described at first approximation by the vertical stress S_v=ρgz with g gravitational acceleration ρ the rock density and z the depth and the maximum and minimum horizontal stresses S_H and S_h.

Above we provided a rather general description of the state of stress, more popular is the following special case: When the three principal stresses are equal in magnitude (S_v=S_H= S_h), the stress ellipsoid is a sphere and the stress state is called lithostatic. Already in 1878 Heim postulated that this enables to describe the state of stress in the Earth´s crust. However, if the state of stress would be everywhere lithostatic only volumetric shape changes would occur but no other types of deformation such as distortion and strain which cause the shaping of our landscape *e.g.* by forming deep sea trenches and mountainous areas. In purely elastic media stresses and strains are related by Hooke´s law, named after the 17th century British physicist Robert Hooke. Terry Engelder (Engelder, 1992) defined the differences from a reference state of stress (*e.g.* lithostatic state of stress) as *tectonic stress.* In the following we use the term state of stress independent from its origin for the sum of all its components, natural or in situ stress or induced stresses by human activities, which is a disturbed in situ stress.

The three principal stresses S_v, S_H and S_h have been used by Anderson (1905) to define the three tectonic regimes, which describe the kinematic behavior of tectonic fault zones. In a normal faulting regime the vertical stress is the maximum principal stress, in a strike slip regime it is the intermediate principal stress and in a thrust faulting regime it is the least principal stress (Fig. 2).

Some confusion appears for the terms deviatoric stress and differential stress. The latter is the difference between the maximum and minimum principal stress, thus σ_d=σ_1-σ_3. The differential stress is causing the deformation of the Earth´s crust. The deviatoric stress σ'_{ij} is the total stress σ_{ij} minus the isotropic part of the stress tensor which is the trace of the stress tensor (the pressure, Jaeger et al., 2007):

$$\sigma'_{ij} = \sigma_{ij} - \delta ij\ (\sigma_{11} + {}_{22} + \sigma_{33})/3$$

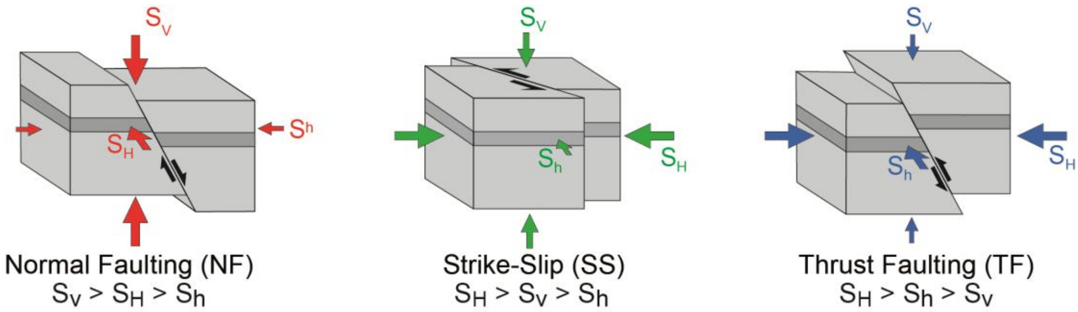


Fig. 2: Tectonic regimes and the role of the vertical stress which is the maximum principal stress in normal faulting regimes, the intermediate principal stress in a strike-slip regime and the least principal stress in a thrust faulting regime.

Furthermore, the state of stress is limited by so-called boundary conditions. For example at free surfaces shear stress cannot exist and stresses normal to the boundary have to be continuous (normal stresses of planes perpendicular to the free boundary are not necessarily continuous across the boundary). This results in vertical and horizontal orientations of the principal stresses at the Earth´s surface. Deviatoric stresses can be released in plastic (hot) material, thus the stresses have to be taken over by the more stiff material, which leads to stress concentrations in more competent layers. Especially in mining such stress concentrations can lead to dangerous situations.

3. The Why and Where of Stress Changes and Concentrations

3.1. Human activities

Any anthropogenic modification of the underground results in changes in stress of the Earth´s crust. Removal of material in wells, shafts or mines creates free surfaces with zero shear stress boundary conditions and normal stresses equivalent to the filling (gas or fluid) of the underground opening. As a consequence, the stresses in the crust have to readjust, which leads to changes in stress orientation and can lead to stress concentrations in the immediate vicinity of the underground opening (Fig. 3). If these stress concentrations exceed the strength of the rock, failure may occur, which can result in the so-called borehole breakouts (despite the name, borehole breakouts do not occur in wellbores only but also in tunnels etc.). Breakouts occur in the orientation of the minimum stress concentration (for isotropic rocks). In the orientation of the maximum stress, the tangential stresses at the borehole wall can result in tensile fractures. The latter process is the base for the so-called hydraulic fracturing, which is under intense current debate in relation with shale gas production.

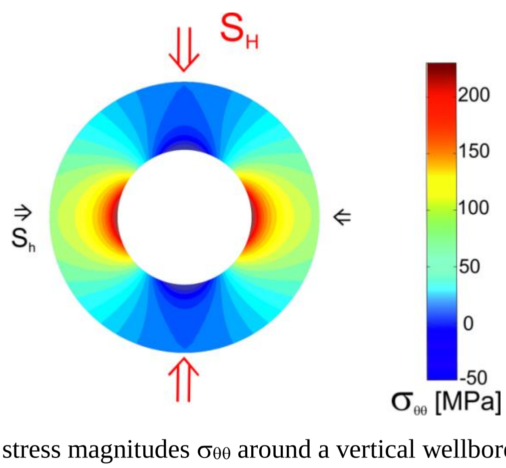


Fig. 3: Distribution of tangential stress magnitudes $\sigma_{\theta\theta}$ around a vertical wellbore situated in a far field stress with the maximum horizontal stress S_H and the minimum horizontal stress S_h. The stress magnitudes concentrate in the orientation of S_h, where the stress magnitudes can overcome the rock strength and lead to the evolution of wellbore failure: borehole breakouts.

In mines and tunnels those failures of the borehole wall can have dramatic consequences for activities and miners (Fig. 4). Despite the facts that a) the stress readjustment at free surfaces is well-known (Leeman, 1964; Cox, 1970) and that b) it was recognized that the stress orientation derived from the orientation of the breakouts is rather independent from depth, lithology and orientation of the tunnel or well (Babcock, 1978), the phenomenon of borehole breakouts has been explained at first by cross-cutting of pre-existing fault zones.

The interpretation could only change because new logging technology, namely the oriented 4-arm caliper tool, was invented to determine borehole cross section geometry. This tool was used in numerous wells and Bell and Gough (1979, 1981, 1982) as well as Gough and Bell (1981, 1982) could empirically relate the breakouts to independent observations of stress orientations. Furthermore, they developed the rock mechanical concept of breakout generation as result of stress concentration in anisotropically stressed rock. This convinced Karl Fuchs during a visit at Ian Gough in such a way that he promoted the breakout investigation as contribution to the Institute´s efforts to improve the knowledge of the state of stress in the Earth´s crust (Blümling et al., 1983).

Anthropogenic influence on the tectonic stress field is manifold, such as potash mining, copper mining or loading of parts of the crust during the impounding of water reservoirs. The 1989 earthquake of M_w=5.4 at Werra/Völkershausen as a consequence of potash mining and the seismicity due to copper mining in Legnica/Glogow in Poland with magnitudes up to 4.5 are examples with broad public perception. Large induced events in the German coal mining sites occurred in the Ruhrgebiet (M_w =4.1, 1888) and Peissenberg (M_w =3.6). An induced event of M_w = 3.8 in 2008 in the Saarland resulted in abandonment of coal mining in that area. However, there had been also economic reasons for that decision.

Fig. 4: Breakouts in tunnel walls can lead to loss of lives or require expensive safety measures. Left: fractures in a shaft wall in the Äspö rock mechanics laboratory in Sweden. Right: tunnel wall deformation in the Lignite Mine near Peissenberg, Germany.

3.2 Application of Stress Field Knowledge for the Use of the Underground

Apart from the unwanted phenomena such as breakouts occurring as a result of stress concentrations, tectonic stress can be used to improve the economic use of the underground significantly. The hydraulic fracturing (Fig. 5) has been invented in the 1940s of the last century to enhance the connection between wellbores to the reservoir in the underground. In this method directed fractures are initiated by pressurization of a wellbore depth section. The fractures develop in the orientation of S_h as soon as the tensile strength of the rock in the wellbore surrounding is exceeded. In normal faulting and strike slip faulting regimes the fractures are oriented vertically, in thrust faulting regimes horizontal fractures can develop.

The process of fracturing causes induced seismicity with small, normally imperceptible earthquakes. When in December 2006 the fracturing of crystalline rock from a geothermal well caused a magnitude M_w=3.2 earthquake at 5 km depth, intense public debate led to abandonment of the project. In the year of the 650th "anniversary" of the Basel M=6.6 earthquake people had been skeptical about larger damages to be triggered by geothermal activities. In 2013 in St. Gallen a magnitude 3.5 event was induced during measures to inhibit gas inflow into a geothermal well, in this case the city parliament decided to go ahead with the project.

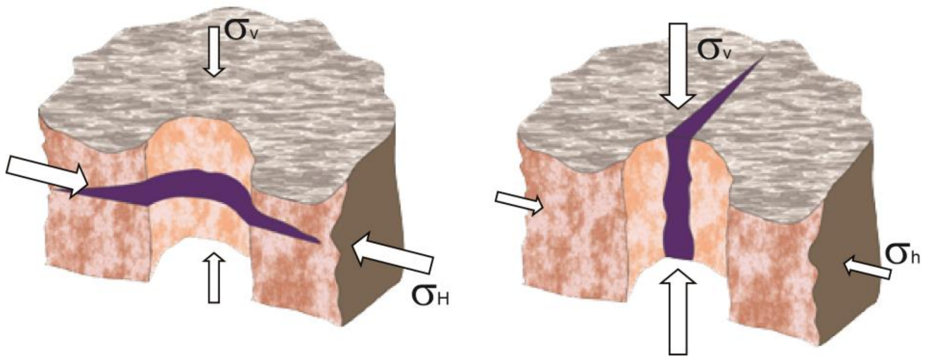


Fig. 5: Hydraulic fractures initiating at a wellbore. These develop when fluid-pressure in the wellbore creates tensile stresses at the borehole wall which exceed the tensile strength of rock mass. At greater distance to the wellbore the pressure necessary to keep fractures open corresponds to the least principal stress. The fractures open according to the principle of least resistance and close when the pressure reduces.

In the past few years hydraulic fracturing was intensified for shale gas production. Following news and films about burning taps in the US (Film "Gasland") the technology is criticized and under intense public discussion, especially since some of the chemicals used in the fracturing fluids are treated as industrial secrets. Residents are afraid that the fracturing fluid might contaminate drinking water if the fluids can migrate along fracture zones or leaky wells to drinking water producing horizons. In Germany, there is also a large resistance against hydraulic fracturing operations in the public because of water contamination issues and potential hazard to nature.

Natural leakage of gas reservoirs to the surface is known in numerous countries. However, only few systematic studies on the relationship between gas leakage in aquifers above producing reservoirs exist (Osborn, 2011). Osborn (2011) showed that the drinking water did not contain fracturing fluids or drill muds. It is difficult to investigate scientifically in how far the appearance of gas in drinking water horizons is amplified by activities of the hydrocarbon industry because in most cases baseline measurements (measurements of natural gas leakage before drilling activities) are missing in most areas.

On the other side, the hydraulic fracturing technology can also be used to reduce hazard and enhance safety. In Germany, *e.g.* in coal mining in the Saarland, the hydraulic fracturing technology was used to drain methane gas from the coal mine areas as a safety measure for the coal miners. In 1967/1968 eight hydraulic fractures in two deep wells at depths of about 600 m have been performed (presentation of Bergner, Saarbergwerke AG). Injection of ca. 155 m^3 and 190 m^3 fluid in the mine Luisenthal was performed with pressures of 22-25 MPa. The pressure build-up curve was interpreted as a modification of rock permeability by fissures and fractures created by the stress concentrations. The fractures reached about 150 m into the formation and later on have been mined through where the fractures could be investigated in-situ (Fig. 6). The gas produced from this activity was burned that time but according to the authors Schmidt-Koehl und Kneuper (1974) would have been sufficient for economic use.

Fig. 6: Hydraulic Fractures in a coal mine in Saarland region. The hydraulically produced fractures have been reached by the mine trajectory (RAG-Archiv Saar).

4. How Much Stress is in the Earth´s Crust?

4.1 About possibilities to measure stress orientations

Stress orientations can only be determined indirectly. All "measurement" methods do not really measure stress but observe deformations from which under certain assumptions about the rheology, the components of the stress tensor can be derived. Thus, stress determinations base on geological and geophysical measurements such as earthquake focal mechanism solutions, interpretation of borehole cross section geometries, geological indicators such as volcanic dykes and faults or overcoring measurements. In recent years numerous methods have been developed to determine the state of stress in the Earth´s crust. In general, two types of methods can be distinguished: those that disturb intact rock (overcoring, hydraulic fracturing) and those based on rock deformation without influence by the measurement (focal mechanism solutions, orientation of geological-tectonical structures, borehole breakouts). Using these methods the orientation of S_h can be determined. Only a few methods pose the potential to determine also stress magnitudes. Figure 7 provides an overview and a categorization of the most important stress indicators.

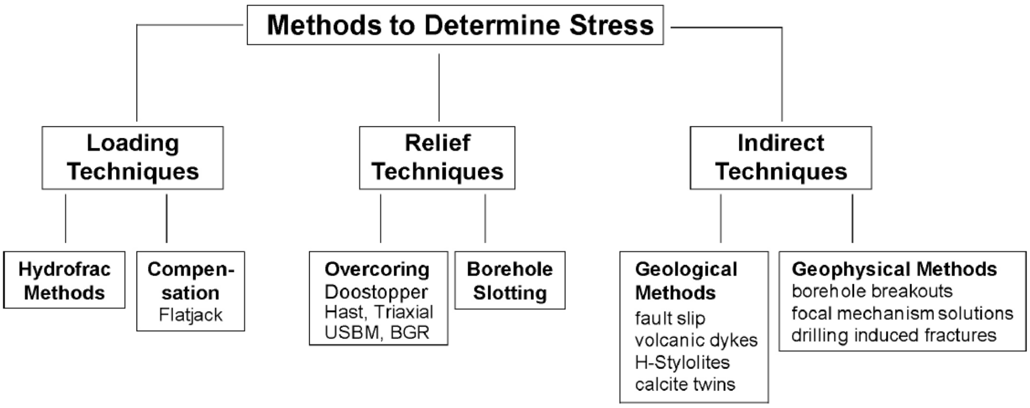


Fig. 7: Overview about the different methods to determine stress orientations or magnitudes of S_h (loading techniques) or the complete stress tensor (relief techniques).

The stress indicators do not only differ by used methodology but also by the rock volume, depth or time span for which they are representative. Data from wellbore breakouts are more or less available for the uppermost 6 km of the crust, despite from some deep industrial or scientific wells such as the continental drill hole KTB in Germany (Brudy, 1997). At greater depth focal mechanism solutions from earthquakes are the only means for information on stress regimes and orientation. Furthermore, it has to be considered that the different methods are valid for significantly different rock volumes (Ljunggren, 2003). Whereas overcoring represents 10^{-3} – 10^{-2} m³ of rock, breakouts 10^{-2} – 100 m³, focal mechanisms indicate the stress state in rather large volumina up to 10^{9} m³. Thus, some methods are only conditionally useful to determine the stress in a larger region because local effects could have been responsible for the results of the measurement, such as anomalies in density, contrasts in material properties etc.

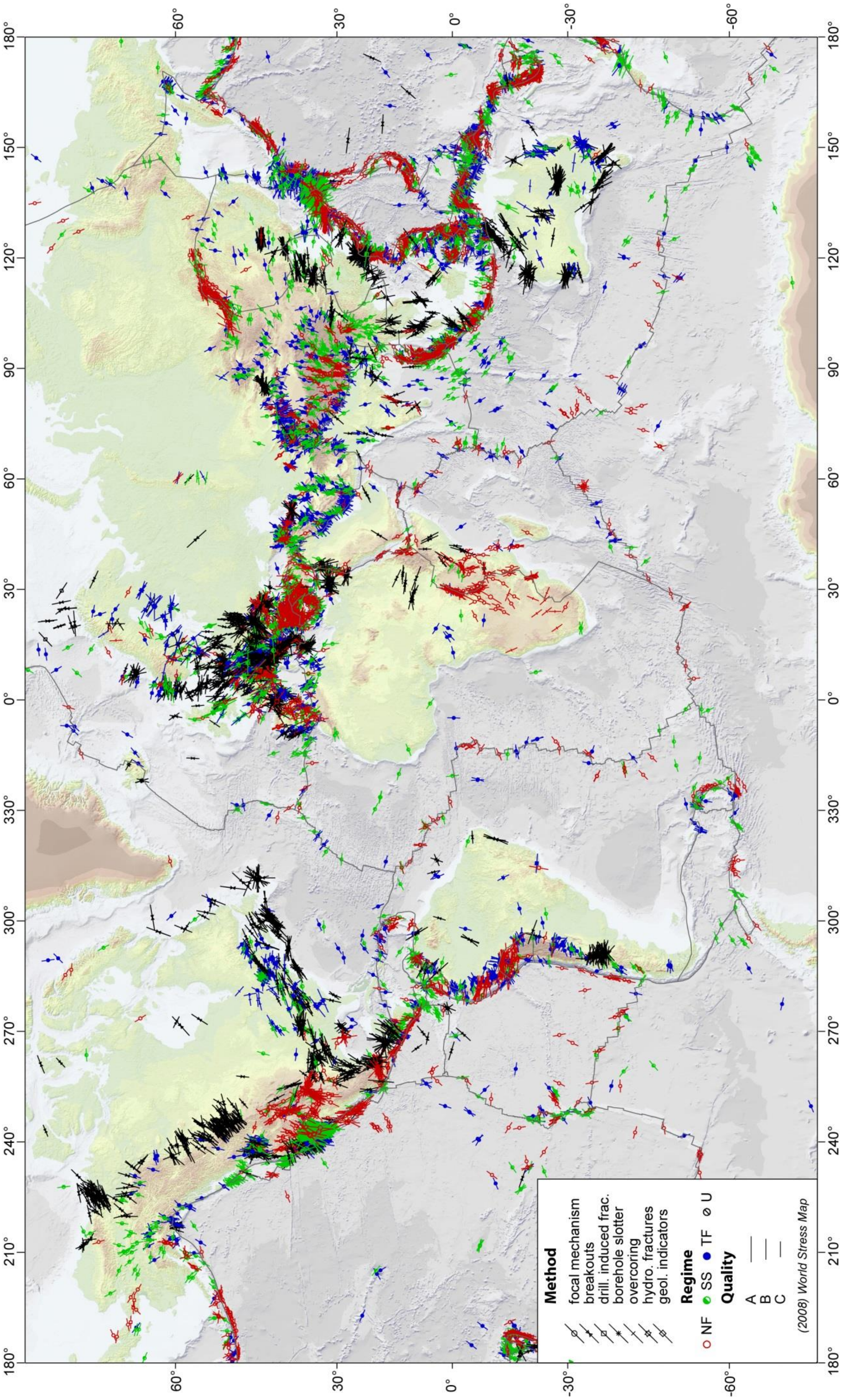
4.2 The World Stress Map Project (WSM Project)

To be able to compare the results of different stress indicators presented in the previous section was a challenge not easy to solve. A first regional compilation for Northern America (Sbar and Sykes, 1973) consisted of 52 data from overcoring, geological indicators, hydraulic fracturing and focal mechanism solutions of earthquakes and enabled the investigation of regional stress patterns. The newly emerging method of stress orientation determination from borehole breakouts (Bell and Gough, 1979) stimulated Karl Fuchs during his time as ILP president, to invent a global database in which data are compiled in a comparative manner, the birth of the World Stress Map (WSM) project.

The WSM project is a joint project of scientific institutions in Academia, industry and public with the goal to describe the stress pattern in the Earth´s crust and to investigate its sources. The ILP task force "World Stress Map Project" had a first highlight in a Nature publication (Zoback et al., 1989) when the World Stress Map contained data at 3,600 locations. After 6 years it ended successfully as ILP project and the results of the global compilation effort and its scientific interpretation was published in a JGR special volume. The WSM database had at that time app. 7,300 data records (Zoback, 1992).

Again it is owed to Karl Fuchs, who secured that the WSM would not be abandoned on a lonesome computer or floppy disk (for the young ones: a storage medium before CDs and USB-sticks). The international effort that had been put into the WSM database would have been lost. Therefore he convinced the Heidelberg Academy of Sciences and Humanities to set up a WSM research center. This was active between 1995 and 2008 at the Geophysical Institute of the University of Karlsruhe under the umbrella of the Heidelberg Academy of Sciences and Humanities. Karl Fuchs headed the project until 2000 and his successor Friedemann Wenzel and Karl Fuchs took care that the WSM is now an independent research project at Helmholtz-Centre Potsdam - GFZ German Research Centre for Geosciences. The third international WSM conference with more than 130 participants from 30 countries and proceedings in Tectonophysics (February 2010, vol. 462) was a scientific highlight. Today the unique and fundamental database of the WSM contains 21,750 data records (Heidbach et al., 2010).

The basic concept of the WSM is the standardized format of the data, a unique quality ranking scheme to guarantee the comparability of the data records from the different stress indicator on a global scale. The quality ranking scheme had been improved and extended during the first project phases in intense collaboration with international experts, new methods and gain of knowledge had been continuously incorporated (Zoback et al., 1991; Zoback, 1992, Sperner et al., 2003, Heidbach et al., 2010). The quality control considers different criteria such as the number of observations from which the mean for the orientation of S_h and the standard deviation is derived. For A-quality data the standard deviation has to be <15°, for B <20°, for C<25° and D<40°). Data with E Quality have no significance for stress interpretation but indicate that they have been checked. The visualization of the data is with stress maps showing the S_H orientation within the uppermost 40 km of the Earth´s crust and the stress regime (for those indicators that provide information about the regime, Fig. 8).


Method
focal mechanism
breakouts
drill. induced frac.
borehole slotter
overcoring
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geol. indicators
Regime
NF
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Quality
A
B
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(2008) World Stress Map

Fig. 8: World Stress Map. The symbols show the orientation of the greatest horizontal principal stress S_h. The length of the symbols is a measure for the data quality, the color indicates the tectonic regime. Red is normal faulting, green denotes strike slip and blue thrust faulting regime.

More detailed description on quality ranking, guidelines for the use of the WSM database, stress indicators and software to generate stress maps are available under www.world-stress-map.org. Whereas at the beginning of the project in the mid-1980s the focus was on the investigation of the long-wavelength stress pattern in the intraplate regions (Zoback et al., 1989; Zoback, 1992; Müller et al., 1992), the systematic compilation of all stress information also along plate boundaries and in areas, which deviate from the general stress trends is in the focus today. This is important to investigate and quantify stress sources also on smaller scales (Fuchs and Müller, 2001; Tingay et al., 2005; Heidbach et al., 2007).

4.3 Quo vadis WSM?

Geomechanical-numerical models for georeservoirs, nuclear waste deposits and seismogenic regions have shown that the model independent kinematic data from satellite geodetic observations such as GPS or PS-InSAR, geological or geomorphological data even in combination with the WSM stress orientation database are insufficient to validate the stress state of the models. However, they could calibrate the models for stress changes *e.g.* due to fluid injection or co-seismic slip during an earthquake. For absolute quantitative statements such as the reactivation potential of faults or the so-called drilling window which is the range of mud pressures during drilling to achieve wellbore stability, stress magnitude data with depth have to be compiled. Only when these data can be used for model validation, geomechanical-numerical models can provide absolute quantitative results.

To meet these demands the WSM advances by implementing data sets on magnitude measurements and lithology (Q-WSM). Currently about 1200 such data are compiled and first analyzed (Zang et al., 2012). Therefore, a quality ranking scheme for stress magnitude measurements will be developed. This challenge can only be solved by intense international co-operation of academic and industrial experts, from the International Society of Rock Mechanics in combination with the hydrocarbon industry. A forth WSM conference is planned to discuss and further develop this new Q-WSM. Furthermore, a new release of the WSM database is in preparation for 2015 with probably an increase to > 30,000 data records.

4.4 Sources and Patterns of Tectonic Stress

An essential goal of the WSM project was to identify and investigate the stress sources and stress patterns. Stress sources act on very different spatial and temporal scales. The motion of tectonic plates determines the long-wave length contribution of the stress pattern (>1000 km). This is normally constant on a long time scale (> 1 Mio years, Zoback, 1992; Zoback et al., 1989; Heidbach et al., 2010). Huge active tectonic fault zones are regional stress sources which create transient deformations and thus temporal changes of the stress pattern (Fig. 9). Locally third order stress sources resulting from local density or strength contrasts or segments of active fault zones can govern the stress field. From the superposition of all natural stress sources results the *in situ* stress state. Table 1 provides an overview on the most important natural stress sources and the wavelengths of the resulting stress patterns. A graphical description about the stress sources is given in Figure 9.

In addition to the natural sources local anthropogenic impacts have to be taken into account. Examples are the impoundment of water reservoirs with the seasonal variation of vertical loads and pore pressures in the underground, mining, excavations of tunnels, drilling of wellbores. The excavation of material or additional loading by changing water levels the stress state is changed locally and in a first approach instantaneously.

Table 1: Overview on the most important natural stress sources in the Earth´s crust. The impact of the stress source at a certain location cannot be deduced from the wavelength because the wavelength is depending on the magnitude of the stress source.

Source	Example	Range of Influence[1]
Plate Boundary Forces	Collisional resistance, Ridge Push	10^3-10^7 km
Volume Forces	Contrasts in density and material properties such as strength and elasticity at mountain ranges, continental margins, Moho, sedimentary basins	10^2-10^4 km
Bending	Glaciation, subduction zones	10^2-10^4 km
Strong Earthquakes	Plate boundaries, intraplate earthquakes	10-10^2 km
Decoupling Horizons	Evaporitic layers, faults with low frictional coefficient, layers with high pore pressure	10-10^2 km
Geological Structures	Faults and fracture systems, diapirs, folded structures	0.01-10 km
Thermal Stresses	Magma intrusions, advection, fluid circulation	0.01-10 km

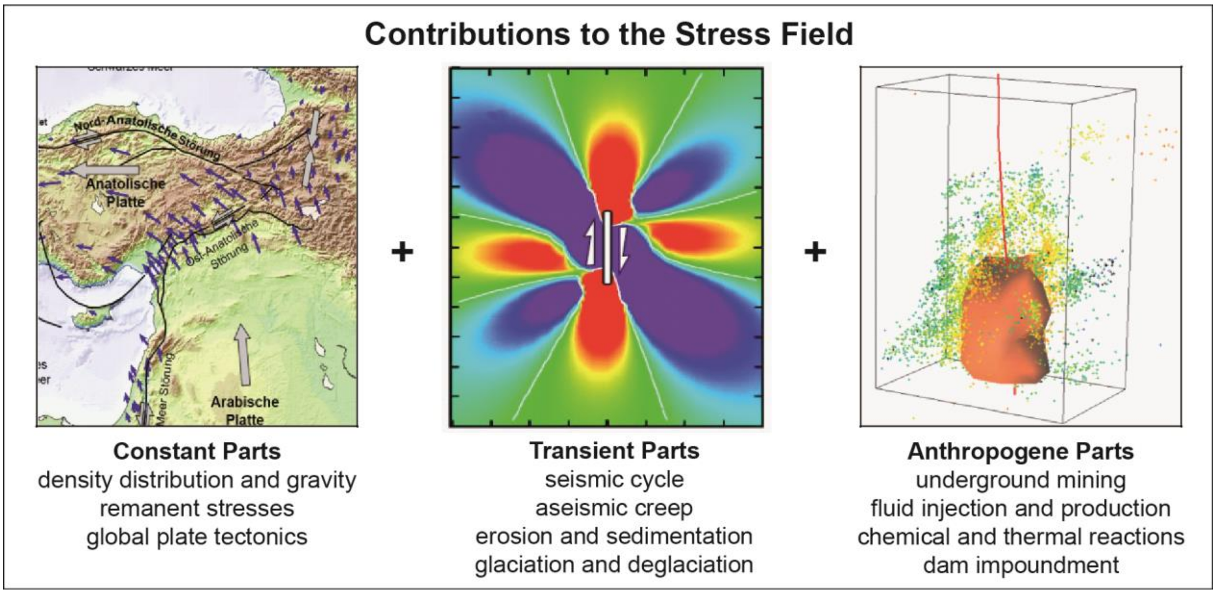

Fig. 9: Sources of stress on different spatial and temporal scales: 1) far field stress from density contrasts in the gravity field, remnant stresses from earlier processes and plate tectonics such as subduction and collision. 2) transient contributions from mass redistributions, stress from post-glacial rebound and not isostatically compensated stress changes and seismic cycles. 3) anthropogenic sources which can be time-independent such as mining activities or time –dependent such as fluid injections or production with varying production or injection rates. The modifications of the stress state through mining depends on fluid pressure, production rate, Volume and material characteristics. Furthermore, the processes can be coupled and are non-linear such as fluid diffusion into the rock matrix, fracture evolution, thermo-hydro-mechanical processes or thermo-chemical reactions.

On reservoir scale the injection or production of fluids and gases changes the state of stress in time and space. The resulting transient processes of fluid migration in porous media and the temperature changes from heat conduction and convection as well as chemical processes can modify the local stress state substantially. The consequences of these measures depend essentially on the rock strength and the initial stress state. If the state of stress is characterized by already high differential stress small stress changes can initiate plastic processes. On the other hand, if stress differences are small, rather small changes of the stress pattern can lead to local changes of the stress regime and to significant stress rotations (Sonder, 1990; Müller et al., 2010).

[1] The numbers given here are an approximation of the dimensions, which can vary from region to region.

4.5 Temperatures and Tectonic Stress at Depth and Dynamics of Planet Earth

At low pressures and temperatures rocks react in a brittle manner if the tectonic stresses exceed the rock strength when the minerals break cataclastically. At higher pressures and temperatures the intracrystalline deformations and grain sliding mechanisms lead to ductile creep of the rock. The transition from brittle to ductile deformation behavior depends on the mineral composition, the deformation rate and exponentially on the temperature. The rheological behavior of the lithosphere is thereby determined to a large extent by the temperature distribution in the Earth´s interior. Temperature contrasts in the Earth´s Mantle lead to density contrasts which are the cause for mantle convection and thus material transport, volcanic activities and finally are a driving mechanism for the movement of large tectonic units - plate tectonics. The latter modifies the crustal shape by deep trenches along subduction zones and orogeny in continental collision zones. In places, where the displacements induce strong increase in strain and stress, the high stresses can be released in form of earthquakes on short time scale or by plastic deformation on a longer time scale. Without these processes the percentage of marine crust would be much higher. In other words, only because of the tectonic processes that lead to hazards such as volcanic eruptions, earthquakes and tsunamis the landscape that man needs to survive was created. Thus, apart from the disastrous effects threatening lives, there is a creative power in these stress related processes which is essential for forming our living environment.

Elastic or plastic material properties (rheology) determines (limits) the maximum possible differential stresses with depth. By the exponential decrease of viscosity with temperature – which can in first approximation be described by an Arrhenius-type equation as an activated process – the transition from brittle to ductile behavior of crustal rocks is within a relatively narrow temperature range because already at 300° C most crustal minerals behave ductile. The rheological behavior of rocks is determined by the most ductile phase, thus most rocks are brittle at temperatures only less than 300°C. For greater crustal depths with temperatures above 300°C rock strength and thus maximum sustainable differential stress reduce exponentially (Fig. 10).

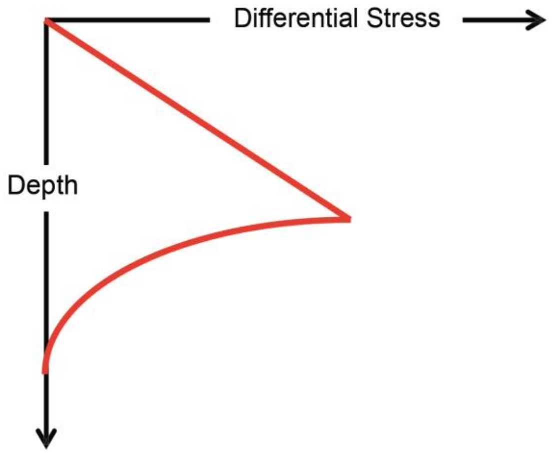

Fig. 10: Sketch of the vertical distribution of maximum differential stress in the crust. For the uppermost crust with low temperatures and low pressures, the differential stress is limited by frictional sliding. At greater depth ductile deformation is limiting the maximum sustainable differential stress.

This temperature-related distribution of deformation characteristics limits the size of potential fracture planes in the Earth´s crust, along which earthquakes could initiate. Geophysicists use the size of the fault zones to estimate the maximum possible magnitude on that plane. From geological observations the lateral extent can be defined, but not the extent to depth. The petro-physicist Frank Schilling emphasized the importance of the temperature distribution for brittle failure. The greatest sizes of fracture planes can occur in subduction zones where due to the subduction cold crustal material is transported to greater depth. The

300° isotherm is in most continental crusts at depths of about 10 km, in subduction zones the isotherm can be at depths to 50 or even 60 km. In so-called high-stress (Uyeda, 1982) subduction zones the angle of subduction is rather small. In comparison to the normal mostly very steeply dipping fracture zones in the continental crust, the fracture planes in low angle subduction zones can be much higher. To estimate the maximum possible earthquakes of an area, the size of the fracture plane and the frictional coefficient are required as input properties. Since the coefficients of friction of most rocks are rather similar, the strong earthquakes with very high magnitudes occur in subduction zones instead of plate interior crust (Fig. 11.). Also for these naturally occurring earthquakes ("tectonic events") the fluid pressure may play an important role as for induced earthquakes (see next section).

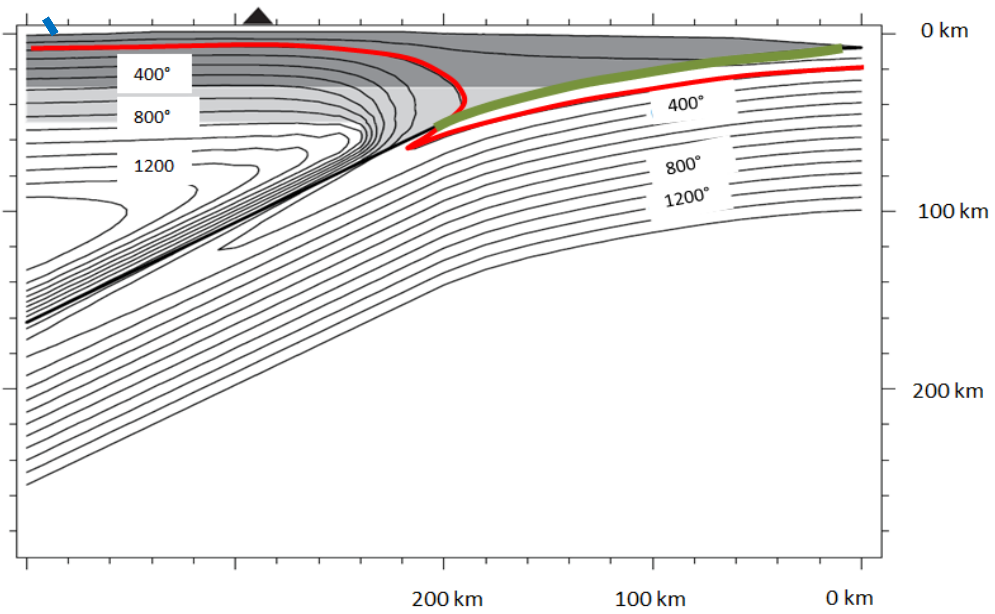

Fig. 11: Sketch of temperature distribution (after Peacock and Wang, 1999) in the Japanese subduction zone. The 300°C isotherm, which limits the brittle behavior of crustal rocks is marked in red. The profile of the maximum earthquake generating fault plane is marked in green in the subducted continental crust. Blue tick (left side) shows the profile of a typically 30-60° dipping fault plane in plate interior continental crust. In this the isotherm limits the depth extend of the seismogenic fault. For the same lateral extent of the fracture zone, earthquakes of M= 8 or larger normally occur along subduction zones and not in continental interiors.

5. Stress Changes with Time

Stress changes with time occur on different time scales depending on the stress sources. The movement of the tectonic plates in the order of several cm/year leads to continuous stress and strain accumulation on a long-term base. During an earthquake a part of these stresses are released quasi instantaneously along the fault plane and contemporarily there will be a stress readjustment in the immediate vicinity of the fault plane. The latter can lead to additional fault slip or reduce the tendency for slip on these faults depending on the distance and orientation of the faults to the ruptured fault zone. This relative stress change is considered as a change in *Coulomb Failure Stress* (King, 1994). With the *Coulomb Failure Stress Concept* the principal spatial progression of the earthquake sequence between 1939 and 1999 along the North Anatolian Fault system could be explained (Stein et al., 1997; Lorenzo-Martin et al., 2006). Transient processes within the earthquake cycle are important because stresses can change by creep or poro-elastic processes occurring after an earthquake. Aseismic creep has been detected by means of GPS observations in the past decade especially along subduction zones and shows the variety of natural processes of stress changes.

Human activities have caused significant changes in the underground not only instantaneously by excavation. For decades, oil and gas production has contributed to economic prosperity. These geotechnical measures have imposed changes in the underground such as local and regional subsidence (Weyburn, Ekofisk-platform) or seismicity in the vicinity of the reservoirs. In Germany earthquakes in the North German Basin (M=3 in 2012, M=4.4 in 2004) are under discussion because they could be caused by gas recovery in this area. Contrary to the induced seismicity of geothermal or hydrocarbon reservoirs during the stimulation (injection), when seismicity is observed during or immediately after injection, the production induced seismicity has a temporal shift to the onset of production, indicating a causal relationship with produced volumes and pressure reduction in the reservoir.

Subsidence above reservoirs can be explained by pore pressure reduction in the reservoir layers. The micro-seismicity from injections can be geomechanically explained by an increase of pore pressure which reduces the effective normal stress. The goal of stimulation measures in hydrocarbon industry is the enhancement of the hydraulic connection between wellbore and reservoir. The goal of stimulations in geothermal wells is to increase the permeability and thus the efficiency of the heat exchange in the underground by pressurization of the wellbore and modification of the stress field locally. In critically pre-stressed rock even small pressure increases can lead to reactivation of faults and lead to the observed and felt seismicity.

Serge Shapiro- former Humboldt fellow at the Geophysical Institute and now professor at FU Berlin uses the observed micro-seismicity during stimulations to characterize the reservoir (Shapiro, 1997; Shapiro et al., 1999). Tobias Müller, Emmy Noether Fellow and leader of a Emmy Noether junior research group *Seismic waves in porous media* at the Geophysical Institute and now at CSIRO investigates qualitatively and quantitatively together with the tectonic stress group of the Geophysical Institute the changes of the stress field as a function of changes in pore pressure using a poro-elastic concept of Rudnicki (1986) and Engelder and Fischer (1994). The interpretation is supported by measurements in hydrocarbon reservoirs, where it was found that during production from a reservoir not only the pore pressure is reduced but also the least principal stress magnitude (Fig. 12). A quasi-linear relationship between pore pressure change and stress change seems to be obvious.

By reduction of the minimum horizontal stress the shear stresses in the rock which are proportional to the difference between maximum and minimum stress can increase, which can lead to slip on fault planes and thus to the observed seismicity in connection to production. This process depends on the initial state of stress, the size of the reservoir, the produced volume and thus is a time-dependent process. Thus, it may take several years of production until a critical stress state will develop. In Lacq the first perceptible seismicity started ca. 10 years after the onset of the production (Grasso and Wittlinger, 1990, Grasso, 1992). In how far reservoir management can improve the pressure in the reservoir by *e.g.* waste water or CO_2 injection to reduce the seismicity, is a future task for geoscientists, not only from the Geophysical Institute of the University of Karlsruhe.

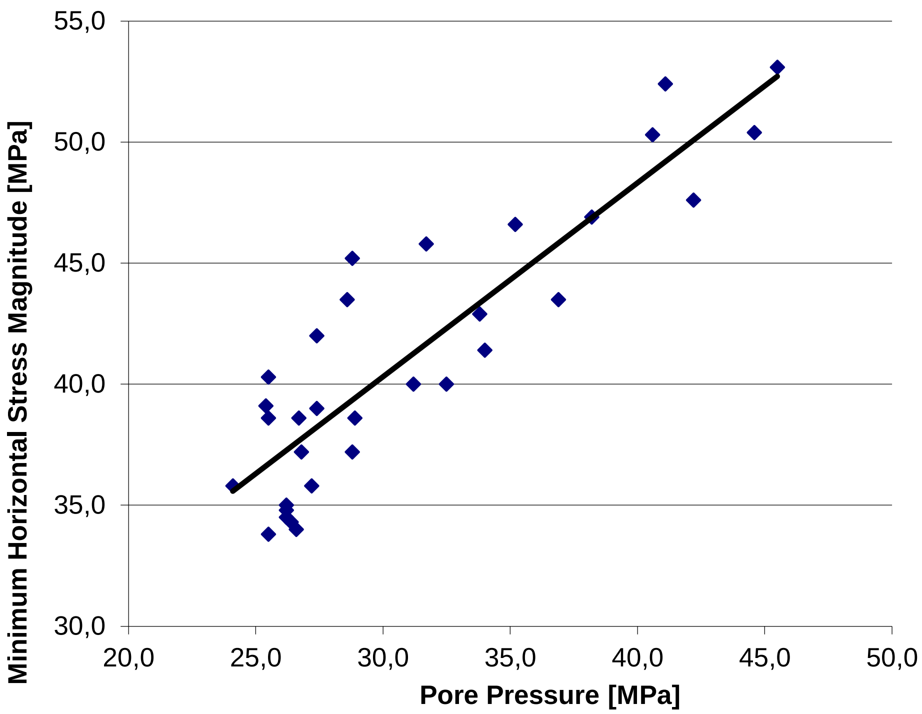

Fig. 12: Change of horizontal stress with change in pore pressure in the Ekofisk field. Data are from Teufel (1996). Due to the production the pore pressure has reduced from 48 MPa in 1969 to less than 25 MPa. The coupling of changes in horizontal stress to changes in pore pressure is around 70-80%.

6. Concluding Remarks

The Geophysical Institute and Karl Fuchs have contributed to modern reservoir management and geomechanical – numerical simulation of stress and strain accumulation and release for strong earthquakes and dynamical processes by systematical theoretical and applied projects about tectonic stresses, its sources, consequences, spatial variations (patterns) and temporal changes. This was motivated to a large extent by the analysis and interpretation of data, such as in the World Stress Map project, where the trends of regional and local stresses in orientations and magnitudes have been discovered. Those observations had been a surprise, but even more surprising were the consequences of those observations in terms of geodynamics and (reservoir) geomechanics as described above. E.g. for the Vrancea-Subduction zone stress analysis was essential to differentiate between the interpretations of the underlying process and to estimate the most probable scenario. In the Geophysical Institute the different disciplines found a kind of fertile soil for intense exchange and co-operation. Especially we benefit from the intense co-operation with the Geodetic Institute with the determination of horizontal and vertical displacements and strain. This will be fortified because the combined interpretation of geodetic and geophysical observations seems to be well established on a global scale, whereas there are only few projects on a regional scale such as the monitoring of gas caverns and CO_2 sequestration. The scientifically based combination of geodetic observations with geomechanical modeling will enable to assess the time-dependent processes of reservoir geomechanics which will be the prerequisite for a successful use of the underground. This is of great importance for the envisioned extended use of the underground for energy storage or synergies of underground use.

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11. Listening to the Earth — The Schiltach Observatory BFO

Walter Zürn

1 A brief history of BFO

The Joint Geoscientific Observatory Schiltach, also known as Black Forest Observatory [BFO] is an interdisciplinary institution which is operated by the Geodetic and Geophysical Institutes of the Karlsruhe Institute of Technology (earlier: University of Karlsruhe) and the University of Stuttgart. The observatory (latitude 48.33°N, longitude 8.33°E, altitude 589 m a.m.s.l.) is located in a seismically rather quiet region about 5 km from anthropogenic noise sources like industry and heavy traffic.

The observatory was established in the years 1971-72 in parts of the abandoned ore mine ”Anton” near the small town of Schiltach in the Black Forest (SW-Germany). The mine was dug into granite and is about 170 m below the surface. Between 1770 and 1850 cobalt minerals and silver were excavated in the mine. In the years 1834 - 1850 more than 732 kg of pure silver and more than 189 t of cobalt ore were retrieved from the so-called ”Reiche Firste” in this mine. Mining activities stopped in the late 1870s and the mine was left open afterwards.

The initiative to establish a broadband geoscientific observing station was taken by Stephan Müller in the mid 1960s shortly after he was appointed to the geophysics chair at Karlsruhe [GPI]. Geodesists Lichte and Mälzer of the Geodetic Institute in Karlsruhe [GIK] joined him in his efforts and an extensive search for a feasible mine in the Black Forest took place right afterwards and soon a decision was made in favor of the “Anton”. The search was strongly supported by mineralogist Rudolf Metz, professor at Karlsruhe University and Black Forest expert. In the summer of 1967 work in the mine started and in December of that year the first instruments (a pair of BLUM-pendulums for tidal measurements) were installed for a test phase. Klaus Strobach was appointed as director of the Institute of Geophysics [IGS] at the University of Stuttgart in 1969 and immediately agreed to the cooperation in the observatory to be constructed. In December of that year a proposal was submitted to the Volkswagenwerk-Foundation which was granted somewhat later. Hermann Mälzer and Jörg Ansorge [GPI] accepted the main responsibility for the next stages. On November 2, 1970 excavation and construction work in the mine began. In September 1971 the construction work of the laboratory and the amagnetic hut started. Most of the construction work, including electric and phone installation was finished in December 1971 and observatory work could begin. In the meantime Karl Fuchs had replaced Stephan Mueller as director of GPI and fully supported BFO.

In the early years the staff of the observatory consisted of two scientists (Dieter Emter and Walter Zürn [WZ], hired August 1, 1972 and January 1, 1974, respectively), two technicians (Heinz Otto and Walter Grossmann, hired July 1, 1971 and October 1, 1974, respectively), a cleaning lady and neighbour (Magdalena Hauer, hired December 2, 1971), and a housekeeper (Alois Hauer, husband of the former, hired on an hourly basis in 1971). The formal director of the BFO, representative for all institutes, Hermann Mälzer, his secretaries, Otto and the Hauers belonged to the GIK. Hermann Mälzer visited the observatory during his directorship on a weekly basis and from the beginning created a friendly atmosphere for discussions and decisions. GPI had hired Walter Grossmann and WZ, while Dieter Emter belonged to the IGS. The director position was remaining in the GIK with Hans-Georg Wenzel following Hermann Mälzer in 1988 and Bernhard Heck following H.-G. Wenzel in 1999.

In 1996 the Hauer family retired and their positions at BFO and GIK were given to the son Alois Hauer Junior and his spouse Martina. They live in their house directly below the observatory, a very favorable situation. Incidentally, this house burned down on February 16, 2004 and was reconstructed completely. Walter Grossmann retired in 1999 and unfortunately the GPI could not support the position at BFO due to restrictions in Karlsruhe, therefore he could not be replaced. Dieter Emter retired 2 years early in the fall of 2000 and his position at IGS and BFO could be filled by hiring Rudolf Widmer- Schnidrig. Thomas Forbriger replaced WZ at BFO and GPI in 2003. Heinz Otto had to retire in 2005 and to replace him was not easy because of the general negative trend for permanent positions at the universities, but after negotiations with Stuttgart fortunately Peter Duffner could be hired in February 2006 as his and Grossmann's successor.

When Erik Grafarend was appointed as director of the Institute of Geodesy in Stuttgart around 1980 this institution also became one of the parent houses of BFO. On several occasions Grafarend played a decisive role in the appointment of new positions of importance for BFO. His successor Nico Sneeuw (since 2004) is a strong supporter of BFO as well. The successor of Strobach at IGS in 1988, Erhard Wielandt, was a great step forward for BFO and its staff. As an instrumental genius, great physicist, and very good friend of BFO from the beginning his contributions are too numerous to be appreciated here in full. He hired Ruedi Widmer-Schnidrig for the BFO position in 2002. He was replaced in 2005 as director of IGS by Manfred Joswig, who participated also as a supporter. After Hans-Georg Wenzel left BFO and GIK in 1998 for a director position at Institute for Earth Measurements [IfE] Hannover, Bernhard Heck as the new director of BFO decided to hire a geophysicist for the staff position at GIK responsible for BFO and Malte Westerhaus was hired in 2000.

At the GPI besides Karl Fuchs, strong advisers and supporters of BFO were Gerhard Müller and since 1979 his successor Helmut Wilhelm. Gerhard Müller had accepted a position in Frankfurt but continued to cooperate and consult WZ. Helmut Wilhelm is a strong theoretician in the field of earth tides and also cooperated and consulted WZ on many issues. He was the first to detect an extension to the tidal potential due to the Earth's ellipticity (Wilhelm 1983). Ten years later Tony Dahlen published a paper on this effect without being aware of Wilhelm's paper. WZ pointed this out to Dahlen who wrote a nice letter of apology to Helmut Wilhelm. The terms first derived by Helmut Wilhelm are included in the modern catalogs of the tidal potential (e. g. Wenzel 1997a).

Helmut Wilhelm also analyzed theoretically the reponse of seismological Earth models to shear forces on the surface (Wilhelm 1986). He especially was a very important and critical correspondent for all the student theses at GPI supervised by WZ. Karl Fuchs instigated especially the participation of BFO (WZ) in the SFB 108, and supported the work over all the years when he was director of GPI and speaker of the SFB. When Thomas Bohlen was appointed to the chair for applied geophysics at GPI in 2009 the BFO again gained a strong supporter.

2 General

The task of the observatory is the measurement, storage and analysis of variables pertaining to deformations of the Earth and temporal variations of the Earth's gravity and magnetic fields in a wide range of frequencies and using a variety of sensors. The major signals provided by the Earth are body waves, surface waves, and free oscillations excited by earthquakes, volcanic eruptions and any other disturbances of the system; the tides of the solid Earth driven by the differential gravitational forces exerted by sun, moon, and to a lesser extent the other planets, including the disturbing effects caused by the motion of huge water masses in the oceans; the gravitational and deformation effects by local, regional, and global atmo- and hydrosphere; and finally the magnetic variations caused by processes in the Earth's core and the sun. Of course, the data are always searched for new or undetected phenomena. One of the prime goals at such an observatory is, of course, also to improve the sensitivity of the sensors and to develop methods for noise reduction.

BFO also functions as a small but efficient research institution. The research carried out by the staff of the observatory and their students at the universities is documented in about 200 publications and goes beyond BFO topics. More than 50 Diploma theses and more than 10 dissertations were produced using data, problems and ideas stemming from the observatory. Dissertations at the Universities at Strasbourg, France, and Louvain-la-Neuve, Belgium (d'Oreye and Zürn 2005, 2006), were also supervised by BFO scientists. Editors of high impact international journals (Nature, Science, AGU journals, Geophysical Journal International among others) rather often approach the scientists at BFO for peer reviews (between only 2000 and 2005 a total of 80 reviews were written). One BFO scientist (WZ) was cited by Journal of geophysical Research for excellence in reviewing. Incidentally, WZ was foreign examiner in Ph.D. and Habilitation examinations at several foreign universities (Cambridge (UK), IPG Paris (twice), Utrecht, Strasbourg, Chambéry (Haute Savoie), Louvain-la-Neuve (Belgium), and Helsinki), while he was not allowed to participate actively in such examinations at Karlsruhe since he was not a member of the ”Lehrkörper”.

BFO presents a unique opportunity for students at both universities to gain knowledge and skills on leading-edge seismological observation techniques. Consequently BFO plays a role in the bachelor and masters programs at KIT. Thomas Forbriger offers a compulsory lecture with exercises on the physics of seismic instruments in the geophysics masters program. Malte Westerhaus teaches BFO research topics in a course on recent geodynamics in the geodetics masters program. In 2012 the first BFO-Winterschool took place. During three days students work with research quality broad-band seismometers on installation and calibration in an observatory environment under the supervision of Thomas Forbriger and graduate students. Ellen Gottschämmer organizes study trips for students in the bachelor program to BFO on a regular basis. Joachim Ritter brings his graduate and undergraduate students to BFO once a year to discuss seismological research for a day with the BFO staff. WZ, Ruedi Widmer-Schnidrig and Thomas Forbriger were responsible for many years for the 4-5 day long field practice course in applied geophysics taking place in the Hegau volcanic region near the Lake of Constance (Thomas Forbriger still is). All this makes the observatory a place for education, too.

Besides the 24h/7d-routine operation the observatory also functions as an experimental station, where new instruments and methods developed by other institutions and colleagues may be compared in their performance with the ”gold standard data” (an expression coined by Prof. Jon Berger, UCSD La Jolla 2009) obtained routinely at BFO. This possibility was used very often during the lifetime of BFO, a few selected examples are listed below.

The observatory consists of an approximately 700 m long almost horizontal mine shaft with side tunnels and vaults, at the end about 170 m below the surface, a second tunnel about 40 m higher up (”Upper Anton”), the laboratory building, and a garage housing an uninterruptable power supply in front of the mine adit, and a small amagnetic hut at about the altitude of the upper mine shaft. The tunnel system is dug into granite, while starting 60 m higher triassic ”Buntsandstein” makes up the country rock. The innermost parts of the main tunnel, between about 400 and 700 m from the entrance, where the observatory sensors are installed is blocked off from the outside atmosphere by two airlocks. The first one was installed in 1974, the second one in 2009. Each of those consists of two very nearly airtight doors about 8 m apart. These locks can be described as simple low-pass filters for atmospheric pressure variations with time constants between 4 and 60 h, thus heavily reducing direct influences of ambient pressure variations on the sensors in the long-period seismic band. They also prevent air currents from the outside and serve to stabilize the temperature near the sensors to a few mK near 10°C. Of course, the sensor positions and azimuths were estimated carefully by the colleagues from the GIK under supervision by Hermann Mälzer.

The laboratory building houses offices and workshops for the staff. Nowadays the observatory is operated by two scientists and only one technician, although the number of sensors and computers has increased steadily. Sensors and data acquisition electronics are operated from uninterruptable power supplies since power outages occur several times per year in this rural environment.

After several tests with horizontal pendulums and short period seismographs the first continuously recording instrument, a short period seismometer, was installed in January 1972. Since then the number of sensors has much increased and at present the following instruments are providing data continuously (24h/7d, unless disturbed):

- Double-sphere superconducting gravimeter GWR OSG-056 with on-line refrigeration of liquid Helium and without running the tilt-feedback (possible because of the stability of the underground).
- LaCoste-Romberg Earth Tide gravimeter ET-19 with electrostatic feedback (LCR ET-19)
- 3-components of Streckeisen STS-1 broadband seismometers
- several Streckeisen STS-2 three-component broadband seismometers
- ASKANIA 2-component borehole-tiltmeter with modernized electronics
- Three 10 m - Invar wire strainmeters (improved Type Cambridge) in azimuths N2°E, N60°E, and N300°E
- 111 m long-baseline fluid-presssure tiltmeter (Type Horsfall) in azimuth N331°E
- 3-components of Fluxgate magnetometers (Rasmussen)
- Overhauser-Proton magnetometer
- Continuously recording GPS-receiver with a special antenna monument near the amagnetic hut
- Pressure transducers in several environments (2 Paroscientific)
- Other meteorological sensors (precipitation, temperatures, wind etc.)

The data are published through international data centers IRIS, SZGRF, GFZ (GGP), BKG, and Intermagnet. In addition there is quite a number of instruments for experiments, reference, and education.

When the observatory started in the early seventies signals were either recorded on photographic film next to the instruments or on chart recorders in the laboratory. The latter were connected to the instrument outputs through copper cables with lengths of several hundred meters. Frequent damages of electronics at both ends of these cables by lightning strikes above the mine were a disastrous consequence of this setup. Films in the mine had to be changed once a week which resulted in severe disturbances of the tiltmeter records and since the two ASKANIA tiltmeters then recording in the same vault as the photographically recording BLUM and MELCHIOR-VERBAANDERT horizontal quartz pendulums had much better signal-to-noise ratio, the recording of the latter two types of instruments was stopped in favor of the ASKANIAS.

In 1979 the first digital recording system was introduced. This consisted of an antialiasing filterbank (25 s cutoff period, 8-pole) and a multiplexer for 16 channels driving a 16 bit A/D-converter (DATUS-PROCON) located in the electronics vault right in front of the first airlock, which in turn was connected (at first by copper cables and later by optical fibers) to a receiver plugged into the RAYTHEON 704 minicomputer in the laboratory about 400 m away. The clock of the computer was synchronized using self-made (Hans Stecker at GPI) electronics to a radio-clock driven by the DCF-time signal transmitter in Meinflingen. The data were recorded on half-inch magnetic tapes. Especially during the period when this system was operating the help by Werner Kaminski at GPI was invaluable with soft- and hardware problems. This system recorded until 1989 with sampling intervals of 2 and 5 s.

The PC-era arrived and after some testing a new system was developed and installed. The same filterbank was used, but now connected to a 20-channel HEWLETT-PACKARD multiplexer and digital voltmeter in the electronics vault. The resolution of the digitization was thus increased from 16 to about 22 bits. In the laboratory a PC was programmed to send information via optical fibers to the HP and to receive and save the data coming in packages of 1 minute. Time pulses all 5 s were selected by a special unit from the DCF-clock and sent to the HP to trigger the sampling sequence. The 5 s -blocks were accumulated in hourly files and recorded on magneto-optical discs and CDs. This system operated until August 2012.

The first A/D-conversion at BFO directly at the sensor was installed in 1990 with the first station of the German Regional Seismic Network [GRSN]. The outputs of the STS-2 broadband seismometer of that system were fed into a QUANTERRA 680 digitizer with a resolution of 24 bits and sampling rates 80, 20, 1, and 0.1 Hz. Data packages were sent to the lab through optical fibers and received at first by a dedicated UNIX-machine (ADEBAHR) and later by a PC running SEISCOMP. In 1996 IRIS/IDA (San Diego) decided to adopt BFO because of the high data quality as an ”affiliated” station of GSN and agreed to record continuously and in near-real time besides the three STS-1s also gravimeter, tilt-, strain- and barometers. However, the expensive recording equipment had to be purchased by BFO, because IRIS at this time was trying to expand into the ”white” areas of the global seismic station distribution and not into central Europe. Between 2002 and 2012 all remaining sensors were provided with QUANTERRA Q330HR digitizers whose internal clocks are synchronized by second pulses from GPS-disciplined clocks in the lab. The SG-signals are recorded on two systems, an AGILENT digital voltmeter (and PC) and a QUANTERRA Q330 in order to have redundancy. The connections between the computers in the lab and the QUANTERRAS consist also of optical fibers. This setup definitely has less sensitivity to close lightning strikes than the early setup using long multiwire copper cables.

In 1990 with the GRSN-station also the data transmission to data centers via the Internet started and again this was expanded to most data streams and occurs now in near-real time. Seismic data are transmitted to the GRSN data center at BGR Hannover and to the IRIS data centers in San Diego and Seattle, magnetic data to Intermagnet, and GPS data to BKG Frankfurt were they are routinely processed. On a monthly basis the data from the superconducting gravimeter are sent to the GGP data center at GFZ Potsdam.The data are also stored in LSDF@KIT.

3 Research

3.1 Earth tides

When the observatory started in 1972 to record Earth tide gravity, tilts and strains the paradigm in the field was to determine the amplitudes and phases of these signals as accurately as possible and then obtain results for the Love numbers h_2, k_2 from the so-called gravimetric and diminishing factors from gravity and tilt and finally strain observations could be used in addition to retrieve the Shida number l_2. These numbers could then be compared to theoretical results obtained from seismologically constrained models (e. g. Wilhelm 1978).

However, measurements told another story. In the late 1960s it had become clear that the tides in the oceans due to their gravitation and deformation of the earth (”loading”) significantly affect the body tide measurements (especially near the coasts but also in the interior of the continents) and methods had to be developed to correct the observations for these effects using models of the ocean tides and the response of the Earth (e. g. Farrell 1972). If these corrections would be good enough, Love and Shida numbers could be retrieved. However, since the ocean loading effects must vary smoothly in space away from the coast they could not explain the dispersion of tidal tilt measurements within one observatory at distances of only a few meters. In 1973 two papers appeared side by side in ”Nature” clearly identifying this problem (Baker and Lennon 1973) and providing a physical explanation for it (King and Bilham 1973): local distortions of the strain field due to cavities, topography and geological inhomogeneities.

3.1.1 Tidal tilts and strains

At BFO it was clear from the beginning of tilt and strain measurements due to close contact with the Cambridge group that these effects are important. Bilham and King came to BFO to install their invar-wire strainmeters (10 m long) at several locations in the mine in order to study the variations of the observed strain amplitudes and phases and their dispersion. Several tiltmeters were installed at about the same time within the pendulum vault: BLUM- and MELCHIOR- VERBAANDERT horizontal quartz pendulums, HUGHES level bubble tiltmeters, and two ASKANIA borehole-tiltmeters fixed to the wall. Originally meant to provide a comparison of their performance these turned out to be important for the validation of the local elastic distortions. Emter and Zürn (1985) summarize all the results together with some 2-D Finite Element [2D-FE] calculations in an invited contribution to a compilation by Harrison of the most important contributions to Earth tide research. The author of this book, J. C. Harrison (1985), refers to this work in his introduction to the chapter as ”an important series of tests ... with sobering conclusions”. Several key experiments were carried out to validate the conjecture of local distortions during the first two decades at BFO (Mälzer et al. 1979; Beavan et al. 1979, Emter et al. 1989).

When the first tidal results from the two ASKANIAs installed 50 cm apart at the N-wall of the vault were obtained there was about a factor of two between the amplitudes. After some effort and a hint by the late Wolfgang Grosse-Brauckmann an error in the calibration of one of them was detected with the help of BODENSEE-WERKE. Many years later it was revealed by Frank Wyatt and Duncan Agnew at La Jolla in 1993 and afterwards verified by Heinz Otto and WZ at BFO as well as by Gerhard Jentzsch at Clausthal that the ASKANIAS suffer from non-orthogonality of the two components by up to 7° varying from unit to unit. After the calibration error was fixed it became clear that both instruments showed much reduced amplitudes for the O_1 and M_2 NS-tilts, with the phase of the semidiurnals and diurnals near zero and 180°, respectively. The bulging of the N-wall due to tidal strains was out-of-phase with the body tide NS-tilts and since the NS-tilt for diurnal tides is rather small at 48° latitude the strain-induced tilt was larger than the body tide (+ocean load) tilt and thus the signal was flipped. Consequently one of the ASKANIAs was installed at the S-wall and indeed in this case we obtained enhancements (100 % for O_1 and 30 % for M_2) of all NS-tilts due to the bulging wall. Afterwards the prediction by Harrison (1976) with 2D-FE-models that the floor of a cavity remains flat while the walls bulge was verified by installing one ASKANIA in the center of the vault. At the same position a vertical 2.5 m Invar-wire strainmeter was installed and it was found that the ”strain” tides were enhanced by a factor of 2 approximately (Heil, 1985).

If the local anomalies of the tidal tilts are caused by the response of the local inhomogeneities to the tidal strains these disturbances should include the signature of the Nearly Diurnal Free Wobble (NDFW). Since diurnal tidal NS-tilts are small at the latitude of BFO we looked for the two experiments which showed the largest discrepancy in the diurnal EW-tilts in terms of the observed complex admittance (diminishing facor and phase). Also the records had to be long enough to separate the diurnal waves P_1, K_1, ψ_1, and Φ_1. The two records chosen are from the ASKANIA mounted in the middle of the N-wall and from a HUGHES-tiltmeter sitting in a niche in the W-wall of the pendulum vault. The complex differences of the resulting diurnal tidal admittances turned out to be in quadrature to the body tide signal and clearly showed the resonance due to the ellipticity of the core-mantle boundary. This is strong evidence for the anomalies to be due to the tides themselves and not e. g. due to calibration, orientation errors or noise (Zürn et al. 1988).

The next idea was to average out small local inhomogeneity effects and approach the global signal by installing an instrument with the longest baseline possible within the mine behind the air-lock. A differential fluid-pressure Horsfall tiltmeter was bought and installed with an azimuth of N25.23°E and a length of 170 m. The design of this instrument required certain properties of the liquid to be used and two different fluorocarbons with densities near twice that of water were used over the years. When the excellent tidal data had been analyzed the results for O_1 and M_2 were close to the predicted sum of body and ocean load tides, although we had expected a small topographic effect from 2D-FE-models (Zürn et al., 1986; Emter et al. 1989). In order to confirm this result in favor of the local elastic effect conjecture the instrument was reinstalled in a different azimuth of N331°E with a length of 111 m and the results were again within a few percent of the predictions with small phase differences. However, a small effect from the topography/geology cannot be ruled out (Otto et al. 1998). Anyway, after these measurements it was pretty clear that long-baseline tiltmeters are able to get closer to the global tidal response because of their averaging property. However, one can never claim that they are only affected to the level of 1 % by the local effects and therefore the Love numbers still can not be determined to the required accuracy.

A very convincing experiment was carried out with a 1 m Invar-rod strainmeter across the ”Heinrich”-cleft in the mine (Beavan et al. 1979; Emter and Zürn, 1985). It is clear that the ”strains” measured with this instrument cannot be related to stresses in the rock (there is no rock between the end mounts) but rather constitute relative displacements of the walls of this cleft. Tides enhanced by a factor of 50 with respect to the predicted body tide strains were observed. Two earthquakes were also recorded and again there were factors of 35 and 56 between these signals and the ones measured with a parallel 10 m Invar-wire unit mounted along the tunnel near the cleft. A factor of approximately 50 was also obtained with both a 2D-FD-model and an analytical model, an elliptical cavity with aspect ratios adjusted to the best of our knowledge to the real cleft.

Heinz Otto had the idea that a crack in one of the niches housing the VERBAANDERT tiltmeters possibly caused excessive drift of those instruments. Therefore two ultra-short strainmeters (less than 10 cm) were installed in that niche, one across the crack and one parallel to it. It turned out that the one parallel to the crack did not show tides within the noise, while the one across the crack measured about 6 times the predicted tides (Zürn et al., 1991).

In the late eighties two new low piers at the S-wall of the seismic vault were constructed side-by-side for the broadband seismometers STS-1 and STS-2 and these were installed on those. Looking at the tides recorded by these two sets of instruments we found a large cavity effect of about 75 and 85 % on the NS-components while the EW-components were only amplified by 20 and 26 %, respectively (Zürn and Emter, 1995). The idea arose that one could possibly be able to see the tides across the gap between the two piers and another ultra-short strainmeter was installed to attempt this. Indeed again a tidal signal could be detected which was enhanced with respect to the prediction (Zürn et al., 1991).

3.1.2 Theoretical considerations on local effects

King et al. (1976) pointed out that the local elastic distortions of regional and global signals do not only occur for tides but also for long period seismic signals like surface waves and free oscillations. This could be verified when the megaquakes off the NW-coast of Sumatra in 2004 and off the E-coast of Tohoku, Japan excited the free modes of the Earth to the largest amplitudes since BFO started recording. King et al. (1976) also suggested methods on how the disturbances could be corrected.

Paul Richards had conjectured that if many instruments at one station record tidal tilts and strains and if the local anomalies are caused by linear reaction to the tidal strains, then these disturbances cannot be independent (the ”Richards constraint” coined by WZ), because only the three horizontal tidal strains are the cause (ε_{NN}, ε_{EE}, and ε_{NE}). The first attempt to verify the validity of this conjecture was performed by Zürn et al. (1979). Twelve residual O_1 and M_2 tilt tides from within the vault at BFO were tested against this hypothesis by casting the constraint into a matrix formalism which allows to form a set of 4x4 determinants which should be zero if the constraint holds. 495 determinants were obtained, however, the results were not encouraging probably because at the time ocean loading corrections caused systematic errors. Zürn and Young (1983) reported on a second study with a new method using 18 components of tilts and strains from BFO. A subset of 11 components including the cleft strainmeter looked like they satisfy the constraint.

3.1.3 Tidal stresses

Of course, the tidal strains in the Earth are caused by the tidal stresses, which in crustal rocks near the surface of the Earth are of the order of some tens of hPa. GLOETZL-stressmeters had been installed in shallow boreholes in the earthquake source region of the Swabian Jura in the framework of the SFB 108 by the Karlsruhe geologists. Dieter Emter and WZ could convincingly demonstrate that these instruments were not coupled to the rock because all they recorded was the (negative) air pressure and during the summer also the temperature. The first effect was caused by the fact that these devices normally measure the difference between rock stress and air pressure and since there was no rock stress acting on the meters the negative air pressure remained. Secondly the electronic equipment for recording the stresses was installed in small huts with controlled temperature. However, when the ambient temperature was higher than a threshold this control unit was saturated and the temperature in the hut followed the outside temperature. However, it had been shown in the lab that the GLOETZL-sondes were able to resolve pressure differences as small as the Earth tide stresses. Therefore it was decided to try to verify this in the BFO mine. Three shallow boreholes (≤2 m) were drilled in front of the airlock and several experiments were carried out in order to find the best expansive additive for the cement with which the sondes were coupled to the rock. In the final installation tidal stresses were clearly recorded and in addition the stresses caused by the seismic waves from the Shikotan earthquake in 1994 (Emter et al. 1996).

Starting when the RAYTHEON 704 was operating at BFO it was possible to run programs while the machine recorded data. During that time David Young from Cambridge University visited BFO for three months and an attempt was made to correlate the origin times of the earthquakes in the Swabian Jura with the Earth tide stresses. Several different statistical methods were used but no significant correlation could be detected (Young and Zürn 1979).

3.1.4 Tidal gravity

For the quality of gravity data the underground is by far not as important as for the horizontal components. However, the BFO mine definitely verifies a very good site for vertical accelerations too. In 1973 BFO was equipped with an ASKANIA GS-15 gravimeter, a little later an ASKANIA GS-12 modified by M. Bonatz and called BN-06 was installed and in 1976 the LCR ET-19 arrived. It turned out quickly that the least noisy of these devices was the ET-19. This instrument is equipped with electrostatic feedback and was modified for optimal performance at BFO by WZ. With the data recorded by this instrument it was possible to demonstrate the errors in the Cartwright-Tayler-Edden tidal potential catalog (Wenzel and Zürn 1990). In addition lower noise levels in the frequency band from 0.5 to 4 cycles/day (cpd) were obtained with this instrument than at other stations with the more sophisticated superconducting gravimeters at the time (Zürn et al. 1991). The absolute calibration of ET-19 (it became known in the 1980s that the factory calibration of the LCRs was slightly off) was improved by a simultaneous record at BFO with two carefully on the vertical calibration line in Hannover calibrated geodetic LCR gravimeters (Wenzel et al. 1991).

In 1994 the ”Bundesamt für Kartographie und Geodäsie” [BKG] loaned its superconducting gravimeter SG102 for half a year to BFO for a parallel registration with ET-19. The goal was to compare these two instruments under identical conditions in terms of their performance and noise levels and to clarify below which frequency the superiority of the SGs over (one of) the best spring gravimeters would show up. Except for the sensors themselves everything else in the data streams and the data processing was identical. The surprise was then that this crossover frequency occurred at a frequency as low as about 0.2 cycles per day (Richter et al. 1995). By chance the important deep 1994 earthquake struck in Bolivia during the period of this simultaneous recording, allowing to compare the signal-to-noise ratios (SNR) of the recorded free oscillations. Unfortunately a liquid helium refill was necessary three days after the quake necessitating to cut all the records into two parts. Nevertheless it could be clearly shown that in that frequency band the ET-19 and STS-1/Z seismometer provided better SNR for the low-degree modes than the SG102. The STS-2/Z had the lowest SNR in that case (Richter et al. 1995). For these reasons the STS-1/Z and ET-19 at BFO were used by Banka and Crossley (1999) in a study of the noise levels of a worldwide collection of superconducting gravimeters as a reference. In their collection then the two BFO instruments were clearly the best. This was in a way a trigger for the producer of the SGs, GWR in San Diego, to look for ways to improve their instruments which was partially successful (Widmer-Schnidrig, 2003).

Rydelek et al. (1991) investigated the M_2 gravity tides recorded by ET-19 at BFO and by eight other instruments of high quality in Central Europe. After subtraction of body tides and ocean load signals the residuals are basically all zero within their error bars (noise, calibration and ocean model bias). This means they cannot be correlated with station properties such as heat flow (which had been claimed by some researchers) and/or crustal structure (Rydelek et al. 1991).

In 1998 ET-19 (after more than 20 years of operation) developed leaks and hence became sensitive to ambient air pressure variations. After a complete overhaul (except for the seals) it was reinstalled in 2009 in the mine but now on a new pier in front of the seismic vault behind the second air-lock. It is now again one of the best long-period vertical seismometers worldwide since ambient pressure variations in that frequency band are heavily damped by the air-locks. However, in the tidal band this damping is not as strong as in the seismic band and therefore the signature of local air pressure in the records is higher there than before the seals became leaky. Nevertheless, Calvo et al. (2014) used the data from ET-19 to study the tides in comparison with other very long records in Europe.

In view of the intended aquisition of a superconducting gravimeter (SG) and the necessary monitoring of the (albeit small: 1000 times less than for good spring gravimeters) drift of such an instrument a series of absolute gravity measurements was started in January 2001. Colleagues from the following institutions owning FG-5 absolute gravimeter (MICRO-g SOLUTIONS) visited BFO irregularly for a few days and measured absolute gravity:

Strasbourg (EOST), Hannover (IfE), Frankfurt (BKG), and Brussels (ROB). First the measurements took place on a pier in the ”Heinrich”-cleft in front of the first air-lock, since 2009 on a new pier in front of the pendulum vault now containing the SG. These instruments observe repetitively the free fall of a test mass measuring its position with a laser interferometer as a function of time measured with a rubidium clock. These measurements serve the purpose of monitoring the drift of the SG. When the tide is large they can also be used for calibration of the SG.

After many years BFO received funding to acquire an SG from GWR in San Diego. After the instrument was ordered the pendulum vault and its immediate environment were secured against rock falls and a container was inserted into the vault the interior of which can be kept dry. In 2009 OSG-056 arrived and was installed by R. Warburton and R. Reineman from GWR and the staff at BFO introduced in its operation. A special feature of this instrument is that there are two gravity sensors inside the dewar in a vertical distance of about 20 cm. The two superconducting test bodies (2.54 cm niobium spheres) suspended in magnetic fields from superconducting coils have different masses, the lower one with 17.7 g and the upper one with the usual 4.34 g. The dewar is filled with liquid He and the sensor temperature is kept at a temperature of 4.5 K. The evaporating He is reliquified by a coldhead. This instrument, in contrast to many other SGs by the same company at the time, does not necessitate He refills, which constitute major disturbances. He gas can be injected slowly and the coldhead is able to liquefy it. Also in contrast to essentially all other SGs the possible tilt feedback by the thermal levelers is turned off and the supports are instead rigidly fixed to the frame because the underground at BFO is more stable than the tiltmeters in the SG are. This was verified long before on that pier by LIPPMANN-tiltmeters measuring excellent tidal signals.

3.1.5 Nearly Diurnal Free Wobble

The earth has four rotational free modes, most importantly: the Chandler wobble with a period of 435 sidereal days and the Nearly Diurnal Free Wobble (NDFW) with a period of nearly 1 sidereal day associated with the Free Core Nutation with a period of 430 sidereal days. Wobbles are observed by observers rotating with the Earth, the corresponding nutations by observers in space. Because the NDFW has its eigenfrequency between the diurnal tides K_1 and ψ_1 and because the tesseral pattern of diurnal tides tries to deform the mantle in such a way that the rotation axis of the mantle differs from the one of the core the Earth reacts resonantly to the tidal forcing, in other words the Love numbers as derived from the diurnal tides exhibit a resonant behaviour. It is like having the Earth on a shake table in a narrow range of frequencies.

In 1987 Jürgen Neuberg at GPI finished his dissertation under supervision of WZ (Neuberg 1987). He analyzed several data sets from BFO in order to retrieve parameters of the NDFW from the obtained tidal admittances in the diurnal tidal band. The data were from the ET-19 gravimeter, the EW-components each from an ASKANIA- and a HUGHES-tiltmeter, and the best of the strainmeters $N2°E$. In addition tidal gravity results from Strasbourg, Bad Homburg, Brussels, Berlin, and Potsdam were used. A nonlinear least squares and several stacking methods were developed to retrieve the eigenfrequency, quality factor, and complex admittance of the NDFW. Of course, the tidal admittances needed corrections for the contributions of ocean loading to the signal. The surprising result was that the eigenperiod of the associated FCN was near 432 instead of the 466 sidereal days predicted from seismologically constrained models. For a possible interpretation of this result were considered: viscomagnetic coupling, effect of the solid inner core, elasticity and anelasticity of the lowermost mantle, and finally an increased dynamic ellipticity of the core-mantle-boundary, the most likely explanation for the shift to higher frequencies. It turns out that the core-mantle-boundary flattening needs only to be increased by 300 to 600 m. Such a fine result could probably never be detected by seismological methods. The results of the stacked gravimeter data and possible interpretations of the anomaly were published by Neuberg et al. (1987, 1990). The BFO data used by Neuberg (1987) had been recorded with chart recorders, therefore part of the work was repeated by Polzer et al. (1996). Although the data were much less noisy it turned out that no improvement could be obtained for the precision of the NDFW parameters, which indicates, that the uncertainties in these results are caused by systematic effects (Zürn 1997). The frequency shift had been obtained independently very shortly before the work at GPI and BFO by the groups analyzing nutation data using results from Very Long Baseline Interferometry, so these results corroborate each other nicely. The methods developed by Neuberg et al. (1989) have become standards within the tidal community with only slight modifications. The data from the superconducting gravimeter at Bad Homburg were already included in the work by Neuberg et al. (1987) and especially for that instrument an analysis of the Chandler wobble and the NDFW was carried out (Richter and Zürn 1988) in addition.

3.1.6 Tidal potential and analysis

While being director of the BFO Hans-Georg Wenzel developed together with Torsten Hartmann (University of Tübingen) an extensive tidal potential catalog (Hartmann and Wenzel 1994, Wenzel 1997a) on the basis of the most precise ephemerides available. This catalog contains 12935 tidal constituents derived from the tidal potentials of Moon (degrees 2 to 6), Sun (2 to 4), Mercury, Venus, Mars, Jupiter, and Saturn (2 only for all planets).

Hans-Georg Wenzel during the same time also developed a program package for tidal analysis (ETERNA) which was widely distributed, accepted and still is extensively used for tidal research (Wenzel 1997b).

3.1.7 Core modes

Gravity signals with periods of some hours are predicted for the translational free oscillation of the Earth’s inner core within the liquid outer core (the Slichter mode) and also for inertial waves in the liquid outer core. At all times the gravity data were searched for traces of such signals. Zürn (1974) showed that under certain conditions a persistent harmonic signal could be detected in digital data even when its amplitude would be smaller than the least significant bit . After a claim was made for the detection of core modes Zürn et al. (1987) showed that what had been observed was very likely not a signal from the core. Later on Zürn (1994) and Zürn and Rydelek (1994) demonstrated with the phasorwalk method that the spectral peak detected in the Brussels record was not caused by a harmonic oscillation but by a transient burst of noise. Up to now no realistic observation of such oscillations was reported.

3.2 Seismology

3.2.1 Local and regional seismology

Almost from the very beginning a 3-component set of short-period GEOTECH S-13 seismometers was recording the seismicity. In 1997 the S-13 horizontals were replaced by two KINEMETRICS SH-1s. The observatory staff, concentrating on long period signals, did not really work on local earthquakes. The routine analysis of the seismograms was carried out by Klaus Bonjer at GPI and his colleagues. The station BFO was, of course, incorporated in the network of the state (Württemberg) seismological service (Landes-Erdbeben-Dienst) in Stuttgart besides its being part of the Rheingraben network operated by GPI. In 1993 these routine tasks of monitoring and analyzing the seismicity in the state were handed over to the newly founded state seismological service of Baden-Württemberg in Freiburg (also named LED) and BFO belongs to that network now.

At first recording of the signals took place on wide ink-chart recorders manufactured at GPI (Volk). In 1986 additional recording on magnetic audio-tapes with high dynamic range (120 dB) by an event-triggered LENNARTZ PCM was introduced. Again the processing of the tapes was carried out at GPI. When the broadband instrumentation was introduced in the late 1980s the frequency range of the short-period seismometers was also covered by these instruments and in 2007 the short-period seismometers were given to the new LED and were deployed at other stations.

3.2.2 Surface waves and free oscillations

BFO is integrated into two more seismic networks besides the LED: the German Regional Seismic Network (GRSN) since 1990 and the Global Seismographic Network (GSN) of the Incorporated Research Institutions for Seismology (IRIS) since May 1996. This means that the broadband data from the STS-2 and STS-1 seismometers sampled with resolution of 24 bits and rates of 80, 20, and 1 Hz, respectively, are continuously delivered to the corresponding data centers and are made freely available to all interested scientists. IRIS also obtains and archives data from other sensors at BFO together with the STS-1 data: gravimeters, tiltmeters, strainmeters and barometers. Until early 1997 the most quiet stations of the GRSN including BFO (of course) were used in GSETT3 (Group of Scientific Experts Technical Test) to verify the possibility of discrimination between nuclear explosions and earthquakes.

Two citations from the independent literature testify to the high quality of the seismic data from BFO. Beauduin et al. (1996) write: ”... in a very good seismic vault such as BFO ...” and Freybourger et al. (1997) say: ”.. because of the well known low level of background noise at BFO ...”. Banka and Crossley (1999) found in their study that ET-19 and STS-1/Z at BFO had clearly the lowest noise levels in the normal mode band for vertical components. This is confirmed by Berger and et al. (2004) in a study of noise levels in the GSN: it turns out that the STS-1/EW seismometer at BFO defines their model of low horizontal noise for many low frequencies.

At BFO and in the working group of WZ at GPI the study of globe circling surface waves and free modes was a central issue from the start. In the early years until 1979 no digital data from BFO were available, as a matter of fact the great Sumbawa earthquake in 1977 could only be recorded on chart recorders at BFO. This event triggered a flurry of activity in the field of normal modes because the IDA network (International Deployment of Accelerometers) had started to operate just in time (Zürn et al. 1991). However, due to the continuing cooperation of WZ with the group of L. B. Slichter and Leon Knopoff at the Institute of Geophysics and Planetary Physics [IGPP] of the University of California at Los Angeles [UCLA] digital records from the ET-4 and ET-11 gravimeters at the South Pole and at UCLA (siblings of ET-19) could be analyzed. Thus the frequency and damping of the ”breathing mode” ${}_0S_0$ could be determined (Knopoff et al. 1979, Zürn et al. 1980) and for other spheroidal modes eigenfrequencies and Qs were also estimated by Xu et al. (1983) from these records.

When the first digital records from BFO became available and a few large earthquakes (Colombia, Dec 12, 1979) had struck, Michael Grünewald (Grünewald 1988) and Christine Fichler at GPI began vigorously analyzing these records for globe circling Rayleigh waves and free oscillations, respectively working towards their doctorates (e. g. Fichler-Fettig et al. 1986). Especially the coupling of toroidal and spheroidal modes was investigated. On the theoretical side Wolfgang Friederich developed a new approach for Gaussian beams and their application to globe-circling surface waves and demonstrated the effects of lateral heterogeneities on focussing and defocussing of surface waves (Friederich 1989) theoretically and with the records from BFO. In any case, the GPI working group on long period seismology, partially financed through the SFB 108 ”Stress and stress release in the lithosphere” by the DFG, was continuously analyzing data from BFO without realizing the quality of the data. Ruedi Widmer had visited BFO with Erhard Wielandt, who had equipped BFO with the prototypes of his broadband seismometers in the early 1980s (the STS-1 to be). When Ruedi Widmer was working on his PhD in La Jolla at the University of California at San Diego [UCSD], he was analyzing many seismograms from the IDA and GSN-networks. He realized that he possibly could also use the digital seismograms from all the BFO-sensors for his work. He came to BFO during the summer of 1988 and extracted the free oscillation records. During his PhD work he looked at many seismograms from all over the world and detected soon that the BFO records belonged to the best as far as SNR was concerned, especially for the horizontal components by the STS-1 prototypes and the ASKANIA tiltmeter, but also for the vertical component and the ET-19 gravimeter.

In 1989 a large quake struck near the Macquarie Islands and when analyzing the records from the BFO strainmeters WZ detected that the toroidal fundamental mode ${}_0T_2$ could clearly and unambiguously be seen in the resulting spectra together with next higher-degree toroidal modes. This had not really been expected. The observation was corroborated by the disappearance of these modes when the areal strain was computed from the three strainmeter signals (Widmer et al. 1992). This observation made it into the textbook by Dahlen and Tromp (1998). These authors write on p. 287: ”The first unambiguous detection of this oscillation did not occur until after ... earthquake on the Macquarie Rise in 1989 (Widmer, Zürn & Masters 1992)”. ${}_0T_2$ was observed with the BFO strainmeter array for four more large earthquakes: Shikotan 1994, Balleny Islands 1998, Wharton Basin 2000, and Peru 2001, before the disastrous megaquake off the W-coast of NW-Sumatra and Andaman Islands struck in 2004 and excited the free oscillations to unprecendented amplitudes since 1964 and all the modes were recorded with extremely good SNR by many instruments including of course the ones at BFO.

On June 15, 1991 Mount Pinatubo in the Philippines produced the secondmost energetic volcanic eruption in that century. During this eruption the ET-19 recorded a very strange signal for about 8 hours which was observed by WZ in real time. Computing a spectrum revealed that the signal was composed essentially of two spectral lines with frequencies of 3.68 and 4.44 mHz. Very quickly it became clear that this signal was observed globally and that it traveled around the globe with the group velocity of Rayleigh waves with these frequencies and that the source was located near Mount Pinatubo (Widmer and Zürn 1992, Zürn and Widmer 1996). Of course, the record archive was checked whether such a signal occurred before unnoticed and it was found that the eruption of El Chichón in Mexico in 1982 also had produced such signals, albeit only for one hour and the frequencies were 3.7 and 5.14 mHz in that case. These frequencies are now understood as eigenfrequencies of the atmosphere which get their energy from the volcano and then push on the surface to excite Rayleigh waves. An enigmatic and still unexplained observation was made a few days before the Mount Pinatubo eruption: on June 10, 1991, for about one hour an oscillation with a frequency of 3.7 mHz was observed at 4 stations with vertical accelerometers: BFO, 2 stations in eastern France and one in northernmost Italy. The frequency indicates that the atmosphere was probably involved in the excitation.

Since BFO provided excellent long-period horizontal seismograms Gabi Laske made an attempt in the early 1990s to retrieve information on the lateral heterogeneities in the mantle by studying the polarization of surface waves. Since Guy Masters at UCSD was also interested in this problem a cooperation was started and Gabi finished her dissertation in La Jolla (Laske et al. 1994). She could show that for the very long periods the polarization represents the large-scale heterogeneous structure of the mantle and corroborates the models obtained by surface wave dispersion and local eigenfrequency data.

When the 1998 great Balleny Islands earthquake had excited free oscillations again close inspection of spectra computed from the records of the ET-19 showed peaks at the periods of some low-degree toroidal modes. This observation was corroborated by spectra from a record of superconducting gravimeters in Membach, Belgium and Strasbourg, France. To explain it, local effects were ruled out and the coupling of toroidal modes to spheroidal modes remained as a possibility, which was corroborated by the synthetic seismograms computed by Gabi Laske. The responsible mechanism is with high probability the Coriolis coupling on a global scale (Zürn et al. 2000).

The small series of megaquakes starting December 26, 2004 made improved observations and measurements on free modes possible. Especially at the low-frequency end of the free mode spectrum the sparse network of SGs [GGP] provides excellent records. Häfner and Widmer-Schnidrig (2012) used the data from GGP to study the splitting of ${}_0S_2$ with improved resolution and thus determined new gross Earth data which can be used in inversions for the density structure of the Earth. Other long period instruments also provided excellent low-frequency mode data. Ferreira et al. (2006) modeled the free oscillation records obtained after the great 2004 Sumatra-Andaman Islands event from a water-tube tiltmeter in Walferdange (Luxembourg) and the Horsfall tiltmeter at BFO and compared these records to the ones from horizontal broadband seismometers. The strainmeters at BFO provided excellent SNRs for the low-degree free modes after the 2004 Sumatra-Andaman Islands (Fig. 1) and the 2011 Tohoku quakes. The complete set of singlets of ${}_0S_2$ could be resolved, ${}_0T_2$ was recorded nicely and even splitting of that mode could be seen for the first time in individual records, and ${}_0S_0$ was observed at good SNR with an amplitude of about 10^{-11}. Zürn et al. (2013) compare these data favorably with the records from the excellent STS-1 horizontal seismometers at BFO and with synthetics computed including the effects of rotation and ellipticity. Thomas Forbriger participated in seismological research in Romania in context with the SFB 461 ”Strong Earthquakes” (Sèbe et al. 2009).

3.2.3 Background free oscillations - the ”Hum”

Intrigued by the observation of the 3.7 mHz oscillations due to volcanoes WZ and Ruedi Widmer-Schnidrig decided in 1995 to send a proposal to DFG for obtaining money for a graduate student who should search the excellent data from BFO for small and unusual mode excitations due to silent earthquakes, volcanoes, or atmosphere. This was not granted due to a lack of promises of detections (phone call to J. Karte, DFG). However, in 1998 Japanese colleagues were the first to publish papers reporting the continuous excitation (called the ”hum of the Earth”) of fundamental spheroidal modes between 2 and 7 mHz and their observation in many good vertical accelerograms. Very quickly then this was confirmed with the data from the ET-19, STS-1/Z, and STS-2/Z at BFO (Zürn et al. 1999, Widmer-Schnidrig 2003). Actually, Benioff et al. (1959) had already searched records from two LCR tidal gravimeters and the quartz extensometer at Isabella, California for such oscillations and concluded that their amplitudes are below the sensitivity of the instruments then and intended to repeat the search when the instruments would be more sensitive.

At first the atmosphere was identified rather convincingly as the energy source of these oscillations with amplitudes less than 1 nGal. Later on the opinions of the involved researchers changed somewhat and infragravity waves in the oceans were made responsible. Since statistics are needed to bring the modes out of the noise it is rather difficult to locate the source. However, several studies succeeded to a certain extent, among them the work by Kurrle and Widmer-Schnidrig (2006) using the best stations of the GRSN as an array.

Dieter Kurrle was very ambitious and he and Ruedi Widmer-Schnidrig detected the ”hum” also in the EW-component seismograms from the STS-1 and STS-2 seismometers at BFO (Kurrle and Widmer-Schnidrig 2008). Two more stations were found in this work to show the ”hum” in horizontal components. However, more importantly, fundamental toroidal modes were also identified by these authors for the first time at about the same amplitude as their spheroidal counterparts. The latter fact raises serious questions on the mechanism of excitation which are still unresolved.

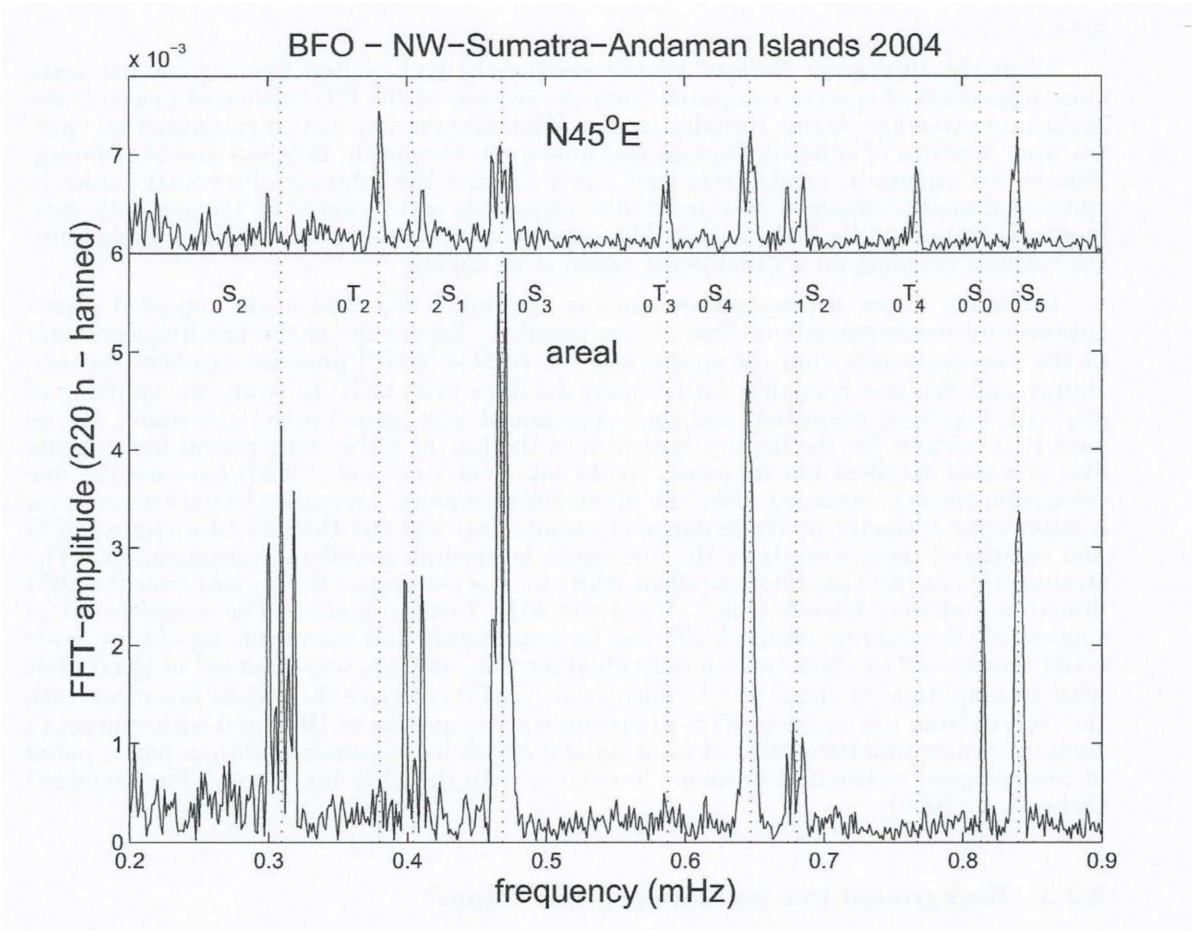

Figure 1: Spectra (FFTs) of two combinations of 220 hour records from the three 10 m invar-wire strainmeters at BFO representing shear strain on a vertical plane striking N45°E (top panel) and areal strain (bottom panel; the areal strain is basically the sum of the three records). Note especially: absence of toroidal modes in the areal strain and their relative enhancement in the shear strain; resolution of all five singlets of $_0S_2$; (partial) splitting of $_0T_2$; high SNR of $_0S_0$ and its absence in the shear strain. Data were calibrated, the tides were removed and a correction for atmospheric pressure loading was applied before combining them. As it should theoretically, the effectivity of the pressure correction for shear strain is much lower than the one for areal strain.

In the context of the work on the ”hum” Kurrle and Widmer-Schnidrig (2010) detected Rayleigh waves with periods larger than 50 s caused by large storms over North Atlantic Ocean. They used GRSN and other networks to locate these sources.

3.3 Magnetic field variations

In cooperation with the Geomagnetic Observatory Fürstenfeldbruck measurements of the magnetic variations were carried out in the amagnetic hut above the mine. Until 1987 this was done with a photographically recording ASKANIA-variograph. Then a digital system consisting of two LEHNER horizontal magnetometers and one vertical fluxgate magnetometer (FÖRSTER-sonde) were installed and operated until about 2000. Ruedi Widmer-Schnidrig then made efforts to join the international network Intermagnet by acquiring new equipment and move the station from the hut into the "Upper Anton"-tunnel about 40 m above the main tunnels where the temperature is much more stable than in the hut. This equipment consists of a three-component RASMUSSEN-fluxgate system and an Overhauser-Proton magnetometer. The required absolute measurements to verify the baselines are still carried out in the hut, only 150 m away. The observatory staff has not done research in geomagnetism, however, the magnetic records were very useful for studies of long-period seismic noise (see below).

3.4 Continuous GPS measurements

Since November 2006 a permanent GPS-station BFO1 is recording continuously with a sampling interval of 15 s. The antenna on a 3.6 m high tripod is located in front of the amagnetic hut and sitting on a massive concrete pier cemented directly onto the granite. Despite the unfavorable location on a slope in the forest the quality of the daily solutions is nearly as good as the ones from free standing antennas. The data are collected at BKG Frankfurt. These measurements have to be considered in the context of the series of absolute gravity measurements in the mine below (Mayer et al. 2008).

3.5 Noise reduction

To study noise and develop methods for its reduction where possible is an important task for researchers working at an observatory. Of course, there is a wide variety of causes of noise: instrumental sources, sensitivity to ambient variables, and sources at distance whose effects cannot be avoided. Heavy shielding is a requirement for all long-period sensors, especially against temperature variations. The two air-locks in the BFO mine help to reduce ambient pressure and temperature variations and also prevent fast exchange of air between inside and outside, for example. To run meteorological sensors and magnetic instruments side-by-side with the seismic sensors helped to identify external noise sources. The ET-19 gravimeter could be operated in the mine environment with the outer thermostat running continuously and with the power to the inner thermostat reduced from the a-priori level thus reducing the instrumentally produced noise. Another example for studies in that direction is the SG with the two different spheres. Together with the company GWR it was decided to have for the first time in such instruments one heavier sphere in order to reduce Brownian motion and to see whether this is the physical mechanism causing some excessive noise in the records of those devices in the seismic band.

3.5.1 Noise caused by atmospheric mass redistributions

Fairly early WZ noticed by looking at chart records of air pressure and band-passed gravity signals from the ET-19 that sometimes there were simultaneous large transients on both. These were quickly identified as produced by cold fronts passing the station at speeds of some tens of m/s and studied in detail by Torsten Müller (Müller and Zürn 1983). The changing Newtonian attraction of the sensor mass by the atmosphere above the station was modeled and could explain the observed signal. It was also found that similar signals only about 5 to 10 times larger occur in the records of horizontal broadband seismometers (STS-1 prototypes). Of course, gravitation cannot be shielded. Early attempts to model the effects to remove them from the vertical records were not very successful because the filter response was not known well enough.

However, at tidal and longer periods it became routine to remove signals correlated with local barometric pressure in gravity with the help of a linear regression. A simple number, about -3.5 $nm/(s^2 \cdot hPa)$, multiplied with the local barometric explains most of this unwanted but unavoidable signal in gravity. After the Shikotan earthquake 1994 this was used for the tidal data from ET-19 and unexpectedly the noise was so much reduced that the hard to observe mode ${}_0S_2$ emerged clearly from the noise (Zürn and Widmer 1995). It turned out that this could not be duplicated with the data from the STS-1/Z seismometer, so an attempt was made by Erhard Wielandt in 1996 to shift noise from one feedback channel of the STS-1/Z to another, but this was unsuccessful. This pressure correction only functions very nicely for the best gravimeters. Only for large pressure disturbances do the STS-1/Z seismometers clearly see these disturbances but the noise reduction only works down to the Low Noise Models based on such instruments, while the gravimeters are better with the help of this correction below about 1 to 2 mHz, i. e. for the lowest-frequency free modes.

From the horizontal records it was clear that the mass redistribution in the atmosphere deforms the crust continuously, more or less. That means that in the regression factor for the gravity records mentioned above there is a small contribution from the free air effect due to the vertical displacement. If there is vertical displacement at some frequency there is an inertial force on the sensor mass which is proportional to frequency squared and thus becomes more and more important as frequency rises. Since the free air and inertial effects have opposite sign compared to the gravitational effect there must be a strong frequency dependence of the admittance of local barometric pressure to gravity including a zero response with the sign changing. Zürn and Wielandt (2007) developed simple models incorporating the inertial effect and showed that for realistic parameters these models all explain the minimum of observed vertical acceleration noise near 3 mHz. Indeed, Bruno Meurers had made an intriguing observation with his SG in Vienna. Reducing the noise with the well-know admittance at long periods he detected a nice wavetrain whose amplitude was increased instead (Zürn and Meurers 2009) thus clearly validating the conjecture by Zürn and Wielandt (2007).

After the success with the vertical components an extensive attempt was made to improve the records from horizontal components using similar methods (Zürn et al. 2007). Similar models were used to try to improve the records with the help of local barometric pressure and its Hilbert transform. Variance reductions up to 80 % could be obtained for some time series, it was also possible to improve SNRs in some mode spectra. However, it must be expected that for traveling pressure waves the effects depend for example on the direction from which they pass over the station, so time-independent admittances for a given component cannot be expected. Nevertheless it appears that a regression with barometric pressure (after converting seismic signals to acceleration or tilt) is always worthwhile. But there are certainly improvements possible.

An important issue here is that the tilts caused by atmospheric loading are the major source of noise at long periods in the horizontal components. Inertial seismometers cannot by themselves distinguish between tilts and horizontal accelerations. Methods to measure tilt alone with some method in order to subtract it from the seismograms containing tilts and the translational accelerations will not work when inertial mass is involved in the tilt measurement (Ferreira et al. 2006).

3.5.2 Noise caused by magnetic field variations

Dieter Emter noticed in 1994 that a magnetic storm was visible in the 3 components of the STS-2 seismometer. This was then studied in more detail by WZ and reported by Klinge et al. (2002). Thomas Forbriger had observed at the TNS station that passing trucks caused signals unrelated to the total mass of those trucks, so the magnetic fields were suspected and this was verified in a detailed analysis of these disturbances. When he had started to work at BFO he followed up on these effects for the whole GRSN, other stations and a variety of instruments (Forbriger 2007). He found out that variations in the magnetic field translate directly into apparent acceleration of the sensor mass. The strength of the effect varies strongly with the instrument, however, for a given instrument it appears to be stable. Once one has determined the sensitivity for a sensor the noise caused by magnetic fields can be reduced with the help of the measured magnetic field variations. An interesting observation is that the noise recorded at MOX could be reduced with the magnetic field records obtained at BFO more than 300 km away, at least for the strong magnetic storm under investigation. In principle instruments could be made sufficiently insensitive against this kind of noise by improvements in design or shielding in contrast to the noise produced by atmospheric masses discussed in the previous section.

At first it was thought that only very strong magnetic storms would be a transient problem. However, Forbriger et al. (2010) found out that sensors with their magnetic sensitivity on the high side are not able to reach the low noise levels needed for good free oscillation recordings due to the always present background magnetic field variations. ET-19 and the strainmeters at BFO have ferromagnetic alloys in their spring and length standards, respectively, but their sensitivity to ambient magnetic fields is lower than that of the seismometers and thus too low to matter.

3.6 Examples of guest experiments

BFO is involved in some planetary exploration programs as a test site for broadband seismometers. The first was the Mars mission NETLANDER which was eventually cancelled because the partner NASA was short of money. The second Mars mission, called ”InSight”, is still in the preparation stage. The seismometer to be flown to Mars was tested at BFO in 2012 for several weeks. A short-period seismometer for the moon, built by the Japanese, was tested simultaneously.

Akito Araya from the Japanese TAMA collaboration for the detection of gravitational waves tested his newly constructed laser interferometric seismometer at BFO and compared his data with the STS-1/Z and ET-19 data for a few weeks in 2000/2001. At present and for more than two years now Mark Zumberge (UCSD La Jolla) is also testing STS-1 seismometers with laser interferometric displacement transducers (called iSTS-1) at BFO.

The ringlaser at the Fundamental Station in Wettzell (Bavarian Forest) can record subdaily fluctuations in the Earth’s rotation rate with very high resolution. In order to achieve this quality the tilts of the platform with respect to the rotation vector have to be measured and used for correction. To that end six small tiltmeters designed and built by Erich Lippmann are set up on the zerodur block on which the laser is mounted. In 2000 these tiltmeters were carefully tested at BFO before they were installed on the ringlaser and proved to be very good and suited for the task (e. g. Widmer-Schnidrig and Zürn 2009). The same kind of tiltmeters were modified by Lippmann later for installation in boreholes and after tests at BFO installed by Carl Gerstenecker (Techn. Univ. Darmstadt) in the vicinity of Istanbul and the Marmara Sea to provide information on impending earthquakes.

The Geoforschungszentrum (GFZ) Potsdam had the intention to install a tiltmeter in the KTB-borehole at great depth where the temperature is above the threshold normal electronics can take without giving up. This instrument was tested in the 1990s in several phases of the development on different piers at BFO, however, it was never installed in KTB.

The Canadian company NANOMETRICS came to BFO also in 2007 to test their newly developed broadband seismometers (Trilliums) against the instruments at BFO. Strong sensitivity to magnetic field variations instigated Forbriger et al. (2010) to study those effects.

In the late seventies BODENSEE-WERKE (successor of ASKANIA), tested three borehole tiltmeters sold to Canadian colleagues before shipping them to Ottawa, where they were then installed at depths of 100 m in the Charlevoix earthquake zone. The three boreholes were located in what was thought to be one solid block. However, the tidal signals recorded were significantly different, demonstrating that boreholes are not free of local effects.

3.7 Additional activities

3.7.1 The 5th force and the Hornberg experiment

In the middle of the 1980s a lot of excitement was produced by the claim that there is a fifth type of fundamental interaction besides gravitation, electromagnetism and the weak and strong nuclear forces. The claim consisted of the gravitational constant (Big G) to be either dependent on distance or on materials. Since geophysicists and geodesists were involved in this claim by having measured with gravimeters down mine shafts in Australia or up 600 m high television antennas in USA, respectively, Gerhard Müller and WZ decided to check this by using large water masses in a hydroelectric lake, the Hornberg reservoir in the southern Black Forest. After a one-week pilot experiment in 1987 the gravity effect of the daily moved large water mass was measured with six LCR field gravimeters for 22 days in 1988. Many additional measurements were carried out to be used for the data analysis or to make sure to make no systematic errors with the help of geodesists Klaus Lindner (GIK) and Norbert Rösch (IfE Hannover) and also Heinz Otto and Walter Grossmann of BFO. Basically Big G was determined by measuring the integrated effect of the water masses and no difference to the laboratory value could be detected with uncertainties of the order of 0.3 %. The effective distances were 39 and 68 m for the two groups of three gravimeters above and below the water, respectively. The most important source of error was the calibration uncertainty of the gravimeters (Müller et al. 1989, Müller et al. 1990). The experiment made it into two books on the physics of the ”fifth force” (Franklin, 1993, Fishbach and Talmadge 1999). However, the results were not accurate enough to refute the claims for a fifth force with a strength of 3% and a range of 200 m.

The seiches of the lake could be observed clearly with the gravimeters also as a function of the water level (Zürn et al. 1991). For a while Helmut Wilhelm and WZ conjectured together with oceanographer Erich Bäuerle that historical observations of seiches in larger lakes could be used to infer the magnitudes of large earthquakes before the start of seismographic observations. However, the possibility of other physical mechanisms (e. g. landslides) for seiche excitation made them abandon this idea and research consequently was stopped.

3.7.2 The UCLA-connection and Antarctica

Karl Fuchs at GPI was very interested to continue the cooperation of WZ with the IGPP at UCLA. Therefore he fully supported the responsible participation of WZ in the move of the two LCR-gravimeters from the old to the new station at the geographic South Pole in the austral summer 1974/1975. WZ also was supported by Karl Fuchs for 6-week research visits to UCLA each year from 1976 to 1981, where WZ helped with the instrumentation and analysis of data obtained at the South Pole and elsewhere (Zürn et al. 1976, Slichter et al. 1979, Rydelek et al. 1982, Knopoff et al. 1989a,b, Zürn et al. 1995, Bos et al. 2000).

When the German government decided to obtain consultative status in the Antarctic Treaty Organization in the very early 1980s this necessitated to establish a research station which is occupied for the whole year. The decision was made to build ”Georg-von-Neumayer” station [GvN] on the Ekström ice shelf. BFO staff (WZ and Heinz Otto) were invited by the Alfred Wegener Institute [AWI] in Bremerhaven to participate in the planning of the geophysical observatory at that station. Heinz Otto went to GvN when it was constructed in the austral summer of 1981/82 to setup the seismic and the geomagnetic observatory together with Alfons Eckstaller (AWI). He also took the ASKANIA GS-15 gravimeter belonging to BFO and installed it in the seismic container on a heavy table whose legs were frozen into the ice. This instrument recorded for several years at GvN and also later at the new station called ”Neumayer”. Since the station was located on a floating ice shelf it recorded essentially the ocean tide under the ice. Tezkan and Yaramanci (1993) analyzed the record and estimated the rheology of the ice.

In the early years the geophysicists to winter-over at GvN were trained for a week or two at BFO. These men held close contact with BFO through telexes. In one case a FORTRAN program was telexed to GvN. It happened that in the single year 1983/84 there were three recent geophysicists from GPI wintering-over in Antarctica (Arno Brodscholl and Klaus Wallner at GvN and Hans-Albert Dahlheim at the South Pole). Very sadly, KlausWallner died in an accident at GvN after the winter. He had carried out his diploma work together with Jürgen Neuberg (”Locko”) doing field gravity work at BFO under the supervision of WZ. Therefore the director of AWI, Gottfried Hempel, asked WZ (and indirectly Locko) to accompany him in an immediate visit to Klaus Wallner’s parents in Rottenburg, a very sad duty. Over the years there were several more geophysicists (both male and female) with their diploma from GPI to winter-over at the German station.

3.7.3 Miscellaneous

In the early days of the BFO the staff (Walter Grossmann, Heinz Otto, WZ, but especially Dieter Emter) participated actively in refraction seismological experiments in Germany, the Alps, France, Britain, Norway and Sweden, Iceland and Namibia. The refraction seismic equipment earlier allocated to Stuttgart had been moved to BFO by Dieter Emter.

In 1983 Dr. Jürgen Schmitz from the Research Center Karlsruhe showed up at BFO. The state government had initiated a study of the mining related radioactivity in Baden-Württemberg and he was the one to carry it out. The baryte ($BaSO_4$) vein which contained the silver also carried small amounts of other very interesting minerals including UO_2 (”pitchblende”). Enhanced levels of radiation and Radon were detected and several long term studies were carried out until 1985 with the help of the observatory staff. It was found out then that radon gas is penetrating the laboratory building from the underground consisting of waste material from the mine. However, it was also found out that opening the windows for ten minutes helped to get rid of this excess amount. After Peter Duffner started working at BFO in 2006 he did a survey of the radioactivity in the mine and found a new hotspot in the main tunnel near the ”Reiche Firste”. He was a member of a voluntary firefighting team in Schramberg and responsible for radioactive issues there. By the way the minerals in ”Reiche Firste” were interesting enough to mineral collectors that break-ins occurred in the late 1990s, interrupting the work to some extent but fortunately not affecting the scientific data.

WZ, together with Klaus Lindner (GIK) participated in two international comparisons (1990 and 1994) of absolute gravimeters at the Bureau International des Poids et Mesures at Sèvres by measuring gravity differences between piers using the field gravimeters of GIK. When Ludger Timmen of IfE Hannover in 2008 carried out one of his absolute gravity campaigns in Fennoscandia for the measurement of the gravity changes due to post-glacial uplift he was accompanied by WZ for about 4 weeks. Two sites in Finland, three in Sweden were occupied with the FG-5 absolute gravimeter for 4 or 5 days each.

In cooperation with Rolf Schick (IGS) experiments were carried out at some volcanoes (Etna, Stromboli, Merapi) using seismometers and fluid-tube tiltmeters (Dreier et al. 1994). Dieter Emter and WZ also analyzed catalogs of volcanic events and looked for correlations with the Earth tide strains (e. g. Emter 1997).

Zaske et al. (2000) obtained borehole water pressure records from one of the boreholes at the Hot-Dry-Rock site at Soultz-sous-Forêts and analyzed the observed tides. The SNR was unexpectedly good and such that an analysis for the NDFW-parameters could be attempted. However, while the analysis gave stable results the period of the corresponding FCN was out of the range obtained by data from SGs and VLBI.

In the framework of the SFB 108 Hadiouche and Zürn (1992) analyzed surface wave data from (only few) stations around the Afro-Arabian Region using the two-station method. Anisotropy was needed and introduced to interpret the observed dispersion, however, this result is preliminary due to the poor coverage and method.

One of the ASKANIA borehole tiltmeters was shipped to Piñon Flat Observatory in California where it recorded for several years in boreholes with depths of 24 and 120 m together with a series of other instruments. The idea was to study crustal deformation in a sliver of crust between the San Andreas and San Jacinto faults. Unfortunately the instrument was damaged by lightning and recording stopped. However, several years of data were obtained and Johnson et al. (1993) analyzed those for the tidal signals. Again significant differences were detected between these data and those from other tiltmeters at the site.

3.7.4 Review articles

The researchers at BFO were over the years invited several times to write reviews in their fields, a very time-consuming kind of work: on surface waves and free oscillations (Müller and Zürn 1984, Masters and Widmer 1995, Zürn and Widmer-Schnidrig 2002, Widmer-Schnidrig and Laske 2007), on the tidal forcing field (Wilhelm and Zürn 1984), on solid Earth tides (Zürn and Wilhelm 1984, Zürn 1997), on the NDFW (Zürn 1997), on tidal triggering of earthquakes and volcanic eruptions (Emter 1997), on highly sensitive tiltmeters (Emter 1989), on deployment and shielding of seismometers (Forbriger 2012), and on strain-seismometers (Zürn 2001).

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12. Strong Earthquakes - from Tectonics to Risk Mitigation

Friedemann Wenzel

Introduction

This paper is not intended as a science article, but rather as reflection on more than 10 years of research around the intermediate depth Romanian strong earthquakes, the initial intentions and what I learned from it. I do not claim that the statements contained in this article will be shared by my colleagues.

Research focus on Romanian intermediate depth earthquakes

Romania is an earthquake prone country, with its capital Bucharest, in terms of earthquake risk, only second to Istanbul, on a European scale. The seismic source generating most of the hazard and consequently risk is the Vrancea intermediate depth seismogenic zone beneath the Carpathian Arc.

Partially collapsed building in Bucharest after the March 4, 1977 earthquake (Foto courtesy D. Lungu)

The Vrancea area is affected by the occurrence of frequent and strong intermediate-depth earthquakes. All these events occur within a narrowly confined seismogenic volume with a lateral extension of 30 x 70 km in an almost vertical stripe that extends from around 70 to 170 km in depth. The observed focal mechanisms of Vrancea earthquakes indicate a thrust regime, i.e. the maximum horizontal stresses are larger than the vertical stress. Two types of focal mechanisms occur. The prevailing type is characterized by a NE-SW striking fault plane and perpendicular maximum compression. All events with $M_W \geq 7$ show this kind of mechanism. Fewer earthquakes have a NW-SE striking fault plane with maximum compression in the NE-

SW direction. According to the seismic tomography seismicity is located within the cold core of the subducting lithosphere indicating that earthquakes cannot be explained by a Wadati-Benioff zone.

The rate of seismic moment release of the intermediate depth seismicity within the confined seismic volume is in the order of $0.8 \cdot 10^{19} \frac{Nm}{yr}$, which is comparable to the one from southern California. This strain-rate is equivalent to approximately $2.6 \frac{cm}{yr}$ slab elongation.

These specifics of this earthquake source zone were considered as advantages for the development of strong ground motion prediction equations, for methods for disaster risk mitigation and disaster management tools, as very credible scenarios could be developed. In 1991, the Universität Karlsruhe (TH) proposed an interdisciplinary scientific collaboration, which was triggered by a United Nations initiative in 1987. The proposal included the formation of a Romanian and German expert group in geosciences and civil engineering, to develop a model for Vrancea earthquakes. The research program contained the research of the earthquake phenomenon itself and their economic and social impact, including the reduction of their effects. The program officially began in 1996, financed by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation). This initiative laid the basis for the foundation of the Collaborative Research Center (CRC) 461 "Strong Earthquakes: A Challenge for Geosciences and Civil Engineering" in Germany and the "Romanian Group for Strong Vrancea Earthquakes" (RGVE) in Romania.

In the beginning of the CRC 461 the following key objectives of the forthcoming research were identified:

- an understanding of the tectonic boundary conditions and causes for the strong intermediate depth seismic activity
- the development of realistic models of ground motion, specifically for the largest conceivable events
- the development of loss models based on the assessment of buildings and infrastructure
- the development of risk reduction options by engineering methods but also by new methods by disaster management and response.

These goals were to be achieved by the cooperation between civil engineering and geosciences. Whereas today strong links between those disciplines are considered mandatory for successful scientific approaches to assessment and reduction of risk in 1995 this was a rather unusual attempt.

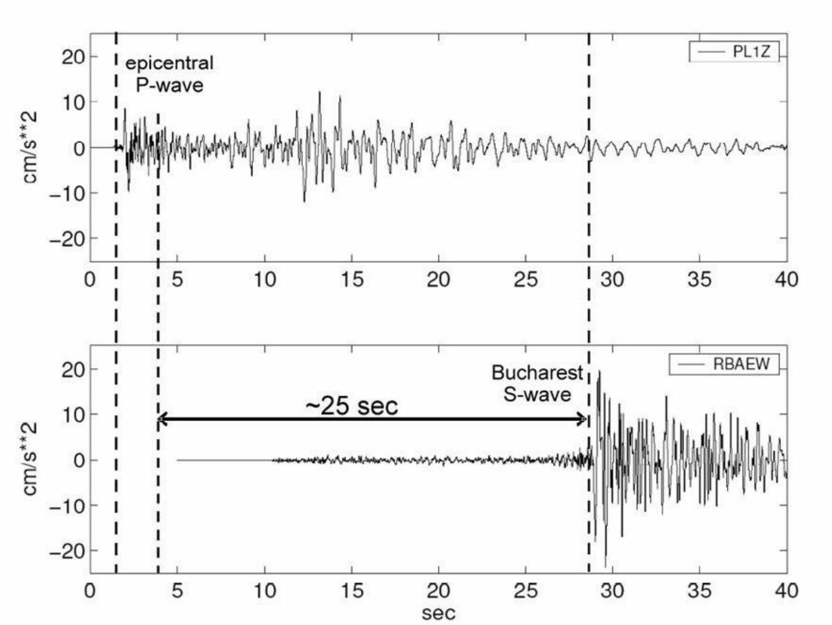
The CRC was financed by DFG during 4 founding periods covering the years 1996 to 2007. The coordinator between 1996 and 2006 was Friedemann Wenzel, followed by Günter Schmidt from 2006 to 2007.

Instead of presenting and discussing the many achievements during 12 years of research I would rather like to point to some "lessons learnt" and surprises that emerged during the project duration. As in common life, there are good and bad surprises.

Developing Earthquake Early Warning Methodologies

The fact that the strong earthquakes have an almost fixed epicentral location suggested to think about possibilities of earthquake early warning, that has been pioneered after the Mexican 1985 earthquake but has found no further application so far in Europe.

Earthquake early warning (EEW) systems have to comply with two requirements: they have to be fast and, at the same time, highly reliable. We have developed two methods for EEW in Bucharest, Romania, and Istanbul, Turkey, that fulfil these needs. The first method uses ground motion observations at a single sensor in the epicentral Vrancea zone, SE-Carpathians, to estimate the level of ground shaking Bucharest will experience in the case of a strong Vrancea earthquake. Average epicentral distances of 130 km towards the Romanian capital provide warning times of about 25 s for all intermediate-depth events. Maren Böse has established scaling relations for all relevant ground shaking parameters that are suitable for EEW. The second EEW method, named PreSEIS, is based on Artificial Neural Networks. It combines seismic real-time observations at many sensors, and issues at regular time steps the most likely source parameters of an earthquake in progress.



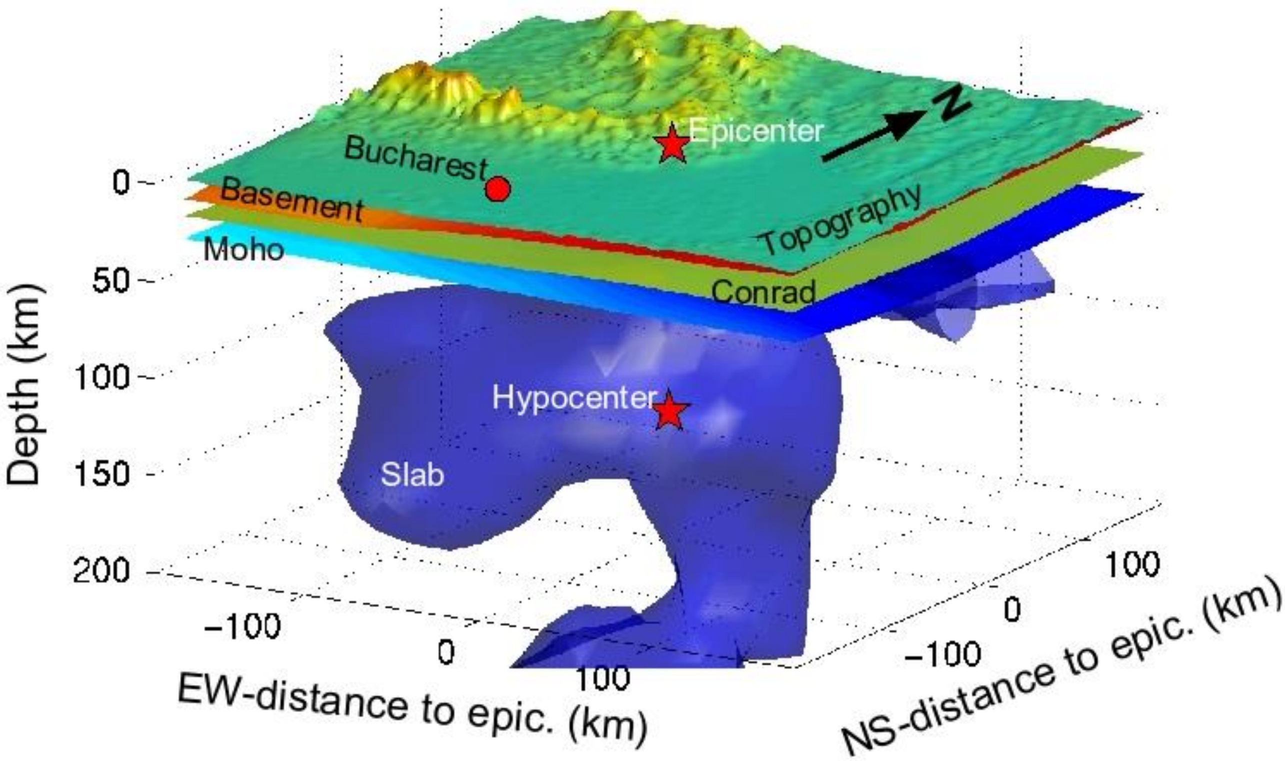
The maximum warning time for Bucharest is defined by the time span between the arrival of the direct P-wave at the detecting EEW sensor in the epicentral area and the S-wave arrival in Bucharest. The expected warning time for Vrancea earthquakes is about 25 s (Maren Böse).

Apart from the fact, that an earthquake early warning system exists today for Bucharest this type of research became standard in Europe with two major European projects on earthquake early warning (SAFER, FP6) and REAKT (FP7) to which KIT scientists but also Rumanian scientists contribute significantly. The internationally most visible research and earthquake early warning including operational systems shifted to the United States (California) and Japan, where a public system is operational since 2007.

Tectonics and Seismic Hazards

25 years ago most engineers had serious doubts that research into tectonics would make a significant contribution to quantify earthquake hazards, although the characterization of seismo-tectonic zones represents one component. The CRC did have the intention to constrain seismo-tectonic models and to link them closely to hazard assessments. For crustal earthquakes, which are not dominant in Romania, this became a standard methodology. Geodetic and neo-tectonic observations allow to constrain maximum magnitudes, return periods on faults, allow the understanding of shear stress increase on the fault and its vicinity. For intermediate depths

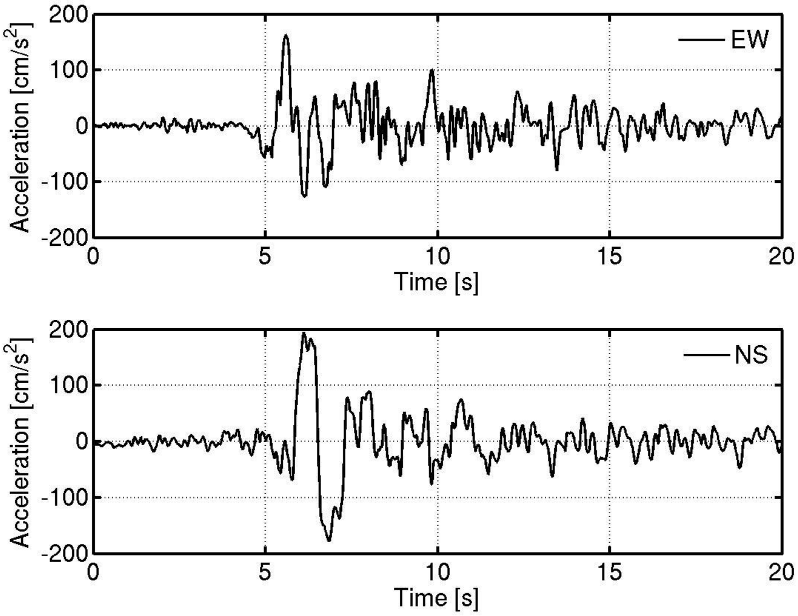
earthquakes this does not work. We used essentially all available methodologies in an advanced form to constrain the Vrancea source zone, starting from high resolution crustal models from refraction seismology, upper mantel seismic tomography, mineralogy, tectonic modelling with Finite Element methodologies, studying recent deformation, uplift and subsidence, etc.. These studies and measurements resulted in a sophisticated model of the Vrancea earthquakes. However, they did not really represent a constraint for hazard assessment. The regional confinement of hypocentres and epicentres was known from seismological observations as an empirical fact. A particular time dependency within the large earthquake sequences could not be detected with reasonable reliability and a constraint on the minimum depth was again not possible.



The 3D elastic model that emerged from geology, refraction seismics, and upper mantle tomography. It was used for modeling earthquake wave propagation, tectonic interpretations and state of stress calculations.

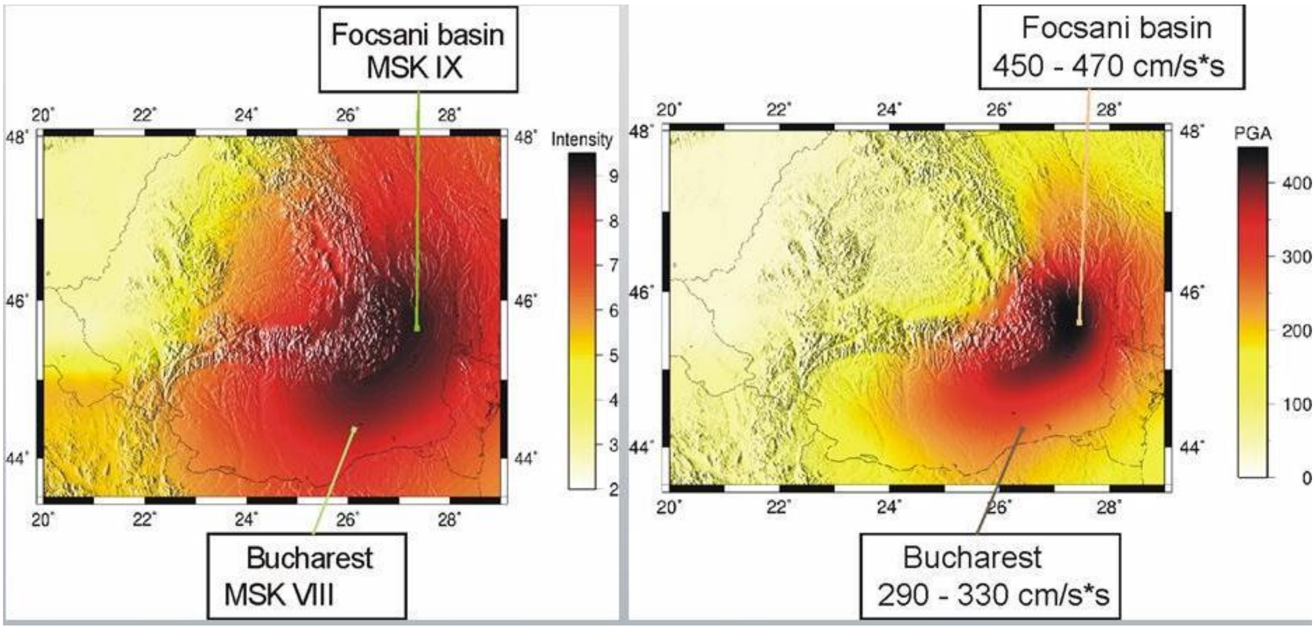
Hazard assessment

Before 1996 there was no hazard assessment available for Romania, based on standards as developed in GSHAP. In consequence of this the Romanian building codes, which have been significantly detailed after the 1977 earthquake, were not rooted in scientific state-of-the-art hazard assessment. In addition to this, the understanding of ground motion was very much shaped by the only digital record that was available from the 1977 earthquake. It happened to show a fairly strong long period spectral content. This feature has been introduced into the code. However, the systematic study of records that were available after the 1986 and 1990 earthquakes showed that the 1977 record was an exception rather than the rule. This is no reason to blame the Romanian engineers, given the fact that many codes on an international scale and many seismic safety considerations were based on another single record, the El Centro (May 18, 1940) accelerogram.



Horizontal acceleration records of the March 4, 1977 earthquake in Bucharest (INCERC). The long-period characteristic of the NS-component made engineers believe that the Vrancea events have much more lower frequencies as compared to standard Eurocode Spectra.

One major achievement of the CRC thus consisted in the development of a state-of-the-art hazard map for various return periods in engineering ground motion parameters such as PGA and spectral values. This work is closely associated with the name of Vladimir Sokolov.



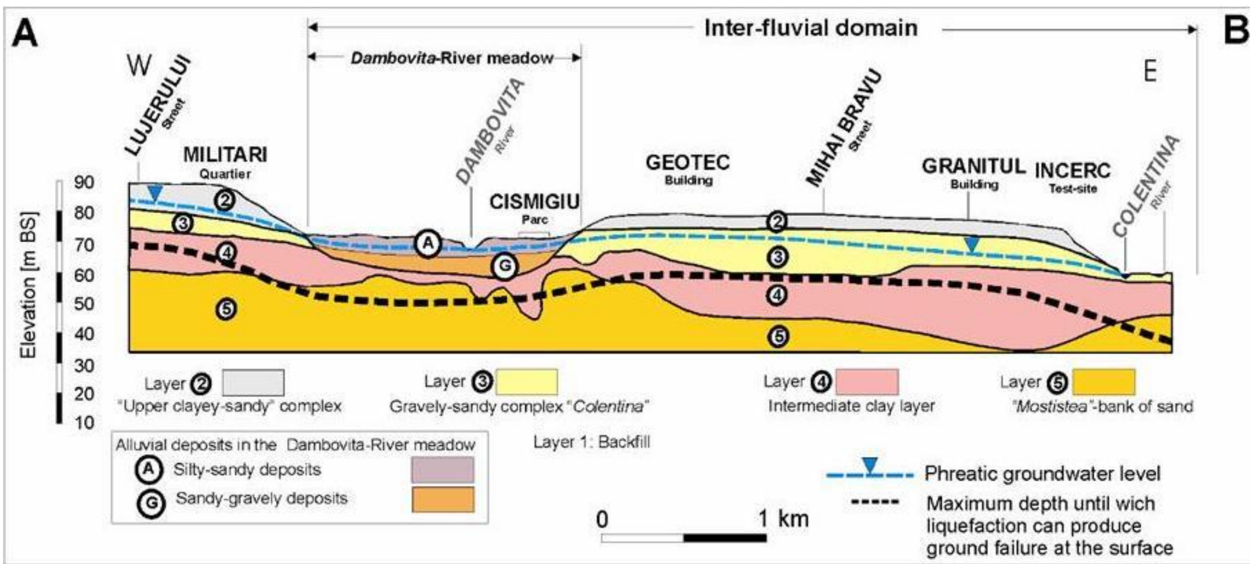
Probabilistic hazard maps for Romania in macro-seismic intensities (left) and peak ground acceleration (right) show the dominant effect of the Vrancea seismicity for the overall hazard, specifically for Bucharest (Vladimir Sokolov).

Seismologists and Cities

The CRC invested significant resources in the installation of an accelerometric network, with the accelerometers triggered by velocity sensors in order to assure that both small and larger events would be well recorded. This work was done over the years by Klaus Bonjer and Romanian colleagues from the National Institute of Earth Physics (NIEP). Initially, when locations for the accelerometers were discussed, the seismologists followed their classical instinct to look for locations that were as quiet as possible in terms of seismic noise, whereas the engineers want to have the instruments at those sides where seismic risk was high in the downtown busy and noisy areas. This was certainly one occasion, where different cultures in different communities had to merge and find the optimal solution from both perspectives. The fact that this process happened is something I consider as success of the CRC. In addition to the benefit of having an operational network this activity funded by the CRC triggered a significant effort by the Romanian to expand on the instruments in place. Even more, the seismologists started to became interested in the noise they could study with continuously recording broad-band instruments. For six months we deployed 30 broad-band instruments in the city and understood some of the noise sources including storms in the Black Sea, the temporal variation during day and night, the spatial variations, frequently controlled by local site conditions. The study of seismic noise is a common branch in seismology today and a field of rapid scientific developments. I'm not sure whether - without the heated debates with our engineering colleagues- we would ever have done this important step.

Risk in an Urban Context

Another issue, initially discussed controversially between geoscientist and engineers, was the question of the liquefaction potential of Vrancea earthquakes in Bucharest. The historic observations reported a number of liquefaction features along the major rivers and their tributaries but only one minor incident in Bucharest. Therefore the engineers basing their judgement on the historic observations were convinced that liquefaction in Bucharest does not play a role. Systematic studies of the ground water level and particularly its change through time by the hydrology research group around Heinz Hötzl changed this picture.



Cross-section showing the near-surface geology and hydrogeology in Bucharest (processed by Dieter Hannich after Dan Lungu).

Until the late 70s and early 80s of the 20^{th} century a lot of industry was located within the city and contributed significantly to lowering the ground water level by abundant water use. It is well known that the hazard of liquefaction becomes small for low ground water levels. Later, industry was moved out of the downtown area and settled in the suburban areas. In consequence of this the ground water table raised continuously and with this the liquefaction potential and risk. We learned that the interaction between hydrological phenomena and the social development and evolution of a city is an important item in studying earthquake risk. We can learn many things from the past, but there are processes between past observations and today which change the risk and can thus cause underestimation (as in this case) or - under different circumstances – overestimation as well.

Earthquake Information System

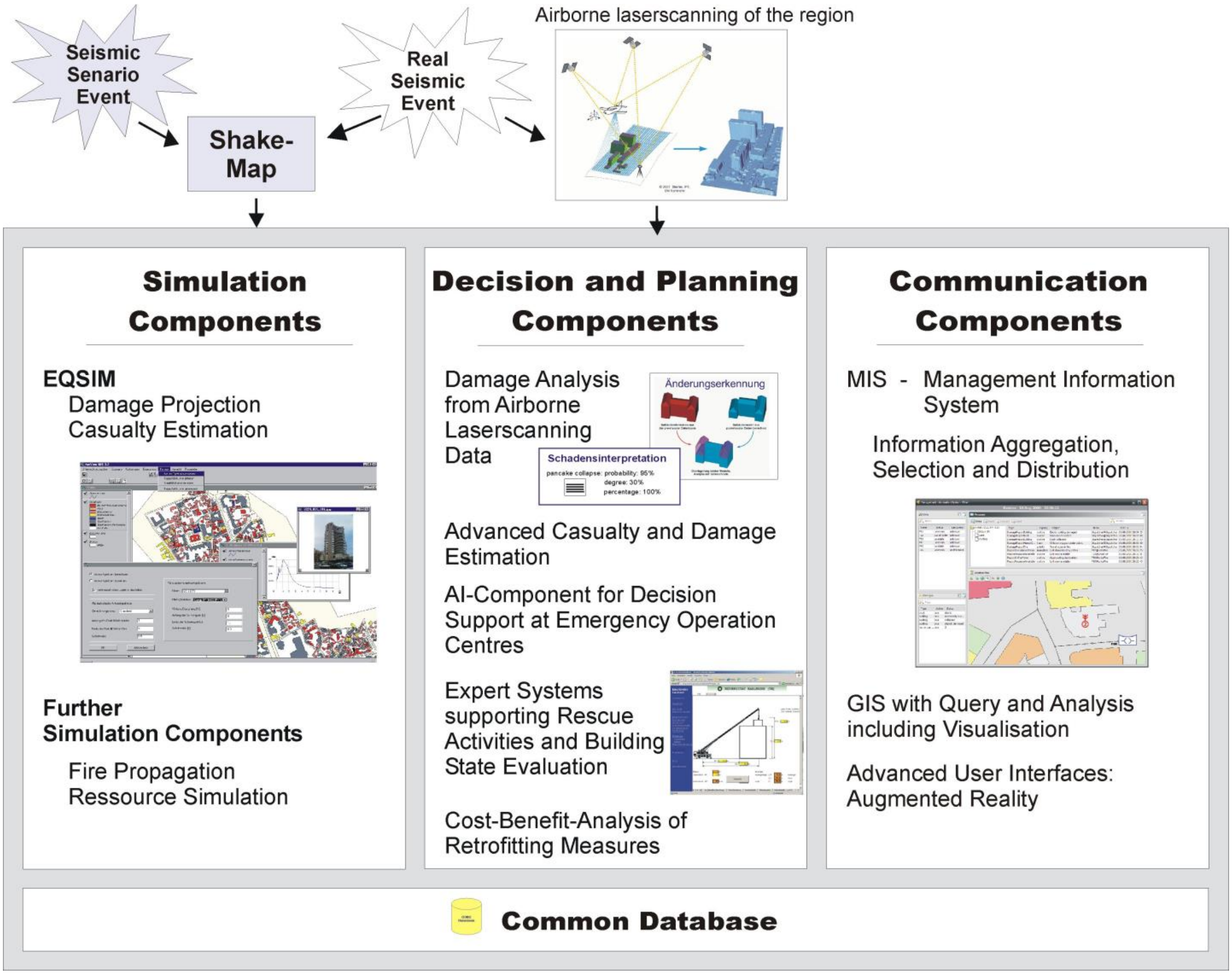
What is quite common from today's perspective was very innovative 20 years ago. Our engineering colleagues, with Fritz Gebauer as leading person, developed an earthquake information system to which almost everybody in the CRC could and had to contribute. The main idea was to provide quantitative information based on observed data and models in the course of an earthquake disaster, starting with early warning, that allowed 25 seconds as warning time, providing a shake map which would show the distribution of ground motion in the city and thus the likely areas of highest damage, running a loss estimation tool, which was established for the downtown area of Bucharest by careful collection of building inventory data and developing vulnerability functions for individual buildings. This sequence of information should be provided to disaster management agencies and institutions to support their decision making. The development of this earthquake information system turned out to be a hub of the entire CRC, where most of the discussions on how to provide which information in which format in which time played a critical role and brought people from various disciplines together. We learnt, that the judgement of the various disciplines are very important to include in this process as the information emerging during a disaster is quite uncertain in the initial phase and becomes more reliable with data coming in with time.

Disaster Management Tool (DMT)

Fritz Gebauer's group was also leading in developing a decision support system that we called Disaster Management Tool that represented an integrated solution to a number of problems that emerge in the practise of disaster risk management. The DMT is a software system supporting decision makers, surveillance and intervention teams during disaster response. It is as well designed for training and mitigation tasks. The DMT consists of components resulting from the different research projects such as fast and reliable damage estimation using seismic data as input, use of up-to-date reconnaissance techniques such as automatic damage interpretation based on airborne laser scanning data, estimation of the trapped victims based on these reconnaissance techniques and the support of disaster management personnel with information and communication tools. The included decision support system helps to coordinate and allocate the limited response resources to enhance their overall efficiency. Onsite rescue operations are supported by an expert system analysing damage information acquired after the earthquake, combined with data about the buildings' construction and occupancy collected prior to the earthquake.

This software tool has been tested in collaboration with the Romanian Civil Protection Command during the ATLAS 2004 exercise and is considered a major success of the German-Romanian collaboration. The final version of the DMT is tested just before the symposium during the ATLAS 2007 exercises in October 2007.

The colleagues, who developed the tool (led by Frank Friedrich) displayed high skills in information technology and high level software architecture. We learnt that the development of future disaster risk management and decision support tools would have to follow this route and today computer science and information technologies are an integral part of research in disaster risk reduction.



Model of the Disaster Management Tool (DMT)

Research in Risks Related to Natural Disasters during and after the CRC

During the time of the CRC was the establishment of the graduate school for natural disasters, which was supported by DFG between 1998 and 2007 and which "produced" 55 PhDs.

The CRC had a significant influence on research directions within the Universitaet Karlsruhe and KIT today. During the 2nd funding period of the CRC the Center for Disaster Management and Risk Reduction Technology (CEDIM, www.cedim.de) has been established as a joint enterprise of Geoforschungszentrum Potsdam (GFZ) and Karlsruhe University in 2002. We received funding from both institutions and developed new methodologies for risk assessment aiming at various disasters (winter storms, hail, floods, landslides, earthquakes, tsunamis, etc.) and the comparison of those risks. I had the opportunity to be the coordinator (Sprecher) of CEDIM between 2006 and 2012 and understood the differences and similarities of various disaster types.

Another initiative that emerged during the CRC was an international non-governmental organisation (NGO), the Earthquakes and Megacities initiative (EMI), which tried to develop models aiming at the integration (mainstreaming) of disaster risk management into city management. EMI is located today in the Philippines, but has been established in Germany with support of the CRC. My work on its board gave me the opportunity to learn disaster risk management for cities, to interact with representatives of many large cities around the world and to see that there is a long way from scientific insight to implementation of mitigation policies, not only in developing countries but also in our own cities. The organisational complexity of cities, the rapid changes in developing countries and the informal processes that play a significant role make disaster risk management of rare events a key challenge.

Final comments

My understanding of earthquakes, when I started the CRC, was quite limited. I considered them as a geological or geophysical phenomenon, mostly a scientific topic. In the course of the years the many colleagues from other disciplines, from other geo-scientific fields, from civil engineering, but also from social sciences and many practitioners taught me how earthquakes turn into disasters. I am very glad that I had this opportunity and that I still have it. I did not try highlighting all achievements and mentioning all contributors. This can be found in the final documents of the CRC 461 project and the many papers published. There are a few colleagues, however, who were very important to me in a personal sense. Karl Fuchs from whom I learned that large collaborative projects can be done; Josef Eibl who made me understand how engineers work and think; Gheorge Marmureanu, Corneliu Dinu and Dan Lungu who successfully fought for the survival of their institutions and science through post-socialist times and were my key partners.

From today's perspective Romania was not the best location to develop our interdisciplinary research for the reasons discussed before. However we still succeeded to establish research in disasters and risks as an important research direction at Karlsruhe University with significant funding, many PhDs, long lasting partnerships and visible results. Science itself and the opening of new directions develop under boundary conditions that are often predefined and not ideal, although we try to convince reviewers and funding agencies that this is the case. New avenues are always risky and mostly cumbersome. I had the fortune to also find them worthwhile and rewarding.

13. The Geophysical Institute (GPI) today

Ellen Gottschämmer, Thomas Bohlen, Thomas Forbriger, Petra Knopf, Joachim Ritter, and Friedemann Wenzel

13.1 The Geophysical Institute today and its role within the KIT

Whereas the inception and buildup of the GPI took place within the framework of the Universität Karlsruhe (TH), the modern GPI is part of the Karlsruhe Institute of Technology (KIT, www.kit.edu). On October 01, 2009, the Karlsruhe Institute of Technology was founded by a merger of Forschungszentrum Karlsruhe GmbH and Universität Karlsruhe (TH). KIT bundles the missions of both precursory institutions: a university of the state of Baden-Württemberg with teaching and research tasks and a large-scale research institution of the Helmholtz Association conducting program-oriented provident research on behalf of the Federal Republic of Germany. Within these missions, KIT is operating along the three strategic fields of action of research, teaching, and innovation.

Since January 2014 the institutes at KIT are grouped into five disciplinary divisions, and GPI belongs to KIT division V *Physics and Mathematics* (Bereich V). GPI also belongs to the KIT Department of Physics (KIT-Fakultät für Physik) that organizes teaching and academic affairs and that is attached to division V *Physics and Mathematics*. The GPI strengthens the mission of the KIT especially in the fields of research and teaching, providing the base for innovations in geophysical measurement technology and methodologies to process and interpret huge –often incomplete – geoscientific datasets in contexts such as Earth’s internal structure or earthquake disaster mitigation.

Interdisciplinary KIT research is also organized in centers. The KIT Energy Center and KIT Climate and Environment Center are supported with GPI contributions. The KIT process leads to many new partnerships with institutions at Campus South (CS, the former university) and North (CN, the former Helmholtz research center). In addition to the close connection to the Institute of Applied Geosciences in both, research (Earth’s structure, geothermal resources, ...) and teaching, we cooperate with the Institute of Meteorology and Climate Research (CN and CS), the Center for Disaster Management and Risk Reduction Technology (CEDIM) including the Institute for Nuclear Energy Technologies, the Institute for Technology Assessment and Systems Analysis, the Institute for Nuclear Waste Disposal, and others.

13.2 Current Research at GPI

We focus on the theoretical challenges of seismology, computer-intensive modeling, and inversions of geophysical observations, as well as on experimental seismology. Our objectives are the development and improvement of exploration methods for hydrocarbons and other underground resources, the development of seismology-supported reservoir management methods, extending the knowledge on the formation, dynamics, and structure of the solid Earth, and the quantification, forecasting, and early warning of natural disasters in a geological/geophysical context.

13.2.1 Applied Geophysics

The members of the research field Applied Geophysics investigate and develop seismic imaging techniques and their application to different spatial scales. Topics include borehole and tunnel exploration and imaging, environmental and engineering geophysics (ground and groundwater related), and hydrocarbon exploration. Currently, the working group is focusing its efforts on the massive-parallelized simulation and inversion of full elastic wavefields for reflection seismic imaging and near surface seismic characterization using shallow seismic surface waves. Scientific work related to these topics is conducted as part of industry cooperations, national and international research programs, and the Wave Inversion Technology consortium (WIT). The developed scientific software for seismic wave simulation and full waveform inversion is distributed under the GPL-licence on www.opentoast.de.

13.2.2 Natural Hazards and Risks

GPI is part of the KIT Center Climate and Environment, and the Helmholtz program ATMO. The Center for Disaster Management and Risk Reduction Technology (CEDIM, www.cedim.de) is the KIT structure within which hazards and risks and their mitigation are addressed. The GPI works on seismic hazard assessment, seismic risk and loss estimations, development of models for shelter needs, and socio-economic vulnerability and resilience on global scale. For earthquakes in particular, we are developing deterministic and probabilistic risk analyses as well as methods to analyze and estimate associated damages and other risks from buildings and infrastructural facilities. In addition we study earthquakes induced or triggered by mining activities, geothermal energy production, CO_2 sequestration, and other processes and safety conditions of waste disposals.

Financial support is provided by KIT-funding, FP6- and FP7- European Union programs, the Geotechnology Program of the Ministry of Education and Sciences, the Deutsche Forschungsgemeinschaft (DFG) and funds of the Global Earthquake Models. We cooperate with firms in the insurance sectors and are part of the Willis Research Network.

Research Topics and Projects

Earthquake Risk and Early Warning

- Seismic Hazard and Risk for Spatially Distributed Systems (DFG)
- 3D Effects of Seismic Ground Motion in the Taipei Basin and Implications for Hazard and Risk (DFG)
- Earthquake Disaster Information System for the Marmara-Region (EDIM)
- Early Warning System for Transport Lines (EWS-Transport)
- Seismic Early Warning (FP-6: SAFER; FP-7: REAKT)

Vulnerability and Damage

- ATMO Helmholtz Programs
- REAKT (www.reaktproject.eu) aims at earthquake early warning
- MATRIX (www.matrix.gpi.kit.edu/) on multi hazard and risk assessment
- NERA (www.nera-eu.org/) earthquake hazard & risk assessment
- SYNER-G (www.vce.at/SYNER-G/) on lifeline vulnerability
- Global Earthquake Model Private Public Partnership (www.globalquakemodel.org/)
- WBI Natural Disaster Management Learning Program
- Earthquakes and Megacities Initiative (EMI)
- CATDAT - Damaging Natural Disaster Databases (Earthquakes, Floods, Volcanoes)

13.2.3 Seismology

The research field *Seismology* is engaged with measuring, analyzing and modeling of seismic wave fields as well as instructing students who are actively included in the research projects. There are two major research facilities: The KArlsruheBroadBand Array (KABBA) and the Black Forest Observatory (BFO). KABBA consists of 42 broadband recording stations which can be installed world-wide for seismological experiments (see Ritter, this volume). The BFO is situated in an old mine where there are stable and perfect conditions to observe extremely low-amplitude signals, especially in the very low frequency band of a few millihertz (see below and Zürn, this volume).

Currently the main research focus is experimental seismology using KABBA (Fig. 13-1). These mobile recording stations measure precisely the ground motion from near-field shaking to tiny teleseismic waves (nanometer scale). KABBA was deployed within four major field experiments in Romania, the Upper Rhine Graben, Scandinavia and California. In addition, other research projects were conducted mainly in connection with seismic noise studies and induced seismicity. KABBA data are stored in the KABBA data center where they can be downloaded for internal work as well as externally. The other foci of the research field *Seismology* are the improvement of seismic instruments, the determination of the structure of the Earth's crust and mantle, the understanding of seismic noise and the analysis of microseismicity, partly embedded in international collaborations.

Seismology at KIT-GPI is widely linked within KIT and contributes to the KIT Center Energy and the KIT Center Climate and Environment. Examples of recent joint projects conducted in co-operation with other KIT institutes include:

- Determination of seismic site effects in Bucharest together with the Institute for Rock and Soil Mechanics and the Institute for Applied Geosciences,
- Study of the relationship between seismic noise and meteorological phenomena with the Institute for Meteorology and Climate Research,
- Study of deformations in the Upper Rhine Graben with the Geodetic Institute, the Institute for Rock and Soil Mechanics and the Institute for Applied Geosciences,
- Investigations of fault frictional properties via the relationship between microseismicity and tremor source parameters at the San Andreas Fault in Cholame, California (KIT Young Investigator Group Project).

In an international context the seismological research is integrated in initiatives such as the ESF program TOPO-EUROPE or the European Seismological Commission. Examples for international seismological experiments are

- URS (URban Seismology) experiment: the seismic wavefield in the city of Bucharest was studied for the analysis of lithospheric structure, site effects for earthquake waves as well as seismic noise characterization. This project was a collaboration with the National Institute for Earth Physics in Bucharest.
- MAGNUS (MAntleinvestiGations of Norwegian Uplift Structures): the goal was to explore the deep structure of the Scandinavian Mountains and to understand the current forces which sustain the high topography. This project was a collaboration with the universities of Aarhus, Copenhagen and Oslo as well as NORSAR. Follow-up research is in planning.
- PERMIT (Parkfield Experiment to Record MIcroseismicity and Tremor): for a better understanding of earthquake rupture processes, tremor was measured at the San Andreas Fault near Parkfield and Cholame, California in a collaboration with the University of California, Riverside.

Bachelor, master and PhD students are instructed in various seismological techniques such as seismic wave analysis, seismic instruments, data processing, array seismology and seismic tomography (Fig. 13-2). Field excursions demonstrate geoscientific themes such as tectonic structures, Earth materials and monitoring systems.

Fig. 13-1: Calibration test with the KABBA instruments in the basement of KIT-GPI. The mobile recording units measured coincidently for two months in order to detect possible instrument malfunctions and to compare the instrument response functions**.**

Fig. 13-2: Instructing students in the installation of a seismological station in the field.

The success of the teaching efforts is reflected in student prizes as well as excellent evaluation of the courses by the students. Students are involved as student research assistants in ongoing projects by conducting field work and analysing high-quality KABBA and BFO data sets for their thesis work.

13.2.4 Black Forest Observatory

The Black Forest Observatory (BFO) is a joint research facility of the Karlsruhe Institute of Technology (KIT) and the University of Stuttgart. Since 1971 it is operated in cooperation of the geophysical and geodetic institutes of both universities. BFO is manned with two scientists and one technician. Main activities of the observatory fall into four categories, which are 1) observation and publication of a continuously recorded multi-parameter geodynamic data set, 2) research, 3) hosting of guest-experiments, and 4) teaching.

The location of the observatory (48.3301 °N, 8.3295 °E) in the middle of the Black Forest was carefully selected at large distances to potential anthropogenic sources of noise. The instruments are deployed in a former silver mine in competent granite rock at a depth of up to 170 m below the surface and at up to 700 m distance from the entrance of the mine. This provides a thermally very stable environment. Two air-locks provide additional protection against air-pressure variations and ensure thermal stability. Because of these favorable conditions and the excellent high precision instruments operated at BFO the observatory is internationally well known as one of the most sensitive sites for long period observations, providing international standards for the scientific community, e.g. for recordings of Earth's free oscillations.

The Black Forest Observatory operates broad-band seismometers (STS-1 and STS-2), gravimeters (superconducting gravimeter SG056, LaCoste Romberg earth-tide gravimeter ET-19), tiltmeters (Askania borehole tiltmeter, Horsfall fluid tiltmeter), three invar-wire strainmeters, magnetometers (GSM-90 Overhauser magnetometer, three Rasmussen fluxgate magnetometers) and a permanent GPS-station. These are supplemented by regularly repeated magnetic base-line measurements and observations of absolute gravity as well as the recording of several environmental observables (air-pressure, humidity, wind speed, precipitation, temperature). Some of the latter are used to correct geodynamic recordings for remaining disturbances. The data are published in near-real-time through international data centers (IRIS DMC at Seattle, SZO at the BGR in Hannover, Intermagnet in Edinburgh, GNSS data center at the BKG in Frankfurt, GGP-ISDC at the GFZ in Potsdam). The recordings are used by many research groups around the globe. Data is made available free of charge to scientific projects as well as to the general public.

The detection of the toroidal background free oscillations of the Earth with BFO data received international attention (Kurrle and Widmer-Schnidrig, 2008). Other prominent examples of research at BFO are the detection of Coriolis coupling of toroidal modes (Zürn et al. 2000), the first unambiguous detection of the fundamental toroidal mode (Widmer et al., 1992), and the until then unnoticed coupling between atmosphere and spheroidal modes of the Earth after large volcanic eruptions (Zürn and Widmer, 1996). BFO research also contributed to the understanding of potential sources of noise and the improvement of observation methods (e.g.: Zürn and Widmer, 1995; Zürn and Wielandt, 2007; Zürn et al., 2007; Forbriger, 2007). References are listed in chapter 11 of this issue (Zürn, Listening to the Earth – the Schiltach Observatory).

The well-known outstanding data quality of the observatory along with its high-quality instruments operating since several decades, makes BFO an attractive place for testing new instruments. Thus, the observatory is a much valued host for guest experiments. Recently seismic sensors newly designed for international space missions (SELENE2 to the Moon, In-Sight to Mars) were evaluated at BFO. Since 2010 an iSTS-1 seismometer with optical interferometric pick-up, designed at IGPP (Scripps, UCSD) is operated as a prototype installation in the BFO vault. Also commercial manufacturers of high-quality instruments (like Streckeisen, Nanometrics, or GWR) have accepted the challenge. These are only a few examples.

Besides being involved in scientific projects beyond BFO at the institutes of both universities, for BFO researchers teaching is a serious task as well. In particular the Master's program at KIT benefits from the scientific expertise made available through the observatory in courses on seismic instruments. Students have the option to gain experimental skills during the BFO-Winterschool. Periodically offered trips to the observatory allow a first contact with observatory seismology to undergraduates.

13.3 Teaching

Following the Bologna declaration, the Geophysics diploma degree course at the GPI was replaced by a Bachelor's degree course, starting in winter semester 2008/09, and a Master's degree course, starting in 2011/2012. Both courses are lively demanded, with more than 100 students enrolled in Geophysics at the moment. While the Bachelor's degree course is implemented for several years and well established by now, the first Master students finished their studies just last year, i.e. in 2013. Furthermore, there are still a few diploma students who are expected to complete their studies in the very near future. At GPI, teaching has a high significance, which is reflected in several teaching awards received by members of the GPI within the last years.

Fig. 13-3: GPI students at the building site of the Gotthard base tunnel, Switzerland, December 2010 (photograph by Niklas Thiel).

Fig. 13-4: GPI students at the KTB drilling site (German deep continental drilling site), July 2012 (photograph by Ellen Gottschämmer).

13.3.1 Bachelor’s degree course

As the former diploma degree course, the current Karlsruhe Bachelor’s degree course, is characterized by a strong focus on Physics and Mathematics, especially during the first semesters. The students attend courses in Classical Experimental Physics, Classical Theoretical Physics, and Higher Mathematics together with the students of Physics, followed by a course in Modern Experimental Physics and the Classical Physics Laboratory Course. Additionally, students get a broad education in Geophysics with Geophysical Laboratory and Field Courses, courses in Experimental Geophysics, and Computing in Geophysics. Students have to complete internship, carried out in a Geophysics company or organization for the duration of approx. six weeks. Geology is taught in several courses including Field Geology. Further practical experience can be gained in Exercises on Geology and during a Geodetic Surveying Course. Specialization is obtained by the choice of several Electives individually picked from courses in Geosciences and other subjects. The Bachelor degree program is accomplished by working on a first scientific project, the Bachelor thesis.

The emphasis on Physics and Mathematics is rather a specialty than the standard in many Geophysics degree courses today. Only six universities in Germany at all offer a Bachelor degree in Geophysics with focus on Physics and Mathematics, while at other universities the Geophysics degree course has been substituted by a more general Geosciences degree with the possibility to specialize in Geophysics, either during an advanced phase of the degree course, or when taking a Master degree afterwards. At GPI in Karlsruhe however, we offer both, a fundamental qualification in Geophysics including a sound education in Physics, Mathematics and Geosciences, as well as an advanced Geophysics program for those who want to specialize further in our research topics, during the Master’s degree course.

13.3.2 Master's degree course

The Master's program at KIT usually takes two years. In the first year, the students take courses in order to specialize in advanced geophysical subjects, all closely related to our research areas, such as Theory of Seismic Waves, Seismological Signal Processing, Array Processing, Seismic Imaging, Physics of Seismic Instruments, Inversion, Tomography, and Engineering Geophysics. The second year of the Master degree course is entirely dedicated to the preparation of the Master thesis. The thesis work is closely tied to the ongoing research at GPI. The Master program is attractive also to students from other universities and other disciplines as demonstrated by the enrollment of such students. The different background and qualification of these students is considered as challenge but also enrichment for both, teaching and learning.

13.3.3 Geophysics for other degree courses

Lectures given by members of GPI are also attended by students from other degree courses. Within the Department of Physics, Geophysics is established as an Elective within the curriculum of the Bachelor's degree program in Physics and Geophysics can be chosen as a secondary subject in the Master's degree program in Physics. However, traditionally the major part of external students comes from the Department of Civil Engineering, Geo- and Environmental Sciences, studying Applied Geosciences. Those students attend the course Introduction to Geophysics 1, and take part in both, the Geophysical Laboratory and Field courses. Due to the highly increased demand over the last years, recently a new Geophysical Field course was established, especially developed for students from the Department of Civil Engineering, Geo- and Environmental Sciences.

Apart from those courses, which are part of the curriculum of the degree course Applied Geosciences, several students attend our lectures as a facultative subject, especially courses in the context of natural hazards, e.g. Introduction to Volcanology or Geological Hazards and Risks. The latter one is also part of the curriculum of GRACE, the KIT Graduate School for Climate and Environment, as well as part of the immersion program of the Bachelor's degree courses Economics Engineering and Industrial Engineering and Management within the Department of Economics and Management.

13.3.4 Development of number of geophysics students at GPI

Both, the Geophysics Bachelor's and the Master's degree courses are lively demanded and working to capacity. The number of Geophysics students in Karlsruhe continuously

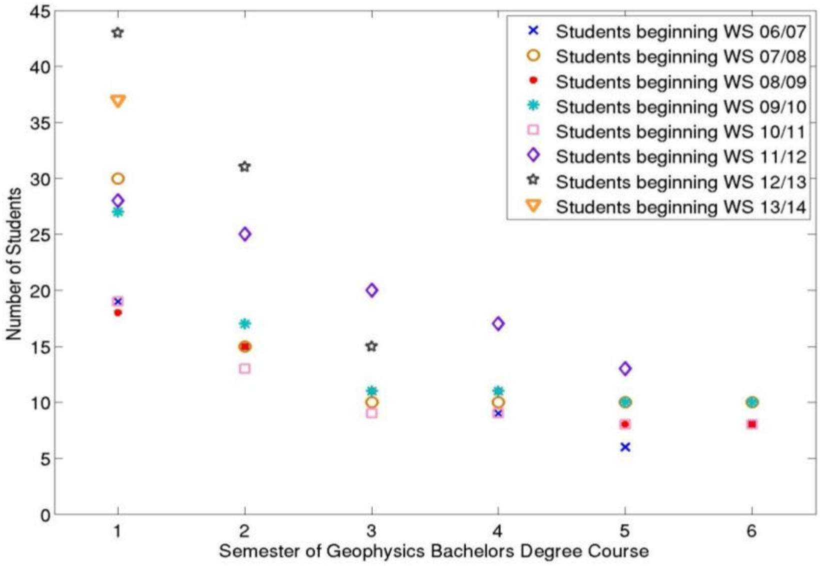


Fig. 13-5: Number of Geophysics Bachelor students over the past eight winter semesters (WS).

increased over the last years (Fig. 13-5), and exceeded 100 students every semester since winter semester 2012/13. Most of those students were enrolled in the Bachelor's degree course, but since the transfer quote to the Master's program is almost 100%, and additional Master's students come from other German and foreign universities (Fig. 13-6), the number of students enrolled in our Master's program is expected to increase within the next years.

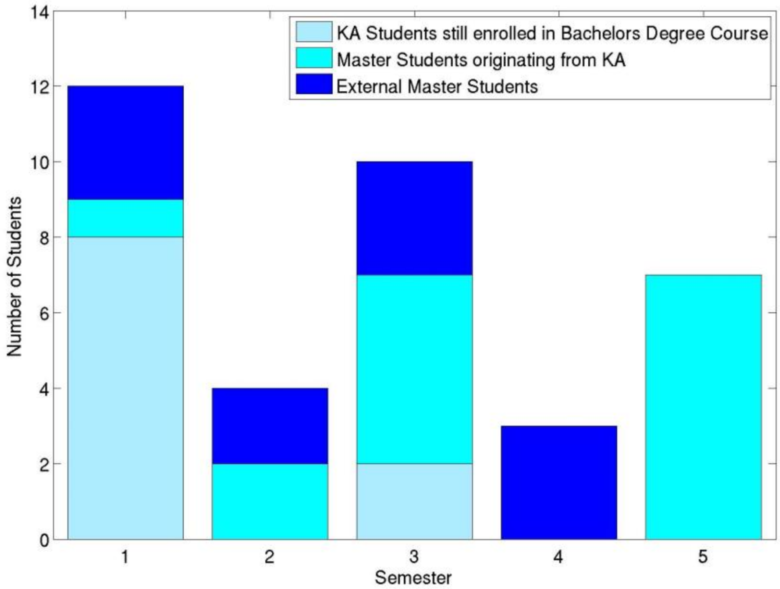


Fig. 13-6: Current number of students in the Geophysics Master course including their background (KA – students which were or still are enrolled as bachelors in Karlsruhe).

13.3.5 New teaching methods and courses

Training for the trainers – the teaching staff of GPI regularly takes part in KIT in-house education and attends courses in several aspects of didactics offered by KIT. This effort has already paid off: The students‘ evaluation of courses and lectures gave many excellent results within the last years, with a particular success of the courses Geodynamics, Physics of Seismic Instruments, Array Processing, Introduction to Experimental Geophysics, Exercise on Simulation of Seismic Waves, and the Exercise on Hazard and Risk Assessment of Mediterranean Volcanoes, which all received the top grade 1.0. The Exercises on Computing in Geophysics and Introduction to Geophysics have repeatedly been voted for the best tutorial of the Department of Physics.

The Teaching Award of the Department of Physics was granted twice to members of GPI within the last years. In 2010, Thomas Forbriger was granted this award, and Ellen Gottschämmer received the Teaching Award in 2012. The awards were presented during the Annual Academic Celebration events of KIT. The awards and their prize money were the basis for the development of new courses for GPI students. Thomas Forbriger introduced and established a Winterschool, held at the Black Forest Observatory (BFO) for three days every year, to give an opportunity to his students to intensively discuss and learn about the physics of seismic instruments, and to apply what was taught during the classroom lecture.

Furthermore, geophysical excursions are funded by the prize money of the Teaching Award. Excursions play an important role in the electives of our curricula. Since spring 2010 the GPI offers at least one field excursion per semester, organized by Ellen Gottschämmer. These field excursions are meant to show our students work environments where geophysicists are active and offer great insight into different aspects of geophysics. In 2010 two excursions were held, one to the construction site of the Gotthard base tunnel (Fig. 13-3), and one to a geothermal power plant and historical oil fields in France. In July 2011 the field excursion led to the volcanic fields of Eifel mountains and in November 2011 we visited the

Landeserdbebendienst Freiburg (state earthquake survey), and combined this field trip with a visit of an abandoned mine on the Schauinsland mountain in the southern Black Forest. In summer 2012 we conducted a field excursion to the site of the continental deep drilling program KTB at Windischeschenbach (Fig. 13-4), and another one to the construction site of the Karlsruhe “Kombilösung”, a major tunnel project in the city of Karlsruhe.

Fig. 13-7: GPI students at the obsidian flow, Rocce Rosse, Lipari Island, August 2013 (photograph by Martin Pontius).

Fig. 13-8: GPI students close to sulfur fumaroles on Gran Cratere, Vulcano Island, August 2013 (photograph by Johannes Käufl).

Several excursions were led to BFO, one of the excursions especially planned for the students in the first year of the Bachelor's program. In conclusion these excursions, especially for young students, are important for both, motivation, and a better understanding of the topics taught in Physics and Geophysics courses.

A particular course was realized in August and September 2013, when Joachim Ritter and Ellen Gottschämmer led a nine-day field trip to Italian volcanoes (Figs. 13-7 to 13-10). The special emphasis of this course was natural hazard and risk of Stromboli, Lipari, Vulcano and Vesuvius volcanoes. Lectures and exercises were performed in situ, in order to connect scientific content to immediate experience. In November 2013, a field excursion was organized to Staufen, where rapid and damaging uplift occurs following a drilling accident, and to the Mont-Terri rock laboratory in Switzerland.

Fig. 13-9: Crater terrace of Stromboli as seen from Pizzosopra la fossa during the visit of GPI, Stromboli Island, September 2013 (photograph by Martin Pontius).

13.4 Technical infrastructure, computer equipment

The electronics workshop of the GPI runs the maintenance of the scientific instruments and cars of the institute. Engineer Werner Scherer, the head of the workshop, is assisted by the technician Hartmut Thomas. They take care of the wide range of geophysical instruments which are used in the laboratory and field exercises during the student courses. There is equipment for geoelectric, geomagnetic and shallow seismic measurements and the data recording. Werner Scherer and Hartmut Thomas also take care of the seismological KABBA instrumentation including in-house development of instruments. They assist the field experiments as well as instruct scientists and students on the use of the delicate equipment.

At the GPI engineer Petra Knopf and Thomas Nadolny operate about 80 high-end desktop workstations for scientific use. All computers have access to our central storage servers which hold about 20 Tbyte of data. All machines are managed within a 1-Gbit-Network and are backed up at the Steinbuch Centre for Computing (SCC) of KIT. With a 10-

GBit network connection to the SCC at KIT Campus North we are able to stream and store huge amounts of data into so-called 'Large Scale Data Facilities' which guarantee long-term and safe data storage.

We also operate several compute and storage servers for special purposes (e.g. real-time data acquisition). A specially configurated network allows real-time data streaming from a seismic monitoring network (KABBA) by means of cell phone communication and internet

In summer 2012 GPI renewed the equipment in our PC pool. There are now 12 high-end workstations, each with I7-8 core CPUs and 16 GB main memory operated by OpenSuse, available for students doing computer exercises, training, programming etc. We are able to use these pool computer, as well as our desktop machines, to run parallel programs in a clustered environment.

The access to several HPC-Systems is required to solve larger numerical problems (e.g. seismic wave propagation for full waveform inversion by massively parallel FD-simulations), which consumes large data storage as well as computation resources. At KIT/SCC we have access to: HC3-System, a HP XC3000 parallel computing facility, IC2-System: 'Institutscluster II', a large cluster system which is partly financed by the GPI. We also run projects on the computer cluster of 'bwGRID', the 'JUROPA'-cluster at Jülich Supercomputing Centre and at the 'HERMIT'-cluster from HLRS Stuttgart. All these computing facilities are the basis for successful student training and research.

Fig. 13-10: GPI students on Vesuvius, September 2013 (photograph by Joachim Ritter).