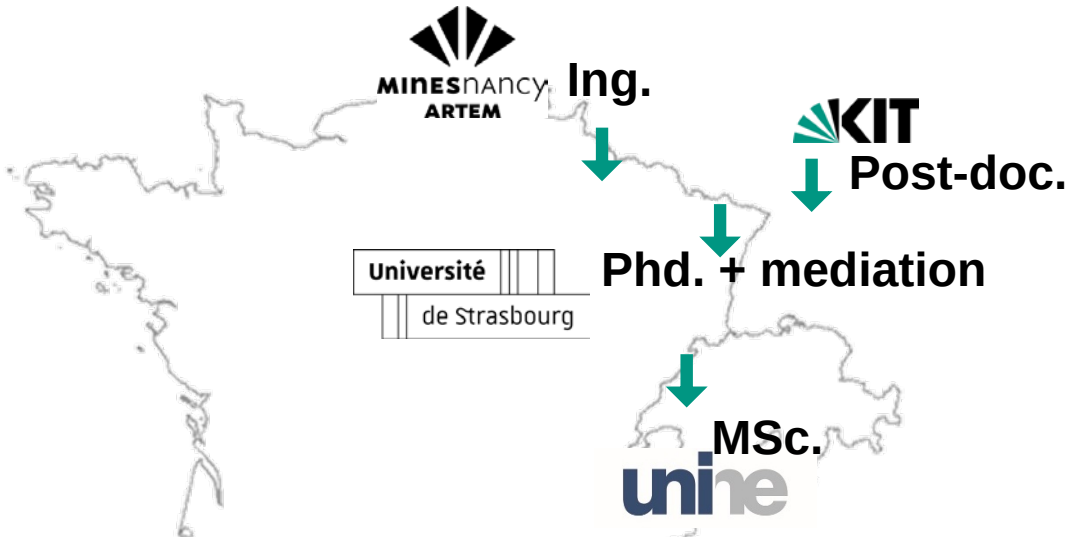
KIT (AGW) – Heisenberg Gymnasium Bruchsal Schulprojekt

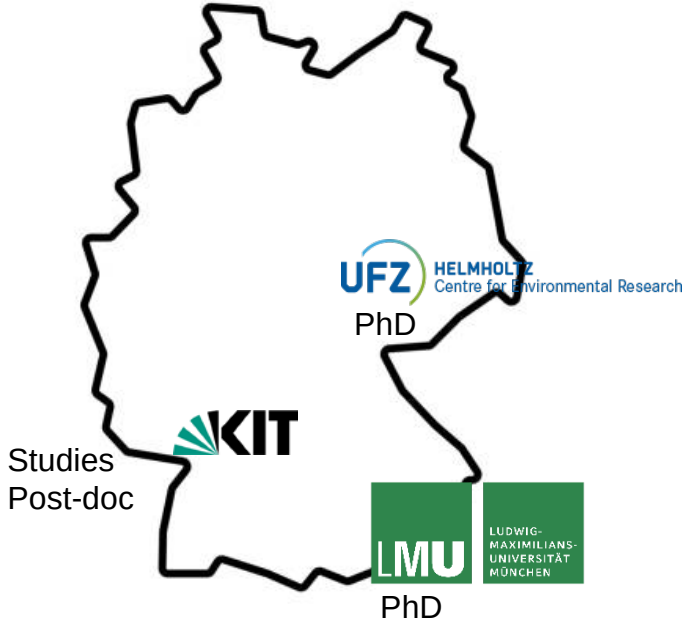
Module 1: Introduction and training of young seismologists

>> *Who we are, why we are here*

- **Dr. Jerome Azzola**
  - Geophysicist
  - Domain of activity: seismology, in connection with geothermal energy



- **Dr. Judith Bremer**
  - Geoecologist
  - Domain of activity: research coordination, citizen science



A school-project to
>> increase scientific literacy,
>> get the reception of young people to seismological concepts and renewable geo-energy technologies,
>> test suitability of RaspberyShakes as sensor for citizen science projects.

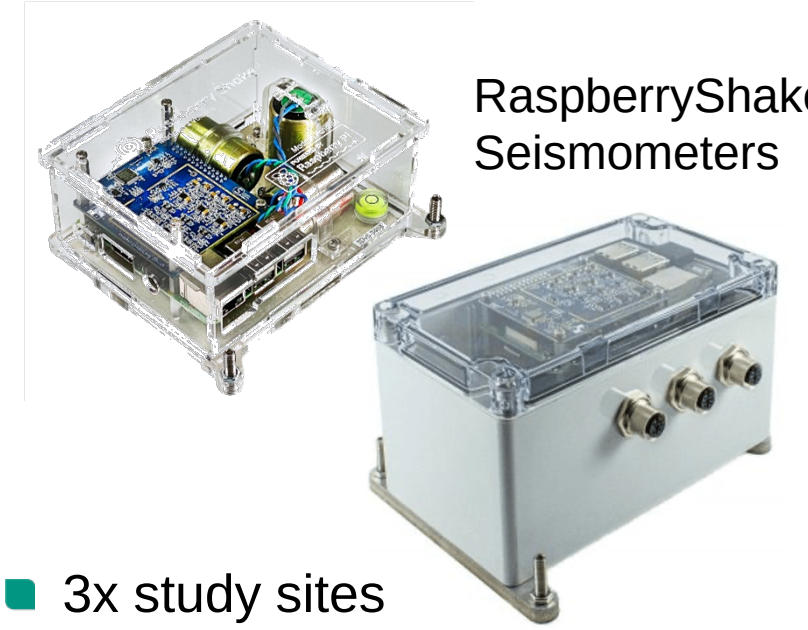
Comparative seismic measurements around the Bruchsal geothermal plant

A role-playing game as an introduction to scientific research

- Gain insight into the role of geophysicists and **seismic measurements** in exploitation of **geothermal energy**
- Gain insight into **scientific research**: observe, formulate an hypothesis, realize / analyze scientific measurements to invalidate or confirm the hypothesis, share results
- Based on a **role play game**: work as a seismologist (in training ☺)

Comparative seismic measurements around the Bruchsal geothermal plant

A role-playing game as an introduction to scientific research



RaspberryShake Seismometers

- 3x study sites
- 3x sensors
- Evaluation of “background noise conditions”

Comparative seismic measurements around the Bruchsal geothermal plant

A role-playing game as an introduction to scientific research

- **September 19 – Module 1: introduction + training course**
- September 26 – Module 2: preparation of field work and site scouting
- September 27 – Module 3: start of measurement campaign at EnBW well site, near a road and at the Heisenberg Gymnasium
- October 04 – Module 4: start of data analysis
- November 14 – Module 5: final workshop

Today, we are going to :

- Tell you more about [your] role, as a geophysicist / seismologist, especially in the field of geothermal energy
- Tell you more about seismology in general, geology and rock mechanics
- Give you a first contact with the tool

What do seismologists study, what is their role?

Study Ground Vibrations

“Ground Shaking events”

Study Earthquakes

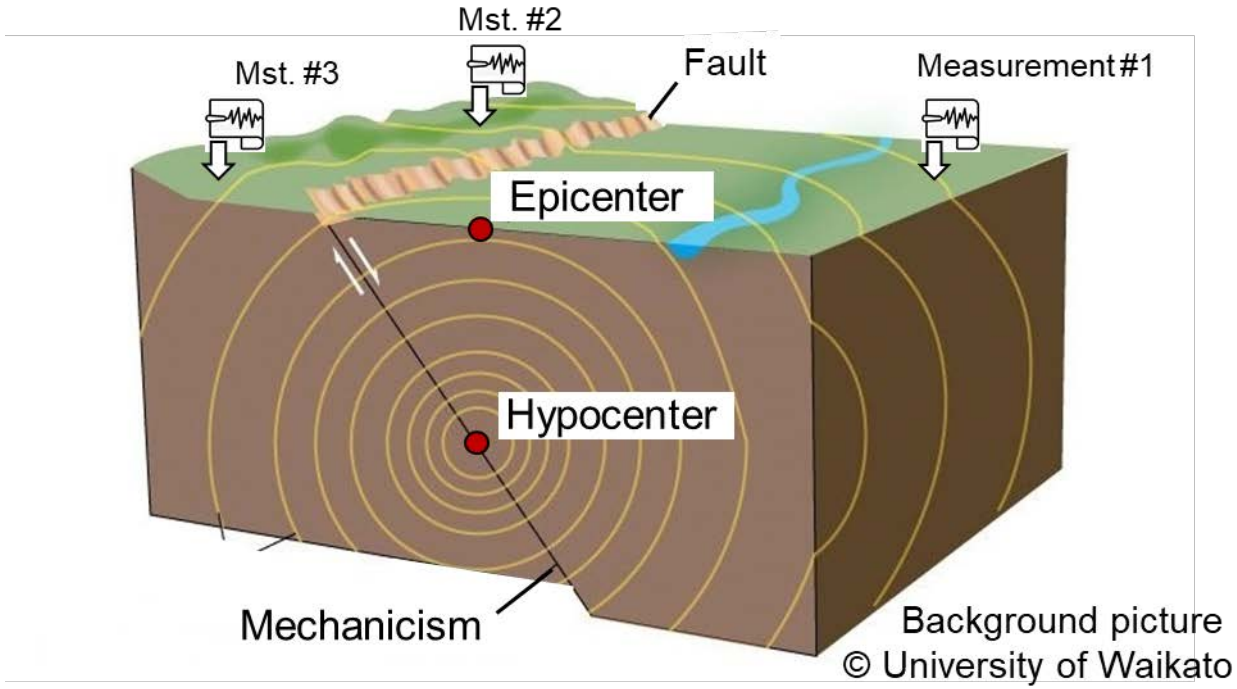
Protect / rescue people from earthquakes

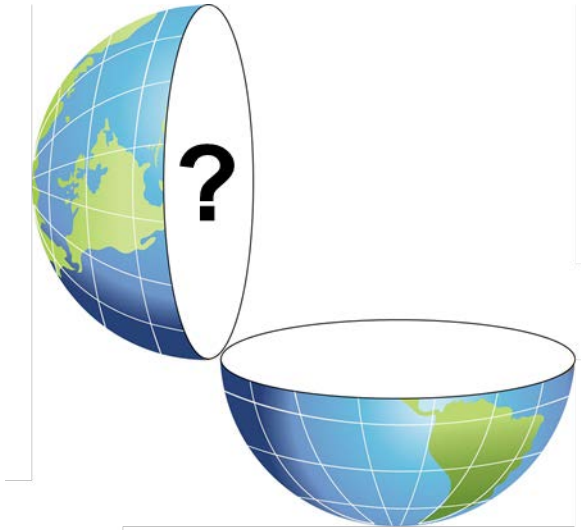
Report about seismic events

>> *Seismologists look at ground vibrations*

- Ground vibrations (**aka.** seismic waves)
- Seismologists focus on different aspects:

Understand ground-shaking events ; investigate earthquakes (origin and mechanism, strength).





Investigate **the propagation medium (typically the Earth)** by analyzing patterns and effects on the recordings of these ground shaking events.

What tools do seismologists use to carry out their studies?

seismogram

seismometer

seismograph

velocimeter

accelerometer

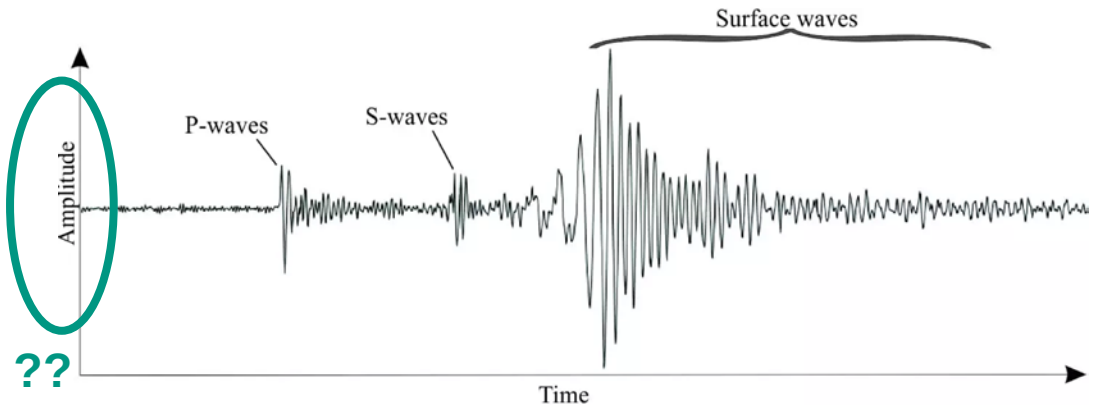
>> *Seismologists use seismometers*

Seismometer = a sensing element, the instrument that responds to ground vibrations.

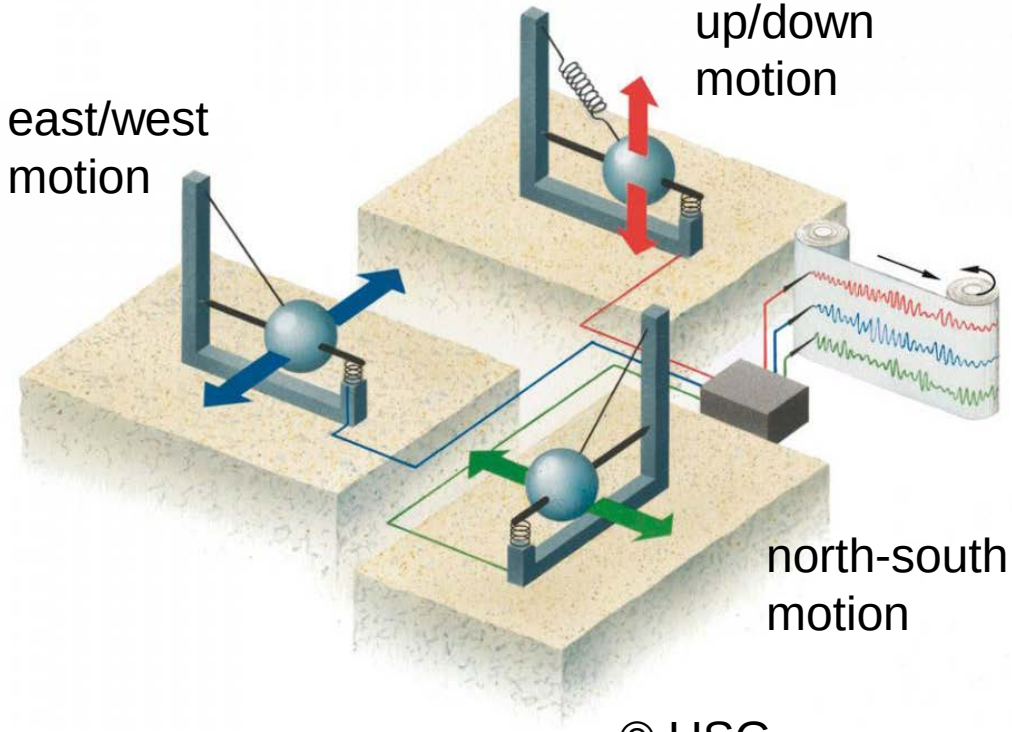
+ Needs a **timing** device (accurate timestamps) and a **recording** device (data management).

+ Earth is 3-D medium: ground vibration characterization requires **3 measurement directions**

→ Sensor(s) + timing + recording device = a **Seismograph.**



Example of seismogram of an earthquake with background noise, P-wave, S-wave, Surface waves



© USG

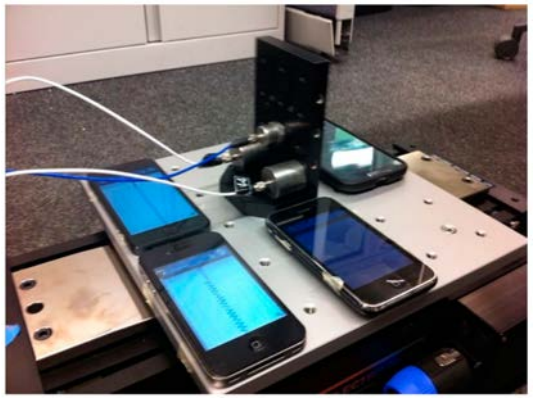
→ **Seismogram** = graphical output.

>> *Seismologists use seismometers*

- Measurement type depends on the sensor
  - **Velocity**
  - **Acceleration**
  - **Displacement**
  - Others (fiber optic sensing)

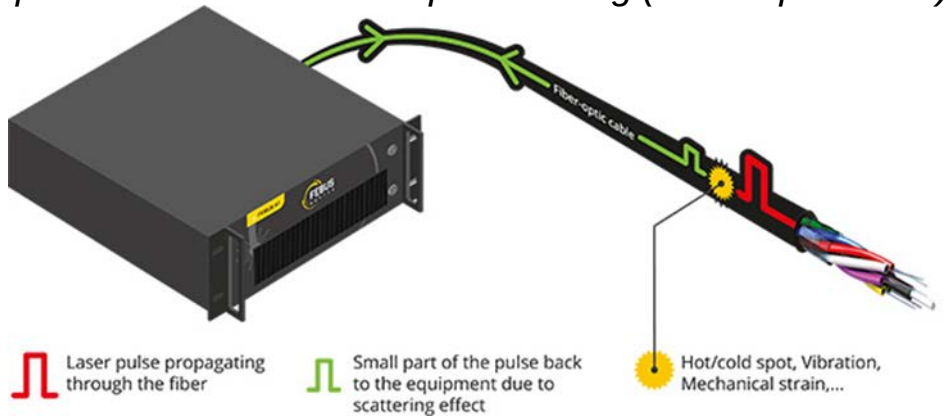
- A mass is suspended to springs, or enslaved. When ground shakes, it has a proportional movement, which can be associated to the measurement type
- Nowadays, various sensors are used depending on the application and queried sensitivity.

Pool of seismometers



Smartphones to provide strong EQ warnings (Feng et al., 2015)

Principle of Distributed Fiber Optic Sensing (febus-optics.com)



>> *What tool are **we** going to use?*

RaspberryShakes, known for affordability, compactness, easy of use

>> Sensors: 3x Seismometers: output a voltage in response to ground vibration, later converted to $V_{X,Y,Z.}$

>> Recording device: “Shake Board” digitizer to receive and processes the sensor data in real-time.

>> Operating system: Raspberry Pi, to access structured data.

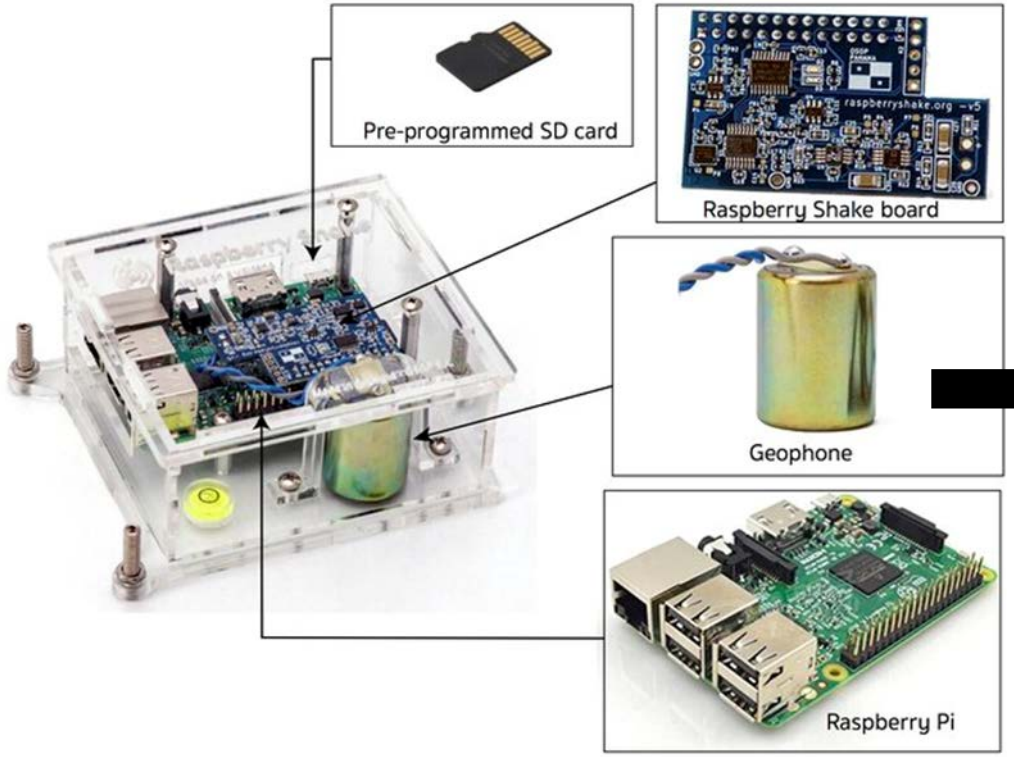
>> *What tool are **we** going to use?*

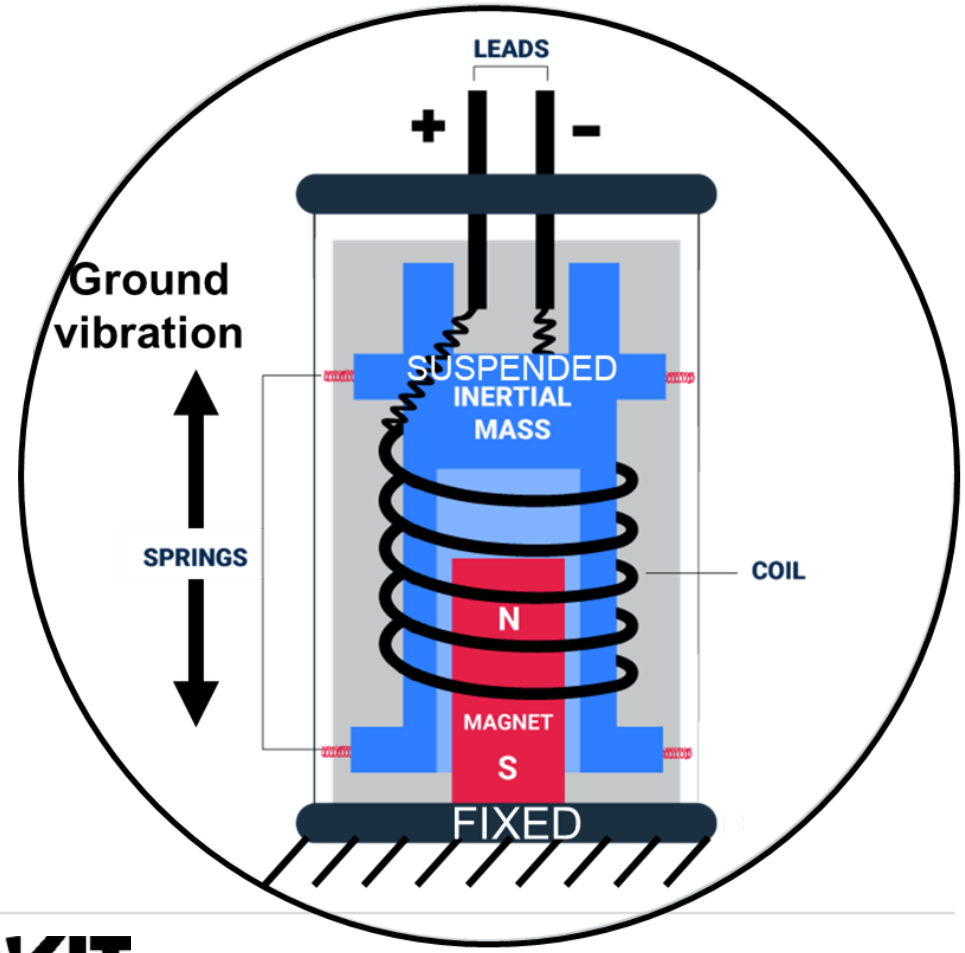
RaspberryShakes, known for affordability, compactness, easy of use

>> A suspended inertial mass wrapped into a copper coil.

>> When ground shakes, relative movement causes an electrical field.

>> Outputs a **voltage** [V] that is further converted to **velocity** [m/s].



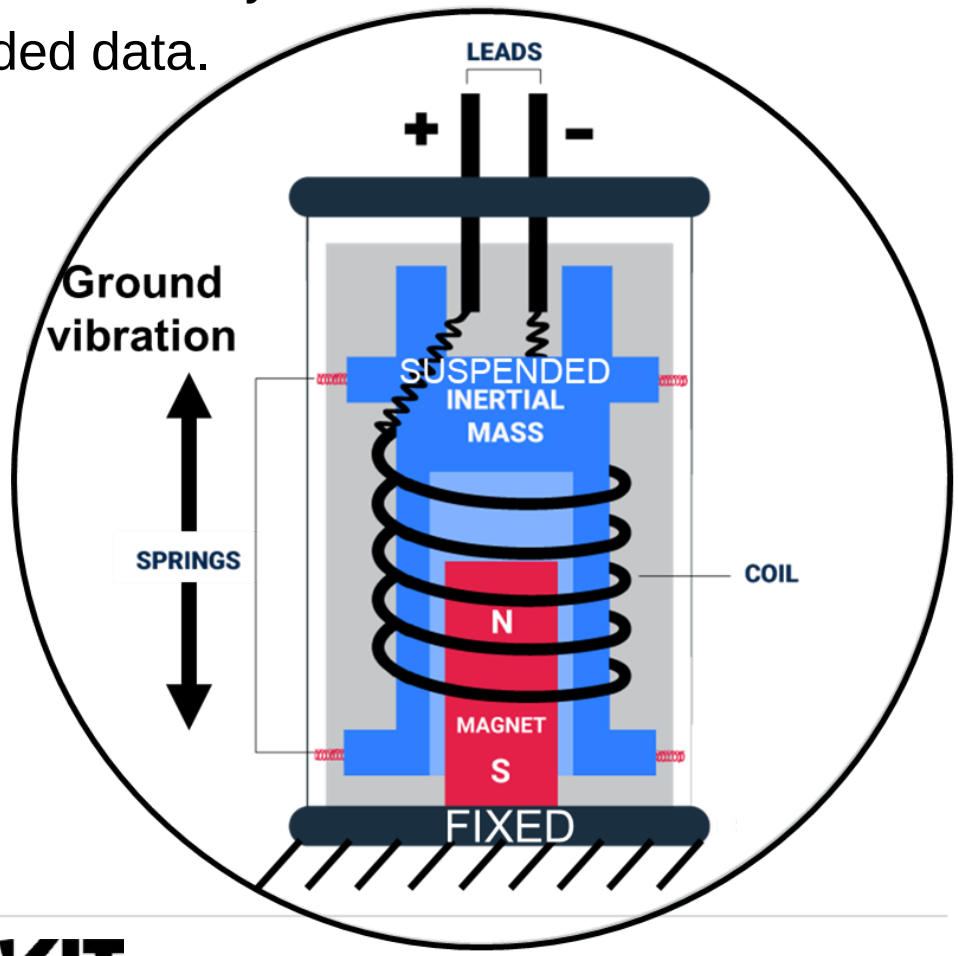


>> *What tool are **we** going to use?*

RaspberryShakes, known for affordability, compactness, easy of use

>> 3x Seismometers output a voltage in response to ground vibration

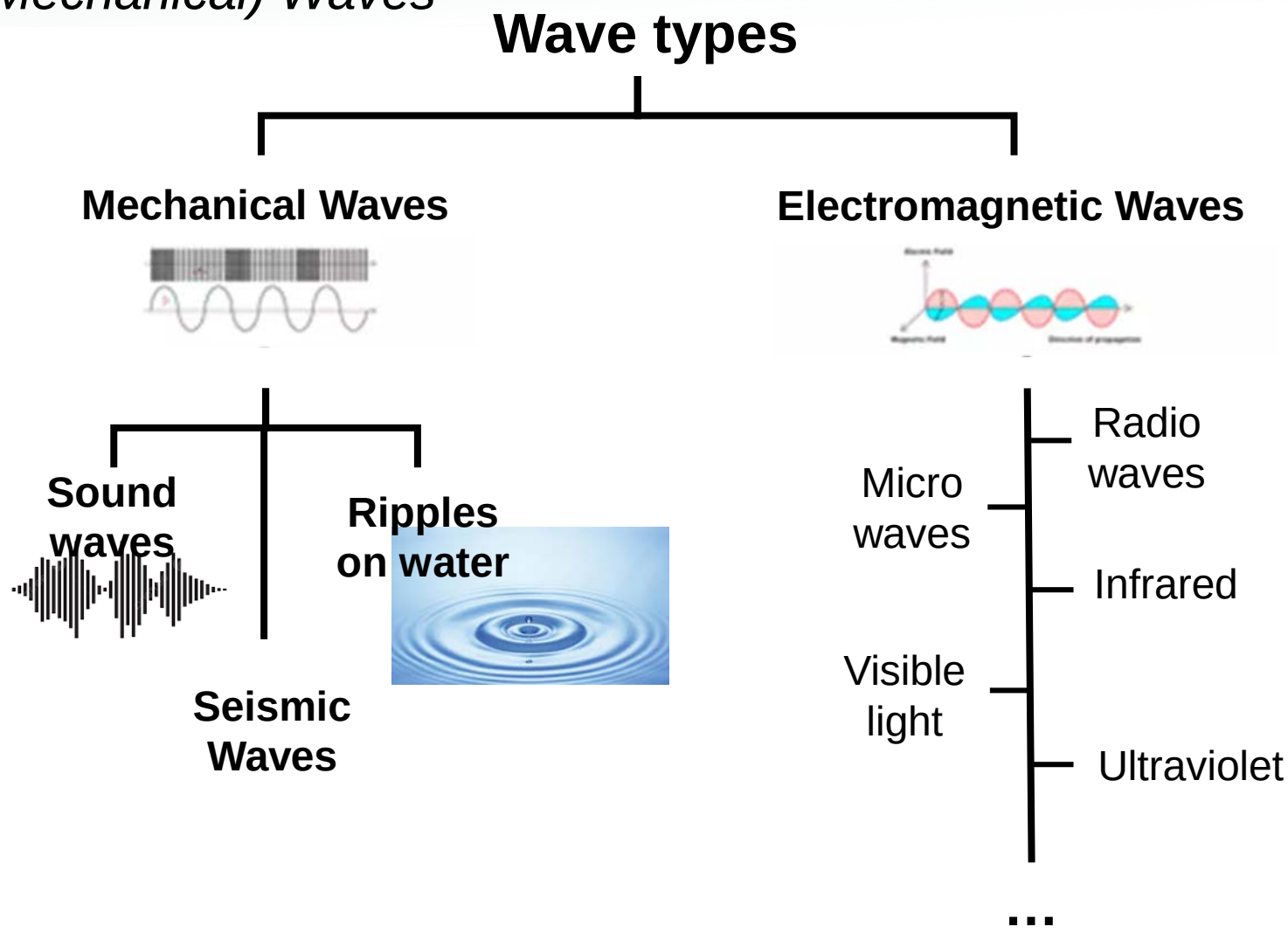
>> Conversion requires to know the "**response**" of the instrument, detailed by producer in a file that contains crucial details to interpret the recorded data.



>> *Ground vibrations, aka Seismic (Mechanical) Waves*

Ground vibrations result from the propagation of **seismic waves** in any material (such as underground).

- A wave transmits information or energy in the form of oscillation through a medium
- **Mechanical wave**: particles vibrate in a material in which the wave propagates,
- **Electromagnetic waves**: unlike for mechanical waves, they do not need a particles/a material to propagate.

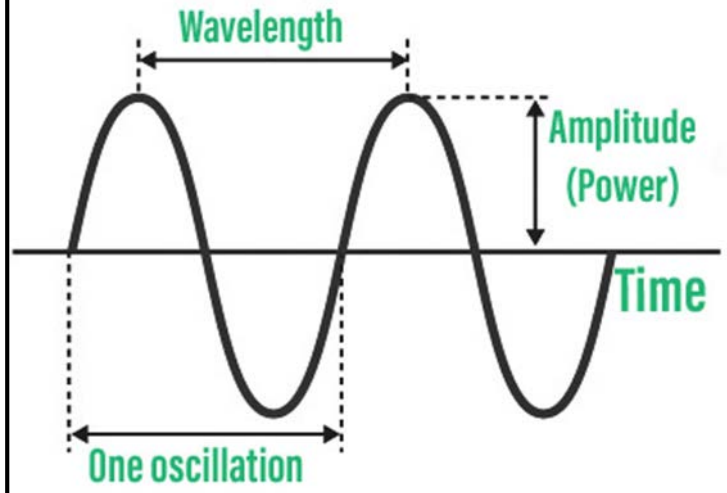


>> How to characterize these waves?

Waveforms = graphical representation of the variation of a physical quantity over time

- Waveforms are characterized in **time-domain**
  - Amplitude and max. amplitude
  - Temporal period (or frequency)
  - Spatial period – wavelength
- One can also decompose waveforms in the **frequency-domain** (Fourier decompositions)

Simple waveform, in **time** domain



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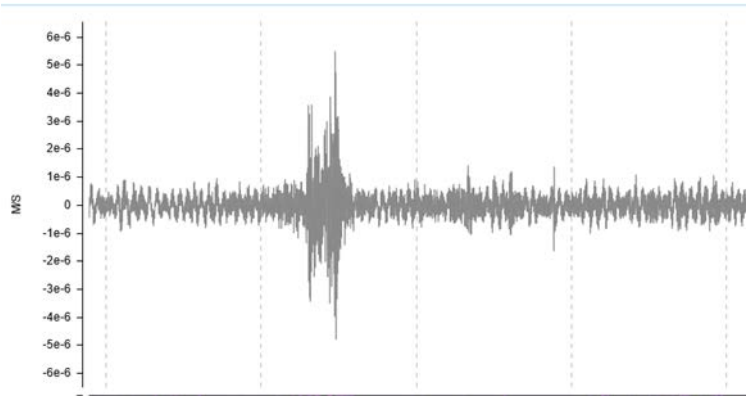
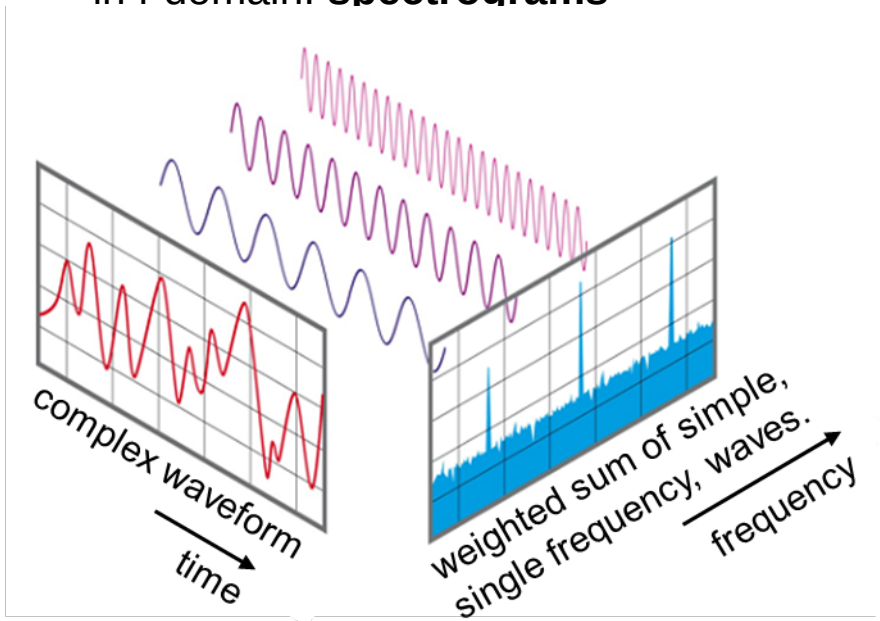
But in general, a waveform looks more like this…



Amplitude ✓ Period/wavelength ✗

reading patterns / characteristics is difficult

Fourier Transformation, description in f-domain: **spectrograms**



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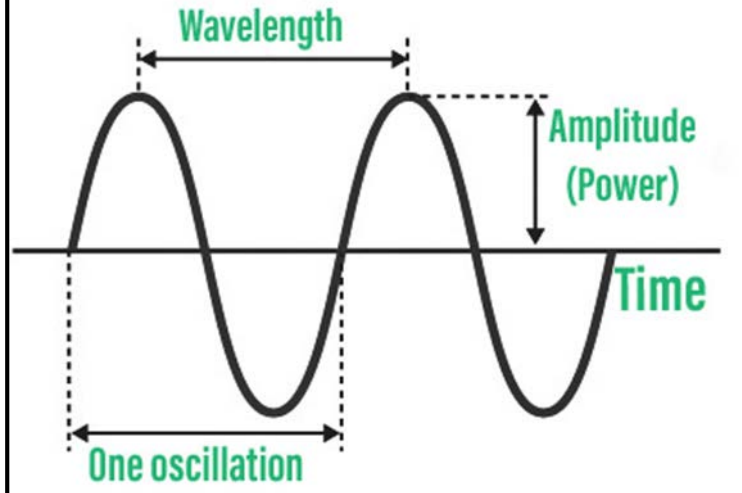
>> *How to characterize these waves?*

They are characterized

- by waveform parameters such as max. / median amplitude (or velocity)
- by frequency content: different freq. ≡ different components / details in the signal
  - >> analogy with musical domain
  - >> analogy with decomposition of visible light

Simple waveform, in **time** domain



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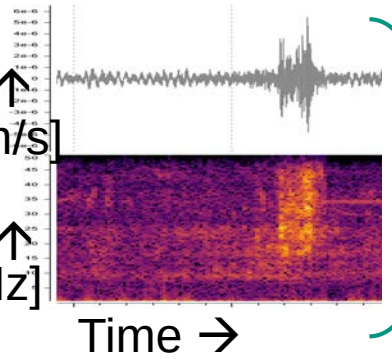
Waveform, in **frequency** domain

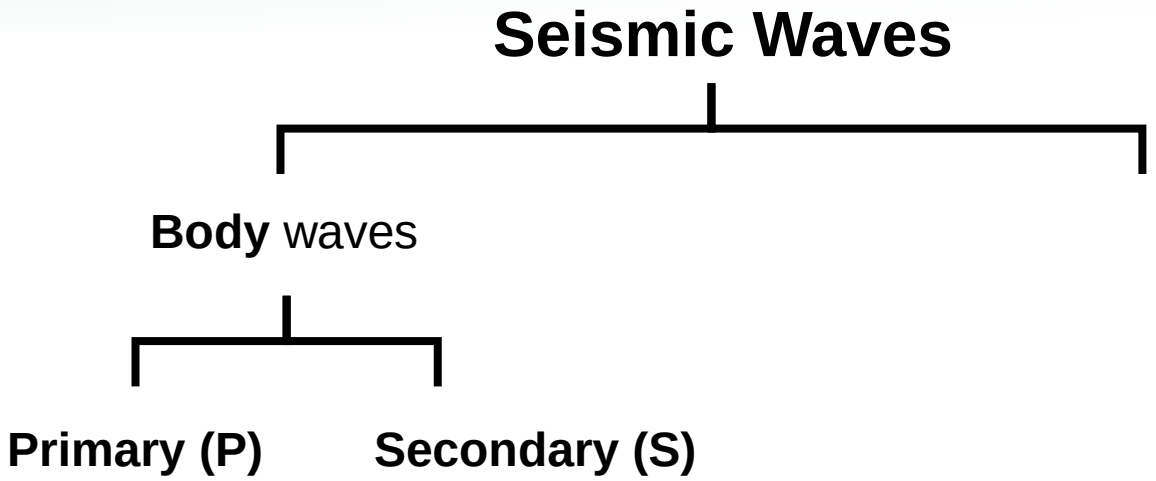
Treble / bass
>> their repartition describes details in sound



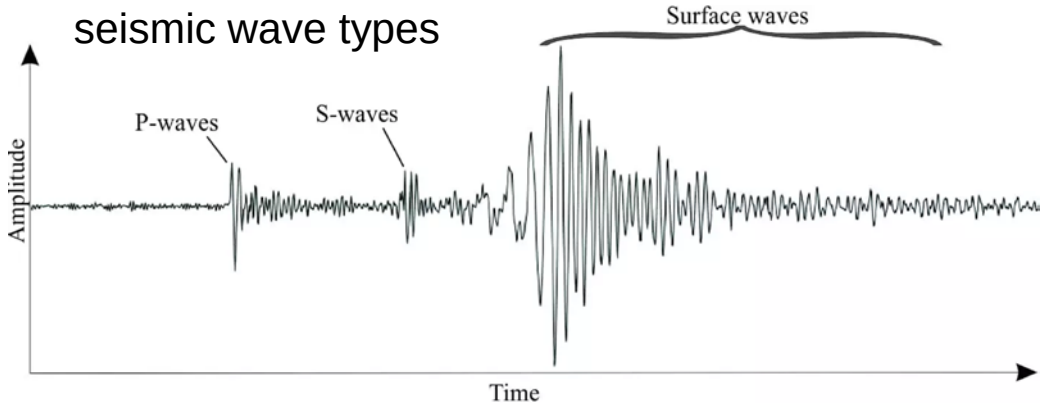
Different components
>> details in the signal associated to different processes

>> *Different types of seismic waves*

Wave Type	Particle Motion	Typical Velocity	Other Characteristics
P – Primary Compressional	Compressions (“pushes”) and dilations (“pulls”) directed in the direction of propagation	V_P ~ 5 – 7 km/s in Earth’s crust Water; ~0.3 km/s in air.	Travels **fastest** in materials P waves in a liquid / gas = **pressure** waves (sound).
S – Secondary **Shear**	Transverse motion, perpendicular to the direction of propagation	V_S ~ 3 – 4 km/s in Earth’s crust;	Travel **slower** than P waves **Don’t** propagate in fluids



Example of waveform with seismic wave types



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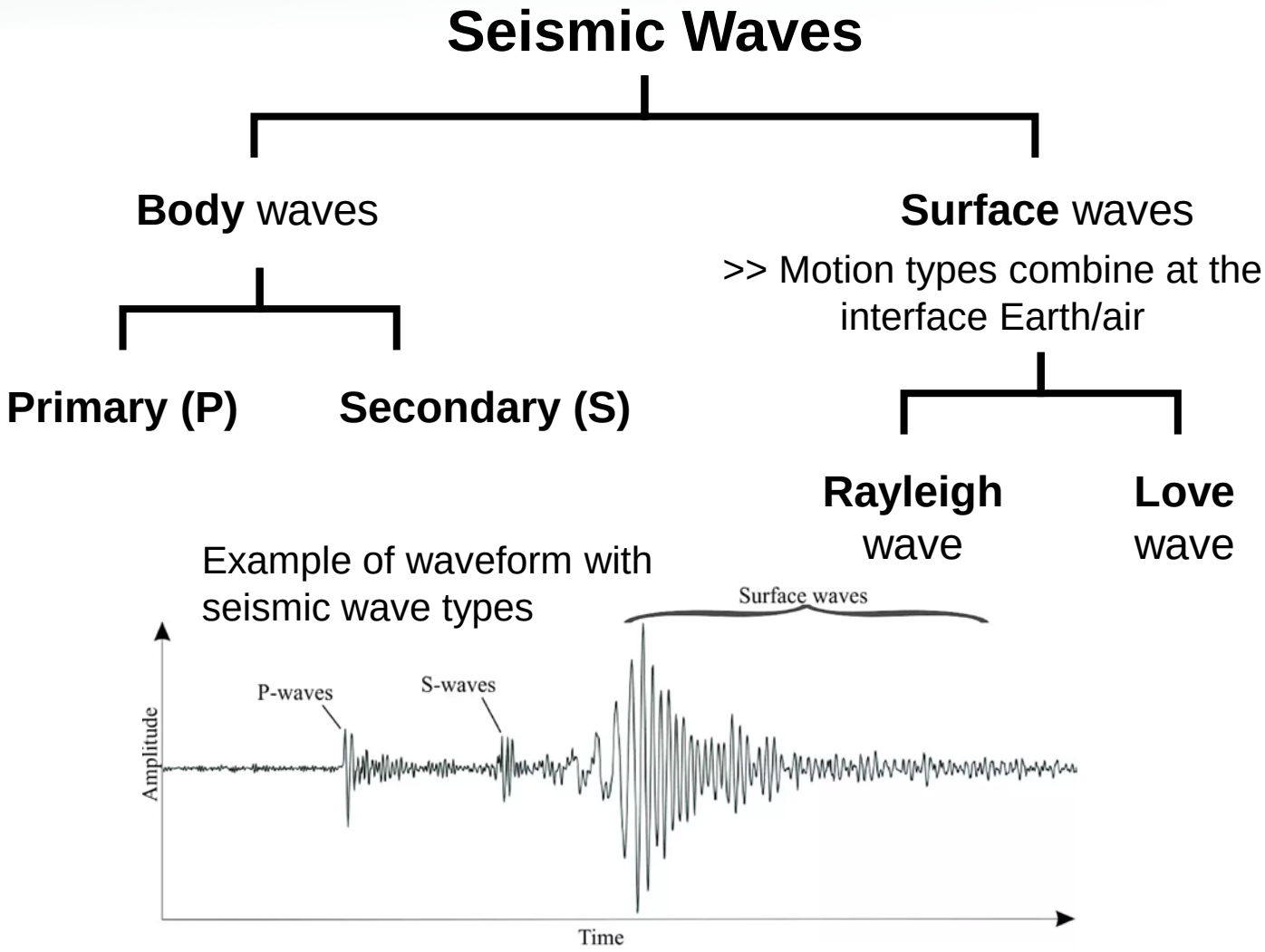
S – Secondary **Shear**	Transverse motion, perpendicular to the direction of propagation	V_S ~ 3 – 4 km/s in Earth’s crust;	Travel **slower** than P waves **Don’t** propagate in fluids
L - Love Surface waves	Exist because of the Earth’s surface: at the interface, compressions and transverse motions interact / combine to form surface waves. They are largest at the surface and decrease in amplitude with depth. **Frequency dependent**: penetration depth and wave velocity (dispersion) is dependent on frequency		
R - Rayleigh, Surface waves			



>> Often, not so easy to identify wave types on waveforms because seismometers record a **mixture** of seismic waves of various origins

>> *Ground vibrates **all the time***

Seismic waves recorded by seismometers have **many origins / provenances**

- Natural origins: ocean noise (swell, wave-wave interactions), wind, wildlife, natural hazard (volcanoes, earthquakes)
- Anthropogenic origins (cars, trains, industry,…)

\+ induced seismic activity (earthquakes triggered by human activity)

Seismic waves = Seismic **signal** + Seismic **noise**

"… the relatively persistent vibration of the ground due to a multitude of causes (e.g. human activity) and classified as the unwanted component of signals" **British Geological Survey (BGS)**

>> To characterize seismic events, we want data clear of seismic noise: needs proper characterization of background seismic noise

>> Seismic noise can also be a type of signal of interest: a "source" available everywhere, all the time, to study the globe structure

Fun fact: seismic background noise and COVID lock-down: https://www.science.org/doi/10.1126/science.abd2438

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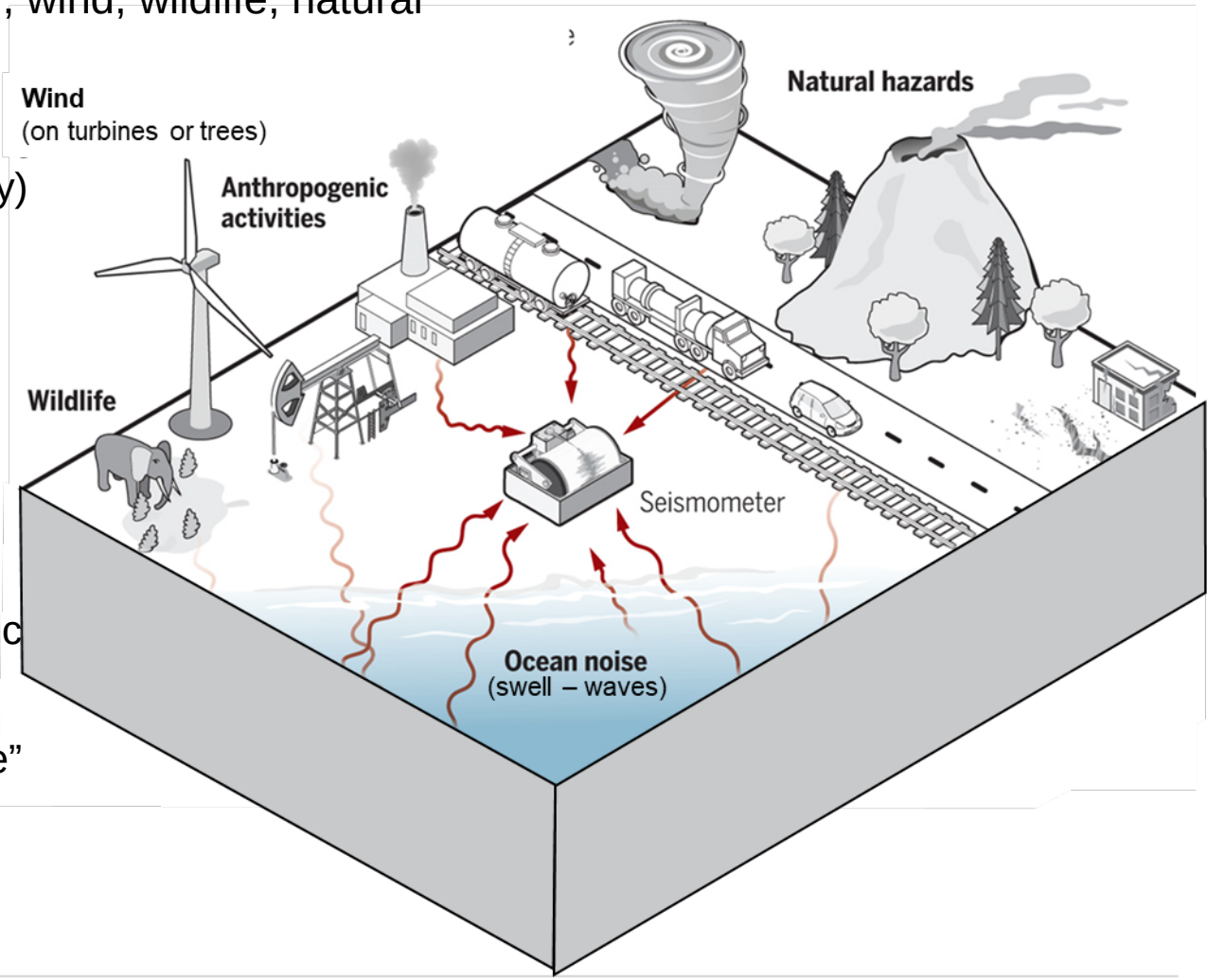
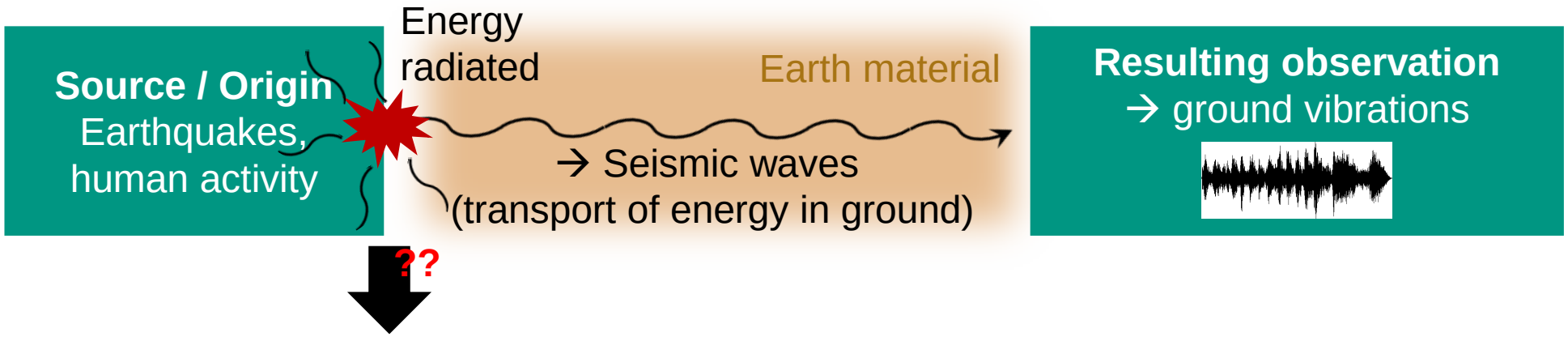




What mechanisms are involved in that energy release?

Let's talk about earthquakes (and faults…)

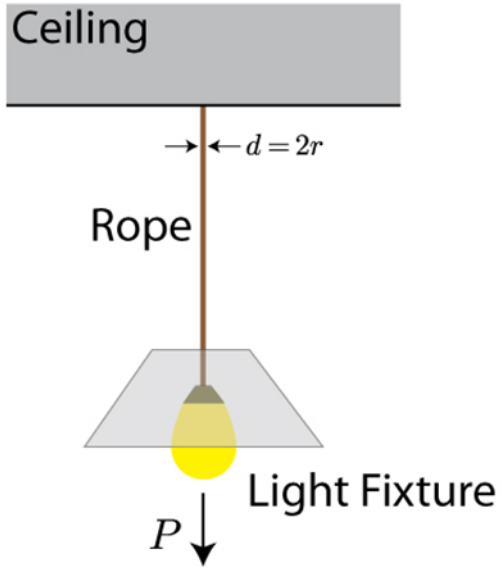
- Natural
- Induced

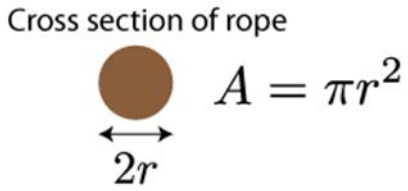
Some preliminary information about rock mechanics

What is mechanical-stress?

- **Force** [Newton, N], is a push (or pull), an action upon a body, resulting from the interaction with another body.
- **Stress σ** is a measure of the **resistance** opposed by a body whenever it is under external forces. Stress has units of **force per area** [N/m^2]

Exple:





$$\sigma = \frac{P}{A} = \frac{P}{\pi r^2}$$

Some preliminary information about rock mechanics

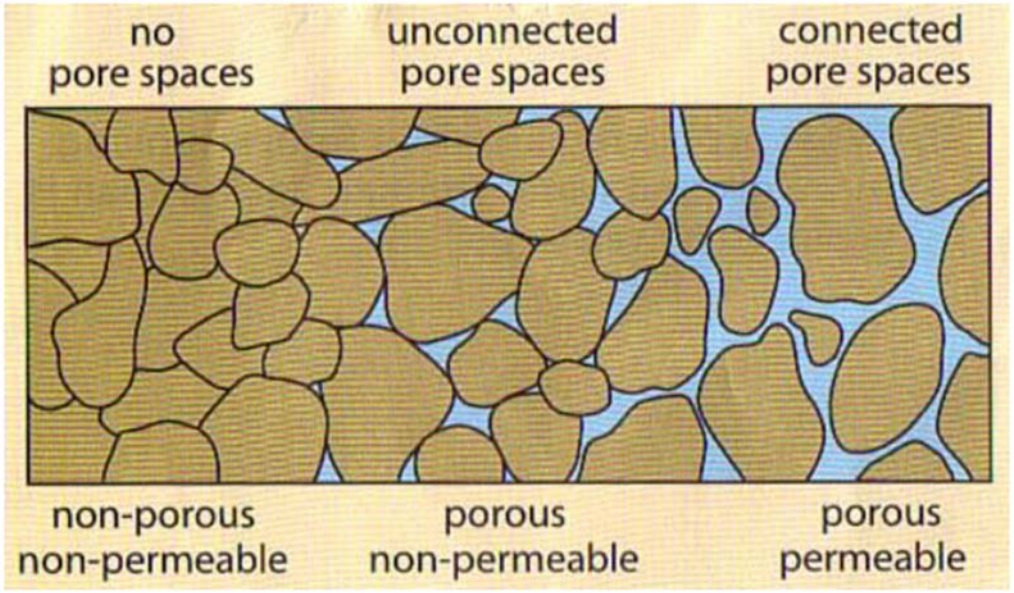
What is the stress-state in rocks?

A rock mass is constituted of

- Grains
- Fluid, that might circulate or not (permeability)
- Voids (pores)

>> Porosity: measure of the ability of rock to **hold** fluids

>> Permeability: a measure of the ability of rock to **transmit** fluids

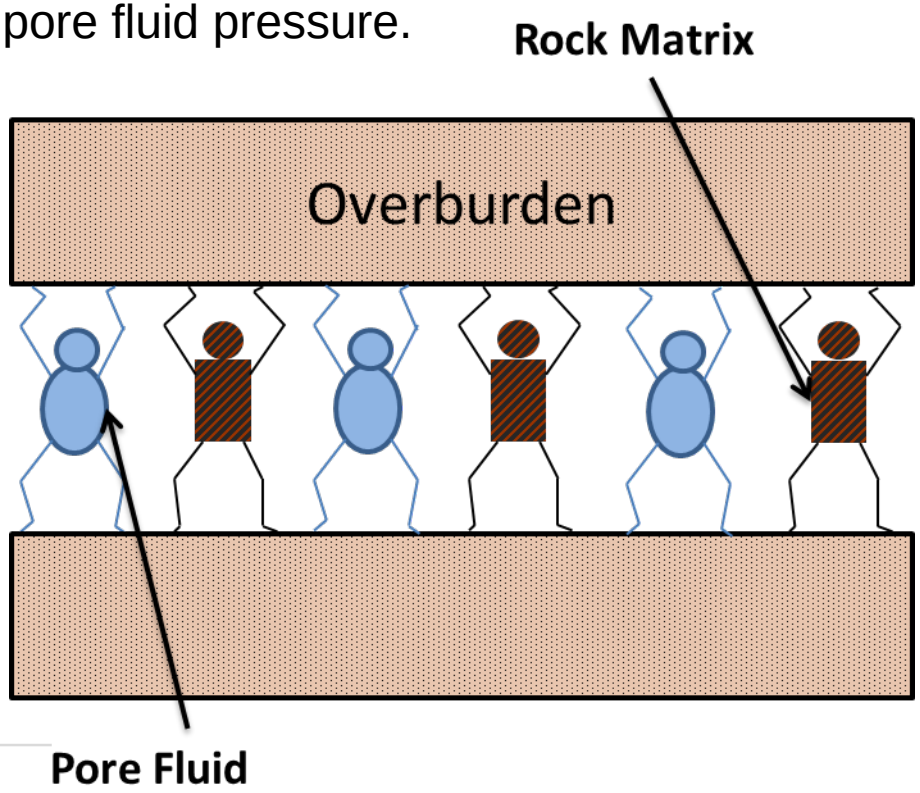


What holds a rock-mass at equilibrium?

The fluid within these pores may also behave mechanically within this rock mass. The weight of the overburden is supported by

>> the vertical grain-to-grain matrix stress and

>> the pore fluid pressure.



>> *Where do earthquakes occur?*

Earth is a complex non-homogeneous medium, full of **fractures/faults**

Def*: "a break that propagates within a rigid medium"*

Examples: - Boundaries btw tectonic plates are made up of systems of faults

- In geothermal energy, faults play a significant role due to their impact on the movement of fluids (porosity / permeability) within the crust.

>> *What causes earthquakes?*

Earth is a complex non-homogeneous medium, full of **fractures/faults**

Def*: "a break that propagates within a rigid medium"*

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- In geothermal energy, faults play a significant role due to their impact on the movement of fluids (porosity / permeability) within the crust.

Elastic rebound theory (Henry Fielding Reid, 1906): EQ occur when accumulated stress along a fault is released.

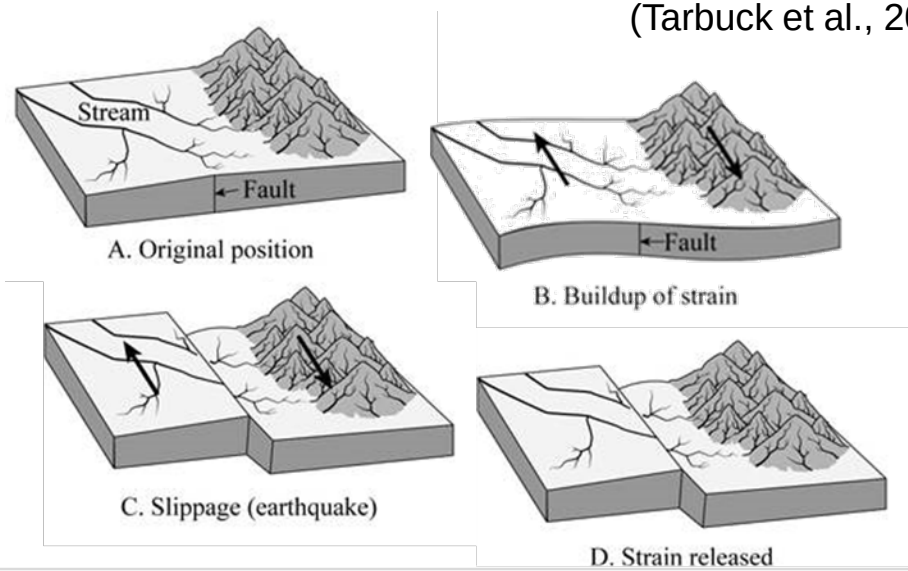
(Tarbuck et al., 2014)

→ Stresses buildup over time (e.g. with slow movement of tectonic plates).

→ At some point, stresses become so great that they exceed friction holding rock masses: the rupture occurs.

→ Accumulated stress / energy is released.

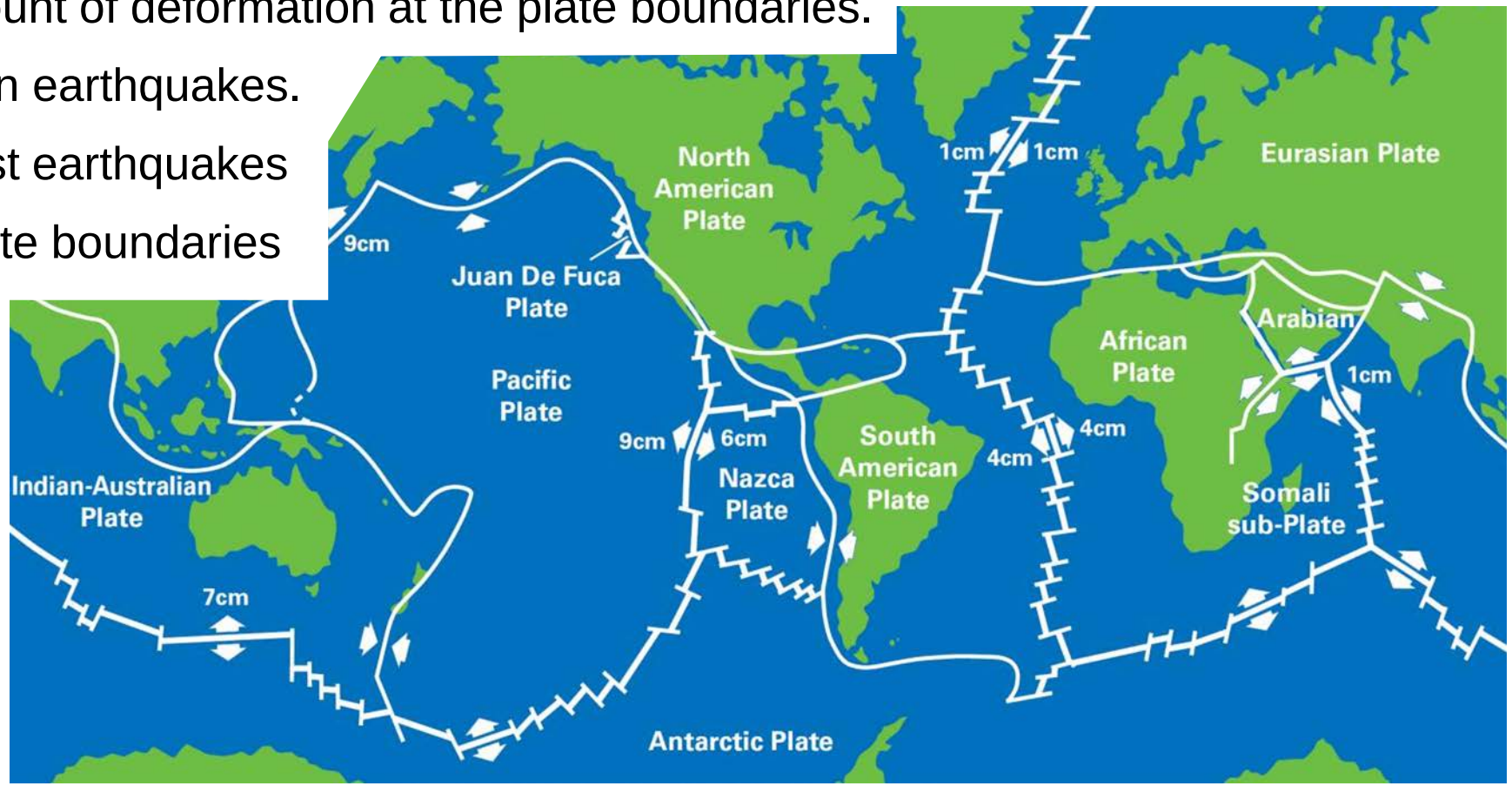
→ Fault sides return to original shape, with offset. (elastic rebound)



>> *Tectonic plates movement and "Natural" earthquakes*

- Tectonic plates move relative to each other (a few cm / year).
- This still causes a huge amount of deformation at the plate boundaries.
- This process in turn results in earthquakes.

>> Observations show that most earthquakes are associated with tectonic plate boundaries



Map of major tectonic plates with direction of movement at boundaries. **BGS ©UKRI.**

>> *Tectonic plates movement and "Natural" earthquakes*

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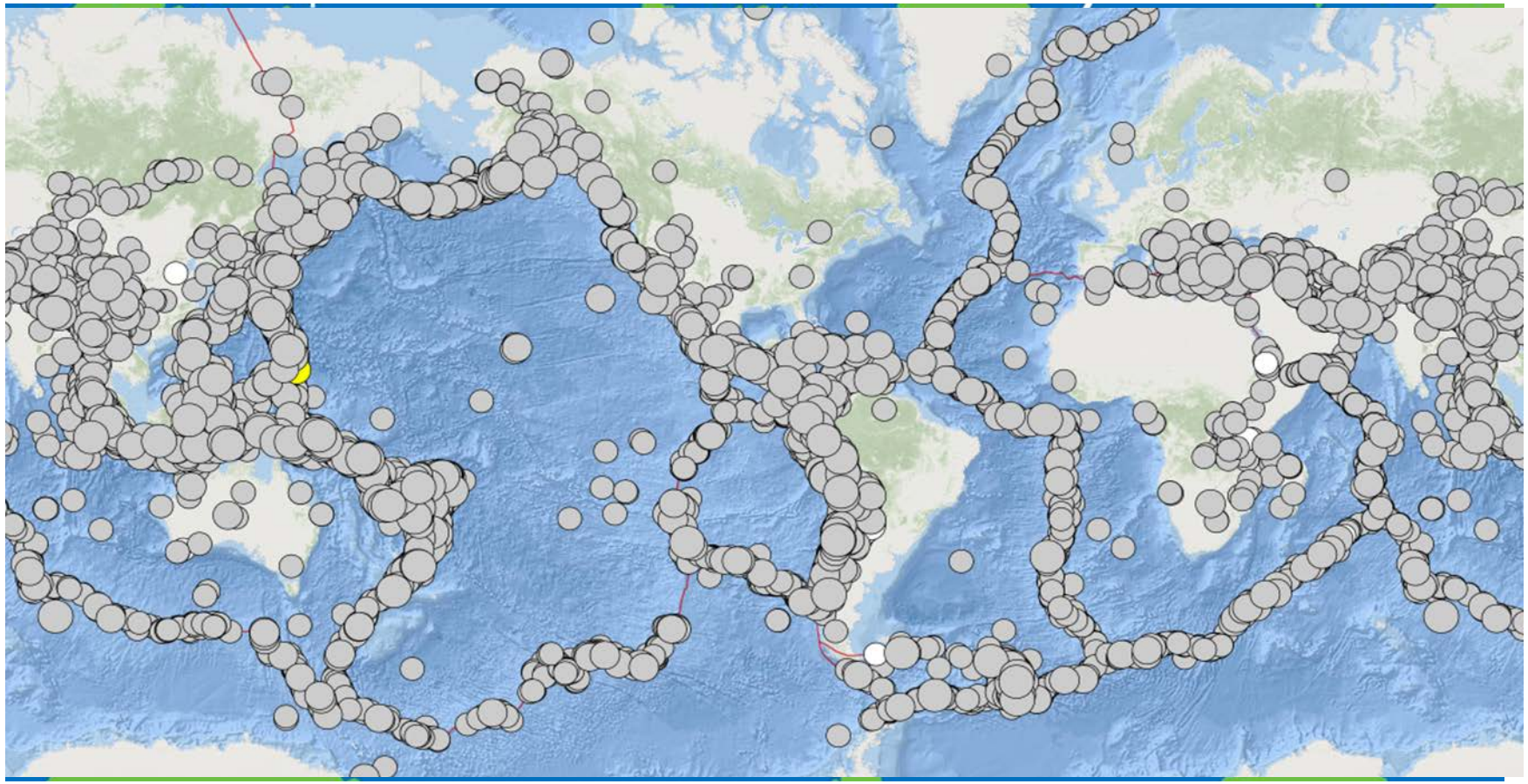
Earthquake epicenters

>> Check it out here: earthquake.usgs.gov/earthquakes/map/



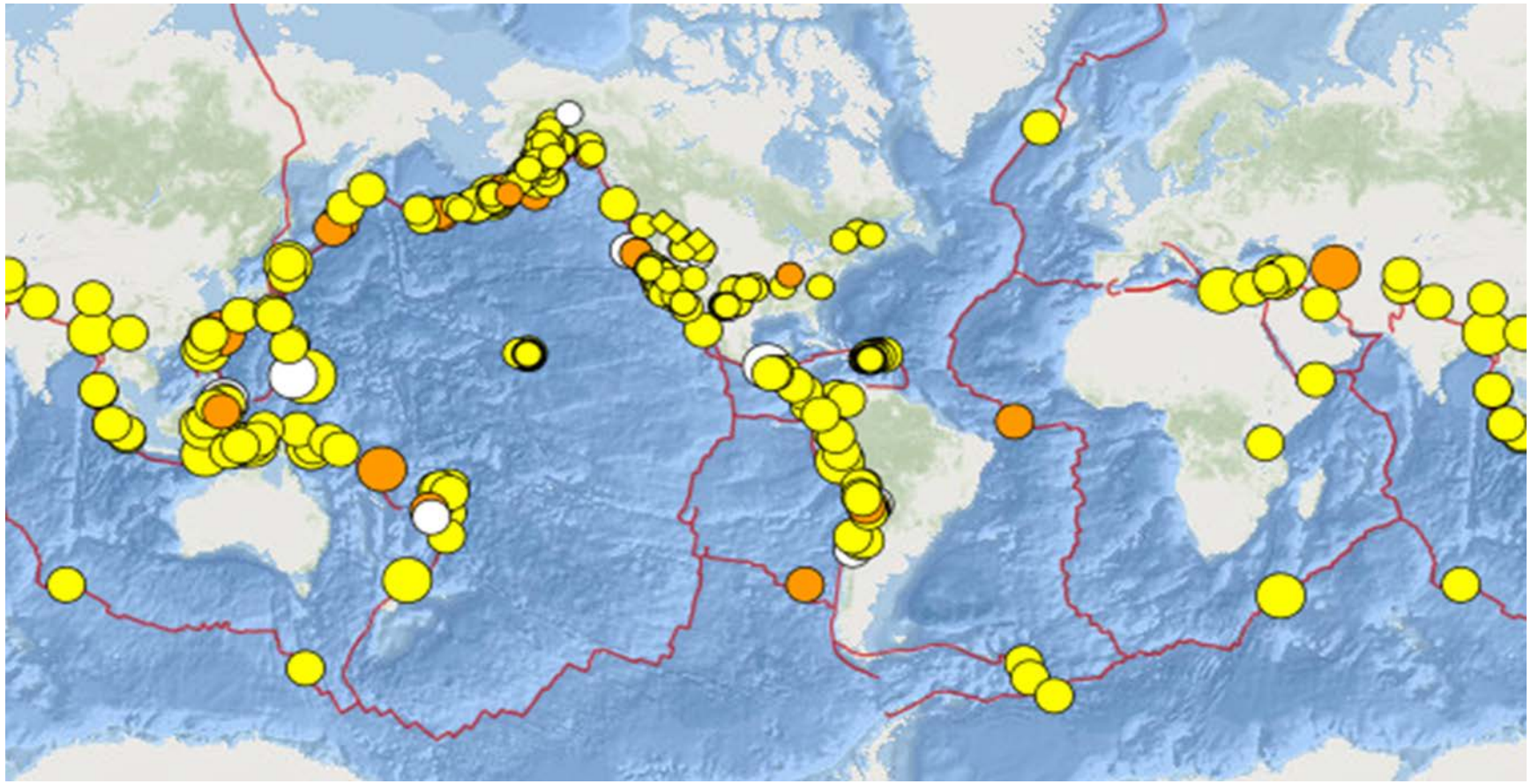
Major (M>5) Earthquakes, recorded by **USGS** since 10 years

>> *Tectonic plates movement and "Natural" earthquakes*

- Observations show that most "natural" earthquakes are associated with tectonic plate boundaries

>> Spatial distribution agrees with the map of the major plate boundaries.

>> What is the underlying mechanism? What happens at these boundaries?



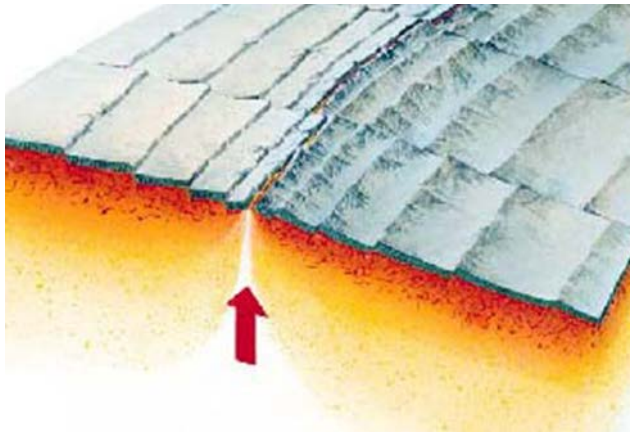
Earthquakes (M>2) recorded by **USGS** since 01.01.2023

>> *Tectonic plates movement and "Natural" earthquakes*

- Different types of boundaries

⇦ ⇨ Divergent
plates move apart

>> Hot magma rises from the mantle, pushes the plates apart (creation of material)



>> Associated with volcanic activity and frequent earthquakes (but rather small in magnitude)

Plate tectonic map of the world showing direction of movement. **BGS ©UKRI.**

>> *Tectonic plates movement and "Natural" earthquakes*

- Different types of boundaries

⇦ ⇨ Divergent
plates move apart

>> In Iceland the Mid-Atlantic Ridge passes on land
>> A natural laboratory to study, on land, the processes occurring deep in the ocean at ridges

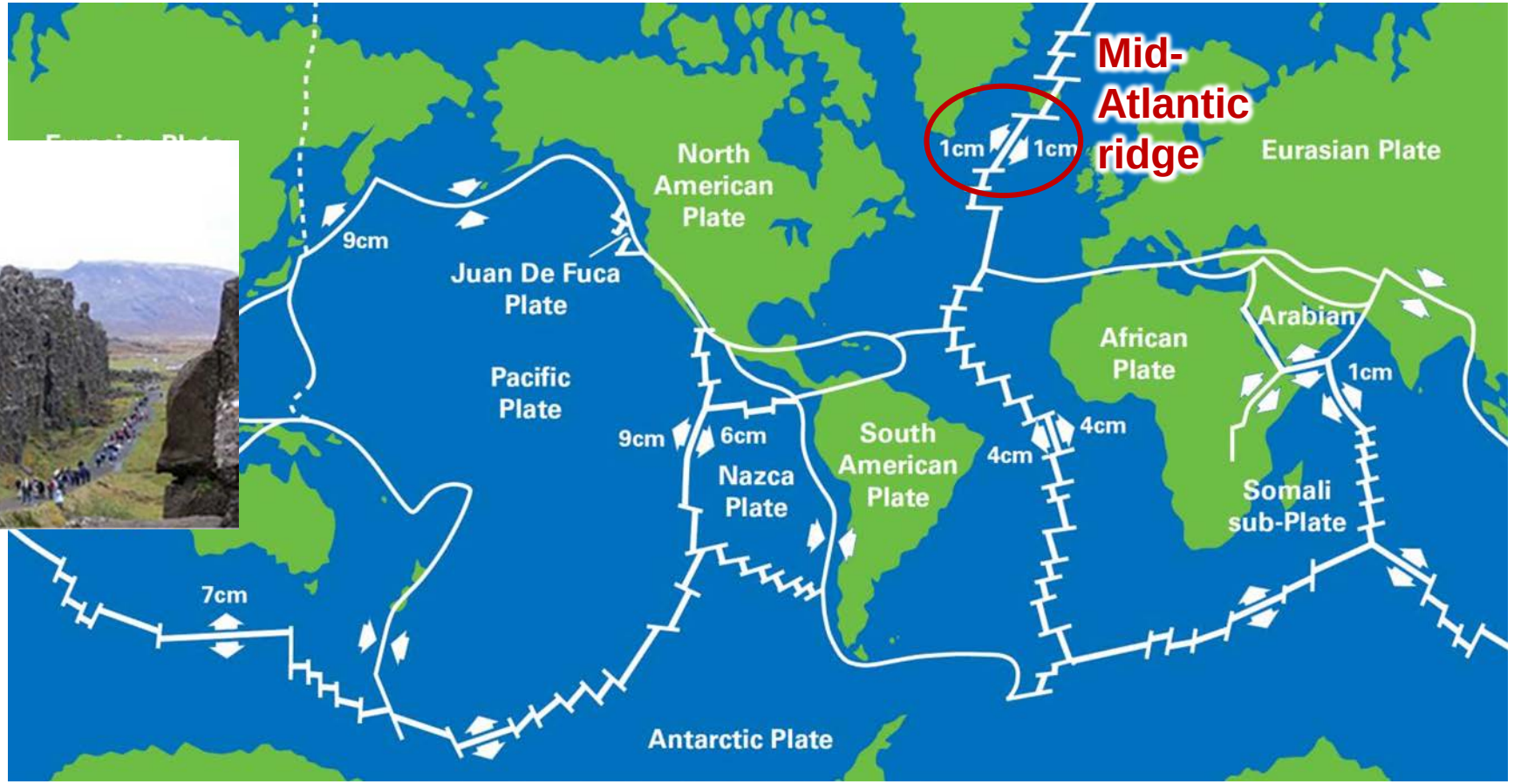
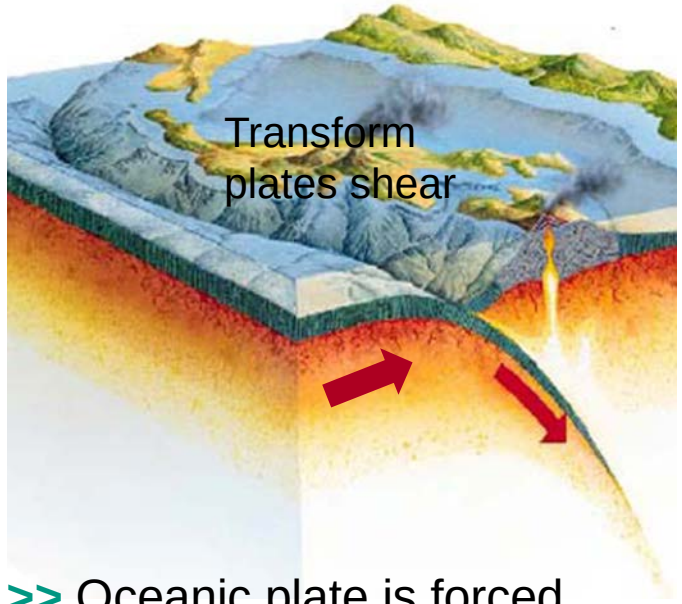


Plate tectonic map of the world showing direction of movement. **BGS ©UKRI.**

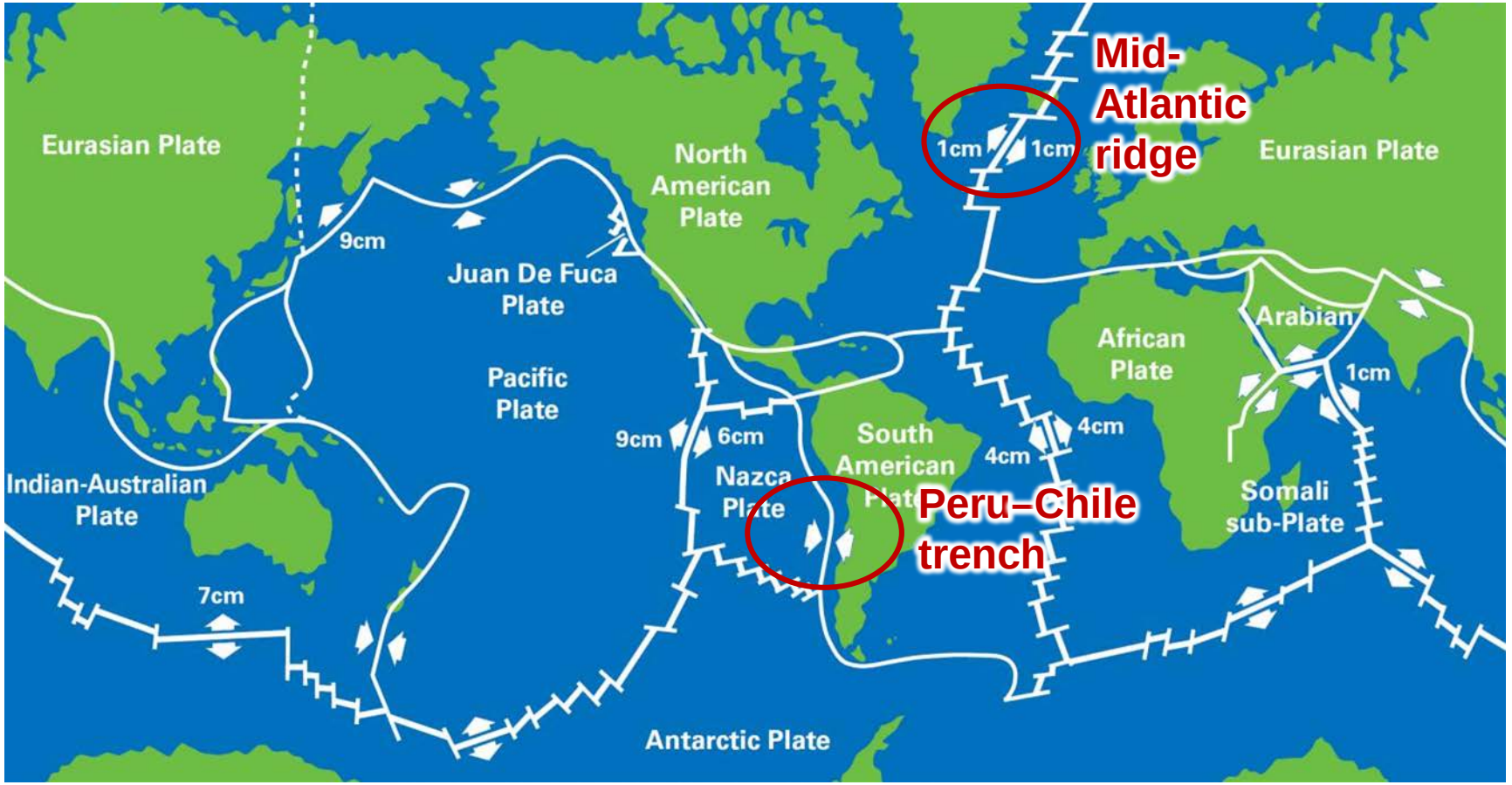
>> *Tectonic plates movement and "Natural" earthquakes*

⇨ ⇦ Convergent plates come together



>> Oceanic plate is forced underneath the continental plate (subduction)

>> Produces most of the strong deep earthquakes (M > 6.0).



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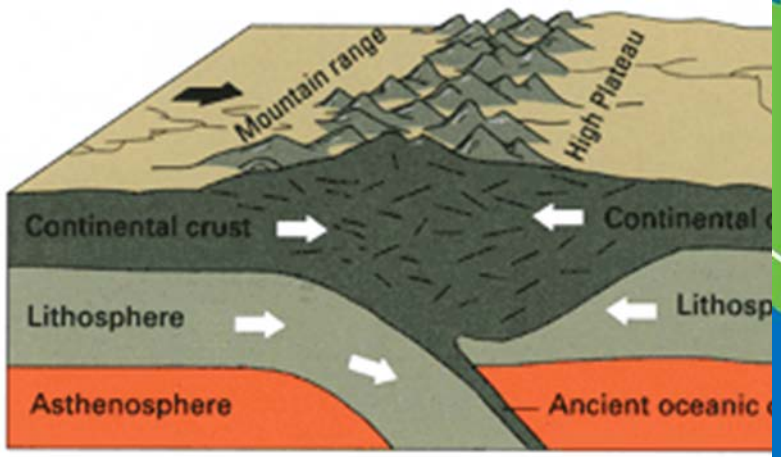
>> *Tectonic plates movement and "Natural" earthquakes*

⇨ ⇦ Convergent
plates come together



© USGS Continental-continental converg

>> Boundary btw continental plates is a zone of collision

>> Dynamic involved in the formation of high mountains (e.g. Himalayas and the Tibetan Plateau)

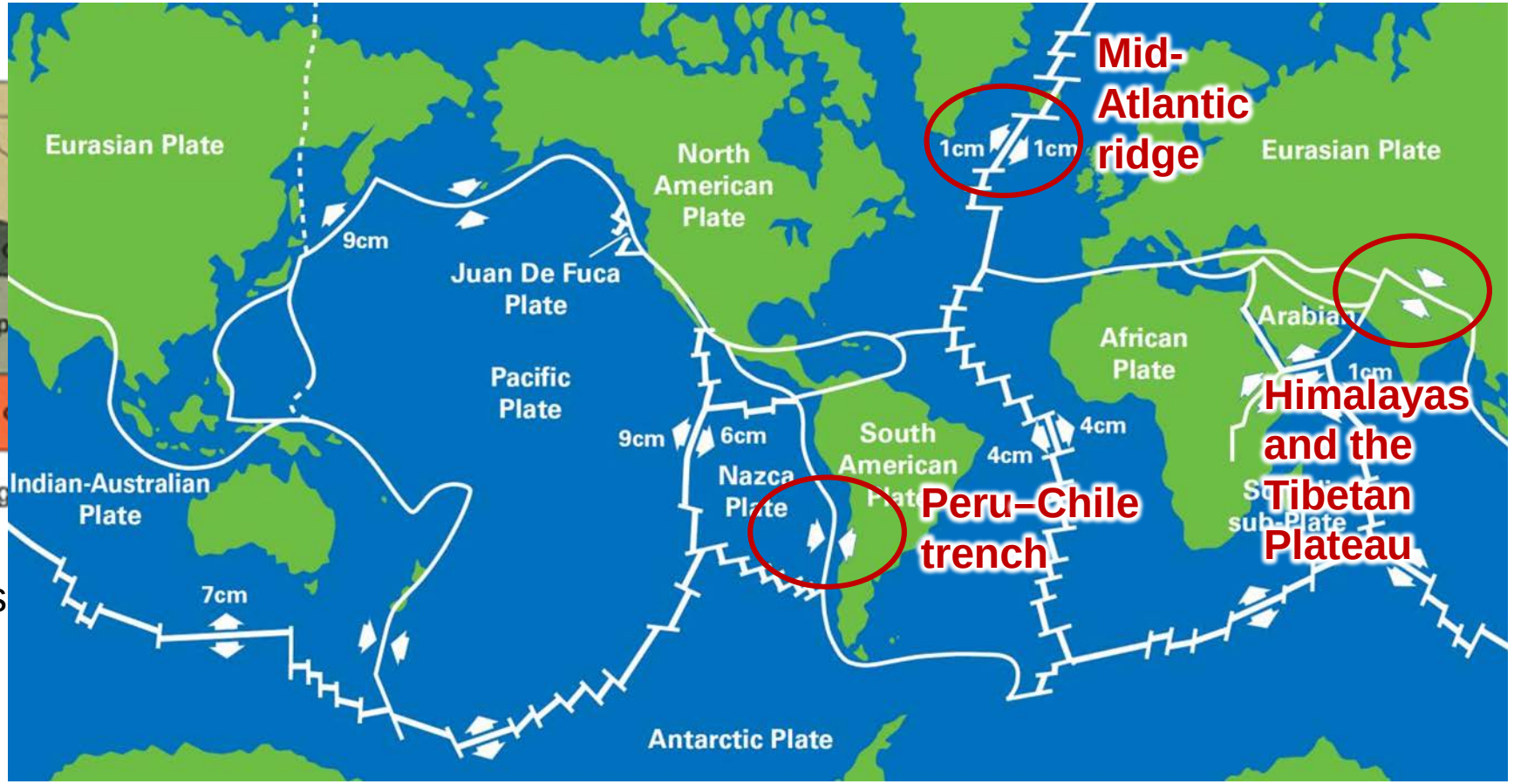
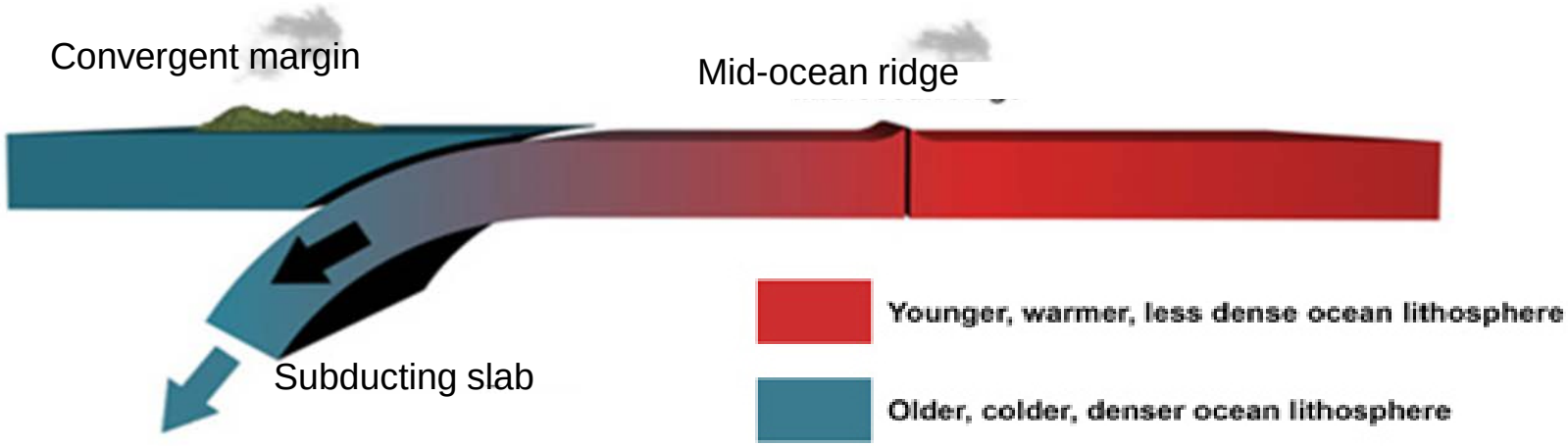


Plate tectonic map of the world showing direction of movement. **BGS ©UKRI.**

>> *Tectonic plates movement and "Natural" earthquakes*

- What drives the movement of tectonic plates?
- Subduction is the major driving mechanism: the **slab pull** theory



after **BGS © UKRI**

1. At the convergent margin, the ocean lithosphere is denser than the underlying mantle

2. Colder plates **sink** at subduction zones.

3. The sinking plate **pulls** the rest of the warmer plate

>> *Tectonic plates movement and "Natural" earthquakes*

Transform
plates shear

>> Movement, but no loss or creation of material.

>> Transform boundaries typically produce large, shallow-focus earthquakes

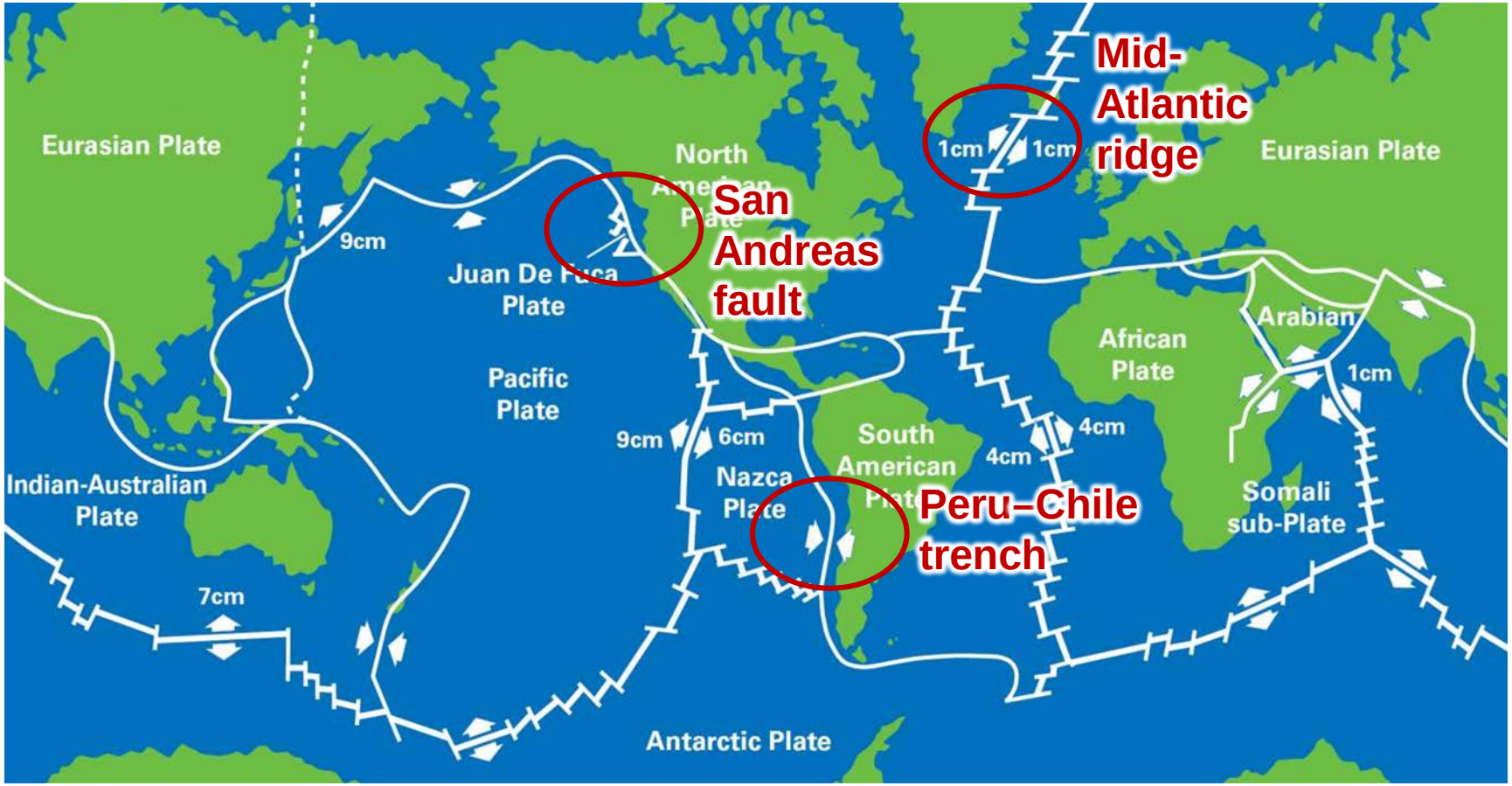
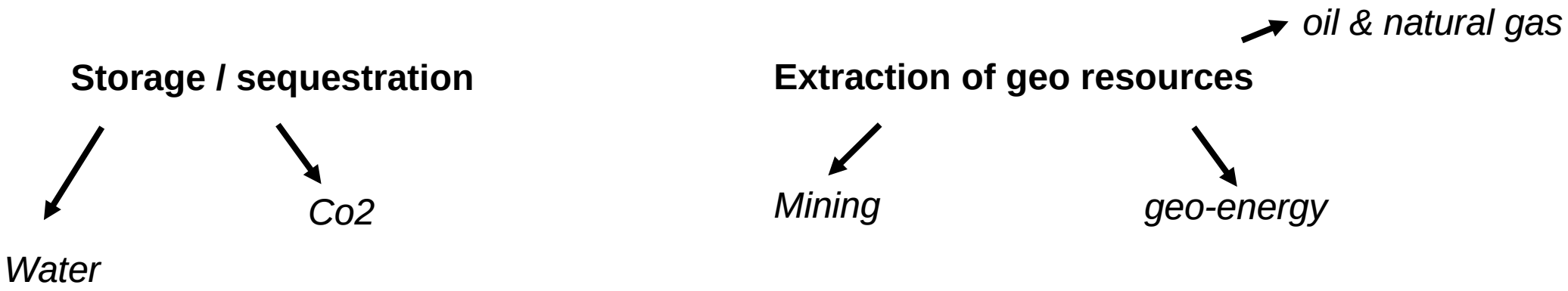


Plate tectonic map of the world showing direction of movement. **BGS ©UKRI.**

- Seismic activity "***directly or indirectly caused by any industrial activity that alters the stress state within the Earth's crust***"
- Induced seismicity is one major societal impact of the exploitation of geo-resources…

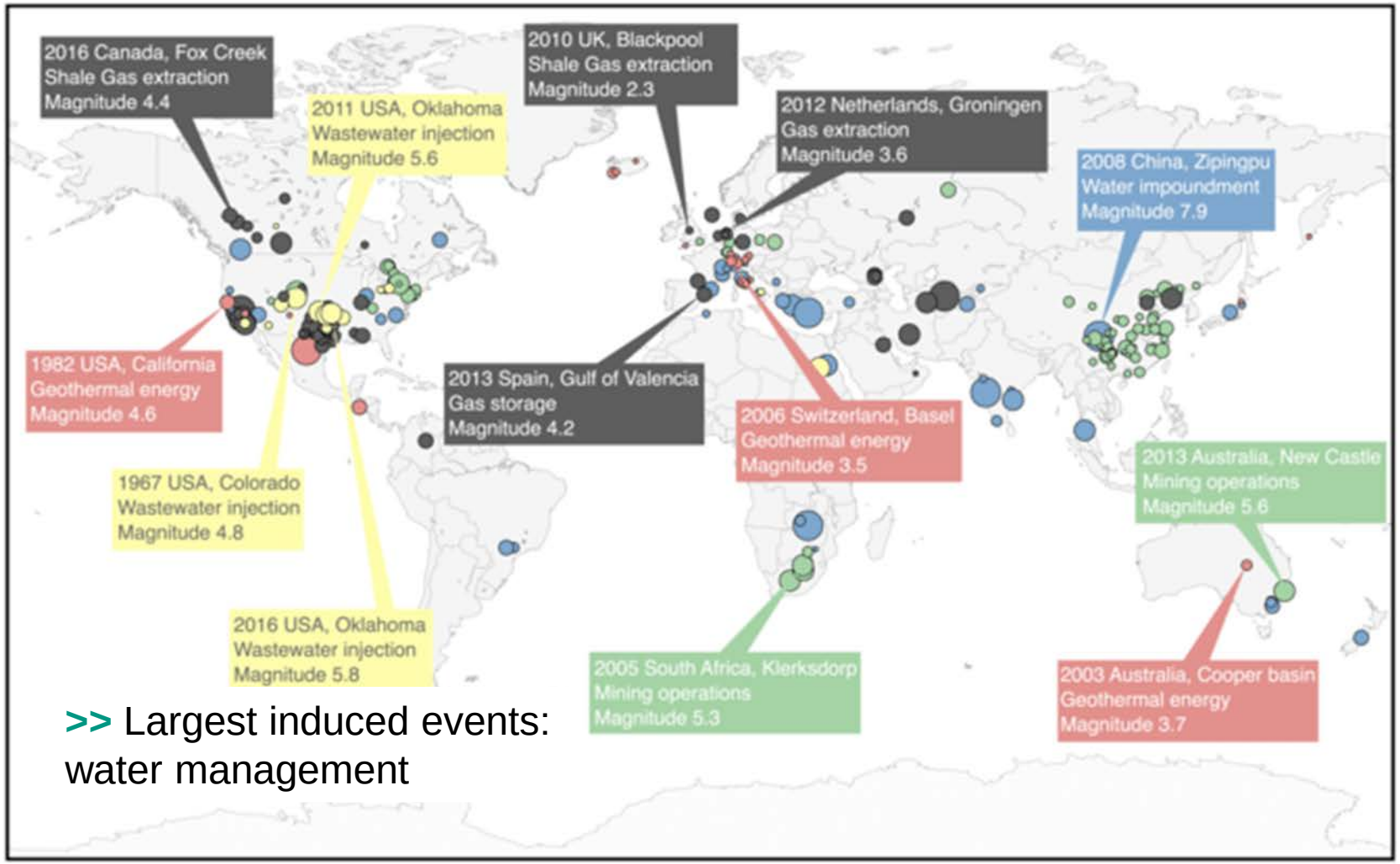
What type of industrial activities you think cause induced seismicity?



>> *Some facts about major cases of "induced" seismic activity*

Distribution of documented cases (→08/2016)

>> Globally distributed over the globe



>> Largest induced events: water management

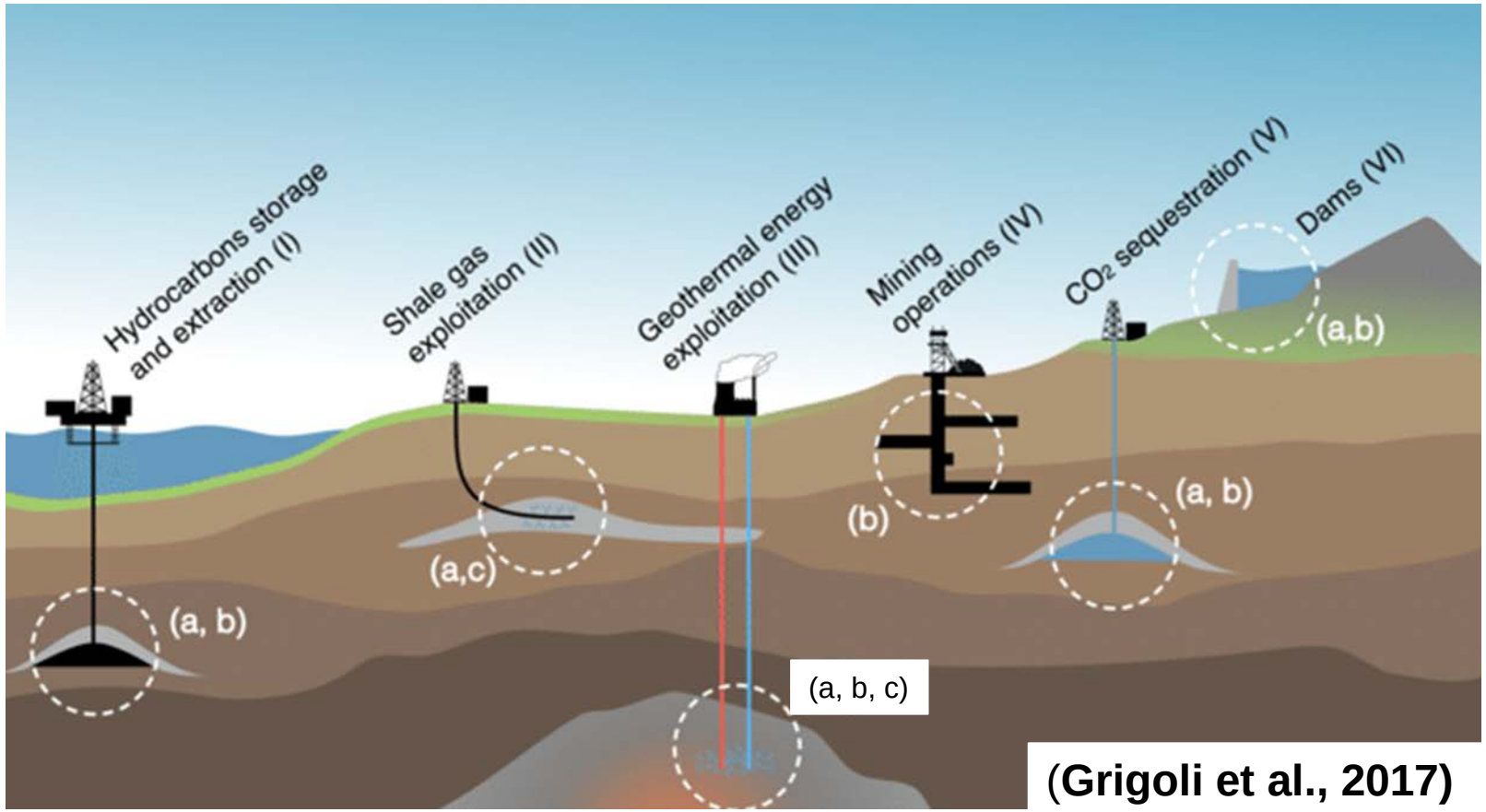
>> First observations connected to coal mining (US - ~1900)

>> But, received public attention beginning of the 21st century (waste-water disposal)

>> Largest number of events associated with mining operations

after **Grigoli et al. (2017)**

>> *What are the driving mechanism?*



(**Grigoli et al., 2017**)

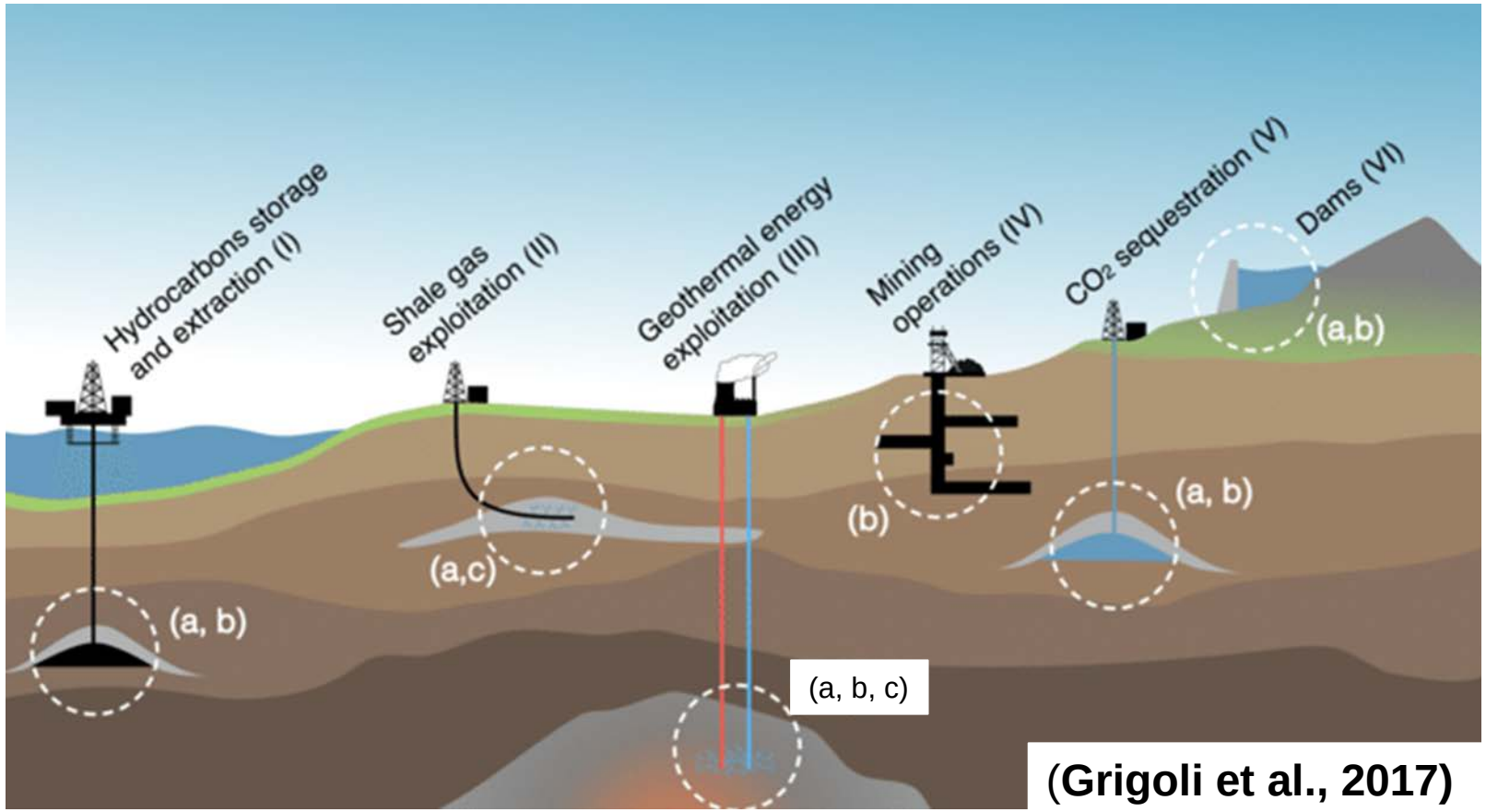
Operations associated with these industries

>> May alter the forces acting on rock masses near faults,

>> May alter the **stress-state** prevailing in the subsurface

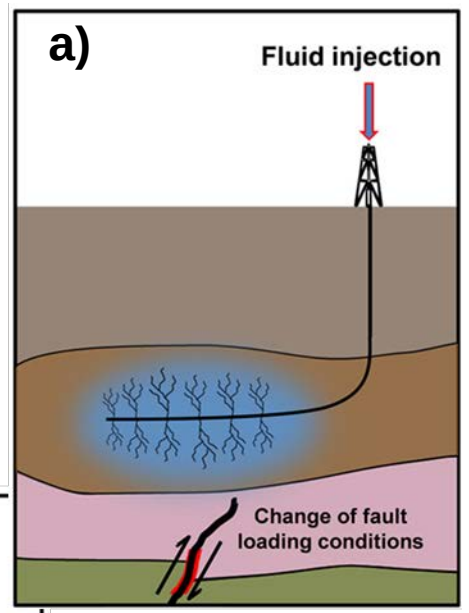
(Stress = a measure of the resistance opposed by a body when subject to forces)

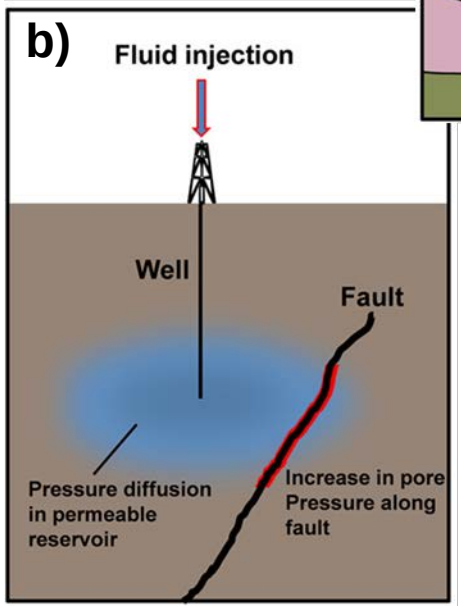
>> *What are the driving mechanism?*



(**Grigoli et al., 2017**)

>> **Volume** and/or **mass** changes
>> Change the loading conditions



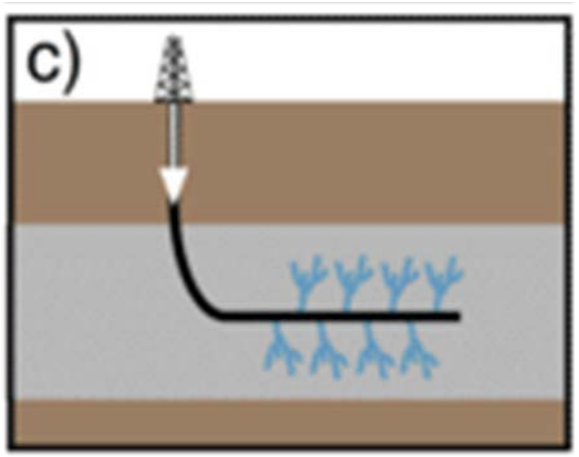


>> **Pore-pressure** changes due to progressive diffusion of fluids

Operations associated with these industries

- may alter the **stress-state** prevailing in the subsurface
- occasionally cause low magnitude events (micro-seismicity, M<2)

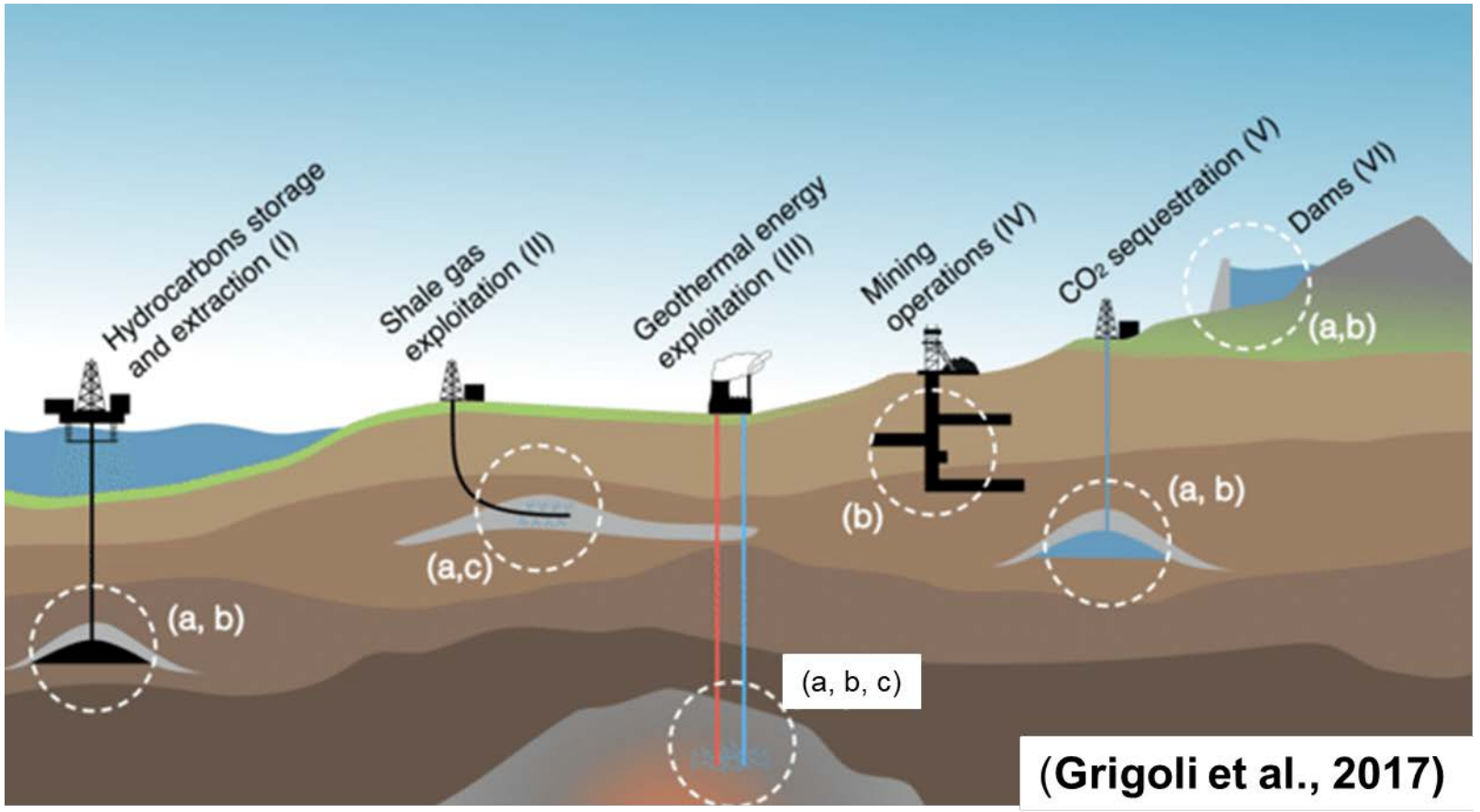
>> *What are the driving mechanism?*



>> Target: naturally-fractured rock that does not sufficiently transmit fluids (not **permeable** enough)

>> Goal: to enhance the ability of fluid to flow, by reactivating the fault systems.

>> How: injection of high-pressure fluid



Enhanced **G**eothermal **S**ystems: EGS technologies aim to create more flow paths

What type of Geothermal TechnologieS to exploit geothermal energy?

>> Distinction according to operation depth (temperature of geothermal resource)

Deep / high temperature

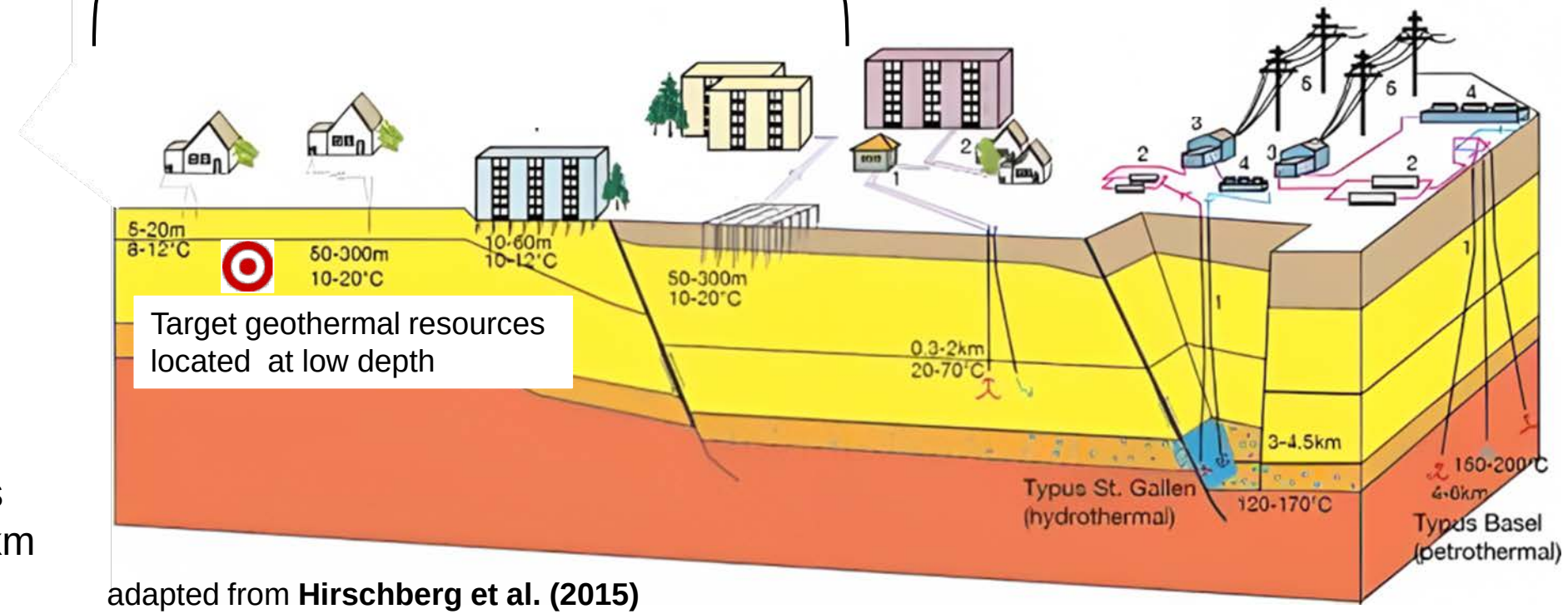
enough "energy" to supply districts with hot water, or produce electricity from a turbine → target deeper zones

Shallow / low temperature

Temperature

Z

temperature rises about 25–30 °C/km



adapted from **Hirschberg et al. (2015)**

What type of Geothermal TechnologieS to exploit geothermal energy?

>> Distinction according to operation depth (temperature of geothermal resource)

>> Targeted rock (permeability)

Deep / high temperature

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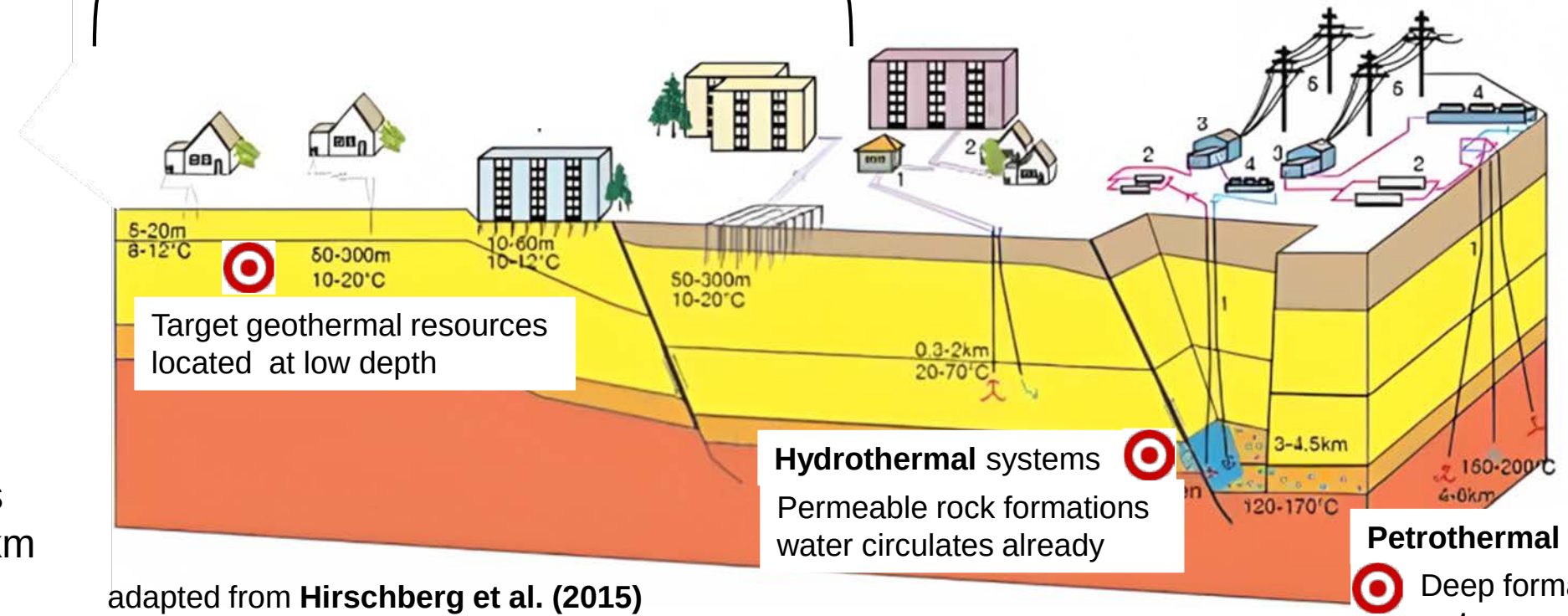
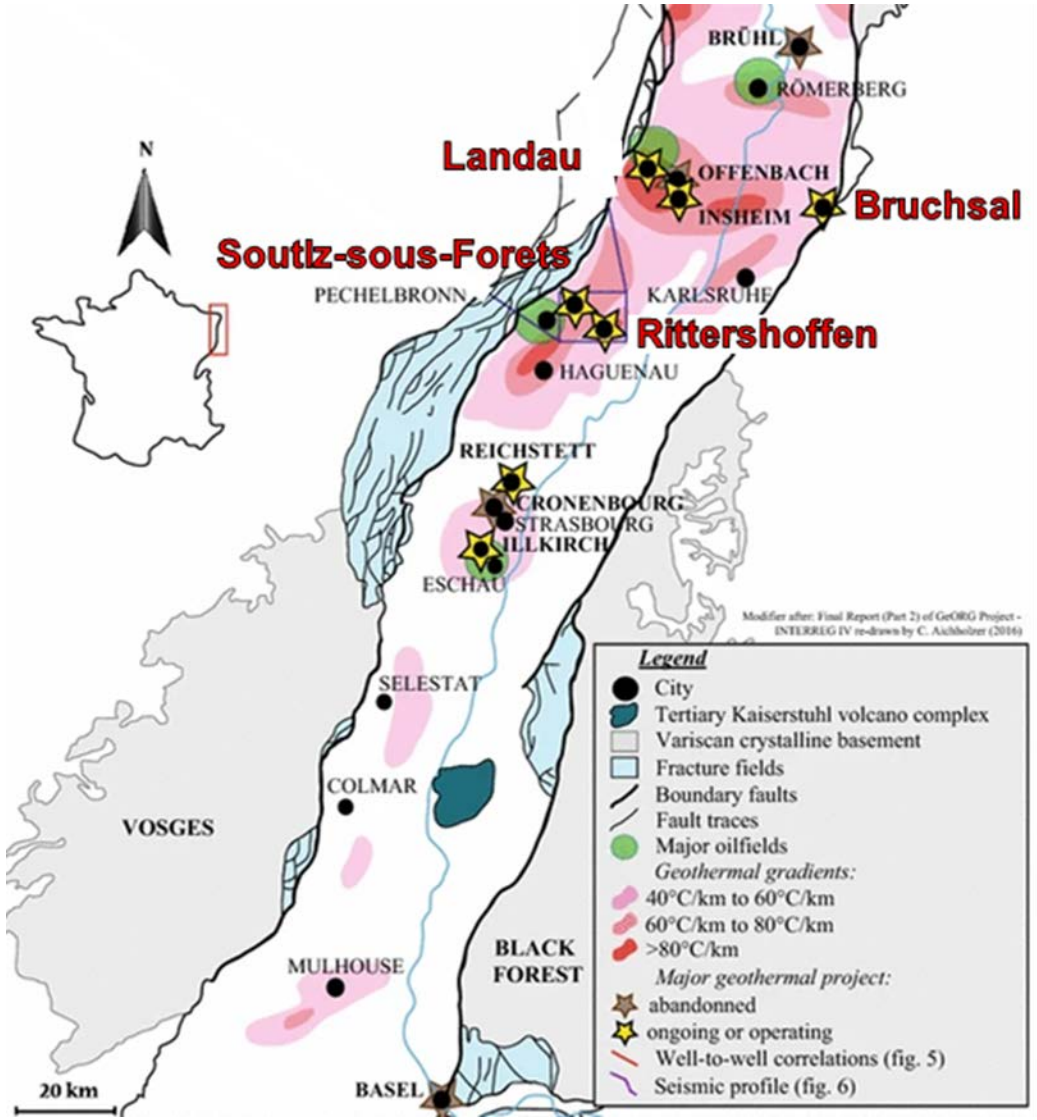


adapted from **Hirschberg et al. (2015)**

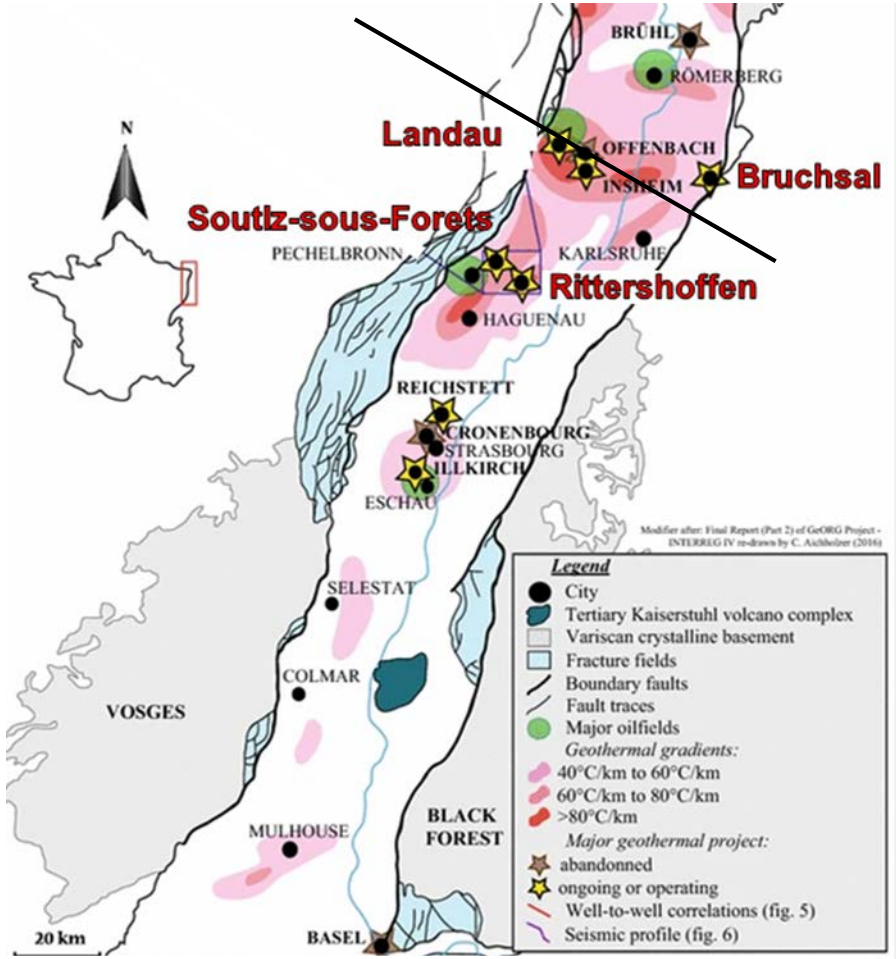
>> *Different types of Geothermal Systems / Reservoirs **in our region (along the Rhine)***



>> A geological specificity (Rhine Graben) which implies that temperature rises more significantly with depth.

>> Leading to the development of the geothermal industry in recent in our region (Soultz-sous-Forets, Rittershoffen, Bruchsal etc.)

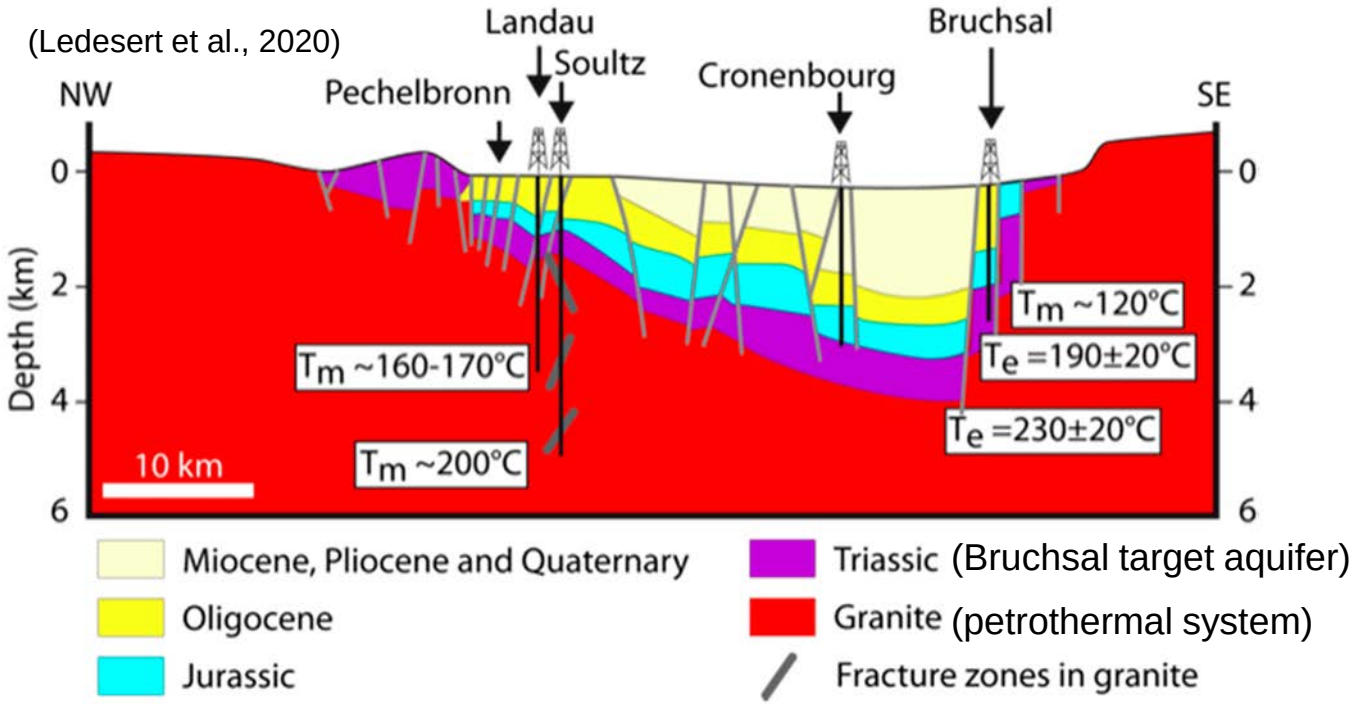
>> *Different types of Geothermal Systems / Reservoirs **in our region (along the Rhine)***



↑ Development of geothermal energy industry in Rhine Grabben region with geothermal anomalies (Aichholzer et al., 2016)

↓ Cut through (cross-section) and target reservoir in Bruchsal and Soultz

(Ledesert et al., 2020)



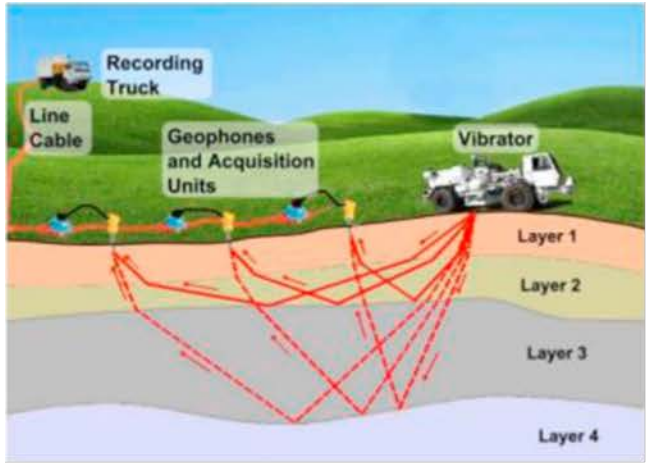
Different geothermal technologies / operated systems

>> Hydrothermal systems (**Bruchsal**): operating existing permeable aquifers to pump the water flowing / heated up (no further enhancement of the system)

>> Petrothermal systems (**Soultz, Rittershoffen**): fractured rock mass, but requires reactivation of the fault systems before operation (EGS technologies)

What are the tasks of seismologists in the field of deep geothermal energy?

During exploration

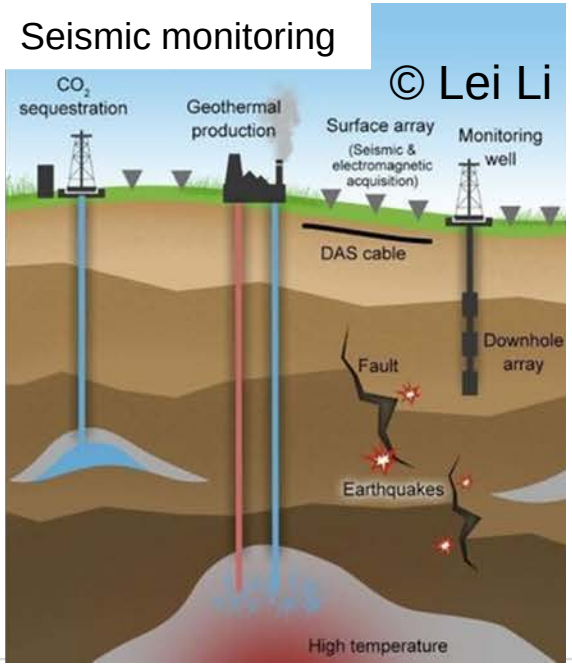


Seismic reflection to characterize subsurface © Janvier Domra Kana

During development

During exploitation

Seismic monitoring



>> *During development: EGS and reservoir stimulation*

- **EGS** project development: reservoir stimulation, which is subject to seismic activity due to fault reactivation (usually, M<2): **micro-seismic activity**

- Seismic measurements make it possible to get an insight into the physical processes occurring at depth

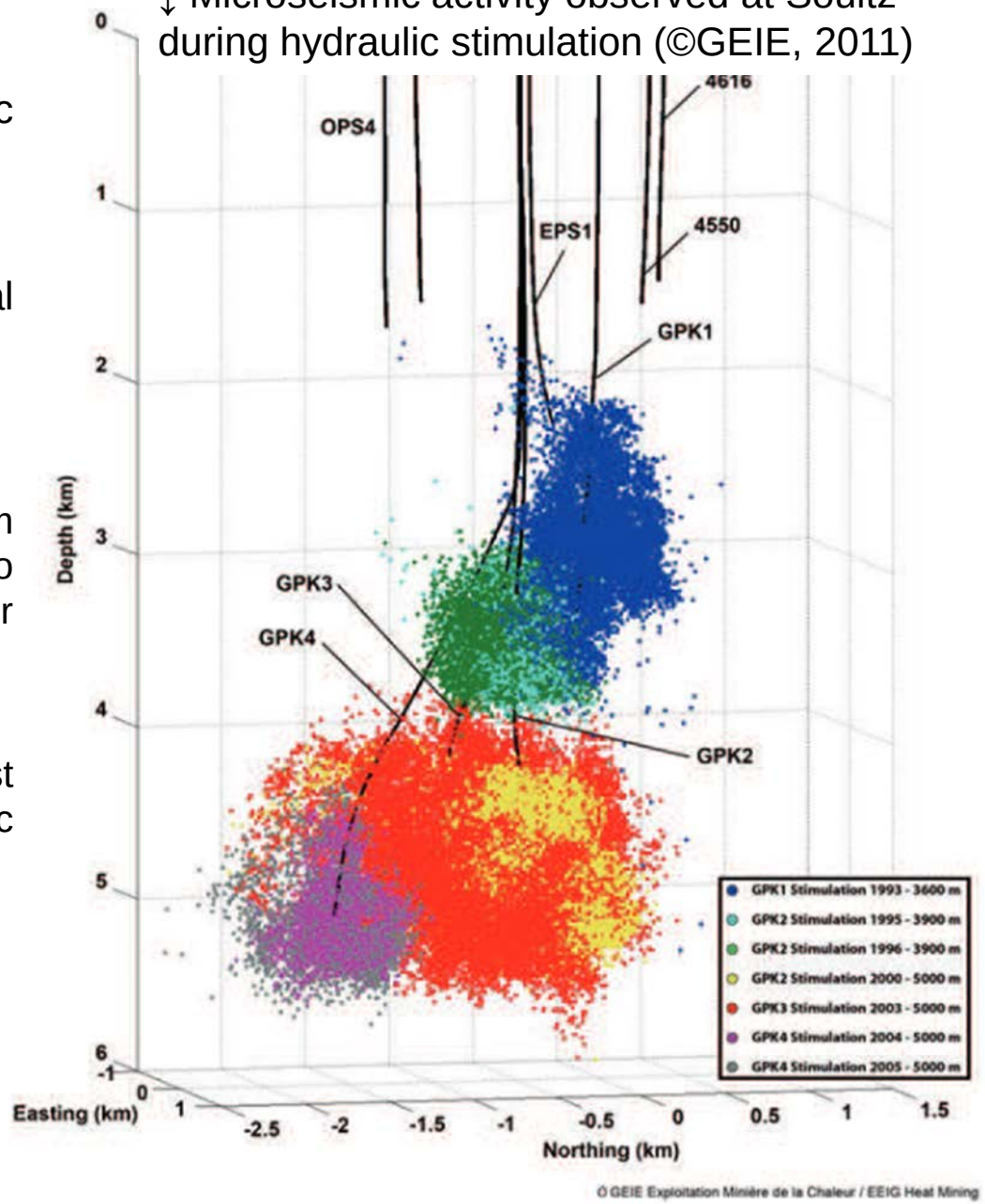
>> Reservoir Characterization

Analysis of spatial distribution of micro-seismic events / associated mechanism offer information about the geometry of the stimulated zone, provide insights into mechanical properties, stress distribution, and the presence of faults or fractures.

>> Optimization of operations

Real-time observation of microseismic events enables operators to adjust stimulation parameters, such as injection rate and pressure, and avoid seismic events that might be felt at surface..

↓ Microseismic activity observed at Soultz during hydraulic stimulation (©GEIE, 2011)



>> *During operation: risk mitigation and reservoir monitoring*

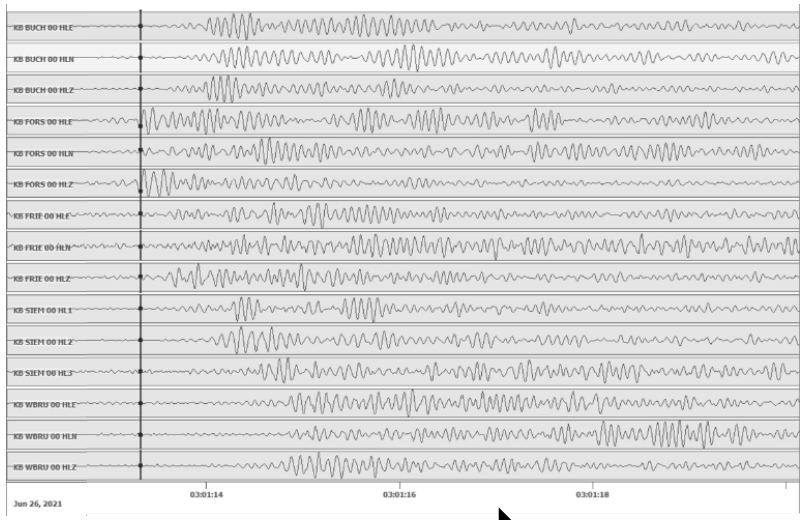
Induced seismicity is one societal impact of geothermal energy industry with significant public concern.

>> Need to minimize possible risks: operations may trigger micro-seismic events, but needs regulation as a result

>> How to manage this hazard?

>> Monitoring seismicity, in real-time, by a third-party

Acquire seismic data (seismic network)

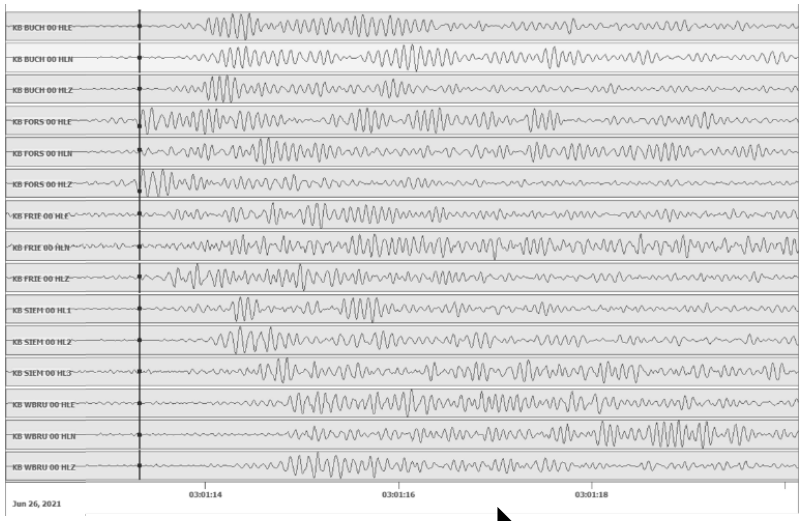


Detect and process (quasi real time)

Report

Need to raise an alert?

>> *During operation: risk mitigation and reservoir monitoring*



Acquire → Detect and process (quasi real time) → Report → **Need to raise an alert?**

>> A framework to raise alerts: Traffic Light System

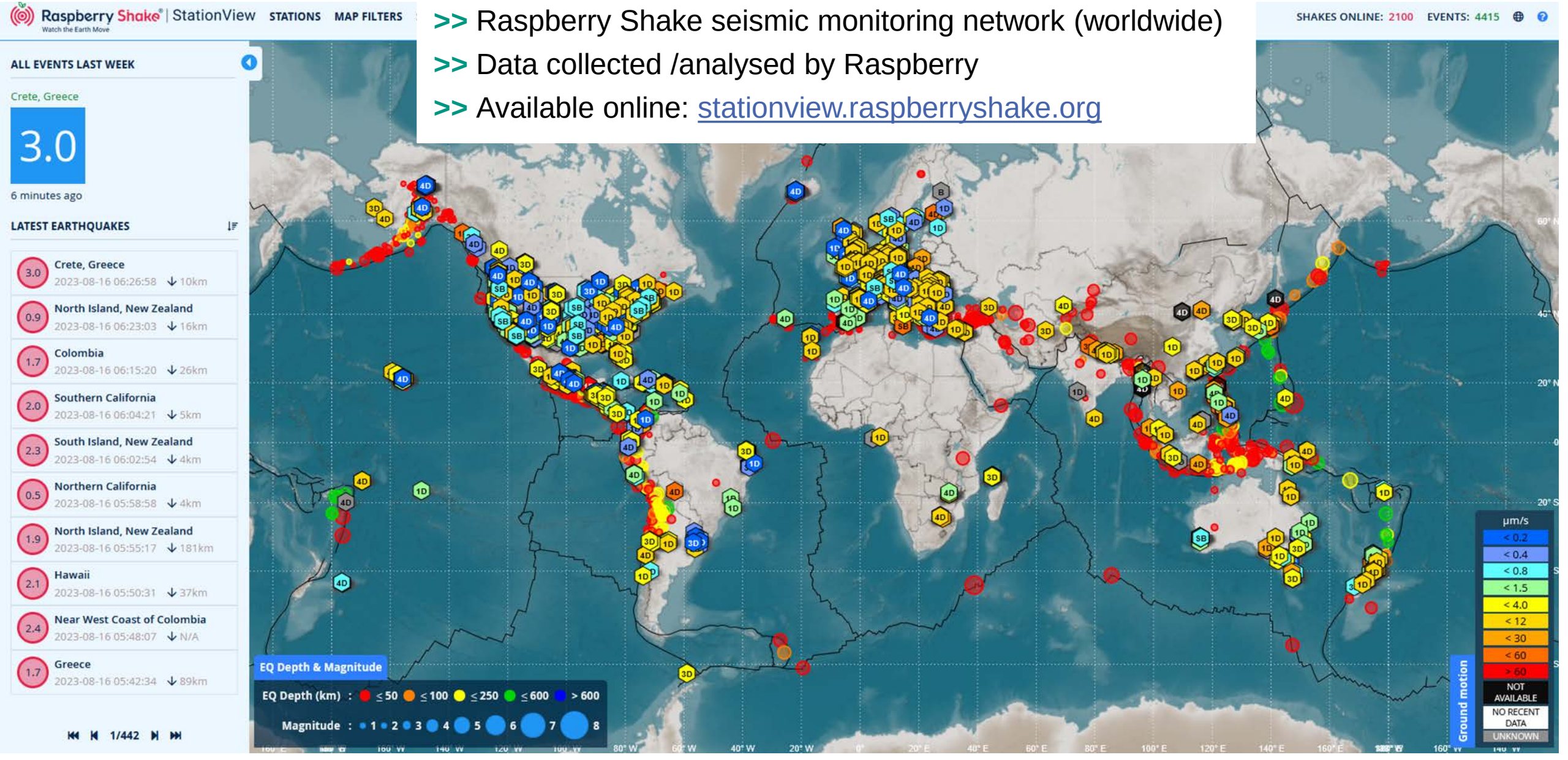
Categories, based on thresholds that apply to earthquake characteristics (magnitude, PGV/PGA), to evaluate and communicate the level of risk, and provide guidance.

>> *Example of seismic monitoring networks*

>> Raspberry Shake seismic monitoring network (worldwide)

>> Data collected /analysed by Raspberry

>> Available online: stationview.raspberryshake.org



>> *Risk mitigation: Surveillance (monitoring) of earthquakes*

>> Latest detected EQ in Baden-Württemberg, Rhineland-Palatinate and neighboring regions

>> Available online: https://erdbeben.led-bw.de/

Baden-Württemberg
REGIERUNGSPRÄSIDIUM FREIBURG
Landesamt für Geologie, Rohstoffe und Bergbau

LGRB

Landeserdbebendienst - Aktuelle Erdbeben

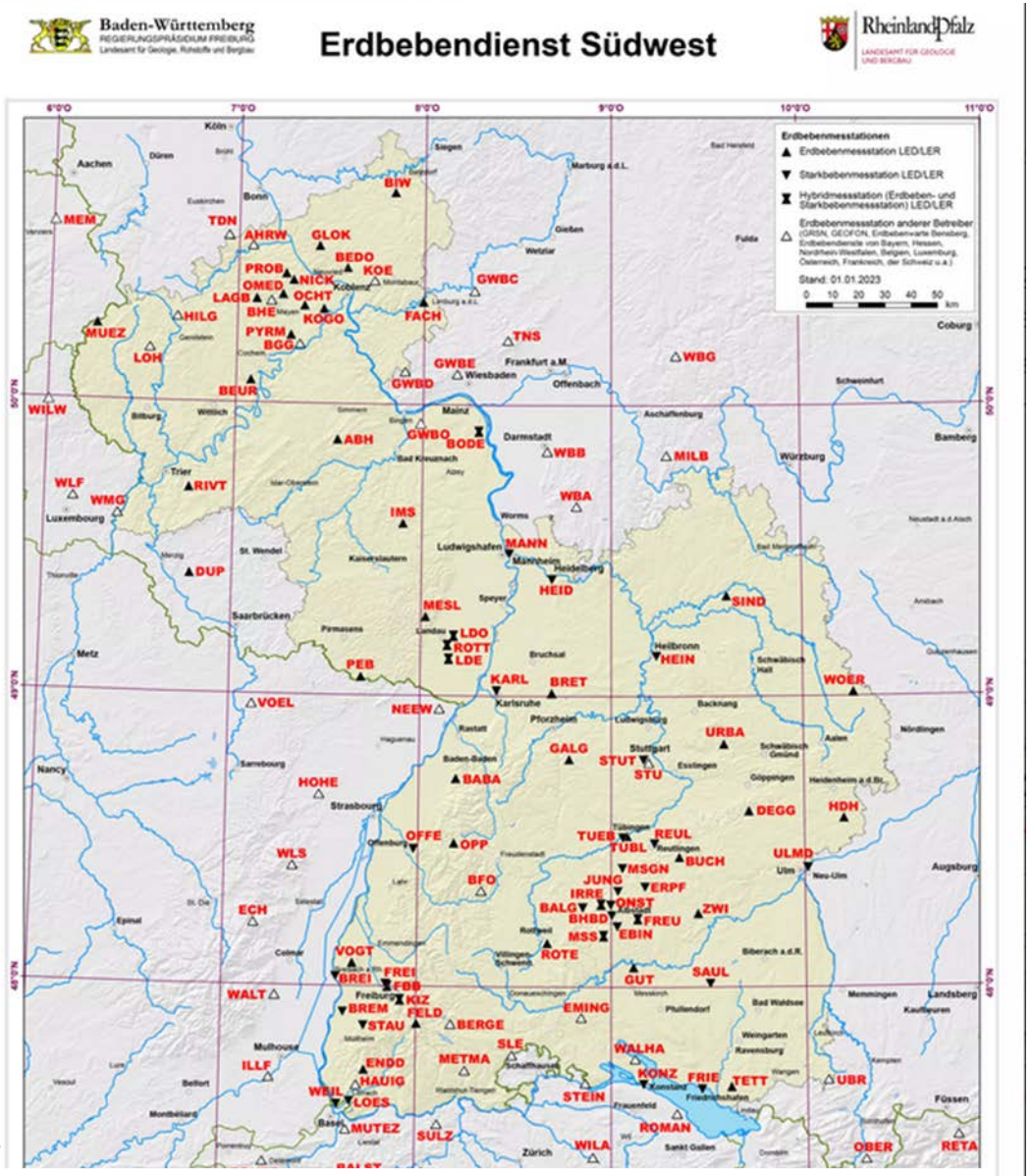
LGRB-Home » Erdbeben » Aktuelle Erdbeben

Baden-Württemberg, Rheinland-Pfalz und benachbarte Regionen

Haben Sie ein Erdbeben gespürt? Bitte teilen Sie es uns hier mit.

10 Einträge anzeigen Suchen

Datum / Uhrzeit	Magnitude	Epizentrum in/bei
18.08.2023 - 05:01	0.8	Wachtberg, Rhein-Sieg-Kreis, NRW
17.08.2023 - 04:10	0.2	Waldorf, Lkrs. Ahrweiler, RP
16.08.2023 - 21:29	0.9	Waldorf, Lkrs. Ahrweiler, RP
15.08.2023 - 14:43	1.0	Wachtberg, Rhein-Sieg-Kreis, NRW
15.08.2023 - 09:44	0.4	Kobern-Gondorf, Lkrs. Mayen-Koblenz, RP
15.08.2023 - 01:27	0.4	Kobern-Gondorf, Lkrs. Mayen-Koblenz, RP
15.08.2023 - 01:25	1.5	Kobern-Gondorf, Lkrs. Mayen-Koblenz, RP



Erdbebenmessstationen des EDSW © LGRB

Phase 1 → location

- By looking at the seismograms from different stations.

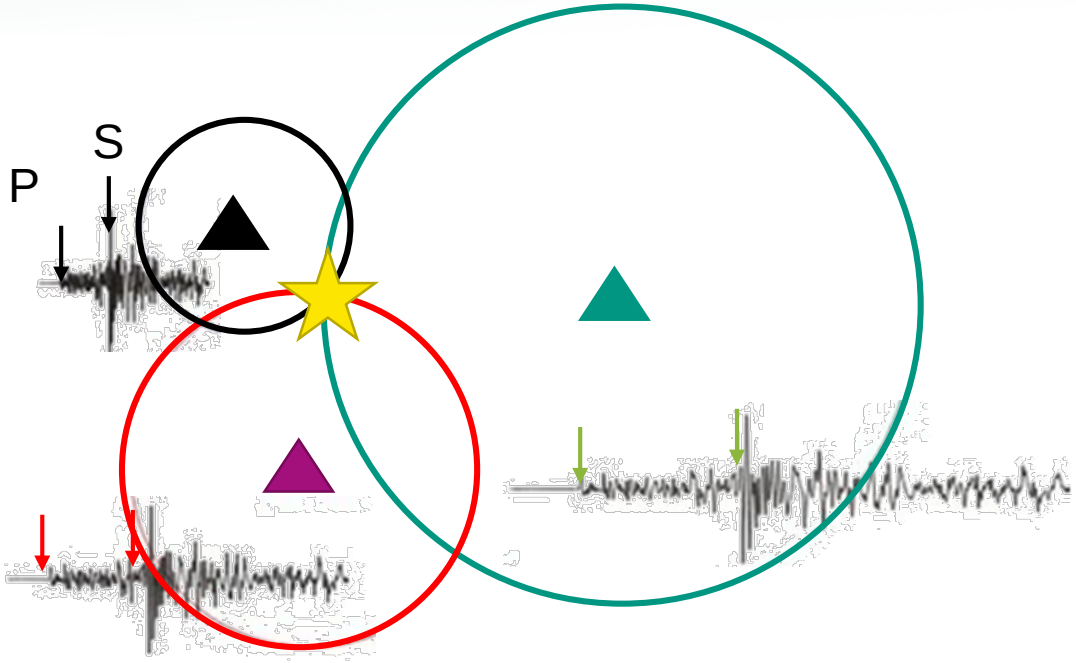
>> closest station first, furthest away last

- Measurement of arrival-times (for P- and S- waves)

>> P- wave arrives before S-wave

>> time difference gives distance to earthquake.

- Three stations are necessary to locate.



>> *How to **characterize** an earthquake?*

Phase 1 → location

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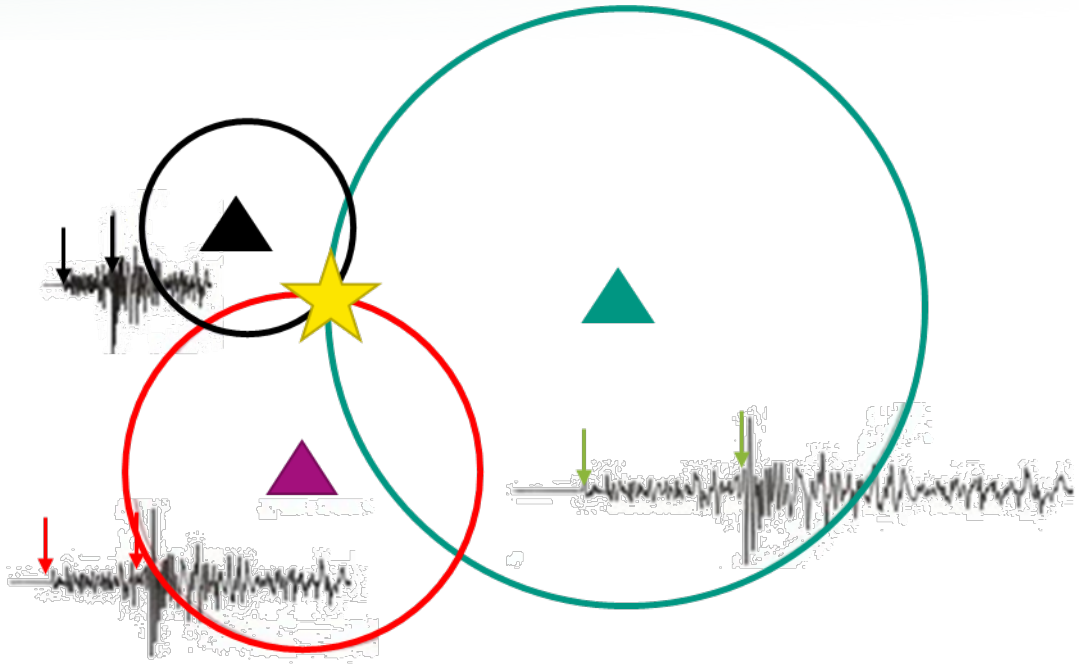
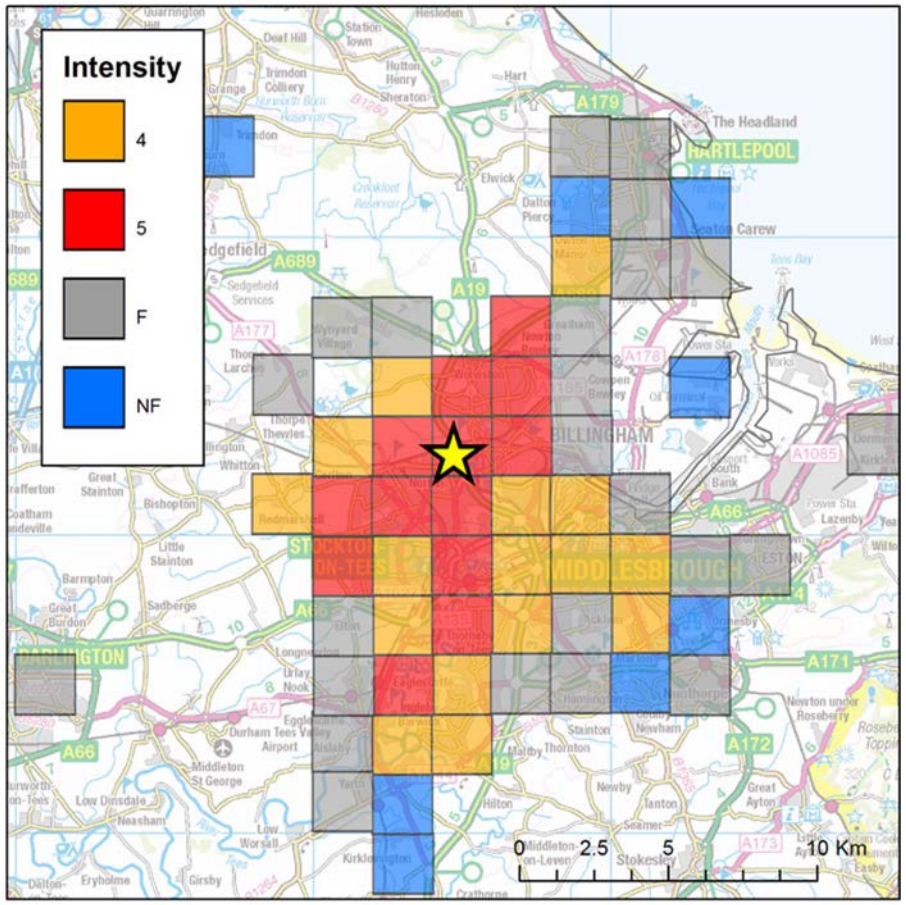


Phase 2 → severity

- Intensity – qualitative measurement of "**strength of shaking**", generally based on observed effects.
- Magnitude – quantitative measurement of "**amount of energy**", based on waveform recordings.

>> *How to **characterize** an earthquake?*

- **Shakemaps (intensity)**



↑ Shakemap (3.1 ML, 23.01.2020, UK) using 840 reports from people who felt the earthquake. **BGS © UKRI**

- **Some facts about EQ magnitude(s)**
  - Scales are non-linear: **+ 1** Magn. unit ≡ Energy x**30**
  - Magnitude 0 does not mean that no energy is released: negative magnitudes are possible

Magnitude	Energy in joules	Notes
-1.0	2000	100 kg person jumps down 2 m
0.0	6.3×10^4	
1.0	2.0×10^6	
2.0	6.3×10^7	Only felt nearby
4.0	6.3×10^{10}	Felt up to tens of km away
5.0	2.0×10^{12}	Energy from 50 000 litres of petrol
6.0	6.3×10^{13}	3.3 Hiroshima-sized A bombs
9.0	2.0×10^{18}	Total annual energy use of UK

>> *How to **characterize** an earthquake?*

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- Reported magnitude can change as more data gets analyzed. In Sumatra (24 Dec 2004), the original magnitude of Mw 9.0 was recalculated to Mw 9.3.
- Highest magnitude ever recorded: earthquake in 1960 (Valdivia, in Chile) → Mw 9.5
- Multiple magnitude scale**s**

Local ($\mathbf{M_L}$) / Richter magnitude (Charles Richter scale, 1935)
→ empirical scale, developed from observations in south-California
→ rigorously applies only in that region

Moment magnitude ($\mathbf{M_W}$)
→ most standard and reliable measure of energy released.
→ based on seismic **moment,** a measure of the event dynamic.

>> *How to **characterize** an earthquake?*

Waveforms can also be used directly (t- / f-domain)

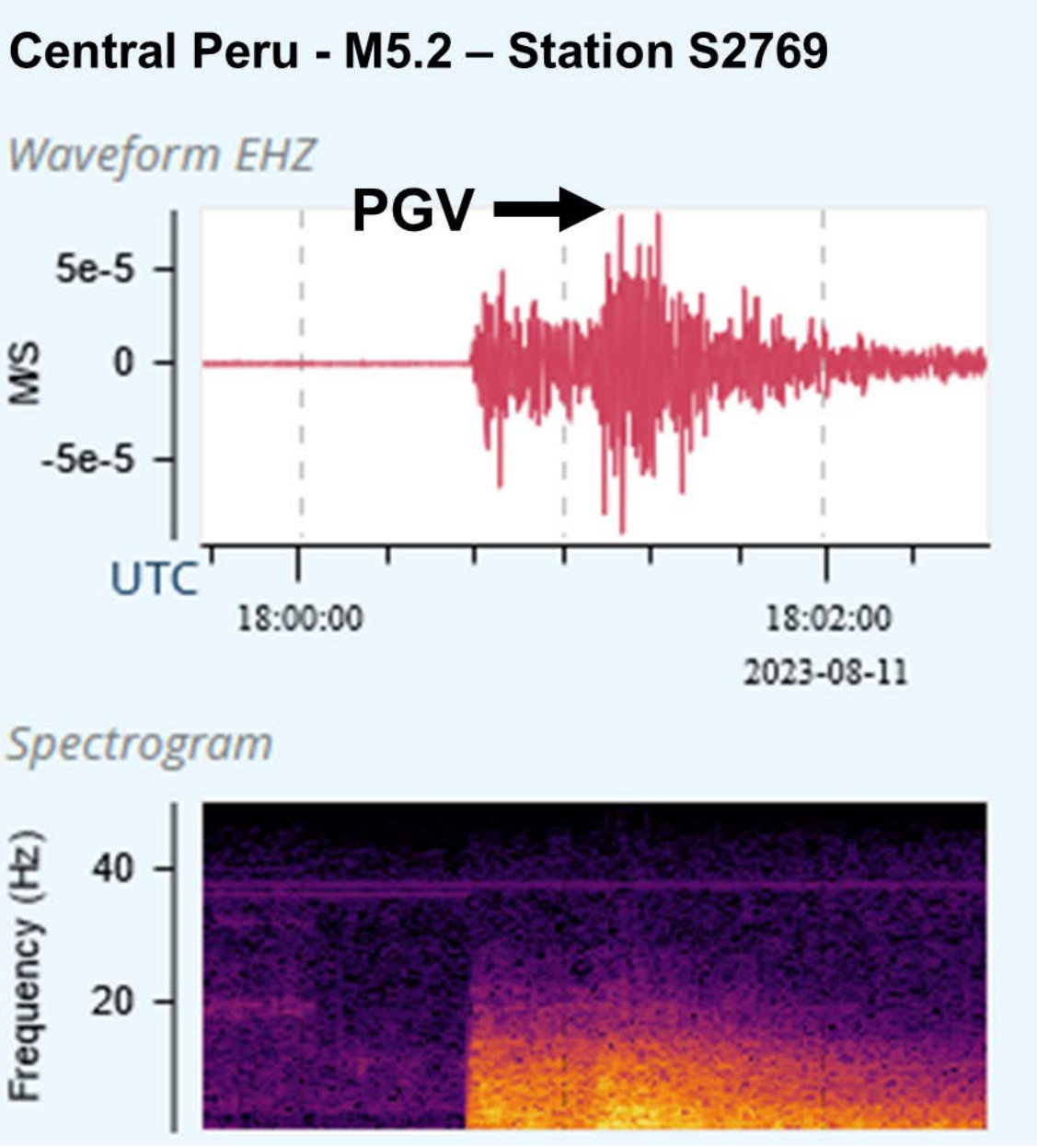
- **Peak ground velocity (PGV)**: measures the maximum velocity of ground motion (TLS)
- **Spectrogram**: P, S, Surface waves generally carry different frequencies

To detected/characterize a seismic event, the **signal** must stand out the **background noise**!

Ok for such a large events…

but what would it be with a station in city centre?

but for microseismic events (M<2)?



>> *Where to **install seismic monitoring stations?***

New seismic station installation requires a evaluation of onsite background noise conditions (aka noise-msts.)

>> that's what we are going to do!

Exple: noise analysis from KIT "BUCH" station, (Munich)

→ Freq. content over time **= Spectrogram**

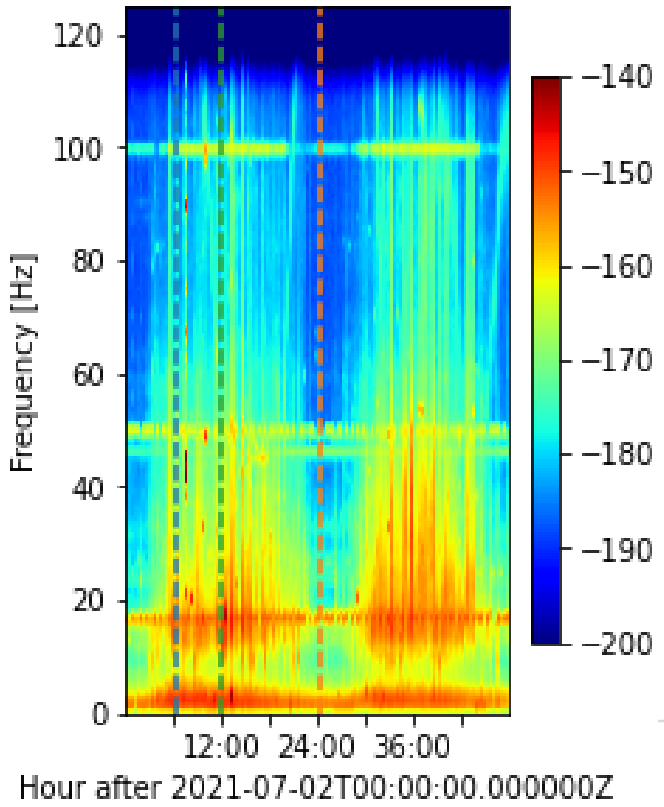
>> High noise = hot color

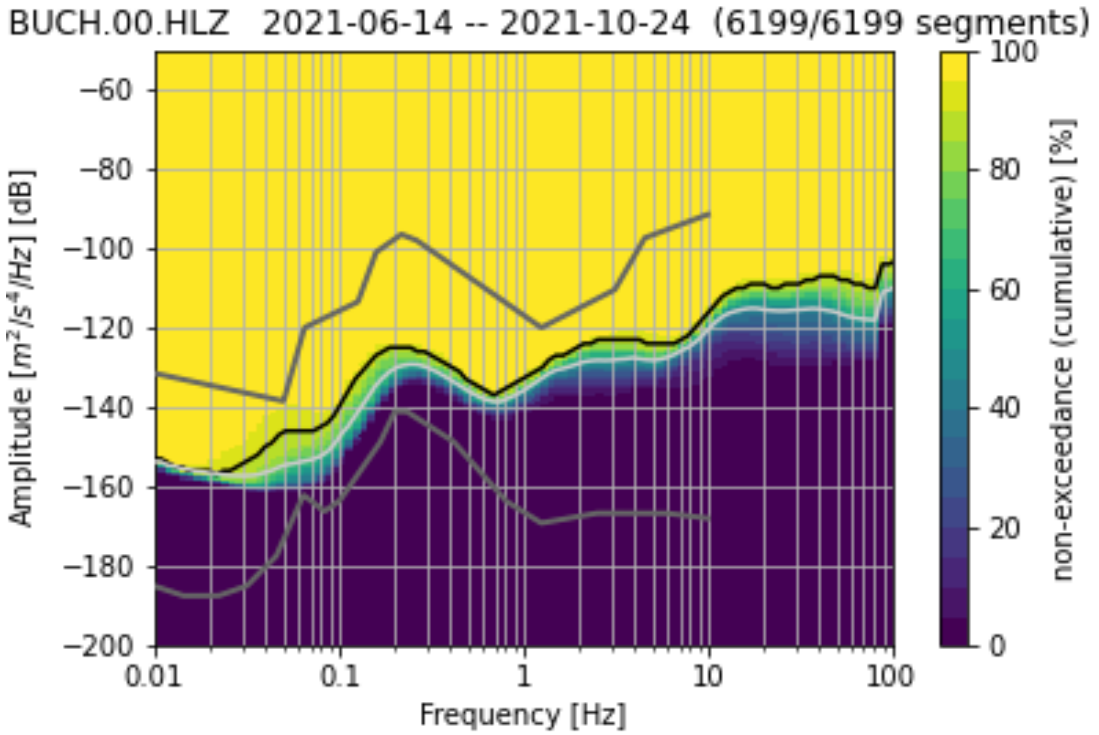
>> Night *vs* day

Impact of human activity

>> Permanent 50 Hz comp

Impact of electrical grid:





↑ Same analysis, repeated in 30 min windows, then resu analysed statistically **= PPSD**

>> for each freq., shows the probability to not exceed a certain level of noise

>> comparison with standard noise levels

Young seismologists in training…

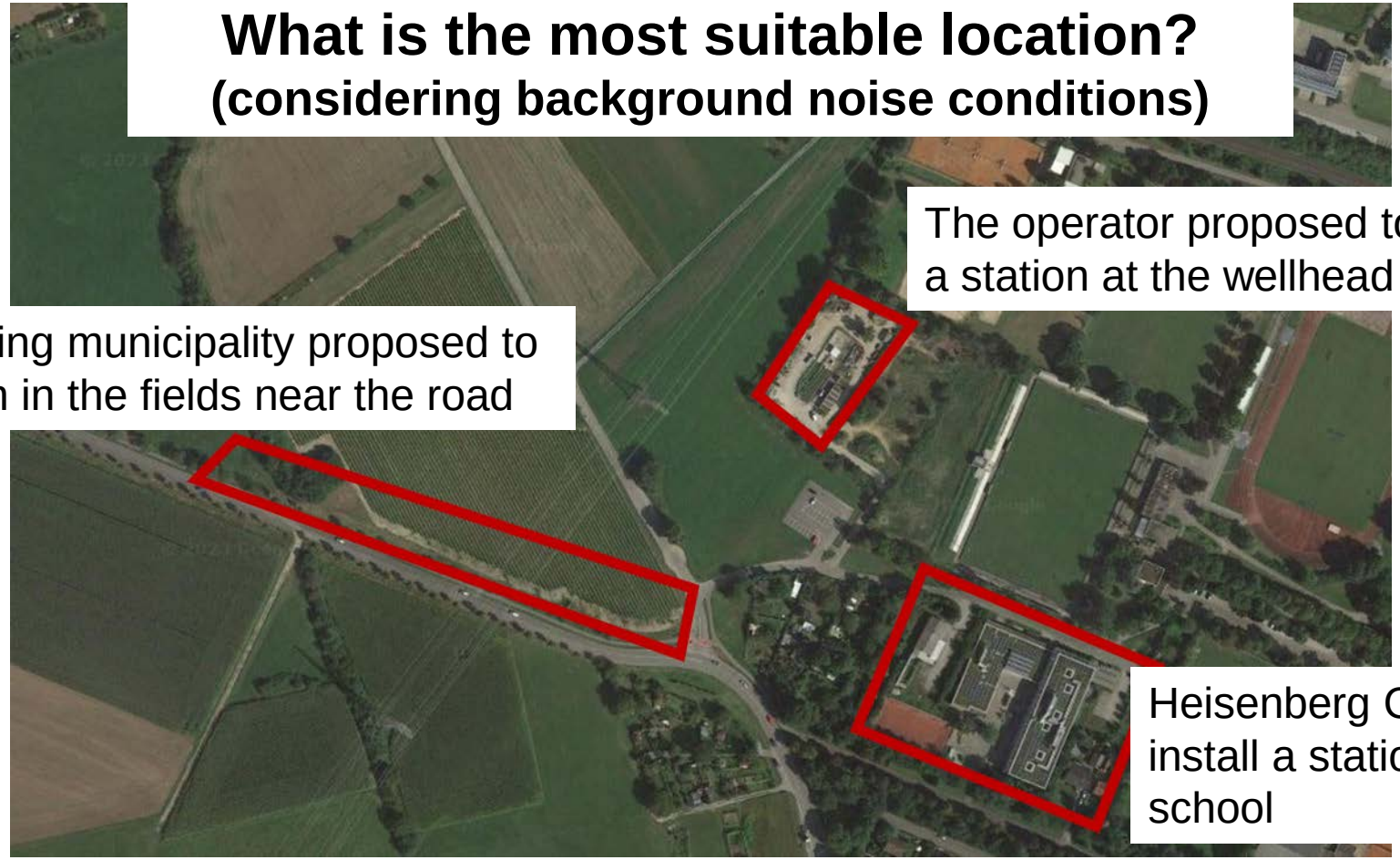
… to install a new seismic station to monitor the Bruchsal geothermal site

>> Back to the role-play game

>> We need a new monitoring station, sensitive to the minute ground vibrations

>> We put out a request for proposals for possible locations

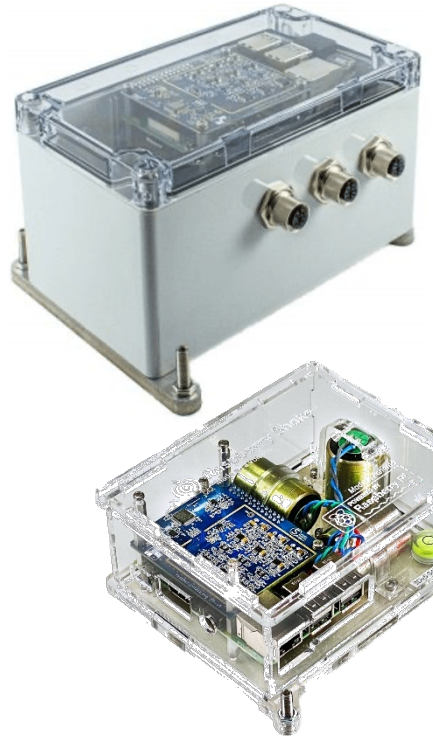
What is the most suitable location?
(considering background noise conditions)



The operator proposed to a station at the wellhead

The surrounding municipality proposed to have a station in the fields near the road

Heisenberg Gymnasium offered to install a station on the land of the school



How to investigate the structure of Earth?

How is the Earth's interior structured?

Direct investigations

- Human exploration:
- Caves: 2.0 km in the Western Caucasus, 2005
- Mines: ~3.5 km in Tau Tona (South Africa), 2002
- Deep wells:
- KTB, Germany (Kontinental Tiefbohr Programm der Bundesrepublik), 9.8 km
- Well “sg3”, Russia, 12.6 km (1970-89)

… but radius of Earth ≈ 6400 km


Kola (Russia) in 2007

Indirect investigations (geophysics)

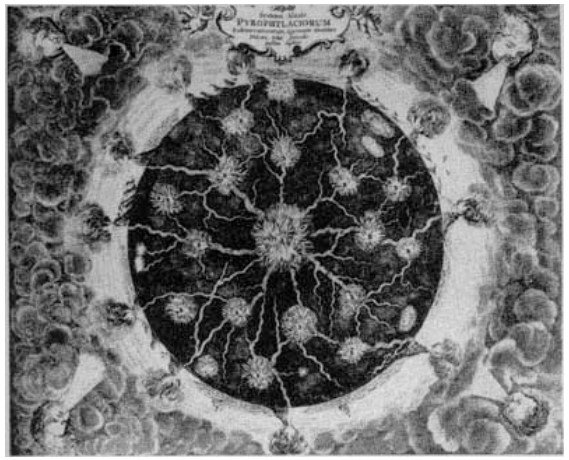
- Seismology: seismic waves propagate in every direction and “**probe” the Earth**.

How to investigate the structure of Earth?

How is the Earth's interior structured?

René Descartes(1596-1650)

A story of the Earth formation. Earth is empty in the middle, the outer layer in an unstable equilibrium. Dried out by the Sun, it cracks and eventually collapses unevenly into the inner layers, expelling the water that forms the oceans. (Wikipedia)

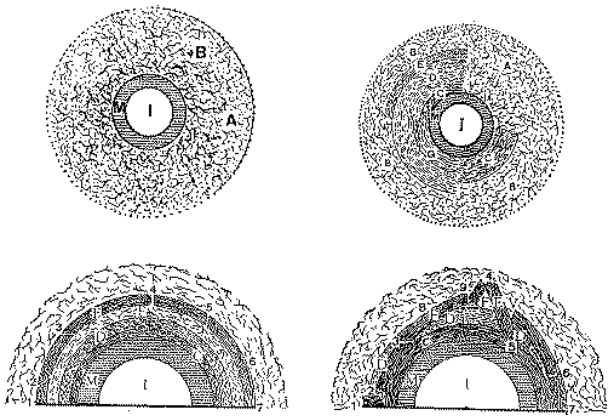


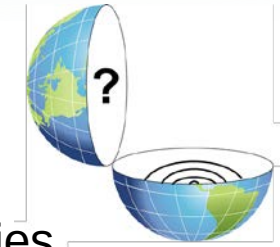
Athanasius Kircher (1602-1680)

The globe is an ancient, cooled Sun. The Earth has an impetuous, central hearth, connected to the volcanoes on the surface by fire conduits with intermediate reserves (Wikipedia)

Aristote (384-322 av. J.-C.)

The Earth is made up of layers of water, air and fire. The surface contains internal cavities and channels. The wind (or inner breath) coming out of the cavities causes earthquakes. When ground into small particles, it catches fire and creates volcanoes. (Wikipedia)





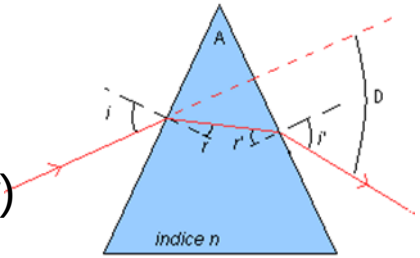
- How to understand the inner-structure of Earth?

>> By analyzing the earthquake recordings over the globe.

>> By inferring the presence of different layers and studying their properties.

- What physical background?

- Analogy with optics: light passing through a prism leads to refraction and reflection (Snell Descartes law)



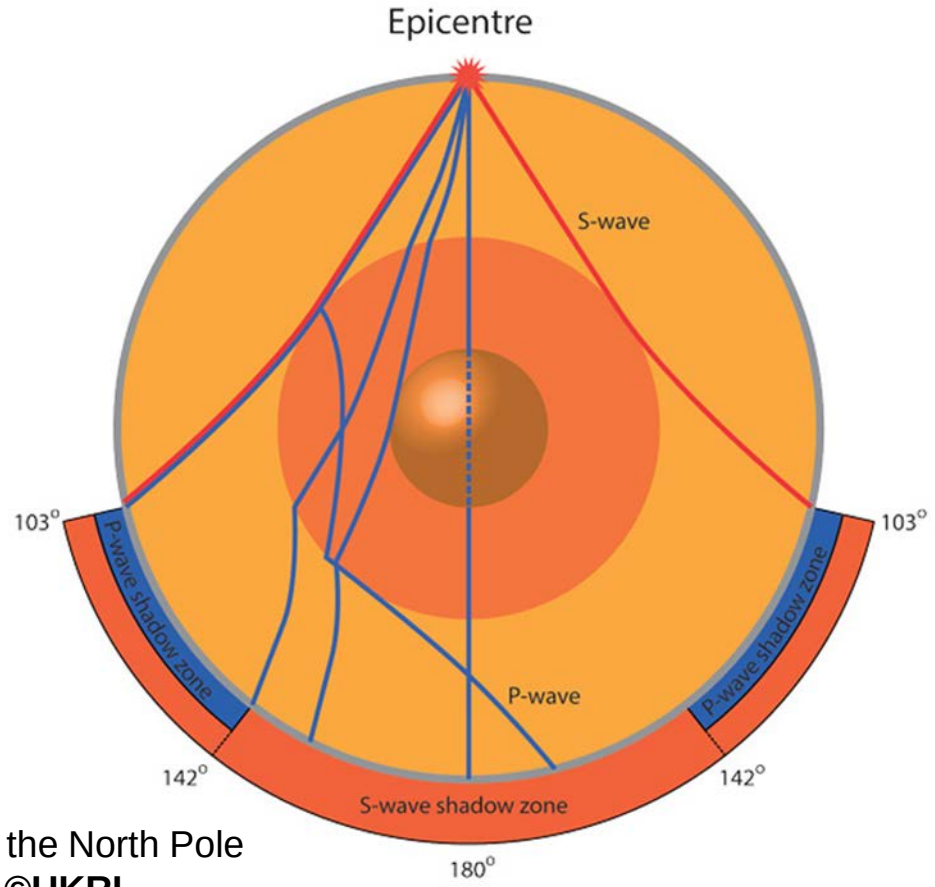
- Propagation velocity depends on density

→ Travel-time measurements from around the globe makes it possible to map **changes in density** and **interfaces** between layers

- The result remains a **model**

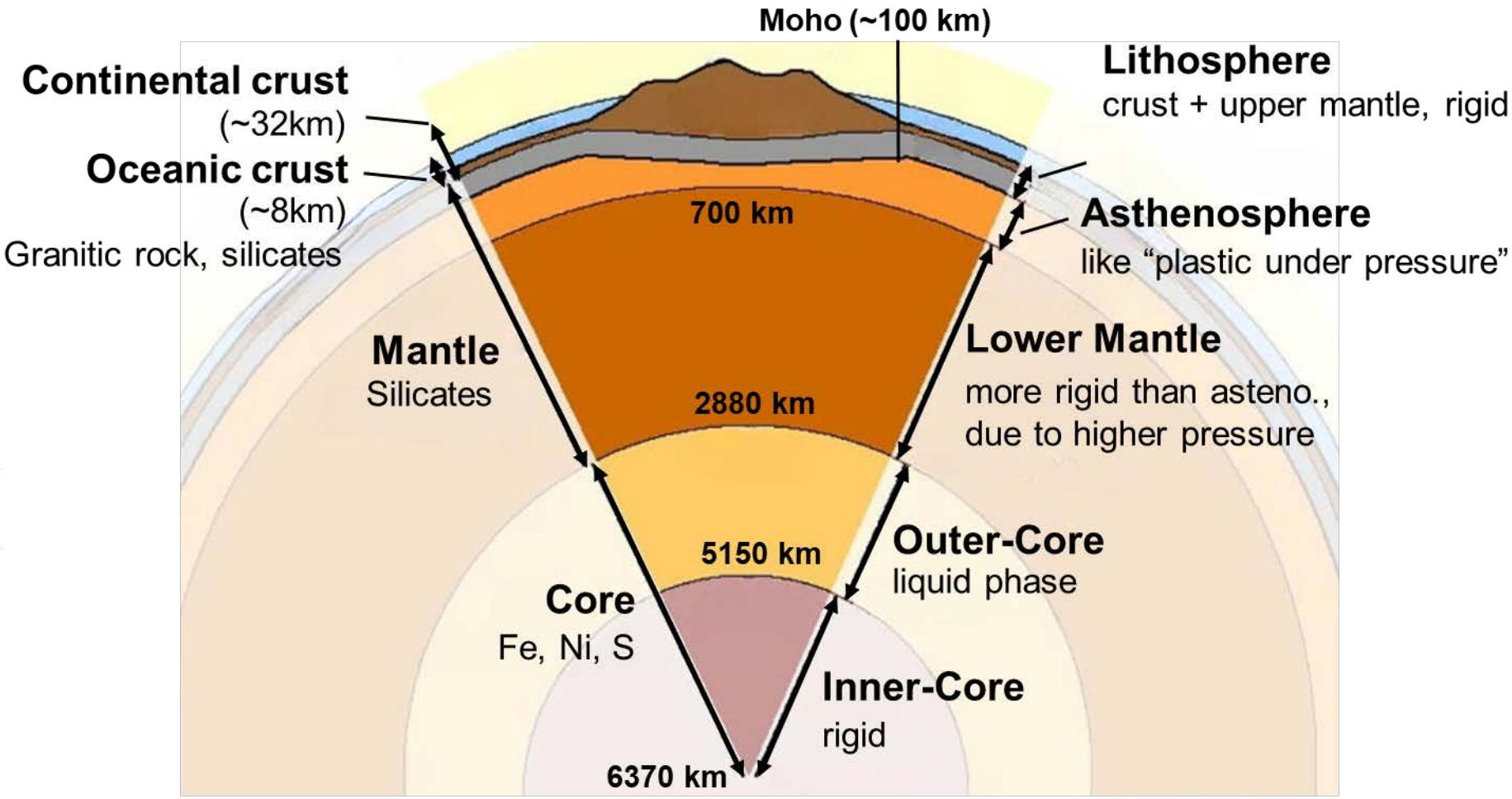
- Earth is a complex (non-homogenous) medium.

- Constantly refined by studied from geophysicists and researchers.



Hypothetical earthquake at the North Pole and related ray paths **BGS ©UKRI**.

- Earthquake travel-times measured around the globe makes it possible to map changes in density and interfaces between layers



- **Plate tectonics**: lithosphere is fragmented in 15 major slabs, or "**tectonic plates**", moving relative to each other (~ few cm / year).

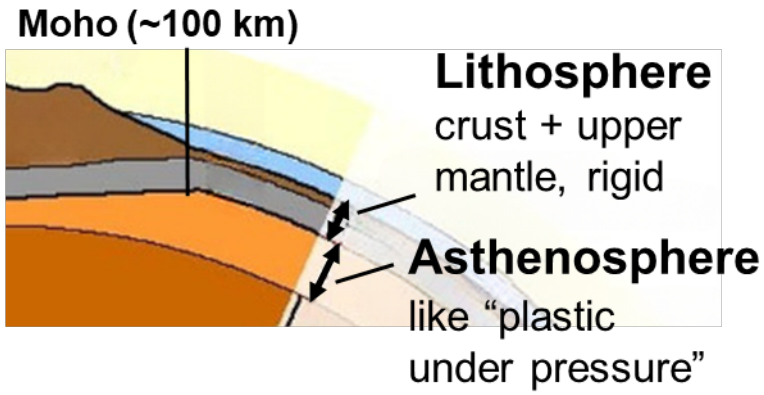


Plate tectonic map of the world showing direction of movement. **BGS ©UKRI.**

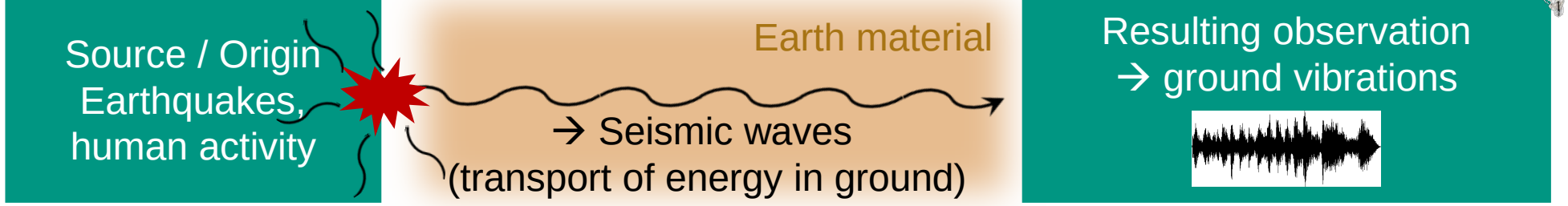
KIT (AGW) – Heisenberg Gymnasium Bruchsal Schulprojekt

Module 2: end of training course + preparation of field work

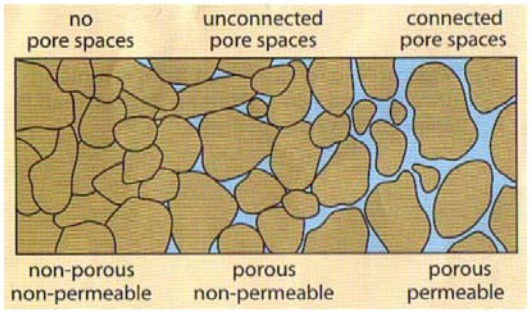
- **September 19 – Module 1: introduction + training course**
- **September 26 – Module 2: preparation of field work**
- September 27 – Module 3: start of measurement campaign at EnBW well site, near a road and at the Heisenberg Gymnasium
- October 04 – Module 4: start of data analysis
- November 14 – Module 5: final workshop

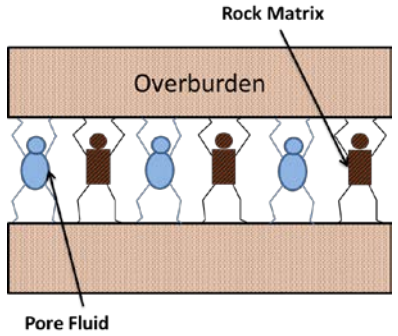
>> *Quick recap*

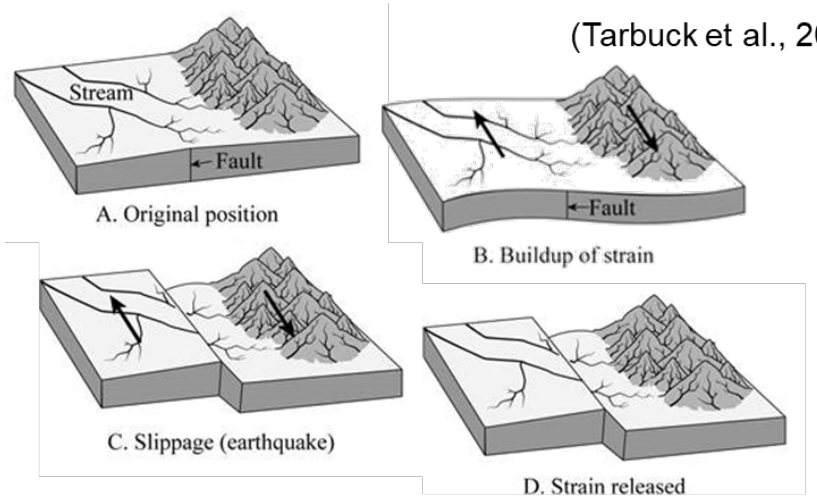
- From the source (energy release) to the measurement (ground vibrations)



- A rock mass **=** grains **+** voids (**pores**) **+** fluid. It has a variable capacity to **hold** and **transmit** fluids

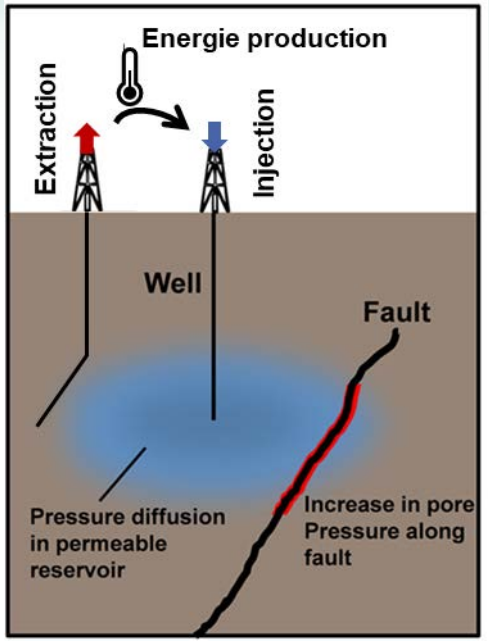




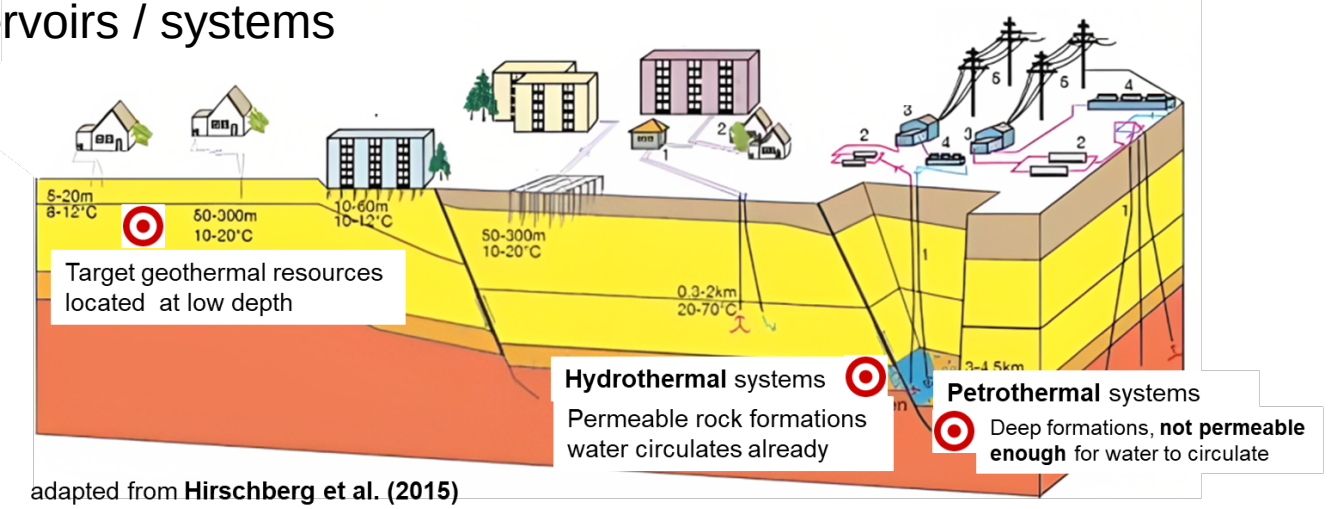


- EQs generally occur in connection with faults / fractures
- Theory of elastic rebound explains the dynamic of EQs
- Most „natural“ EQs occur at tectonic plate boundaries

>> *Quick recap*



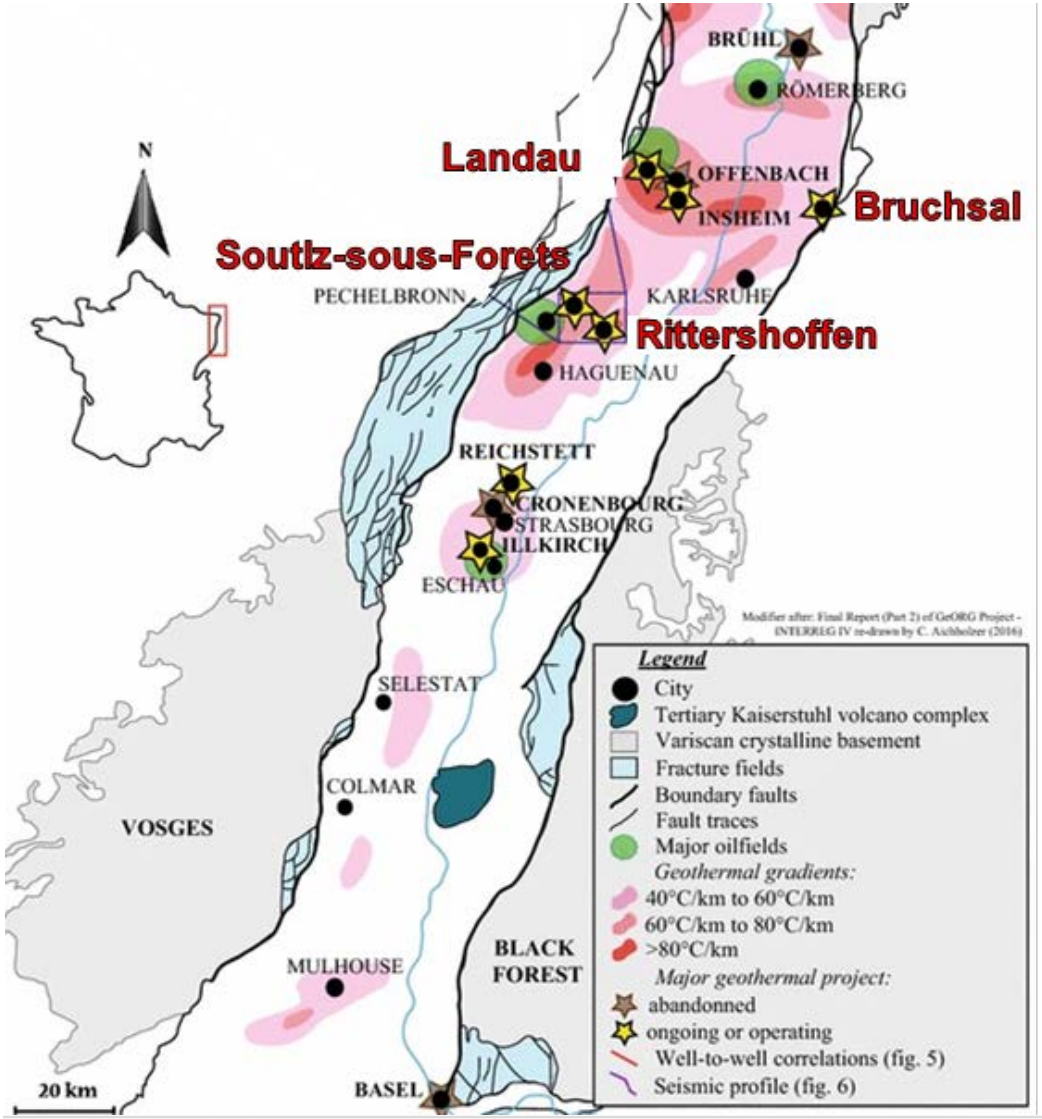
- EQs can be induced when extracting/storing geo-resources underground
- Water injections associated with geothermal energy technologies can change the stress conditions at the fault (pore pressure change), which in turn results in EQs (generally M<2, micro-seismic events)
- Different geothermal technologie**s** are used to operate geothermal resources located in different types of reservoirs / systems



adapted from **Hirschberg et al. (2015)**

- **Hydrothermal systems** (e.g. Bruchsal) target permeable rock masses where geothermal **fluid naturally circulates** between wells. But still requires conditions to operate the resource at **economic** rates…
- **Petothermal systems** target deep fractured rocks masses, but **not permeable enough** for the fluid to naturally circulate (they require EGS technologies).

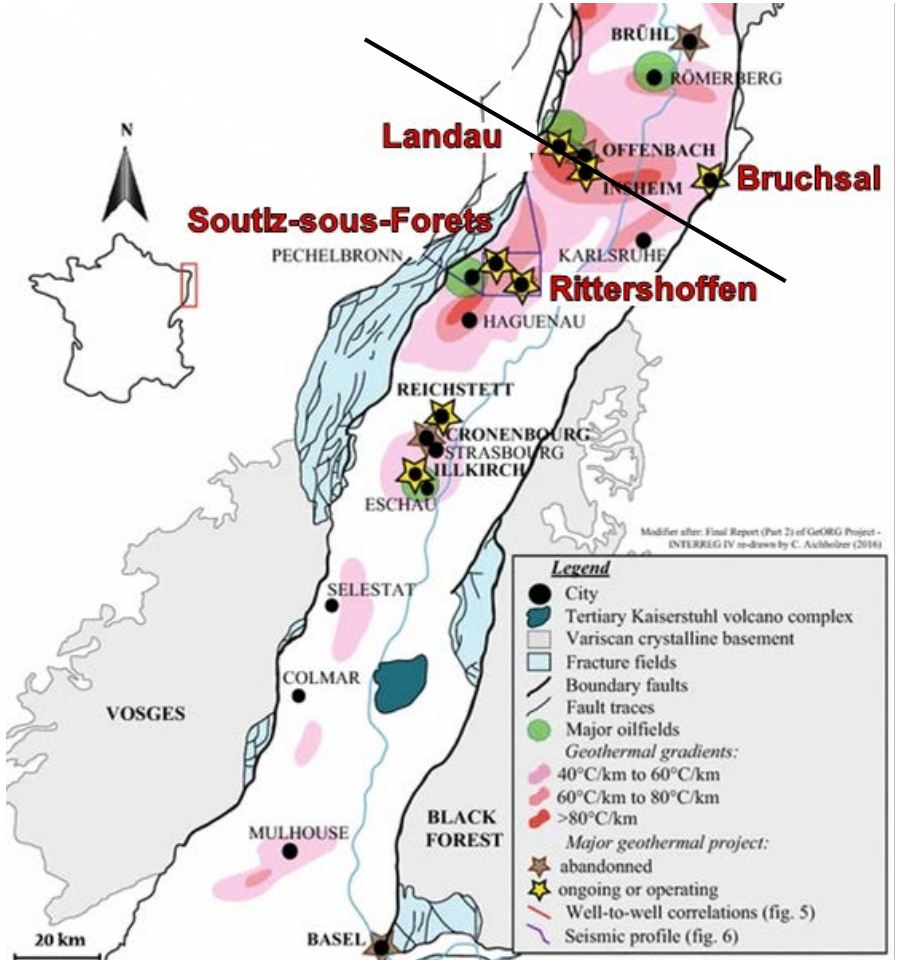
>> *Different types of Geothermal Systems / Reservoirs **in our region (along the Rhine)***



>> A geological specificity (Rhine Graben) which implies that temperature rises more significantly with depth.

>> Leading to the development of the geothermal industry in recent in our region (Soultz-sous-Forets, Rittershoffen, Bruchsal etc.)

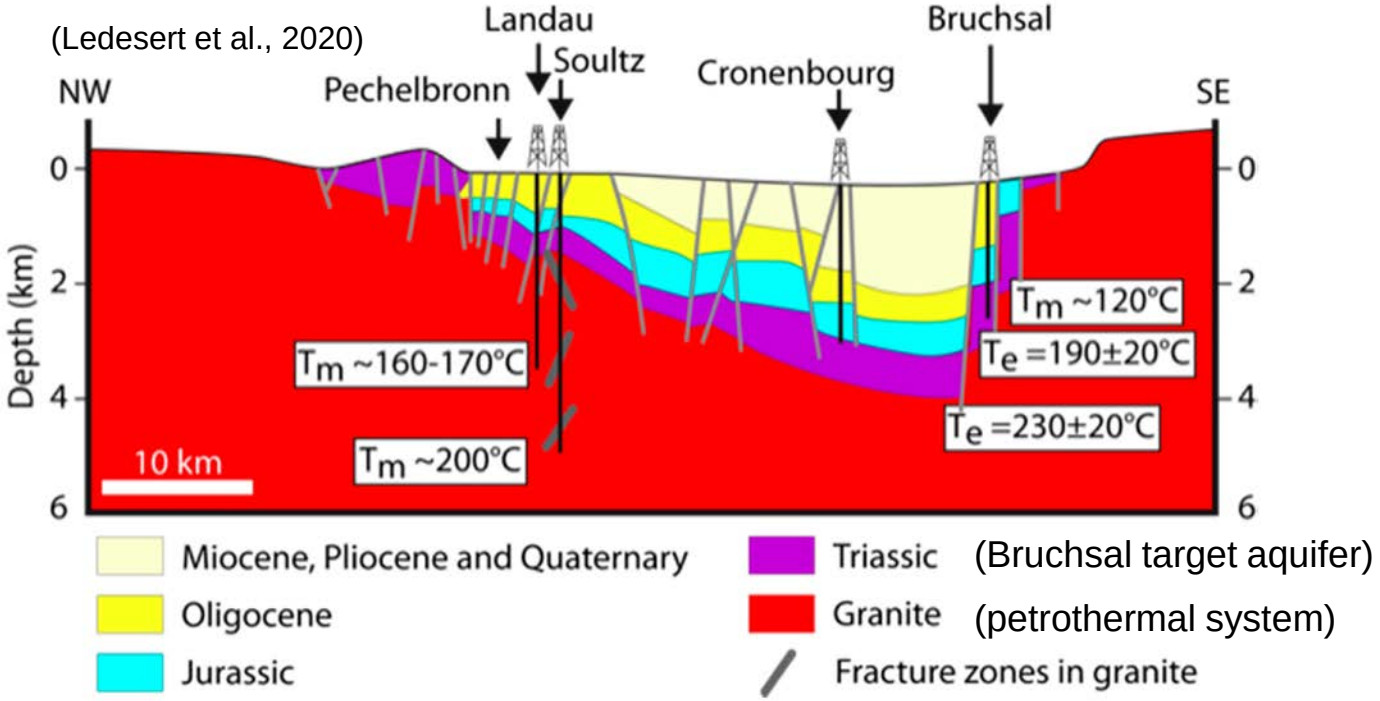
>> *Different types of Geothermal Systems / Reservoirs **in our region (along the Rhine)***



↑ Development of geothermal energy industry in Rhine Grabben region with geothermal anomalies (Aichholzer et al., 2016)

↓ Cut through (cross-section) and target reservoir in Bruchsal and Soultz

(Ledesert et al., 2020)



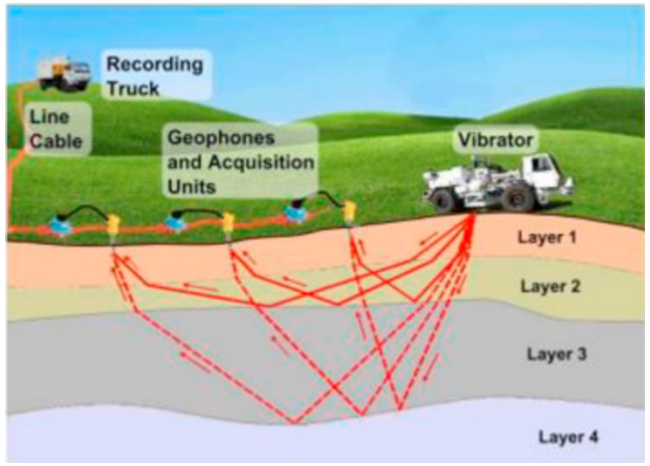
Different geothermal technologies / operated systems

>> Hydrothermal systems (**Bruchsal**): operating existing permeable aquifers to pump the water flowing / heated up (no further enhancement of the system)

>> Petrothermal systems (**Soultz, Rittershoffen**): fractured rock mass, but requires reactivation of the fault systems before operation (EGS technologies)

What are the tasks of seismologists in the field of deep geothermal energy?

During exploration

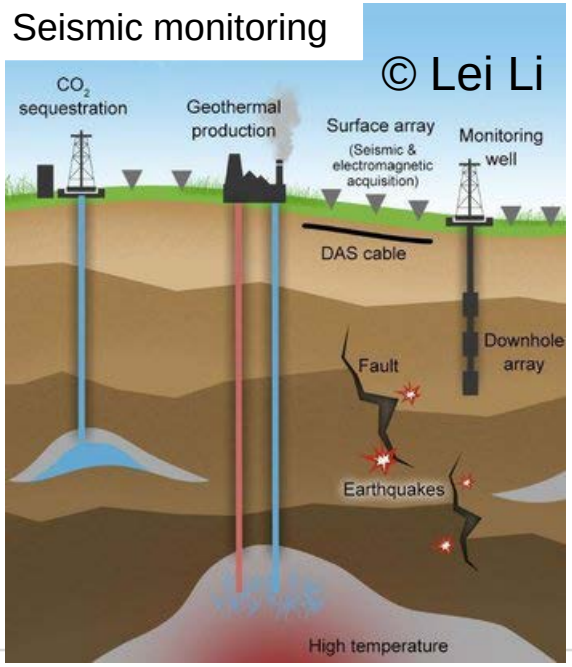


Seismic reflection to characterize subsurface © Janvier Domra Kana

During development

During exploitation

Seismic monitoring



>> *During development: EGS and reservoir stimulation*

- **EGS** project development: reservoir stimulation, which is subject to seismic activity due to fault reactivation (usually, M<2): **micro-seismic activity**

- Seismic measurements make it possible to get an insight into the physical processes occurring at depth

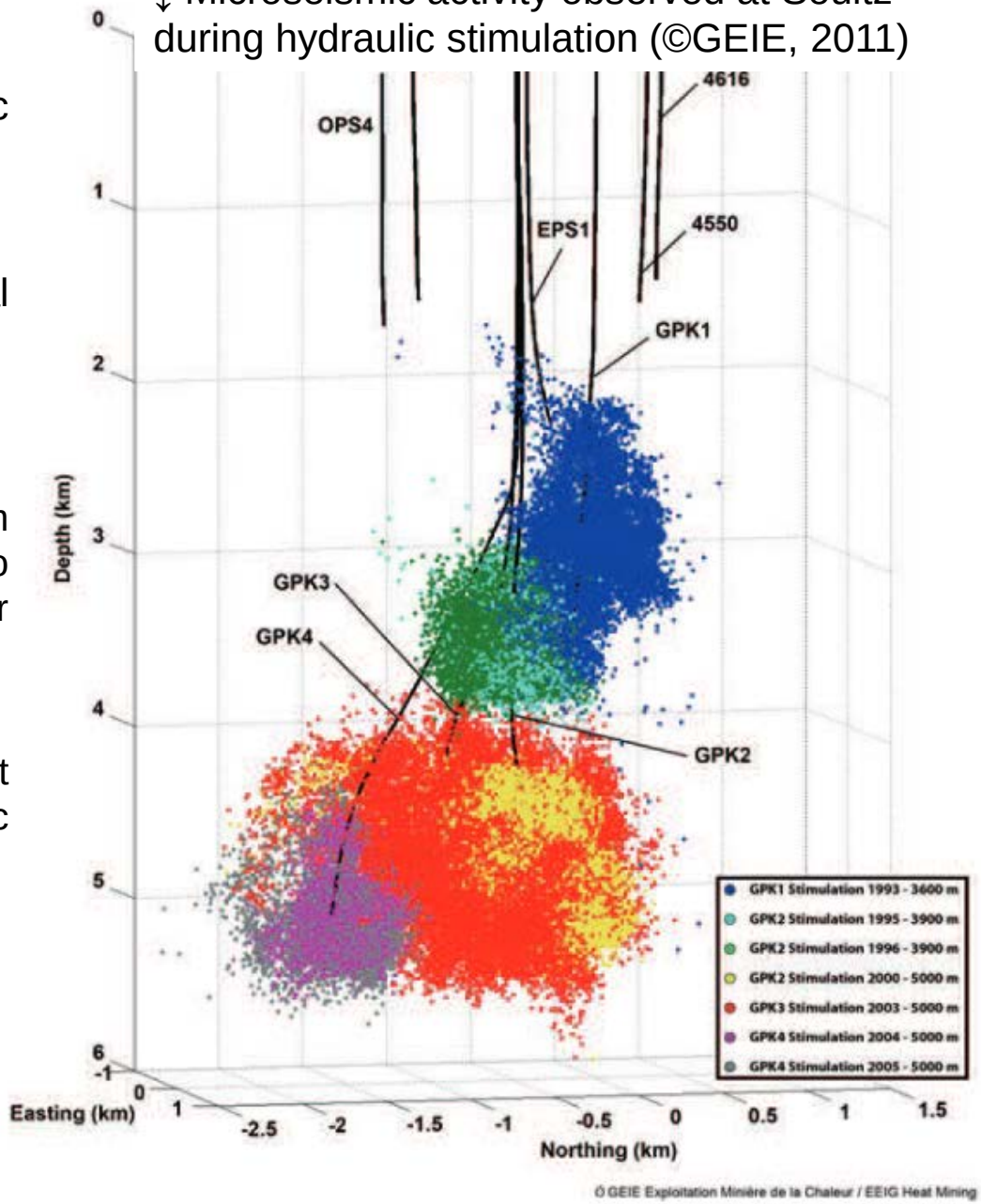
>> Reservoir Characterization

Analysis of spatial distribution of micro-seismic events / associated mechanism offer information about the geometry of the stimulated zone, provide insights into mechanical properties, stress distribution, and the presence of faults or fractures.

>> Optimization of operations

Real-time observation of microseismic events enables operators to adjust stimulation parameters, such as injection rate and pressure, and avoid seismic events that might be felt at surface..

↓ Microseismic activity observed at Soultz during hydraulic stimulation (©GEIE, 2011)



>> *During operation: risk mitigation and reservoir monitoring*

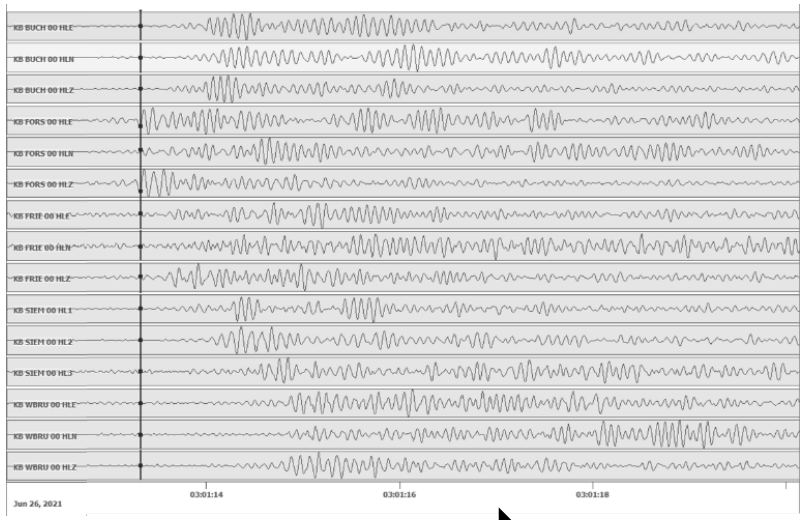
Induced seismicity is one societal impact of geothermal energy industry with significant public concern.

>> Need to minimize possible risks: operations may trigger micro-seismic events, but needs regulation as a result

>> How to manage this hazard?

>> Monitoring seismicity, in real-time, by a third-party

Acquire seismic data
(seismic network)



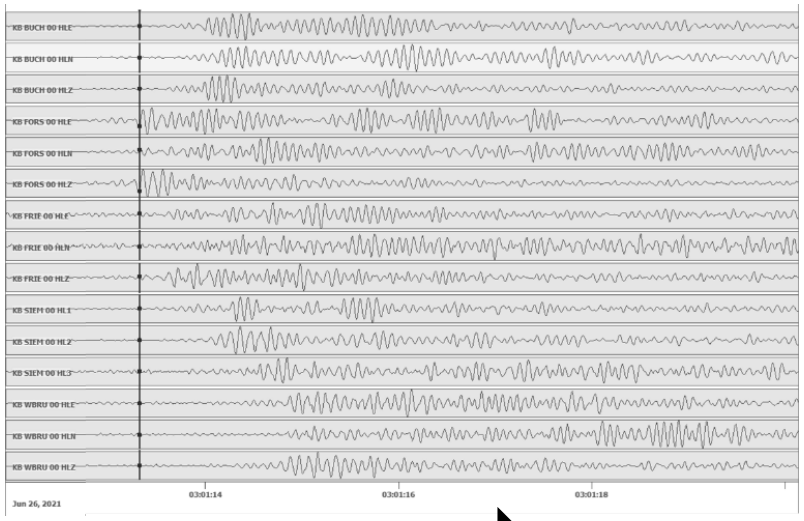
Detect and process
(quasi real time)

Report

Need to raise an alert?

>> *During operation: risk mitigation and reservoir monitoring*

Acquire



Detect and process (quasi real time)

Report

Need to raise an alert?

>> A framework to raise alerts: Traffic Light System

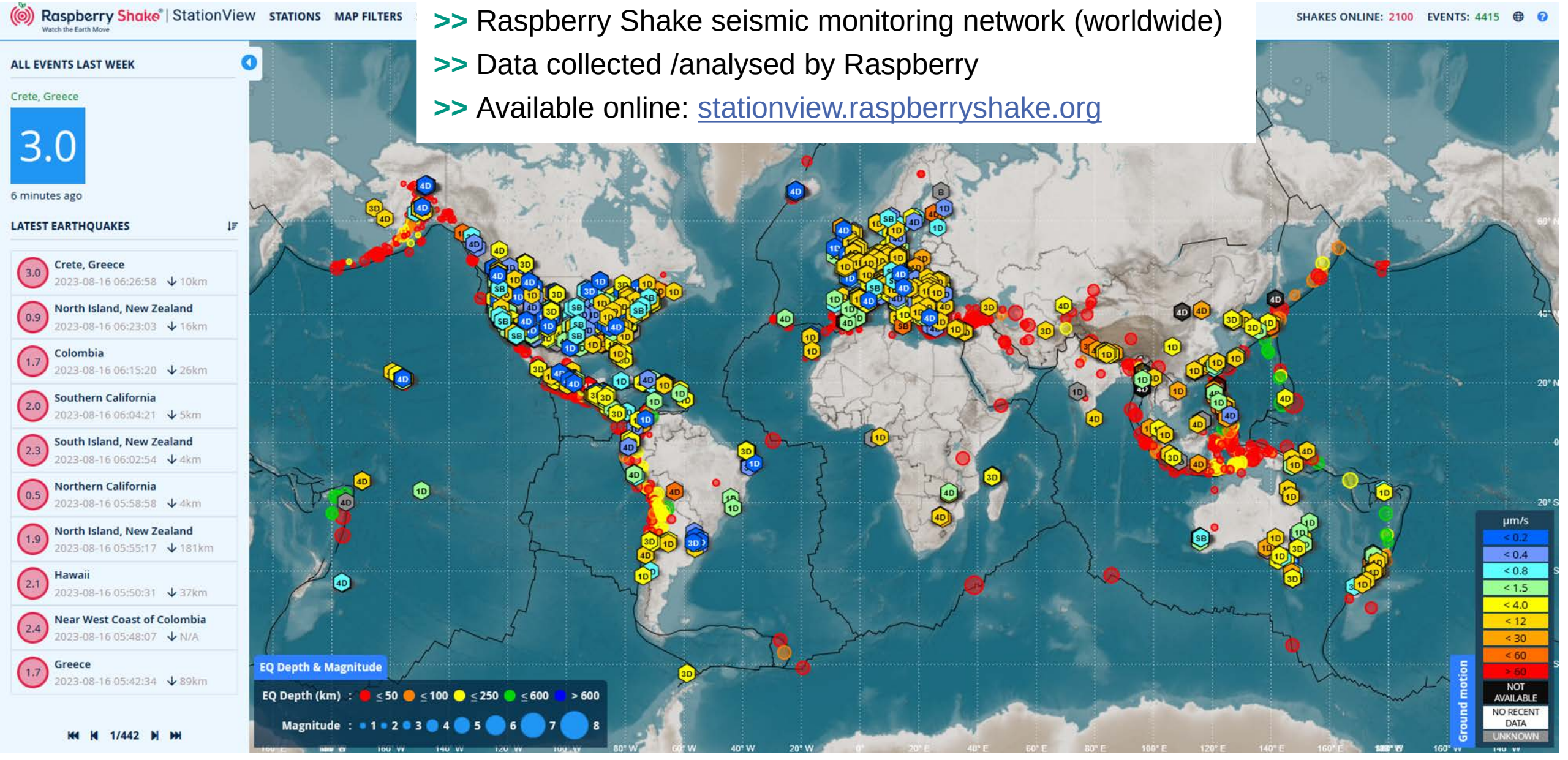
Categories, based on thresholds that apply to earthquake characteristics (magnitude, PGV/PGA), to evaluate and communicate the level of risk, and provide guidance.

>> *Example of seismic monitoring networks*

>> Raspberry Shake seismic monitoring network (worldwide)

>> Data collected /analysed by Raspberry

>> Available online: stationview.raspberryshake.org



>> *Risk mitigation: Surveillance (monitoring) of earthquakes*

>> Latest detected EQ in Baden-Württemberg, Rhineland-Palatinate and neighboring regions

>> Available online: https://erdbeben.led-bw.de/

Landeserdbebendienst - Aktuelle Erdbeben

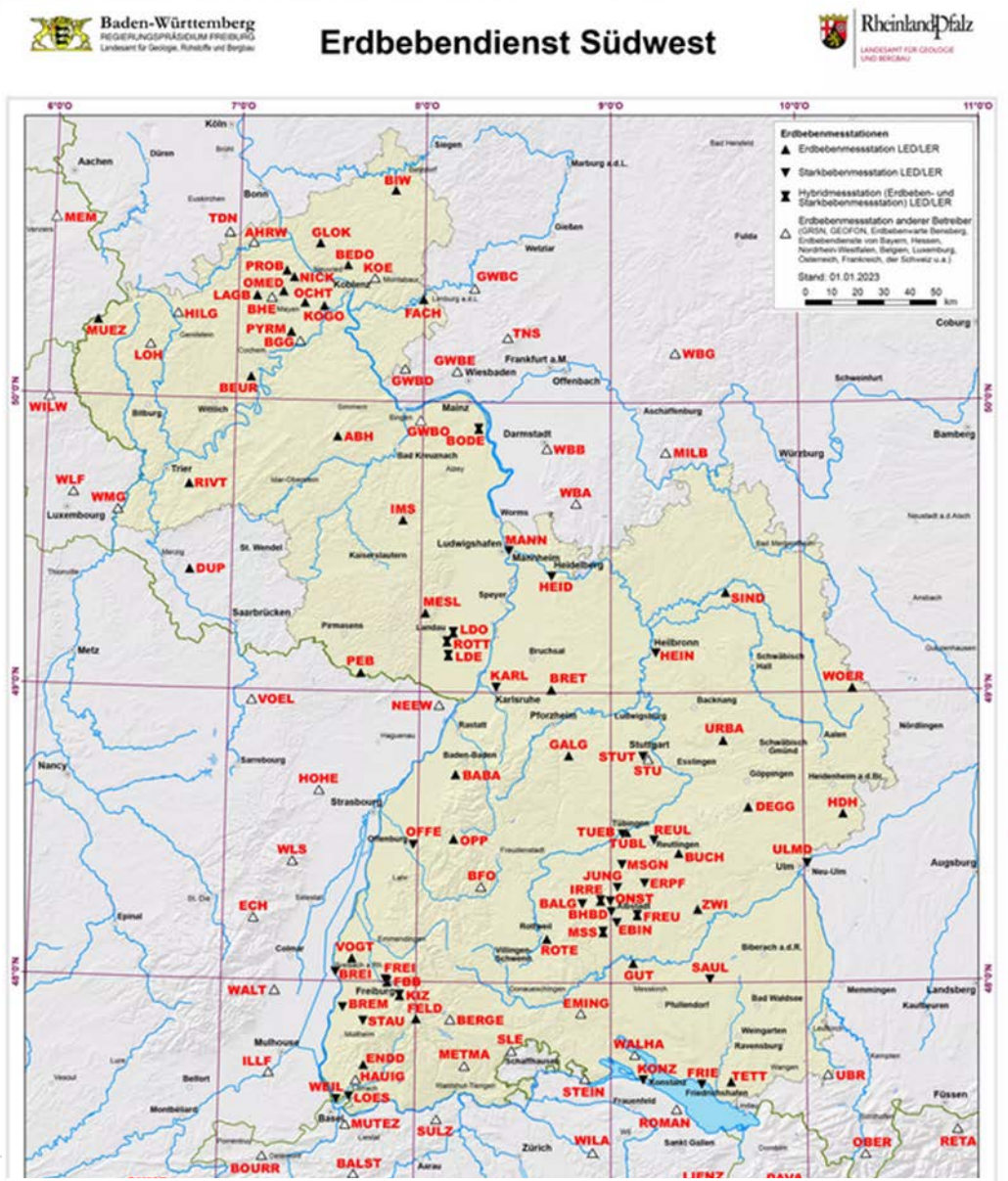
LGRB-Home » Erdbeben » Aktuelle Erdbeben

Baden-Württemberg, Rheinland-Pfalz und benachbarte Regionen

Haben Sie ein Erdbeben gespürt? Bitte teilen Sie es uns hier mit.

10 Einträge anzeigen Suchen

Datum / Uhrzeit	Magnitude	Epizentrum in/bei
18.08.2023 - 05:01	0.8	Wachtberg, Rhein-Sieg-Kreis, NRW
17.08.2023 - 04:10	0.2	Waldorf, Lkrs. Ahrweiler, RP
16.08.2023 - 21:29	0.9	Waldorf, Lkrs. Ahrweiler, RP
15.08.2023 - 14:43	1.0	Wachtberg, Rhein-Sieg-Kreis, NRW
15.08.2023 - 09:44	0.4	Kobern-Gondorf, Lkrs. Mayen-Koblenz, RP
15.08.2023 - 01:27	0.4	Kobern-Gondorf, Lkrs. Mayen-Koblenz, RP
15.08.2023 - 01:25	1.5	Kobern-Gondorf, Lkrs. Mayen-Koblenz, RP



Erdbebenmessstationen des EDSW © LGRB

Location

- By looking at the seismograms from different stations.

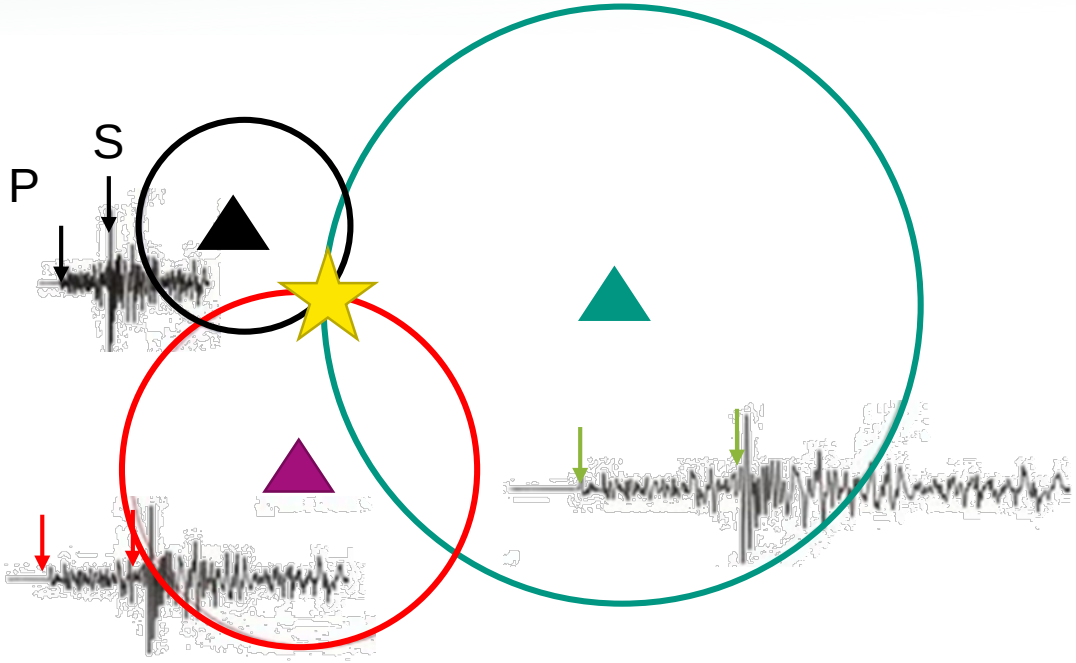
>> closest station first, furthest away last

- Measurement of arrival-times (for P- and S- waves)

>> P- wave arrives before S-wave

>> time difference gives distance to earthquake.

- Three stations are necessary to locate.



>> *How to **characterize** an earthquake?*

Location

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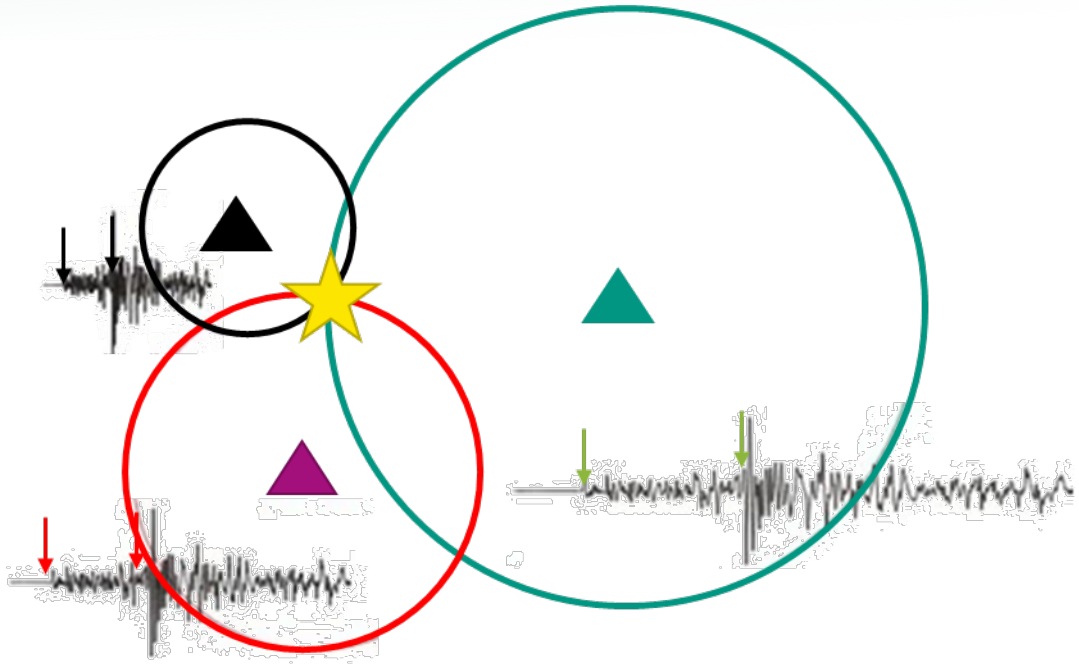
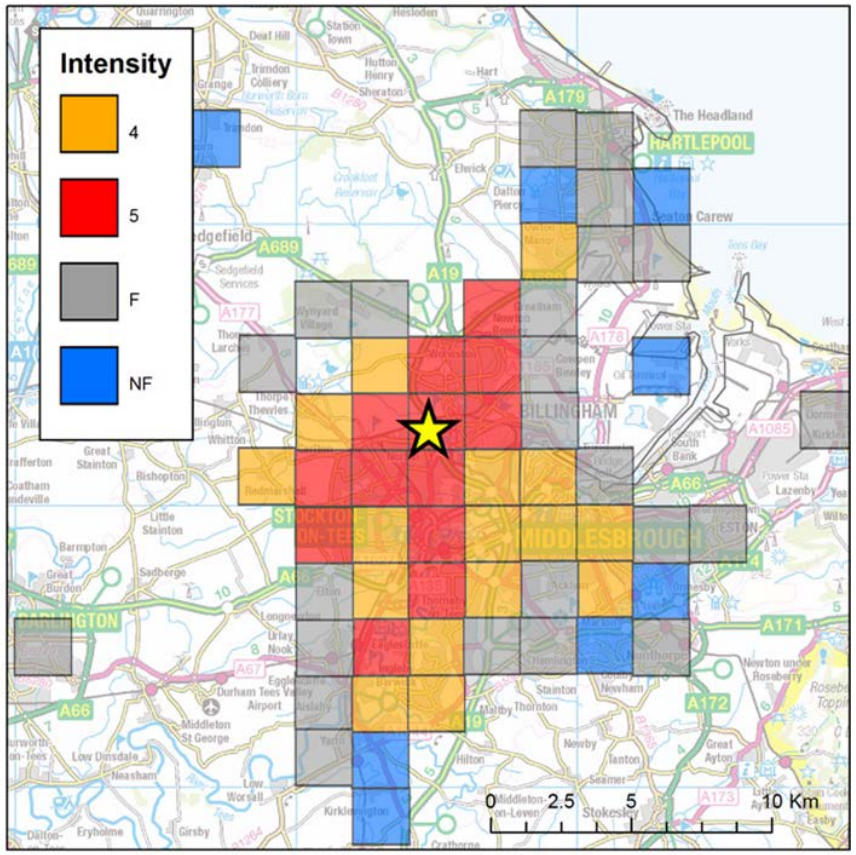


Severity

- Intensity – qualitative measurement of "**strength of shaking**", generally based on observed effects.
- Magnitude – quantitative measurement of "**amount of energy**", based on waveform recordings.

>> *How to **characterize** an earthquake?*

- **Shakemaps (intensity)**



↑ Shakemap (3.1 ML, 23.01.2020, UK) using 840 reports from people who felt the earthquake. **BGS © UKRI**

- **Some facts about EQ magnitude(s)**
  - Scales are non-linear: **+ 1** Magn. unit ≡ Energy x**30**
  - Magnitude 0 does not mean that no energy is released: negative magnitudes are possible

Magnitude	Energy in joules	Notes
-1.0	2000	100 kg person jumps down 2 m
0.0	6.3×10^4	
1.0	2.0×10^6	
2.0	6.3×10^7	Only felt nearby
4.0	6.3×10^{10}	Felt up to tens of km away
5.0	2.0×10^{12}	Energy from 50 000 litres of petrol
6.0	6.3×10^{13}	3.3 Hiroshima-sized A bombs
9.0	2.0×10^{18}	Total annual energy use of UK

>> *How to **characterize** an earthquake?*

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9.0	2.0×10^{18}	Total annual energy use of UK

- Reported magnitude can change as more data gets analyzed. In Sumatra (24 Dec 2004), the original magnitude of Mw 9.0 was recalculated to Mw 9.3.
- Highest magnitude ever recorded: earthquake in 1960 (Valdivia, in Chile) → Mw 9.5
- Multiple magnitude scale**s**

Local ($\mathbf{M_L}$) / Richter magnitude (Charles Richter scale, 1935)
→ empirical scale, developed from observations in south-California
→ rigorously applies only in that region

Moment magnitude ($\mathbf{M_W}$)
→ most standard and reliable measure of energy released.
→ based on seismic **moment,** a measure of the event dynamic.

Waveform analysis

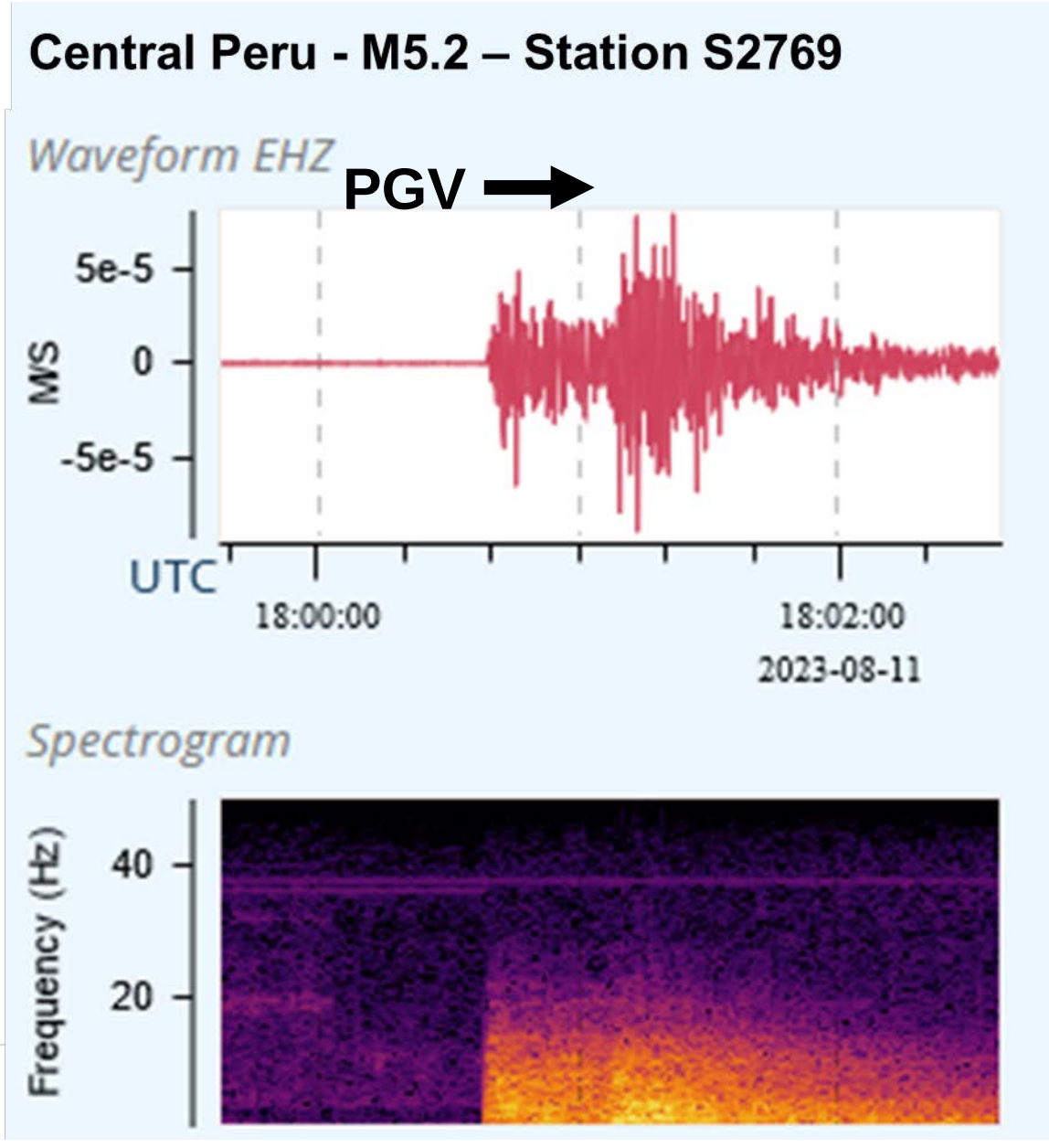
- **Peak ground velocity (PGV)**: measures the maximum velocity of ground motion (TLS)
- **Spectrogram**: P, S, Surface waves generally carry different frequencies

To detected/characterize a seismic event, the **signal** must stand out the **background noise**!

Ok for such a large events…

but what would it be with a station in city centre?

but for microseismic events (M<2)?



>> *Where to **install seismic monitoring stations?***

New seismic station installation requires a evaluation of onsite background noise conditions (aka noise-msts.)

>> that's what we are going to do!

Exple: noise analysis from KIT "BUCH" station, (Munich)

→ Freq. content over time **= Spectrogram**

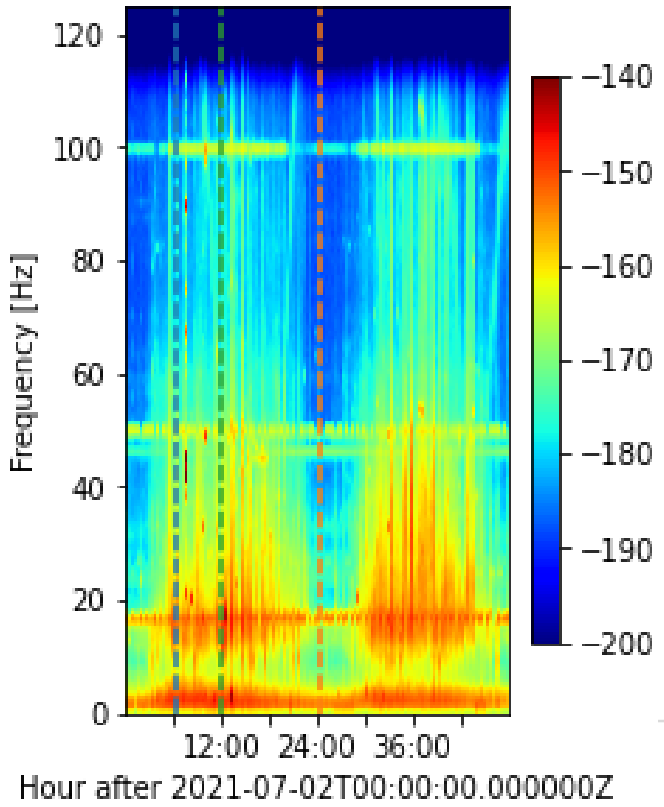
>> High noise = hot color

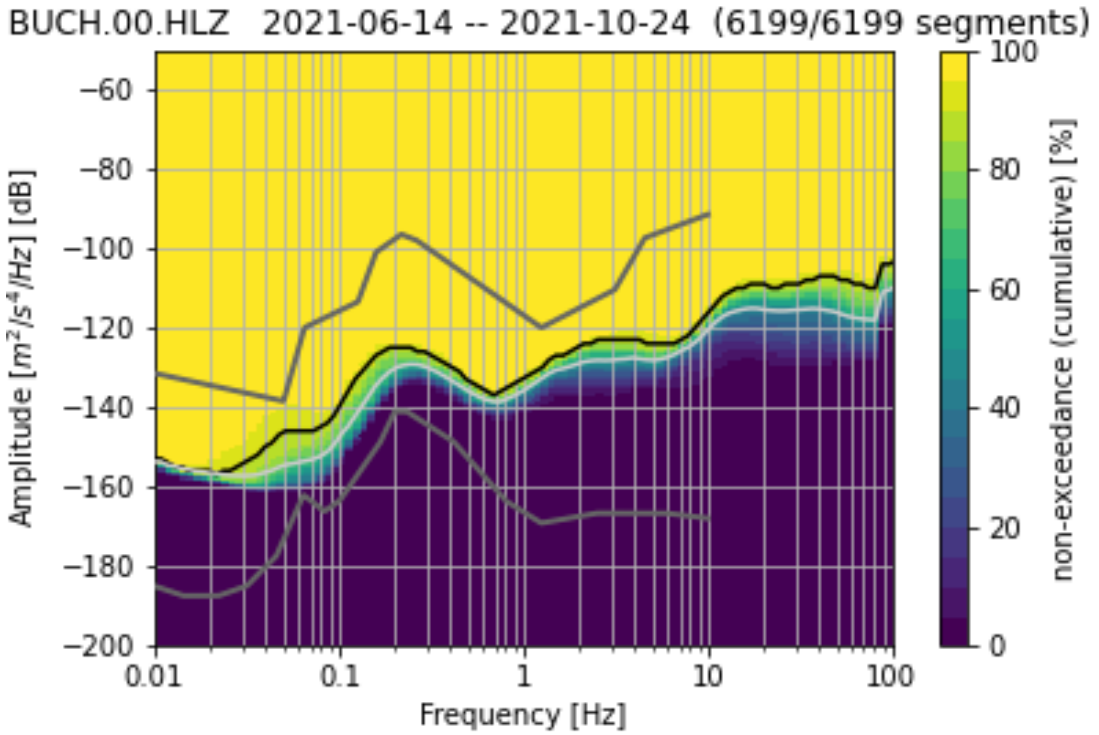
>> Night *vs* day

Impact of human activity

>> Permanent 50 Hz comp

Impact of electrical grid:





↑ Same analysis, repeated in 30 min windows, then resu analysed statistically **= PPSD**

>> for each freq., shows the probability to not exceed a certain level of noise

>> comparison with standard noise levels

Now that you passed the training lesson…

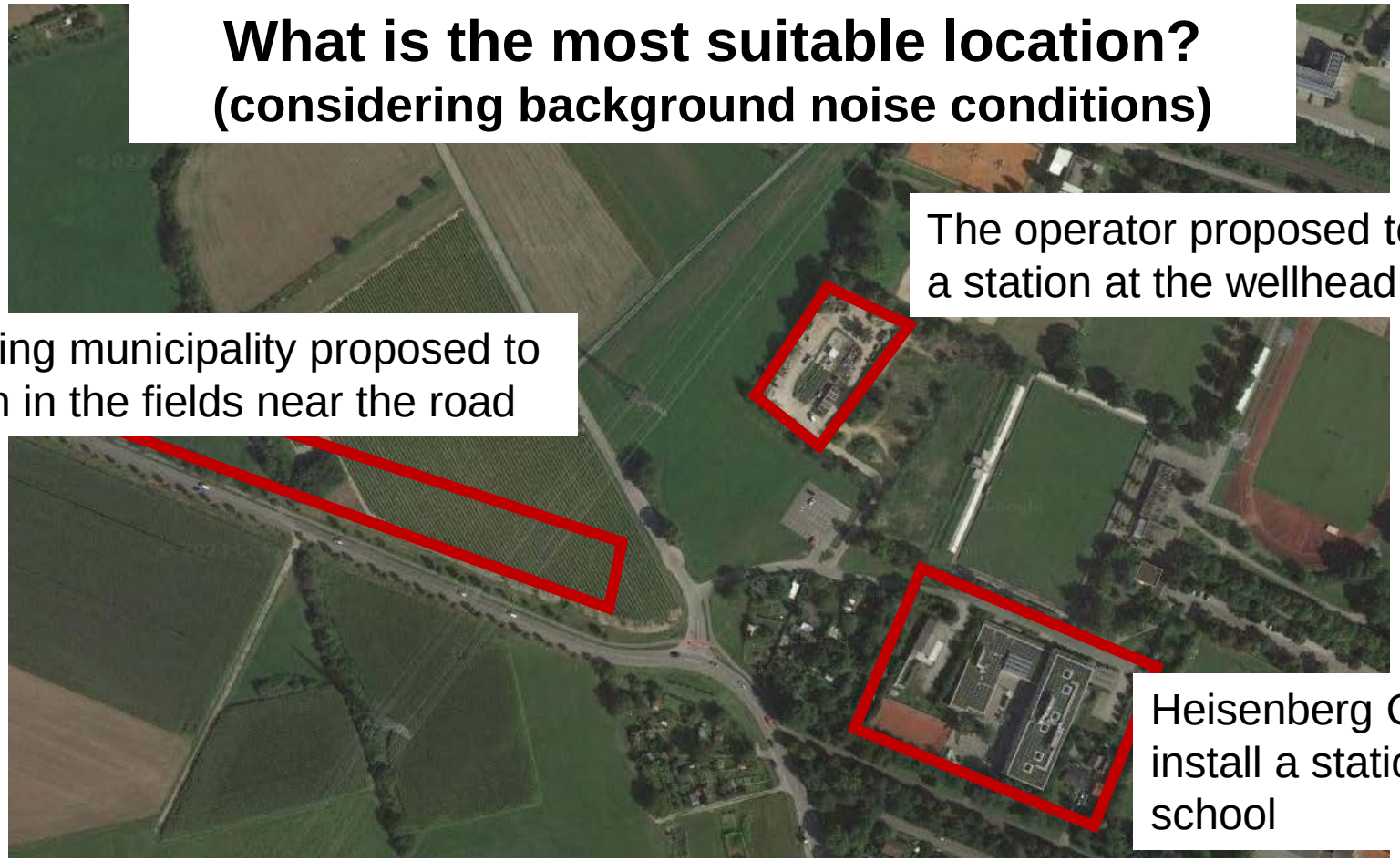
… to install a new seismic station to monitor the Bruchsal geothermal site

>> *Back to the role-play game*

>> We need a new monitoring station, sensitive to the minute ground vibrations

>> We sent out a request for proposals for possible locations

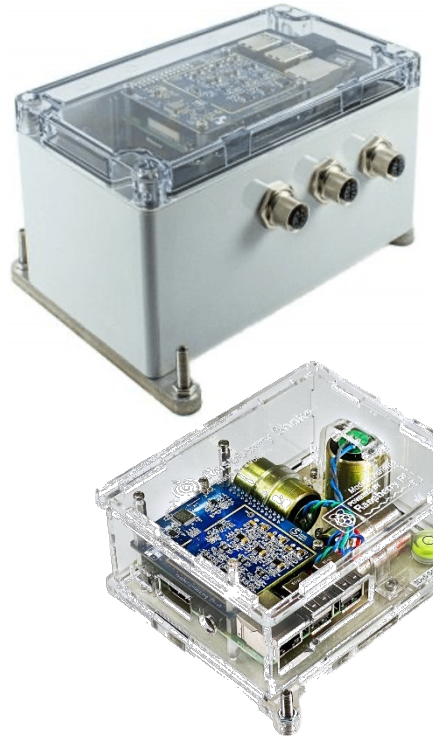
What is the most suitable location?
(considering background noise conditions)



The surrounding municipality proposed to have a station in the fields near the road

The operator proposed to a station at the wellhead

Heisenberg Gymnasium offered to install a station on the land of the school



>> *Requirements to carry out seismic measurements*

- Of course, we need power supply … but not only

- We want to know **when** the data is acquired: time-stamped data,

>> requires the connection of a GNSS/ GPS antenna: GPS signals provides highly accurate time info.

- We want to know **where** data is acquired,

>> requires to locate the seismograph, with a navigation system

- We want **structured** data,

>> requires that RaspberryShakes saves / transmits standardized data

- We want the seismometer to collect **reliable** ground vibrations

>> requires to pay attention to the tool installation

>> are the seismometers correctly oriented ??

>> are ground vibrations reliably transferred to the sensor ??

>> *Installation: criteria for selecting the location*

- Find the location where to install the material. Some criteria:

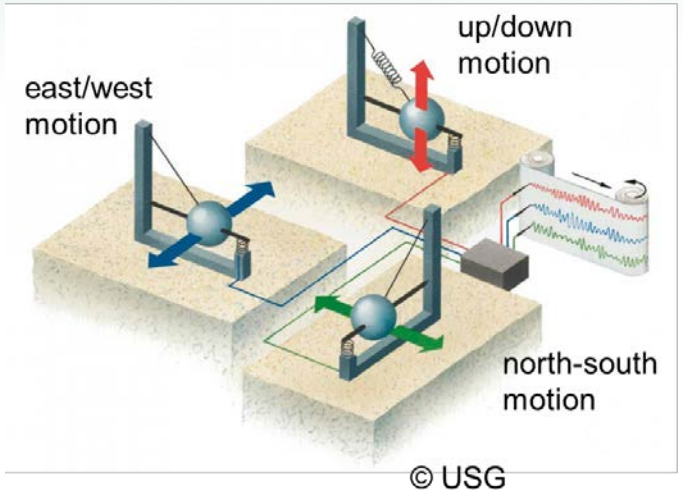
>> we must be able to power the equipment

>> we must have enough satellite coverage: for GPS signal, possibly to transmit data via mobile network

>> we must find a location isolated enough: not to have to constantly interfere with the seismograph

>> ideally, we must avoid floor coverings that can bias / dampen the amplitudes.

>> *Installation: steps to install the sensor*



- Find the location where to install the material.

- Do necessary connections,
- Check the orientation of the tool (with compass),
- Check the levelling of the tool (bubble on RS),
- Check station ID/name + location (longitude and latitude in WGS84 coordinate system).

>> Lets try it with the RS at the library

Station ID	IP address of RS	Location – longitude (WGS84)	Location – latitude (WGS84)	Installation date & time	Recovery date & time	Comments

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>> *How to access the RaspberryShake?*

- Remote (via router) / local (via wire) access, using a LAN connection (Ethernet cable)

- How to identify the RaspberryShake?

>> It is recognized by ID and IP address

>> IP address = "Internet Protocol address“

>> a numerical label assigned to each device connected to a computer network, used for communication

- How to access the RaspberryShake?

>> Usually, access to the RS via SSH

>> SSH = “Secure Shell”

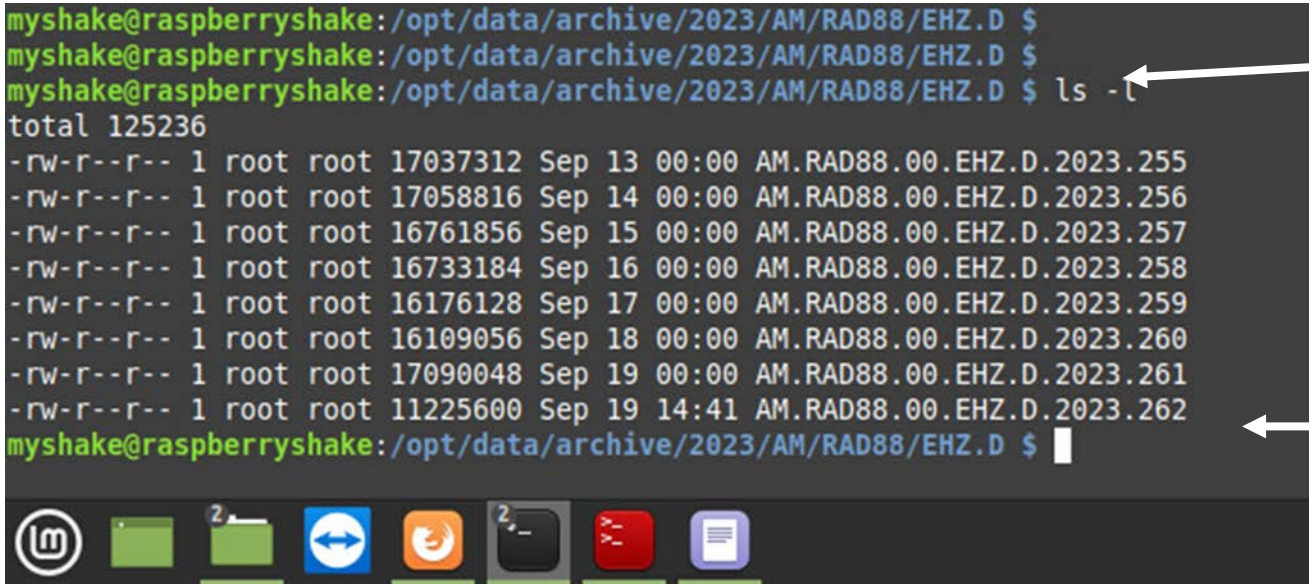
>> a network protocol and cryptographic technology used to secure data communication over a computer network

>> Let's try with the station at the library, **ID** = R46D5, **IP** = 10.11.18.189

>> *How are the data files structured?*

Data are accessible from the RaspberryPi, following standards in seismology:

>> "SEED" format, or **S**tandard for the **E**xchange of **E**arthquake **D**ata



Directory tree

Mini-SEED files
→ directly downloadable and readable, e.g. in python, using the correct library

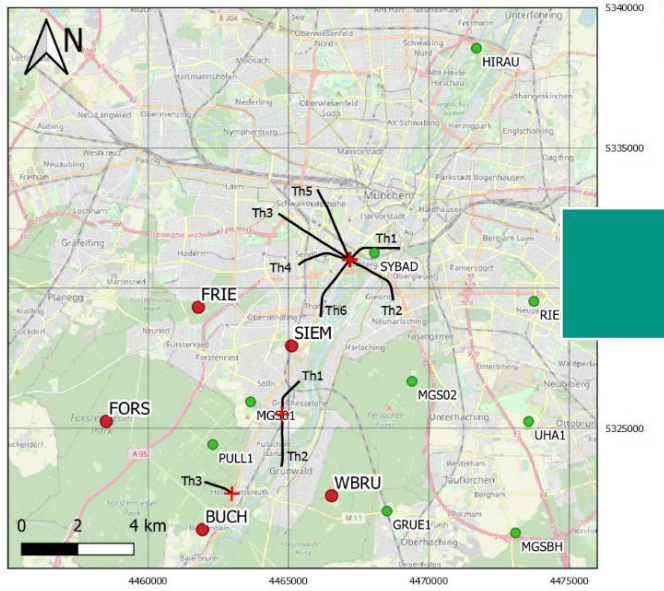
- Directory tree follows a logic:

>> Year / Name of Network [AM] / Name of Station / Name of Channel [N/E/Z]

- 1 file / channel / day. Names of files follow a logic:

>> Name of Network [AM] . Name of Station . 00 . Name of Channel [N/E/Z] . Year . Day nbr. of year [1→365]

>> *Data transmission*



Data

- Real time seismic monitoring implies:

>> Multiple stations around the study site

>> Data collection at multiple locations / stations

>> Data **transmission** to 1 central computer / server for the time processing of all the datasets…

- It involves

>> A router to send out the data

>> A processing machine to collect the data

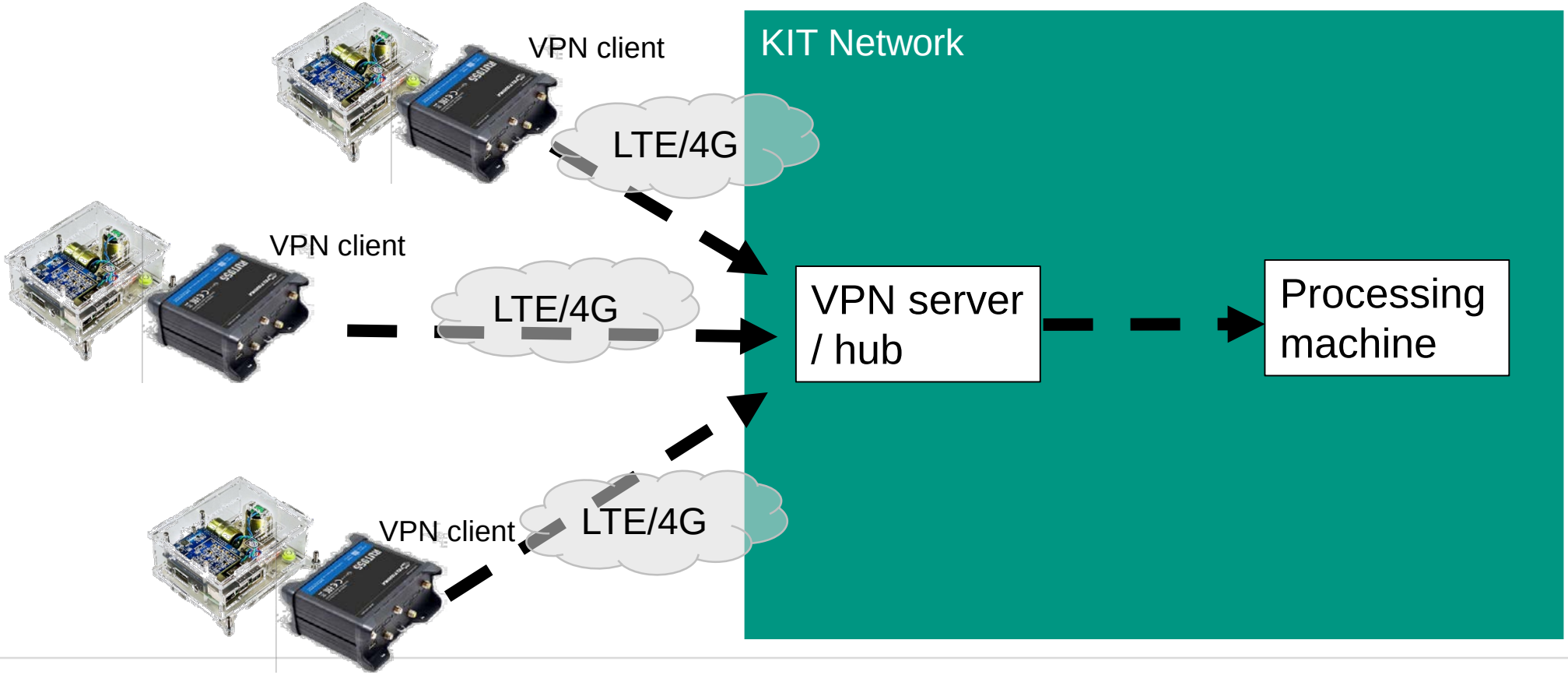
>> *SeisComP* (Seismic Communication Processor): an open-source software that provides a platform for

  - **collecting** (runs a server that pulls the data from the sensor),
  - **archiving** (in a “standard” architecture),
  - **processing**,
  - **distributing** data

We want to connect **each sensor** to the severs that collect the data, in a secured and flexible way

>> Using a Virtual Private Network (VPN), like a secured “tunnel” for data

>> Data are transmitted using LTE/4G



Configuration of tools from web-interfaces:

- Using IP addresses of tools
- Different actions possible from web-interface, e.g. run down the tool

After that the RS is online…

- First visualization of data from RS website → https://dataview.raspberryshake.org/#/
- Get useful data from RS website: station response file → https://stationview.raspberryshake.org/#/?lat=-0.00000&lon=0.00000&zoom=1.783

>> What do we need for the installation?

>> What do we need for the installation?

Sensor + cables + GNSS antenna

Data transmission

Power

>> *What do we need for the installation?*

Outdoor version, offline, archiving data on SD card

Power supply

Protection

- Signposting
- Shovel

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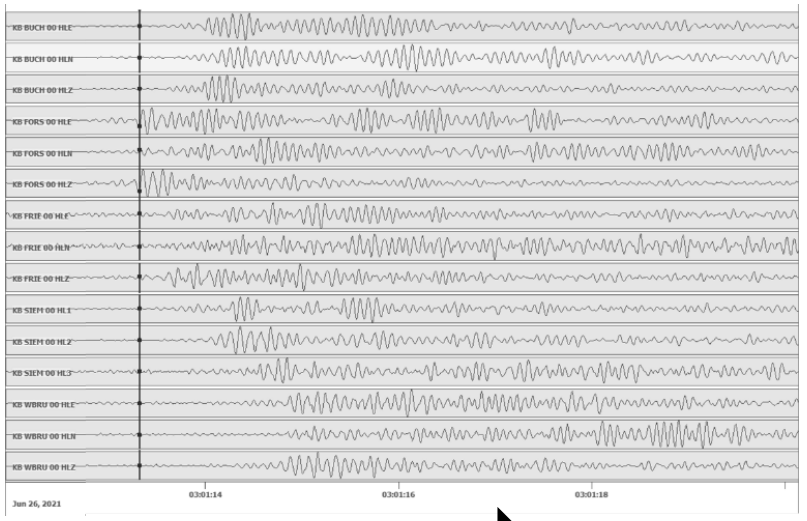
Module 4: analysis of Raspberry Shake data

- **September 19 – Module 1: introduction + training course**
- **September 26 – Module 2: preparation of field work**
- **September 27 – Module 3: start of measurement campaign at EnBW well site, near a road and at the Heisenberg Gymnasium**
- **October 04 – Module 4: start of data analysis**
- November 14 – Module 5: final workshop

>> *Goals for module 4*

- Gather all the data in one dataset
- Show you how to run the scripts / adapt some parameters
- Show you how to read / interpret the measurements

>> *Monitoring induced seismic activity*



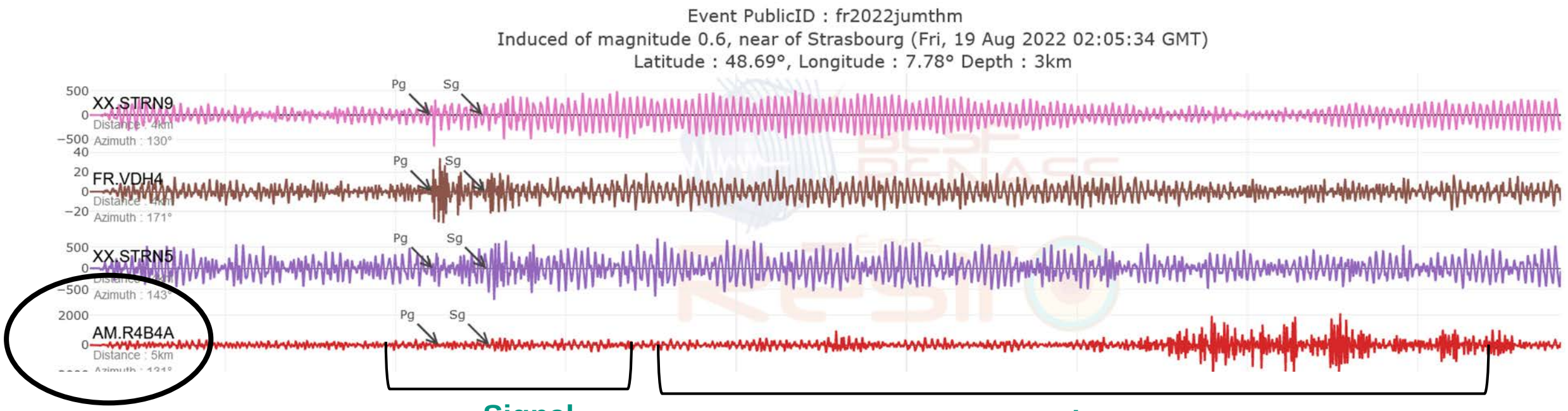
Acquire → Detect and process (quasi real time) → Report → **Need to raise an alert?**

>> A framework to raise alerts: Traffic Light System

Categories, based on thresholds that apply to earthquake characteristics (magnitude, PGV/PGA), to evaluate and communicate the level of risk, and provide guidance.

>> *Monitoring induced seismic activity*

To detected/characterize a seismic event, the **signal** must stand out the **background noise**!



>> RaspberryShake station

>> In the network monitoring the Strasbourg region

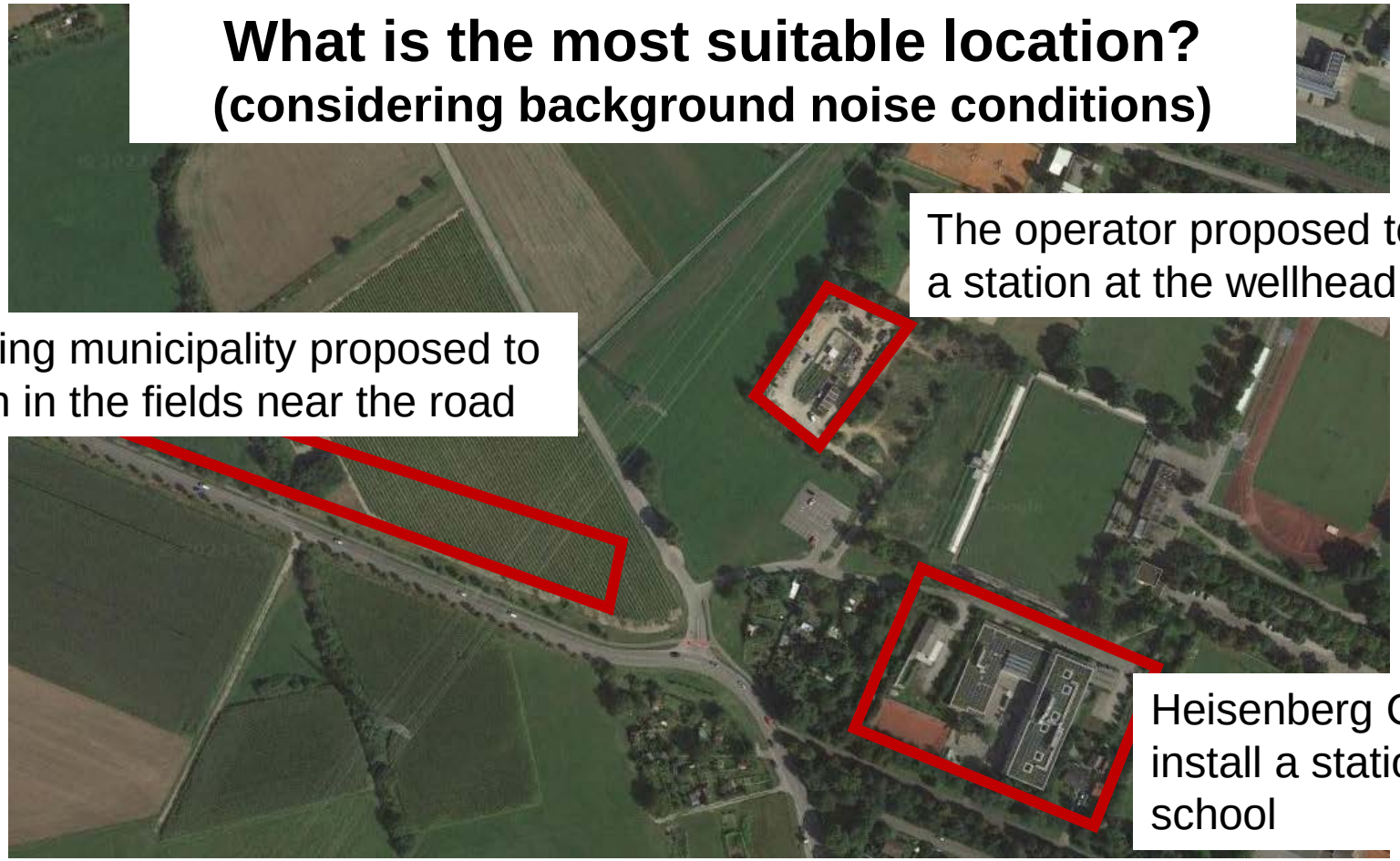
>> **Noise measurements** to evaluate the level of background seismic noise, at a given site

waveforms.franceseisme.fr/?event_publicid=fr2022jumthm

>> *Back to the role-play game*

>> We need a new monitoring station, sensitive to the minute ground vibrations
>> We put out a request for proposals for possible locations

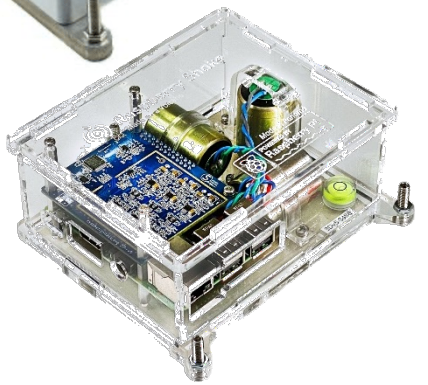
What is the most suitable location?
(considering background noise conditions)



The operator proposed to a station at the wellhead

The surrounding municipality proposed to have a station in the fields near the road

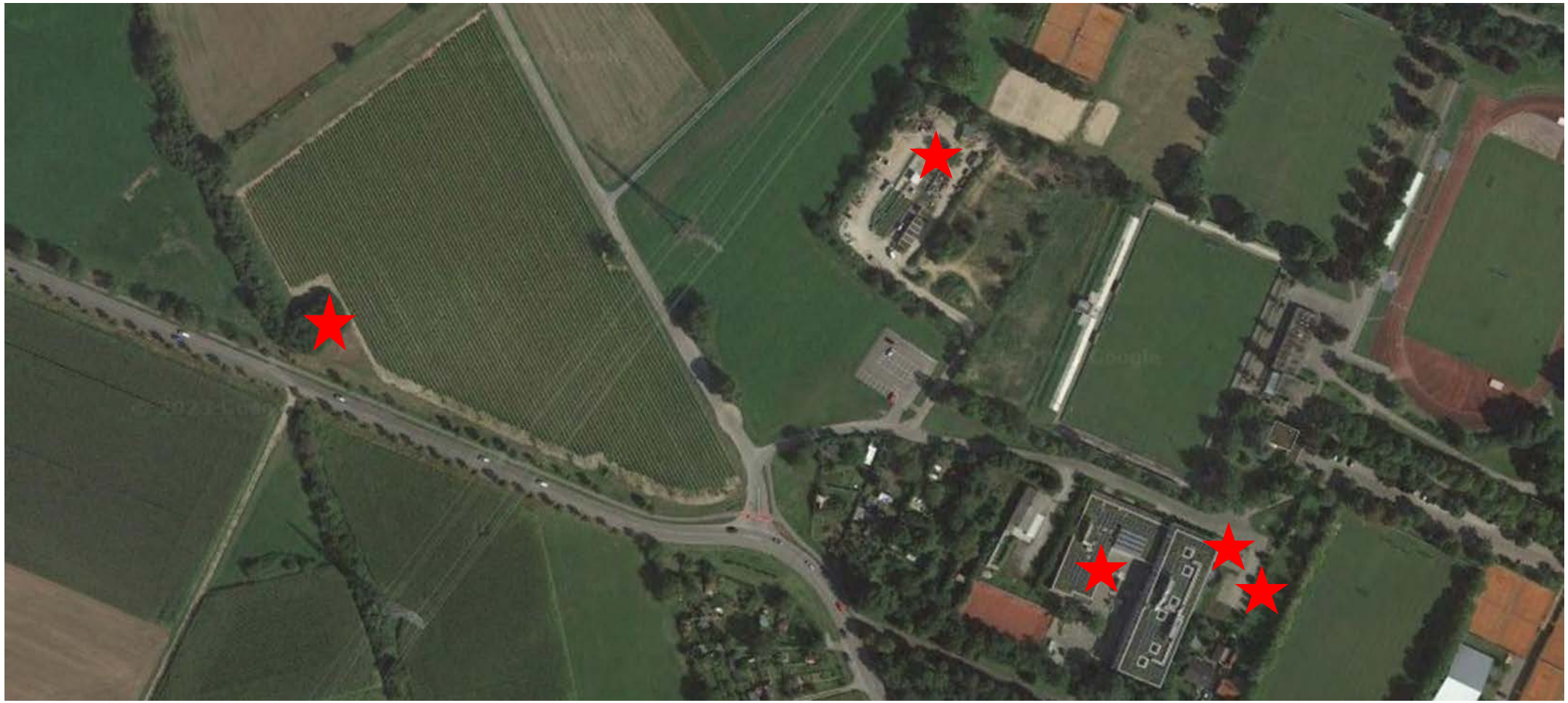
Heisenberg Gymnasium offered to install a station on the land of the school



>> *Back to the role-play game*

>> We acquired background seismic noise during one week at 5 locations

>> How to compare the locations and evaluate the noise level?



>> *How to evaluate the background seismic noise level?*

I. Estimate the noise level at specific periods of time, analyze changing behaviors over periods (e.g. day / night)

>> Analyze the amplitude of ground vibrations

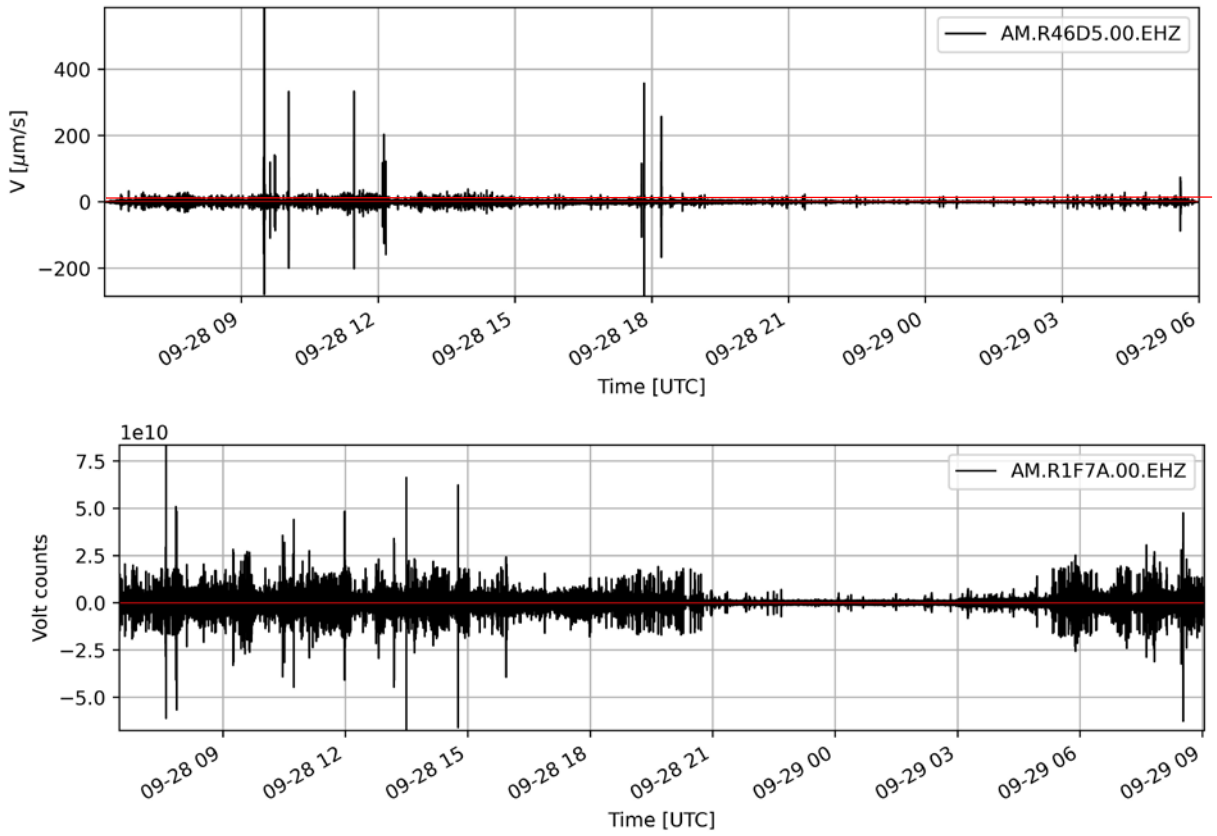
II. Estimate some indicators in 30 min windows, then analyze results statistically

>> Frequency content of the signals

>> *How to evaluate the background seismic noise level?*

I. Estimate the noise level at specific periods of time, analyze changing behaviors over periods (e.g. day / night)

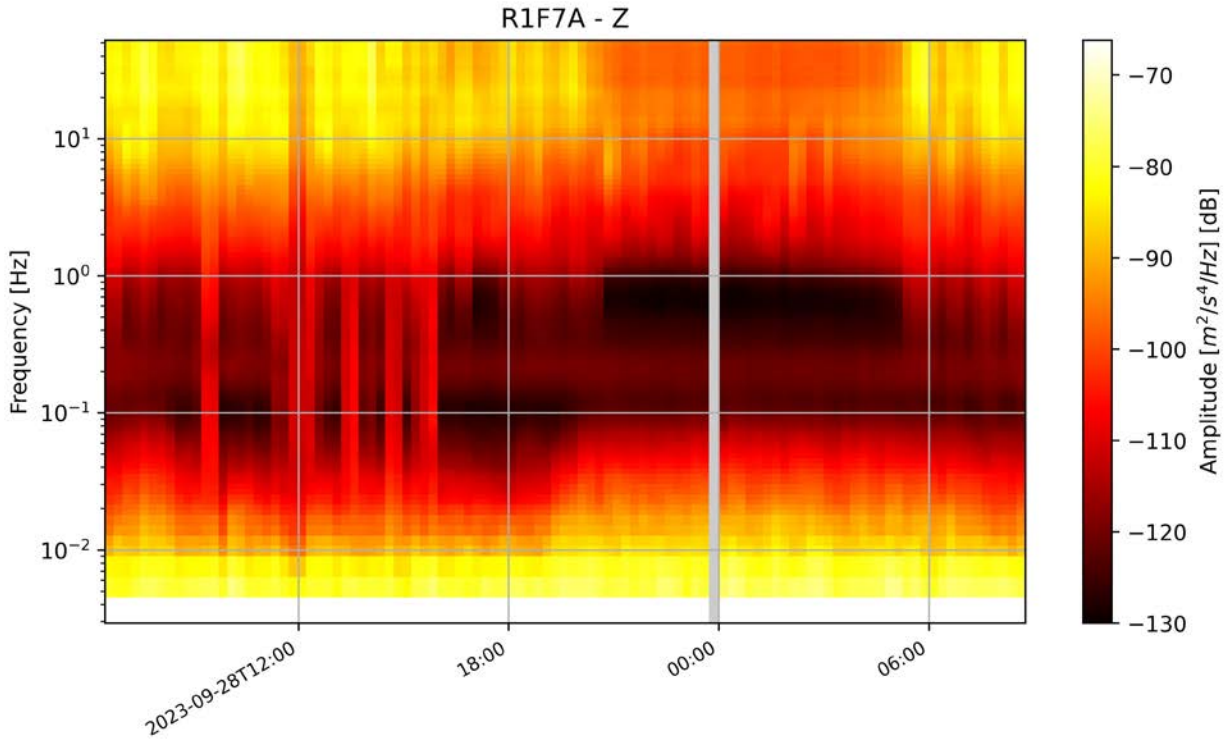
>> Analyze the amplitude of ground vibrations



>> we require noise amplitudes lower than 2 µm/s (in red)

II. Estimate some indicators in 30 min windows, then analyze results statistically

>> Frequency content of the signals



Spectrogram = Freq. content over time

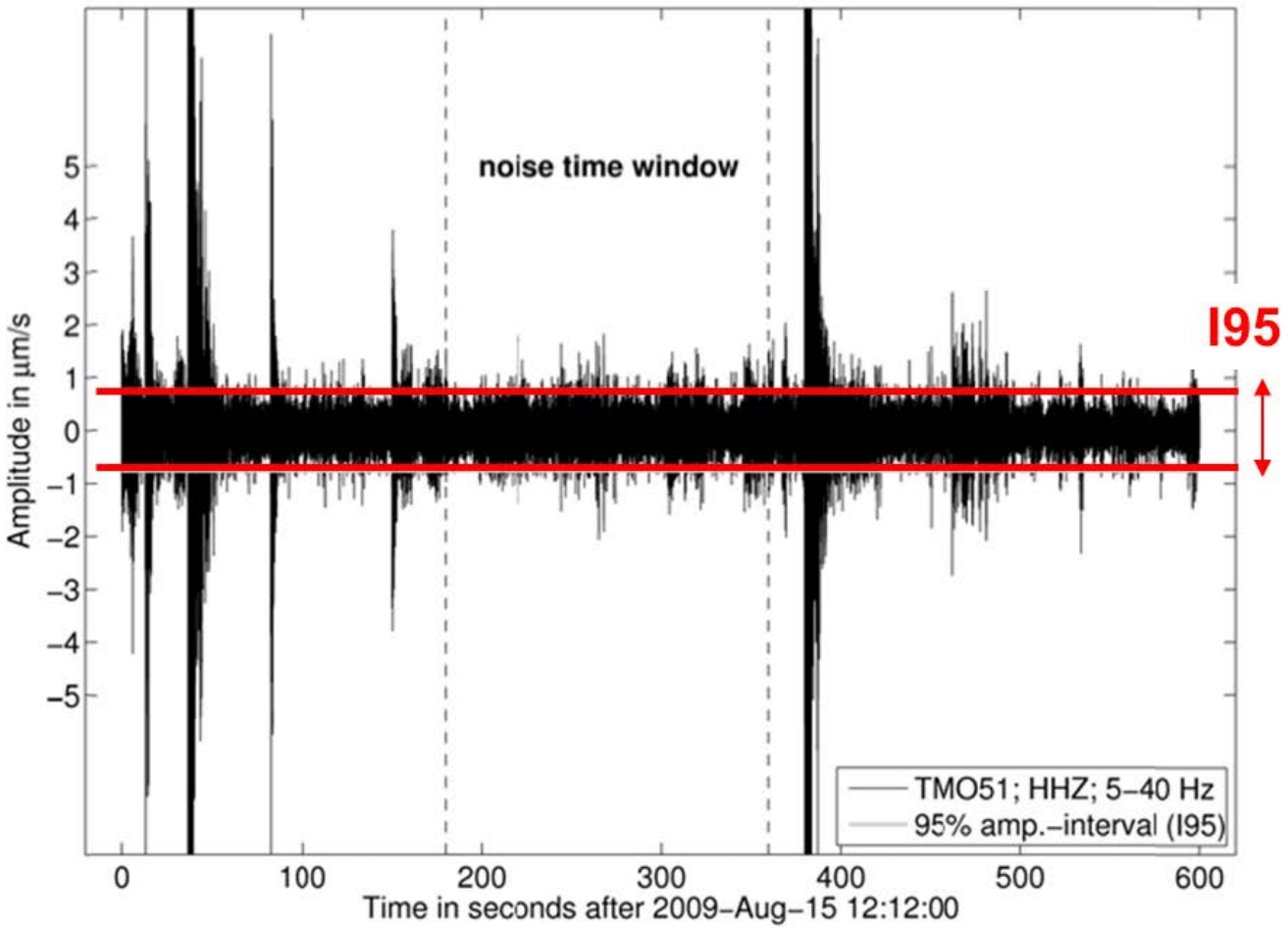
>> High noise = yellow color levels

>> Night *vs* day: Impact of human activity

>> *How to evaluate the background seismic noise level?*

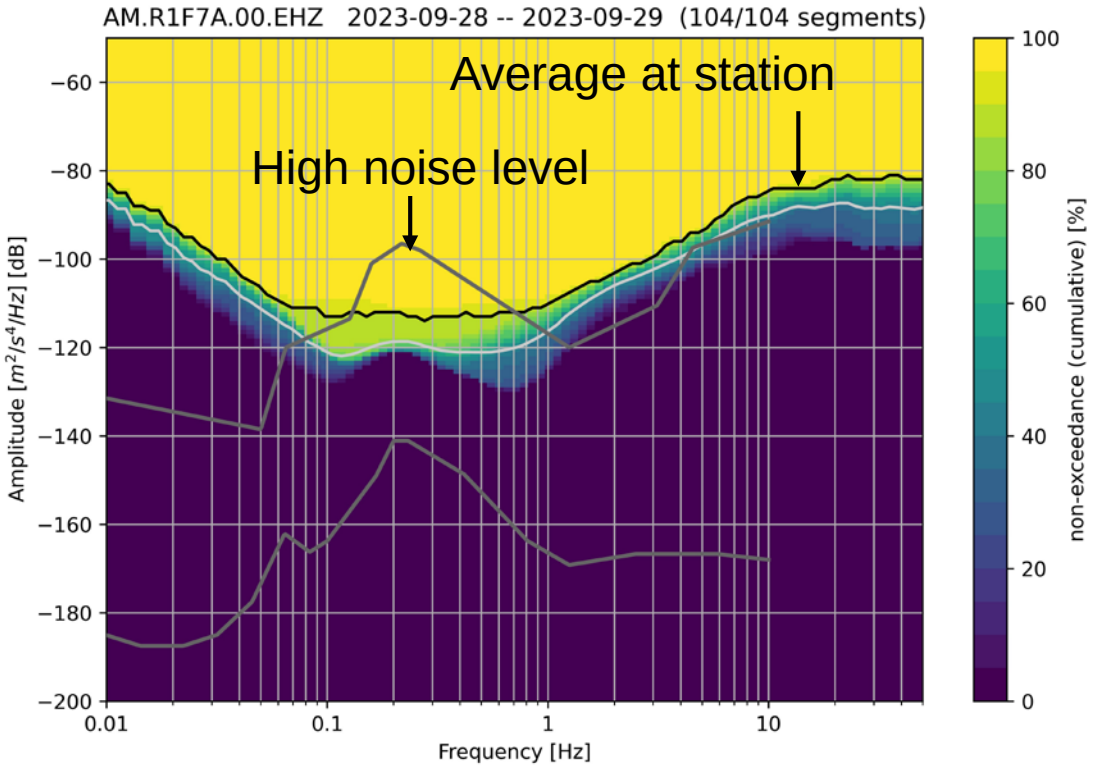
I. Estimate the noise level at specific periods of time, analyze changing behaviors over periods (e.g. day / night)

>> Analyze the amplitude of ground vibrations



II. Estimate some indicators in 30 min windows, then analyze results statistically

>> Frequency content of the signals



PSD = analysis of spectral content in 30 min windows.

for each freq., shows the probability to not exceed a tain level of noise

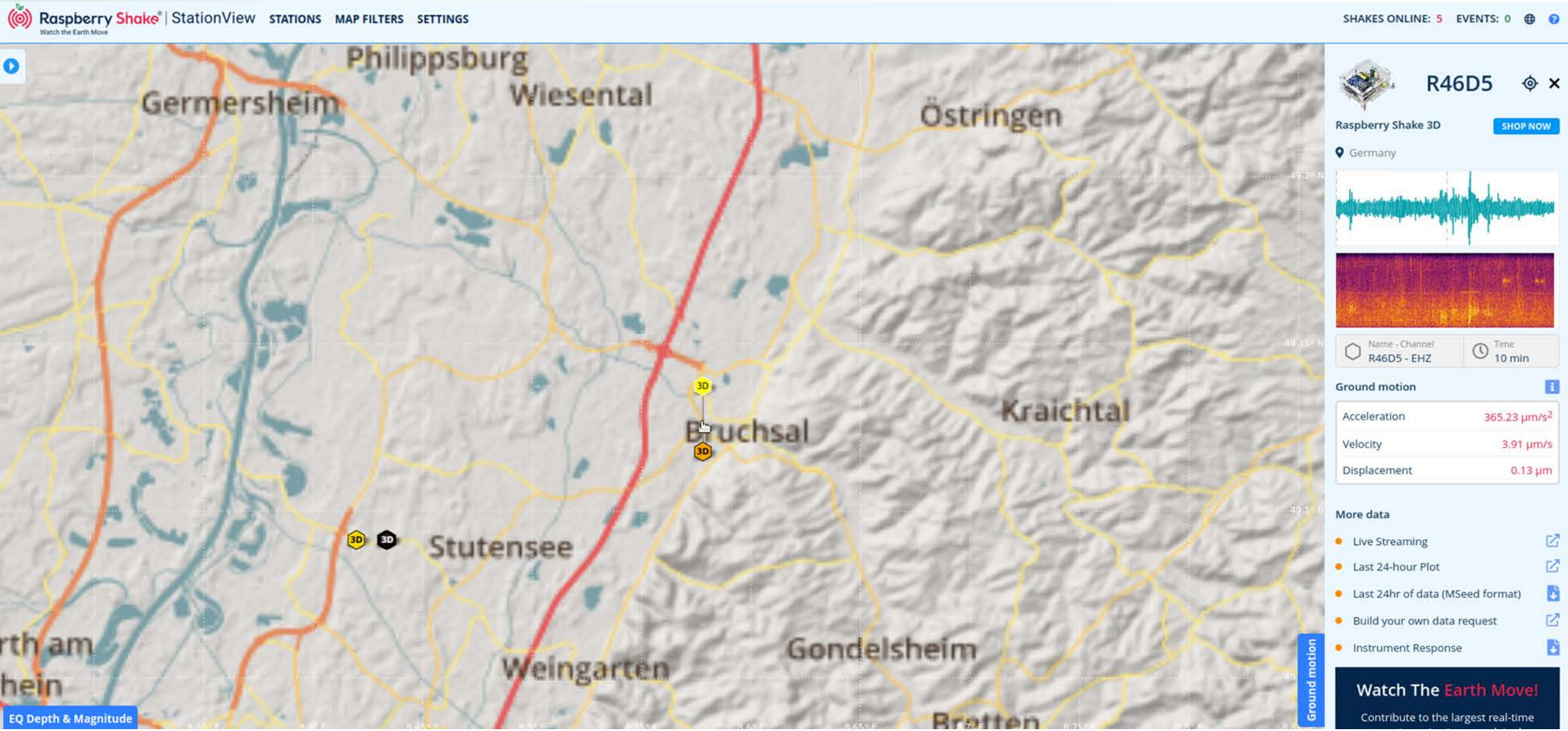
comparison with standard noise levels

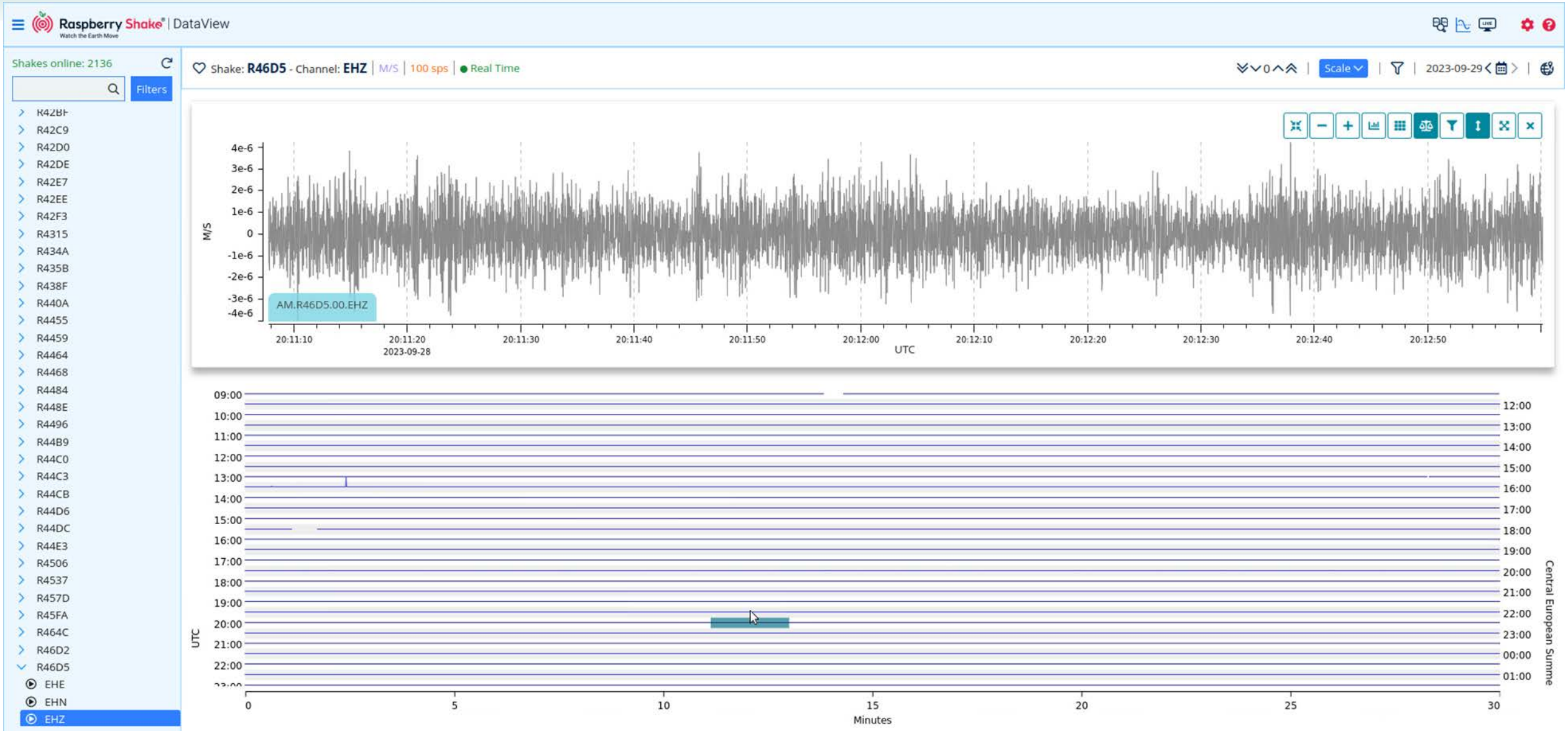
- Until module 5 (November 14) >> more or less in autonomy (but don’t hesitate to contact me!)

- Change the location of the RS in library

- Continue to run the scripts

- Compare behaviours at different locations. Present a video


Raspberry Shake | StationView
STATIONS
MAP FILTERS
SETTINGS
SHAKES ONLINE: 5
EVENTS: 0
Philippsburg
Germersheim
Wiesental
Östringen
Kraichtal
Bruchsal
Stutensee
Weingarten
Gondelsheim
Bretten
R46D5
Raspberry Shake 3D
SHOP NOW
Germany
Name - Channel
R46D5 - EHZ
Time
10 min
Ground motion
Acceleration
365.23 µm/s²
Velocity
3.91 µm/s
Displacement
0.13 µm
More data
Live Streaming
Last 24-hour Plot
Last 24hr of data (MSeed format)
Build your own data request
Instrument Response
Watch The Earth Move!
Contribute to the largest real-time
EQ Depth & Magnitude
Ground motion


Raspberry Shake | DataView
Watch the Earth Move
Shakes online: 2136
Filters
R42C9
R42D0
R42DE
R42E7
R42EE
R42F3
R4315
R434A
R435B
R438F
R440A
R4455
R4459
R4464
R4468
R4484
R448E
R4496
R44B9
R44C0
R44C3
R44CB
R44D6
R44DC
R44E3
R4506
R4537
R457D
R45FA
R464C
R46D2
R46D5
EHE
EHN
EHZ
Shake: R46D5 - Channel: EHZ | M/S | 100 sps | Real Time
Scale
2023-09-29
4e-6
3e-6
2e-6
1e-6
0
-1e-6
-2e-6
-3e-6
-4e-6
M/S
AM.R46D5.00.EHZ
20:11:10
20:11:20
2023-09-28
20:11:30
20:11:40
20:11:50
20:12:00
UTC
20:12:10
20:12:20
20:12:30
20:12:40
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22:00
23:00
00:00
01:00
Central European Summe
0
5
10
15
20
25
30
Minutes

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Module 4’ bis: analysis of Raspberry Shake data

- Gather all the data in one dataset

>> Done

- Show you how to run the scripts / adapt some parameters

>> Done for one script (plotting data)

>> Requires additional information for second one

- Show you how to read / interpret the measurements

>> *How to evaluate the background seismic noise level?*

I. Estimate the noise level at **specific periods of time**, analyze changing behaviors over periods (e.g. day / night)

>> Analyze the **amplitude** of ground vibrations

>> **Frequency** content of the signals

II. Estimate some indicators in **every** 30 min windows, then analyze results **statistically**

>> Analyze the **amplitude** of ground vibrations

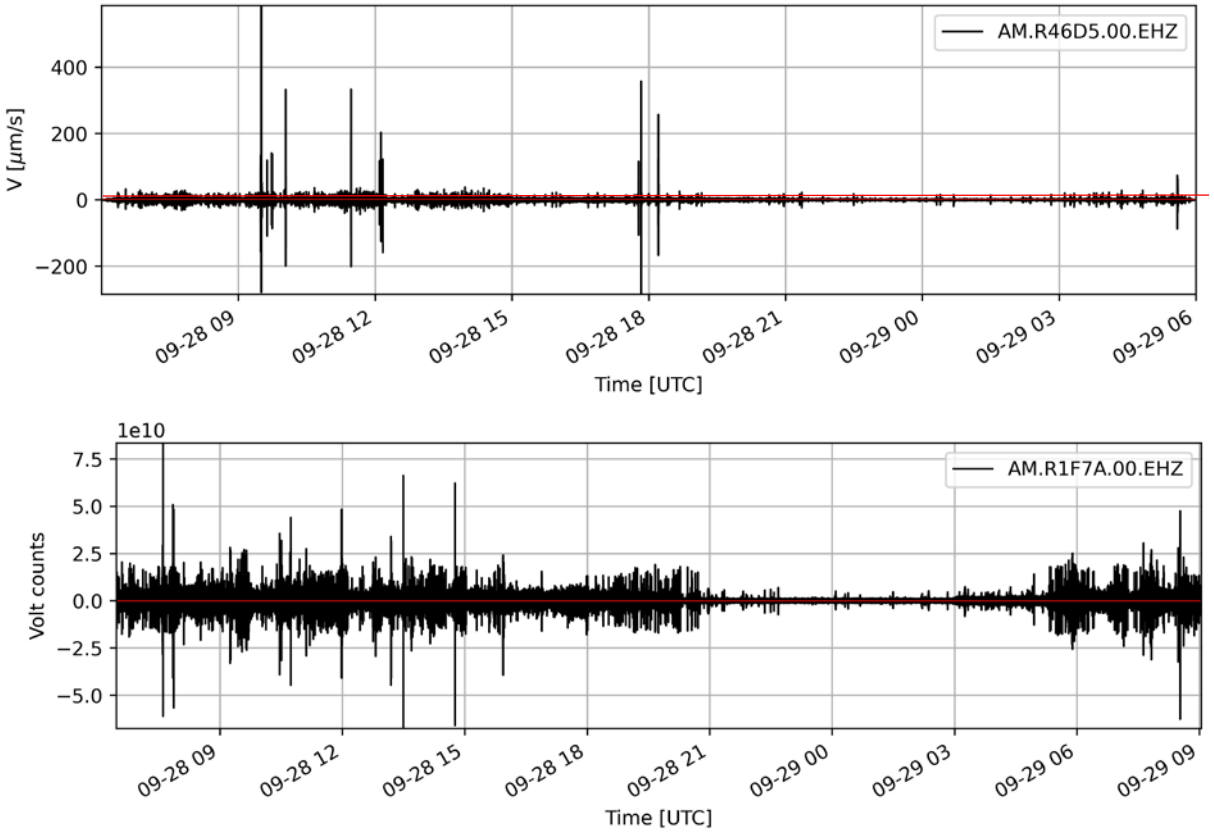
>> **Frequency** content of the signals

>> *How to evaluate the background seismic noise level?*

I. Estimate the noise level at specific periods of time, analyze changing behaviors over periods (e.g. day / night)

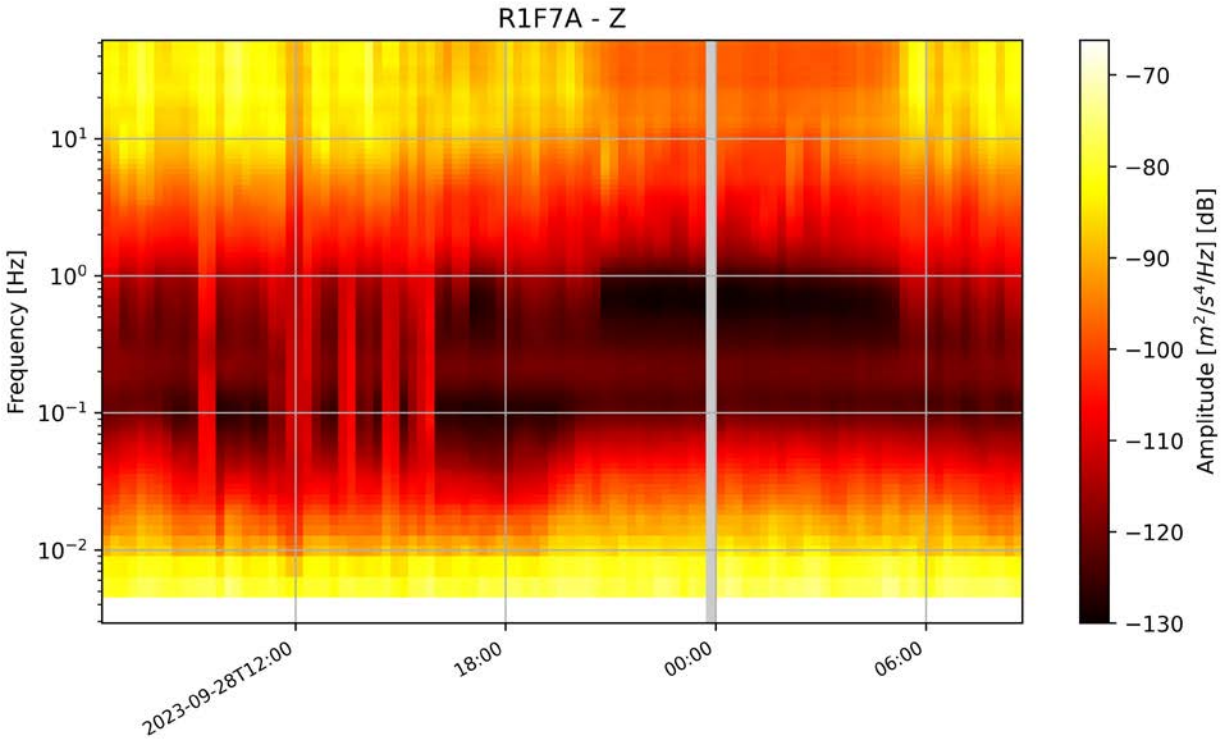
II. Estimate some indicators in 30 min windows, then analyze results statistically

>> Analyze the amplitude of ground vibrations



→ We require noise amplitudes **lower than 2 µm/s** (in red)

>> Frequency content of the signals



Spectrogram = Freq. content over time, evolution of details in signal

→ High noise = yellow color levels

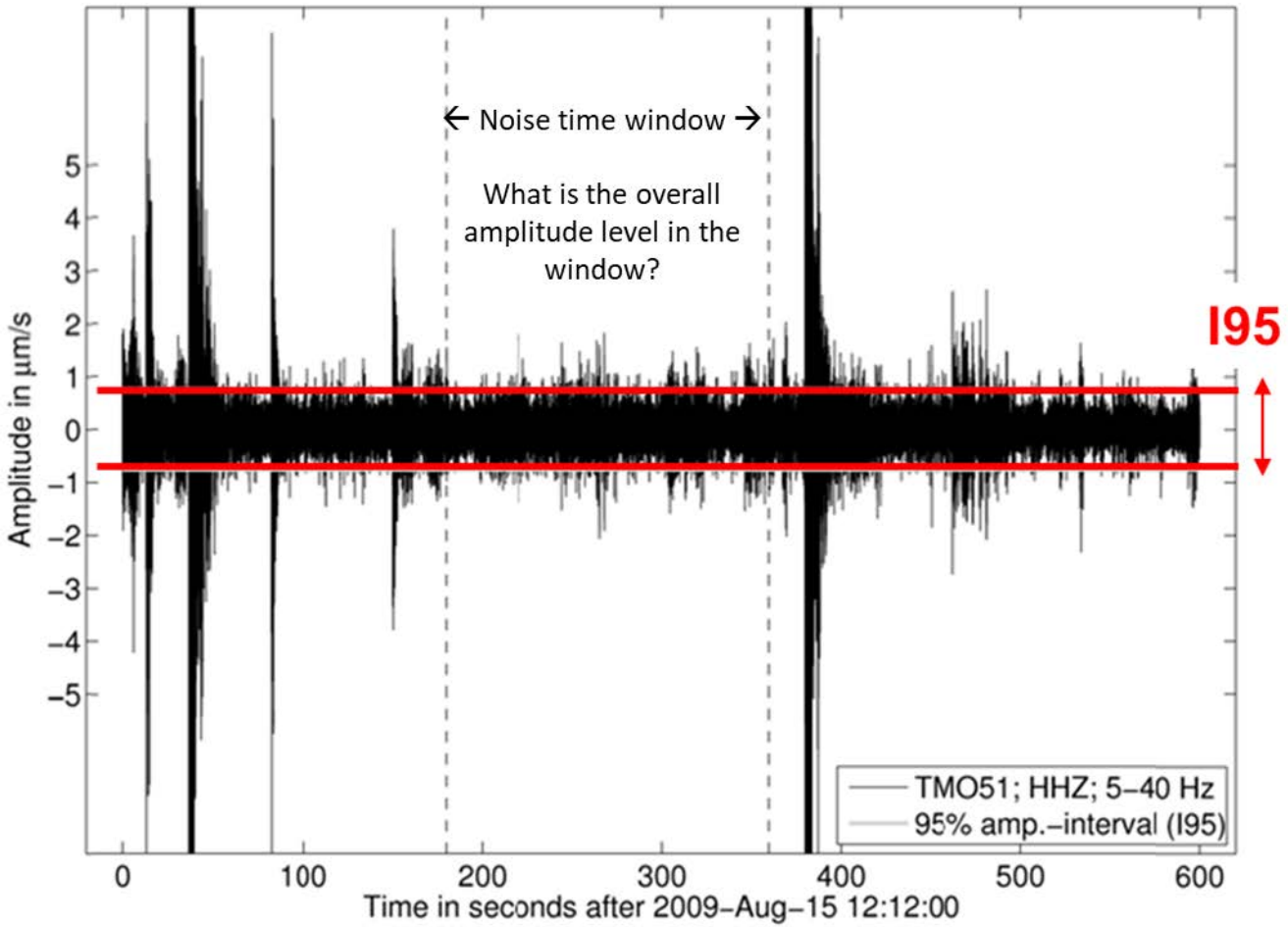
→ Night *vs* day: Impact of human activity

>> *How to evaluate the background seismic noise level?*

I. Estimate the noise level at specific periods of time, analyze changing behaviors over periods (e.g. day / night)

II. Estimate some indicators in 30 min windows, then analyze results statistically

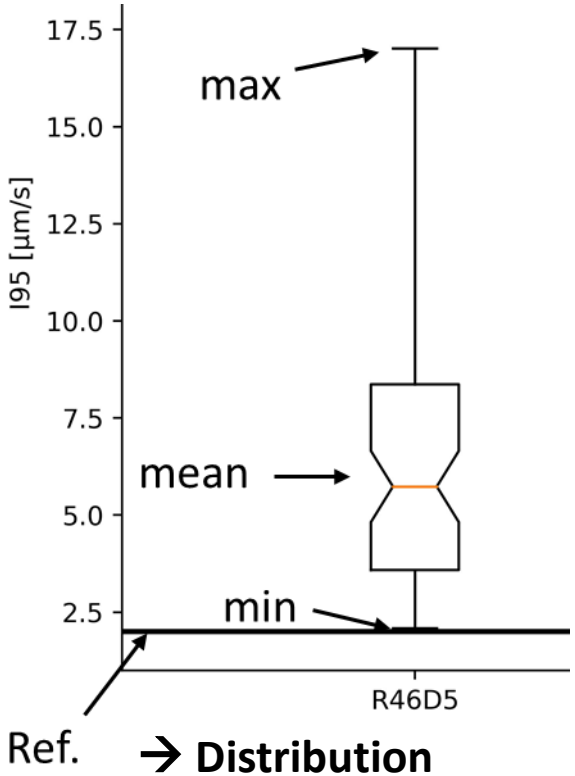
>> Analyze the amplitude of ground vibrations



>> *How to evaluate the background seismic noise level?*

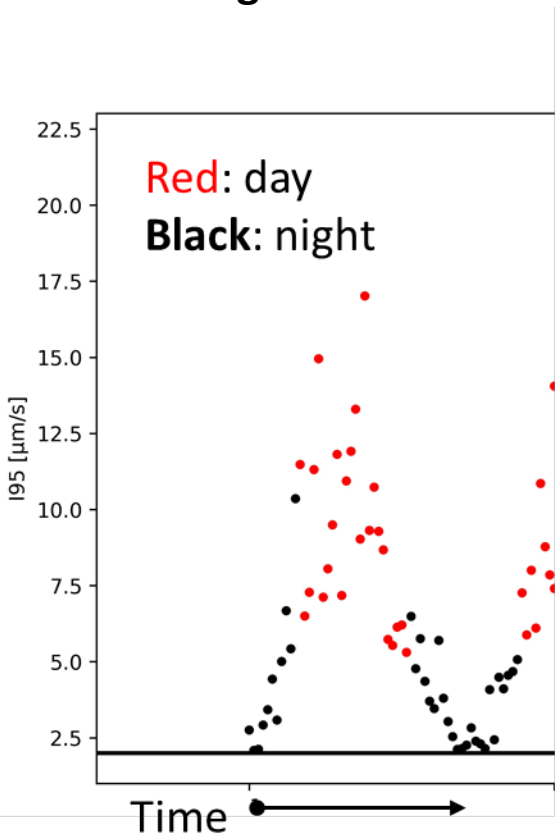
I. Estimate the noise level at specific periods of time, analyze changing behaviors over periods (e.g. day / night)

>> Analyze the amplitude of ground vibrations



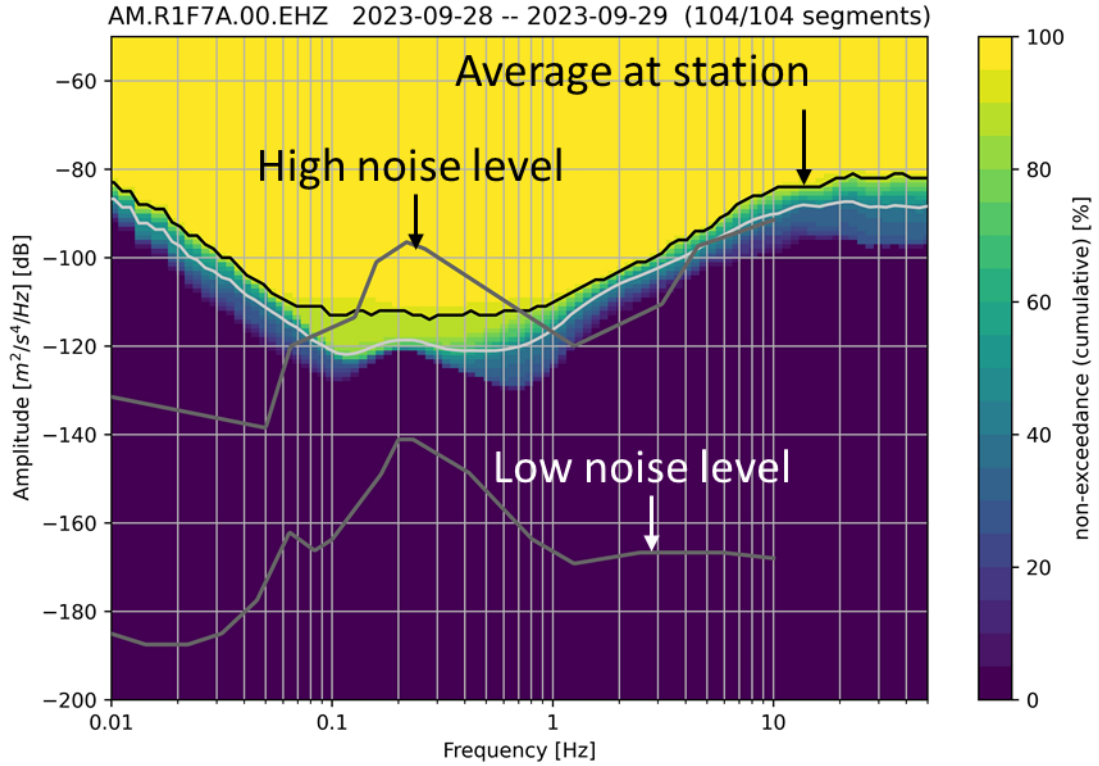
→ **Distribution per station**

→ **All values, in each segment**



II. Estimate some indicators in 30 min windows, then analyze results statistically

>> Frequency content of the signals



ProbabilisticPSD = statistical analysis of spectral content

→ for each freq., shows the probability to not exceed a certain level of noise

→ comparison with standard noise levels

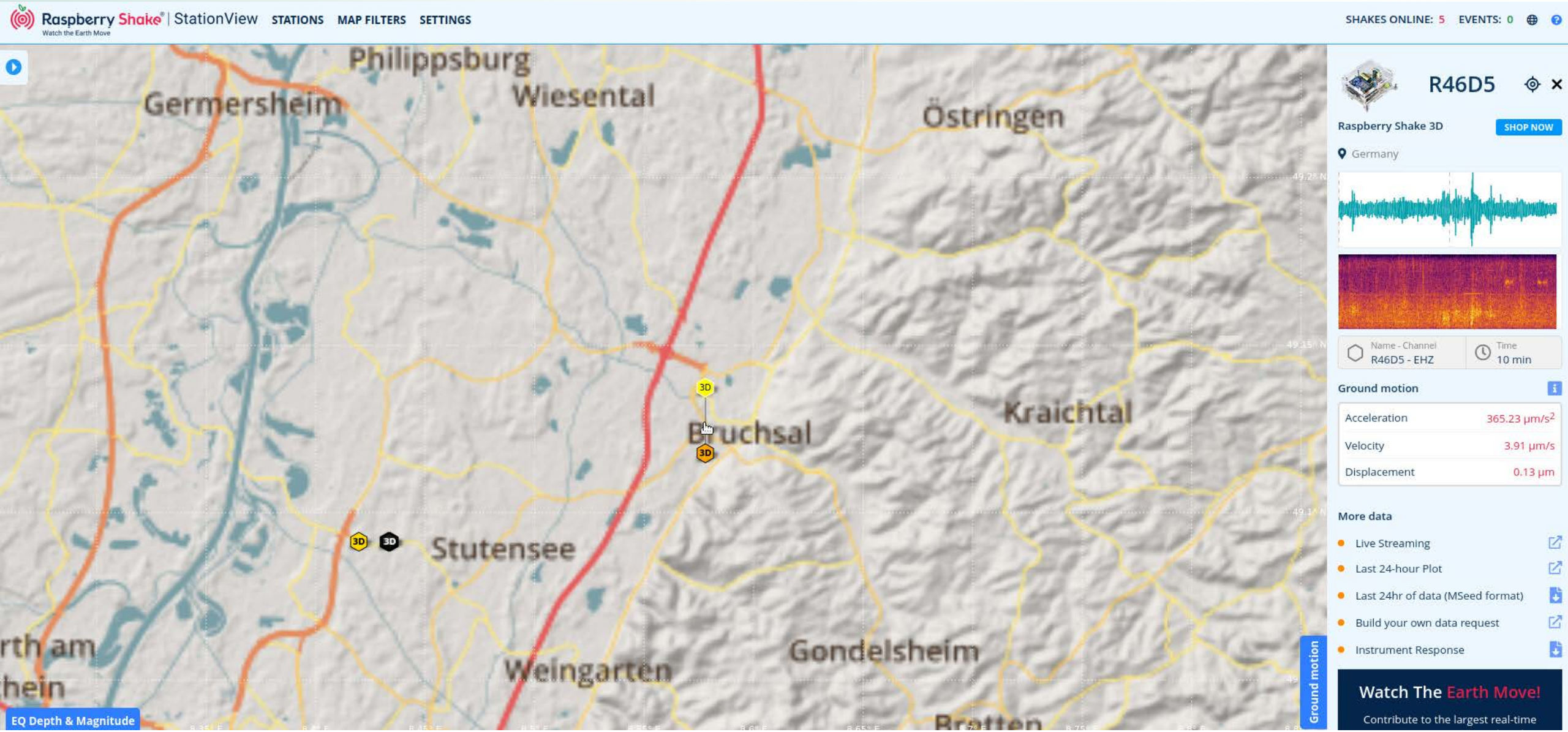
- Until module 5 (November 14) >> more or less in autonomy

(but don’t hesitate to contact me!)

- Change the location of the RS in library

- Continue to run the scripts
  - Each group 1 station / 1 dataset
  - Gather your observations: statistical analysis, or temporal analysis around specific events
  - In view of presenting (video / powerpoint…)

- Module 5: we will compare behaviours at different locations.


Raspberry Shake | StationView
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SHAKES ONLINE: 5
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Philippsburg
Germersheim
Wiesental
Östringen
Kraichtal
Stutensee
Weingarten
Gondelsheim
3D
R46D5
Raspberry Shake 3D
SHOP NOW
Germany
Name - Channel
R46D5 - EHZ
Time
10 min
Ground motion
Acceleration
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Displacement
0.13 µm
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Last 24hr of data (MSeed format)
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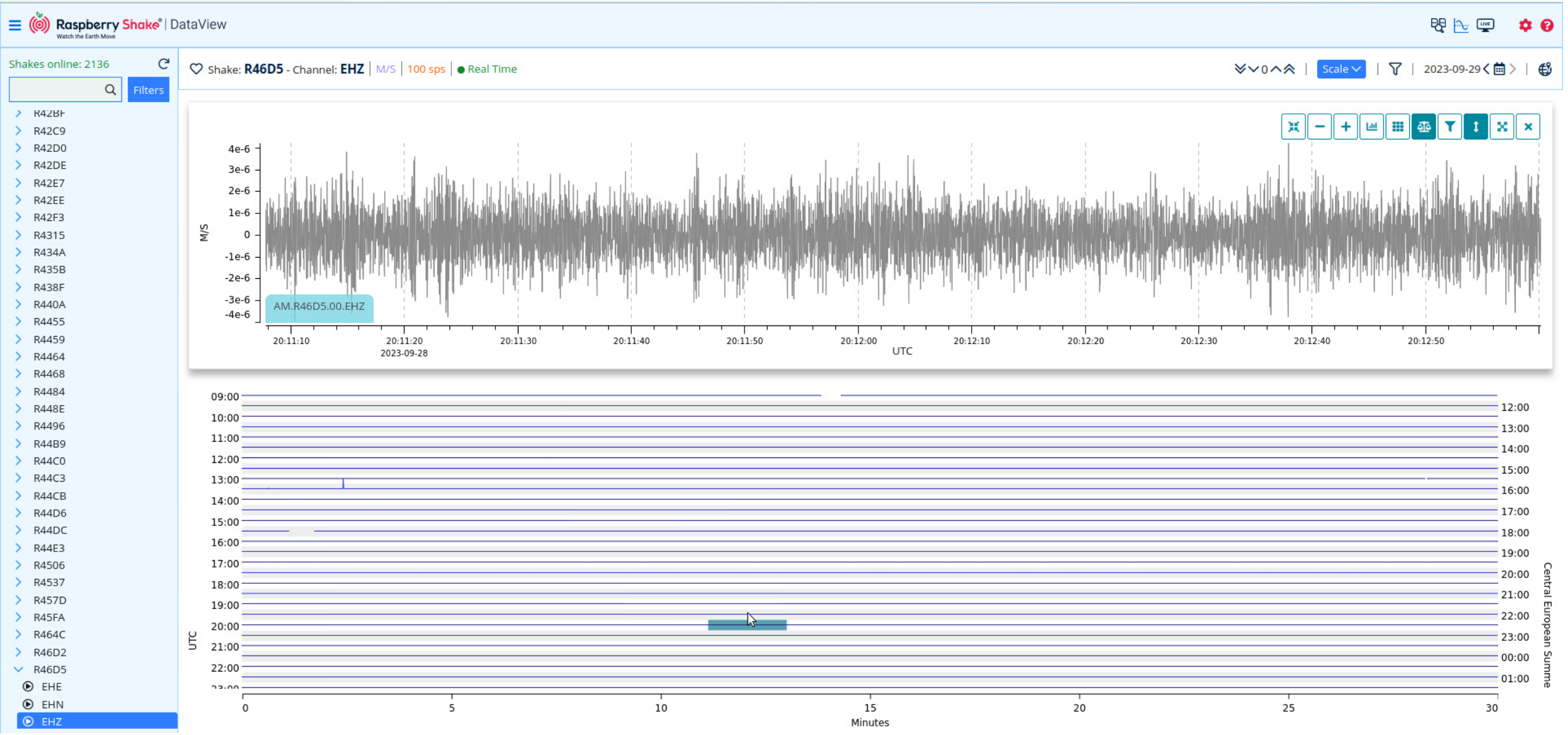
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R42C9
R42D0
R42DE
R42E7
R42EE
R42F3
R4315
R434A
R435B
R438F
R440A
R4455
R4459
R4464
R4468
R4484
R448E
R4496
R44B9
R44C0
R44C3
R44CB
R44D6
R44DC
R44E3
R4506
R4537
R457D
R45FA
R464C
R46D2
R46D5
EHE
EHN
EHZ
Shake: R46D5 - Channel: EHZ | M/S | 100 sps | Real Time
0
Scale
2023-09-29
4e-6
3e-6
2e-6
1e-6
0
-1e-6
-2e-6
-3e-6
-4e-6
M/S
AM.R46D5.00.EHZ
20:11:10
20:11:20
2023-09-28
20:11:30
20:11:40
20:11:50
20:12:00
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Minutes

Station ID	RS IP address	Location - longitude / latitude (WGS84)	Installation / recovery date	Comments
R46D5	10.11.18.189	49.133, 8.5825	Sep 26, 9:00	In the library
R1F7A	10.11.20.182	49.134, 8.583	Sep 27, 10:43	In the teacher room LZ1
R83D2	169.254.173.212	49.134, 8.5835	Sep 27, 11:00	In the garden
RB11B	169.254.4.210	49.135, 8.5765	Sep 27, 11:30	Along the road
RF93C	169.254.51.196	49.1355, 8.581	Sep 27, 12:30	At the ENBW site

Connect a computer to the Raspberry Shake [RS]

Connect to the computer network where the RS Shake is currently connected. Does the seismic station include a router?

- If yes, connect the Ethernet cable between the router and the computer, or connect to the Wifi network of the router (password: Meletta-1260).
- If not, connect the Ethernet cable between the RS and the computer.

Search for the ID and IP address of the RS. Does the seismic station include a router?

- If yes, you need to use the IP address that the router gives to the RS once the two are connected together. In our infrastructure, it is **10.11.1W.1** for each router and **10.11.1W.XYZ** for each RS.
- I not, the RS gets the IP from itself. You need to use the "discovery IP address".

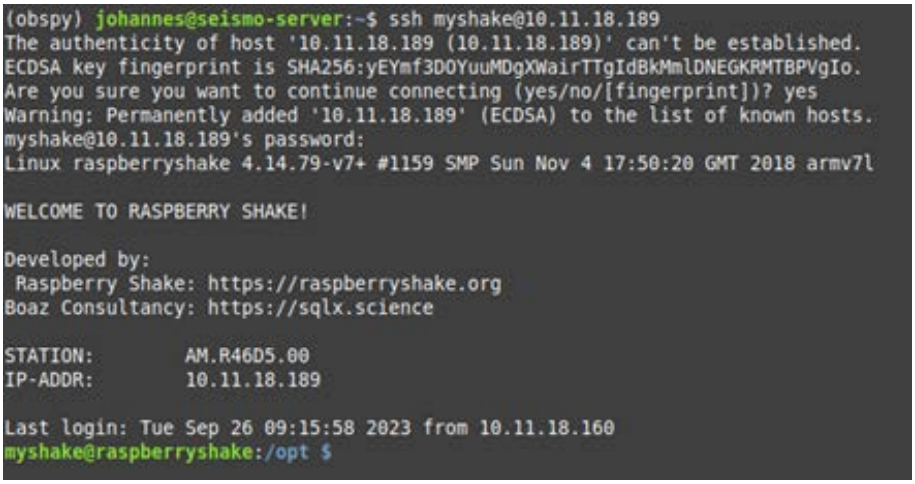
>> In the following, let us take the example of the router with static IP 10.11.18.1 (the one in the library) and the RS with IP 10.11.18.189. We assume that we save the data in D:/HEISENBERG. You need to adapt the command lines with the IP address you looked for and the correct directory pathname.

Open a command prompt on your computer. Open the Start menu or press the Windows key + R. Enter cmd or cmd.exe in the Run command box. Press Enter.

>> A command prompt makes it possible for users to type commands as text to interact with the system, to request the computer to execute some tasks accordingly.

Verify that you are connect to the same network as the RS. In the prompt, enter the command line
ping 10.11.18.189
and change the IP address accordingly.
>> The returned message should state that bytes are returned.

Connect to the RS. In the prompt, enter the command line
ssh myshake@10.11.18.189
and change the IP address accordingly.
>> If it is the first time you connect, it will request your permission. Enter "yes".
>> Enter the password, which is "shakeme" (it is not displayed while typing).
>> You are now connected to the Linux distribution of the RS (on the Raspberry Pi). You land on the "**/opt**" ("optional") directory. Data are stored in the directory "**/opt/data/archive**".



Data are stored following the **SEED** format on the RS. Hence, the directory tree follows a logic: in the directory "/opt/data/archive", we save data in sub-directories using the following tokens:
>> [/opt/data/archive] /Year/ Network [AM] / Station / Channel [N/E/Z]

We save 1 file per channel and per day. Following **SEED**, the names of files follow a similar logic:
>> Network [AM] . Station . 00 . Channel [N/E/Z] . Year . Day nbr [1 to 365]

```
myshake@raspberryshake:/opt $ cd /opt/data/archive/2023/AM/R46D5/EHZ.D/
myshake@raspberryshake:/opt/data/archive/2023/AM/R46D5/EHZ.D $ pwd
/opt/data/archive/2023/AM/R46D5/EHZ.D
myshake@raspberryshake:/opt/data/archive/2023/AM/R46D5/EHZ.D $ ls -l
total 6900
-rw-r--r-- 1 root root 2776576 Sep 20 09:06 AM.R46D5.00.EHZ.D.2023.263
-rw-r--r-- 1 root root 4278272 Sep 26 12:45 AM.R46D5.00.EHZ.D.2023.269
myshake@raspberryshake:/opt/data/archive/2023/AM/R46D5/EHZ.D $
```

Cheat-sheet. **bash** scripting language for Linux distributions.
>> "**exit**": To stop the connection between the RS and the computer.
>> "**pwd**". To check the current directory. When coding, you have to be aware of your **Current Directory** (entering the command **pwd** will give you the current Directory). It is possible to read files and run programs located in the current Directory without mentioning the full path : they are directly executable
>> "**ls -l**": To display the content of a the current directory, in form of a list.
>> "**ls -l** /AAA/BBB/CCC": To display the content of "/AAA/BBB/CCC". Rather than the current directory.
>> "**cd** /AAA/BBB/CCC": To change the current directory, and move to "/AAA/BBB/CCC".
>> Use the tab key to facilitate navigation within the directories: it will complete the directory name automatically if it exists. Double click on tab will give you all possibilities within reach.
>> "**cd ../**": instead of moving forward to a next directory, it makes it possible to move backward to a parent directory.
>> "**mkdir** /AAA/BBB/DDD/": To create a new folder in the directory "AAA/BBB/".
>> "**cp** /AAA/BBB/CCC/file1 /AAA/BBB/DDD/": To copy the file1 located in "/AAA/BBB/CCC" to a new location "/AAA/BBB/DDD/".
>> "**cp** /AAA/BBB/CCC/* /AAA/BBB/DDD/": To copy all the files in "/AAA/BBB/CCC" to a new location "/AAA/BBB/DDD/".

Transfer data from the Raspberry Shake [RS] to your computer

Follow the four first steps of "Connect a computer to the Raspberry Shake [RS]"

Transfer the queried data. In the prompt, enter the command line
scp –r myshake@10.11.18.189:/opt/data/archive/* D:\HEISENBERG
and change the IP address and the destination (D:\HEISENBERG) according to your needs.

Notes:
>> The "-r" means recursive mode: it will clone the directory tree
>> The asterisk (*****) is used as a wildcard character to match more characters in a filename or a string.
>> You can use it to avoid specifying a station name, or select the files of all 3 channels with 1 command line: 2023/AM/*/EH*.D/*, for example.

Example:

```
(obspy) johannes@seismo-server:~$ scp -r myshake@10.11.20.236:/opt/data/archive/2023/AM/*/*Z*/*68 /media/johannes/USB_KIT_AGW/RS_data9/
myshake@10.11.20.236's password:
AM.RB11B.00.EHZ.D.2023.268                                    100% 8690KB  83.7KB/s   01:43
```

With data being available after transfer locally, on the computer, with the same directory tree:

Data quality check using Python – Obspy library

Start "**Anaconda Prompt**" (see example below, [1]).

Enter "**conda activate obspy**". This will switch to the python environment where **obspy** was installed

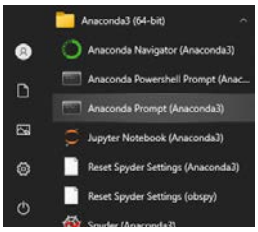
Enter the following command line to launch the Quality Check program (see below):
python -m obspy.imaging.scripts.scan D:\HEISENBERG --no-x --no-gaps
and change the IP address and the destination (D:\HEISENBERG) according to your needs.

A figure will be generated (see example below, [2]). You can save it in your directory.

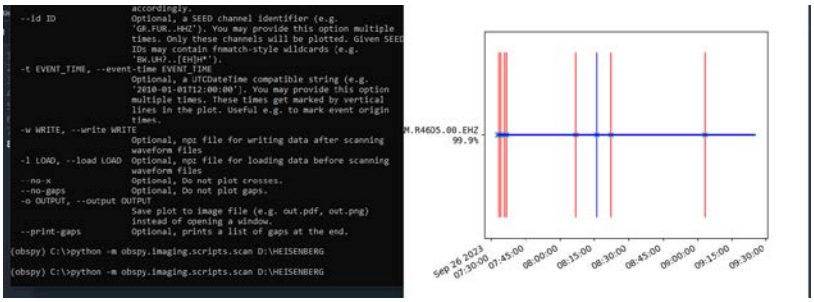
Notes:
>> you can apply this to all the measurements simultaneously (i.e. for all stations). For that, group all the data files in the same directory, for example D:\HEISENBERG above. Hence, the folder "AM" should include one folder / station.
>> "--no-x --no-gaps" are optional. More info about the available options can be found by entering "python -m obspy.imaging.scripts.scan --h", or by visiting the website here.

Example:

[1]



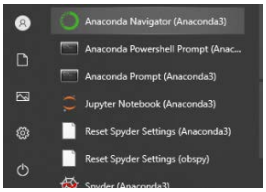
[2]



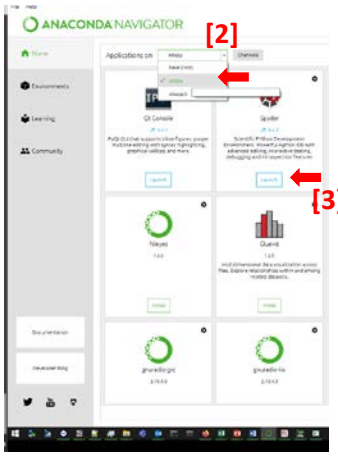
Loading data for visualization using Python - Obspy library.

Start and load the environment. Start "**Anaconda Navigator**" (see example below [1]). Select the "**obspy**" environment, where the obspy library was installed (see example below [2]). Launch the "**Spyder**" software (see example below [3]). Spyder is an interface from where you can write / run scripts and enter command lines in a console.

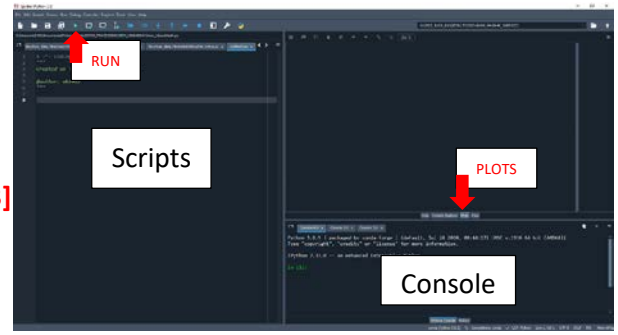
[1]



[2]



[3]



Load the necessary functions in your environment from the obspy library. In the console, enter successively the following:
"**from obspy.core import read**"
"**import os, glob**"

Notes:
>> The **os** library makes it possible to mimic some functions of the bash script language, to move to a specific directory (os.chdir("/your/Directory/Pathname")) or to make a new directory (os.mkdir("/your/NewDirectory/Name")).
>> The **glob** library makes it easy to search for specific files, and store the locations / full path in a list of names, a list of strings. For example, glob.glob("/your/Directory/Path/*") will return all the files located at the level of the asterisk *. It is quite useful when you want to apply the same processing to many files.

Read a file. For example, "D:/HEISENBERG/AM.R46D5.00.EHZ.D.2023.269", we want to load the data file in a variable called for example "qst", for "queried stream" (it could be any other word). Enter the following command:
"**qst = read("D:/HEISENBERG/AM.R46D5.00.EHZ.D.2023.269")**"

```
In [1]: from obspy.core import read

In [2]: import os, glob

In [3]: qst = read("D:/HEISENBERG/AM.R46D5.00.EHZ.D.2023.269")
```

Notes:
>> When coding, you can define **variables** according to your needs, to store data / information/ parameters. A variable is defined by it a **type** (what kind of value the variable will hold), a **name** (how you will use the variable later in the code), and a **value** (what the variable points to). Variables have specific types. What you find in brackets "" is a list of characters: we call that a string. Just as integers (1, 4, 10) or floating numbers (3.16, 8.117, ...), strings are a type of variable possible in the python language.
>> You cannot use "\" signs in Windows directory names: replace it by "/"

>> Here we enter the **full pathname** of the data file (D:/HEISENBERG/AM.R46D5.00.EHZ.D.2023.269) Another option is to move the current directory to "D:/HEISENBERG/", using the os library: os.chdir("D:/HEISENBERG "). And then enter qst = read("AM.R46D5.00.EHZ.D.2023.269"), because the file is directly readable from the current directory

What happened? Obspy "automatically" recognizes the **SEED** format, builds a **Stream** (the variable "qst") and stores the data inside. An obspy **Stream** can contain multiple seismogram **Traces.** Each trace represents a single time series recorded from a seismometer, and includes metadata.

Play around with the loaded data.
>> Enter the name of your variable in the console to display the content. Here, the **Stream** "qst" contained **9 Traces** (see picture below) because the acquisitions were momentarily interrupted at multiple times.

>> Applying the function "**.merge()**" to the stream makes it possible to merge all the data in one single trace.

```
In [5]: qst
Out[5]:
9 Trace(s) in Stream:
AM.R46D5.00.EHZ | 2023-09-26T07:32:53.645999Z - 2023-09-26T07:33:17.045999Z | 100.0 Hz, 2341 samples
AM.R46D5.00.EHZ | 2023-09-26T07:33:17.081000Z - 2023-09-26T07:34:07.741000Z | 100.0 Hz, 5067 samples
AM.R46D5.00.EHZ | 2023-09-26T07:34:07.776000Z - 2023-09-26T07:35:50.536000Z | 100.0 Hz, 10277 samples
AM.R46D5.00.EHZ | 2023-09-26T07:35:50.567000Z - 2023-09-26T07:36:41.207000Z | 100.0 Hz, 5065 samples
AM.R46D5.00.EHZ | 2023-09-26T07:36:41.240999Z - 2023-09-26T08:06:53.110999Z | 100.0 Hz, 181188 samples
AM.R46D5.00.EHZ | 2023-09-26T08:06:53.144000Z - 2023-09-26T08:16:07.884000Z | 100.0 Hz, 55475 samples
AM.R46D5.00.EHZ | 2023-09-26T08:16:07.572000Z - 2023-09-26T08:22:01.572000Z | 100.0 Hz, 35401 samples
AM.R46D5.00.EHZ | 2023-09-26T08:22:01.763000Z - 2023-09-26T09:03:06.253000Z | 100.0 Hz, 246450 samples
AM.R46D5.00.EHZ | 2023-09-26T09:03:10.013000Z - 2023-09-26T09:25:05.513000Z | 100.0 Hz, 131551 samples

In [6]: qst.merge()
Out[6]:
1 Trace(s) in Stream:
AM.R46D5.00.EHZ | 2023-09-26T07:32:53.645999Z - 2023-09-26T09:25:05.515999Z | 100.0 Hz, 673188 samples (masked)
```

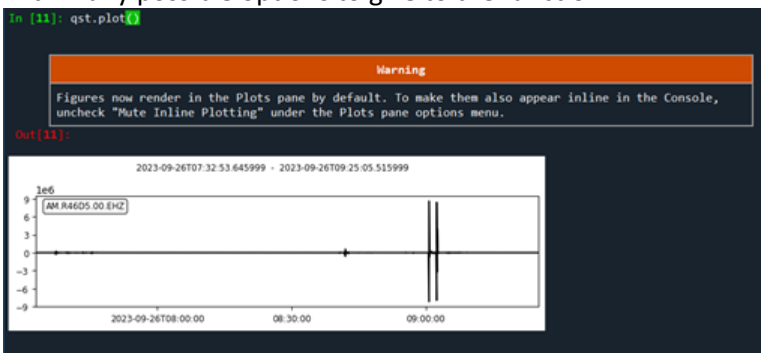
>> Metadata from each **Trace** are accessible as showed below (like for time-stamps, amplitude data,…)

```
In [4]: qst[0].stats
Out[4]:
         network: AM
         station: R46D5
        location: 00
         channel: EHZ
       starttime: 2023-09-26T07:32:53.645999Z
         endtime: 2023-09-26T07:33:17.045999Z
    sampling_rate: 100.0
           delta: 0.01
            npts: 2341
           calib: 1.0
         _format: MSEED
           mseed: AttribDict({'dataquality': 'D', 'number_of_records': 10, 'encoding': 'STEIM2', 'byteorder':
'>', 'record_length': 512, 'filesize': 1544192})

In [8]: qst[0].data
Out[8]:
masked_array(data = [15149 15670 15773 ..., 16977 17026 16728],
             mask = [False False False ..., False False False],
       fill_value = 999999)

In [9]: qst[0].times()
Out[9]:
masked_array(data = [0.0 0.01 0.02 ..., 6731.85 6731.86 6731.87],
             mask = [False False False ..., False False False],
       fill_value = 1e+20)
```

>> Data in a Stream (or Trace) can be plotted with the **plot()** function. In that case, we display Voltage counts, not velocity (conversion needs to be done before…). In addition, a tutorial is available here, with many possible options to give to the function.



Glossary:

Command prompt / command lines: a command prompt makes it possible for users to type commands as text to interact with the system, to request the computer to execute some tasks accordingly.

IP address, "Internet Protocol address“, a numerical label assigned to each device connected to a computer network, used for communication.

"SEED" format, or **S**tandard for the **E**xchange of **E**arthquake **D**ata.

SSH “Standard Shell”, a network protocol and cryptographic technology used to secure data communication over a computer network.

SCP “Secure Copy Protocol”, a network protocol used for securely transferring files between a local host and a remote host or between two remote hosts over a network.

Anaconda is a widely-used open-source distribution of Python, also available from Windows distributions.

ObsPy is an open-source Python toolbox which provides a set of tools and libraries for working with seismic data, ObsPy is widely used in the field of seismology for various tasks related to seismic data analysis and research.

Glossary – Glossar

- **Epicenter:** the point on the Earth's surface directly above the hypocenter of an earthquake. It is the location where the seismic waves generated by the earthquake are first felt or detected.

***Epizentrum**: der Punkt auf der Erdoberfläche direkt über dem Hypozentrum (s.u.) eines Erdbebens. Es ist der Ort, an dem die seismischen Wellen, die durch das Erdbeben erzeugt werden, am ersten gespürt oder erkannt werden.*

- **Earthquake service:** organization or service dedicated to monitoring and providing information about earthquakes. They play a crucial role in monitoring seismic activities, issuing alerts, and providing information to the public, government agencies, emergency responders, and other stakeholders in regions prone to earthquakes.

***Erdbebendienst**: Eine Organisation oder ein Dienst, der sich der Überwachung und Bereitstellung von Informationen über Erdbeben widmet. Erdbebendienste spielen eine entscheidende Rolle bei der Überwachung seismischer Aktivitäten, der Ausgabe von Warnungen und der Bereitstellung von Informationen für die Öffentlichkeit, Regierungsbehörden, Rettungskräfte und andere Interessengruppen in erdbebengefährdeten Regionen.*

- **Frequencies**: they tell us how often a specific pattern or event repeats in a given timeframe. They are crucial for understanding the pitch of sounds, the characteristics of waves, and various phenomena in the natural world. High frequencies correspond to rapid cycles, resulting in high-pitched sounds or waves, while low frequencies involve slower cycles and produce lower-pitched sounds or waves.

***Frequenzen**: Sie geben an, wie oft ein bestimmtes Muster oder Ereignis in einem gegebenen Zeitraum wiederholt wird. Sie sind entscheidend für das Verständnis der Tonhöhe von Geräuschen, der Eigenschaften von Wellen und verschiedener Phänomene in der Natur. Hohe Frequenzen entsprechen schnellen Zyklen und erzeugen hochfrequente Geräusche oder Wellen, während niedrige Frequenzen langsamere Zyklen beinhalten und niederfrequente Geräusche oder Wellen erzeugen.*

- **Geothermal Systems - Petrothermal systems**: a type of geothermal technology that exploits resources in formations that are not permeable enough for water to circulate. Reservoir needs to be enhanced then by various methods.

***Petrothermalsysteme**: Sie zielen auf Formationen ab, die nicht durchlässig genug sind, damit Wasser zirkulieren kann. Das Reservoir muss dann durch verschiedene Methoden verbessert werden.*

- **Geothermal Systems - Hydrothermal systems**: a type of geothermal technology that exploits thermal resources in the form of hot water located in a permeable aquifer to provide heat or power. They target permeable rock formations where water circulates naturally.

***Hydrothermalsysteme**: eine geothermische Technologie, die Energieressourcen in Form von heißem Wasser in einem durchlässigen Grundwasserleiter zur Wärmegewinnung oder Stromerzeugung ausnutzt. Sie zielen auf durchlässige Gesteinsformationen ab, in denen das Wasser natürlich zirkuliert.*

- **Hypocenter** (or focus point): the actual location within the Earth where an earthquake originates or initiates. It is the point beneath the Earth's surface where the fault slip or rupture occurs, releasing energy and generating seismic waves that spread in all directions.

Hypozentrum *(oder Fokus): der Ort innerhalb der Erde, an dem ein Erdbeben seinen Ursprung hat oder initiiert wird. Es ist der Punkt unterhalb der Erdoberfläche, an dem der Bruch oder die Ruptur der Verwerfung auftritt, wodurch Energie freigesetzt wird und seismische Wellen erzeugt werden, die sich in alle Richtungen ausbreiten.*

- **Intensity**: a measure of the strength of shaking which is based on testimonies and reports about the effect of the seismic waves on the people, objects and buildings.

Intensität*: ein Maß für die Stärke der Erschütterung, das auf Zeugenaussagen und Berichten über die Auswirkungen der seismischen Wellen auf Menschen, Gegenstände und Gebäude beruht.*

- **Local magnitude** (often denoted as "ML"): a measurement of the strength of an earthquake. It is referenced on a magnitude scale. This measurement is based on the maximal amplitude of ground motion produced by an earthquake. Local magnitude scale was one of the first magnitude scales developed for measuring the strength of earthquakes and is often associated with the Richter scale, which was originally used to estimate local magnitudes in southern California (USA).

Lokale Magnitude *(oft als "ML" bezeichnet): ein Maß für die Stärke eines Erdbebens. Sie wird auf einer Magnitudenskala angegeben. Dieses Maß basiert auf der maximalen Amplitude der von einem Erdbeben verursachten Bodenbewegung. Die lokale Magnitudenskala war eine der ersten Magnitudenskalen, die zur Messung der Stärke von Erdbeben entwickelt wurde, und wird häufig mit der Richterskala in Verbindung gebracht, die ursprünglich zur Schätzung lokaler Magnituden in Südkalifornien (USA) verwendet wurde.*

- **Moment magnitude** (“M0”): another measurement of the strength of an earthquake. It is referenced on a magnitude scale, as local magnitudes. Moment magnitude takes into account the seismic moment, which is a measure of the total energy released by an earthquake. Seismic moment is calculated based on factors such as the area of the fault that slipped, the amount of slip along the fault, and the rigidity of the Earth's crust. The formula has been adapted to fit to local scales, but the magnitude values may differ, especially for the largest earthquakes.

Momentmagnitude *("M0"): ein weiteres Maß für die Stärke eines Erdbebens. Sie bezieht sich wie die lokalen Magnituden auf eine Magnitudenskala, aber die Momentmagnituden beruhen auf einer physikalischen Messung der bei einem Erdbeben freigesetzten Energiemenge. Die Formel wurde an die lokale Skala angepasst, aber die Magnitudenwerte können abweichen, insbesondere bei den größten Erdbeben.*

- **Seismometer**: an instrument that responds to ground vibrations (the sensing element).

Seismometer*: Ein Instrument, das auf Bodenvibrationen reagiert (das Sensorelement).*

- **Seismograph**: generally composes of the sensor(s), plus a timing and a recording device.

Seismograph*: Im Allgemeinen besteht er aus dem Sensor oder den Sensoren, einem Zeitmesser und einer Aufzeichnungsvorrichtung.*

- **Seismogram**: the graphical output of the seismograph.

***Seismogramm**: Die grafische Ausgabe des Seismographen.*

- **Seismicity – Induced seismicity**: earthquakes that are triggered or induced by human activities. These activities particularly involve the extraction or injection of fluids into the Earth's subsurface. These earthquakes are caused by changes in pressure, stress distribution, or other geological conditions resulting from human activities, rather than natural tectonic processes.

***Seismizität – Induzierte Seismizität**: Erdbeben, die durch menschliche Aktivitäten ausgelöst oder induziert werden. Bei diesen Aktivitäten geht es insbesondere um die Förderung oder Injektion von Flüssigkeiten in den Erduntergrund. Diese Erdbeben werden durch Veränderungen des Drucks, der Spannungsverteilung oder anderer geologischer Bedingungen aufgrund menschlicher Aktivitäten verursacht, nicht durch natürliche tektonische Prozesse.*

- **Seismicity - Micro seismicity**: small-scale seismic events or earthquakes that are too minor to be felt by humans (generally magnitudes below 2) but can be detected and recorded by sensitive seismographs.

***Seismizität - Mikroseismizität**: seismische Ereignisse oder Erdbeben, die zu gering sind, um von Menschen wahrgenommen zu werden (in der Regel Magnituden unter 2), aber von empfindlichen Seismographen erkannt und aufgezeichnet werden können.*

- **Seismic noise**: the relatively persistent vibration of the ground due to a multitude of causes (e.g. human activity) and generally classified as the unwanted component of signals.

***Seismisches Rauschen**: Die relativ konstante Vibration des Bodens aufgrund einer Vielzahl von Ursachen (z. B. menschlicher Aktivitäten) und wird im Allgemeinen als unerwünschter Bestandteil von Signalen klassifiziert.*

- **Traffic Light System**: a framework for monitoring and warning that uses a color-coded approach to communicate the status of geothermal reservoirs or wells. It helps operators, regulators, and other stakeholders assess the condition and behavior of geothermal systems and make informed decisions based on predefined thresholds.

***Ampelsystem**: ein Überwachungs- und Warnsystem, das den Status von geothermischen Reservoiren oder Bohrlöchern anhand eines farbcodierten Ansatzes anzeigt. Es hilft Betreibern, Aufsichtsbehörden und anderen Interessengruppen, den Zustand und das Verhalten geothermischer Systeme zu beurteilen und fundierte Entscheidungen auf der Grundlage vordefinierter Schwellenwerte zu treffen.*

- **Waves**: A wave transmits information or energy in the form of oscillation through a medium. When particles vibrate in a medium in which the wave propagates, then the wave is known as a mechanical wave. Unlike mechanical waves, electromagnetic waves do not need a medium to propagate.

***Wellen**: Eine Welle überträgt Informationen oder Energie in Form von Schwingungen durch ein Medium. Wenn Partikel in einem Medium vibrieren, in dem sich die Welle ausbreitet, wird die Welle als mechanische Welle bezeichnet. Im Gegensatz zu mechanischen Wellen benötigen elektromagnetische Wellen kein Medium zur Ausbreitung.*

- **Waveform:** a graphical representation of the variation of a physical quantity over time.

***Wellenform**: Eine grafische Darstellung der zeitlichen Entwicklung einer physikalischen Größe über die Zeit.*

- **Seismic waves**: a type of mechanical wave that propagates through the Earth's interior as a result of the release of energy during geological processes (e.g. earthquakes, volcanic activity). Seismic waves are responsible for the ground shaking and vibrations felt during an earthquake and play a crucial role in helping scientists study the Earth's interior structure.

***Seismische Wellen**: Eine Art mechanischer Welle, die sich als Folge der Freisetzung von Energie während geologischer Prozesse (z.B. Erdbeben, vulkanischer Aktivität) durch das Innere der Erde ausbreitet. Seismische Wellen sind verantwortlich für das Beben des Erdbodens und die Erschütterungen, die bei einem Erdbeben spürbar sind, und spielen eine entscheidende Rolle dabei, Wissenschaftlern bei der Erforschung der inneren Struktur der Erde zu helfen.*

- **P-waves**: also known as a primary waves or compressional waves, is a type of seismic wave that travels through the Earth during an earthquake or other seismic events. P-waves are the fastest seismic waves and are the first to be detected by seismographs.

***P-Welle**: Auch als Primärwelle oder Kompressionswelle bekannt, ist eine Art seismischer Welle, die sich während eines Erdbebens oder anderer seismischer Ereignisse durch die Erde bewegt. P-Wellen sind die schnellsten seismischen Wellen und werden als erste von Seismographen erfasst.*

- **S-waves**: also known as a secondary waves or shear waves, is another type of seismic wave that propagates through the Earth during seismic events like earthquakes. S-waves are slower than P-waves and can only travel through solid materials.

***S-Welle**: Auch als Sekundärwelle oder Scherwelle bekannt, ist eine andere Art von seismischer Welle, die sich während seismischer Ereignisse wie Erdbeben durch die Erde bewegt. S-Wellen sind langsamer als P-Wellen und können nur durch feste Materialien hindurchgehen.*

- **Surface waves** (Love and Raleigh waves): type of seismic wave that travel along the Earth's surface due to the interaction of body waves (P-waves and S-waves) with the surface interface. Unlike body waves that propagate through the Earth's interior, surface waves stay closer to the Earth's surface and can cause significant ground shaking and damage.

*"**Oberflächenwellen**" (Love und Raleigh): Art von seismischen Wellen, die sich aufgrund der Wechselwirkung von Körperwellen (P- und S-Wellen) mit der Oberflächengrenzfläche entlang der Erdoberfläche ausbreiten. Im Gegensatz zu Körperwellen, die sich durch das Erdinnere ausbreiten, bleiben Oberflächenwellen näher an der Erdoberfläche und können erhebliche Bodenerschütterungen und Schäden verursachen.*

```
# -*- coding: utf-8 -*-
"""
Plots the amplitude vs time information from the data files recorded by the RS


Local functions:
    - get_PAZ: To load the instrumental response (RESP or XML files) for a
    given station / channel
    - get_Data: To load DATA for a given station / channel from ROOTDATA
    Search for data at a given julday, Network name specified in ROOTDATA
    - plot_stream: To plot the content of the stream object Qst_copytrace by trace,
after
    removal of instrument response, and save the plots in QOUT
    Optional: Deine a specific plotting window from Qstart_plot to Qend_plot


local variables:
    See below

@author: Jerome Azzola [KIT]
"""


# ============================================================================
# LIBRARIES
# ============================================================================
import os, sys, datetime, glob
import numpy as np
import matplotlib.pyplot as plt
from obspy.core import UTCDateTime, Stream, read
from obspy.signal import PPSD
from obspy.core.inventory.inventory import read_inventory


# ============================================================================
# IN an OUT PARAMETERS
# ============================================================================

# Change these parameters depending on your request
Qstart = UTCDateTime(2023, 9, 20, 23, 0, 0) # start of the time series to load
Qend = UTCDateTime(2023, 10, 10, 2, 0, 0) # end of the time series to load

# Change these parameters once only
MAIN_FOLDER = 'C:/Users/wb2462/Documents/DEEPSTOR/HEISENBERG/' # the folder where
your project is situated
stations_names = ["R46D5", "R1F7A", "R83D2", "RB11B", "RF93C"] # the stations we are
interested in
want_rmvResponse = True # [bool] do you want to remove he instrumental response or
not
QChannel = 'Z' # [str] queried channel to be analysed: 'Z', 'E', 'N' or '*' for all


# Automatically assigned parameters
QOUT = MAIN_FOLDER +'OUTPUT/' # [str] folder to store all the output figures / data
ROOTSDS = MAIN_FOLDER + 'RS_DATA/' # [str] folder with RS data: root of the SDS
repository
ROOTINV = MAIN_FOLDER + 'RS_inventory/' # [str] folder with inventory files for all
queried stations
ROOTDATA = ROOTSDS + str(Qstart.year) + '/*/'
QInvType = 'STATIONXML' # [str] type of inventory to load to remove the instrumental
response



# ============================================================================
# LOCAL FUNCTIONS
# ============================================================================

# ============================================================================
# To load the instrumental response (RESP or XML files) for a given station / channel
```

```
# ============================================================================
def get_PAZ(Qdir, QSTA, Qchannel, Qformat):

    # Search the queried file
    if Qformat == 'STATIONXML':
        myfiles = glob.glob(Qdir + '*' + str(QSTA) + '*.xml')
    elif Qformat == 'RESP':
        myfiles = glob.glob(Qdir + '*' + str(QSTA) + '*.resp')
    else:
        print('Unrecognized PAZ file format')
        sys.exit()

    if len(myfiles)> 1:
        myfile = glob.glob(Qdir + '*' + str(QSTA) + '*' + str(Qchannel) +
'*.resp')[0]
    else:
        myfile = myfiles[0]

    # Read the information from file using obspy
    inv = read_inventory(myfile, format=Qformat)

    return inv


# ============================================================================
# To load DATA for a given station / channel from ROOTDATA
# Search for data at a given julday
# Network name specified in ROOTDATA
# ============================================================================
def get_Data(QSTA, QChannel, ROOTDATA, ROOTINV, QInvType, QDayNbr):

    # Search all necessary files
    Qfiles = glob.glob(ROOTDATA + QSTA + '/*' + QChannel + '*/*' + str(QDayNbr))

    # Read the files in an obspy stream object
    St2return = Stream()
    for Qfile in Qfiles:
        Qst = read(Qfile)
        St2return += Qst

    return St2return



# ============================================================================
# To plot the content of the stream object Qst_copytrace by trace, after
# removal of instrument response, and save the plots in QOUT
# Optional: Deine a specific plotting window from Qstart_plot to Qend_plot
# ============================================================================
def plot_stream(Qst_copy, Qpaz, QOUT, want_rmvResponse = False, Qstart_plot=None,
Qend_plot=None):

    for Qtr in Qst_copy:
        # convert from volt counts to velocity
        pre_filt = [0.001, 0.005, 45, 50]
        if want_rmvResponse:
            Qtr = Qtr.remove_response(inventory=Qpaz,
                                      pre_filt=pre_filt,
                                      output="VEL")
        # filter the data before displaying
        Qtr = Qtr.filter("bandpass", freqmin=5.0, freqmax=40.0)
        # optional: reduce the time series
        if Qstart_plot and Qend_plot:
            Qtr = Qtr.slice(starttime = UTCDateTime(Qstart_plot),
                      endtime = UTCDateTime(Qend_plot))
        # plot the waveform
        fig = plt.figure(figsize=(10, 3), dpi=500)
        plt.plot(Qtr.times('matplotlib'), Qtr.data*1e6, 'k-',
                 label = Qtr.get_id(), linewidth = 1)
        plt.plot([Qtr.times('matplotlib')[0], Qtr.times('matplotlib')[-1]],
```

```
                  [2, 2], 'r-', linewidth = 0.5)
        plt.gca().xaxis_date(); fig.autofmt_xdate()
        plt.gca().set_xlabel('Time [UTC]')
        if want_rmvResponse:
            plt.gca().set_ylabel('V [$\mu$m/s]')
        else:
            plt.gca().set_ylabel('Volt counts')
        plt.xlim(Qtr.times('matplotlib')[0], Qtr.times('matplotlib')[-1])
        plt.ylim(np.min(Qtr.data)*1e6, np.max(Qtr.data)*1e6)
        plt.legend(); plt.grid()
        fig.savefig(QOUT +
'/Trace_'+str(Qtr.stats.station)+'_'+str(Qtr.stats.channel),
                    bbox_inches = "tight", dpi = 500)
        del Qtr

    return 0



# ================================================================================
# INIT
# ================================================================================
if not os.path.isdir(QOUT):
    os.mkdir(QOUT)

QDayNbrs = np.arange(Qstart.julday, Qend.julday+1, 1)

if not os.path.isdir(ROOTSDS):
    print('ERROR: please move the main data directory to folder RS_DATA')
    sys.exit()

if not os.path.isdir(ROOTINV):
    print('ERROR: please move the instrument responses to folder RS_inventory')
    sys.exit()

# ================================================================================
# Loop over all the querried stations
# ================================================================================
for QSTA in stations_names:

    # ============================================================================
    # Import the data of interest
    # ============================================================================
    Qpaz = get_PAZ(ROOTINV, QSTA, QChannel, QInvType)
    Qst = Stream()
    for qday in QDayNbrs:
        Qst_temp = get_Data(QSTA, QChannel, ROOTDATA, ROOTINV, QInvType, qday)
        Qst += Qst_temp
        Qst = Qst.merge(fill_value = 0)
        del Qst_temp
    Qst = Qst.slice(starttime = Qstart, endtime = Qend)

    # Plot the waveforms
    plot_stream(Qst, Qpaz, QOUT, want_rmvResponse,
                Qstart_plot=None, Qend_plot=None)
    del Qst
```

```
# -*- coding: utf-8 -*-
"""
Evaluation of the seismic background noise conditions at potential measuring stations

For all stations defined by stations names (stations_names), computes PSD and
I95 values in successive Qmins long windows and outputs a statistical analysis
of the values (PPSD and boxplot of I95 values)


Local functions:
    - do_I95: To compute I95 statistics for a given stream, after filtering and
    removal of instrument response
    - get_PAZ: To load the instrumental response (RESP or XML files) for a
    given station / channel
    - get_Data: To load DATA for a given station / channel from ROOTDATA
    Search for data at a given julday, Network name specified in ROOTDATA
    - do_PPSD: To compute the Probabilistic Power Spectral Density (PPSD)
    and Spectrogram from RS data from a given station QSTA and a given channel
QChannel
    - plot_stream: To plot the content of the stream object Qst_copytrace by trace,
after
    removal of instrument response, and save the plots in QOUT
    Optional: Deine a specific plotting window from Qstart_plot to Qend_plot


local variables:
    See below

@author: Jerome Azzola [KIT]
"""


# ============================================================================
# LIBRARIES
# ============================================================================
import os, sys, datetime, glob
import numpy as np
import matplotlib.pyplot as plt
from obspy.core import UTCDateTime, Stream, read
from obspy.signal import PPSD
from obspy.core.inventory.inventory import read_inventory


# ============================================================================
# IN an OUT PARAMETERS
# ============================================================================

# Change these parameters depending on your request
Qstart = UTCDateTime(2023, 9, 28, 10, 0, 0) # start of the time series to load
Qend = UTCDateTime(2023, 10, 3, 10, 0, 0) # end of the time series to load
QChannel = 'Z' # [str] queried channel to be analysed

# Change these parameters once only
MAIN_FOLDER = 'C:/Users/wb2462/Documents/CITIZEN_SCIENCE/HEISENBERG/' # the folder
where your project is situated
stations_names = ["R46D5", "R1F7A", "R83D2", "RB11B", "RF93C"] # the stations we are
interested in
QInvType = 'STATIONXML' # [str] type of inventory to load to remove the instrumental
response
Qmins = 30 # [mins] duration of the windows used for the computation of statistics
(I95 and PPSD)

# Automatically assigned parameters
QOUT = MAIN_FOLDER +'OUTPUT/' # [str] folder to store all the output figures / data
if not os.path.isdir(QOUT):
    os.mkdir(QOUT)
QOUT = QOUT + QChannel + '_' + Qstart.strftime(format = '%j-%H%M%S') + '_' +
Qend.strftime(format = '%j-%H%M%S')
ROOTSDS = MAIN_FOLDER + 'RS_DATA/' # [str] folder with RS data: root of the SDS
repository
```

```
ROOTINV = MAIN_FOLDER + 'RS_inventory/' # [str] folder with inventory files for all
queried stations
ROOTDATA = ROOTSDS + str(Qstart.year) + '/*/'




# ================================================================================
# LOCAL FUNCTIONS
# ================================================================================

# ================================================================================
# To compute I95 statistics for a given stream, after filtering and removal of
# instrument response
# ================================================================================
# Resources:
# From a signal-to-noise ratio (SNR) of around 3, it is considered that a
# seismic wave can be reliably identified. This criterion sets the average
# background noise amplitude necessary at a station monitoring seismic events at
reservoir depth.
# Noise acquisitions, carried out during several days, can allow to estimate the
amplitude of the back-ground-noise from a statistical point of view
# test measurements over several days before setting it up are recommended.
# In successive windows of duration Qmins, we compute the amplitude interval
# which contains 95% of the amplitude values of the investigated time series. The
width of the interval in noted I95. The metric is analysed in a statistic way over
all computed windows.
# I95 should be at least within ±2 µm/s, better under ±1 µm/s.
# The reference value I95 must be observed in continuous operation (24/7).
#
[https://www.fkpe.org/fileadmin/user_upload/Microsite_FKPE/dokumente/Induzierte_Seism
izitaet/fkpe_ind_seis_monitor_120709_final.pdf]
def do_I95(Qst, Qpaz, Qmins):

    # We initialize the start time of the trace and the expected endtime
    startT_Q = Qst[0].stats.starttime;
    num_traces = len(Qst);
    endT = Qst[num_traces-1].stats.endtime;
    compteur = 0;

    # While it is possible to define a following window, we compute a I95 value
    while startT_Q < endT:

        # Define the data subset
        sliced_st = Qst.slice(startT_Q, startT_Q + 60*Qmins).copy()
        sliced_st = sliced_st.remove_response(inventory=Qpaz,
                                              pre_filt=[0.001, 0.005, 45, 50])
        sliced_st = sliced_st.filter("bandpass", freqmin=5.0, freqmax=40.0)

        # For each available trace, we compute the data
        nbr_traces=len(sliced_st);
        for ii in np.arange(0, nbr_traces, step=1):
            if (ii==0):
                my_data = sliced_st[ii].data;
            else:
                my_data = np.concatenate((my_data, sliced_st[ii].data))

        # Then we compute the I95 and refresh the start time of the current trace
        Q3 = (np.quantile(my_data, 97.5/100)-np.quantile(my_data, 2.5/100))
        startT_Q_new = sliced_st[len(sliced_st)-1].stats.endtime;
        del sliced_st, my_data

        # Then we create/append the output array
        if (compteur==0):
            I95 = Q3; times2save = startT_Q_new;
            startT_Q = startT_Q_new; compteur=compteur+1;
            del Q3, startT_Q_new
        else:
```

```
            I95 =  np.append(I95, Q3); times2save = np.append(times2save,
startT_Q_new);
            startT_Q = startT_Q_new; compteur=compteur+1;
            del Q3, startT_Q_new

    return I95, times2save


# ================================================================================
# To load the instrumental response (RESP or XML files) for a given station / channel
# ================================================================================
def get_PAZ(Qdir, QSTA, Qchannel, Qformat):

    # Search the queried file
    if Qformat == 'STATIONXML':
        myfiles = glob.glob(Qdir + '*' + str(QSTA) + '*.xml')
    elif Qformat == 'RESP':
        myfiles = glob.glob(Qdir + '*' + str(QSTA) + '*.resp')
    else:
        print('Unrecognized PAZ file format')
        sys.exit()

    if len(myfiles)> 1:
        myfile = glob.glob(Qdir + '*' + str(QSTA) + '*' + str(Qchannel) +
'*.resp')[0]
    else:
        myfile = myfiles[0]

    # Read the information from file using obspy
    inv = read_inventory(myfile, format=Qformat)

    return inv


# ================================================================================
# To load DATA for a given station / channel from ROOTDATA
# Search for data at a given julday
# Network name specified in ROOTDATA
# ================================================================================
def get_Data(QSTA, QChannel, ROOTDATA, ROOTINV, QInvType, QDayNbr):

    # Search all necessary files
    Qfiles = glob.glob(ROOTDATA + QSTA + '/*' + QChannel + '*/*' + str(QDayNbr))

    # Read the files in an obspy stream object
    St2return = Stream()
    for Qfile in Qfiles:
        Qst = read(Qfile)
        St2return += Qst

    return St2return


# ================================================================================
# To compute the Probabilistic Power Spectral Density (PPSD) and Spectrogram
# from RS data from a given station QSTA and a given channel QChannel
# ================================================================================
# Used ressources:
#
[https://docs.obspy.org/packages/autogen/obspy.signal.spectral_estimation.PPSD.html]
# Class to compile probabilistic power spectral densities for one combination of
network/station/location/channel/sampling_rate.
# Calculations are based on the routine used by [McNamara2004]. For information on
New High/Low Noise Model see [Peterson1993].
#
[https://docs.obspy.org/packages/autogen/obspy.signal.spectral_estimation.PPSD.plot_s
pectrogram.html#obspy.signal.spectral_estimation.PPSD.plot_spectrogram]
# Plot the temporal evolution of the PSD in a spectrogram-like plot.
```

```
#
[https://docs.obspy.org/packages/autogen/obspy.signal.spectral_estimation.PPSD.plot.h
tml#obspy.signal.spectral_estimation.PPSD.plot]
# Plot the 2D histogram of the current PPSD.
def do_PPSD(ROOTDATA, ROOTINV, Qstart, Qend, QSTA, QChannel, QInvType, QOUT):

    startDay = Qstart.julday; endDay = Qend.julday
    Qfilename = str(QSTA) + '_' + QChannel
    compteur = 0

    for iday in np.arange(startDay, endDay, 1):

        # Get the querried data in an obspy stream
        Qst = get_Data(QSTA, QChannel, ROOTDATA, ROOTINV, QInvType, iday)

        if len(Qst) >0:

            Qpaz = get_PAZ(ROOTINV, QSTA, QChannel, QInvType)

            # If first loop, we initialize the object PPSD and add the stream
            # otherwise, we just add the stream
            if compteur == 0:
                Qnyquist = Qst[0].stats.sampling_rate/2
                ppsd = PPSD(Qst[0].stats, metadata=Qpaz, skip_on_gaps=True,
                            db_bins=(-200, -50, 1.0), ppsd_length = 60*Qmins,
                            overlap=0.5, special_handling=None,
                            period_smoothing_width_octaves=1.0,
                            period_step_octaves=0.125, period_limits=None)
                ppsd.add(Qst); compteur += 1
            else:
                ppsd.add(Qst); compteur += 1
            del Qst

    # plot the PPSD
    ppsd.plot(show=False, show_noise_models=True, show_coverage=False,
                  show_percentiles=True, percentiles=[90],
                  show_mean=True, cumulative=True,
                  xaxis_frequency=True, period_lim=(0.01, Qnyquist))
    fig = plt.gcf(); fig.set_size_inches(9, 6); fig.set_dpi(500)
    fig.savefig(QOUT + '/PPSD_' + Qfilename + '.png',
                bbox_inches = "tight",
                dpi = 500)

    # plot the spectrogram
    try:
        ppsd.plot_spectrogram(show = False, cmap = 'hot', grid = True,
                          clim=[-130, None], y_axis_frequencies = True)
        fig = plt.gcf(); fig.set_size_inches(9, 5); fig.set_dpi(500)
        plt.gca().set_title(QSTA + ' - ' + QChannel)
        fig.savefig(QOUT + '/Spectrogram_' + Qfilename + '.png',
                    bbox_inches = "tight",
                    dpi = 500)
    except:
        print('!! Could not generate the spectrogram from PPSD object !!')

    # save resulting object in form of a npz dataset for further processing
    ppsd.save_npz(filename = QOUT + '/PPSD_' + Qfilename + '.npz')


# ================================================================================
# To plot the content of the stream object Qst_copytrace by trace, after
# removal of instrument response, and save the plots in QOUT
# Optional: Deine a specific plotting window from Qstart_plot to Qend_plot
# ================================================================================
def plot_stream(Qst_copy, Qpaz, QOUT, want_rmvResponse = False, Qstart_plot=None,
Qend_plot=None, Qmax = None):

    for Qtr in Qst_copy:
        # convert from volt counts to velocity
        pre_filt = [0.001, 0.005, 45, 50]
```

```
        if want_rmvResponse:
            Qtr = Qtr.remove_response(inventory=Qpaz,
                                      pre_filt=pre_filt,
                                      output="VEL")
        # filter the data before displaying
        Qtr = Qtr.filter("bandpass", freqmin=5.0, freqmax=40.0)
        Qtr = Qtr.decimate(4)
        # optional: reduce the time series
        if Qstart_plot and Qend_plot:
            Qtr = Qtr.slice(starttime = UTCDateTime(Qstart_plot),
                      endtime = UTCDateTime(Qend_plot))
        # conversion to micro meter / sec
        if want_rmvResponse:
            Qtr.data = Qtr.data*1e6
        # plot the waveform
        fig = plt.figure(figsize=(10, 3), dpi=500)
        plt.plot(Qtr.times('matplotlib'), Qtr.data, 'k-',
                 label = Qtr.get_id(), linewidth = 1)
        plt.plot([Qtr.times('matplotlib')[0], Qtr.times('matplotlib')[-1]],
                  [2, 2], 'r-', linewidth = 0.5)
        plt.gca().xaxis_date(); fig.autofmt_xdate()
        plt.gca().set_xlabel('Time [UTC]')
        if want_rmvResponse:
            plt.gca().set_ylabel('V [$\mu$m/s]')
        else:
            plt.gca().set_ylabel('Volt counts')
        plt.xlim(Qtr.times('matplotlib')[0], Qtr.times('matplotlib')[-1])
        plt.ylim(-15, 15)
        plt.legend(loc = 'upper right'); plt.grid()
        fig.savefig(QOUT +
'/Trace_'+str(Qtr.stats.station)+'_'+str(Qtr.stats.channel),
                    bbox_inches = "tight", dpi = 500)
        del Qtr

    return 0



# ================================================================================
# INIT
# ================================================================================
print("################################################################################")
print("Start at "+str(datetime.datetime.now()))
print("################################################################################")

if "all_I95" in locals():
    del all_I95

if not os.path.isdir(QOUT):
    os.mkdir(QOUT)
else:
    os.chdir(QOUT)
    for qfile in glob.glob('*'):
        os.remove(qfile)

if not os.path.isdir(ROOTSDS):
    print('ERROR: please move the main data directory to folder RS_DATA')
    sys.exit()
if not os.path.isdir(ROOTINV):
    print('ERROR: please move the instrument responses to folder RS_inventory')
    sys.exit()

QDayNbrs = np.arange(Qstart.julday, Qend.julday+1, 1)

# ================================================================================
# Loop over all the querried stations
# ================================================================================
all_I95 = []; all_times = []
for QSTA in stations_names:
```

```
    # ================================================================================
    # Import the data of interest
    # ================================================================================
    Qst = Stream()
    for qday in QDayNbrs:
        Qst_temp = get_Data(QSTA, QChannel, ROOTDATA, ROOTINV, QInvType, qday)
        Qst += Qst_temp
        Qst = Qst.merge(fill_value = 0)
        del Qst_temp


    # How many successive windows will we use for the analysis
    try:
        nbr_windows = int(Qst[0].stats.npts/(Qmins*60*100))
    except:
        nbr_windows = 0

    # If number of successive windows is not sufficient, move to the next station
    # otherwise, we load the inventory / instrument response
    if nbr_windows <= 1:
        stations_names.remove(QSTA)
        continue
    else:
        Qpaz = get_PAZ(ROOTINV, QSTA, QChannel, QInvType)
    print("- - - - - - - - - - - - - - - ")
    print(Qst)
    print(str(nbr_windows) + " individual " + str(Qmins) +"mins-long windows are used
in the processing")
    print("- - - - - - - - - - - - - - - ")


    # ================================================================================
    # Plot the waveforms
    # ================================================================================
    Qst_copy = Qst.copy()
    #plot_stream(Qst_copy, Qpaz, QOUT, want_rmvResponse = True, Qstart_plot=None,
Qend_plot=None, Qmax = 6)
    del Qst_copy


    # ================================================================================
    # While startT_Q + Qmins is bellow endT, for eah trace of Qst
    # We slice the trace and compute amplitude statistics in subtrace
    # ================================================================================
    print("Computing I95 ")
    [I95, times2save] = do_I95(Qst, Qpaz, Qmins); I95 = I95 * 1e6
    all_I95.append(I95)
    all_times.append(times2save)
    print("- - - - - - - - - - - - - - - ")


    # ================================================================================
    # Compute, plot and save PPSD + Spectrogram of loaded stream
    # ================================================================================
    print("Computing PPSD ")
    #do_PPSD(ROOTDATA, ROOTINV, Qstart, Qend, QSTA, QChannel, QInvType, QOUT)
    print("- - - - - - - - - - - - - - - ")


# ================================================================================
# Finally plot the outcomes of the I95 analysis
# ================================================================================
# kk = np.where(all_I95[2] < 0.5)[0]
# all_I95[2][kk] = 2
# kk = np.where(all_I95[3] < 0.5)[0]
# all_I95[3][kk] = 10

# first plot the statistics for all the I95 measurements carried out in all the
windows
plt.figure(figsize = (8, 6), dpi = 500)
```

```
plt.boxplot(all_I95, meanline=True, notch=True,
            showmeans=False, showfliers=False,
            labels=stations_names, whis = 10e10)
plt.xlabel('Station name'); plt.ylabel('I95 [µm/s]');
plt.plot([0, len(all_I95) + 0.5], [2, 2], 'k-', linewidth = 2)
plt.xlim([0.5, len(all_I95) + 0.5]); plt.yscale('log')
plt.ylim([0.5, 200])
plt.savefig(fname= QOUT + '/I95_boxplot.png')
plt.savefig(fname= QOUT + '/I95_boxplot.svg', format = 'svg')
plt.show()

# first plot the statistics for all the I95 measurements carried out in all the
windows
plt.figure(figsize = (8, 6), dpi = 500)
plt.boxplot(all_I95, meanline=True, notch=True,
            showmeans=False, showfliers=False,
            labels=stations_names, whis = 10e10)
plt.xlabel('Station name'); plt.ylabel('I95 [µm/s]');
plt.plot([0, len(all_I95) + 0.5], [2, 2], 'k-', linewidth = 2)
plt.xlim([0.5, len(all_I95) + 0.5])
plt.ylim([-0.5, 45])
plt.savefig(fname= QOUT + '/I95_boxplot2.png')
plt.show()

# first plot the statistics for all the I95 measurements carried out in all the
windows
plt.figure(figsize = (8, 6), dpi = 500)
plt.boxplot(all_I95, meanline=True, notch=True,
            showmeans=False, showfliers=False,
            labels=stations_names, whis = 10e10)
plt.xlabel('Station name'); plt.ylabel('I95 [µm/s]');
plt.plot([0, len(all_I95) + 0.5], [2, 2], 'k-', linewidth = 2)
plt.xlim([0.5, len(all_I95) + 0.5])
plt.ylim([-0.5, 15])
plt.savefig(fname= QOUT + '/I95_boxplot2.png')
plt.show()


# first plot the statistics for all the I95 measurements carried out in all the
windows
# all_I95_copy = all_I95
# for ii, i95 in enumerate(all_I95_copy):
#     kk = np.where(i95>30)
#     all_I95_copy[ii][kk[0]] = 2
plt.figure(figsize = (5, 3), dpi = 500)
violin_parts = plt.violinplot(all_I95, showmeans=True, showmedians=True,
showextrema=False, widths=0.8)
plt.ylabel('I95 [µm/s]');
#plt.plot([0, len(all_I95) + 0.5], [2, 2], 'k-', linewidth = 2)
plt.xlim([0.5, len(all_I95) + 0.5])
plt.yscale('log'); plt.yticks(ticks=[1, 10], labels = ['1', '10'])
plt.xticks(ticks=[1, 2, 3, 4, 5], labels = ['ST1 \n Groundlevel', 'ST2 \n 1st
floor','ST3 \n Garden', 'ST4 \n Roadside', 'ST5 \n Powerplant'])
plt.ylim([0.6, 30])
for vp in violin_parts['bodies']:
    vp.set_facecolor('k')
    vp.set_edgecolor('k')
    vp.set_linewidth(1)
    vp.set_alpha(0.5)
vp = violin_parts['cmeans']
vp.set_edgecolor('r')
vp.set_linewidth(2)
vp = violin_parts['cmedians']
vp.set_edgecolor('b')
vp.set_linewidth(2)
plt.savefig(fname= QOUT + '/I95_boxplot2.png')
plt.show()
```

```
# also plot the I95 values, with a distinction between windows defined in night/day
time (color)
Qnames = stations_names.copy()
Qnames.append('')
Qnames = np.array(Qnames, dtype=object)
plt.figure(figsize = (12, 6), dpi = 500)
for ii in np.arange(len(all_I95)):
    colors2save = []
    for qt in all_times[ii]:
        if qt > UTCDateTime(qt.year, qt.month, qt.day, 5, 0, 0) and qt <
UTCDateTime(qt.year, qt.month, qt.day, 17, 0, 0):
            colors2save.append('r')
        else:
            colors2save.append('k')
    plt.scatter(np.linspace(ii+1, ii+2, num=len(all_I95[ii])), all_I95[ii], c =
colors2save, s = 50, marker='.')
plt.xlabel('Station name'); plt.ylabel('I95 [µm/s]');
plt.plot([0, len(all_I95) + 1.5], [2, 2], 'k-', linewidth = 2)
plt.xlim([0.8, len(all_I95) + 1.2]); plt.grid(); plt.yscale('log')
plt.xticks(ticks = np.arange(len(all_I95)+1)+1, labels = Qnames,
horizontalalignment='left')
plt.ylim([0.5, 100])
plt.savefig(fname= QOUT + '/I95_values.png')
plt.savefig(fname= QOUT + '/I95_values.svg', format = 'svg')
plt.show()

plt.figure(figsize = (12, 6), dpi = 500)
for ii in np.arange(len(all_I95)):
    colors2save = []
    for qt in all_times[ii]:
        if qt > UTCDateTime(qt.year, qt.month, qt.day, 5, 0, 0) and qt <
UTCDateTime(qt.year, qt.month, qt.day, 17, 0, 0):
            colors2save.append('r')
        else:
            colors2save.append('k')
    plt.scatter(np.linspace(ii+1, ii+2, num=len(all_I95[ii])), all_I95[ii], c =
colors2save, s = 50, marker='.')
plt.xlabel('Station name'); plt.ylabel('I95 [µm/s]');
plt.plot([0, len(all_I95) + 1.5], [2, 2], 'k-', linewidth = 2)
plt.xlim([0.8, len(all_I95) + 1.2]); plt.grid()
plt.ylim([-0.5, 17])
plt.xticks(ticks = np.arange(len(all_I95)+1)+1, labels = Qnames,
horizontalalignment='left')
plt.savefig(fname= QOUT + '/I95_values2.png')
plt.show()

print("################################################################################")
print("End at "+str(datetime.datetime.now()))
print("Check results in "+ QOUT)
print("################################################################################")
```