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Applied geophysics in schools to raise knowledge and awareness about geothermal energy and seismology

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ABSTRACT

The Upper Rhine Graben region is favorable to the exploitation of deep geothermal energy, which could play a significant role in the decarbonization of the energy sector. However, there is a significant lack of awareness on this topic and related subjects. To address this gap, a school project was developed, centered on a role-playing game that engages students in applied geophysics. This innovative approach involves students using Raspberry-Shake sensors to delve into the practical aspects of seismology and seismic monitoring around a geothermal power plant in Bruchsal. We present practical activities and learning experiences designed to impart knowledge and understanding of geothermal energy, with a focus on potential applications in the region. It is complemented by a social scientific analysis aimed at assessing the students' understanding and the impact of the project on their awareness levels. The concept of autonomous monitoring by non-professionals could be further developed into participatory monitoring networks engaging residents in geothermal projects.

Specification table

Subject area	1900: General Earth and Planetary Sciences 1908: Geophysics 2105: Renewable Energy, Sustainability and the Environment 3300: General Social Sciences 3304: Education
Category/categories of societal impact	Education, Economic, Environmental, Societal, Technological
Sustainable Development Goals (SDGS) the research contributes to	*GOAL 4: Quality Education* *GOAL 7: Affordable and Clean Energy* *GOAL 13: Climate Action*
Related published article	
C. Meller, E. Schill, J. Bremer, O. Kolditz, A. Bleicher, C. Benighaus, P. Chavot, M. Gross, A. Pellizzone, O. Renn, F. Schilling, T. Kohl, Acceptability of geothermal installations: A geoethical concept for GeoLaB, Geothermics, Volume 73, 2018, Pages 133–145, ISSN 0375–6505, DOI: 10.1016/j.geothermics.2017.07.008	
Conference Paper	
American Geoscience Union – Fall Meeting Thursday, 14 December 2023 (Poster) Engaging schools and local communities through Raspberry Shake seismometers: a citizen science approach around the geothermal research infrastructure DeepStor, Germany J. Azzola, J. Bremer, E. Gaucher, K. Schätzler, F. Bauer, E. Schill, T. Kohl https://agu.confex.com/agu/fm23/meetingapp.cgi/Paper/1250784DOI: 10.5445/IR/1000168939	
Stage of research	
Complete	

Societal impact

The transition to a decarbonised and sustainable energy system is a contemporary challenge for society that requires breakthrough technologies for renewable energy generation or storage, but also economic and societal transformations [1]. On the societal level, the successful implementation of the necessary infrastructure hinges on achieving social acceptance. This study focuses on deep geothermal projects, which are facing opposition in the renewable energy sector, especially at the local level [2]. These projects are designed to operate geothermal fluids from deep underground reservoirs. Unlike shallow geothermal systems, which rely on near-surface heat, these projects access much higher

Abbreviations: URG, Upper Rhine Graben; RS3D, Raspberry-Shake 3 component seismometer.

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temperatures at depths exceeding 1 km, taking advantage of the elevated temperatures found at such depths for electricity generation and/or direct heating applications. Targeting these deeper reservoirs entails potential environmental risks, driving public debates and concerns [3]. The risks of inducing seismicity, i.e. causing earthquakes due to changes in subsurface stress conditions caused by fluid injection and extraction [4], is at the forefront of public debates [5].

A prerequisite for a public debate on the opportunities and risks of geothermal energy use is awareness of geothermal technologies and related underground processes, e.g. seismological phenomena. In this way, decisions on the use of geothermal energy can be made on a sufficiently factual basis. However, the processes involved are complex, and even projects with strong public relations can experience a perceived information deficit, which may be due to ineffective communication channels between project developers and communities [5]. A lack of opportunities for citizens to get involved in research and development projects is also noted. Providing broad information on various levels as well as opportunities for participation are therefore important building blocks for the successful development of geothermal energy use [6].

Science education – as the basis for knowledge transfer – and informed decision-making, begins at school. However, seismology and geothermal energy are frequently omitted from school curricula, despite their potential regional importance. This can significantly reduce public awareness. One explanation can be the connection to specialized scientific disciplines. Seismology is often perceived as a complex and mathematical discipline, while geothermal energy is considered a niche area within the broader energy sector. This perception can limit the interest of lay people and prevent curriculum developers from including these topics into regular lessons.

However, to interpret and evaluate seismological phenomena, an intuitive understanding is important, for which own experiences are necessary. This is particularly relevant to understand the origin of ground vibrations recorded by seismic sensors. Signals may be related to earthquakes, but also non-hazardous and non-perceptible environmentally induced noise, originating from human or natural sources. The absence of hands-on learning experiences can hinder public understanding. Hence, applied geophysics activities in the framework of geothermal projects could contribute to increasing public awareness of geothermal technologies and seismicity.

Practical school projects are therefore particularly relevant as they offer hands-on experiences to enhance understanding of complex topics, stimulate learning and interest, and foster scientific literacy. When designed with an interdisciplinary approach, they incorporate diverse elements of the curriculum and promote cross-disciplinary understanding. Schools also have the potential to act as multipliers of knowledge and awareness, since schools, teachers and students are usually integrated in a lively network, and intergenerational effects can be expected.

This study addresses this opportunity and documents an interactive school project conducted in a school near the Bruchsal geothermal power plant (Fig. 1), aiming to assess the effectiveness of this approach to raise awareness and overcome communication barriers. It actively engages high school students in evaluating seismic noise levels at various locations around their school and the geothermal plant's injection site.

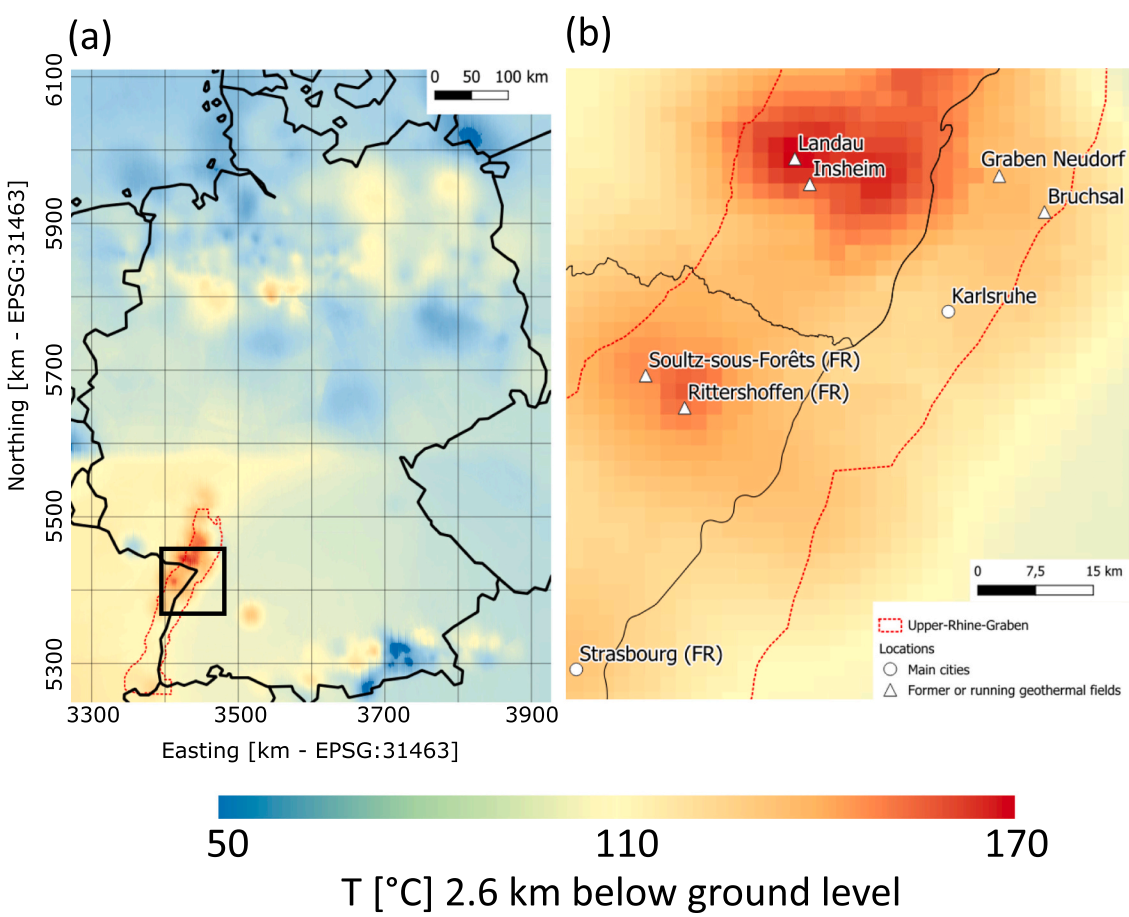

Fig. 1. Map of Germany situating the Rhine Graben (red line). The colored background shows the temperature at a depth of 2.6 km below surface. The zoom on the right shows the location of Bruchsal and nearby major cities and geothermal projects (in white).

Methodological approach

The project involves a school in the city of Bruchsal, in the south-west of Germany, within the Upper Rhine Graben (or URG, Fig. 1). It is a major geological rift valley that experiences elevated subsurface temperatures, with values exceeding 120°C at depths of ~2.6 km [7], making it well-suited for geothermal energy production. The thermal anomaly is primarily controlled by deep fault systems, which facilitate the movement of hot fluids through the fractured sedimentary layers and the underlying crystalline basement. These geological conditions create a natural reservoir of geothermal energy, which is harnessed by several projects in the region, including the Bruchsal geothermal plant next to the school involved in this project (Fig. 2). The context of the project in the URG illustrates a valuable case study for understanding geothermal systems and their potential for sustainable energy production.

A group of 14 high school students aged between 15 and 16 from a national STEM program participated in the project. The school project is structured in five modules (Table 1). It is framed as a role-play, in which students act as seismologists in a geothermal project (Fig. 3a). Their task is to test different locations for installing a seismic station to monitor the plant's activity, which involves quantifying the seismic noise generated by human activity and determining the best location to detect earthquakes, i.e. the one with the least impact of environmental noise.

The first session aims to train students as new "seismologists" in a geothermal project. It provides basic knowledge of geothermal technologies and the local geological context, and discusses the role of geophysics, in particular seismology, in geothermal projects. We place particular emphasis on explaining the origin of induced seismicity and the mitigation strategies, involving seismic monitoring. Then, the students receive training in operating the Raspberry-Shake 3D sensor (RS3D, see Fig. 3b). These devices are compact, plug-and-play and affordable geophones that have the potential to democratize access to seismic data. We use the RS3D to offer practical experience in real-time acquisition and processing of ground vibrations (i.e., velocities). The training includes access and reading of raw data from the sensor via its Linux interface. Finally, the students are involved in planning the fieldwork, selecting five sites to test near the geothermal plant and in the school, with different expected levels of ambient noise (Fig. 2).

After deploying the stations under the guidance of the supervising scientists and teachers, groups are created and assigned a location to maintain the seismic stations during data acquisition, i.e. one week. The students collaborate on data analysis and interpretation using Python scripts for data visualization and background noise estimation. The scientists write the scripts and train the students to define inputs, understand outputs and run the scripts.

Table 1
Breakdown of the five sessions with the objectives, disciplines and capabilities targeted by the developers of the educational materials, i.e. involved scientists and teachers.

Session	Objective	Involved topics	Involved capabilities
1	Introduction, training and discussions	Natural sciences, mathematics, physics	Cognitive flexibility
2	Fieldwork preparation	IT, physics	Scientific demands analysis, organization,
3	Fieldwork	IT, physics	Observation, systematic working approach
4	Data collection and analysis	(Geo-)Physics, programming	Data analysis, critical thinking
5	Final workshop	Synthesis and analysis of data and results	Communication, teamwork, inferential thinking

In addition, the students were provided with a questionnaire during the initial and final sessions. The survey intended to self-evaluate their understanding of related topics and the effectiveness of the activity to increase awareness from a social scientific perspective. The questionnaires are available as supplementary material and cover:

- Affective imagery, as proposed by [8]
- Self-assessment of knowledge
- Risk evaluation
- Project evaluation

Geophysical and social scientific results

A visualization script allows the students to screen the data. Students learn to interpret the time-series, i.e. waveform features like amplitude and frequency. The seismic data helps to identify anthropogenic disturbances such as passing cars or significant activities at the site, such as the environmental noise generated by a school parents' evening. Each group analyzes the weeklong data to compare background noise levels at different locations, revealing temporal and spatial variations in ground vibration levels associated with proximity to areas of significant human activity. For a more systematic comparison of the locations, the students use a second script that generates the violin plots illustrated in Fig. 4a. In the final session, groups present their findings, collectively discuss them, and draw conclusions (Fig. 4b). The garden location proves to be the

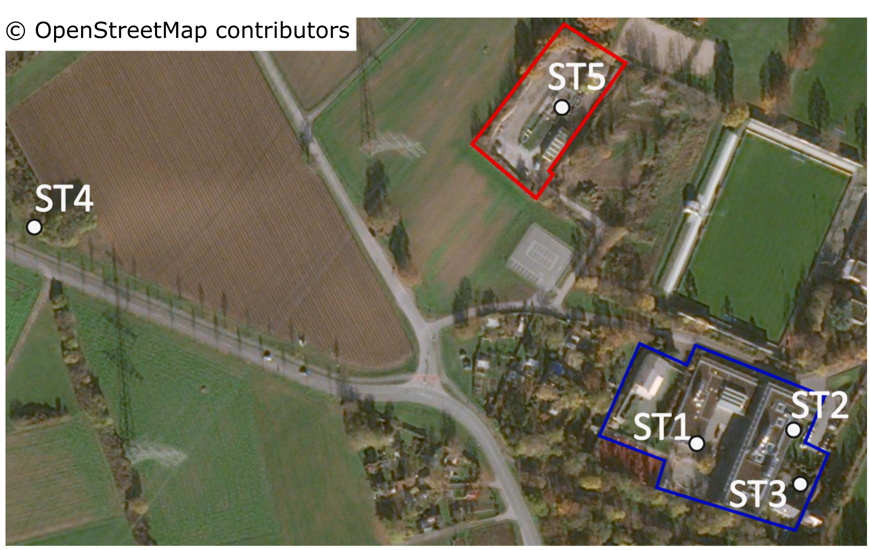

Fig. 2. Focus on the study-site with the geothermal plant (red), the school (blue) and the tested locations (white dots, ST1-ST5).

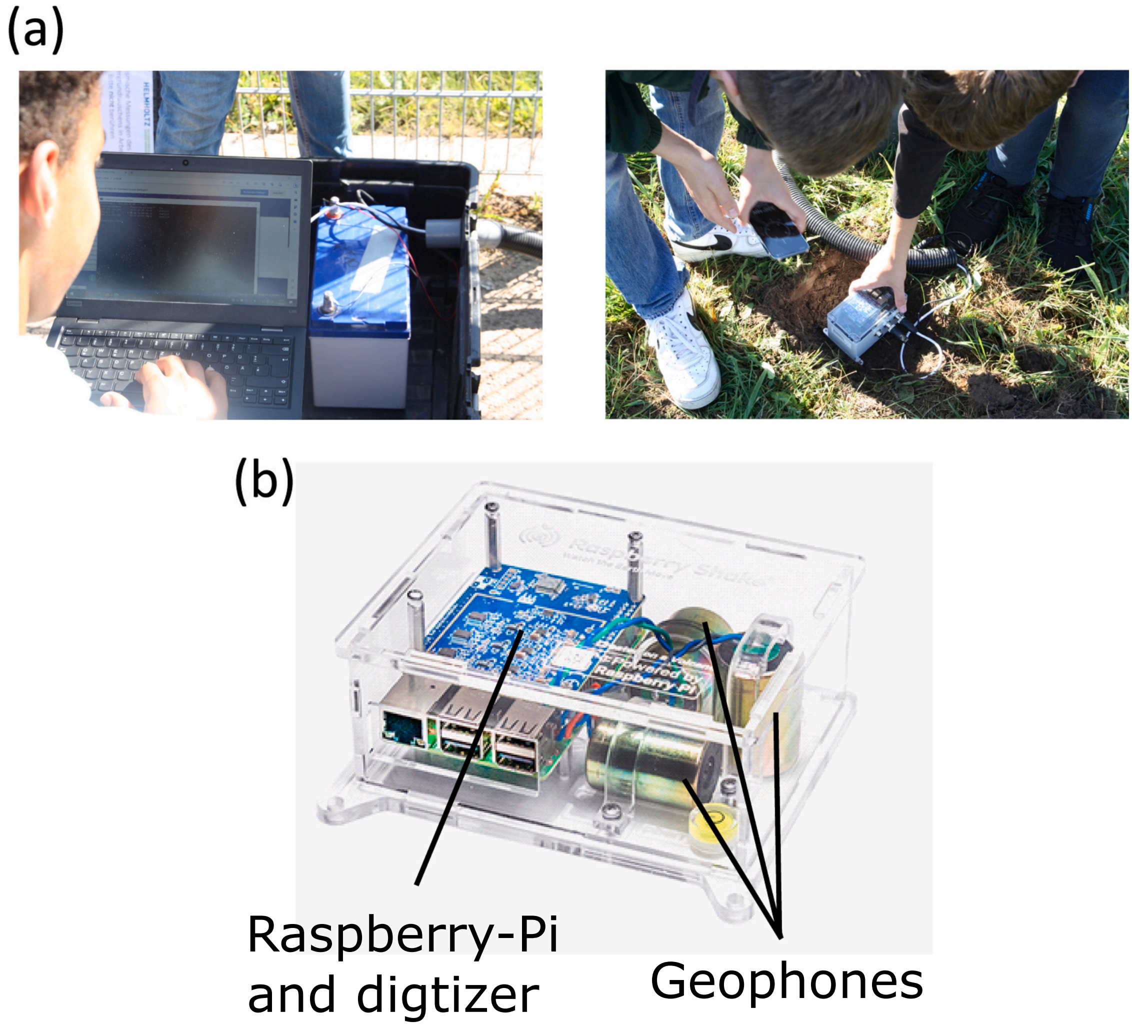

Fig. 3. (a) Pictures from the school project. (b) Picture of the RS3D highlighting its main components.

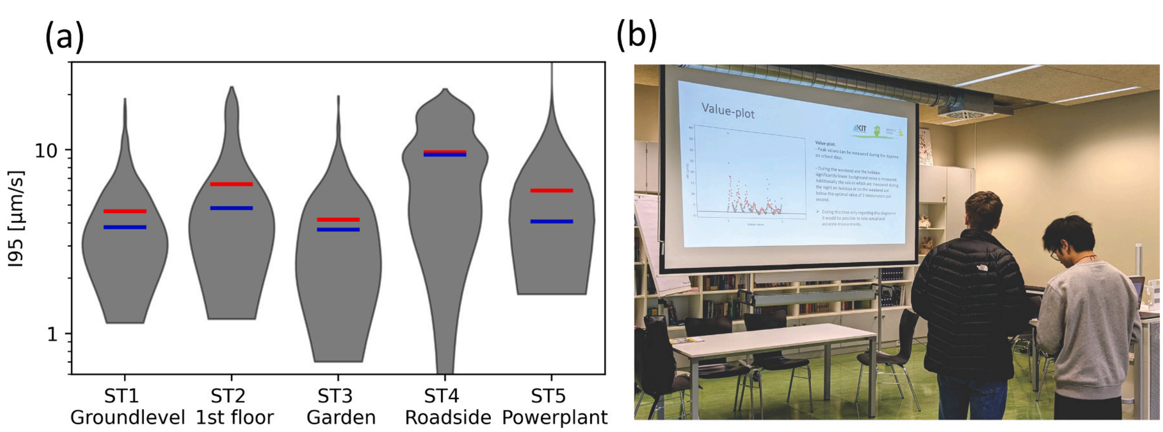

Fig. 4. (a) Comparison of seismic noise levels at the five station locations (ST1 to ST5) corresponding to various recording environments. The processing is based on segmenting the velocity time series acquired by RS3D into time windows. In each 30-minutes data window, we evaluate the range of velocities that includes 95 % of the recorded amplitude (noted as “I95”). For each station, the violin plot shows the distribution of I95 values with the border of the plot showing the density curve, the blue line indicating the mean and the red line the median. (b) Picture from the last session where students present the results of data processing and their interpretation.

most isolated and the quietest location, among tested ones.

Fig. 5 focuses on the results of the social scientific evaluation and outcome analysis. Students are asked to rate their level of knowledge about geothermal energy and seismology. A key observation is that they assess their knowledge and experience as very limited during the initial session. For instance, most of them are unaware that their school is situated close to a geothermal power plant (see Q1.8) and few are informed about seismology (Q1.1 to 1.3). Questions 2.1–2.7 illustrate

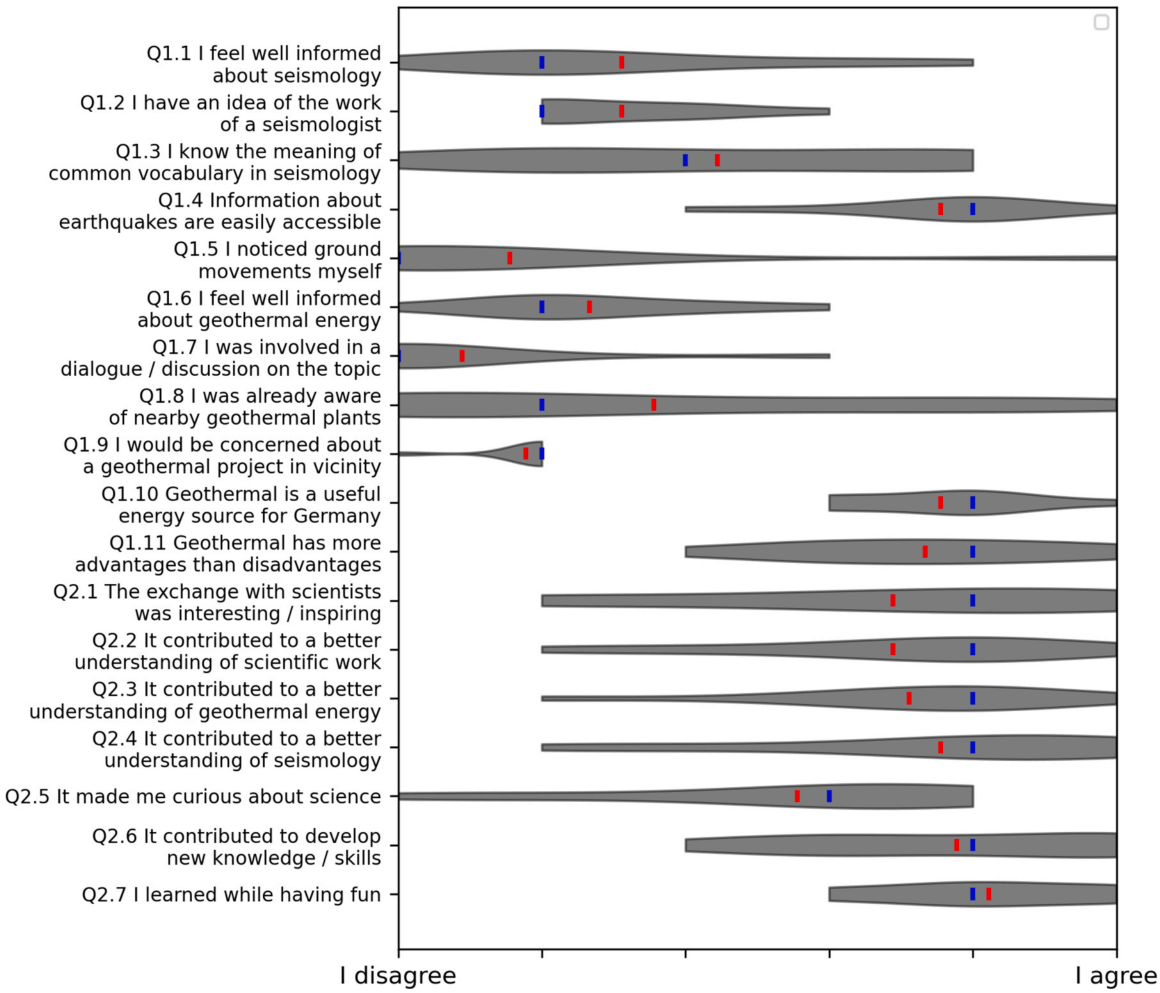

Fig. 5. Results of the survey in violin plots. For each question, the agreement was quantified on a 6-point scale. The border of the plot shows the density curve derived from each distribution of answers, the blue line indicates the mean and the red line the median. The survey including questions 1.1–1.11 is carried out at the start of the project (n = 14), where the students self-evaluate their knowledge about seismology (1.1–1.4) and geothermal energy (1.6–1.8) and share their view of the topics (1.5 and 1.8 – 1.11). Questions 2.1–2.7 are asked during the last session of the project.

the results of the survey conducted during the last session, with questions about the impact of the project.

Dissemination of knowledge and project results is also an important component of the project. After completion, scientists, teachers and students have been involved in events, conferences and the publication of videos and articles. The multiplier effect, which is particularly strong in educational environments, is observed in discussions among the students, project presentations at a national teachers' conference, a school-wide parents' evening and a UNESCO event, and participation in a school competition by the local "Lions Club".

Discussion

Increase of knowledge and awareness

The evaluation showed that the project raised the student's interest and curiosity for the related topics (Fig. 5). It contributed to the students' scientific literacy and to a better understanding of the covered topics. By collecting and analyzing their own seismic data, they have gained a better understanding of ground vibrations, including that vibrations are not limited to perceptible earthquakes, but that our Earth is constantly in motion. Geothermal energy projects also emphasize the importance of renewable and sustainable energy sources. As an outcome, young people can develop clearer opinions on the topics discussed, leading to a more solid and grounded perception.

However, intensive engagement with a particular topic within the field of geothermal energy can also lead to an overemphasis on that particular aspect. This was also demonstrated when the students were asked to write down the first three words that came to their mind when they thought about deep geothermal energy. Words like earthquake and seismometer dominated at the end of the project, whereas energy and heat were the most common in the first survey. Similarly, in the pre-project survey, groundwater contamination and unknown risks were identified as the most significant hazards associated with geothermal projects (Fig. 6). After the project, seismicity and high costs were the most frequent responses. Despite all the limitations due to the very small number of students surveyed, this observation is not surprising directly after an intensive engagement with a specific topic, in this case seismicity, including a site visit of a plant.

Implications

Such science education projects benefit scientists, schoolteachers and students in terms of exchange of perspectives. Regarding the students' education, they integrate multiple subjects, including math, informatics, physics, engineering and geosciences, thereby offering a holistic educational approach. Moreover, the activities promote a scientific mindset by emphasizing meticulous data collection, critical thinking, and problem-solving skills among students. Collaboration with universities and experts further enhances the credibility of these projects

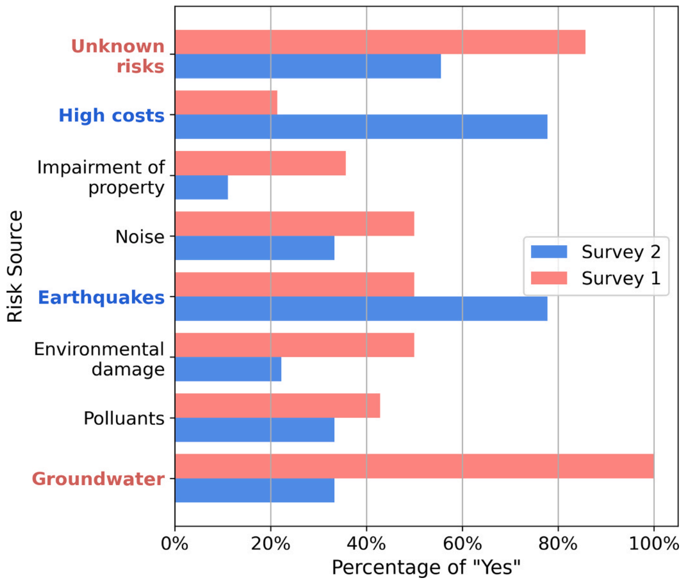

Fig. 6. Students are asked whether they associate the exploitation of geothermal energy with the proposed hazards. The number of positive responses is expressed as a percentage of the total number of responses (n = 14). The survey is conducted at the beginning (red) and after the project (blue) and the two most represented answers of each survey are highlighted by bold labels.

by providing access to valuable resources and expertise. The use of innovative technologies, such as RS3D in this case, can improve the accessibility and appeal of scientific disciplines to a wider audience and enable non-professionals to participate in monitoring networks, as suggested by [9].

In terms of societal impact, post-project dissemination activities amplify the school's own multiplier effect. The wide range of activities proposed in and outside of schools actively involve students and school actors in various networks, facilitating the dissemination of the scientific knowledge and information presented by the project to individuals unfamiliar with the subjects it addresses. The (limited) evaluation data show an increased perception of seismic risks after the project. However, it must be kept in mind that this survey was carried out directly after the project and catches a glimpse of the short-term project effect. The longer-term effect could be different and should be subject to a more extensive participatory monitoring project accompanied by a social scientific study. However, it should be noted that the project approach should not be aimed at minimizing the pupils' perception of risk. Rather, the aim is to impart knowledge as transparently and engaging as possible. From our point of view, role-playing games on a factual, scientific basis are still an effective way to familiarize students with geothermal operations and seismic monitoring, as they encourage active involvement and hands-on learning. This familiarization process with a complex topic such as seismicity could be a prerequisite for constructive dialogue with the public [10]. A future project, building on the experience of this project, could focus somewhat more on risk management strategies to achieve a better balance between the provision of knowledge about seismic risks and their management.

This science education project also served as a test of hardware, software and data processing workflows for autonomous measurements in future citizen science projects for our research on participatory approaches. For example, a participatory seismic monitoring network involving residents near a geothermal project could be established to enhance transparency and understanding of seismic monitoring practices. This could be a benefit for both geothermal plant operators and residents. On the "technical" side, involving the public in monitoring efforts can enhance the monitoring network by considerably increasing the density of sensors. On the "societal" side, such projects can encourage community engagement, transparency and, ideally, lead to a more informed perception of the related topics during this critical phase of deep geothermal energy development.

Conclusions

This study presents a school project that seeks to promote effective information transfer on complex scientific topics such as geothermal energy and seismology through hands-on learning in geophysics. It highlights the need for such initiatives, particularly in regions with significant potential for renewable energy development, such as geothermal energy in the URG. Additionally, it underlines the benefits of technology and experiential learning – in this study, using affordable and accessible geophones – in enhancing understanding and generating interest in geothermal energy. To gain more comprehensive insights from social scientific analyses on the effects of science education and participatory approaches in the context of controversial energy technologies, it is essential to conduct further studies involving a larger and more diverse group of participants across different settings. Nevertheless, the knowledge and insights obtained from this project provide valuable understanding that can be adapted to other target groups and to other settings outside schools.

Author contributions

JA: Developed the educational materials, led the teaching modules and the data acquisition, designed the algorithms and wrote and prepared the original draft.

JB: Coordinated the project, refined the educational materials, contributed to the implementation of the modules, conducted the social scientific analysis, and contributed to manuscript writing.

CRediT authorship contribution statement

Jérôme Azzola: Writing – original draft, Software, Resources, Methodology, Data curation. **Judith Bremer:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Ethical statement

Data in this study have been collected with the prior consent of the participants and researchers agreed to maintain the highest level of data protection rights of the participants. Hence, the study did not include any identifying information.

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Conflict of Interest

The authors declare no competing interests.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.socimp.2025.100116.

Data availability

The educational material developed in the frame of the school project, as well as the Python codes for data processing, are publicly available from the KIT data-repository (DOI: 10.5445/IR/1000175156).

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