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GeoLaB - Geothermal Laboratory in the Crystalline Basement

Thomas Kohl[1], Eva Schill[1,2], Friedemann Wenzel[1], Michael Kühn[3], Olaf Kolditz[4] and Ingo Sass[2,5]

[1]Karlsruhe Institute of Technology, [2]Technische Universität Darmstadt, [3]German Research Centre for Geosciences, [4]Centre for Environmental Research, [5]Darmstadt Graduate School of Excellence Energy Science and Engineering

eva.schill@kit.edu

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ABSTRACT

In Central Europe, the largest geothermal potential resides in the crystalline basement rock with important hotspots in tectonically stressed areas. To better harvest this energy form under sustainable, predictable and efficient conditions, new focused, scientific driven strategies are needed. Similar to other geo-technologies, the processes for environmental sustainability in the subsurface need to be investigated in large-scale facilities. The proposed new underground research laboratory GeoLaB (Geothermal Laboratory in the Crystalline Basement) will address the fundamental challenges of reservoir technology and borehole safety. The specific objectives of GeoLaB are 1) to perform controlled high flow rate experiments, CHFE, in fractured rock, 2) to integrate multi-disciplinary research to solve key questions related to flow regime under high flow rates, or higher efficiency in reservoir engineering, 3) risk mitigation by developing and calibrating smart stimulation technologies without creating seismic hazard, and 4) to develop save and efficient borehole installations using innovative monitoring concepts. Planned experiments will significantly contribute to our understanding of processes associated with increased flow rates in crystalline rock. The application and development of cutting-edge tools for monitoring and analyzing will yield fundamental findings, which are of major importance for safe and ecologically-sustainable usage of geothermal energy and further subsurface resources. As an interdisciplinary and international research platform, GeoLaB will cooperate with the German Research Foundation (DFG), universities, industrial partners, and professional organizations to foster synergies and technological and scientific innovations. GeoLaB is designed as a generic underground research laboratory in the crystalline rock adjacent to the Rhine Graben, one of the most prominent geothermal hotspots in Germany. GeoLaB is an analogue site representative of the world‘s most widespread geothermal reservoir rock, the crystalline basement. In an initial phase, the suitability of a site for GeoLaB located either in the Black Forest or the Odenwald, will be proven by geological, geophysical, and geochemical drilling exploration. At the selected site, a two km long gallery will be excavated, tapping individual caverns, from which controlled, high flow rate experiments will be conducted at depths of 400 m. The experiments will be continuously monitored from multiple wells, drilled from the underground laboratory or from the surface. This will create a unique 4D-benchmark dataset of thermal, hydraulic, chemical and mechanical parameters. Hence, GeoLaB will become a cornerstone for the target-oriented development of the enormous geothermal resource. With its worldwide unique geothermal laboratory setting, GeoLaB allows for cutting-edge research, associating fundamental to applied research for reservoir technology and borehole safety, bridging laboratory to field scale experiments and connecting renewable energy research to social perception. GeoLaB comprises a novel approach that will shape research in earth science for the next generations of students and scientists.

1. INTRODUCTION

Geothermal power and heat production started >100 yrs. ago by tapping in high enthalpy hydrothermal systems. Still today, most of the geothermal plants produce from high enthalpy reservoirs with temperature up to 300°C that are typically located at shallow depth situated near volcanic areas. In general (i.e. Western U.S., Italy, or Iceland), the performance per well is about of 2-5 MW_{el}. Non volcanic areas such as the crystalline basement central Europe are characterized by low-enthalpy resources that differ in temperature distribution requiring therefore drilling depths of 3-5 km (Tester, 2006). The exploitation and large-scale industrial development, in particular of the latter systems, is subjected to barriers including technological, economic and social issues. The high fix costs from drilling, the cost-intensive development of specific technology for the deep reservoirs in low enthalpy areas, and the environmental and social impact from induced seismicity represent major obstacles.

Thus, successful development of geothermal energy requires an economic perspective and social acceptance. Both issues will be significantly advanced with the proposed infrastructure GeoLaB and its innovative and far-sighted research opportunities. It is designed as location of key experiments for reservoir engineering regarding high flow, high heat exchange, controllable seismicity, and borehole safety. It will serve as a hub for scientific and industrial research but also as a site, where societal acceptance can be explored and developed from the very beginning.

In nuclear waste research underground research laboratories (URL) are categorized into a generic or of a site-specific type. Following the definition from OECD (2013) the role of a generic URL – like GeoLaB - is primarily aimed at increasing basic understanding but is commonly located at sites with geological properties that are similar to the target formation. In contrast, the role of a site-specific location is considered as the continuation of a site characterization program when specific site information or direct access to the relevant parts of the host rock is required. As such, the approach of GeoLaB fits perfectly into the category of a generic URL, in which fundamental research activity can be conducted with the specific goal to understand processes linked to geothermal reservoir assessment, but in which specific in situ temperature conditions can only be extrapolated by large-scale testing. It may be noted already here, that the current FORGE (Frontier Observatory for Research in Geothermal Energy) concept is a perfectly complimentary approach, which represents the site-specific case.

2. SCIENTIFIC CONCEPT OF GEOLAB

GeoLaB targets the sustainable and economic development of geothermal energy, is located in a prime geothermal hotspot location in Germany, and provides the research infrastructure for key scientific questions around geothermal energy such as hydraulic coupled processes and induced seismicity in crystalline rocks. It is unique in bridging the gap between the laboratory and reservoir scale, in serving as focal point for science and technology development, and in integrating research on scientific issues with the social research regarding participation and acceptance of the public. GeoLaB will help to better understand the underlying processes strongly enhance our reservoir-modelling capabilities, while increasing our understanding of flow in fractured media, and promote reservoir exploitation. By the present initiative, a new class of URLs for the characterization of high permeable structures is introduced, that contrasts nuclear waste URLs exploring host rock as "barrier" for transport processes by targeting low permeable rock.

In the following, the key challenges will be addressed to be explored by a specific geothermal URL, related to the geothermal reservoir (topic: hydraulic coupled processes, mechanics of induced seismicity, safety of borehole completion) and to the acceptance of geothermal research (sociological component).

2.1 Importance of hydraulic coupled processes in fractured rock

At high flow rates, such as required in geothermal systems, transient mechanical interaction becomes important. Therewith, fluid driven transport will become a dynamic process in which parameters may change with time. Such a 4D process is principally affected by

1) Thermal effects through convection, vapour diffusion or thermo-mechanical effects
2) Effect of mechanical interaction on tracer propagation
3) Mechanical interaction from poro- and thermo-elasticity
4) Chemical effects from temperature and pressure change.

Therewith, injection in fractured reservoirs can include a high variety of interactions induced from hydraulic fields (Gaucher *et al.*, 2015), known as THMC for thermal, hydraulic, mechanical, and chemical interaction (Kolditz, 2013, Kolditz *et al.*, 2012). The insight in these interactions is especially a demanding task for process identification, test design and forecast of reservoir behavior by numerical models. As an experimental infrastructure GeoLaB will allow for modification and calibration of new theoretical concepts on the scale relevant for reservoir management. Until now, these models are based mostly on laboratory measurements quantifying the interaction between single fracture(s) and the matrix, fully neglecting complexity of fracture networks or alteration in matrix and effects from the difference in scale.

2.2 Mechanics of induced seismicity

Mechanics of induced seismicity: Although the conditions of earthquake generation are principally well understood, the coupling of the hydraulic and mechanical processes poses large challenges. It remains unclear, what is the maximum energy release (maximum magnitude) from induced seismicity and how induced seismicity can be controlled. It is undisputed that the seismic hazard increases with the magnitude of hydraulic perturbation in the underground. Traffic light systems, based on local networks have been regarded as most useful for reducing the hazard of induced earthquakes: if a magnitude threshold is exceeded, injection operations will be adjusted to avoid earthquakes of greater consequence (McGarr *et al.*, 2015). Therefore, applying controlled, high flow rate experiments, CHFE, is a prerequisite for the investigation of these effects.

The interaction of hydraulic and mechanic processes in the subsurface is typically observed indirectly i.e. by the pattern, event rate, magnitude, and focal mechanism of earthquakes. The consistent observation of large magnitude events, LME, occurring during the shut-in phase, is under debate with first concepts that consider the on-going fluid diffusion even after shut-in (Shapiro *et al.*, 2007) and the hydraulic impact on changing the flow paths (Segall and Lu, 2015, Schoenball *et al.*, 2014). The observation of pressure, flow and stress changes in the reservoir under various loading conditions is the key for validating concepts on avoiding LMEs in geothermal sites. It requires a close investigation of rock mechanics under the conditions met during flow experiments.

2.3 Borehole integrity

Most of the research on well integrity is performed by and for hydrocarbon industry. Only little is known for the special requests in brittle magmatic or metamorphic rocks. The brittle behavior may lead to an extended damage zone, which should be taken into account while planning safe operations. Also temperature gradients and chemical gradients induced by reservoir operation may affect the borehole integrity in longer terms. The goal of the experiments within GeoLaB on well integrity is focused on a secure, long term stable, thermal shock resistant cementation and effective abandonment.

2.4 "Virtual GeoLaB"

GeoLaB will be accompanied by a virtual reality project which will support both, the infrastructure arrangement, and the science cases in planning and documentation. The "Virtual GeoLaB" will build adequate long-term data infrastructures for large and complex scientific projects. A virtual reality concept for a complex scientific project such as the GeoLaB from the very beginning is novel and includes the following aspects.

1) GeoLaB is a complex infrastructure project concerning a variety of different aspects such as the technical layout, geotechnical constructions as well as the entire facility management (power supply, IT media, ventilation, safety installations etc.). The "Virtual GeoLaB" will serve as a supporting planning and operation tool for the GeoLaB construction as a visual data base of all important information in a precise geometrical context.
2) The "Virtual GeoLaB" will contribute to the CHFE's logistic preparations, e.g. planning the experimental design as well as the required specific infrastructure and equipment for it. During the tests it can provide on-line data access to experimental data and will serve as a persistent data repository of the key experiments. Due to the expected large amount of experimental

data a visual support in a time-spatial context (data are linked to their geometric position and duration) will be very helpful for quick data access and data search later on.

3) In addition to the experimental data, "Virtual GeoLaB" will include related model information. Data availability from one platform is very helpful not only for the conceptual model development but also for model calibration and validation purposes. In addition to geometric information it will also incorporate possible parameterizations including statistical information.
4) The major advantage of a virtual reality concept is the comprehensive data analytics at any time depending on the real-time available information. Modern VR facilities can handle large data sets in a 3D stereoscopic manner allowing an immersive exploration suited for largely heterogeneous data (geometrical context, experimental data, simulation results, etc.).

3. GEOLAB INFRASTRUCTURE

The proposed GeoLaB, is designed as a generic underground research laboratory. It will serve as a scientific platform that supplies a worldwide unique infrastructure in the crystalline basement to the national and international scientific community. Existing high-level EGS research and technology development forms the basis for the goals of GeoLaB and is adapted to the specific requirements of reservoir technology. The specific objectives of GeoLaB are:

1) to perform CHFE in fractured rock,
2) to integrate multi-disciplinary research to solve key questions related to flow regime under high flow rates, or higher efficiency in reservoir engineering,
3) risk mitigation by developing and calibrating smart stimulation technologies without creating seismic hazard, and
4) to develop save and efficient borehole installations using innovative monitoring concepts

The focus on CHFE in fractured crystalline rock requires defining specific technical criteria that bring up clear differences to nuclear waste laboratories. They are:

1) Low complexity of the geology in terms of lithology changes in favour of a rather homogenous crystalline matrix. Fluid injection into high permeable zones such as faults or interconnected permeable natural fractures will keep fluid pressure low. This way, large-scale fracking will be prevented. Ambient hydraulic transmissivities in the order of 10^{-4} m s^{-1} similar to those of the Soultz reservoir are anticipated.
2) The hydraulic boundary conditions should represent ambient situations at far-field without infiltrating into artificial structures. As such, a "flooding" of other galleries would yield a safety issue but also would harm the total experimental results due to artificially imposed boundary conditions. Since extensive drainage may occur in old mining areas, minimum distances must be respected.
3) Injection into favourably oriented fractures for reactivation in the ambient stress field is an intrinsic pre-requisite of a geothermal URL implying differential stress magnitudes above approx. 3-5 MPa depending on the local stress field. Topography induced perturbations to the stress field should be minimized with maximum variations of 1 MPa to be tolerated.
4) Clay minerals are known to reduce the mechanical / frictional strength of fractures, i.e. the pressure required to cause shear during hydraulic stimulation. Hydrothermal alteration products in the matrix and on the faults should cover the illite to smectite range.

With these technical criteria in mind, the basic layout of the GeoLaB infrastructure initiative in the crystalline basement is projected as illustrated in Figure 1.

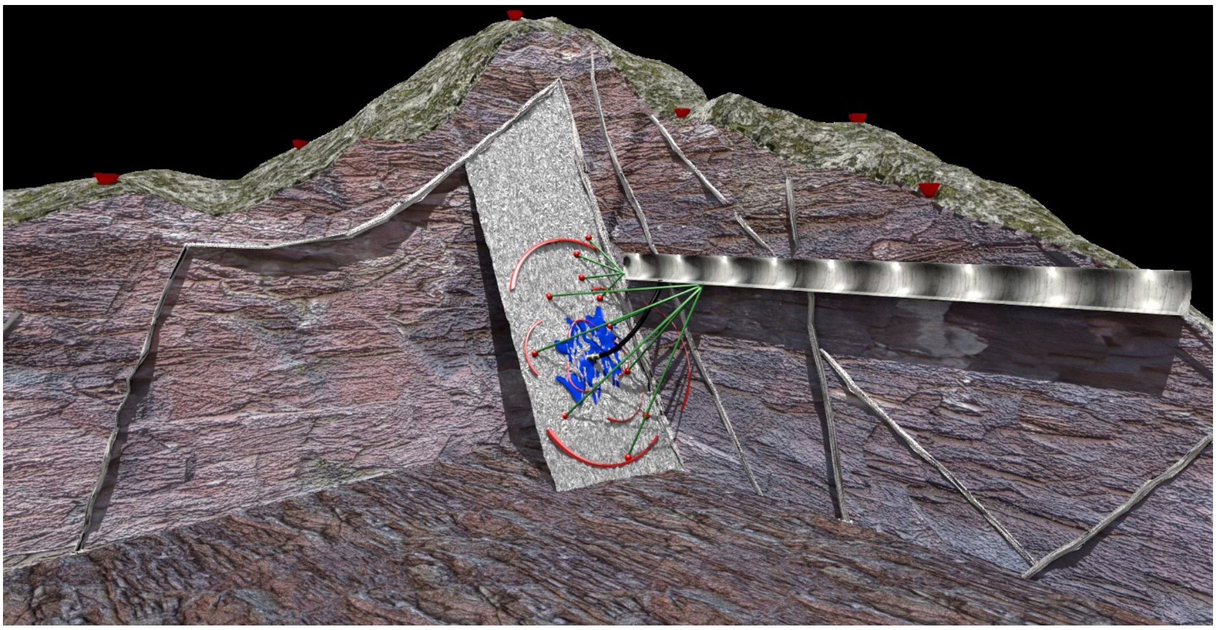

Figure 1: Layout of the experimental studies enabled by GeoLaB from caverns connected to a central gallery.

A key factor of GeoLaB is the existence of fault zones that can be used for the simulation of reservoir behavior. It is foreseen that these structures are accessed from GeoLaB from the cavern structures. Given the heterogeneous structure of fault zones with cataclastic deformation bands or discontinuous joints (to be easily reactivated in shear), a "safety" distance of approx. 100 m from the cavern wall to the fault is intended based on empirical observations on the width of damage zones in the crystalline basement of Soultz (Massart *et al.*, 2010) Therewith, length of the monitoring wells are anticipated to be approx. 150 m when directed from the cavern wall. These measures prevent also possible impacts from nearfield damage zones next to the walls and small-scale stress variations induced by the constructions.

GeoLaB will be situated at the outcrop of the crystalline basement at the Upper Rhine Graben to take advantage of topography for easily accessing a larger overburden depth (i.e. typical depth domains for criteria 3 is 300-500 m depending on surface topography). Moreover, this has the advantage to reduce costs for the construction and operation of the platform. As such, it reduces pumping costs due to possible drainage at surface and it saves the costs for constructing shafts and elevators. The location in the direct vicinity of the Rhine Graben provides further advantages:

Besides the geothermal relevance of this area, another advantage of the proposed location is linked to the evolution of the Upper Rhine Graben formation. Depth domains today being vertically separated by more than 5 km originally had been in close vicinity (Figure 2). The GeoLaB location accessible through a horizontal adit corresponds therefore closely to the crystalline basement subsided in the Upper Rhine Graben at depths of >5 km. Both sides are similarly tectonically stressed with a dominant N-S trending stress field and alteration patterns due to circulating fluids. This way, GeoLaB is a typical analogue site of a deep geothermal reservoir, fulfilling many criteria of a deep reservoir and with perfect generic structures that can be easily accessed.

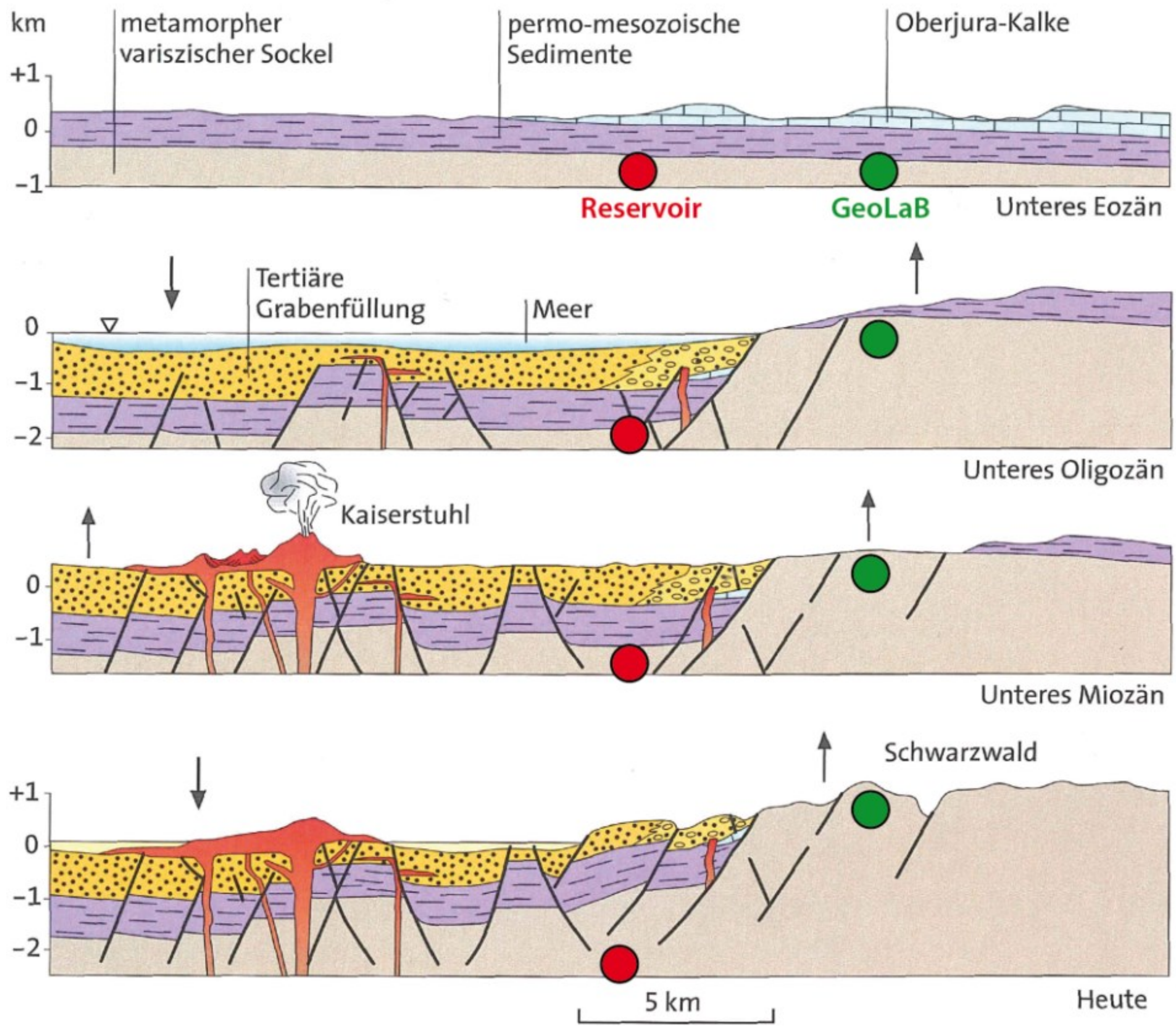

Figure 2: Formation of the Upper Rhine Graben. Two originally close locations (red circle = reservoir, green dot = GeoLaB site) have been vertically displaced, with one site now easily accessible as "generic" laboratory and the other today representative for a geothermal reservoir (Frisch and Meschede, 2007).

4. SITE SELECTION

The above mentioned four criteria are the basis of the site selection process. In a first step existing URLs in basement rock have been analyzed accordingly. Following a common approach in geo-technologies dating back to more than 40 years, various worldwide initiatives foresee experiments in existing underground facilities such as URLs or tunnels to overcome these problems. Table provides an overview of most important URL facilities in the crystalline basement.

Table 1: Selection of the worldwide most important URLs in basement rock.

Name	Country	Lithology	Scientific interest	Maximal depth (m)
Grimsel Test Site (GTS)	Switzerland	Granitic	Nuclear waste disposal research, (geothermal)	450
Bedretto Lab	Switzerland	Granitic	Geothermal, seismology	1800
Äspö Hard Rock Laboratory (Äspö HRL)	Sweden	Granitic	Nuclear waste disposal research, (geothermal)	500
Onkalo	Finland	Granitic	Nuclear waste disposal research	420-520
AECL URL	Canada	Granitic	Nuclear waste disposal research (decommissioned)	240-420
SnoLab	Canada	Metamorphic	Nuclear physics	2000
Mizunami URL	Japan	Granitic	Nuclear waste disposal research	500 (planned to 1000)
Josef URL	Czech Republic	Meta-sedimentary	Nuclear waste disposal research, (geothermal)	200
Mine Reiche Zeche	Germany	Metamorphic	Drilling technology, seismics, (geothermal)	230
Lindau Test Site	Germany	Granitic	Access water storage	90
Sanford URL	USA	Metamorphic	Physics, biology, (geothermal, EGS Collab)	1500

None of the existing URLs matches all four main criteria established during the first site selection processes for GeoLaB (Schill *et al.*, 2016). Among European URLs in granitic host rock, only Äspö (S), Bedretto (CH), and Grimsel (CH) are accessible for large-scale research purposes. Of these, hydraulic conditions necessary for CHFE are present at Äspö and Lindau, only. While at the Lindau Test Site insufficient overburden represents a criteria of exclusion for the existing design of the tunnel, at Äspö HRL the general stress situation is unsatisfactorily described and furthermore includes most likely thrust faulting. Both URLs may be used in a qualified sense for complementary experiments. In agreement with these findings and the criteria for GeoLaB, we have carried out further studies in the southern Black Forest and Odenwald for the following reasons:

1) The basement outcropping in the Black Forest/Odenwald complex represents to a large extend the lithology of the geothermal host rock in the URG.
2) Appropriate hydrothermal alteration is widely observed (Brockamp *et al.*, 2015).
3) Extended fracture networks are indicated (Stober and Bucher, 2014).
4) Apart from overburden the Lindau Test Site indicates the general suitability of the southern Black Forest. Hydraulic condition fixed in criterion 1 are achieved (Himmelsbach *et al.*, 1998) and the regional stress field represents or at least approximates conditions of major EGS projects in the URG.

5. INTERACTION WITH THE PUBLIC

The success of the energy transition ultimately depends on the public acceptance of new and often domestic power generators such as windmills, hydraulic power stations, geothermal power plants, etc. Acceptance is influenced by technical aspects, by economic implications for the local population, by the required change in lifestyle, by the state of knowledge, by the style of interaction with public, by the credibility of institutions, etc. These influencing factors are not static but can change in time if, e.g., people feel the necessity of a fast energy transition as urgent issue. Thus, a continuous interaction with the public is required.

On the one side, being able to provide base-load heat and power, geothermal energy is a kind of backbone for the future energy mix. On the other side, although being successfully installed in a growing number of plants, its acceptance has suffered from project failures in the recent past. Especially, the EGS technology is often perceived as uncontrollable technology. Despite first scientific achievements, perceptible seismicity and lately also ionizing radiation remain major subsurface-related aspects and are perceived as such in the critical public debate on deep geothermal energy. In this respect, several communication guidelines have been published for EGS.

From a social scientific perspective, the ambiguity in acceptability may partly relate to the distribution of scientific knowledge in society that itself led to a rising number of knowledge experts and proto-experts (Nowotny, 1993). So-called proto-expertise, i.e. scientific and technological knowledge of different kinds and degrees applied in different contexts, is gained among others from being confronted with different projects, institutions, or experts (Chavot and Masseran, 2012). Resulting novel configurations of knowledge and knowledge claims need to be addressed.

Similarly, the large-scale infrastructure project GeoLaB represents a potential societal conflict area. On one hand, there may be sceptic or critical sections of the population, and on the other hand, there is the huge potential of GeoLaB to generate knowledge for the implementation of a sustainable energy harvesting technology. For the success of GeoLaB, an overall expertise among all stakeholders is required for scientific reasons and public insights. Data preparation for the documentation of changes in the subsurface (preservation of evidence) and providing open access to data and results using different scientific and non-scientific platforms is seen as a central part of stringent communication strategy within the GeoLaB project. This concept of transparency guarantees a maximum spread in the scientific community and therefore, an external quality control of the GeoLaB experiments and studies. Moreover, it is also an important means of exchange with stakeholders.

Beyond the scientific and technological orientation of the infrastructure, GeoLaB forms a platform for science communication, participation and dialogue of stakeholders from industry, politics, administration and society. Complying public engagement, this aims at eliminating the asymmetry in terms of knowledge and communication. Early involvement of stakeholders with different roles in the innovation process may prevent proto-expertise from acquiring a life of its own. In this respect, geoethics employs concepts of open platforms for the engagement of all relevant stakeholders by exchange of knowledge and experience between the worlds of professionals, researchers, industry, authorities and the public. Such a platform needs to offer the possibility for open discussion on technical aspects such as site selection and risks, but also on related aspects such as regulatory and economic issues (Meller *et al.*, 2018). This is ideally realized in a participatory process.

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