# Task 1.1

## Task Title

Reservoir exploration, assessment & characterization

## Research Partners

Workers active in the current phase of the task activities belong to the following research groups within Switzerland:

- University of Bern, Institute of Geological Sciences:
  - Rock-Water Interaction Group (Prof. Larryn Diamond)
  - Structural Geology Group (Prof. Marco Herwegh)
- University of Geneva, Section of Earth and Environmental Sciences:
  - Reservoir Geology & Basin Analysis Group (Prof. Andrea Moscariello)
- University of Lausanne, Institute of Earth Sciences:
  - Applied Geophysics Group (Prof. Klaus Holliger)
- University of Neuchâtel, Centre for Hydrology and Geothermics:
  - Geothermics Group (Prof. Benoît Valley)
- ETH Zurich, Geological Institute:
  - Rock Deformation Laboratory (Prof. Jean-Pierre Burg)
- University of Fribourg, Unit of Earth Sciences:
  - Tectonics Group (Prof. Jon Mosar)
  - Sedimentology Group (Prof. Anneleen Foubert)

Collaboration is underway with other researchers at:

- HydroIsotop GmbH, Germany
- Uni Freiburg, Germany
- National University of Mexico
- University College London

Collaborations with industry partners include:

- GeoEnergie Suisse
- Axpo | neue Energien (now defunct)
- Corporation for Swiss Petroleum SEAG
- SIG
- Nagra

## Current Projects (presented on the following pages)

### Deep saline aquifers as reservoirs for geothermal energy and CO2-sequestration

Muschelkalk aquifer in the Swiss Molasse Basin: properties relevant to geothermal energy and gas storage
L. Aschwanden, A. Adams, L. W. Diamond, M. Mazurek

Structural Characterization of the Greater Geneva Basin for Geothermal Ressources Assessment
N. Clerc, A. Moscariello, P. Renard

Quantitative petrography workflow for reservoir rock characterization
B. Segvic, C. A. González, G. Zanoni, A. Moscariello

Rock typing of deep geothermal reservoirs in the Greater Geneva Basin
E. Rusillon, A. Moscariello

Petrography of a potential CO2 seal in the Lower Jurassic in the southwestern Molasse Basin
D. D. Couto, B. Šegvić, A. Moscariello

Geological data management: an essential tool to manage subsurface resources
M. Brentini, A. Moscariello

Reactive transport modelling of 3 geothermal systems located in Switzerland, Germany and Mexico
C. Wanner, L. Peiffer, F. Eichinger, K. Bucher, P. A. E. Pogge von Strandmann, H. Niklaus Waber, L. W. Diamond

### Fractured crystalline rocks as reservoirs for geothermal energy

Accessible analogues of fault-hosted geothermal energy systems: hydrothermal breccia (Grimsel, CH)
D. Egli, M. Herwegh, A. Berger, L. Diamond, K. Holliger, L. Baron, T. Zahner, C. Madonna, Q. Wenning

Structurally controlled hydrothermal pathways at Grimsel Pass, Aar Massif.
T. Belgrano, M. Herwegh, A. Berger

Fault anatomy, porosity and pore connectivity: the La Sarraz fault system
N. Schmitt, J. Mosar, S. A. Miller, B. Valley

Deep Geothermal Well Optimization Workflow
B. Valley, F. Ladner, P. Brunner, S. A. Miller

### Geophysical exploration for deep geoenergy reservoirs

Seismic energy dissipation in response to wave-induced fluid flow in a cracked glass sample
C. Mallet, E. Caspari, B. Quintal, K. Holliger

The application of crosswell electromagnetics and magnetotellurics to geothermal exploration
F. Samrock, N. Shah, M. O. Saar

Detecting induced seismicity on various scales: Monitoring the Grimsel injections
V. Gischig, J. Doetsch, T. Kraft, H. Maurer, S. Wiemer

### Task Objectives

With respect to geothermal energy production and geological storage of CO2 in Switzerland, the task has the following general goals:

- Characterize potential reservoirs
- Refine estimates of exploitation potential
- Provide science-based guidelines for exploration companies
- Develop geological models and geophysical exploration techniques to reduce risk of exploration failure

In addition, the task will

- provide Swiss-specific reservoir data to Task 1.2 (Reservoir modelling)
- provide acquired data to Task 4.3 (Swisstopo public archive)

### Interaction Between the Partners – Synthesis

- Numerous workshops have been held between partners in the NRP70 projects and the Geothermie2020 consortium
- Meetings of Task 1.1 members have been held with those of the closely associated Tasks 1.2 and 1.4
- A conference session entitled "Geothermal Energy, CO2 sequestration and shale gas" has been convened by SCCER-SoE members at the upcoming 13th Swiss Geoscience Meeting in Basel and it has attracted 38 scientific presentations.

### Highlights 2015

- An NRP70-Swisstopo-BFE-funded research drillhole on Grimsel Pass had been cored to 250 m depth to permit characterization of a geothermally active fault system in crystalline rocks (Belgrano et al. and Egli et al.). The drillhole is now being used to test geophysical exploration techniques.
- NRP70-funded research has shown that matrix porosities and permeabilities of the regional Muschelkalk aquifer depend strongly on burial depth (Aschwanden et al.)
- Geothermie2020/SCCER-SoE research has shown that reef carbonates in the Malm aquifer within the greater Geneva Basin have promisingly high porosities and permeabilities (Clerc et al).

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# Muschelkalk in the Swiss Molasse Basin: properties relevant to geothermal energy and gas storage

*L. Aschwanden*[1], *A. Adams*[1], *L.W. Diamond*[1], *M. Mazurek*[1]

1) Rock-Water Interaction Group, Institute of Geological Sciences, University of Bern, Baltzerstrasse 1+3, CH-3012 Bern, Switzerland

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## 1. Introduction

In the Swiss Molasse basin (SMB), deep aquifers are one of the options under investigation for geothermal energy production and for storage of gas. Particularly the Middle Triassic carbonate rocks within the Upper Muschelkalk show encouraging aquifer properties along the northern margin of the SMB. However, the dimensions and distribution of porous and permeable zones within the aquifer are spatially heterogeneous and current knowledge of the aquifer properties constitutes an insufficient basis for exploration. The present study aims at providing a conceptual regional model of the Muschelkalk which helps to define the magnitudes and the 3D distribution of porosity and permeability throughout the basin. This reservoir characterization is based on the investigation of drill cores and borehole log data provided by Nagra and the Corporation for Swiss Petroleum (SEAG).

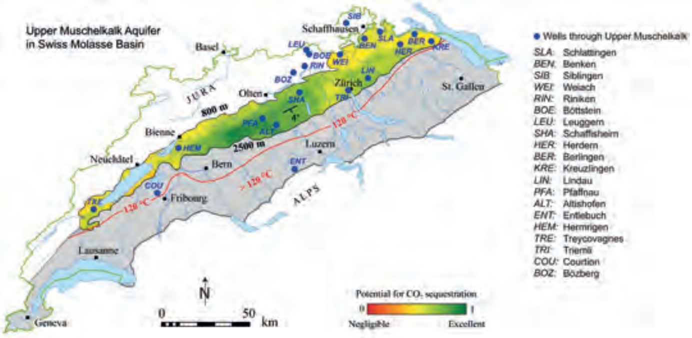

**Fig. 1:** *$CO_2$ storage potential of the Upper Muschelkalk aquifer in the Swiss Molasse Basin within the technically favoured depth range for $CO_2$ storage (800–2500 m). The 120 °C isotherm (red line) marks the minimal temperature required to produce geothermal electricity. Thus, the area south of the isotherm is of prime interest for geothermal exploration. The blue dots mark all the wells that penetrate the Upper Muschelkalk aquifer (modified after Chevalier et al., 2010 and Signorelli et al., 2004).*

## 2. Methods

The drill cores are being investigated by a variety of laboratory methods, including:

- Density, porosity and permeability analyses of plug samples
- GEOTEK Multi-Sensor Core logger (MSCL) for measurements of P-wave velocity and bulk density along entire drill cores (at a resolution of 5 mm)
- Visual logging of the geometry and frequency of macroscopic structures in the drill core (e.g. fractures)
- Identification of deposition environments (facies analysis)

The analyses permit both quantitative and conceptual understanding of the distribution and magnitudes of the aquifer properties.

## 3. Results

Robust correlations have been found between MSCL-density and plug porosity (Fig. 2a), and between plug porosity and plug permeability (Fig. 2b), allowing calculation of the distribution and average of these key properties along entire drill cores.

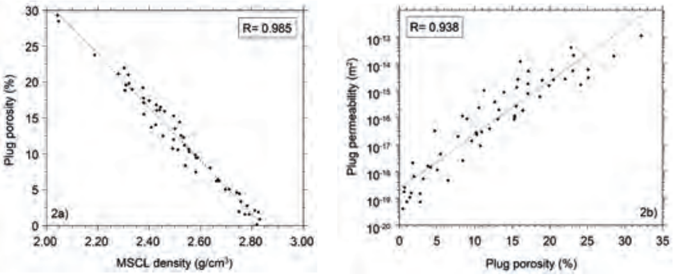

**Fig. 2:** *Correlation between* ***a)*** *bulk dry density (measured along entire drill cores using a GEOTEK Multi-Sensor Core Logger; MSCL) and plug porosity, and* ***b)*** *between plug porosity and plug permeability.*

Figure 3 shows the downhole correlation between the porosity calculated from borehole logs and from MSCL-density logs.

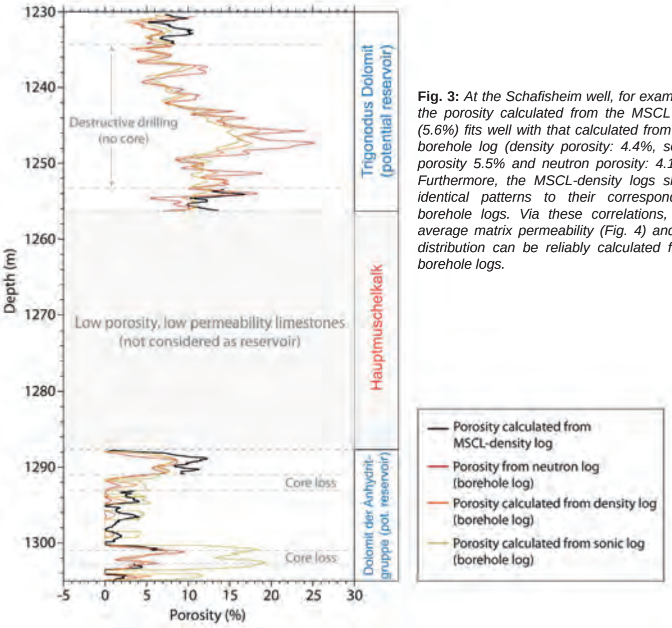

**Fig. 3:** *At the Schafisheim well, for example, the porosity calculated from the MSCL log (5.6%) fits well with that calculated from the borehole log (density porosity: 4.4%, sonic porosity 5.5% and neutron porosity: 4.1%). Furthermore, the MSCL-density logs show identical patterns to their corresponding borehole logs. Via these correlations, the average matrix permeability (Fig. 4) and its distribution can be reliably calculated from borehole logs.*

Figure 4 illustrates the change of porosity and permeability with increasing aquifer depth. The permeability is calculated from the correlations illustrated in Figures 2 and 3.

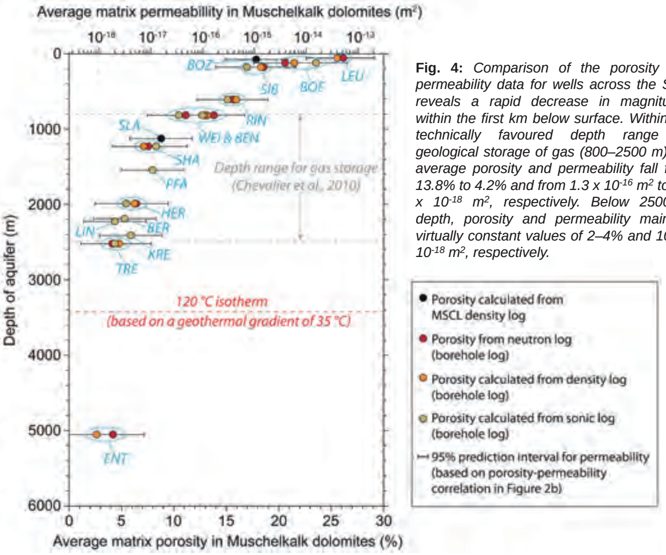

**Fig. 4:** *Comparison of the porosity and permeability data for wells across the SMB reveals a rapid decrease in magnitudes within the first km below surface. Within the technically favoured depth range for geological storage of gas (800–2500 m) the average porosity and permeability fall from 13.8% to 4.2% and from 1.3 x $10^{-16}$ $m^2$ to 1.7 x $10^{-18}$ $m^2$, respectively. Below 2500 m depth, porosity and permeability maintain virtually constant values of 2–4% and $10^{-17}$–$10^{-18}$ $m^2$, respectively.*

## 4. Conclusions

The results for the available wells demonstrate that, in the absence of interconnected fracture networks, the porosity and permeability of the rock matrix in the Middle- and Upper Muschelkalk are too low for geothermal electricity production at depths greater than the 120 °C isotherm (≥ 3000 m; Fig.3). Even for applications at shallower depths, such as the geological storage of gas or geothermal heat production, the matrix porosity and matrix permeability have only suboptimal magnitudes. Future work will be directed at characterizing the distribution of fracture networks in the SMB. In addition to structural studies, in-situ hydraulic tests will be an important means of quantifying the total permeability at the formation scale.

### References

Chevalier, G., Diamond, L. W. and Leu, W. (2010). Potential for deep geological sequestration of $CO_2$ in Switzerland: a first appraisal. Swiss Journal of Geosciences, 103(3), 427–455.

Signorelli, S., Andenmatten Berthoud, N., and Kohl, T. (2004). Geothermischer Ressourcenatlas der Schweiz. Erarbeitung und Bewertung des geothermischen Potentials der Schweiz. Schlussbericht. Bundesamt für Energie, Bern.

Acknowledgment:
We thank Nagra and SEAG for providing drill cores and borehole log data

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# Structural Characterization of the Greater Geneva Basin for Geothermal Ressources Assessment

*Nicolas Clerc (1,2); Andrea Moscariello (1) & Philippe Renard (2)*

*(1): University of Geneva*
*(2): University of Neuchâtel*

## Objectives and Context of the project

This PhD project consists in the investigation of the structural evolution and characterization of fault-systems development within the Greater Geneva Basin on the basis of subsurface (2D seismic and well) data and geological surface observations.
In collaboration with a second PhD project on rock-typing aiming at characterizing and understanding the distribution of reservoir facies and properties across the Greater Geneva Basin (Elme Rusillon, UNIGE), the ultimate goal is to build consistent knowledge about the deep subsurface geology of the Greater Geneva Basin integrated in 3D geological models, In order to identify and understand better the distribution and characteristics of productive geothermal reservoir zones and to provide informed recommendations to enable the planning of subsequent phases of the «GEothermie 2020» program.

The «GEothermie 2020» program is a large multiphase program launched in 2013, driven by the Geneva State authorities and Industrial Services of Geneva (SIG). It aims at evaluating the deep subsurface geology across the transnational Swiss-French Greater Geneva basin and develop the deep geothermal energy ressource in the Canton.

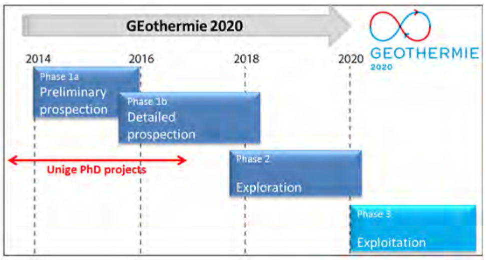

GEothermie 2020
2014
2016
2018
2020
GEOTHERMIE 2020
Phase 1a
Preliminary prospection
Phase 1b
Detailed prospection
Phase 2
Exploration
Phase 3
Exploitation
Unige PhD projects

*Fig. 1: The «GEothermie 2020» Geneva State program*

In parallel, through the elaboration of 3D geological model, this PhD work also contributes to the European INTERREG and Swiss projects GeoMol.

## Introduction

The study area covers the Greater Geneva administrative region, a Swiss-French transnational zone of about 2'200 km$^2$ located at the southwestern extremity of the North Alpine foreland molasse basin (Fig. 2).

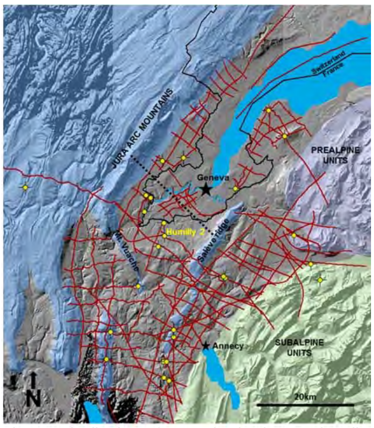
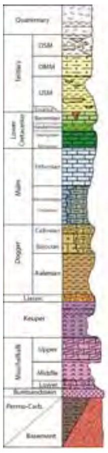


*Fig. 2: Distribution of 2D seismic data and wells reaching Mesozoic and/or deeper units across the Greater Geneva Basin. The dash line corresponds to location of figure 2.*

The Basin consists of a thick sedimentary cover of Mesozoic age, principally composed of carbonate and marl formations, overlying a crystalline basement often incised by depressions filled with Permo-Carboniferous sediments. The top of the Mesozoic series forms an erosive and highly karstified surface, overlain by siliciclastic Tertiary molasse sediments of Late Oligocene to Early Miocene age, over which lies Quaternary sediments mainly of glacial to fluvioglacial origin (Fig. 3).
Tectonically, the Greater Geneva Basin is restricted between the internal reliefs of the Jura arc Mountains in the Northwest and the front of the Alpine thrusts at the Southeast of the Bornes Plateau (Fig. 4).



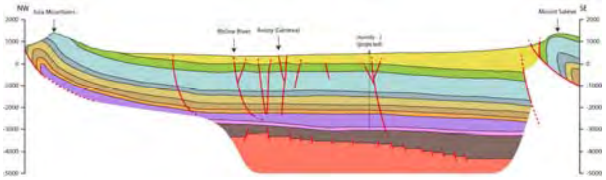


*Fig. 3: Synthetic stratigraphic column and geological cross-section across the Geneva Basin (modified after PGG report, 2011). Refer to Figure 1 for profile location.*

In the Geneva region, this overall NW-SE shortening is laterally accommodated by a series of major NW-SE sinistral wrench fault systems known as (from SW to NE): the Vuache, Cruseilles, Le Coin and Arve fault zones and internally absorbed by the intra-basin Salève thrust anticline (Fig. 4). Toward the South of the study area, the maximum horizontal stress rotates toward a more E-W direction, in line with the shortening direction of the basin.

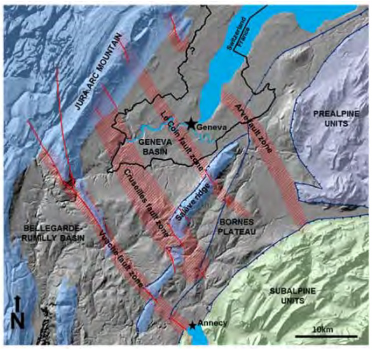


*Fig. 4: Regional structural scheme of the Geneva Basin and Bornes Plateau.*

## Methods and discussion

The seismic dataset for this study consists of about 1'500 km of 2D seismic lines of different age and quality among which, about 210 km are located over the Swiss territory (Fig. 2). Among the 24 wells reaching the Mesozoic and deeper units (Lower Cretaceous to Permo-Carboniferous) over the study area, Humilly-2 well crossing the entire sedimentary sequence down to the Permo-Carboniferous sediments (MD = 3051 m) is located in the center of the zone. Being equiped with time-depth pairs measurements, it serves as principal reference well for the seismic tie and horizons identification. The latter are then propagated across the rest of the study area.

From seismic data and surface observations, investigations are being carried out to delineate the geometries, (extensions, orientation) of the major fault zones crossing the basin (Fig. 4 & 5). Smaller-scale conjugate fault systems can be mapped from 2D seismic lines (Fig. 5), however, their 3D continuation and orientation are more difficult to infer from 2D seismic. Therefore, their interpretation requires a better understanding of the relationship between the different objects that form the regional structural framework and the cinematics of their development within the structuration history of the basin.

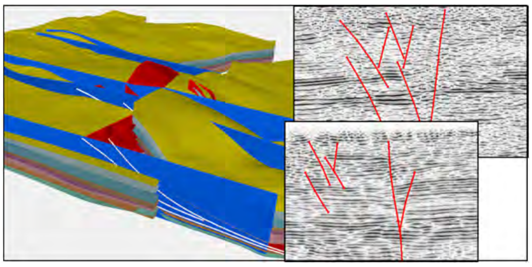


*Fig. 5: regional (left) and smaller-scale (right) fault systems inferred from 2D seismic data*

Relationships between large-scale fault systems in the Mesozoic sedimentary cover and underlying basement structures, as well as certain seismic facies signatures (i.e. Kimmeridgian reef complex structures) are also being investigated.

## Conclusions

- The use of 2D seismic data brings some challenges to characterize geometries of smaller-scale faults systems in 3D.
- Assuming local variations of tectonic context, the use of surface structural observations from neighbouring outcropping reservoir units or analogues can help to predict the fault framework in the deeper subsurface.
- Structural restoration exercise at the basin scale is expected to guide the interpretation and characterization of smaller-scale fault objects within the basin.
- Understanding the development of regional- and smaller-scale conjugate fault systems is of primary importance to identify zones of enhanced reservoir properties (i.e. fracture development).

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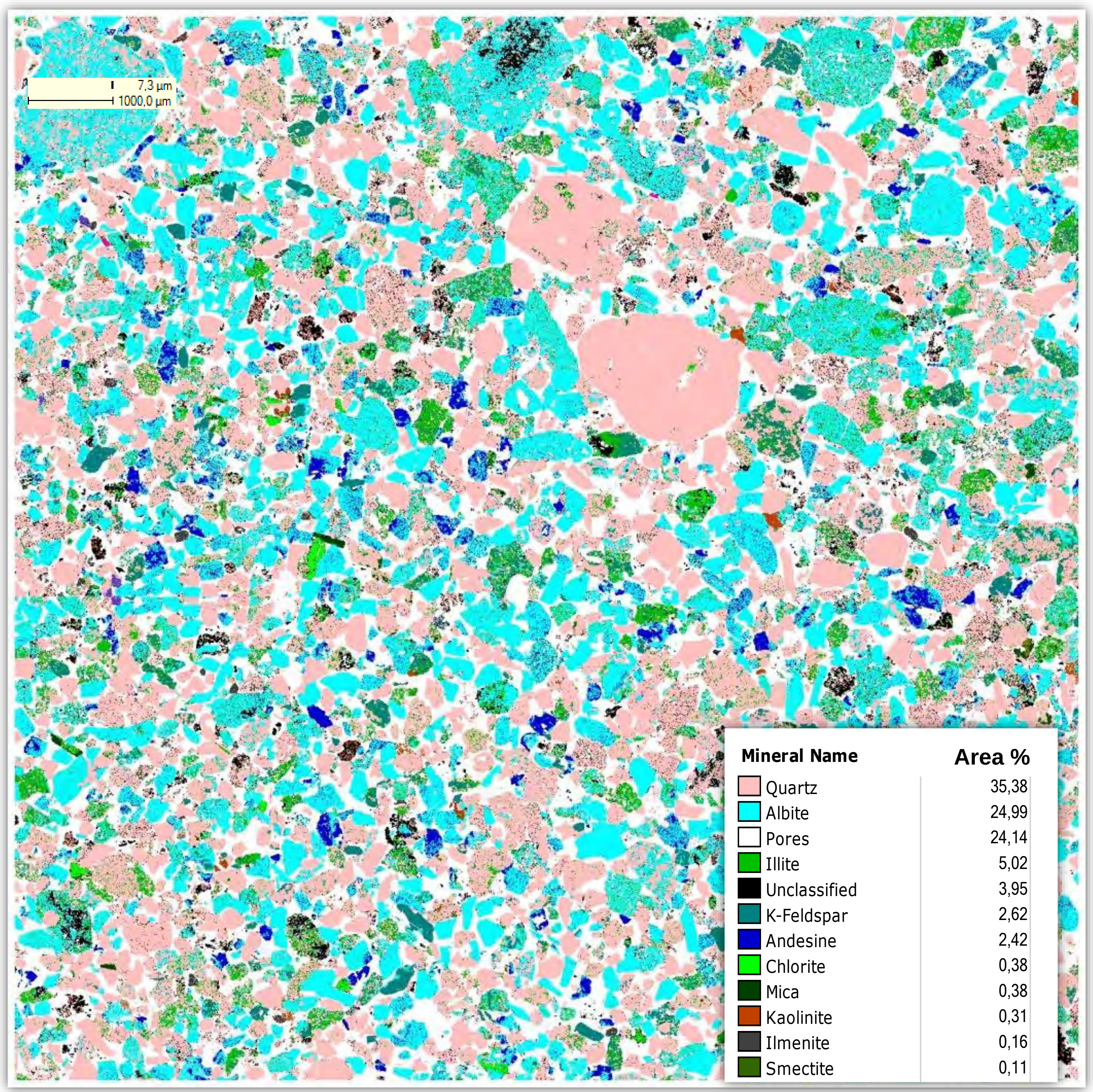
# Quantitative petrography workflow for reservoir rock characterization

*B. Segvic, C. Arbiol, G. Zanoni, A. Moscariello*
*Rock Typing Lab - Department of Earth Sciences, University of Geneva, 13 Rue des Maraîchers, CH-1205 Geneva*

## 1. Introduction

Understanding the nature of reservoir rocks is an essential step for successful exploration and management of geo-resources in the subsurface. Location and extraction of geothermal fluids and hydrocarbons, effective geological sequestration of carbon dioxide in complex geological environments requires therefore an in-depth knowledge of both composition and texture of the rock matrix. Mineral components in fact intrinsically control basic petrophysical parameters such as grain density and directly or indirectly influence many of the wireline log responses such as density, resistivity, spontaneous potential, gamma ray, sonic etc.

Accurate and reproducible determination and quantification of mineral paragenses is, therefore, essential in terms of petrophysical, wireline, and engineering interpretations.



| Mineral Name | Area % |
|---|---|
| Quartz | 35,38 |
| Albite | 24,99 |
| Pores | 24,14 |
| Illite | 5,02 |
| Unclassified | 3,95 |
| K-Feldspar | 2,62 |
| Andesine | 2,42 |
| Chlorite | 0,38 |
| Mica | 0,38 |
| Kaolinite | 0,31 |
| Ilmenite | 0,16 |
| Smectite | 0,11 |

***Figure 1.*** *QEMSCAN® image showing a typical composition of fine-grained sandstone rich in volcanic material altered to I-S clay assemblage, The Golfo San Jorge area, Argentina*

## 2. Methods

Despite the advances in instrumentation and associated quantification techniques, mineral analysis methods are prone to a range of uncertainties. For instance, data derived from traditional mineralogical analytical methods may be subject to potentially large errors; optical analysis can be controlled by grain size and the experience of the petrographer whilst X-ray diffraction (XRD) can be influenced by the presence of phases with variable or poor crystallinity and may be sensitive to differences in sample preparation.

QEMSCAN® technology (Fig. 1) on the other hand is designed to characterise and visualise the distribution of detrital and diagenetic phases and porosity in cuttings, core and outcrop samples based on the analytical reproducibility and the reference to baseline geochemical data from X-ray fluorescence analyses. Still, in case of reservoir rock rich in clay content or pyroclastic material, QEMSCAN® technology is routinely supplemented by X-ray diffraction (XRD) (Fig. 2) and Electron microscopy (SEM) (Fig. 3) studies in order to have a better definition on mineral phases having similar chemistry but different crystallographic characteristics (e.g. clay minerals, zeolites, some inosilicates, etc.).

Other analytical techniques such as microprobe, micro-tomography, cathodoluminescence etc. are also used to investigate different generation of cementation, pore shape and connectivity, specific chemical composition of minerals etc.

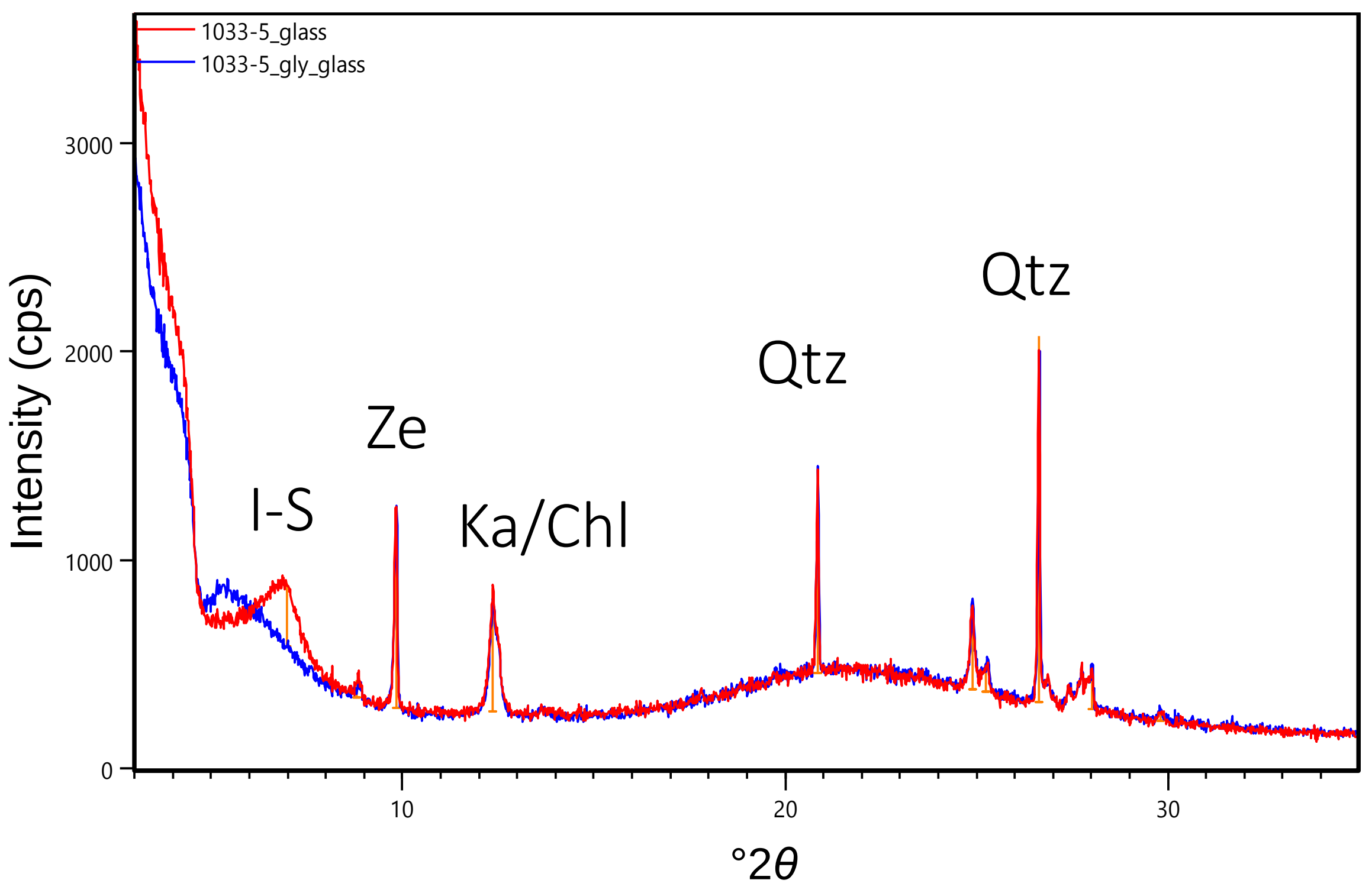


**Figure 2.** *Air-dried and glycolated XRD patterns on clay fraction, a sandstone from The Golfo San Jorge area, Argentina*

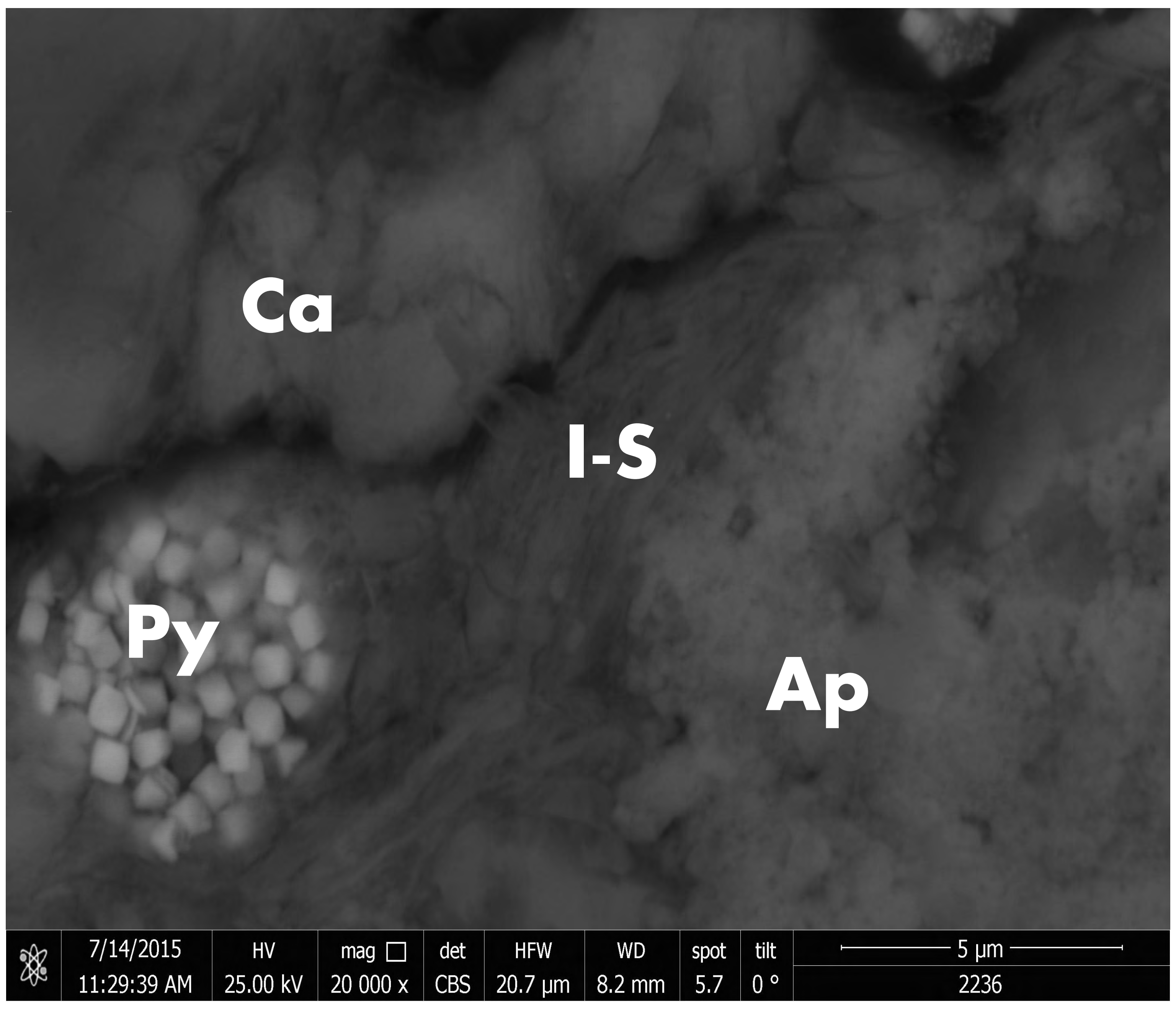
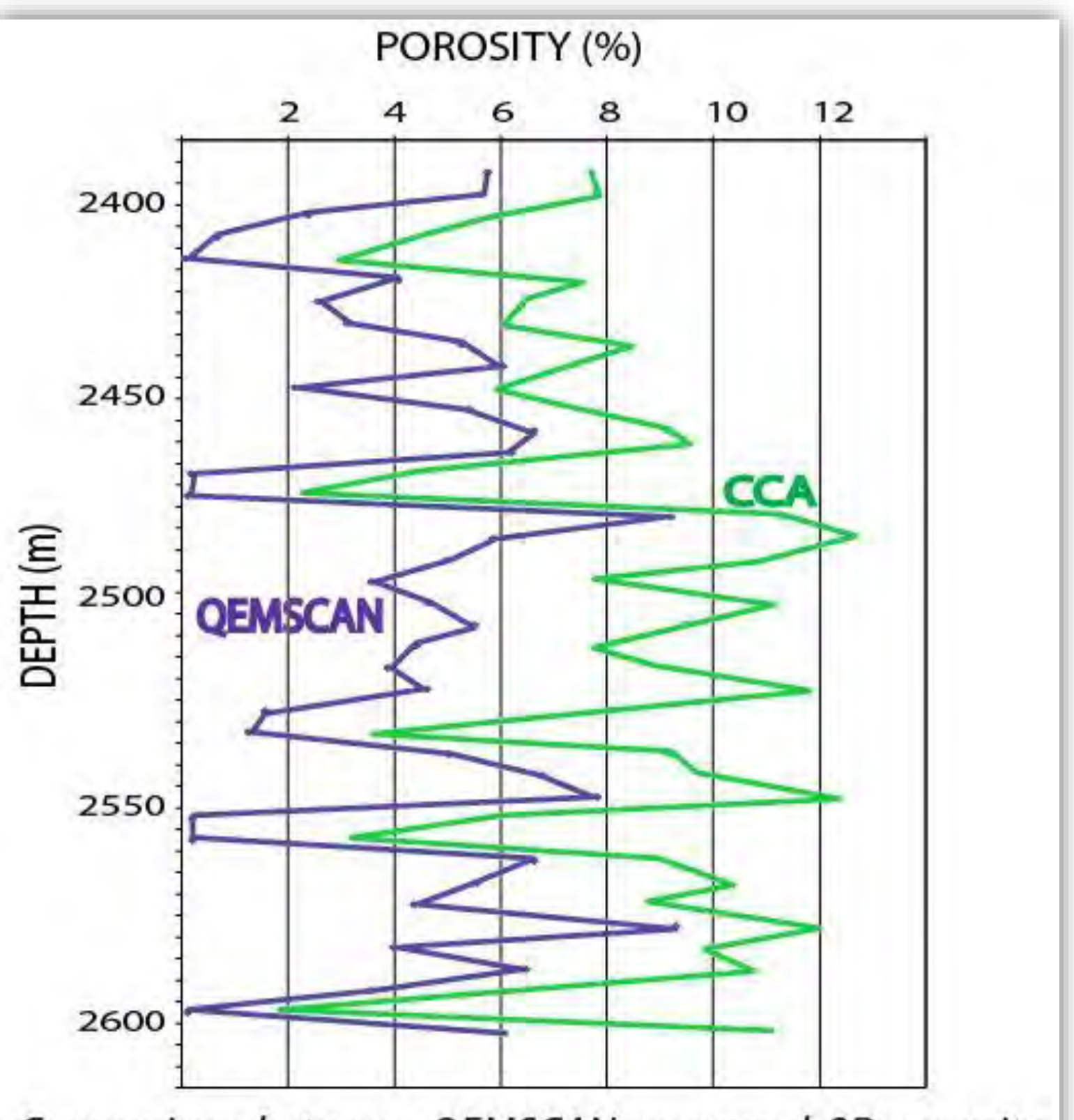


***Figure 3.*** *SEM BSE image showing a detail on the composition of the Toarcian (lower Jurassic) black shale source rock from the Greater Geneva basin near the French-Swiss border*

## 3. Conclusions

The UniGE **Rock Typing Lab** has developed an integrated approach to mineralogical analysis of reservoir rocks. This approach is vital when it comes to low-permeability, clay-rich or petrographically heterogeneous reservoirs, especially through non-cored or horizontal wells where only cuttings are available. The data generated in our laboratory are readily used to:

- Generate true mineralogical vertical log with minerals quantified which can be used to validate petrophysical log evaluations
- Evaluate of the nature and quantify of pore-plugging minerals
- Generate an independent density curve based on true mineralogy used to calibrate and validate existing wireline logs.
- Generation of an independent 2D porosity vertical log which can give a fair indication of reservoir properties variability in absence of wireline logs or conventional core analyses.



*Comparison between QEMSCAN-measured 2D porosity and 3D porosity data from Conventional Core Analyses (CCA).*

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# Rock typing of deep geothermal reservoirs in the Greater Geneva Basin

*Elme Rusillon*, Andrea Moscariello**

**University of Geneva*

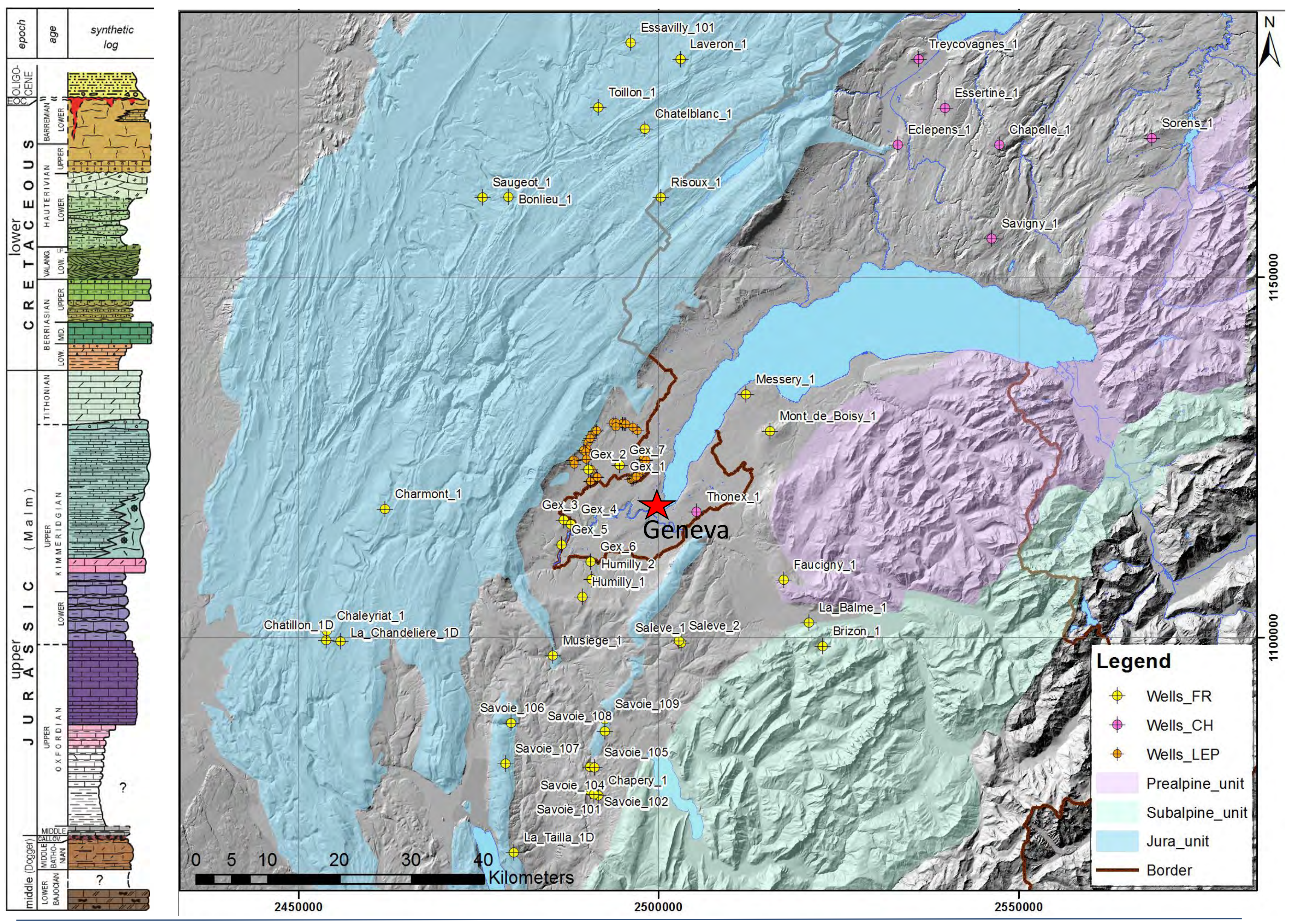
## Abstract

The aim of this PhD research is to characterize the potential reservoirs in the Geneva Basin for deep geothermal targets.

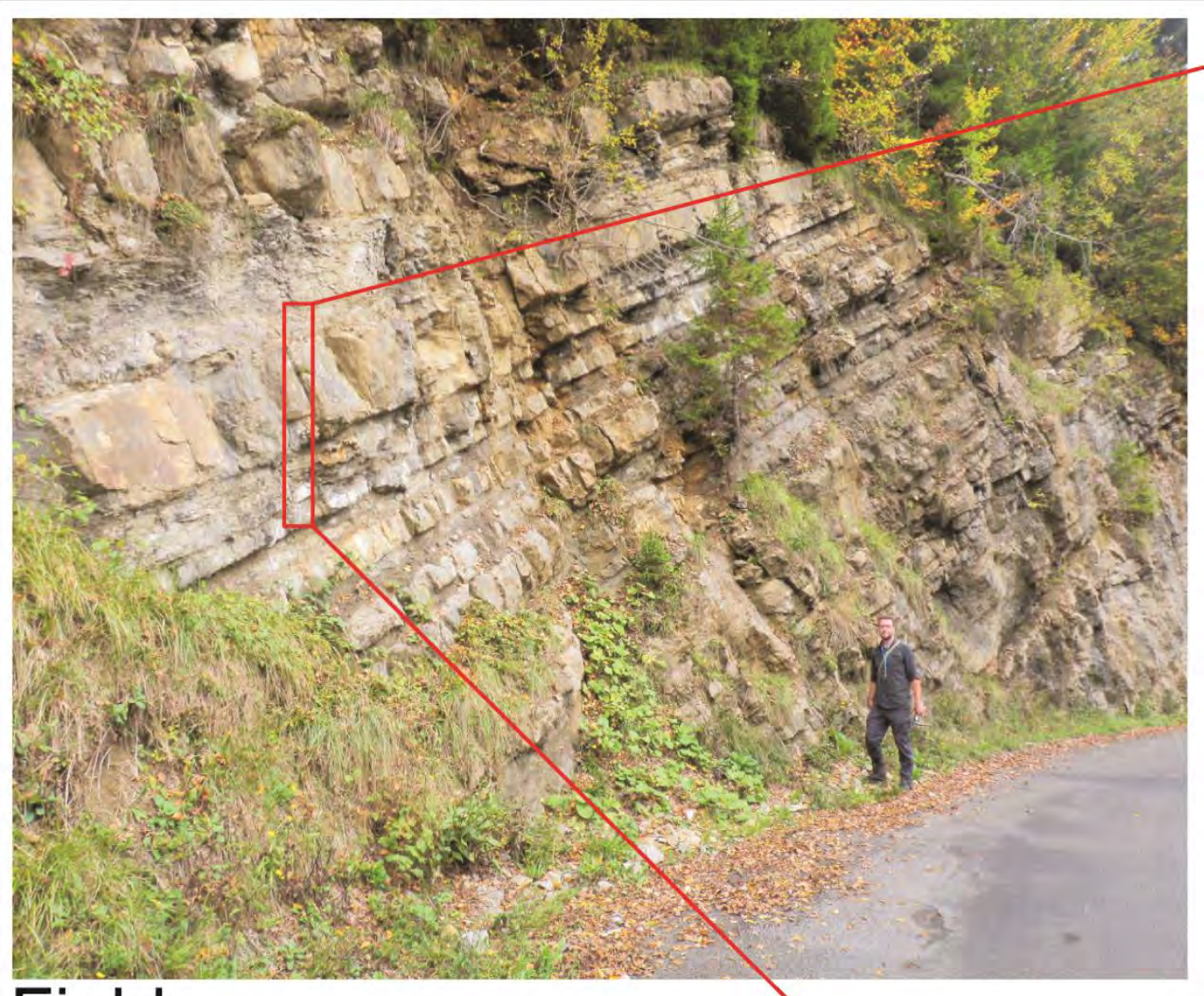
The reservoir characterization study includes 1) detailed petrophysical analysis based on existing well reports, e-logs and core material, 2) a micro-facies study using conventional petrography and automated QEMSCAN analysis, and 3) a diagenetic study by optical cathodoluminescence. Field investigations on specific reservoir analogues is also carried out to develop a better understanding of the facies lateral variability and thus a better constraint of the reservoirs geometry.

This study is associated with another PhD project focusing on basin structural analysis, including 3D geological modelling derived from 2D seismic, well data and field study (Nicolas Clerc, UNIGE/UNINE). These two integrated studies will help to understand better the distribution of productive reservoir facies and fractured zones within the Greater Geneva Basin.

## 1. Settings



## 2. Methods

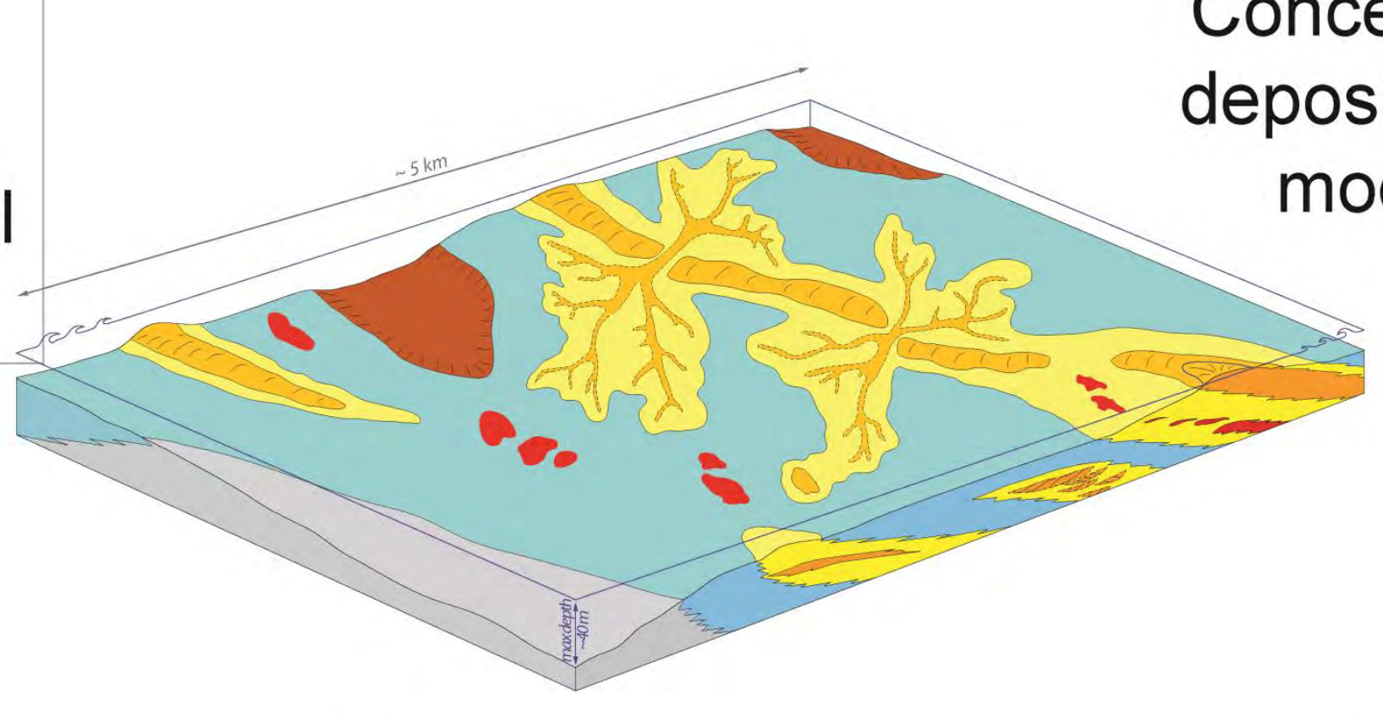


Field
- Facies recognition and comparision from well to field scale
- Outcrop analogue for reservoir lateral variation
- Link to core observations and measurements

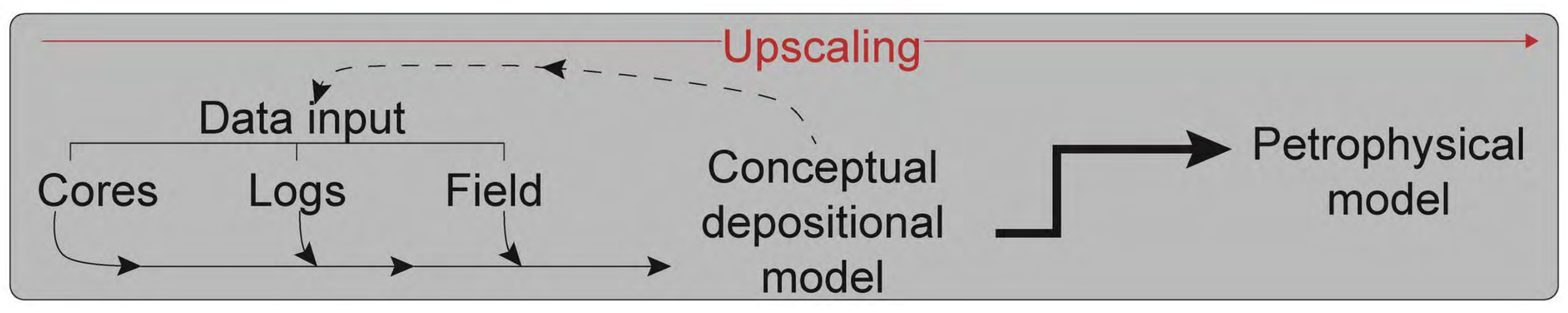
*Φ&K*lab ↔ *Φ&K*log

Cores
- Core macro-description and sampling
- Micro-facies analysis on thin section
- Pore space analysis: diagenetic study and micro-tomography analysis
- Petrophysical measurements on plugs

Logs
- Curves digitalization
- Log signature interpretation
- Petrophysical analysis on potential reservoirs



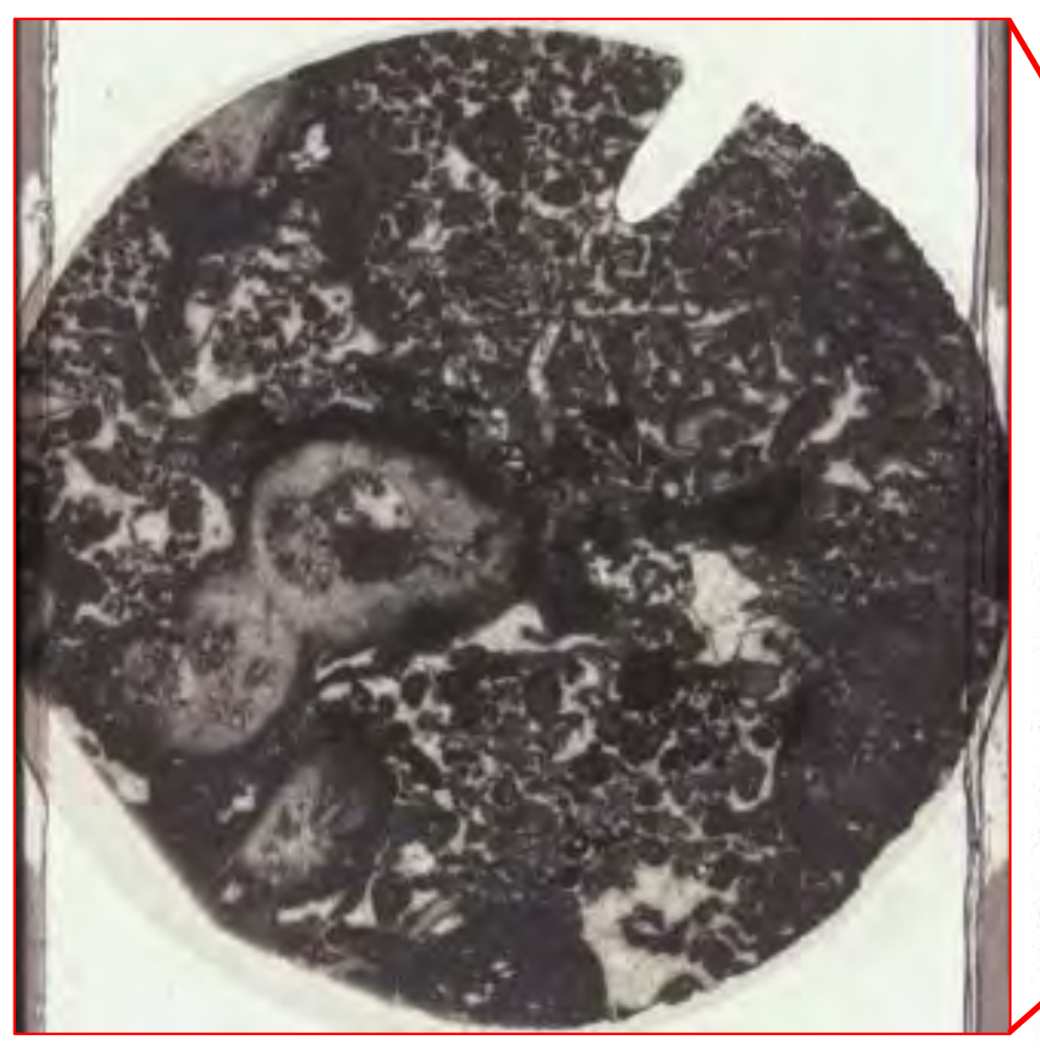
Conceptual depositional model

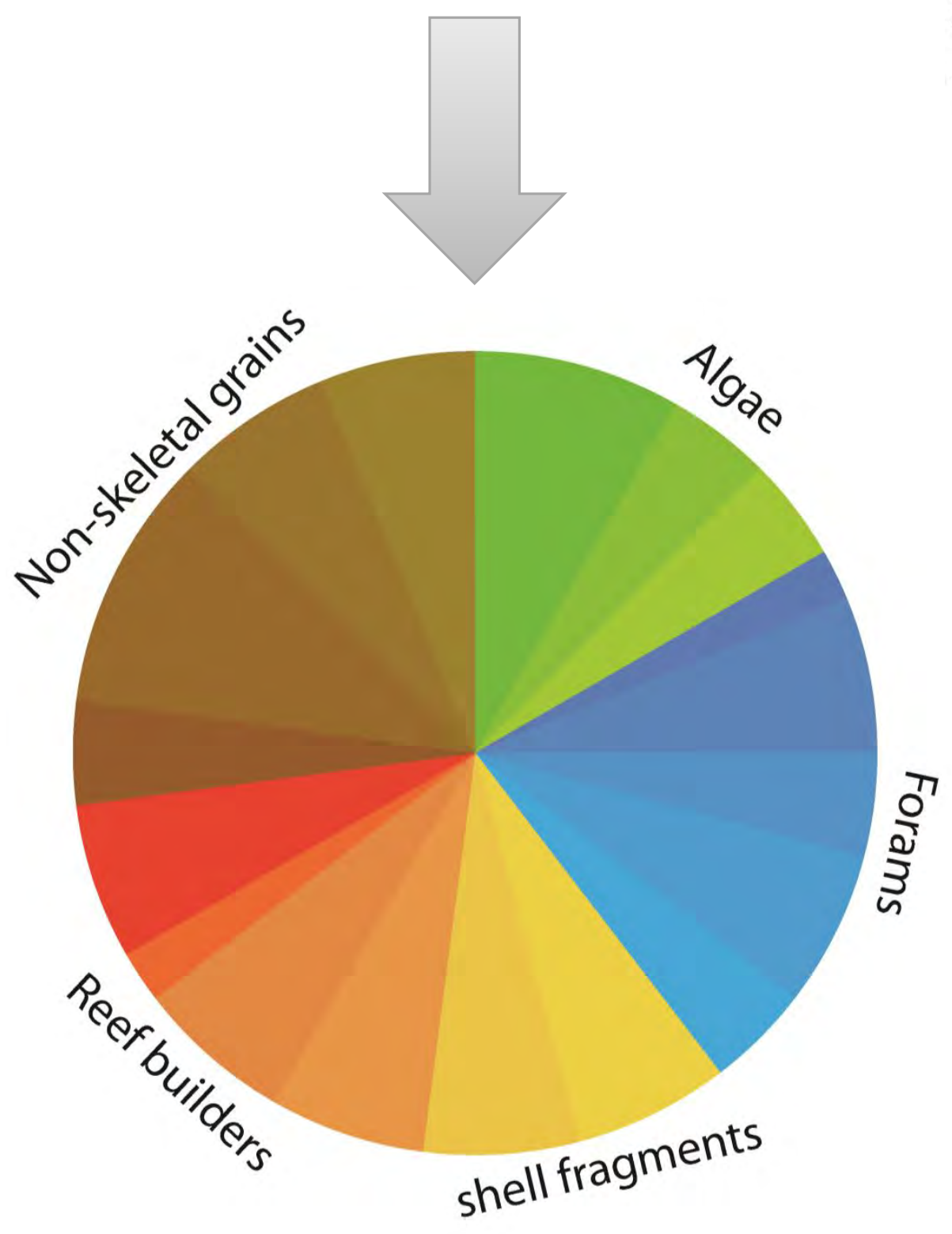

Upscaling
Data input
Cores
Logs
Field
Conceptual depositional model
Petrophysical model

GEOTHERMIE 2020

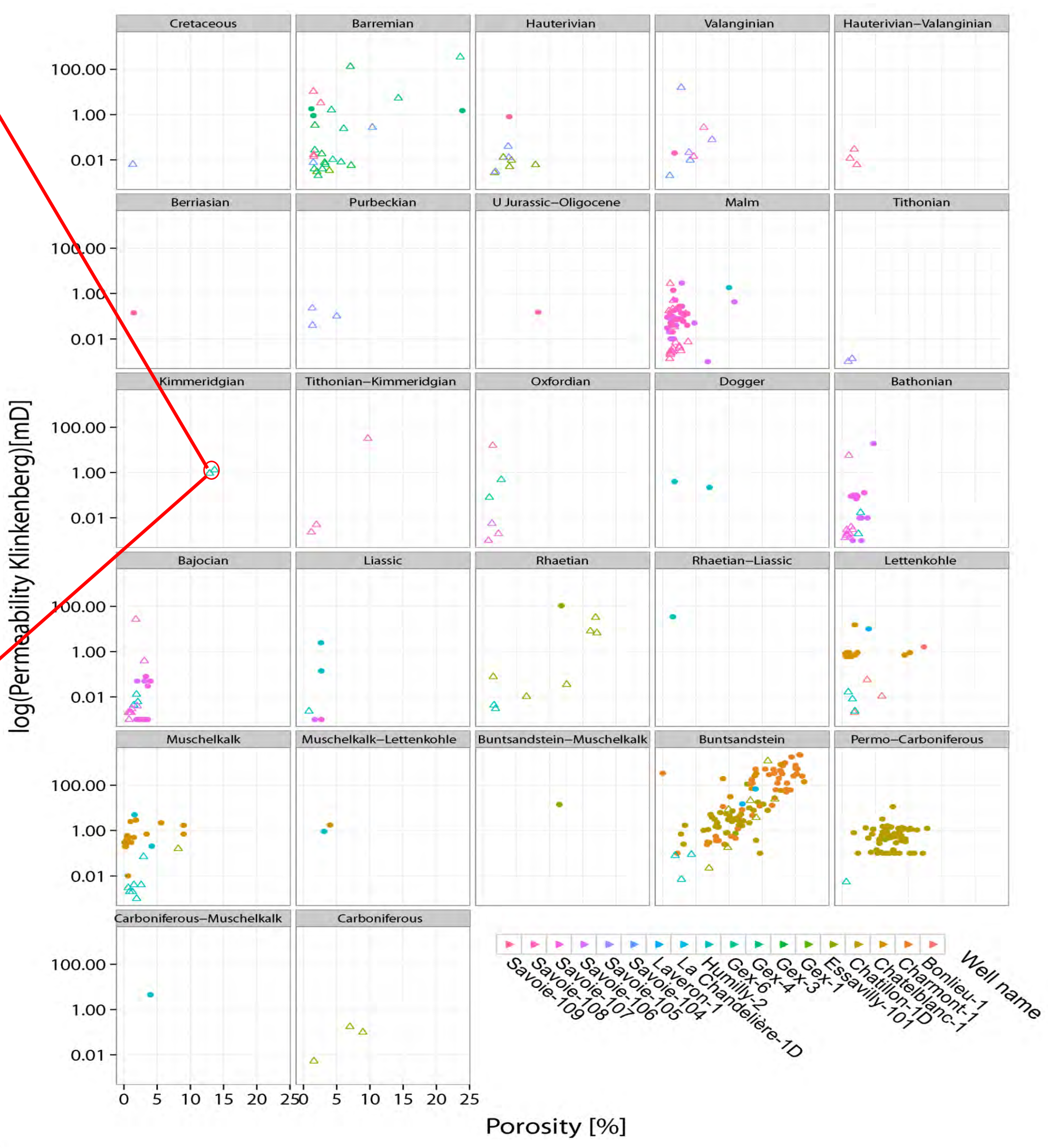
- Objectives: assessment of geothermal reservoir potential in the Greater Geneva basin
- Concept: rock typing and reservoir geometry
- Research questions: Which are the geological units to target for geothermal exploitation? What is the potential output?
- Main partners involved: Services Industriels Genevois (SIG), Etat de Genève (GESDEC)
- Status of the project: feasibility study

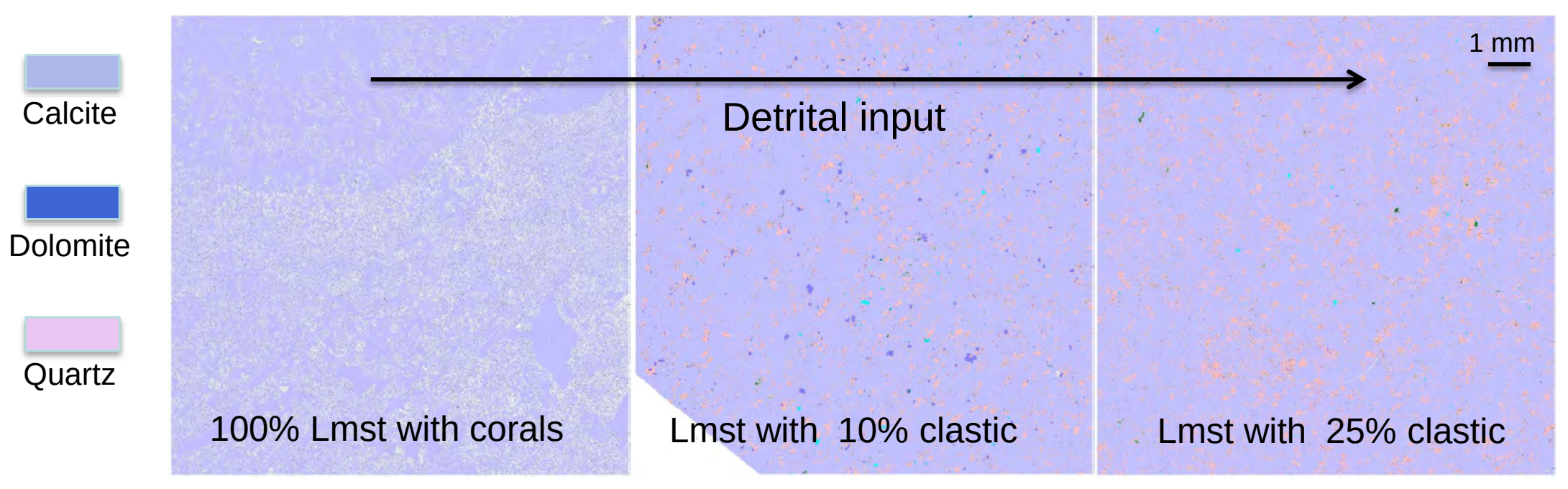
## 3. Preliminary results





Φ and k from reports and new measurements





QEMSCAN images of carbonate rocks with indication of increased clastic content

Kimmeridgian Reef complex in Humilly-2 well:
- Small patchy distal reefs with low reef-frame/interstitial sediment ratio
- Φ & k on plug, sonic Φ, mud losses and fresh water inflow suggest potential reservoir capacity

## 4. Conclusions

*Reservoir targeting and characteristic assessment*

- ✓ Well reports investigation: information sorting and gathering in a well data base, data digitalization and display
- ✓ New core and microfacies study: reconstruction of depositional environment evolution through time at basin scale
- ✓ Outcrop analogue analysis: evaluation of reservoirs geometry
- ✓ Well logs correlation and interpretation: assessment of strata thicknesses, facies lateral variability and petrophysical parameters
- ✓ New measurements: complementation and confirmation of existing well data, new insights on rock petrophysical characteristics and comparison with well logs derived parameters
- ✓ Integrated research: link between intrinsic reservoir rock types and recognized fractured zones

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# Petrography of a potential $CO_2$ seal in the Lower Jurassic in the southwestern Molasse Basin

*Damien Do Couto*, Branimir Šegvić*, Andrea Moscariello**

**University of Geneva*

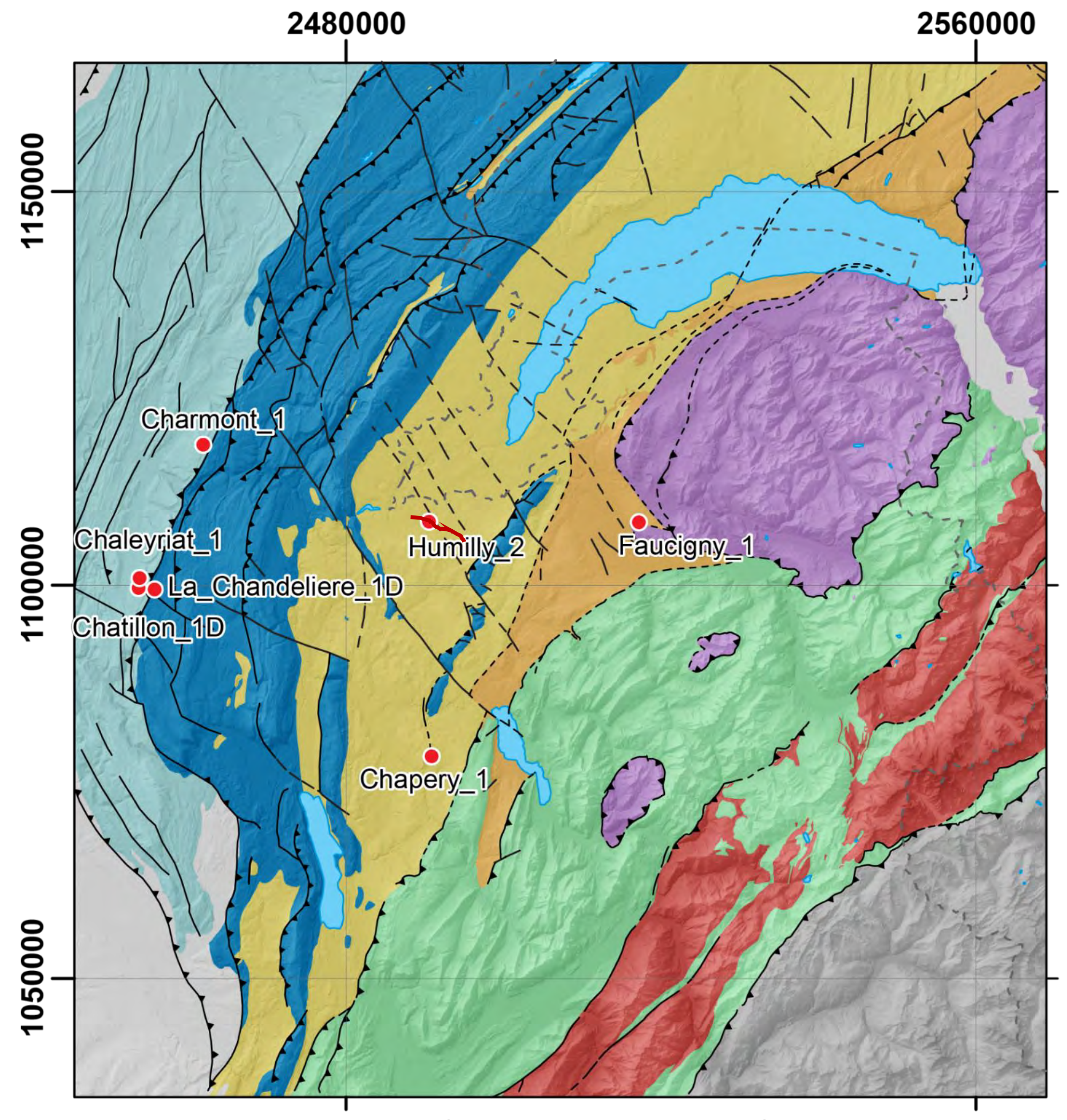
## Abstract

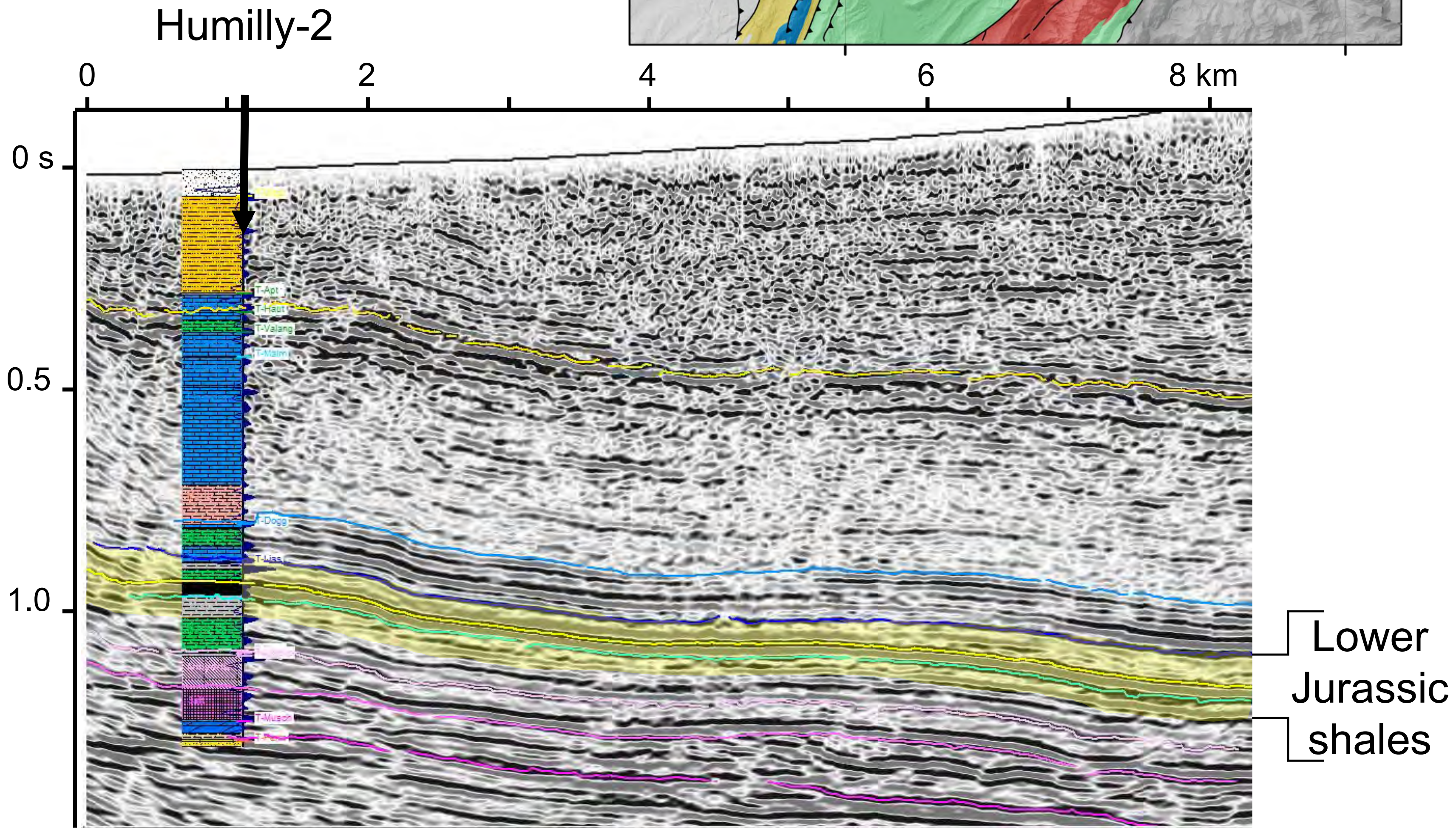
The Lower Jurassic shales (Posidonia shales) are considered as a potential effective seal under the Molasse Basin in the frame of $CO_2$ storage, and as potential source rocks. Our study aims to characterize the petrography and geochemistry of the Lower Jurassic shales in several wells (Figure 1) in order to define their potential seal effectiveness and source rock potential. On this occasion we present the preliminary results on the petrography of the Lower Jurassic shales.

## 1. Introduction

The Lower Jurassic shales in the southwestern part of the Molasse Basin is made of an alternation of marls, calcareous and black shales.

Its thickness tends to increase toward the Alpine front system.





## 2. Methods

- **QEMSCAN**

1. Petrography
2. Porosity
3. Clay identification

- **X-Ray diffraction**

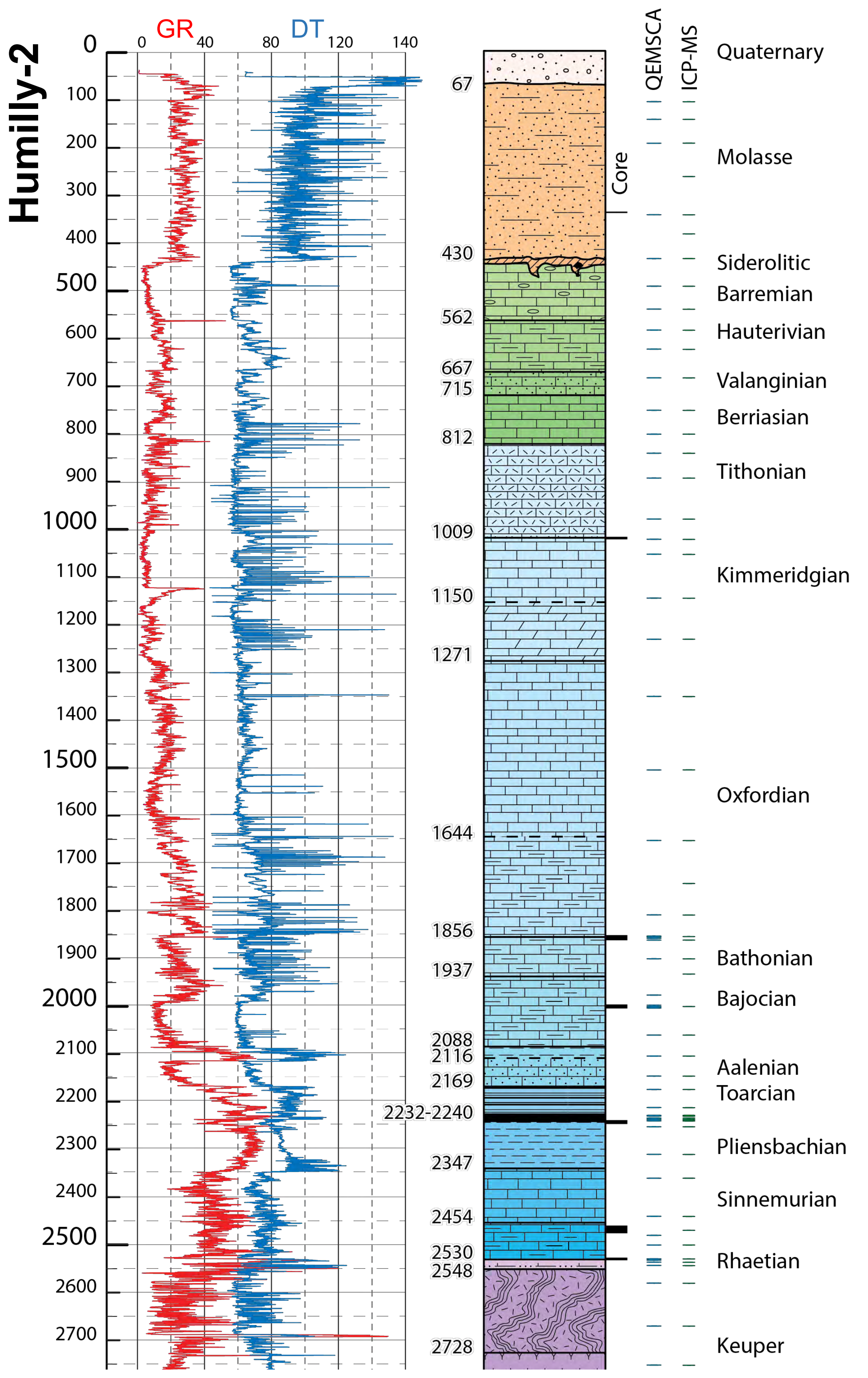
1. Mineralogy
2. Clay identification

- **ICP-MS**

1. Major elements
2. Trace elements

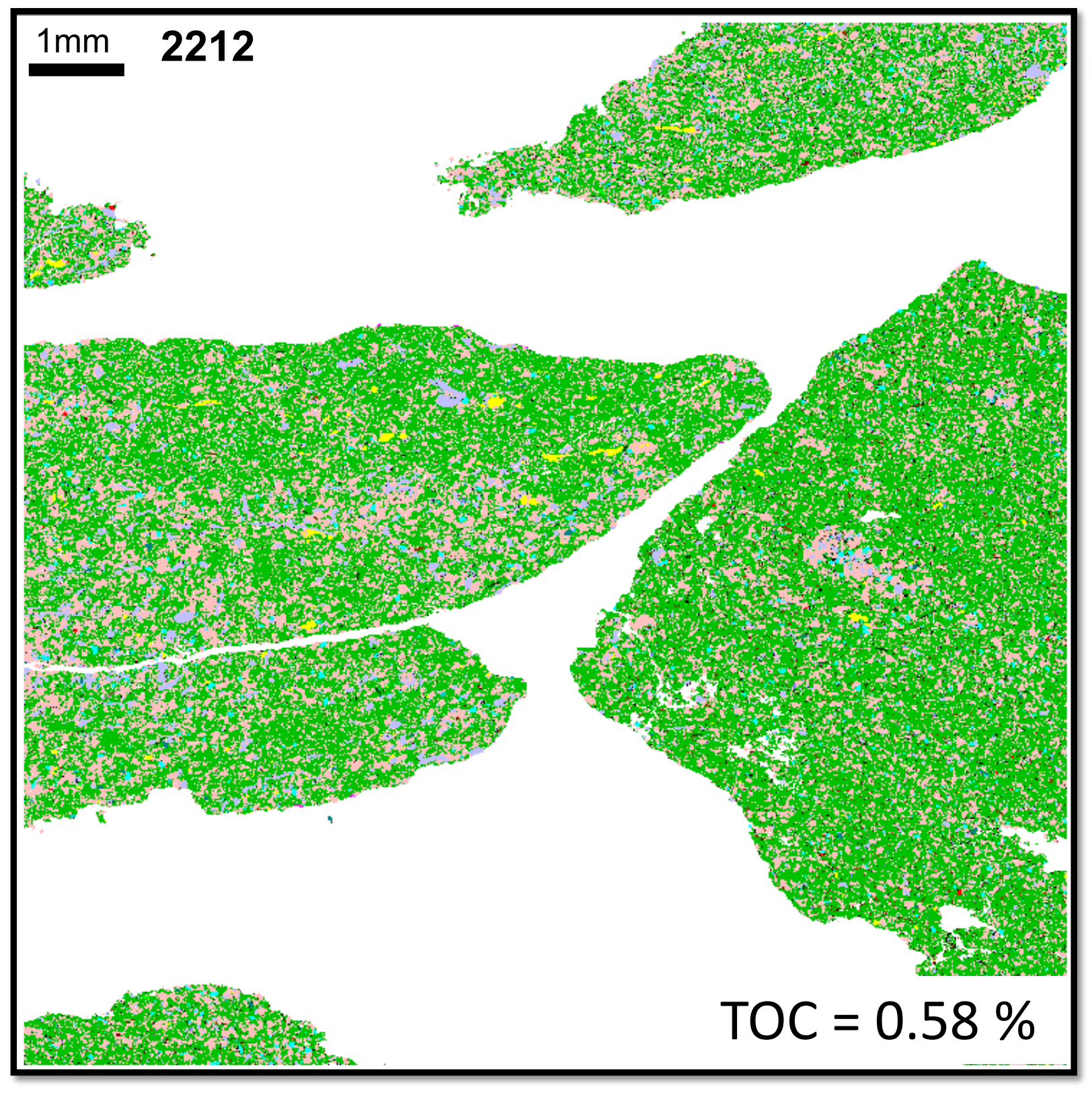
- **Rock-Eval pyrolysis**

1. Organic content
2. Source-rock maturation

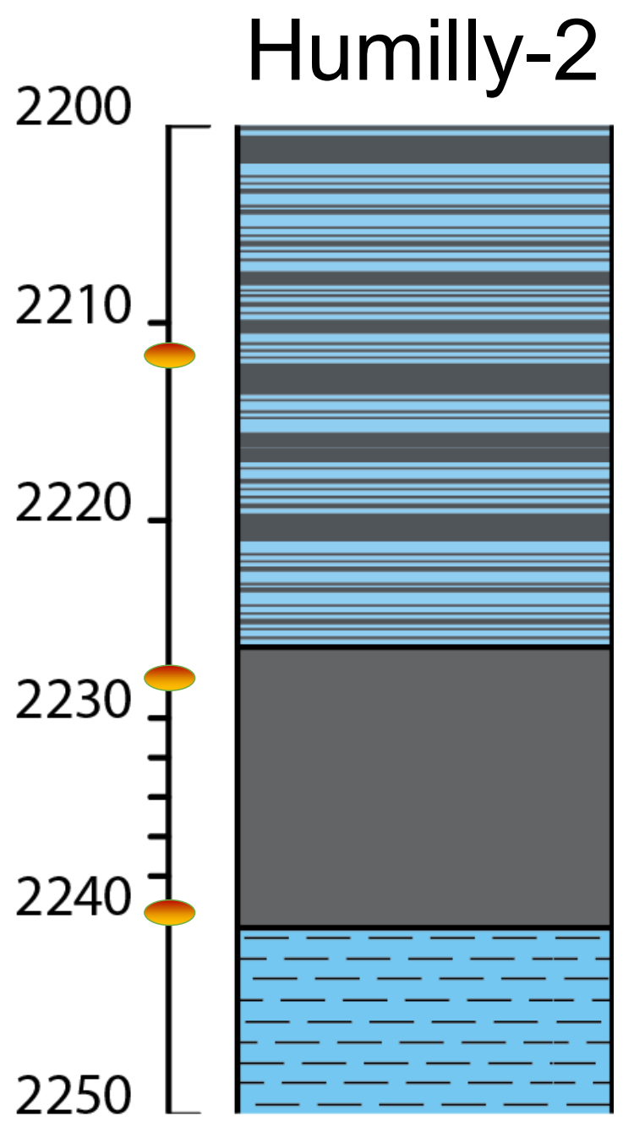


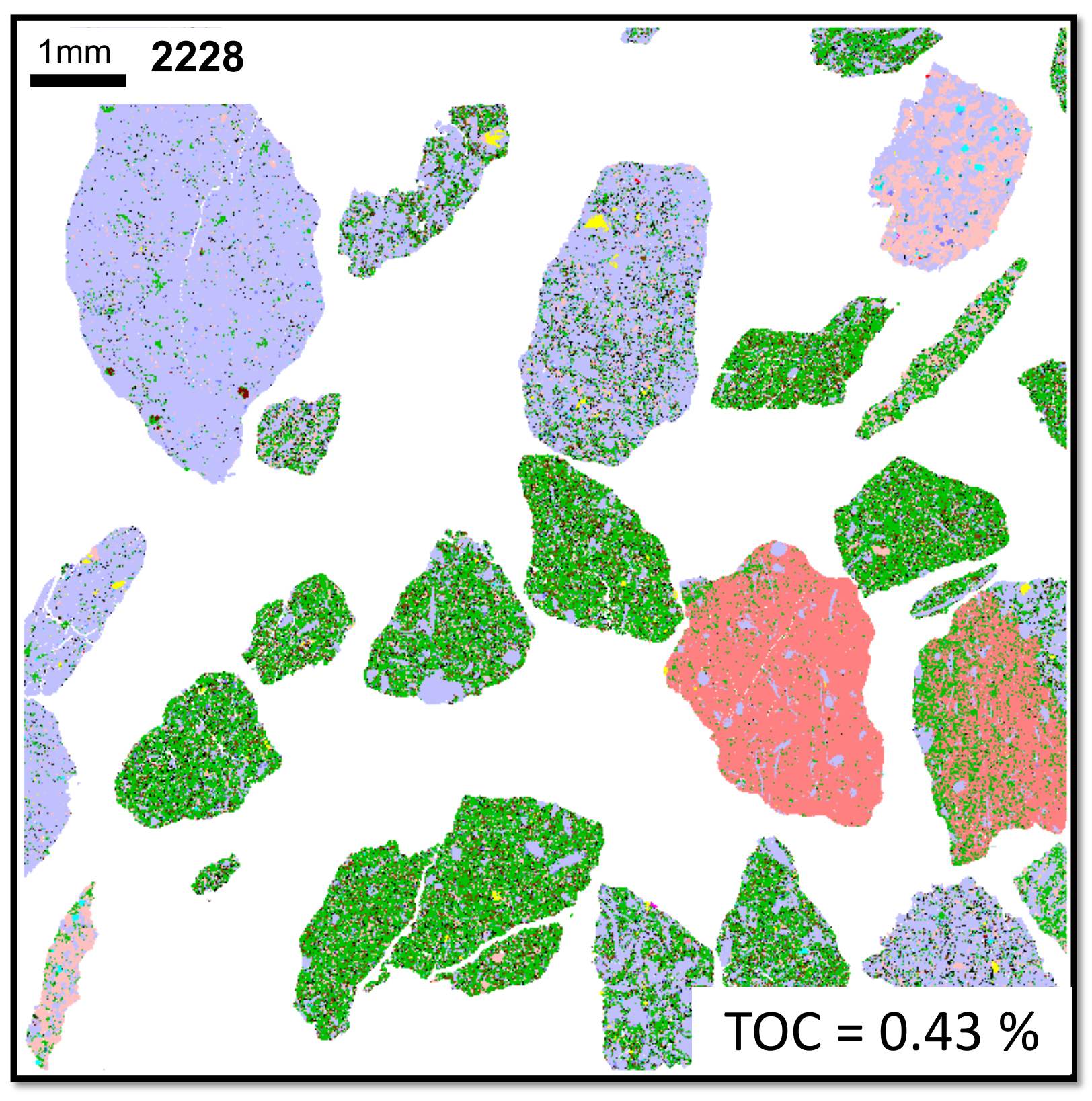
## 3. Results

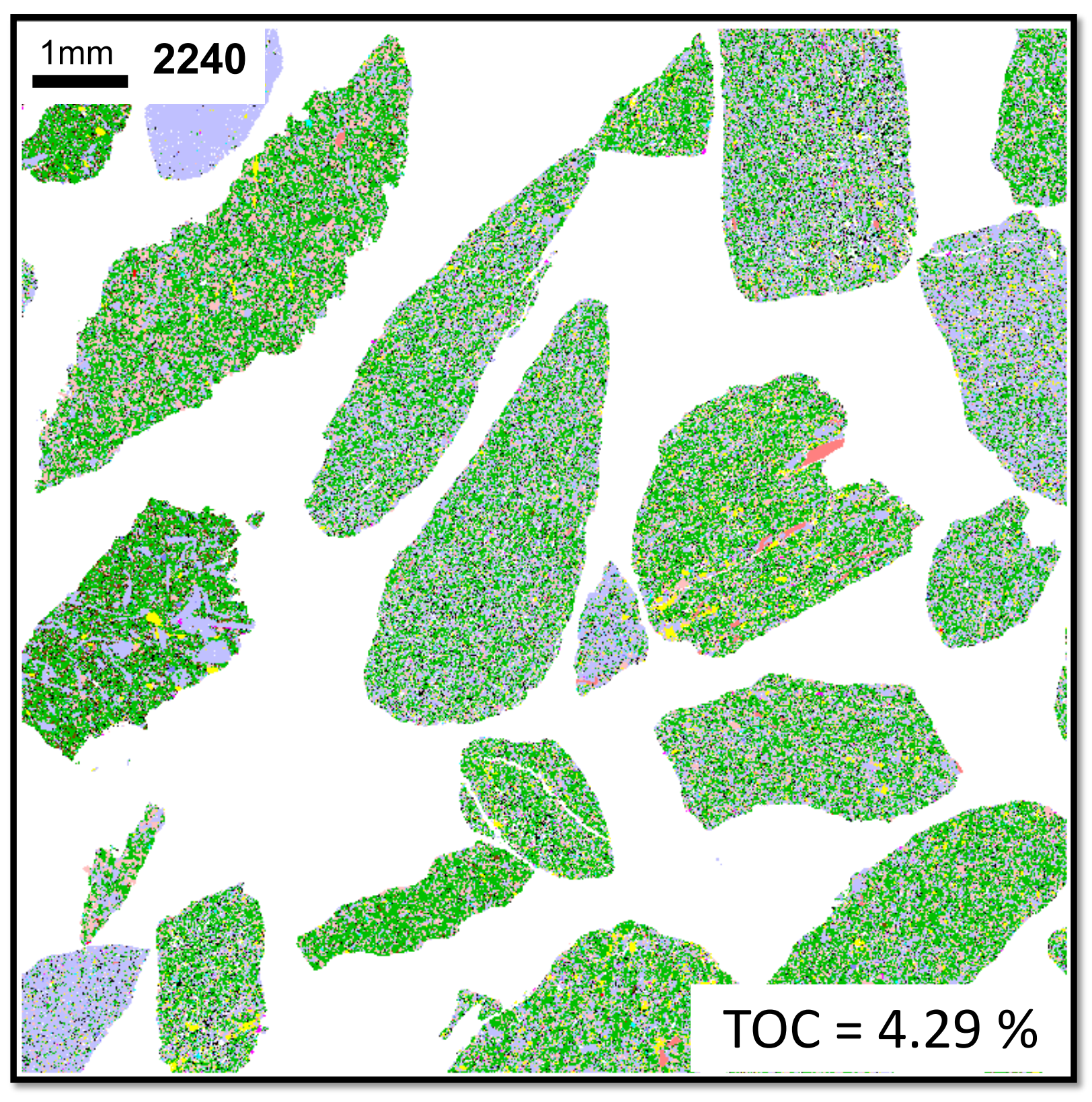
### QEMSCAN



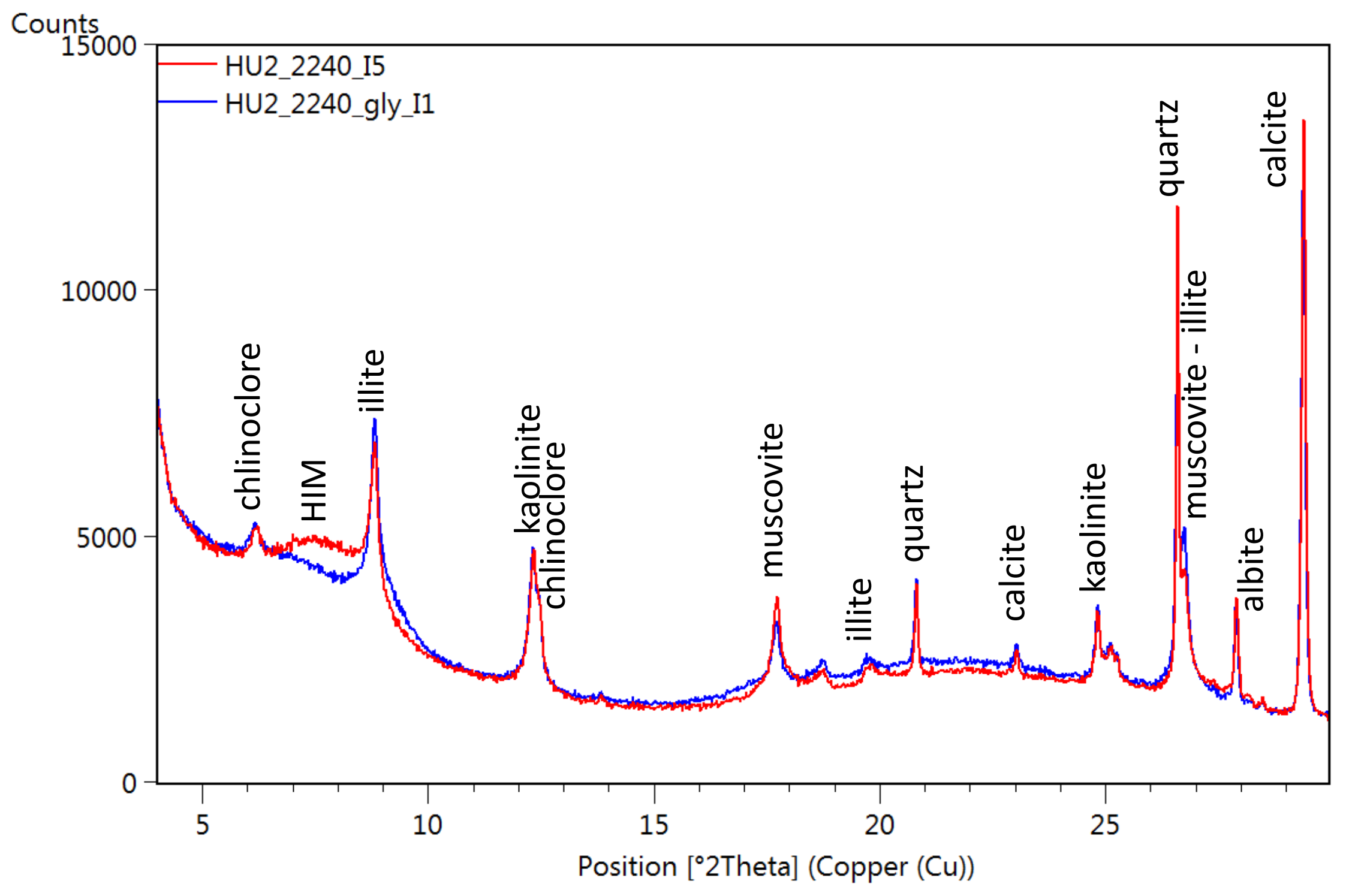
- Mineralogy
- Texture
- Grain size
- Lithotypes







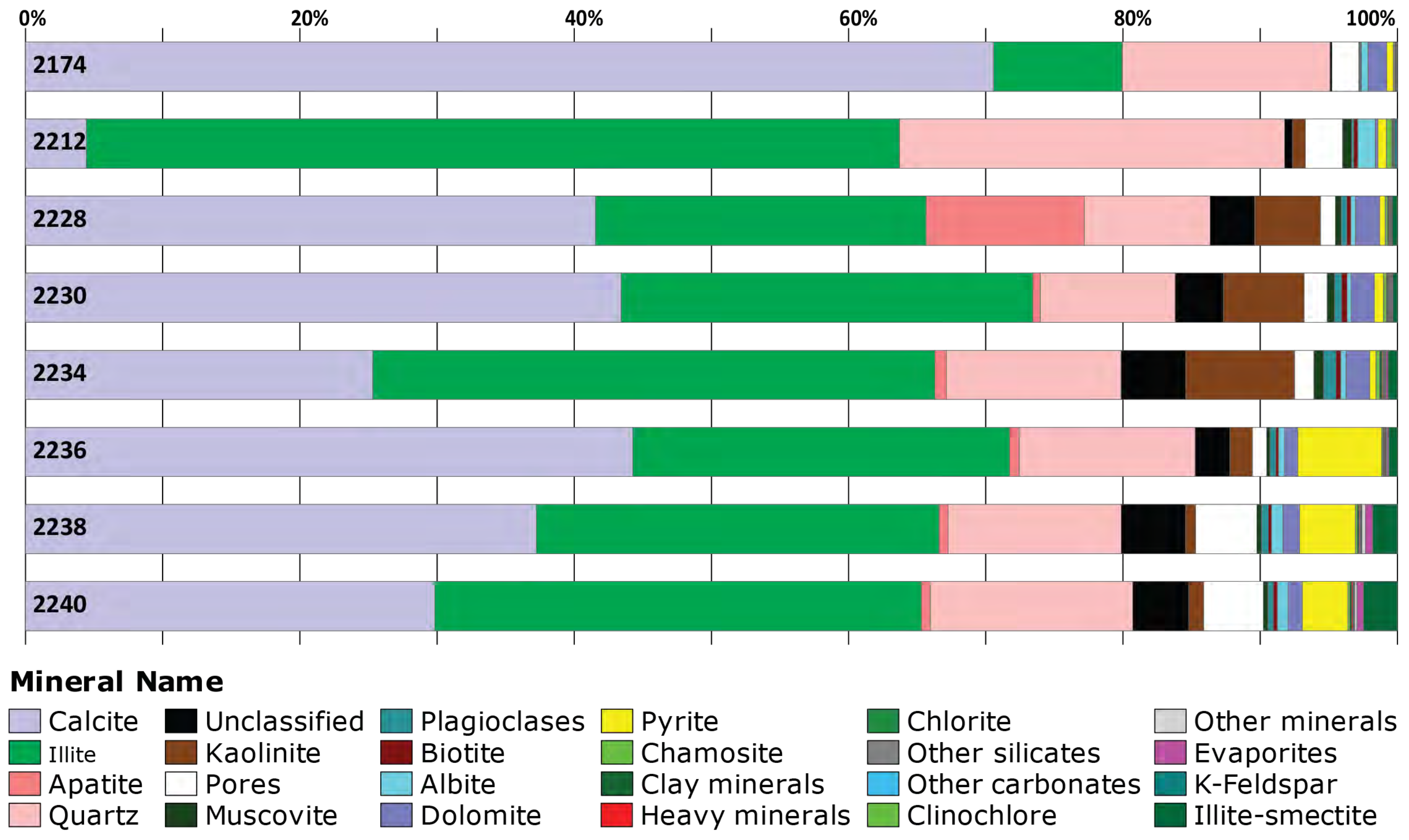
### X-Ray diffraction



Clay fractions:

- Illite and I-S
- Kaolinite
- Chlorite (chamosite and chlinochlore)
- HIM = Hydroxy-interlayered minerals
- Micas (Muscovite)

### Modal mineralogy



## 4. Conclusions & perspectives

- ✓ Combined QEMSCAN and XRD analysis ➔ high definition analysis tools to evaluate the mineralogy and microtextures of shales.
- ✓ Most of the clay fraction in the Toarcian shales of the Humilly-2 well is made of illite, kaolinite, chlorite, illite-smectite and HIM.
- ✓ The higher the clay fraction, the higher TOC amount.
- ✓ Total whole-rock geochemistry characterization (ICP-MS), and organic geochemistry is to be correlated with the petrography.
- ✓ A brittleness index will also be calculated from the bulk mineralogy and compare to geophysical data (digital logs, elasticity, velocity).

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# Geological data management:
# An essential tool to operate subsurface resources

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## 1. Introduction

The deep subsurface and its natural resources belong to the State. A detailed and accurate knowledge of them is therefore key to allow their effective exploitation and management.

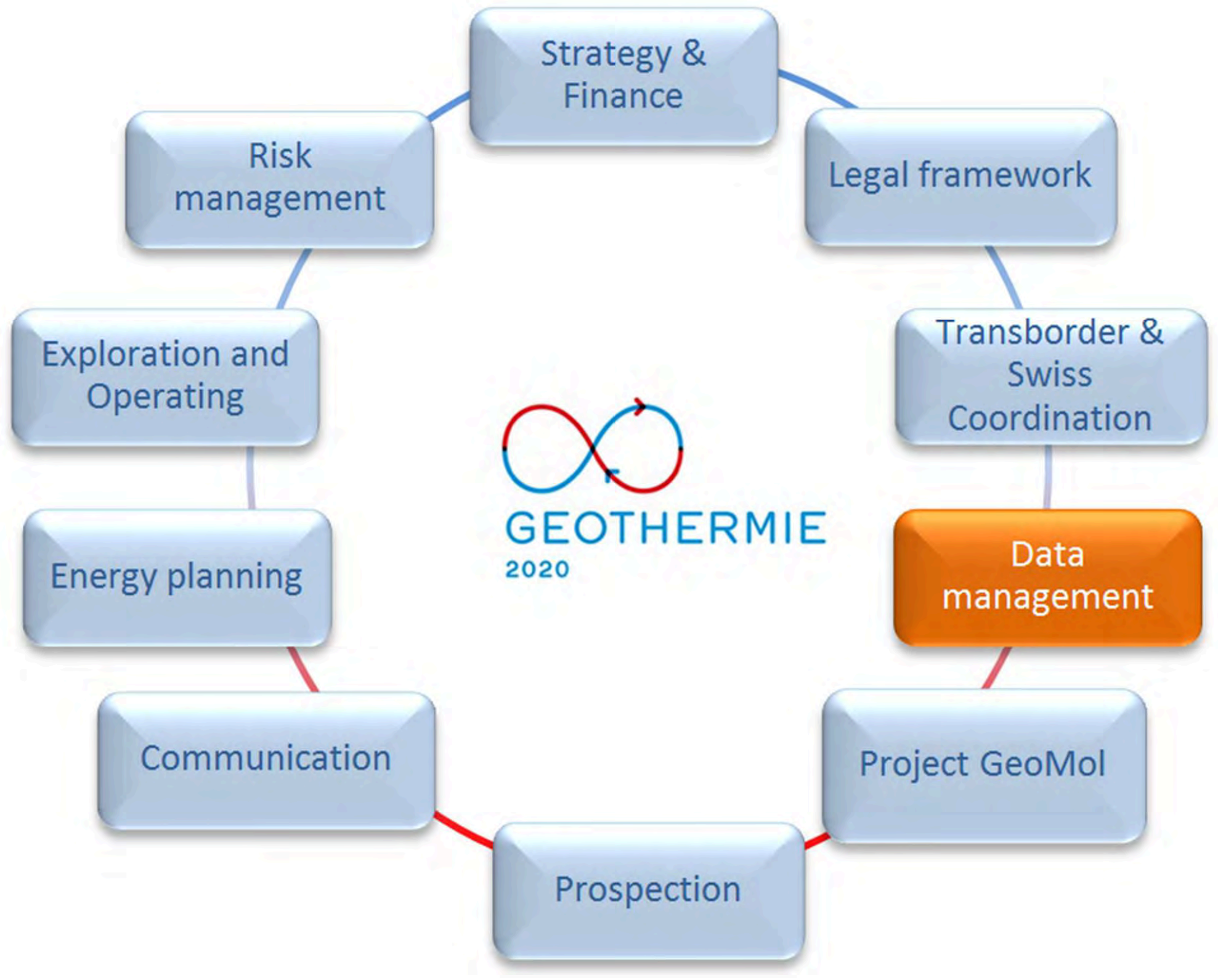
Funded and supported by the State of Geneva, this project focuses on centralization and enhancement regional geological data. A substantial work on the basin stratigraphy has to be done in order to correlate data.

In parallel, building a database capable to host 2D and 3D geological information, as seismic lines, boreholes, reports, outcrops and models is in progress (in collaboration with Stéphanie Favre, PhD at Unige).

## 2. Context

### Framework

GEothermie 2020 is a program piloted by the SIG (Services Industriels de Genève) and the State of Geneva. The aim is to develop the geothermal energy in the Geneva basin. Different axes must be approached to deal with the overall project. The issue discussed in this poster is the **data management**.



### Data

In Geneva, there are a lot of data, such as data fields, shallow drilling, seismic, but it was noted that these data have never been assembled and standardized.

At the University of Geneva, a wealth of information about regional geology, as diploma, thesis, papers, exists. However, some are:

- Summarily archiving
- Isolated
- Only in paper
  - Access /consultation difficult
  - Sustainability of the document
- Not valued
  - Knowledge loss risk

Diploma Geneva: Location Map

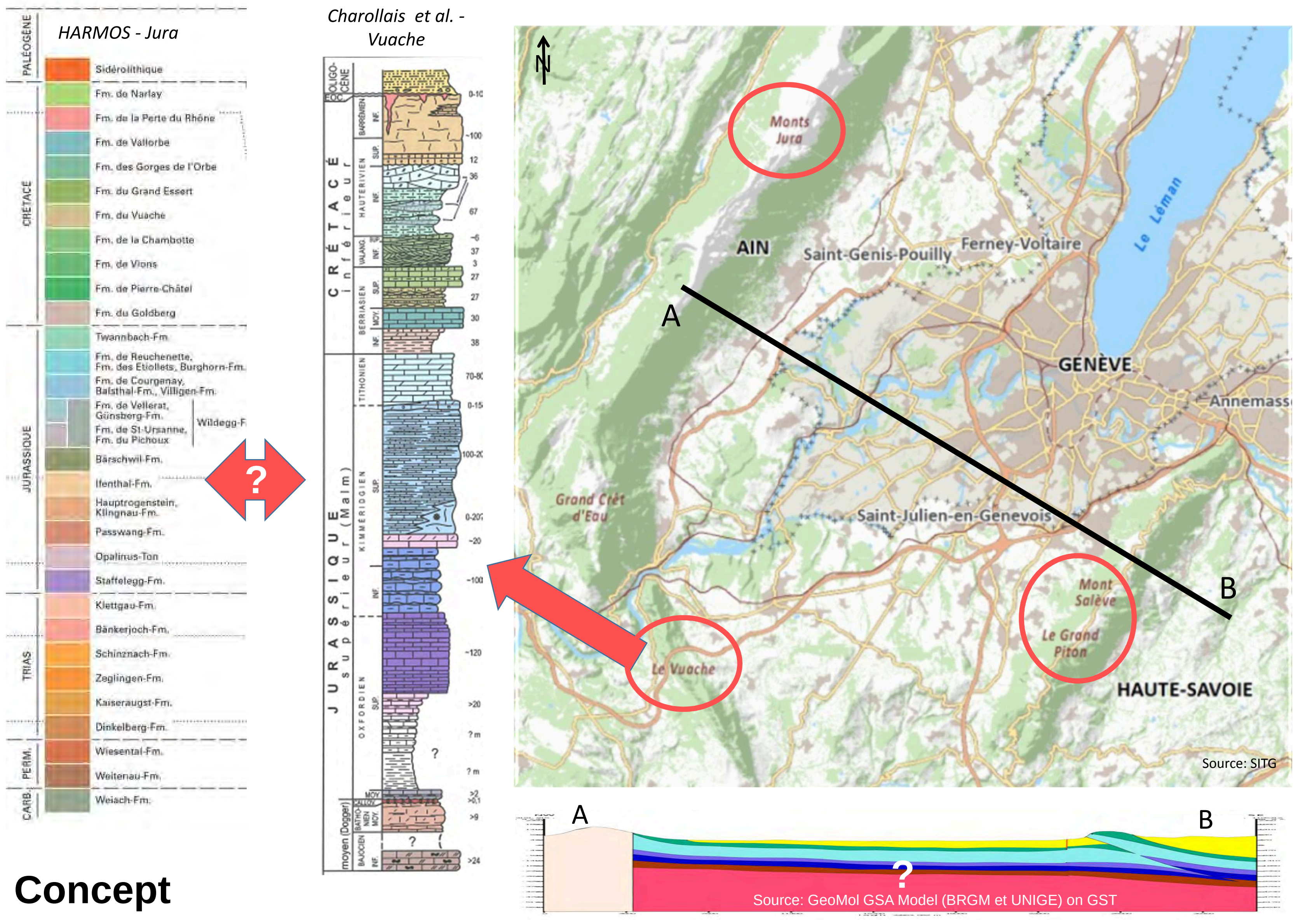
## 3. Objectives

- ➢ **Collect all data**
- ➢ **Build a geological database**
- ➢ **Create a complete 3D model of the Geneva basin**
- ➢ **Develop an integrated management of the subsurface resources**
- ➢ **Give an easier access to the geological information**

## 4. Methods

### First steps

- Application of an unique stratigraphy :
  - HARMOS (swisstopo stratigraphy): critical, strengths, weaknesses, loss of information
- Assessment of rock characteristics
  - Lateral variability within the geological basin
  - Difference between outcrops and boreholes
- Relevance of geological data
  - Level of accuracy for a model cantonal
  - Selection of the useful and necessary information



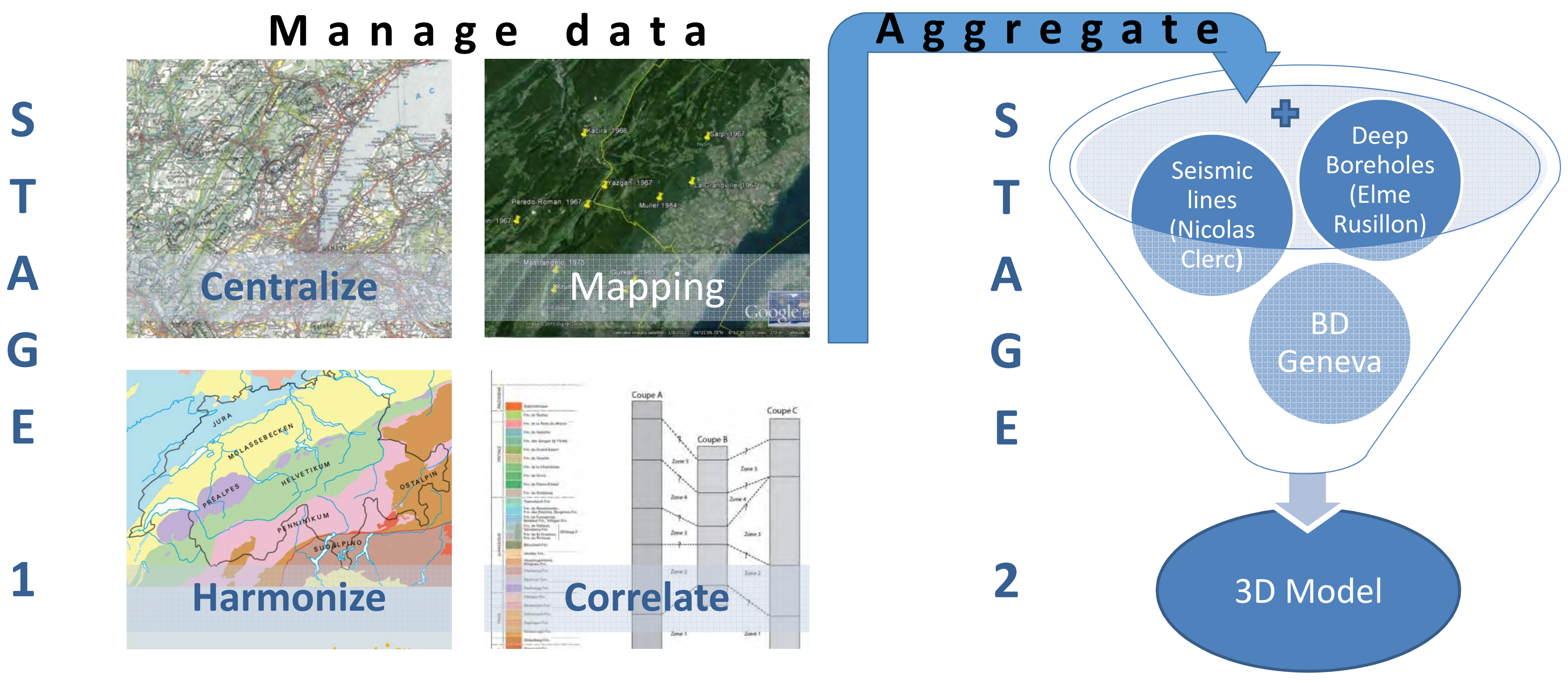
### Concept

Studying the geology of mountains surrounding the area:

- Salève
- Jura
- Vuache

in order to have a better understanding of the Geneva's deep geology.

### Diagram summarizing



## 5. Conclusions

The deep subsurface geology of the Geneva basin is not yet well known. The GEothermie 2020 program offers the opportunity to improve it by collecting new data. These data need to be owned by the State, organized and managed by them. For decades, geology studies has been done in Geneva surrounding areas. It's important to integrate them with the past and future data from the subsurface and to valorize them through a complete data management system.

The future database will offer users (scientists, engineer and public) capabilities to find, extract, validate (relevance, quality), interpret and process geological data. Finally, it will provide tools for the State of Geneva to manage its subsurface resources like Geothermal energy!

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# Reactive transport modeling of 3 geothermal systems located in Switzerland, Germany and Mexico

C.Wanner[1], L. Peiffer[2], F. Eichinger[3], K. Bucher[4], P.A.E. Pogge von Strandmann[5], H.N. Waber[1], L.W. Diamond[1]

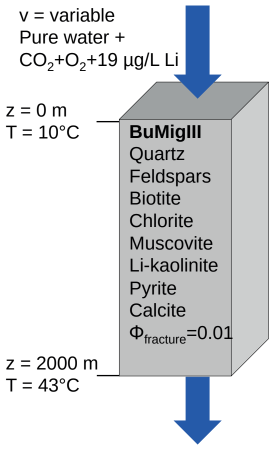
## Introduction

Reactive transport modeling RTM provides a unique opportunity to quantitatively assess coupled thermal-hydrological-chemical-mechanical (THCM) processes. Since launching the SCCER-SOE we have been involved in performing THC simulations using the code TOUGHREACT V3 in conjunction with 3 geothermal or geothermal-like sites located in Switzerland, Germany and Mexico. This poster summarizes the highlights of the 3 case studies.

## 1. Analogue study from the Gotthard rail base tunnel

- The success of enhanced geothermal systems is dependent on the fracture surface made accessible during reservoir stimulation
- Fluid circulation alters the newly accessible fracture surface area
- Stable Li isotopes are fractionated during Li uptake by secondary mineral precipitation (e.g. clay formation)
- Does water circulation along fractured crystalline rocks cause detectable Li isotopic fractionation at elevated temperatures?
- Can we use this information to estimate the corresponding fracture surface area?

### Model setup

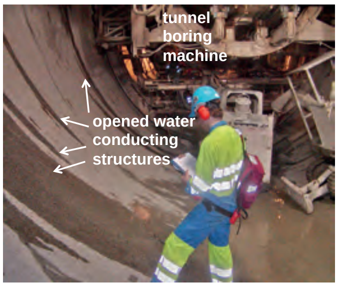

v = variable
Pure water +
$CO_2$+$O_2$+19 µg/L Li

z = 0 m
T = 10°C

**BuMigIII**
Quartz
Feldspars
Biotite
Chlorite
Muscovite
Li-kaolinite
Pyrite
Calcite
$\Phi_{fracture}$=0.01

z = 2000 m
T = 43°C

### Water sampling



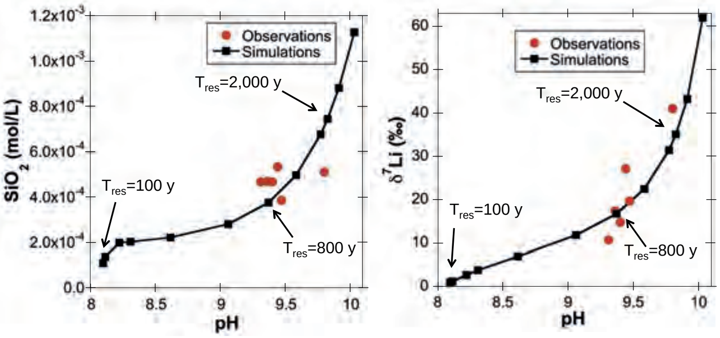
### δ⁷Li and [Li] measurements

| | Sample | $\delta^7$Li | [Li] (mg/L) |
|---|---|---|---|
| **Bristner Granite** | A005 | 8.6 | 1.62 |
| | A039 | 9.0 | 2.86 |
| | A043 | 9.1 | 3.23 |
| **BuMigIII** | A100 | 10.7 | 0.014 |
| | A102 | 19.7 | 0.013 |
| | A029 | 41.1 | 0.010 |

### Reaction rates

$$r = A_{rfrac} k_{25} \exp\left[\frac{-E_a}{R}\left(\frac{1}{T} - \frac{1}{298.15}\right)\right] \cdot \left[1 - \left(\frac{Q}{K}\right)\right]$$

### Model results



### Key findings

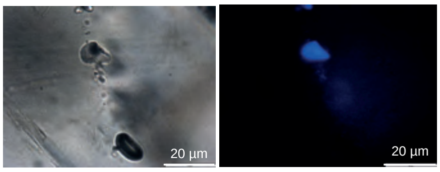
- Alteration of fracture surfaces may lead to a strong variation of $\delta^7$Li values at temperatures of up to 43°C if [Li] are sufficiently low
- For simple systems with known residence times and low [Li], fracture surface areas may be estimated based on $\delta^7$Li values and species concentrations by performing RTM simulations

## 2. Calcite scalings in geothermal wells in S Germany

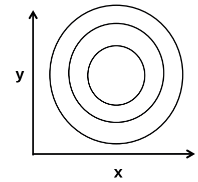
- What causes the formation of large amounts of calcite precipitates in geothermal wells drilled into the Bavarian Molasse Basin (carbonate-dominated Malm aquifer)?

### Calcite precipitates

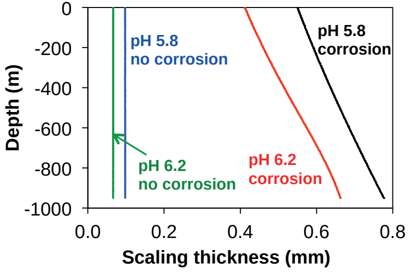
### Methane and petroleum inclusions



### Model setup (radial mesh)



### Model results (pump-surface)



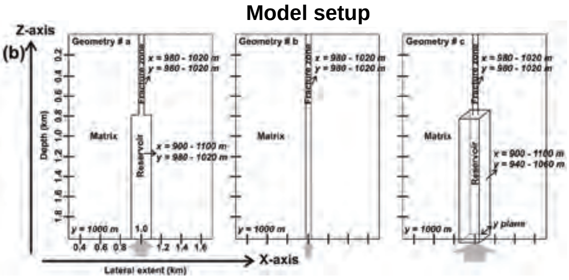
### Key findings

- Enhanced corrosion, low reservoir pH values and high pumping rates all contribute to scaling formation
- Additional processes such as stripping of $CO_2$ into the methane-rich gas phase may form a major control on scaling formation as well

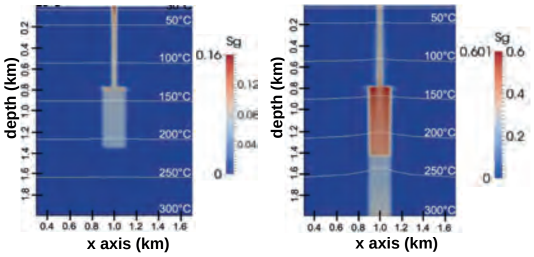
## 3. Potential EGS site at Acoculco, Mexico

- Can we assess the depth and geometry of hidden geothermal systems based on $CO_2$ flux measurements and RTM simulations?

### Model setup



### Model results (low vs. high $CO_2$ content)



### Key findings

- $CO_2$ fluxes at the surface are highly sensitive to the dissolved $CO_2$ content of the deep fluid
- It is likely that at Acoculco a small scale geothermal reservoir exists at a depth of 2000-3000 m

### Publications

[1] Peiffer, L., Wanner, C., Pan, L. 2015. Numerical modeling of cold magmatic $CO_2$ flux measurements for the exploration of hidden geothermal systems. Journal of Geophysical Research, in press. Wanner, C. 2015. [2] Reaktive Transportmodellierungen zu den Karbonatausfällungen in den Geothermieanlagen Dürrnhaar und Kirchstockach. Bericht vom 12.3.2015 zuhanden der Süddeutschen Geothermie Projekt GmbH. [3] Wannner, C., Bucher, K., Pogge von Strandmann, P.A.E., Waber, H.N. 2015. Tracking water-rock interaction in fractured crystalline rocks by Li isotope fractionation. Goldschmidt Conference 2015, Prague (Abstract)

### Affiliations

[1]University of Bern, Switzerland; [2]Universidad Nacional Autónoma de México; [3]Hydroistop GmbH, Germany;[4]University of Freiburg, Germany; [5]University College London, UK

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# Accessible analogues of fault-hosted geothermal energy systems: hydrothermal breccia (Grimsel, CH)

*Daniel Egli [1], Ludovic Baron [2], Tom Belgrano [1], Alfons Berger [1], Larryn Diamond [1], Marco Herwegh [1],*
*Klaus Holliger [2], Claudio Madonna [3], Quinn Wenning [3], Tobias Zahner [2]*

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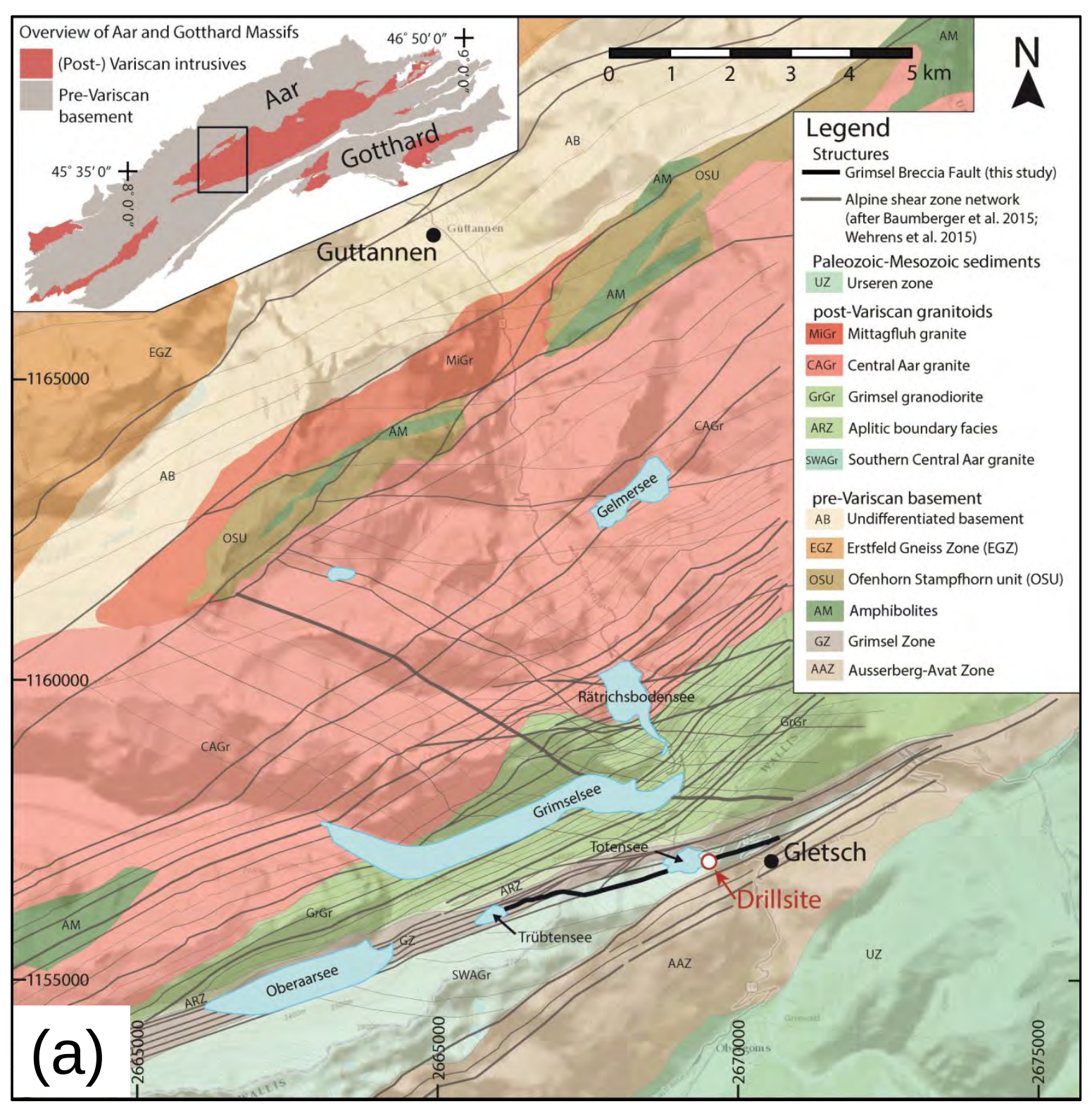
## 1. Introduction

Naturally porous and permeable rock masses constitute an attractive alternative to hydraulically enhanced geothermal systems, which in the past have caused significant artificial seismicity. However, the knowledge about such natural systems is still insufficient due to the inaccessibility of the deep northern Alpine foreland. This gap is meant to be bridged on the basis of an analogue study on an active hydrothermal breccia in the crystalline basement of the Aar massif. Detailed geological, geophysical and hydrological analyses on drill cores, the drill hole, as well as on surface exposures should improve the knowledge of natural hydrothermal systems as a potentially exploitable energy source. To that end, a cored drillhole through a known active hydrothermal breccia on the Grimsel Pass (Stalder 1964, Hoffmann 2004) has been performed during summer 2015. This active hydrothermal system in basement rocks of the Aar massif represents an analogue for potential geothermal reservoirs in the deep crystalline subsurface of the northern Alpine foreland as well as for other hydrothermal springs in the Aar and Aiguille Rouge massifs (e.g. Brigerbad, Leukerbad, Lavey les Bains).

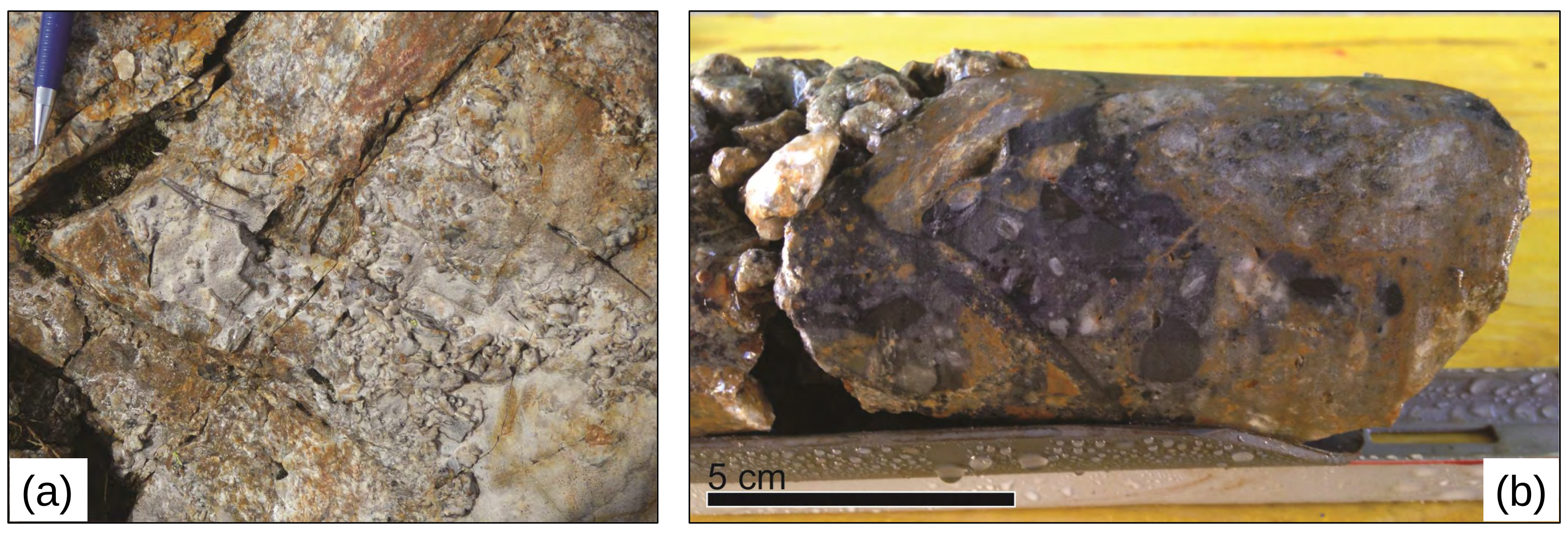


*(a) Geological map of the Aar Massif along the Haslital. Modified after Wehrens (2015) and Baumberger (2015), (b) Overview of the drill site on the Grimselpass, (c) Trace of the targeted breccia zone from the drill site towards Sidelhorn.*

## 2. Methods and objectives

### *2.1 Structural characterization (UniBe)*

Structural analyses from micro- to mesoscale will be performed on the drill cores of the Grimsel hydrothermal field as well as on surface exposure describing the ductile and brittle deformation (shear zones, fractures, joints). Their spatial distribution around the central breccia zone as well as their continuity and permeability will provide additional constraints on the water flow paths in such hydrothermal systems and further advance the understanding of their structural evolution. Porosities and permeability will be characterized using X-ray tomography and direct permeability measurements. Furthermore, the microscale evolution of the hydrothermal system will be investigated using modern geochemical and mineralogical methods. These results will provide a better understanding of the evolution and mechanisms within long-lived hydrothermal systems.



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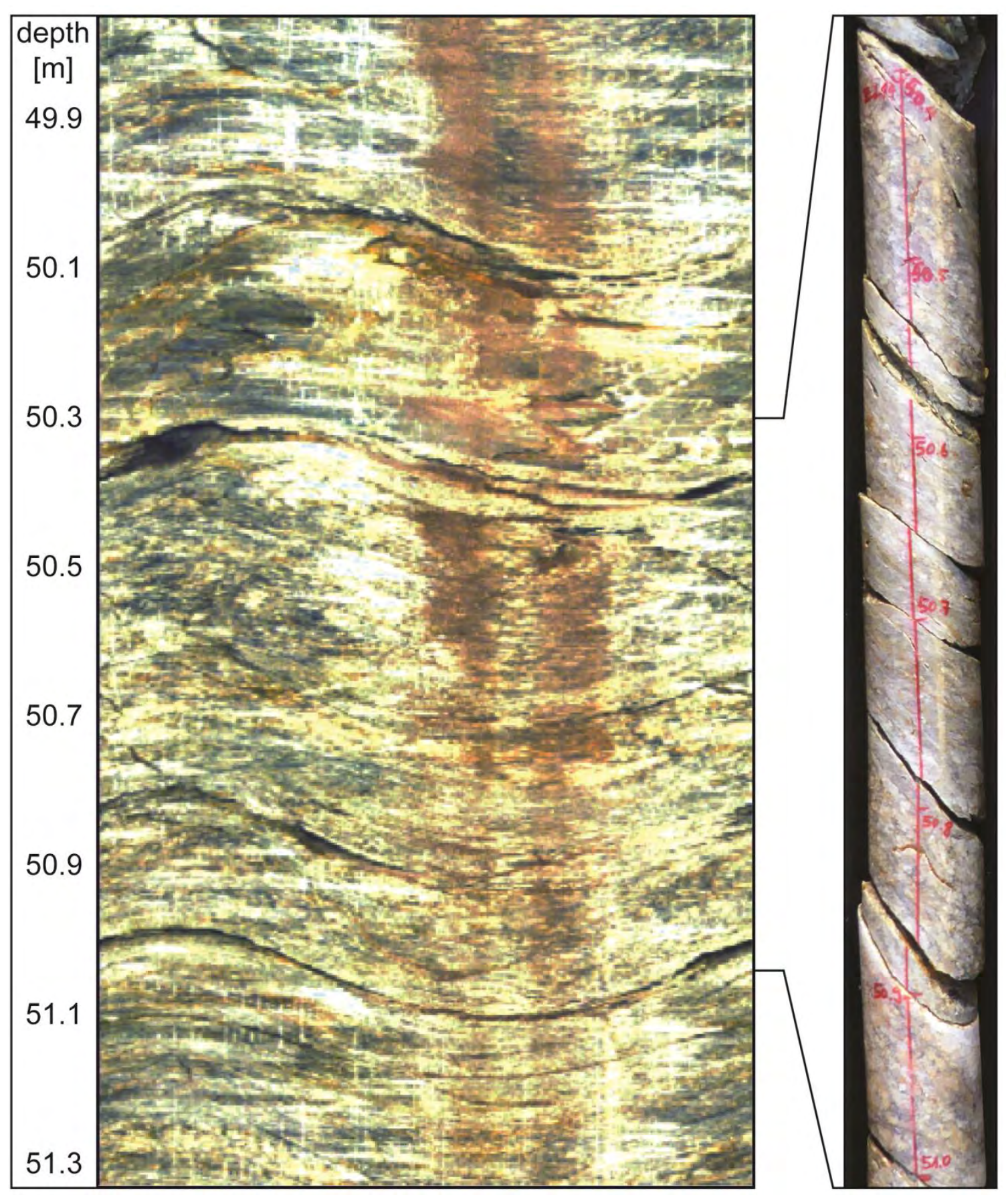
### *2.2 Geophysical borehole logging (UniL)*

Geophysical borehole logging will provide a highly resolved, continuous record of the key rock physical properties along the borehole. While the focus will lie on sonic, electric, and nuclear techniques, we also plan to acquire a comprehensive set of optical and acoustic televiewer logs. These televiewer images can then be transformed into digital pseudo-cores, which in turn can be correlated with the retrieved core material and permit to complement it in zones of poor core retrieval. Quite importantly, televiewer logging allows for identification and orientation of individual fractures crossing the borehole, which is often not possible based on the core evidence alone. The rock physical data will then serve as basis for modelling the observed attenuation of the sonic log data with the objective to invert this parameter for the permeability of the probed rock volume.



*Optical Televiewer image of the borehole section 49.9 - 51.3 m and the corresponding drill core from 50.4 - 51.0 m.*

### *2.3 Petrophysical characterization of reservoir rocks (ETH)*

In order to better understand the behaviour of deep, hot reservoirs, we will combine several methodologies to systematically explore the relationship between permeability of fractured media, the attenuation of seismic waves and electrical conductivity. The experimental work will be conducted on core and outcrop samples mainly in the Rock Deformation Laboratory at the ETH.

The porosity and permeability of core samples from the Grimsel granite and the Upper Muschelkalk will be characterized. Connected porosity will be measured by He-picnometry. The transient step method will be used for low-permeability samples and the standard constant pressure difference method for high permeability samples. Measurements of attenuation and the elastic moduli at seismic frequencies (1-100 Hz) will be carried out. Measurements will be made at confining pressures up to 100 MPa and temperatures up to 250°C, with various saturating fluids salinities. Electrical properties will be measured with an impedance spectrometer over the range $10^{-1}$-$10^{6}$ Hz.

## 3. Expected output

This multidisciplinary study uses a range of complementary aproaches and is aiming at providing a better understanding of naturally permeable rock formations and active hydrothermal systems in basement rocks in particular. We hope to thereby enhance methods for exploration and eventually exploitation of geothermal reservoirs to improve chances of finding suitable sites for successful geothermal energy production.

**Acknowledgments**
This project is part of the NRP70 program and is funded by the Swiss National Science Foundation. We thank Swisstopo, the Swiss Federal Office of Energy, NAGRA and the Kraftwerke Oberhasli AG for additional financial and practical support.

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# Structurally channelled hydrothermal activity in crystalline basement at the Grimsel geothermal analogue site

Energy Turnaround
National Research Programme NRP 70

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## Introduction

Current understanding of fracture-controlled fluid flow in the geothermally prospective Northern Alpine Foreland Basement is based on limited borehole data, modelling studies and the investigation of analogue geological settings (e.g. Black Forest). We present an alternative crystalline basment analogue at Grimsel Pass (Aar Massif, Central Swiss Alps), where excellent outcrop allows detailed characterisation of a brittle strike-slip fault and its resident fossil and active hydrothermal systems.

Distinctive epithermal mineralisation and active thermal fluid discharge (28˚C; the highest documented in the Alps) associated with the fault are used to demonstrate fluid pathway extent, morphology and structural associations.

## Project

### Questions for geothermal exploration/exploitation

- Which structural situations favour naturally enhanced fracture networks?
- What potential fluid sealing structures exist in basement?

### Framework

- Detailed mapping and 3D modelling of the Aar Massif shear zone network by Wehrens (2015) and Baumberger (2015).
- Data for this study collected in 2014, currently in preperation.
- Borehole investigations completed in September 2015

## Study Area

The fault outcrops over ~4.5 km at Grimsel Pass in crystalline basement of the southern Aar Massif (Fig. 1), which underwent greenschist facies, compressional and transpressional Alpine deformation.

## Methods

Mapping and 3D modelling digitally in the Move™ suite. Line intercept analyses of macrofracture density and aperture counted along tape and grouped into 5m bins.

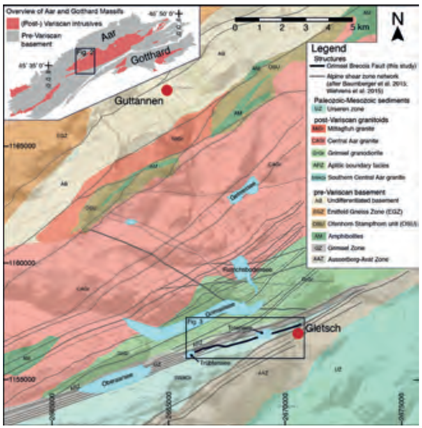

Figure 1. Geological map of the Haslital after Stalder (1964) and Abrecht (1994). Alpine shear zone network after Baumberger (2015) and Wehrens (2015).

## Mapping targets

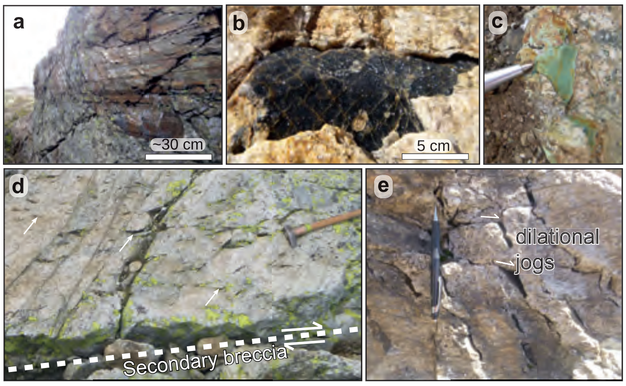

Figure 2. Field photographs. a) Late fault surface cutting breccias. b) Typical epithermal quartz-chalcedony sulphide mineralisation. c) Celadonitic chalcedony infill between Totensee and Gletsch. d) Damage zone fractures around secondary breccia. e) Mineralised fractures.

## Mapping results

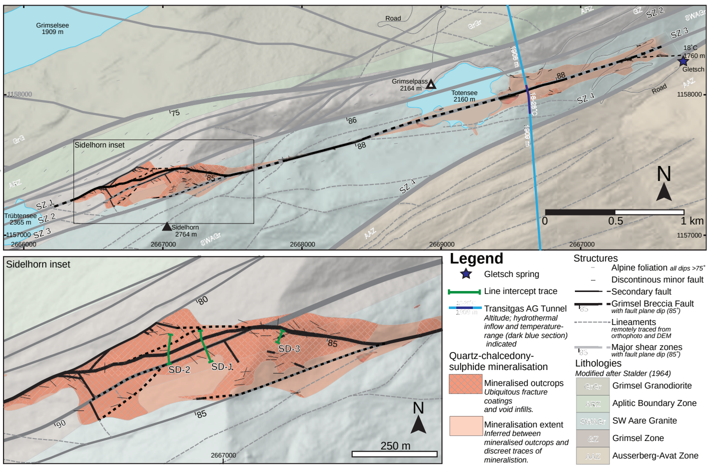

Figure 3. Grimsel Breccia Fault and its mineralised zone. Note variable fault-zone thickness and related along-strike variations in fluid access; also sealing along SZ 1 (Sidelhorn inset). Lithologies after Stalder (1964), Abrecht (1994) and major SZs after Baumberger (2015) and Wehrens (2015).

### Line intercept analyses of fracture network

- Fracture aperture and density decays with distance from fault core.
- Variable distributions as well as absolute values between lines.
- Damage zone 15-30 m either side of fault, though elevated fracture density occurs up to 70 m from fault core.

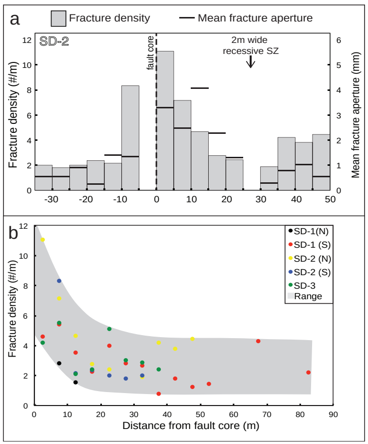

Figure 4. Line-intercept discontinuity analyses. Positive distances from fault core are to the North. Empty columns correspond to no outcrop.

## Summary model

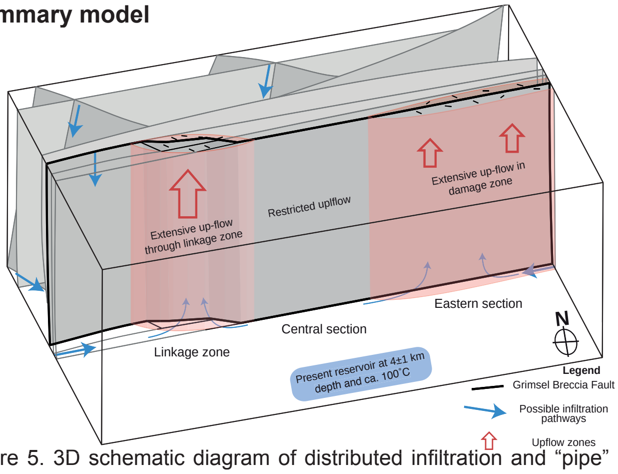

Figure 5. 3D schematic diagram of distributed infiltration and “pipe” like, focused up-flow zones along the Grimsel Breccia Fault.

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Stalder, H. A. (1964). Petrographische und mineralogische Untersuchungen im Grimselgebiet (Mittleres Aarmassiv). Schweizerische Mineralogische und Petrographische Mitteilungen, 44(1), 188–384.

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# Fault anatomy, porosity and pore connectivity: the La Sarraz fault system

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## Abstract

Understanding fault properties in the alpine foreland is of strategic importance for the development of the geothermal resources in Switzerland. In this project we use the outstanding natural laboratory of the La Sarraz fault system to lay down the conceptual bases to describe fault system characteristics from the pore scale to the scale relevant for geothermal project developments.

## 1. Introduction

The understanding of the distance to failure (criticality) of the faults in the Alpine foreland is of strategic importance for the development the geothermal resources in Switzerland. Fault evolution involves highly coupled processes leading to a complex anatomy of fault zones. In turn, this complex anatomy will have a leading impact on current fault properties, behavior and stability. It is thus required to develop geological-tectonic models of faults relevant for the Swiss foreland basin that go beyond a simplistic geometrical description of the geological features but include geo-mechanical attributes like stress, strength, criticality and permeability at a scale relevant for project development. This is an important but challenging task. Conceptual bases should be laid down in order to enable this type of model to be developed.

To tackle this problematic, our study will initially rely on an outstanding natural laboratory situated along the La Sarraz fault system because this NW-SE oriented right-lateral fault system shows spectacular outcrops in quarries in the Éclepens region (Fig. 1). In an initial phase, our project focusses on a detailed description of the fault anatomy, porosity and pore connectivity and their impact on overall fault characteristics.

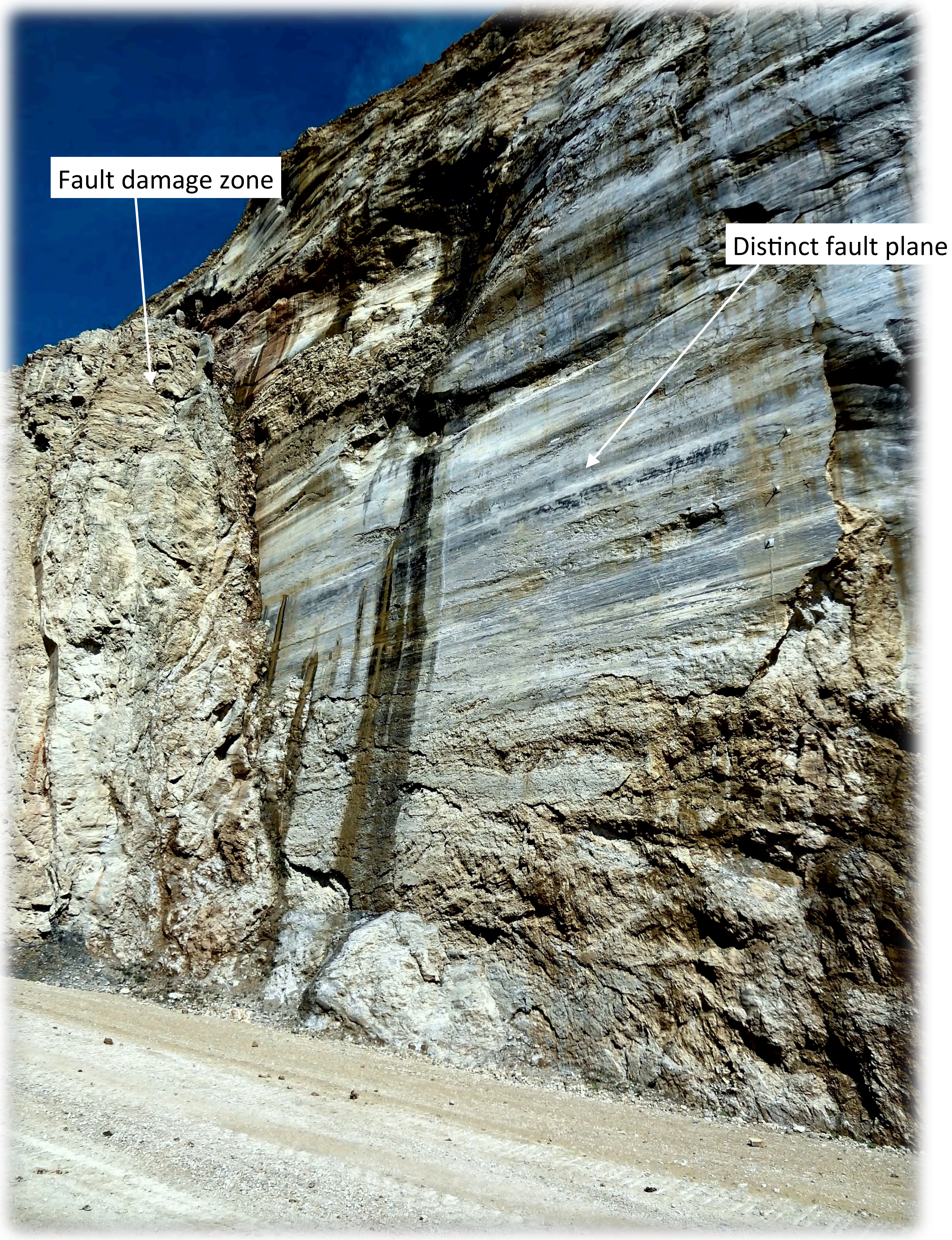

**Figure 1:** Section of the La Sarraz fault system outcropping in the La Sarraz quarry. Ondulating distinct fault planes with strongly marked striations and fault damage zone are visible on this picture.

**Figure 2:** Detailed view of the damaged fault core with brecciated and heavily veined limestones.

## 2. Objectives

The objective of the current project is to generate a detailed understanding of the fault pattern at the quarry scale and to relate it to variations in fault anatomy and fault rocks characteristics down to the pore scale. These characteristics will be linked to hydromechanics properties of the fault segments in order lay down fault maturation and fault anatomy conceptual models relevant for the Swiss foreland basin.

## 3. Methods

Initially, we will perform structural analyses of fault patterns in the quarry and the vicinity to constrain the paleo-stress field. Photogrammetric methods and lidar scan will be used for this purpose. Subsequently we will make a detailed study of the structural features on distinct fault damage zones to determine the fault anatomy and kinematics. The fault will be drilled through and image with borehole televiewers in order to decipher its detailed anatomy. Finally, we will sample the damage zone from the undeformed border to the highly strained central section and analyze the samples in a multi-scaled X-ray micro-tomography scanner (CTscan). A picture of the highly damaged and veined fault core is presented in Fig. 2. The CTscans will provide quantitative assessments of the damage and associated pore space geometry. The high-resolution 3D CTscan images will serve as the numerical domain from which we overlay with a finite element or finite difference mesh in order to model fluid flow through the pore system and assess variation in permeability.

## 4. Outlook

This initial project is starting in September 2015. It inscribes itself in a broader plan with the studies of the stress field and the seismogenic behaviour of the larger scale La Sarraz – Pontarlier strike slip system.

## Acknowledgments

This work is supported by Swisstopo. The Eclépens site of LafargeHolcim is warmly thanked for giving access to their quarry.

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# Deep geothermal well optimisation workflow

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## Abstract

An optimal well control is essential to deploy the innovative technology called “multi-stage stimulation concept” that should help unlocking the large potential of geothermal energy for electricity production in Switzerland. The tools developed within this project will enable a fast decision process for selecting an optimal well trajectory. This is part of the overall strategy of Geo-Energie Suisse to bring down the costs and risks associated with the development of deep geothermal projects.

## 1. Introduction

Accessing and developing deep geothermal resources remains challenging. Risks are associated with drilling and completion as well as with reservoir stimulation. In order to mitigate these risks, Geo-Energie Suisse AG – the leading industry driven centre of competence for deep geothermal energy for power and heat production in Switzerland – has developed an innovative completion scheme referred a “multi stage stimulation concept”. Instead of working with long open hole sections, as is typical for previous EGS projects, it is now proposed to isolate sections along the borehole and to enhanced the permeability of potential feed zones individually (Figure 1, left side). In order to succeed with this completion scheme, the borehole trajectory must be optimized for:

1) Maximizing the probability of intersection with potential feed zones (existing fractures);

2) Insuring sufficient borehole stability in order (a) to limit drilling difficulties associated with borehole instability and (b) to obtain a hole which is sufficiently in gauge to not compromise a well completion with swellable packers for reservoir segmentation and subsequent staged stimulation.

Both criteria are not necessarily compatible and an optimum must be determined in order to decide on the best well path. The main objective of this project is to develop a workflow in order to facilitate the optimal well trajectory selection.

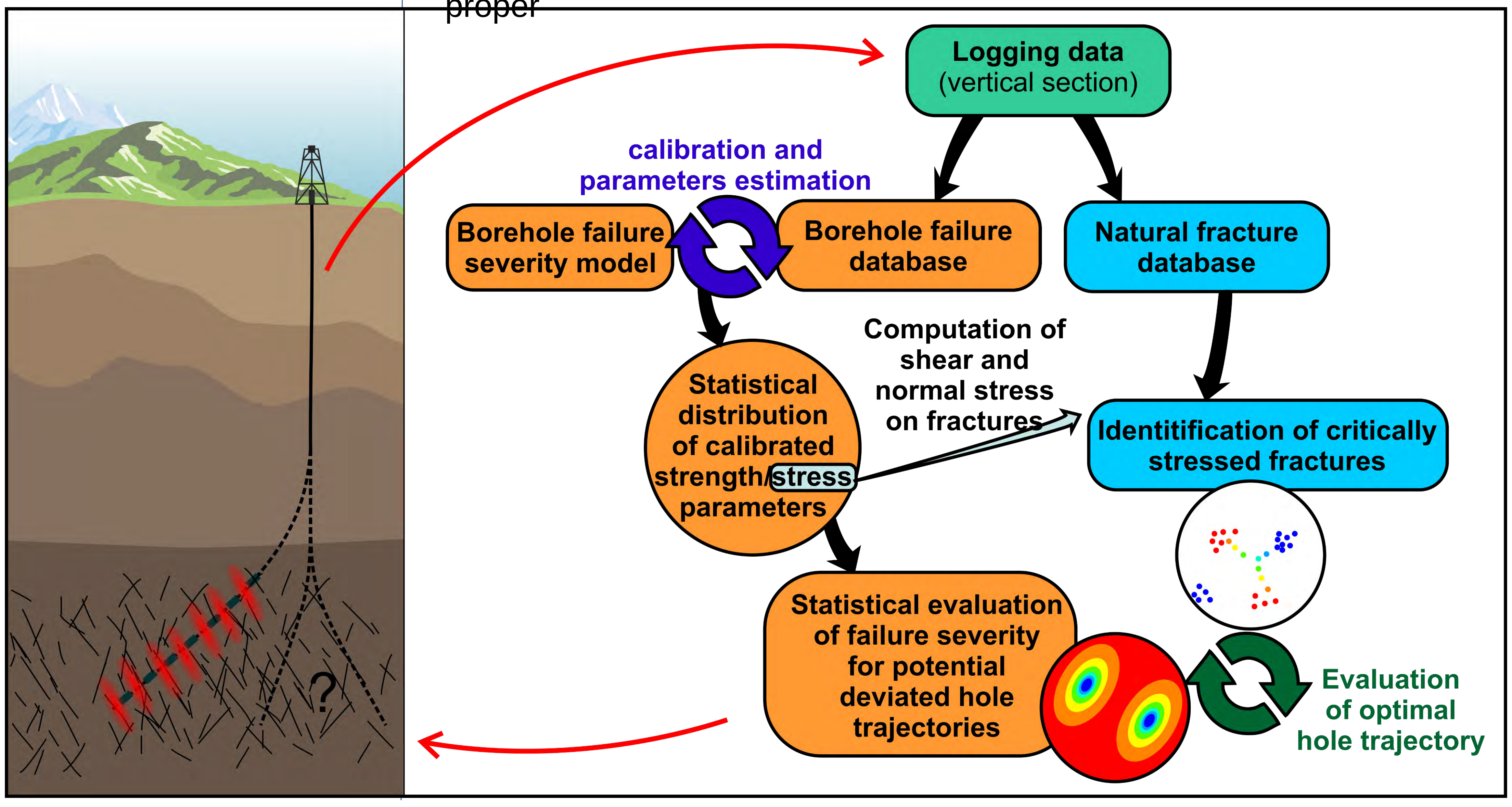

**Figure 1:** Left: potential deviated hole completion with multi stage stimulation concept. In order to optimize the reservoir development and to minimize the risk, an appropriate borehole trajectory must be found to maximize the intersection with potential feed zones while insuring sufficient borehole stability. Right: proposed high-level workflow to deal with this borehole optimisation problem. The main objective of the project is to develop the details of this workflow.

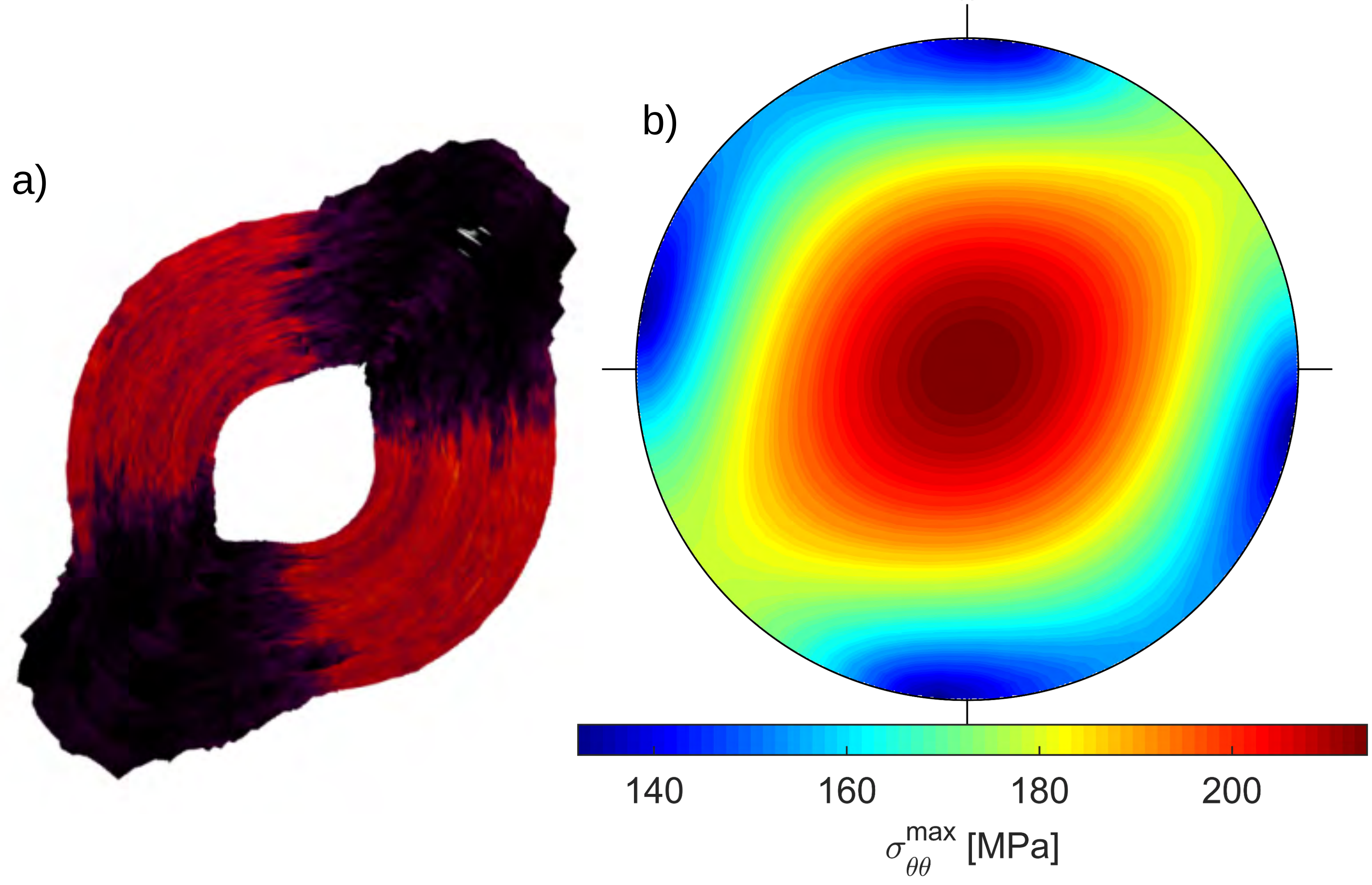

**Figure 2:** a) Observed breakout in the BS1 borehole at 4955 m depth. In this case, the borehole is subvertical. b) computed maximum effective tangential stress at the borehole wall as a function of hole direction. The results are presented as contouring on a stereographic projection (lower hemisphere, equal area). A vertical hole will plot in the center of the projection while an horizontal hole on the rim of the projection. The stress assumption is *SHmax* direction N143° with *Sv* = 100 MPa, *SHmax* = 120 MPa, *Shmin* = 64 MPa and *Pp* = 39 MPa (possible stress scenario at 4 km depth).

## 2. Approach

It is well known that deep boreholes can experience severe stress induced failure of their walls (so-called borehole breakouts). An example of such borehole failure is presented on Fig. 2a. This is a 3D geometry of the BS1 borehole in Basel reconstructed from acoustic televiewer data. The typical “lemon-shape” of the borehole section is due to the stress redistribution around the borehole leading to maximum tangential stresses exceeding the rock strength. Methods to evaluate the relative severity of borehole failure for various drilling direction are well documented. Fig. 2b presents such results showing that in this case, a vertical hole will induce larger tangential stress and thus more severe failure than an deviated hole. However, In the current state of the knowledge, we cannot reliably predict the initiation, extension and final shape of borehole breakouts. This is largely due to the lack of proper input parameters: in-situ stresses are often poorly constrained, particularly at early project stage, and the estimation of the in-situ strength is usually poor (no cores or damaged cores, no or few mechanical tests). This is also due to a gap in understanding the processes at play at the borehole wall during initiation and accumulation of damage leading to the formation of borehole breakouts.

In order to deal with this uncertainties, we propose to develop a workflow based on statistical approaches dealing with rigorous parameter estimation and risk analyses. The outline of this work flow is presented on the right side of Fig. 1. The idea is to use data from the vertical section of the borehole to calibrate plausible failure models. The solution will not be unique (multiple combination of stress/strength parameters will equally match the observed data). Then, these calibrated models can be used to predict borehole severity and associated uncertainty for potential borehole deviation and assess risks associated with potential drilling scenarios.

## 3. Expected research outputs

The outputs of this project will reduced cost and risks associated with deep geothermal well. The workflow presented above will be developed and tested on existing data sets and applied to future Geo-Energie Suisse projects like the Haute-Sorne project planned for 2017.

## Acknowledgments

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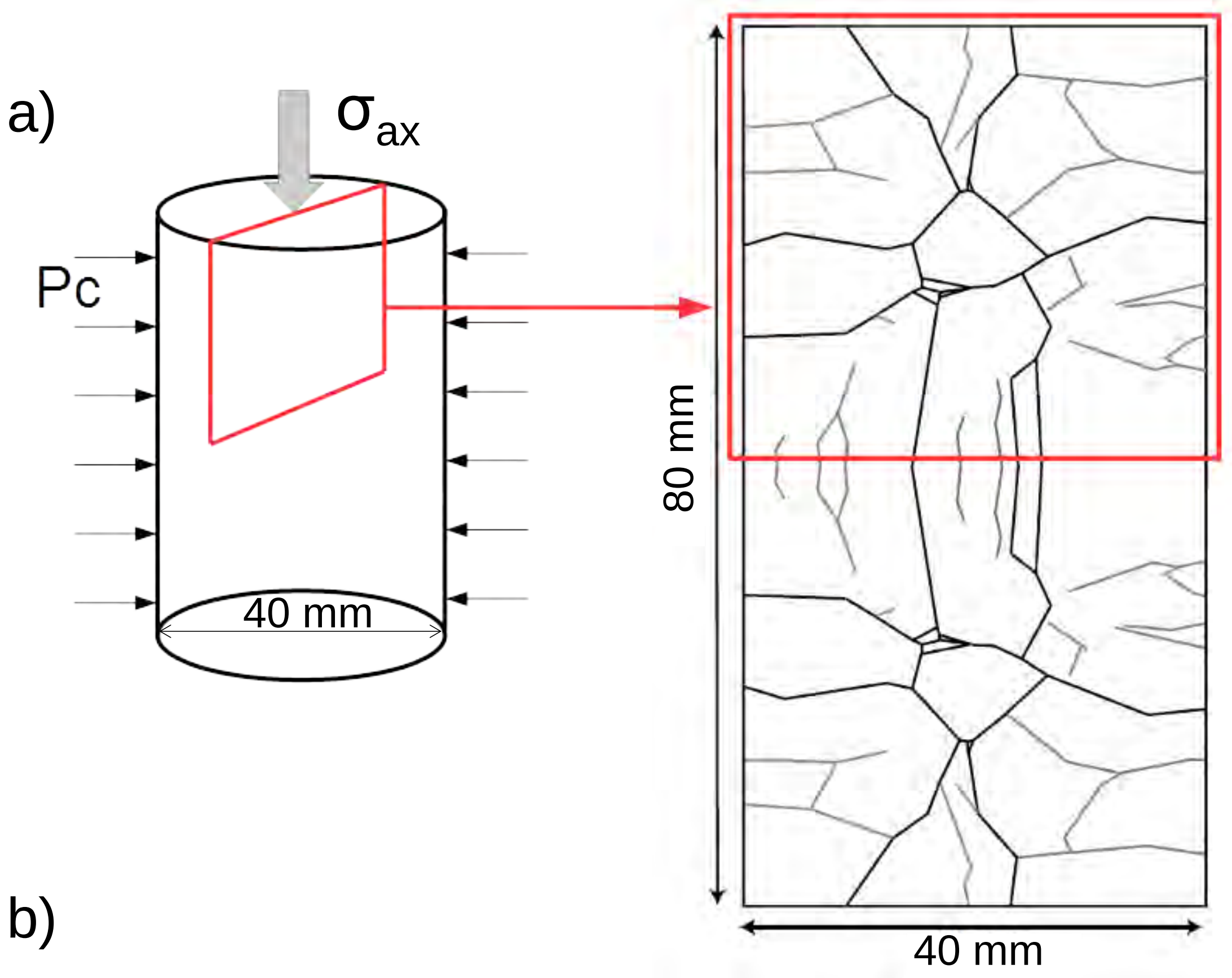
# Seismic energy dissipation due to wave-induced fluid flow in fractured media

*Céline Mallet, Beatriz Quintal, Eva Caspari & Klaus Holliger*

## 1. Summary

The hydraulic characterization of fractured rocks has a number of important applications, such as the sustainable use of groundwater, the optimized production of hydrocarbons and geothermal energy, and the safe storage of nuclear waste. Recent evidence indicates that the attenuation of seismic waves in such environments is not only sensitive to the presence of fractures per se, but also to some key properties of fracture networks, notably the interconnectivity of the fractures. This in turn offers the perspective of linking seismic observations to the hydraulic properties of fractured rocks. To further explore this avenue and to test and complement the few existing numerical studies, we consider laboratory data from creep tests performed on a thermally cracked water-saturated glass sample. From these measurements, we infer the seismic attenuation caused by viscous friction in response to wave-induced fluid flow through the crack network. To improve our understanding of the fracture parameters governing seismic energy dissipation, numerical simulations based on a vertical cross-section through the cracked sample are compared to the laboratory data.

## 2. Laboratory and numerical experiments



(Mallet et al. 2013, 2014, International Journal of Fracture)

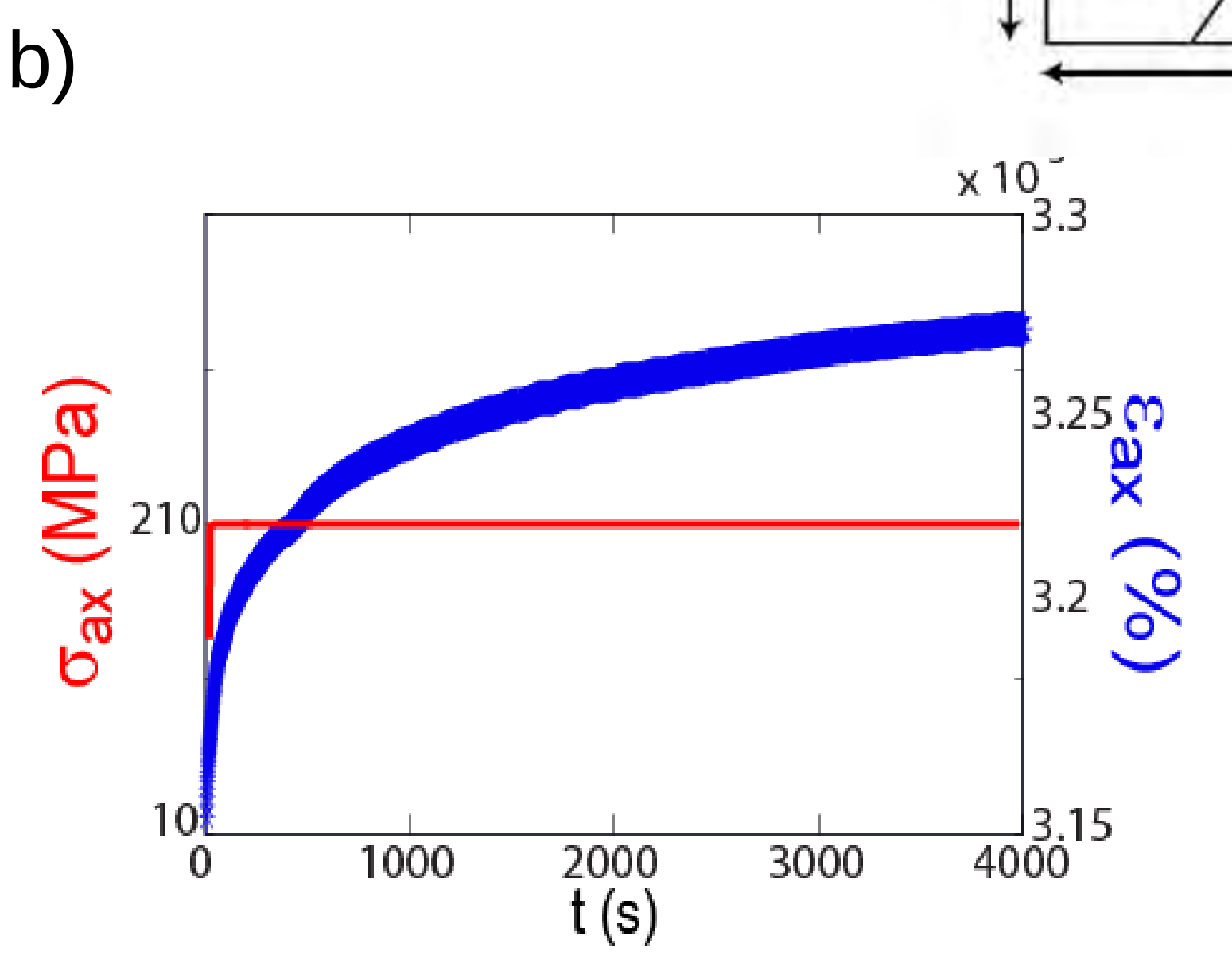


Figure 1: a) Schematic illustration of experimental creep test (left) and digitized crack network along vertical cross-section through sample (right). b) Results of creep test with $\sigma_{ax}$ denoting the applied axial loading and $\varepsilon_{ax}$ the resulting strain as functions of time (Mallet et al. 2015, JGR).

- ➢ Transforming Young's modulus into the frequency-domain then allows for estimating the attenuation, as quantified by the inverse quality factor, 1/Q, as a function of frequency, f (Figure 2).

- ➢ Numerical simulations are performed based on Biot's quasi-static poroelastic equations (Quintal et al. 2011, JGR) for the 2D image of the cracked sample (Figure 1a), using the following equations (left) and material properties (right):

- Stress equilibrium:

$$\nabla . \sigma = 0$$

- Darcy's flow:

$$i\omega \frac{\eta}{k} w = -\nabla P_f$$

| | Glass matrix | Cracks |
|---|---|---|
| Permeability | $10^{-5}$ mD | 1 mD |
| Porosity | 0.1% | 99% |
| Bulk modulus | 56.2 GPa | 0.02 GPa |
| Shear modulus | 32.8 GPa | 0.001 GPa |

- ➢ Comparison of laboratory data and numerical results:

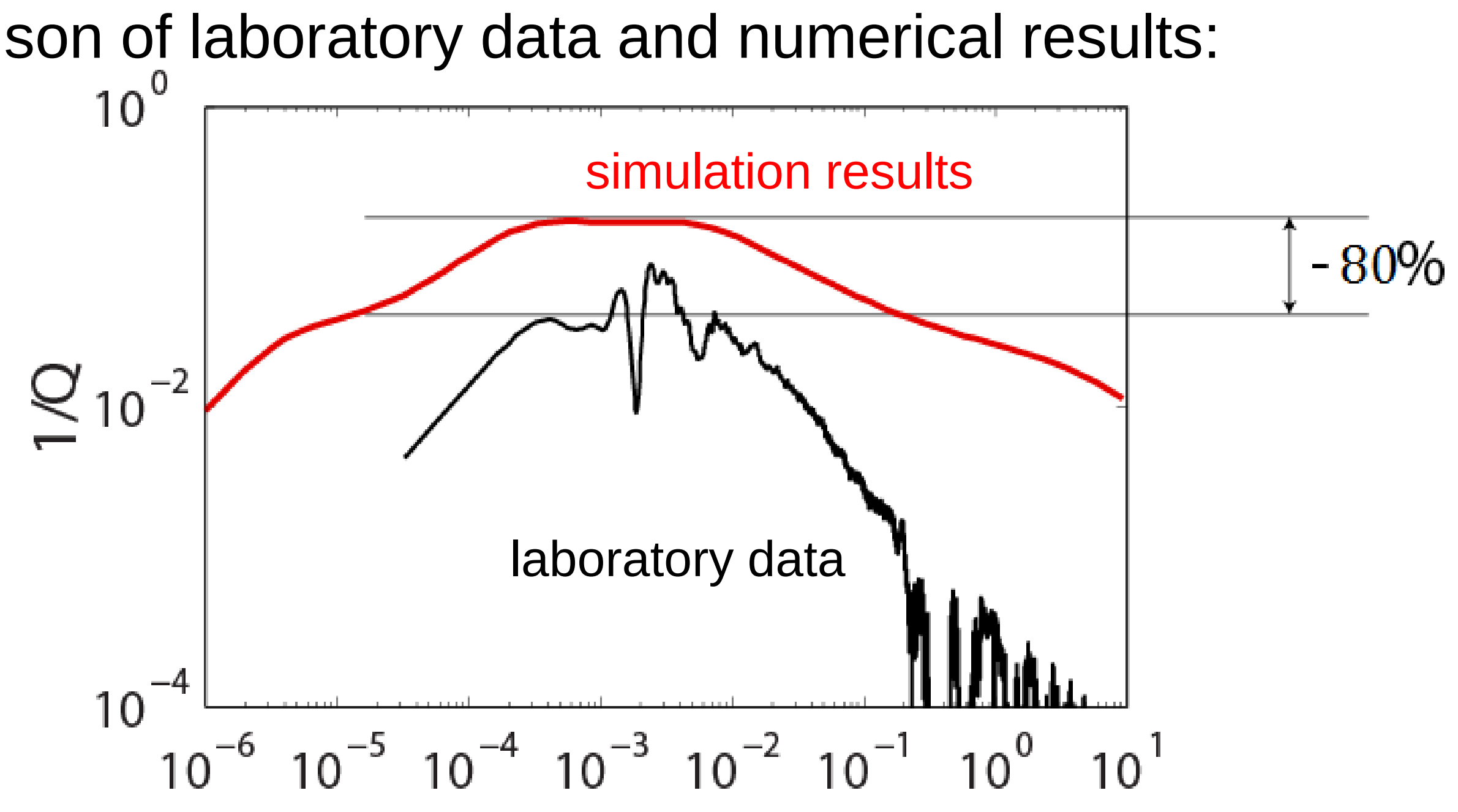
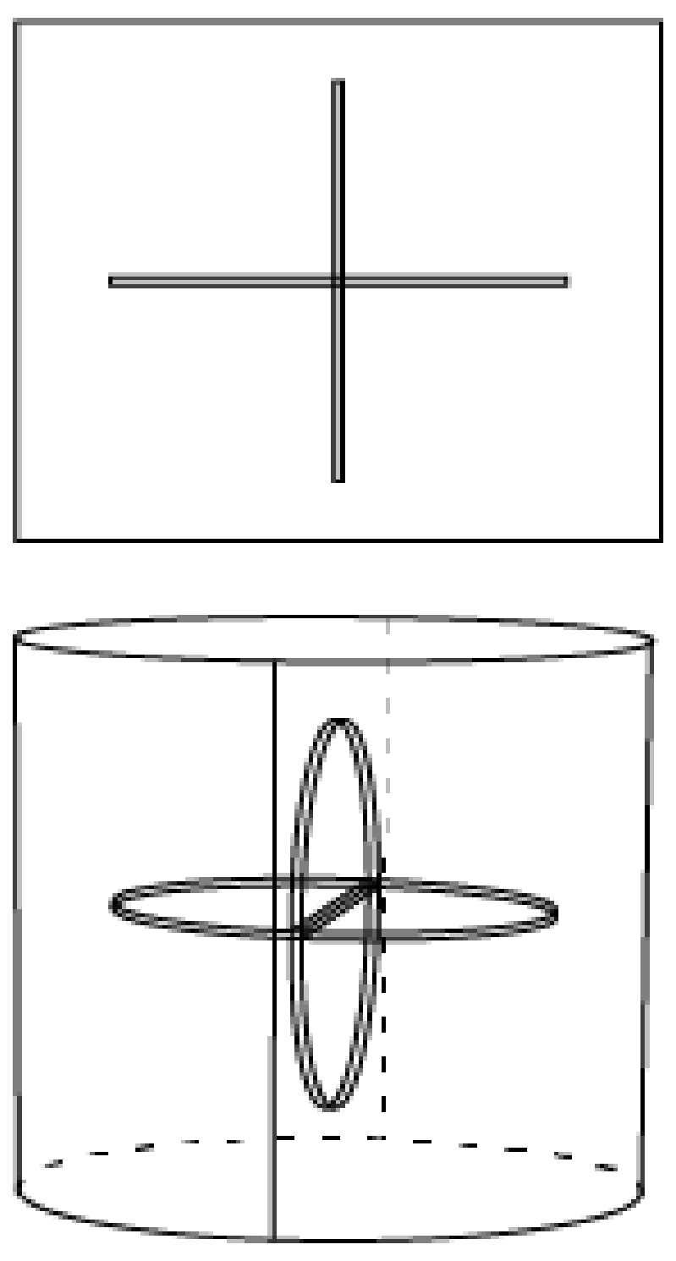


Figure 2: Attenuation as a function of frequency.

## 3. Attenuation: 2D versus 3D



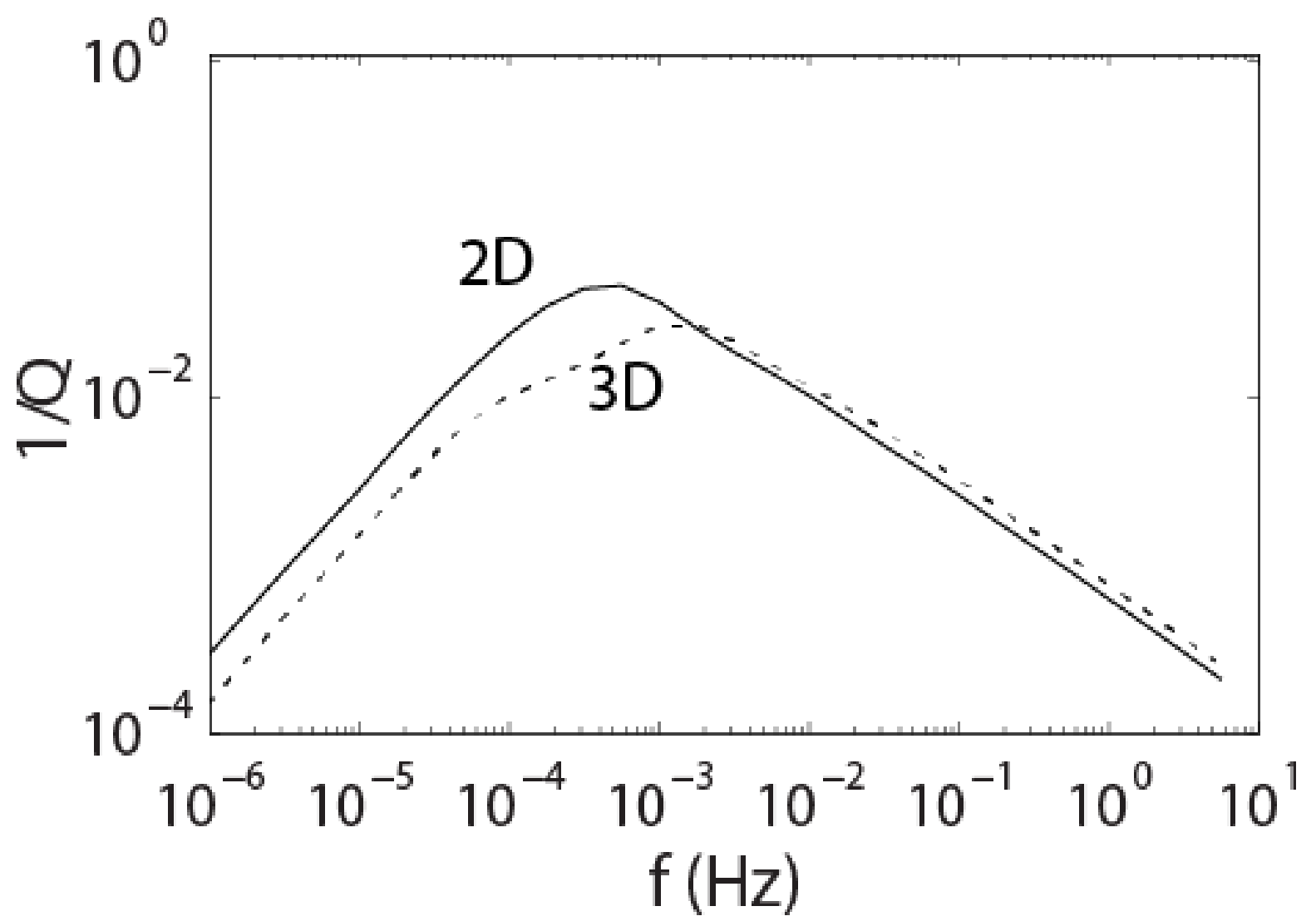


Figure 3: Numerical results for 2D and 3D simulations of a pair of intersecting cracks having the same average material properties as the complete 2D model (Figure 1a).

- ➢ Attenuation is 36% larger in the 2D case, which may explain part of the discrepancy between observed and simulated attenuation (Figure 2).

## 4. Attenuation: sensitivity to characteristics of the cracks

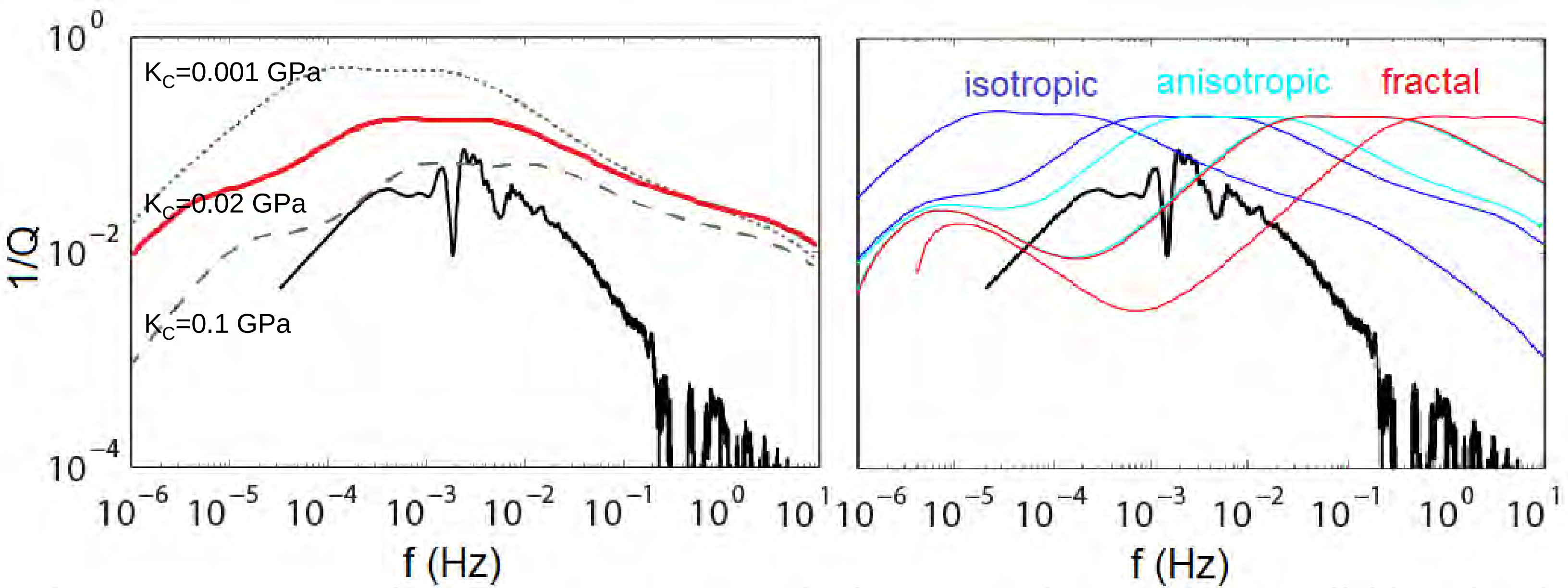


Figure 4: Numerical results for variations of the compressibility (left) and the permeability (right) of the cracks compared to laboratory data. The permeability models are based on the assumption of isotropic, anisotropic or fractal crack distributions.

- ➢ The overall magnitude of attenuation is sensitive to the crack compressibility.
- ➢ The frequency at which the attenuation peak occurs is sensitive to the permeability of the cracks.

## 5. Discussion

- ➢ The strains employed in laboratory-based creep test are much larger than those of seismic waves and the associated non-linear effects must be expected to influence the inferred attenuation characteristics.
- ➢ Through comparisons with numerical simulations, we were, however, able to demonstrate that the pronounced frequency dependence of the inferred attenuation can be largely explained through wave-induced fluid through the crack network.
- ➢ The misfit between the laboratory measurements and the numerical simulations is of the order of the accuracy with which attenuation can be inferred from seismic data. This misfit can at least in part be explained by the simplification of the crack network to 2D and the large uncertainties with regard to key crack properties, such as compressibility and permeability.

## 6. Outlook

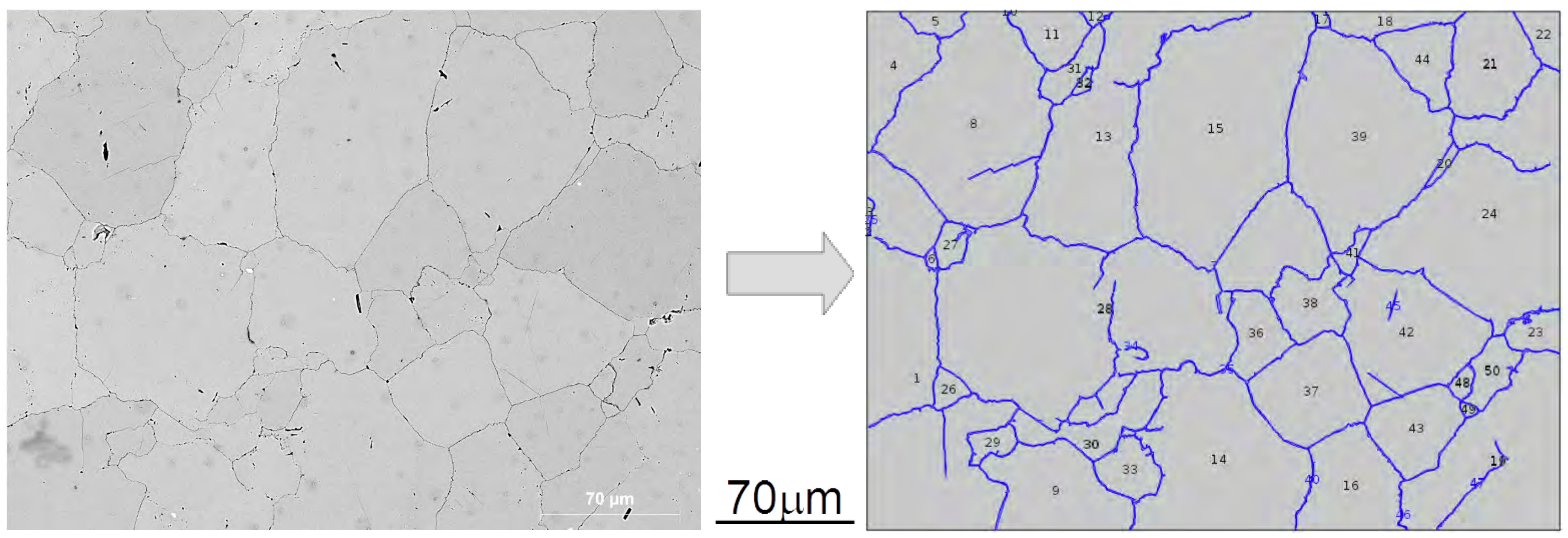


Figure 5: SEM image of thermally cracked Carrara marble (Arena et al. 2014, Computers & Geosciences).

- ➢ Our key objectives for the future are (i) to expand the current study to more realistic crack networks and (ii) to extend the validity and applicability of our findings beyond laboratory scale.
- ➢ A new dataset that includes 2D and 3D images, as well as pressure-dependent ultrasonic and static measurements on dry and saturated samples, will be numerically studied to better constrain the compressibility and permeability of the cracks.

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# The application of crosswell electromagnetics and magnetotellurics to geothermal exploration

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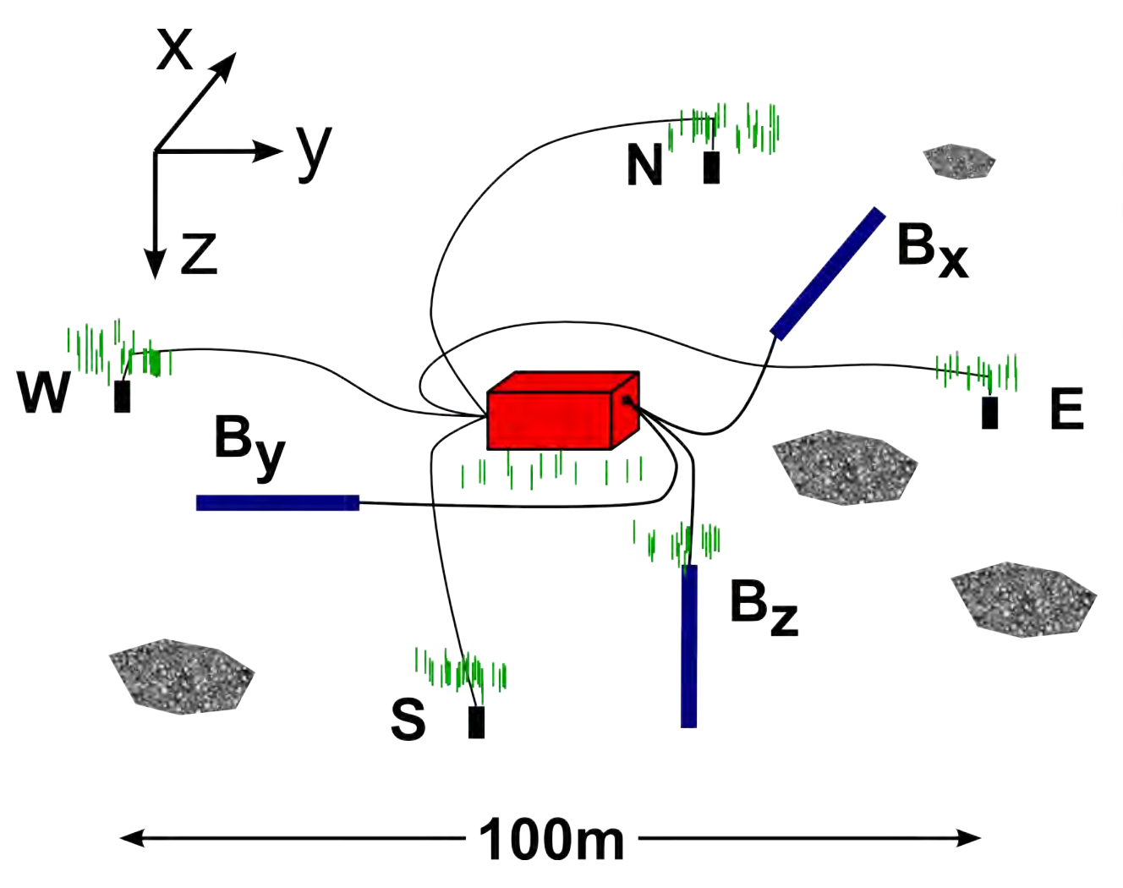
## Abstract

Electrical resistivity is an important geophysical parameter for geothermal reservoir characterisation since it is sensitive to fluids, porosity and permeability as well as hydrothermal alteration mineralogy.
Electromagnetic (EM) sounding encompasses a variety of methods, which address different target depths and dimensions. Their ultimate goal is to recover the subsurface structure and properties of the Earth based on the electrical resistivity distribution.

## Magnetotellurics

The magnetotelluric (MT) method is based on the analysis of naturally occuring time-varying EM fields, which have their origin in the Earth's electromagnetic environment.
The subsurface resistivity structure ρ(x,y,z) is recovered by interpreting the frequency-dependent impedance tensor Z(ω), which relates the observed magnetic, **B**=$\mu_0$**H**, and electric, **E**, fields. With MT one can sound depths up to tens of kilometres.

$$\begin{pmatrix} E_x(\omega) \\ E_y(\omega) \end{pmatrix} = \begin{pmatrix} Z_{xx}(\omega) & Z_{xy}(\omega) \\ Z_{yx}(\omega) & Z_{yy}(\omega) \end{pmatrix} \cdot \begin{pmatrix} H_x(\omega) \\ H_y(\omega) \end{pmatrix}$$



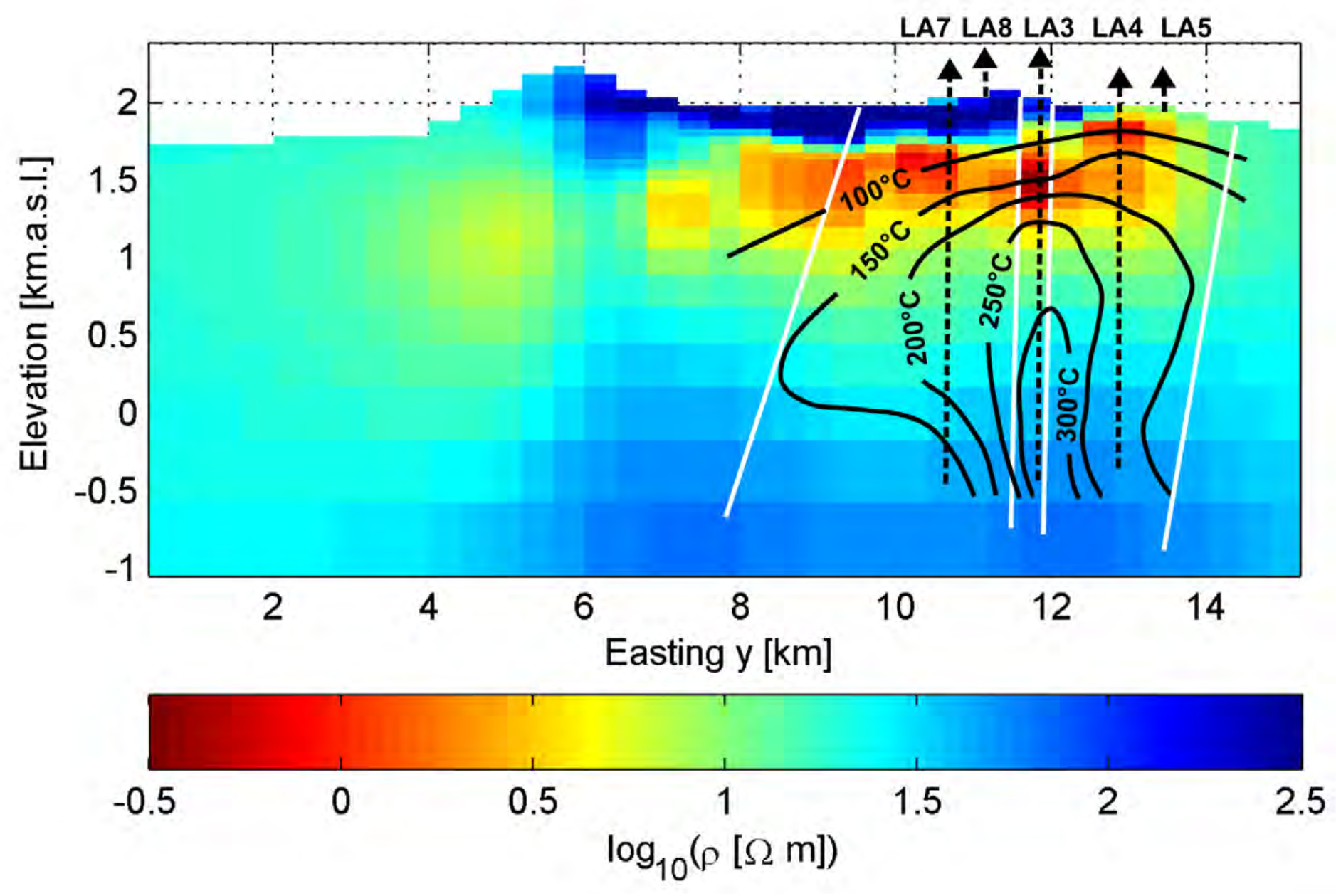


**Fig. 1 (left):** Standard setup of an MT measurement site. **Fig. 2 (right):** Example from the Aluto-Langano geothermal field, Ethiopia. Vertical EW slice through a 3-D model recovered by 3-D inversion of MT data (Samrock et al., 2015). The resistivity distribution is governed by the temperature dependent hydrothermal alteration mineralogy.

We plan to conduct an MT survey at the heat flow anomaly in Northern Switzerland. The goals of this project are twofold:

1. Evaluation of MT data quality in this densely populated region. Can we improve the data quality using state-of-the-art robust and remote reference processing methods?
2. Construction of a 3-D electrical resistivity model of the region. Can we map conductive fractured zones in the resistive crystalline basement? Such zones might indicate permeable pathways for geothermal fluids that migrate upwards and give rise to the observed heat flow anomaly.

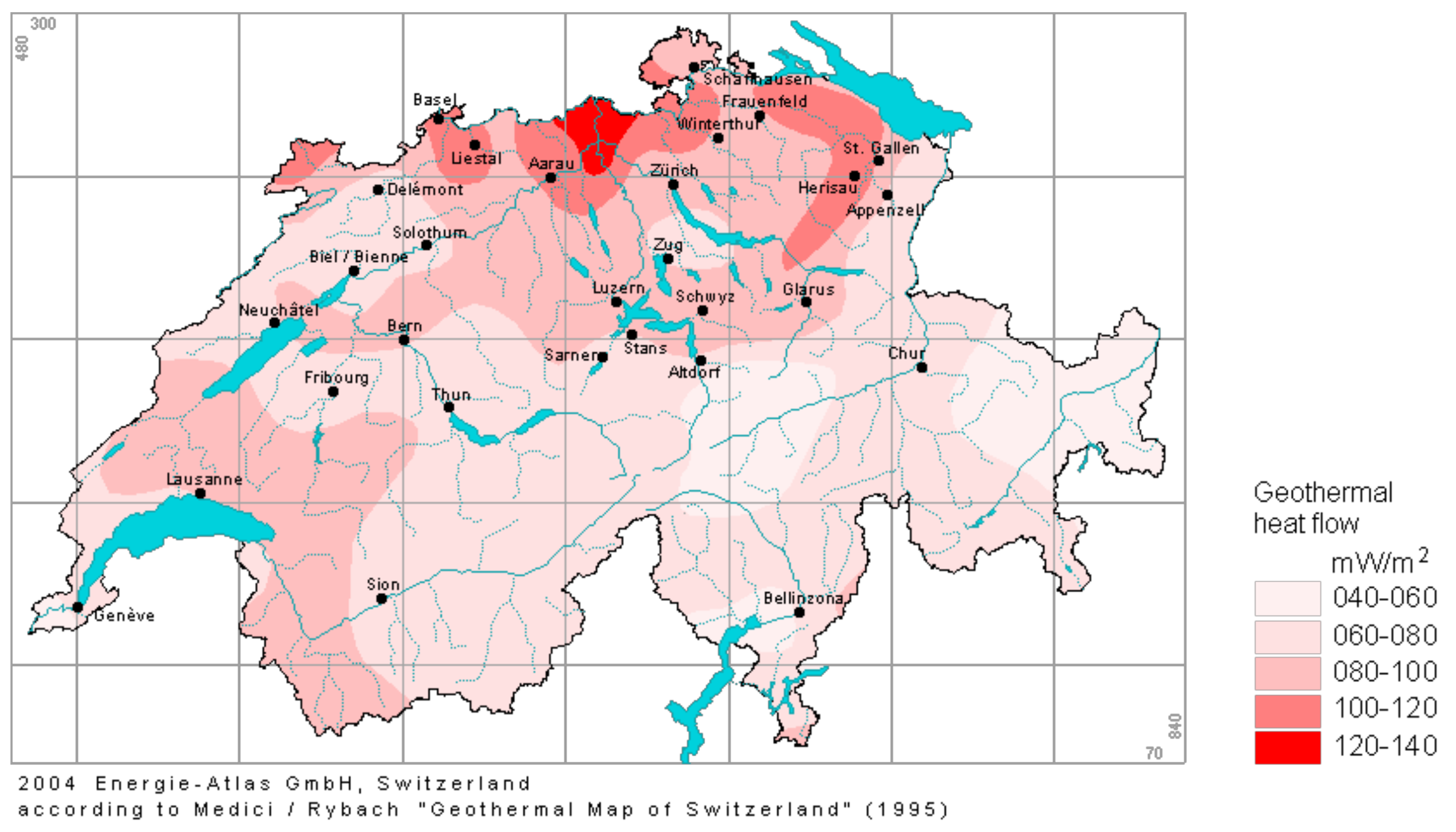


**Fig. 3:** Geothermal heat flow map according to Medici and Rybach (1995). The heat flow anomaly is located in the region NE of Aarau.

## Crosswell electromagnetic tomography

Crosswell EM is a frequency-domain controlled source method where magnetic dipole transmitters (TX) and receivers (RX) are placed in adjacent wells to image the inter-well volume.

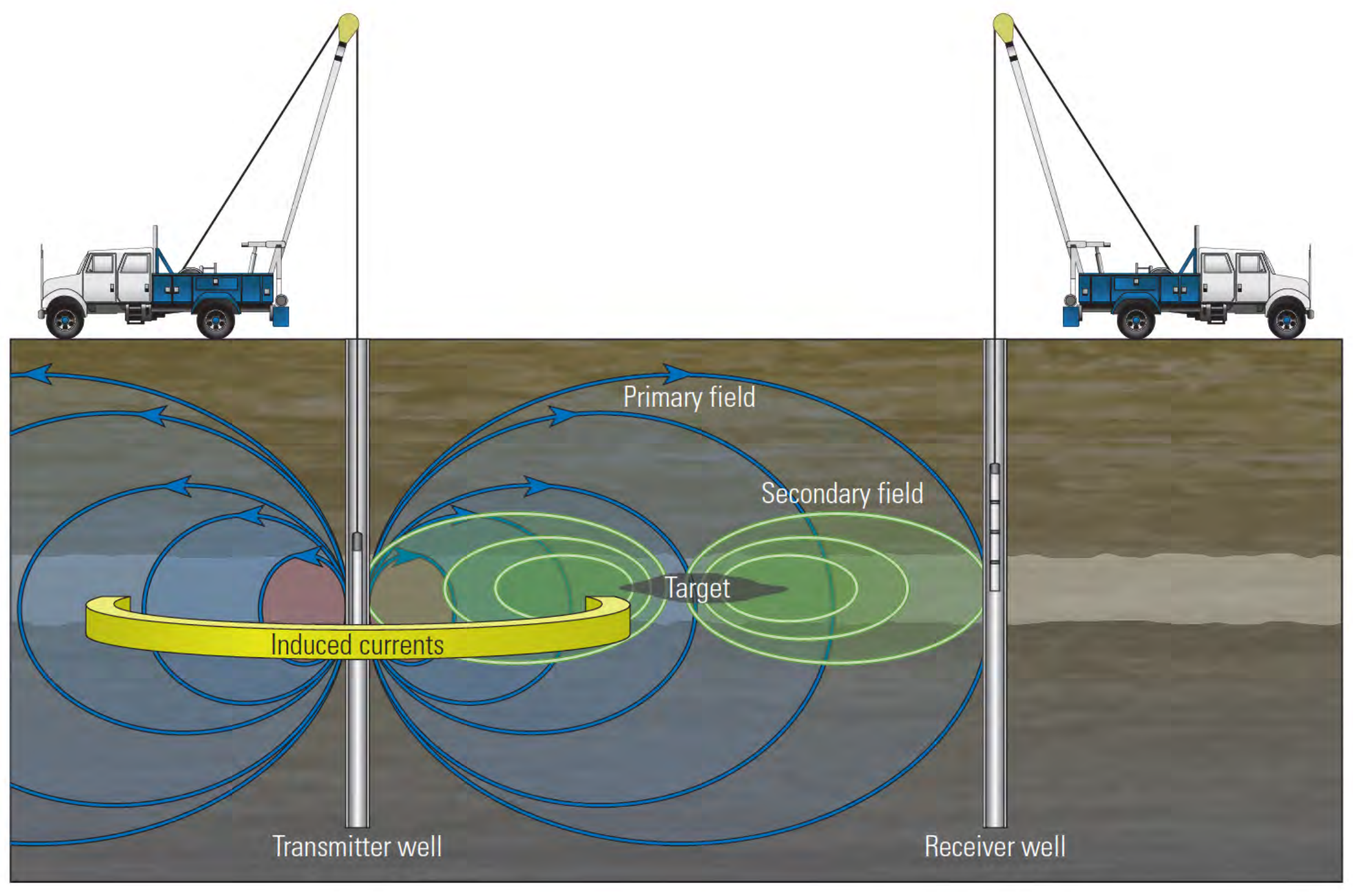


**Fig. 4:** Basic setup and principle of crosswell EM (Oilfield review summer 2009, 21, no. 2. Schlumberger).

We performed a 3-D forward modelling study using the X3D-code (Avdeev et al. 1997, 2002) to investigate the sensitivity of crosswell EM to changes in inter-well resistivity. As source we used a vertical magnetic dipole with a transmitter moment of 1000 Am$^{-2}$.

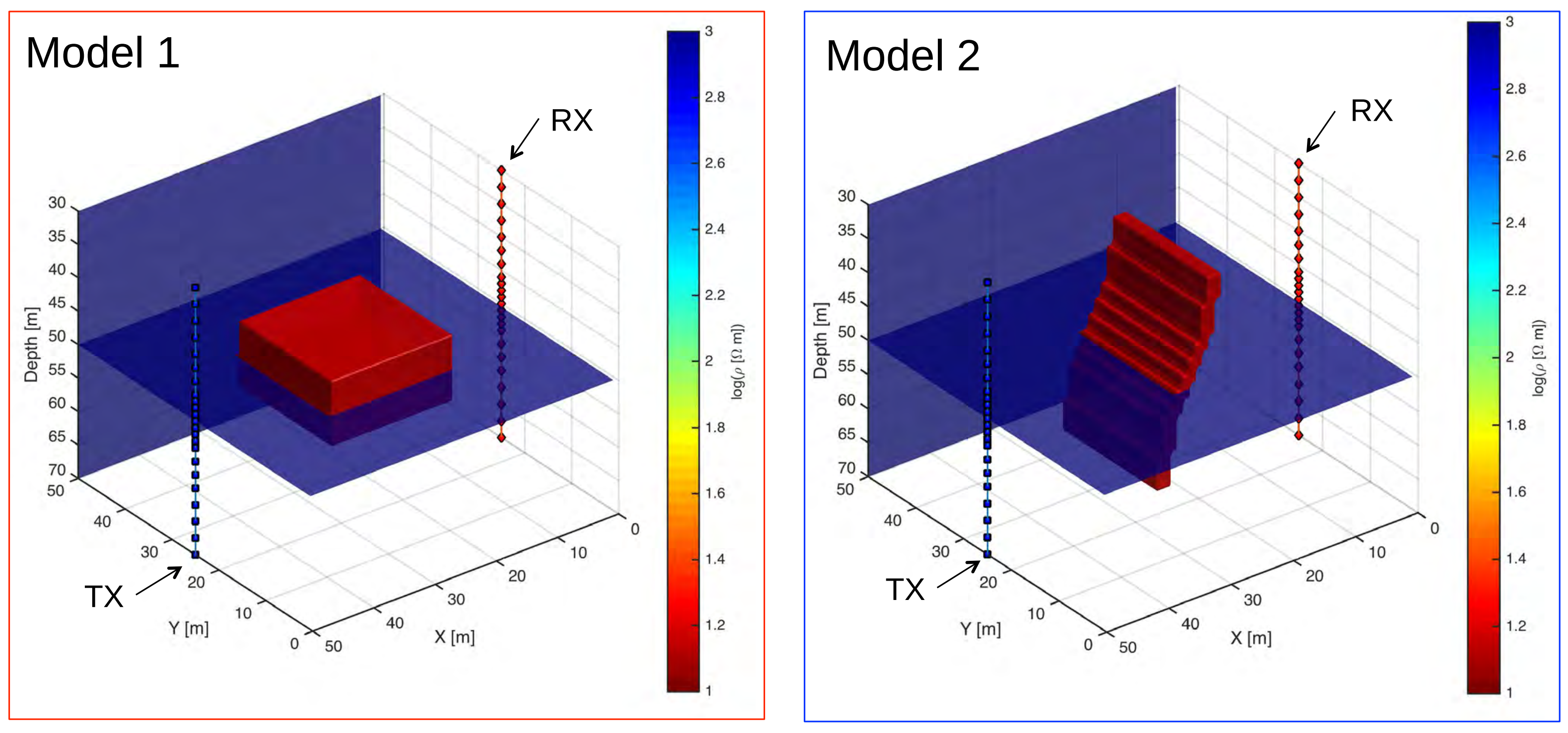


**Fig. 5:** Crosswell configuration and setup of Model 1 (left) and Model 2 (right). Blue symbols denote transmitter locations (TX) and red symbols receiver locations (RX).

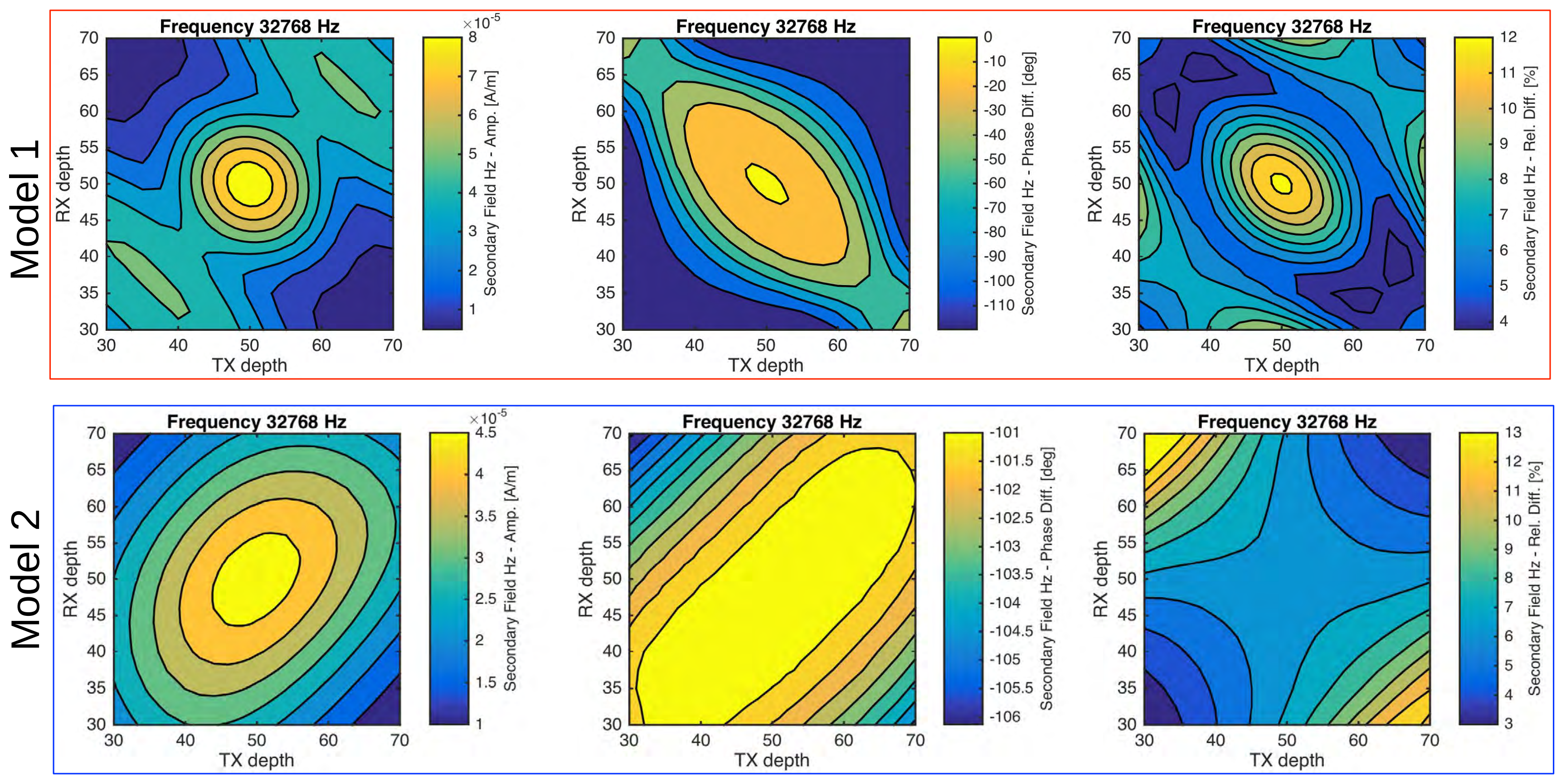


**Fig. 5:** Secondary field for Model 1 (top) and Model 2 (bottom). Field properties are shown in terms of absolute amplitude, phase difference and relative difference of the vertical component Hz w.r.t the primary field.

- Our study shows that crosswell EM data are sensitive to the inter-well structure and secondary fields are above typical instrumental noise levels (cf. Wilt et al., 1995).
- This method can therefore help to improve mapping of fluids in hydraulic stimulation experiments like at the DUG in Grimsel.
- Open questions remain about system design and instrumentation.
- A solution to the 3-D inverse problem of crosswell EM is currently being developed at ETH by A. Geraskin et al..

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# Detecting induced seismicity on various scales: Monitoring the Grimsel injections

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Schweizerischer Erdbebendienst
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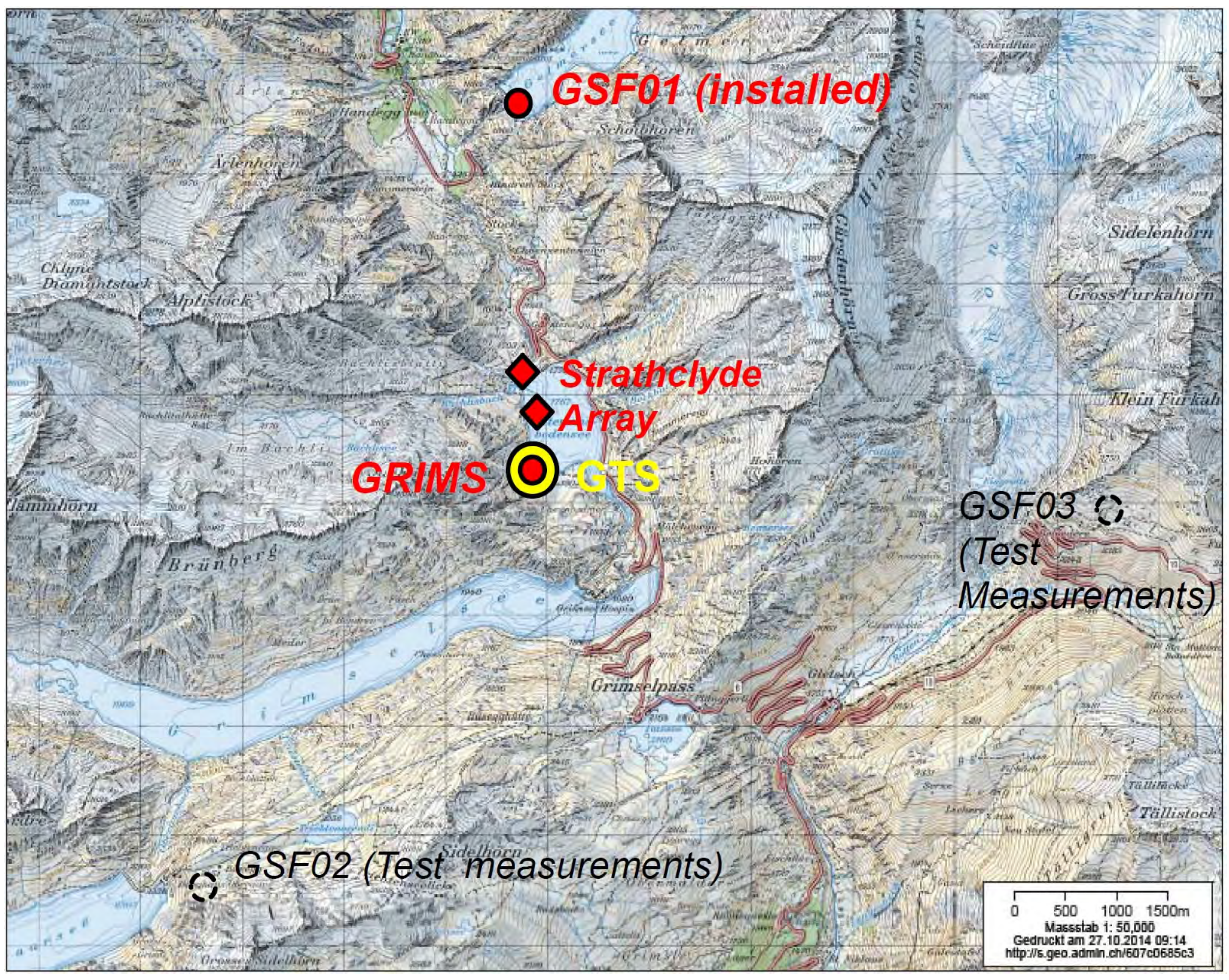
## Introduction

The hydraulic stimulation experiment at the Grimsel Test Site (GTS) will be monitored on different scales and with various sensor types. A regional-scale network with mostly surface seismic stations will record natural seismicity around the GTS. A local-scale network will detect micro-seismic events during hydraulic fracturing (for stress field characterization in the pre-experiment phase) and during a fault stimulation experiment (main experiment). Here, we present the current state of the installations and first recordings. The goal is to build a unique induced seismicity dataset during a set of comprehensively monitored injection experiments.

## Regional-scale seismic monitoring

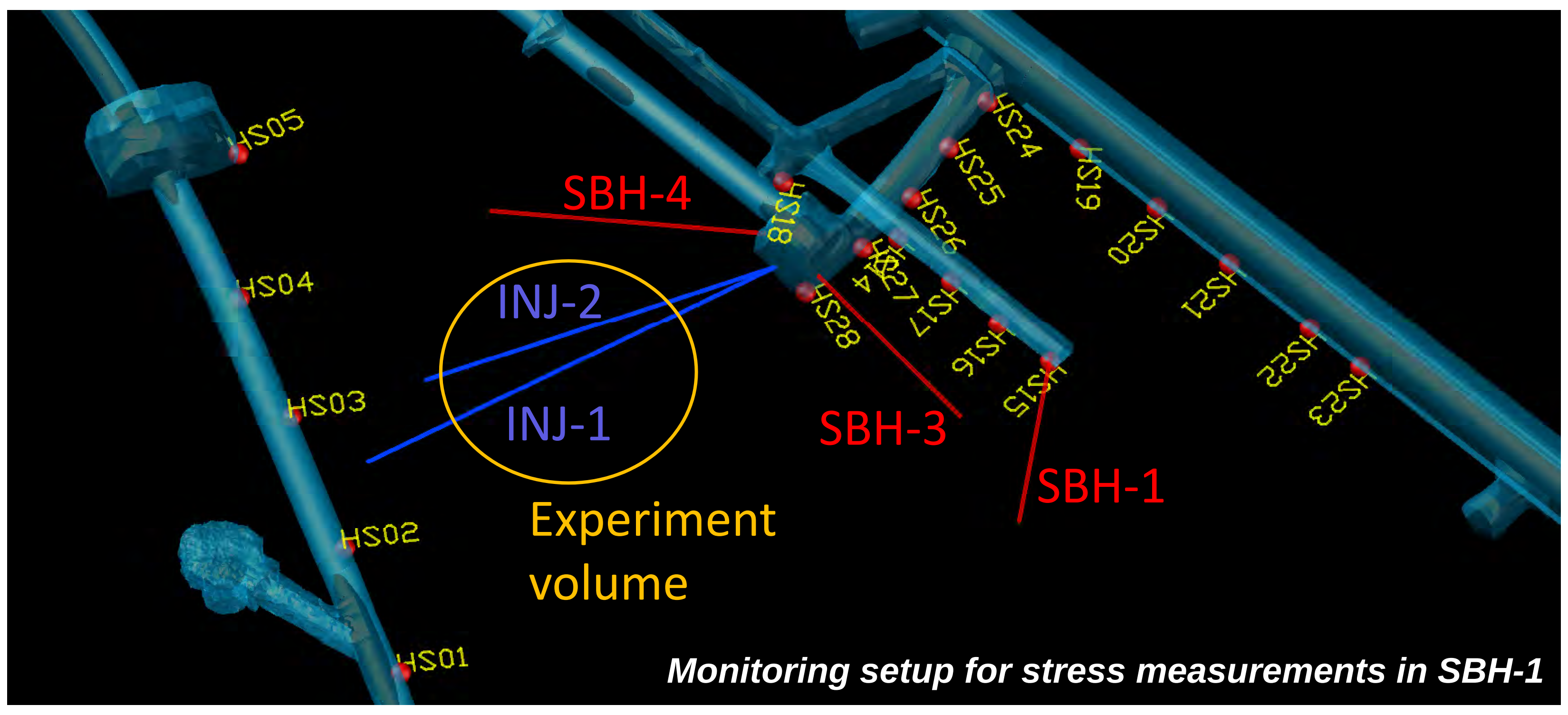


*Strathclyde Array: One borehole sensor in the GTS, two sensor arrays next to Räterichbodensee installed by the Strathclyde University, Glasgow.*

**Purposes:**

- Lowering local detection threshold of Swiss Seismic Network.
- Improve location accuracy for earthquakes around the GTS.
- Find constraints on regional stress field from earthquakes.
- Detect induced seismicity during resevoir impoundment of Rätrichbodensee and Grimselsee.

## Local-scale seismic monitoring during hydro-fracturing for stress characterization



*Monitoring setup for stress measurements in SBH-1*

**Pre-experiment phase:**
Stress measurements in boreholes SBH-1, SBH-3 and SBH-4 including overcoring and hydro-fracturing.

**Main experiment:**
Controlled fault stimulation in borehole INJ-1 and INJ-2
Micro-seismic events are expected during hydro-fracturing and stimulation.
Monitoring network will be adjusted for each experiment.

## Sensor types

Piezosensor (GMuG) clamped to rock surface

Regional

- Station **GRIMS** :
  3C-broadband + 3C-strong motion station,
  BB-bandwidth **120s – 50 Hz**
  SM-bandwidth **DC – 200 Hz**
- Station **GSF01**: 3C-short-period, bandwidth **1 - 100 Hz**

Local

- Piezosensor GMuG: 1 component sensor, bandwidth **1 - ~300 kHz** not calibrated
- Wilcoxon accelerometers: 1 component sensor, bandwidth: flat response **50 Hz – 40 kHz**

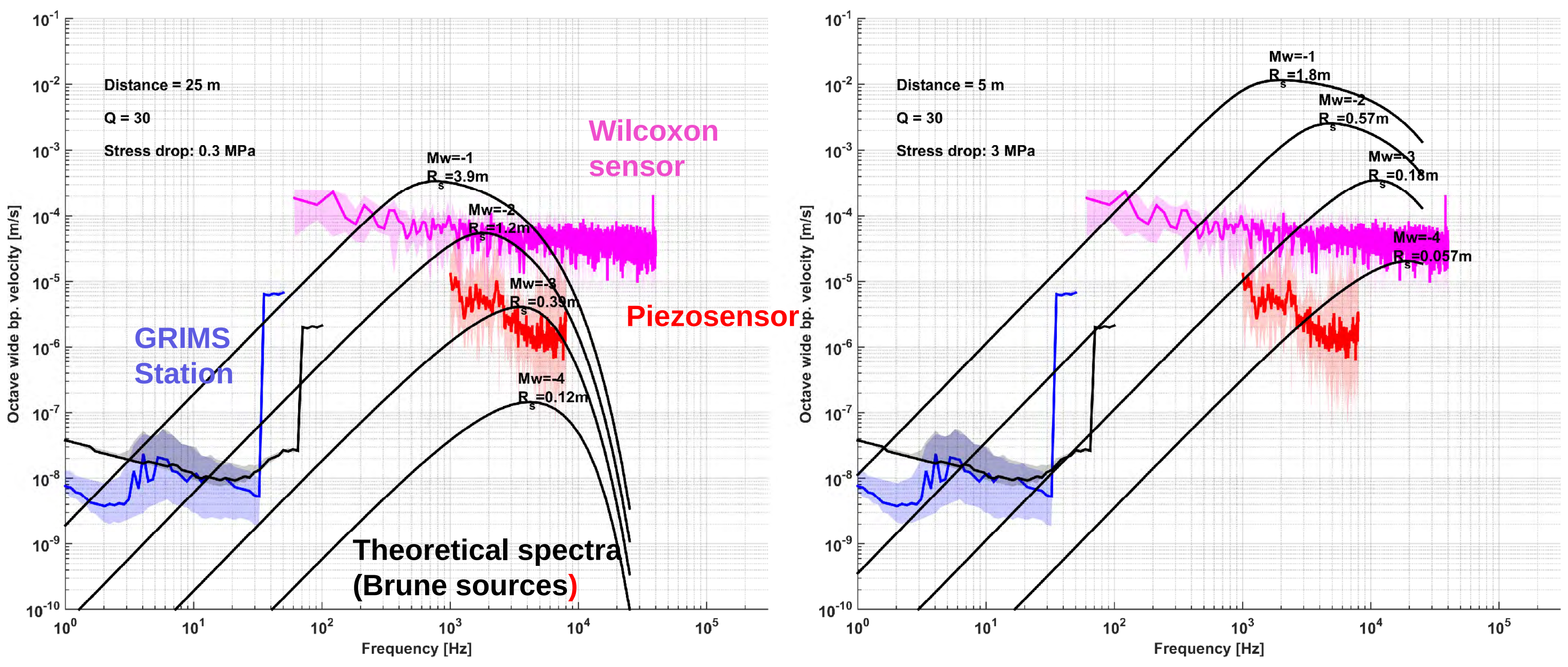
6 Sensor positions are equipped with both sensor types to estimate the local sensor response of uncalibrated piezosensors.

**Wilcoxon accelerometer**

## Sensitivity

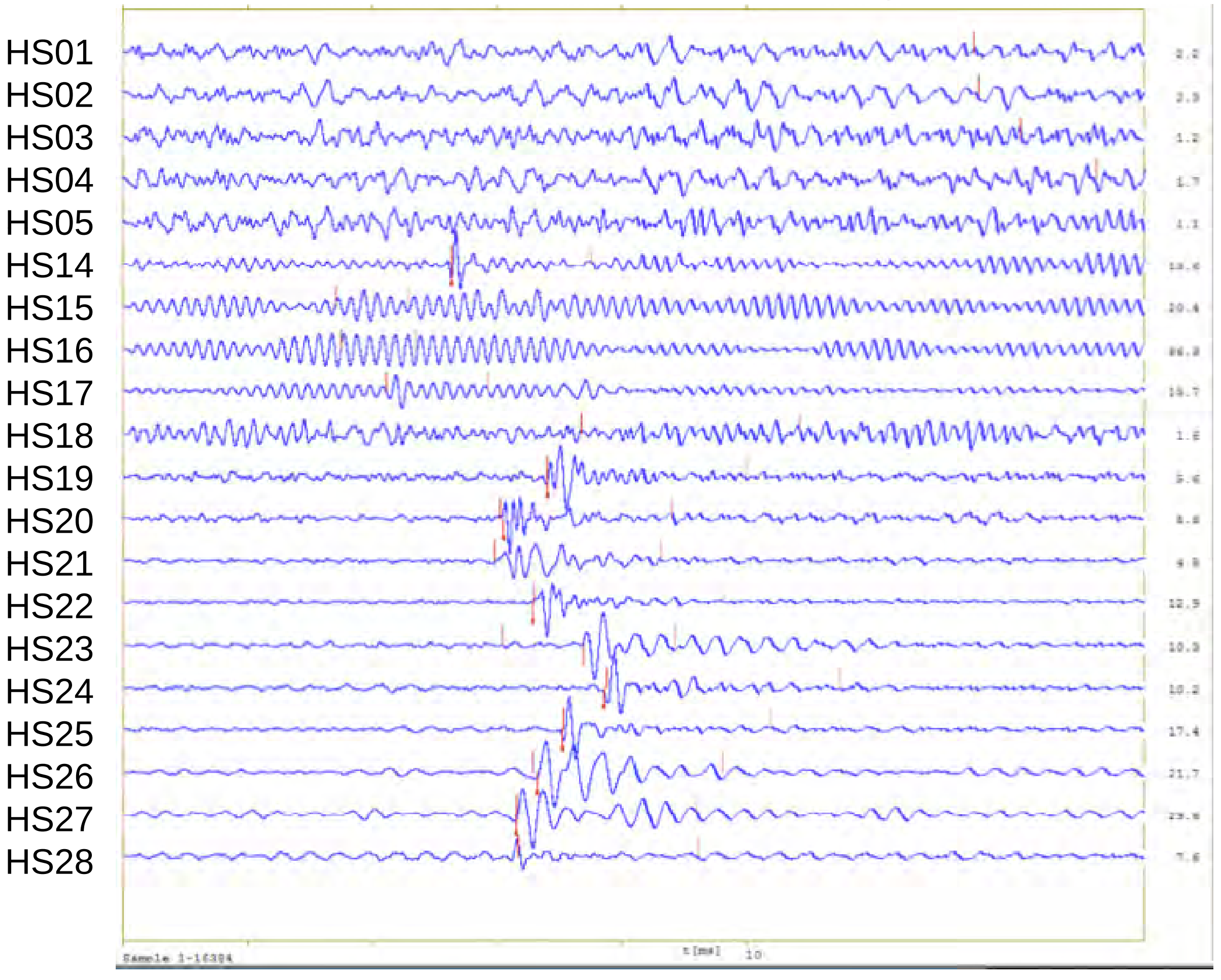
Response of piezosensors can be retrieved for sensor locations that include Wilcoxon sensors and for the overlapping frequency band. Noise spectra are compared with theoretical spectra for different magnitude levels, source-receiver distances and stress drops.

Here an example for sensor location HS28 and for the GRIMS station:



Events with magnitudes as low as **M-4.0** are likely to be detected.
Location accuracy expected to be on the order of ~**10 cm**

## Seismic event recorded during hydraulic fracturing



Event occured during hydro-frac at ~11 m depth in SBH-1

Event location within **< 1m** of known hydrofrac location

## Outlook

- Hydro-fracturing currently being performed and more events are being recorded.
- Detection and location parameters are progressively optimized as several experiments are performed.
- First seismicity catalogues expected in the next weeks/months.
- Future post-processing and analysis will include improved location with inhomogeneous and anisotropic velocity models, refined magnitude estimate, etc.