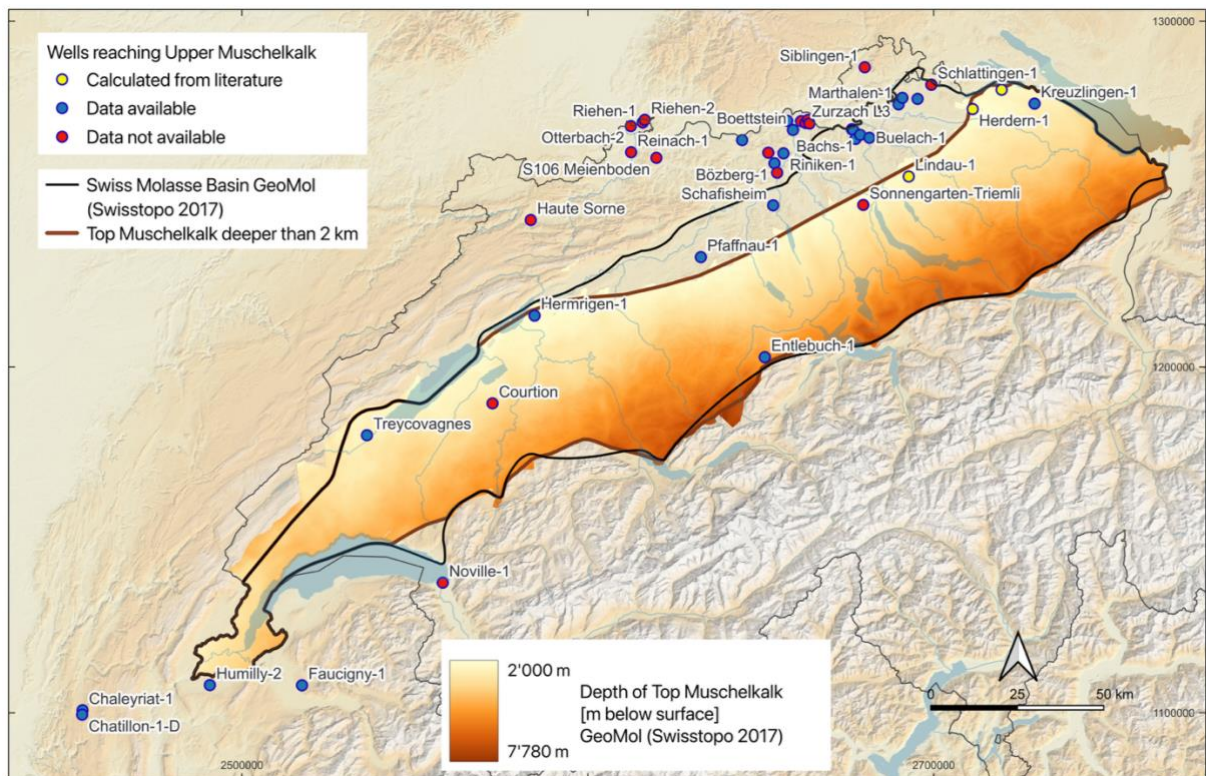




Final report from 23 June 2026

CPG-CH

Unlocking the Potential of the Swiss Molasse Basin and the Need for Further Exploration





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Summary

The deep Swiss subsurface is relatively poorly understood, inhibiting its exploitation for geothermal energy, carbon storage, or critical minerals. A comprehensive understanding of the Swiss Molasse Basin is needed to tap into its potential. We document here an attempt to quantify Switzerland's potential for CO₂ Plume Geothermal (CPG), which uses CO₂ as the working fluid for geothermal extraction. The existing and available wellbore data and seismic data obtained mainly from previous oil and gas exploration were found to be insufficient to understand the subsurface on a level needed to make informed assessment. Although additional legacy data could be made public, the limited usability of this data for our purpose makes it unlikely to substantially improve our understanding of the Swiss subsurface. We therefore make recommendations on how to equip researchers and project developers with the insights and data needed to fully unlock the Swiss subsurface for energy production and storage, carbon storage, or critical mineral production.

Zusammenfassung

Der tiefe Schweizer Untergrund ist bisher unzureichend charakterisiert, was seine Nutzung für tiefe Geothermie, Kohlenstoffspeicherung und die Gewinnung kritischer Mineralien einschränkt. Ein umfassendes Verständnis des Schweizer Molassebeckens ist Voraussetzung, um sein Potenzial auszuschöpfen. Wir beschreiben einen Versuch, das Potenzial der Schweiz für CO₂ Plume Geothermal (CPG) zu quantifizieren, bei dem CO₂ als Arbeitsmedium für die geothermische Förderung dient. Die verfügbaren Bohrloch- und seismischen Daten, die überwiegend aus früheren Öl- und Gasexplorationen stammen, reichen für eine fundierte Bewertung des Untergrunds nicht aus. Selbst eine Veröffentlichung weiterer historischer Datensätze dürfte unser Verständnis des Schweizer Untergrunds nur begrenzt verbessern. Aus diesem Grund formulieren wir Empfehlungen, wie künftige Forschung und Projektentwicklung die erforderlichen Daten und Erkenntnisse erarbeiten können, um den Schweizer Untergrund für die Energieerzeugung und -speicherung, die Kohlenstoffspeicherung sowie die Gewinnung kritischer Mineralien vollständig zu erschliessen.

Résumé

Le sous-sol profond suisse est encore mal connu, ce qui freine son exploitation pour l'énergie géothermique, le stockage du carbone et l'extraction de minéraux critiques. Une compréhension approfondie du bassin molassique suisse est indispensable pour exploiter pleinement son potentiel. Nous présentons ici une tentative de quantification du potentiel de la Suisse en matière de CO₂ Plume Geothermal (CPG), qui utilise le CO₂ comme fluide de travail pour la production d'énergie géothermique. Les données de puits et sismiques existantes, issues principalement d'anciennes explorations pétrolières et gazières, se sont révélées insuffisantes pour appréhender le sous-sol avec le niveau de précision requis pour une évaluation fiable. Bien que des données historiques supplémentaires puissent être rendues publiques, leur applicabilité limitée à notre étude rend peu probable une amélioration significative de nos connaissances du sous-sol suisse. Nous formulons donc des recommandations visant à doter les chercheurs et les développeurs de projets les connaissances et les données nécessaires pour exploiter pleinement le potentiel du sous-sol suisse, que ce soit pour la production et le stockage d'énergie, le stockage du carbone et l'extraction de minéraux critiques.



Main findings

- Switzerland successfully utilizes shallow geothermal heat, but lags in deep geothermal use and Carbon Capture, Utilization, and Storage (CCUS). Innovative technologies like CO₂ Plume Geothermal (CPG) could bridge this gap by simultaneously generating low-carbon baseload electricity and storing CO₂.
- Strategic evaluation of the deep Swiss Molasse Basin (SMB) below 2 km is currently limited by a lack of data, proprietary restrictions on legacy oil/gas wells, and low-resolution 2D seismic data that cannot accurately map critical fault systems.
- To reliably de-risk and model deep georesources, Switzerland requires a coordinated data campaign, including modern 3D seismic mapping and fit-for-purpose wellbore data at a density of at least one deep well per 1,000 km².
- Overcoming the immense capital costs of deep subsurface exploration requires an “interest-pooling” model, where public and private entities co-finance deep drilling and data collection while mandating public data sharing.



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List of abbreviations

CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilization and Storage
CPG	CO ₂ Plume Geothermal
CRS	Common Risk Segments
GSHP	Ground-Source Heat Pump
PFA	Play Fairway Analysis
SFOE	Swiss Federal Office of Energy
SMB	Swiss Molasse Basin



1 Background: The Push for Holistic Deep Subsurface Exploration

Switzerland faces a growing demand for low-carbon, domestically produced, and baseload energy and energy storage capacity, and is increasingly looking to the subsurface to help meet that demand. Shallow geothermal heat utilization is widely adopted, with Switzerland boasting one of the highest densities of ground-source heat pumps (GSHPs) per km² globally (Lund and Toth, 2020). However, regarding deep geothermal energy, where temperatures are hot enough to produce electricity or provide direct heat (without the use of a heat pump), Switzerland lags its neighbors and produces to date zero electricity and has only a few direct heat utilization projects. In terms of CO₂ geological storage, several potential storage complexes in Switzerland have been identified within the Molasse foreland basin (Chevalier et al. 2010) and opportunities for potential pilot injection tests have been evaluated (e.g. Schultz et al. 2024, Madritsch et al. 2026), though no explicit siting process for storage projects has yet been launched.

Novel technologies such as CO₂ Plume Geothermal (CPG) may offer a promising pathway to both generate geothermal electricity and store CO₂ in the subsurface. CPG is a Carbon Capture, Utilization, and Storage (CCUS) technology that uses supercritical CO₂ as a geothermal working fluid. The thermal and physical properties of supercritical CO₂ allow it to extract nearly twice as much heat as water for a given injection pressure, which is a common operational constraint in geothermal and CCUS systems (Randolph & Saar 2011, Adams et al. 2015). For a reservoir to be viable for CPG, it must first be suitable for carbon capture and storage (CCS) operations: reservoir pressure must stay above the critical pressure of CO₂ (ca. 7.4 MPa), permeability must be sufficiently high to be able to inject CO₂ at high rates, and an impermeable caprock must exist to prevent upward migration of CO₂. Additionally, the reservoir must be hot enough for geothermal energy recovery. The minimum reservoir temperature for CPG varies with depth and permeability, but a lower limit of 120 °C serves as a useful delimiter (Adams et al. 2015). Identifying reservoirs which meet all criteria is a central challenge in realizing this promising technology but also offers synergies with potential geothermal and CCS projects.

The CPG-CH project, funded through the geoenergy research program of the Swiss Federal Office of Energy (SFOE), was initiated by researchers at ETH Zürich and AdTerra Energy, to conduct the first-ever evaluation of CPG capacity in Switzerland. The project aimed to integrate new borehole data with previous investigations into Switzerland's capacity for CCUS in order to perform techno-economic analysis and ultimately identify regions best suited for CPG.

Previous studies into Switzerland's capacity for CCUS identified the Swiss Molasse Basin (SMB) as a prime candidate for CO₂ storage but limited their search to 2.5 km depth (Chevalier et al. 2010, Giardini et al. 2021). However, with geothermal gradients in the SMB ranging from 25 to 40 °C/km (Rybach 1992), a reservoir at 2.5 km depth is near the minimum depth required for CPG, while deeper and hotter reservoirs would enable significantly more efficient heat extraction. The SMB dips towards the southeast, reaching depth of up to 7 km. We therefore sought to extend these investigation areas by investigating reservoir conditions where the SMB reached up to 5 km depth. In particular, we focused on the Middle Triassic dolostone unit known as the Trigonodus Dolomite, which has the highest permeability and porosity of the Upper Muschelkalk formation and which is hydraulically sealed by the so-called "Gipskeuper" units (alternating shale & gypsum/anhydrite) (Chevalier et al. 2010, Giardini et al. 2021).

2 Insufficient Data and Knowledge Gaps

The deep portions of the SMB are largely unexplored. Data from 40 wells that reached the Upper Muschelkalk formation were found, most of which were from past exploration for oil and gas. Of these 40 wells, 27 wells had accessible data for the CPG-CH study and only 9 wells intercepted this unit at



depths greater than 2 km (Figure 1). About half of these wells have only one permeability measurement, which impedes a detailed assessment of permeability variability. Furthermore, the well data are spatially sparse, leaving vast areas almost completely unexplored, such as the region between St. Gallen and Luzern and the area south of Bern. Critically, there is a lack of well data in major fault zones in the Upper Muschelkalk formation, limiting the knowledge of fault permeabilities that can be extracted.

The scarcity extends to other promising deep geologic units: the lower Triassic Buntsandstein formation is poorly mapped, and its existence is uncertain across approximately half of the SMB. The shallow crystalline basement has also been identified as a potential geothermal reservoir, owing to a region of increased permeability (Thury et al. 1994), but of the limited data from wells reaching the basement unit, permeabilities were often either not available or not well constrained (i.e. using different methodologies to define permeability).

Legacy oil and gas well data in Switzerland are of limited use to understanding the subsurface for our purpose. First, data accessibility is a primary limitation as much of the private well information remains proprietary. Second, available vintage data frequently lack the relevant sampling protocols, petrophysical measurements, and coring programs necessary for a definitive assessment of target reservoir/caprock pairs. Crucially, vintage exploration targets often did not correspond to entire stratigraphic sections; consequently, many wells did not provide adequate characterization of critical rock units, such as the underlying granitic basement. This scarcity of fit-for-purpose data hinders the understanding of the subsurface, thereby preventing informed investment decisions on CPG and also projects pursuing established geothermal and CCS approaches (see also Moscariello 2019).

Further characterization of the Swiss deep subsurface is also hindered by limitations in the availability and quality of reflection seismic data. 2D seismic profiles have been acquired in the 1970s and 80s across much of northern Switzerland in search for oil and gas. This extensive dataset was considered during the elaboration of the region's large-scale 3D model GeoMol (Swisstopo 2017). Notably, this legacy 2D seismic data is very heterogeneous, stemming from many different acquisition campaigns. Also, spatial coverage of this data is variable, with large regions containing virtually no seismic data ("white spots"), leaving the structural geology of these areas poorly understood and almost entirely speculative. Furthermore, the majority of the legacy 2D seismic datasets remain proprietary or confidential, preventing a cohesive, public assessment of its potential for reservoir characterization (Figure 2).

While these 2D seismic profiles would benefit from reprocessing using modern techniques (Nagra 2014 with references therein), experience has shown that even reprocessed legacy 2D seismic will lack the resolution to accurately map the sub-vertical fault systems (e.g. strike-slip) and discrete karst features required to estimate geothermal and CCS viability. Recent 3D seismic acquisitions in the Geneva Basin have highlighted the unreliability of these 2D lines, revealing legacy interpretations to misplace faults or fail to image complex features visible only in 3D seismic data. Particularly for likely fractured reservoirs such as the Upper Muschelkalk aquifer, this data is regarded as essential for robust prospect identification for geothermal exploitation (see also Madritsch et al. 2025).

Together, the lack of data and lack of data suitability below 2 km depth severely hampered the execution of the CPG-CH project. A Play Fairway Analysis (PFA) for deep CPG potential was abandoned. An alternative method, the Common Risk Segments (CRS) approach – though better suited for highly uncertain datasets, was also found to lack sufficient quantitative data. These inconclusive outcomes are consistent with broader findings reported in the SCCER-SOE report (Giardini et al., 2021), highlighting the low availability of reservoir engineering and production data (such as hydraulic test data), leading to a low understanding of the dynamic behavior of the reservoir, in terms of injectivity, permeability, and temperature. The existing information is only sufficient for creating overly simple models with substantial uncertainty given that the ranges of critical parameters are still very poorly defined.

Ultimately, this persistent scarcity of deep data precludes a robust capacity estimation for a wide range of subsurface georesources, including CCS, CPG, geothermal thermal storage, and possible extraction of critical raw materials (e.g. lithium) from geothermal fluids.



3 Towards a Holistic Subsurface Understanding

Additional data are critically needed to move forward and enable a robust, quantitative assessment of deep Swiss georesources. No single data type can fully bridge the gaps in our understanding, and the spatial distribution of these data needs vary from basin to site scale. Furthermore, data collection and processing methods are rapidly evolving, with new techniques emerging and existing techniques becoming more efficient. We identify here the types of data needed and suggest an estimate of the density and/or proximity of data required at each scale.

3.1 Data Types

3.1.1. Geologic and Physical Properties Data

There is no substitute for data collected from wells intersecting a geologic formation. The following data must be acquired from new or existing deep wells:

- Wellbore logs and comprehensive geologic interpretation are needed to better understand the extent and variability of geologic units. This includes multiple measurements within reservoir units to understand the spatial distribution of permeability and porosity, as well as temperature gradients along the wellbore. Mud logs and drilling logs are relatively straightforward to collect and can be used to characterize multiple geologic horizons in addition to the target formation.
- Hydraulic tests are crucial for gathering reservoir engineering information, such as average reservoir permeability and storage capacity, needed for reservoir development & management plans and economic assessment.
- Drill core from deep reservoirs is costly to collect but is an invaluable source of geologic and physical parameter data.

3.1.2. Structural Data (Faults)

Subsurface fluid flow is often governed by fault zones and distributed fracture networks. While faults can provide the primary permeability needed for geothermal and mineral production, they may also endanger the sealing capacity of the overlying caprock for CCS and CPG. Conversely, smaller-scale fractures, often below seismic resolution, are critical for establishing effective well-to-well connectivity and wider reservoir permeability. It is therefore essential to understand the density, orientation, and mechanisms of fracturing and faulting in formations of interest.

Current structural data of the SMB, including faults and horizon maps, are best represented by the GeoMol dataset, based on 2D seismic data from as early as the 1960s (see discussion above). This kind of data is only able to capture major fault zones with vertical throws exceeding several tens of meters. Consequently, the characteristics of secondary fracture networks remain largely unknown. A better knowledge of these structural subsurface characteristics would allow for more informed estimates of well-to-well permeability and potential CO₂ leakage pathways. Despite their importance, there is a lack of well data from faults, resulting in uncertainties regarding their hydrogeological significance and how they will react to injection/production.

The following data should be acquired:

- 3D reflection seismic data is critical. Results from recent acquisitions across Switzerland for geothermal energy developments show that structural and geologic interpretations based on existing 2D seismic data can be drastically revised by 3D data. The GeoMol dataset was built on the basis of 2D seismic data that has limited reliability when it comes to identifying steep features, such as strike-slip faults.



- Complementary to the above, passive geophysical methods, such as Magnetotellurics (MT), gravity and passive seismic, should be considered. These methods can potentially help identify regions of high porosity, hot upflow, or elevated salinity, which are key to geothermal production and mineral extraction. These methods do so in a more cost-efficient and less invasive way than active seismic.
- Well data (e.g. those listed above) intersecting faults given in the GeoMol dataset or higher resolution 3D seismic surveys, including high quality geophysical logs and insitu testing, are needed to understand hydrogeological significance. Fracture networks properties (fracture density, orientation, and thickness) can be estimated from acoustic image logs. When analyzed together with proxy data, such as documented regions of lost returns while drilling, relationships between faults/fractures and permeability (or lack thereof) can be better understood.

3.1.3. Hydrochemistry Data

Thorough hydrochemical analysis of reservoir brine can help to identify operational risks critical to any geothermal, CCS, or CPG operation. Scaling in wells/pipelines and the reservoir itself can be mitigated, but this comes at extra cost and depends on the reservoir fluid composition. Beyond risk mitigation, hydrochemistry serves as a vital exploration tool for characterizing geothermal systems; isotopic and chemical tracers provide critical insights into the nature and origin of the subsurface fluids. There is also a potential for mineral extraction (such as lithium or other critical raw materials) in deep geothermal fluids, in which case it is imperative that hydrochemistry and geochemistry data is collected from future deep boreholes alongside physical reservoir parameters. This data is necessary to understand fluid composition and concentration, thereby enabling the techno-economic viability of this resource to be assessed.

3.2 Data Density at Different Scales

3.2.1. Basin Scale (order of 1,000+ km²)

Play Fairway Analysis (PFA) is a commonly used methodology adapted from the petroleum industry used to identify areas at the basin scale where favorable geological factors, such as heat flow, reservoir permeability, and seal integrity, intersect spatially and warrant further investigation. PFA offers a first-pass assessment in data-poor environments, where data is interpolated over large areas based on limited information. But even so, the data publicly available in the deep Swiss Molasse Basin is so sparse that the distances between well data is 10s or 100s of kilometers and the spacing between available seismic lines in the east can exceed 30 kilometers.

To conduct a meaningful PFA of the deep SMB, with an area of roughly 10,000 km², we recommend the following:

- Modernly reprocessed or newly acquired 2D seismic lines with a spacing of roughly 10 km and a 3D seismic survey conducted every 2000 km². Available 2D seismic lines in western Switzerland have a spacing on the order of 1-3 km, while in eastern Switzerland it is up to 40 km between lines. Publicly available 3D seismic data are currently available in just five locations in Switzerland: Geneva, Eclépens, Les Vernes Method, Riehen, and St. Gallen. These locations are at the western, northern, and eastern fringes of the SMB, with significant distance between them.
- Deep well data (of the quality given in section 3.1) at roughly 1 well per 1000 km², half of which should be drilled below 4 km depth. This corresponds to 10 wells total. Compare this to the less than 5 available well datasets in Switzerland which give permeability data in the Muschelkalk formation below 2.6 km.

With this data, techno-economic modeling of CPG, geothermal, and CCS projects can be performed, albeit with relatively large uncertainty bands on key parameters like reservoir permeability, thickness, and temperature.



3.2.2. Regional Scale (order of 100 km²)

Once a favorable region has been identified from PFA, additional data is collected to reduce uncertainty in key reservoir parameters. This involves first seismic data acquisition in order to confirm the structural properties of the reservoir suitable for CPG/geothermal/CCS, then drilling to confirm whether sufficient heat and permeability are present.

- A 3D seismic survey is recommended to resolve potential sub-vertical faults and possibly fractures corridors that are considered to govern permeability in saline aquifers such as the Muschelkalk at greater depths. Such structures are critical to both geothermal and CCS (and therefore, CPG) projects, as they provide needed permeability and also pose risk as a potential leakage pathway through cap rocks.
- Ultimately, deep wells provide the most critical data, but at the highest cost. Ideally, a well drilled within the same structural block or within a 10 to 20 km radius, assuming geological and stratigraphic continuity, serves as a robust proxy for estimating permeability and temperature. However, in structurally complex or faulted settings, geological conditions can shift rapidly over distances as short as 1 to 2 km. In such environments, a well 20 km away may tap into an entirely different hydraulic system or structural compartment, potentially rendering calibration data misleading. In the absence of existing deep wells nearby, geological analogs must be used. Thus, the well data collected elsewhere at the basin scale can still provide significant value.
- To assess fracture systems at the reservoir scale, deviated or even horizontal wells have to be considered (Frieg et al. 2015).
- Complementary to the above, passive geophysical methods, particularly gravity and seismic, are recommended to estimate porosity and regions of potential fluid upflow.
- Hydro- and geochemical data acquired on the regional scale from shallow wells as well as soil gas surveys would be valuable constraints on fluid circulation and flow pathways in the subsurface.

This data will serve to reduce the uncertainty in the techno-economic modeling of the project, helping developers decide on whether to proceed or to determine the value of collecting additional data to further constrain the site. The proposed data density required is only an estimate or a starting point for further analysis, with higher data density potentially required to adequately characterize more heterogeneous regions of the subsurface.

4 Going Forward: A Collaborative Strategy

Future data collection in the deep Swiss Molasse Basin should be undertaken in a systematic way to maximize synergies across multiple subsurface applications, including CCS, geothermal energy, and mineral extraction. Data should be made publicly available and follow best practices for data collection, analysis, and management.

To fund the necessary cost-intensive deep data acquisition recommended in this paper, an interest-pooling approach could be adopted in Switzerland. Such models enable public and private stakeholders with diverse interests (e.g. geothermal energy, CCS, critical raw materials, underground nuclear waste disposal) to collaboratively finance drilling and data collection. For example, if one group finances drilling a well to a certain depth, another interested group could pay for additional data collection or drilling to a greater depth to meet their specific data needs. Preexisting, non-public data is “low-hanging fruit” that, if made publicly available, would provide a step-change in the amount of data available. Such data will require significant reanalysis using modern methods to integrate with currently available data in a holistic way.

International and local precedents show how such a collaborative strategy can maximize the value of data gathering campaigns:



- The TU Delft Campus Geothermal Project (the Netherlands) serves as a primary example of an "Open Science" approach, where utility, industry (like Shell and EBN), and academic bodies established a consortium. This model decoupled base drilling costs from geological characterization costs, allowing industry partners to fund advanced logging and academic partners to fund deep coring and drilling depth beyond the primary reservoir target. This discounted the cost for data acquisition and reduced the discovery risk for subsequent regional projects. (TU Delft, 2024)
- The United Downs Deep Geothermal Power Project in Cornwall, United Kingdom demonstrates how the high cost of deep drilling can be de-risked through dual-commodity production: geothermal energy and lithium extraction. This bundling of energy and mineral exploration partners attracted a more diverse capital base than a traditional heat project could command, subsidizing the high cost of deep stratigraphic logging. (GEL Energy, 2024)
- Federal subsidy programs supporting the development of geothermal energy in Switzerland have proven essential because they contribute to a better understanding of the subsurface at large. They also incentivize the innovative data-gathering necessary to understand the deep subsurface. This funding locally fills the data gap by linking commercial projects and subsurface exploration, providing the essential engineering knowledge needed to enable geothermal energy and other subsurface utilizations such as CCS and at scale.

By leveraging synergies and shared interests and unbundling research costs from production capital, such cooperative strategies can systematically eliminate Switzerland's geological "white spots". This collaborative approach facilitates a transition toward a de-risked, 3D-mapped and characterized subsurface required to enable investment in geothermal energy, CCS, CPG, and mineral extraction.

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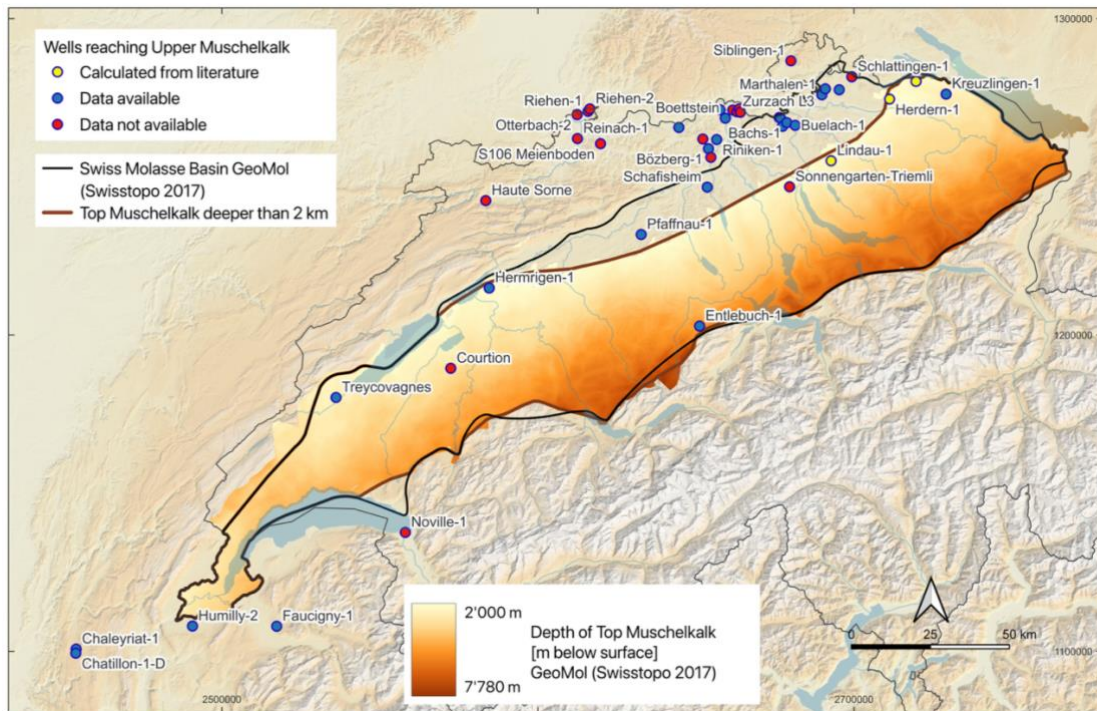


Figure 1: Wells reaching the Upper Muschelkalk unit and the (non-) availability of permeability data. Note that only 9 wells are located in the study area where the Upper Muschelkalk is deeper than 2 km. The only well in Switzerland with available permeability data in the Upper Muschelkalk below 2.6 km is the Entlebuch-1 well.

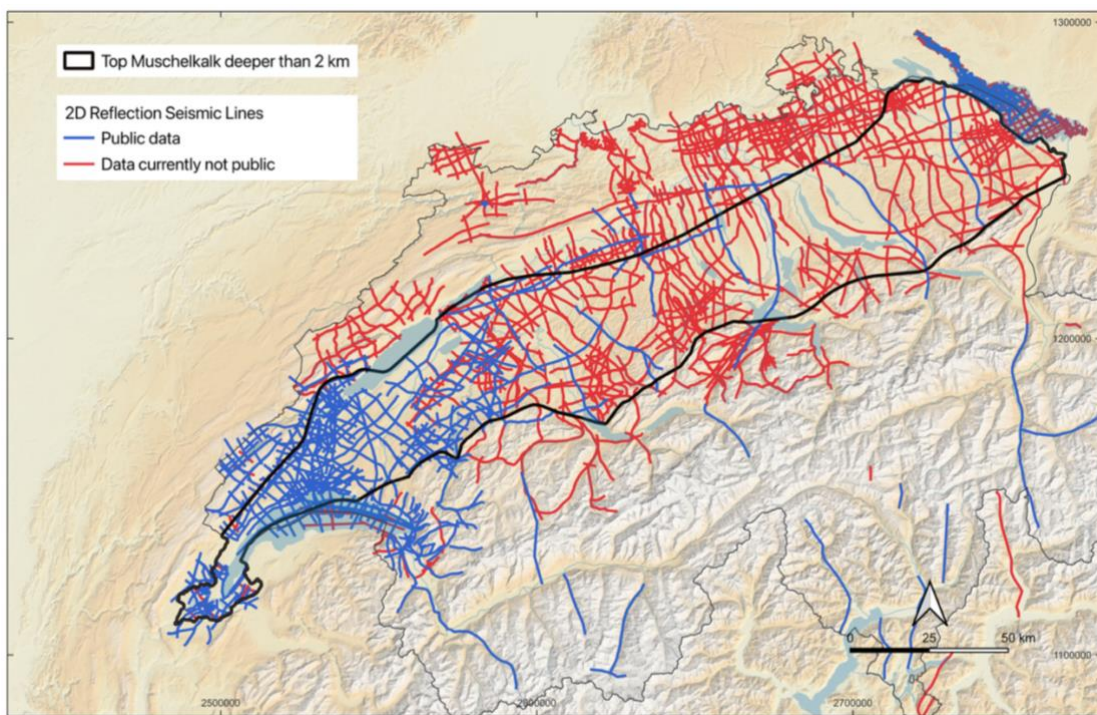


Figure 2: Legacy 2D Seismic studies conducted in Switzerland. Blue lines are publicly available; red lines are not.