Multi-Criteria Analysis for Geothermal Energy Planning to Reduce CO_2 Emissions in Switzerland

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Work Package 1 focusing on the Thermal Energy System Modelling at the Mesoscale: developing spatially resolved decarbonization pathways for thermal energy¨

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Abstract

The DeCarbCH project targets Switzerland's goal of achieving negative CO_2 emissions by 2050 through the assessment of decarbonizing heating and cooling systems. It focuses on harnessing shallow hydrothermal energy to mitigate CO_2 emissions, particularly in densely populated areas like the Swiss Plateau. Switzerland's extensive use of geothermal source heat pumps and its geological diversity make it suitable for low, medium and high enthalpy geothermal energy. The Swiss Plateau, covering 30% of the country and characterized by high population density, offers significant potential for geothermal applications in various sectors. Direct-use systems for agricultural and industrial purposes highlight geothermal energy's versatility and sustainability. Learning from successful European projects, Switzerland aims to replicate emissions reduction through geothermal district heating and industrial integration. Multi-Criteria Analysis (MCA) emerges as a vital tool for decision-making, considering factors like CO_2 emissions, subsurface temperature distribution, economic viability, and social acceptance. MCA facilitates informed and sustainable geothermal resource development. Despite Switzerland's geothermal potential, challenges persist, including outdated temperature models, limited reservoir characterization, and incomplete fault mapping. Addressing these gaps is crucial for maximizing geothermal energy benefits. In conclusion, the DeCarbCH project emphasizes geothermal energy's transformative potential in Switzerland's energy transition portfolio. Through innovative technologies and collaborative frameworks like MCA, Switzerland can accelerate geothermal adoption, reduce carbon emissions, and progress towards environmental and energy sustainability.

Introduction

The DeCarbCH project aims at assessing the decarbonation of heating and cooling in Switzerland within the context of the negative CO_2 emissions commitment to be achieved by 2050.

In this context the project presented here consisted at demonstrating the potential of developing shallow hydrothermal energy in Switzerland to enter the energy mix while reducing CO_2 emission. Shallow hydrothermal energy holds significant promise for Switzerland and Europe as a whole, offering a sustainable and versatile energy source with the potential to decarbonize various sectors while meeting the needs of densely populated areas.

Geothermal source heat pumps (GSHPs) are widely used for heating and cooling buildings throughout the country making Switzerland one of the world country with the highest number of shallow geothermal wells per inhabitant (Rybach, 2022; Link, 2023) . In urban areas like Zurich and Geneva, where space heating demands are high, GSHP

systems extract heat from the shallow subsurface during the winter to warm buildings and provide hot water. The temperature thresholds for GSHP systems typically range from 5°C to 30°C, making them suitable for a wide range of climates.
Beside shallow geothermal energy systems, Switzerland, with its geological diversity and abundant water resources, possesses favorable conditions for harnessing medium tohigh enthalpy hydrothermal energy (e.g. Eberhard, 2016; Giardini et al., 2021; Kohl et al., 2003; Link et al., 2020; Moscariello, 2016, 2019; Rybach, 1992; Wilhelm et al., 2003).
The project presented here focuses on the area morphologically defined as Swiss Plateau, or Central Plateau (Fig 1). It stretches from Lake Léman in the southwest to Lake Constance in the northeast. It is one of Switzerland's three geographical regions and covers 30% of the country and it is the most densely populated region. The northern part of the Plateau is flanked by the Jura and the Rhine, the south by Lake Léman and the Alps.

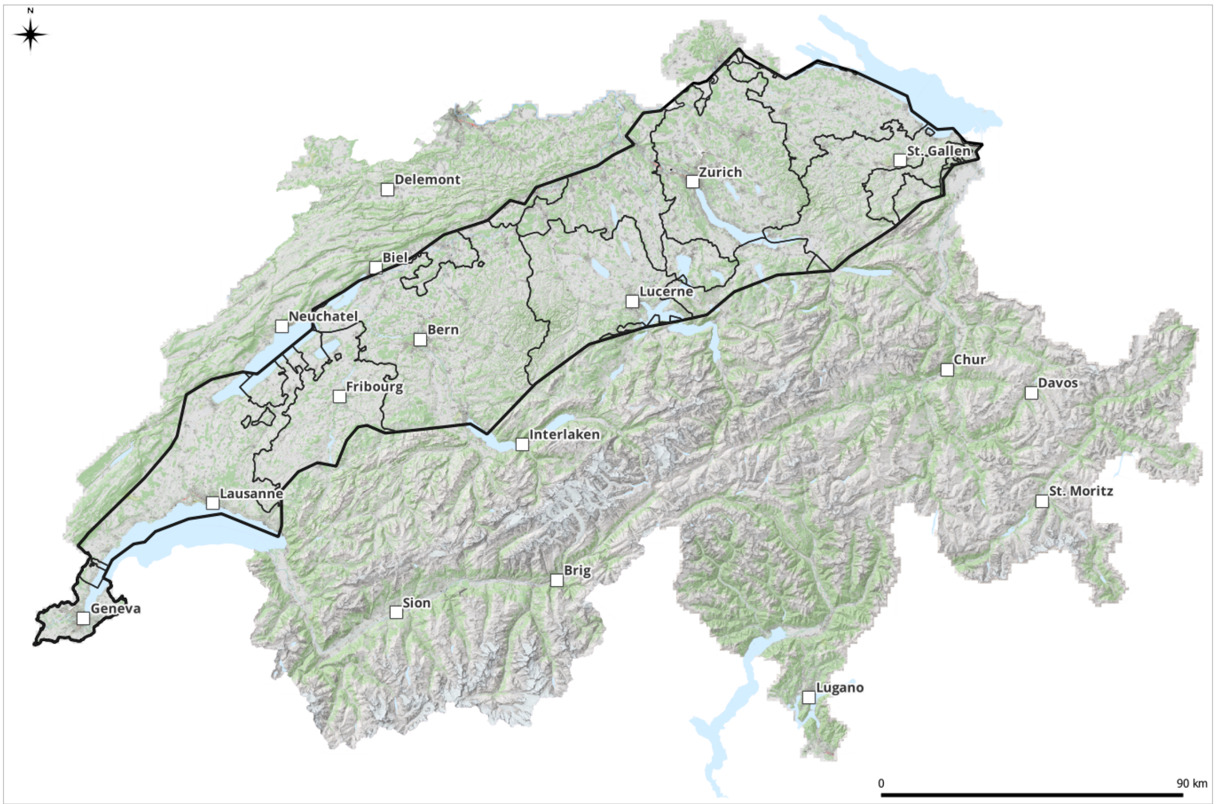

Figure 1 – Map of the area of interest: the “Swiss Plateau” delimited in black lines.

Moreover, Switzerland has been exploring the potential of direct-use systems for agricultural and industrial applications. Hot water extracted from shallow geothermal reservoirs can be utilized for greenhouse cultivation, fish farming, and industrial processes such as food drying and space heating. With the right infrastructure and regulations in place, direct-use systems can help reduce carbon emissions from conventional heating methods while enhancing energy efficiency in densely populated areas.

In Europe, hydrothermal energy is gaining momentum as countries seek to transition to low-carbon energy sources. Following the well consolidated successfully experience of the Dogger geothermal reservoirs in the Paris Basin, Germany has been a pioneer in geothermal district heating projects, particularly in cities like Munich and Stuttgart. All these projects utilize the heat stored in the upper layers of the Earth's crust to provide centralized heating for residential and commercial buildings. By tapping into geothermal reservoirs, Germany has reduced its reliance on fossil fuels and achieved significant emissions reductions in urban areas.

Furthermore, hydrothermal energy holds great potential for decarbonizing industrial processes in densely populated areas across Europe. In countries like the Netherlands and Belgium, where industrial activities are concentrated in urbanized regions, integrating heat and cooling from shallow geothermal systems (GSHP) with hydrothermal systems into industrial processes can help reduce greenhouse gas emissions and improve air quality. For example, the use of geothermal energy for district heating in Rotterdam's industrial port area has demonstrated the feasibility and benefits of utilizing shallow hydrothermal resources in densely populated industrial hubs.

Overall, geothermal energy offers a sustainable, versatile and scalable solution for meeting heating, cooling, and power generation needs in Switzerland and Europe. By leveraging technologies such as geothermal source heat pumps, direct-use systems, and district heating networks, countries can reduce their carbon footprint, enhance energy security, and promote sustainable development in densely populated areas. In addition, innovative solutions concerning the underground storage of heat as per example in aquifers (ATES: aquifer thermal energy storage) opens new avenues to maximize the benefits of both energy extraction and sustainable reutilization of waste energy (e.g. Fleuchaus et al., 2020; Danillidis et al., 2022). However, realizing the full potential of geothermal energy will require continued investment, innovation, and collaboration among stakeholders across the region.

Multi-criteria analysis (MCA) is a valuable tool in the characterization of shallow hydrothermal systems, particularly when considering factors such as CO_2 emissions and subsurface temperature distribution. By integrating multiple criteria into the decision-making process, MCA enables stakeholders to assess and prioritize various aspects of shallow hydrothermal projects, thereby facilitating informed and sustainable development strategies.

One of the key criteria considered in MCA for shallow hydrothermal characterization is the impact on CO_2 emissions. As the world transitions towards low-carbon energy sources to mitigate climate change, evaluating the greenhouse gas footprint of different energy options becomes crucial. Shallow hydrothermal systems offer the potential to significantly reduce CO_2 emissions compared to fossil fuel-based heating and cooling technologies. By harnessing the heat stored in the shallow subsurface, these systems can provide renewable energy for heating, cooling, and power generation with minimal carbon emissions. MCA allows decision-makers to quantify and compare the CO_2 emissions associated with shallow hydrothermal projects against alternative energy sources, helping prioritize investments in projects with the greatest carbon mitigation potential.

Another important criterion in geothermal characterization is the distribution of subsurface temperatures. Understanding the spatial variability of temperature gradients within the subsurface is essential for identifying suitable locations for geothermal development. High subsurface temperatures indicate areas with greater heat potential, making them favorable sites for geothermal energy extraction. MCA can integrate geospatial data, geological surveys, and numerical modeling techniques to assess the temperature distribution across a region and identify optimal sites for shallow hydrothermal projects. By considering factors such as geological structure, hydrothermal activity, and thermal conductivity of rock formations, MCA helps stakeholders make informed decisions about resource allocation and project planning.

Furthermore, MCA enables the integration of additional criteria relevant to geothermal characterization, such as economic viability, technical feasibility, environmental impact, and social acceptance. By incorporating stakeholder preferences and objectives into the decision-making process, MCA facilitates a holistic assessment of geothermal projects, considering diverse interests and perspectives. This participatory approach helps build consensus among stakeholders, fosters transparency in decision-making, and promotes sustainable development of geothermal resources.

Methodology

Multi-criteria analysis (MCA) is a decision-making technique used to evaluate and compare alternative options across multiple criteria or factors simultaneously. It provides a structured framework for decision-makers to assess the relative importance of various criteria and their respective performance levels for each alternative. MCA involves the collect of data and systematic process of defining criteria, assigning weights to them based on their significance, scoring alternatives against these criteria, and synthesizing the results to facilitate informed decision-making. By considering multiple dimensions of a decision, MCA helps stakeholders navigate complex trade-offs and select the most suitable option that best aligns with their objectives and preferences.

Data collection

Two categories of data were considered: i) surface and ii) subsurface data. Surface data collection consists of a large analysis on the CO_2 production from industries using the STATENT dataset. This task was performed by the Energy Efficiency group led by Pr. Martin Patel at UNIGE and delivered to the GE-RGBA group.

Subsurface data are key elements to identify potential exploration areas. Subsurface maps in Switzerland cover a large panel of data e.g., geological layers, temperatures, thermal gradient, faults and thrusts, reservoir properties. First, bibliographic research was carried out leading to the collection of all available scientific report and articles, research manuscript and public report available on the Swiss Molasse Plateau.
Numerous data, such as maps, are available in numerical format in the public domain and accessible through the Swiss Federal Office of Topography (Swisstopo). Several of the

acquired subsurface data are critical to the project such as: geological maps, subsurface geological unit depth, isotherms and geological unit temperatures, and geophysical data.

Source	Data	Type
swisstopo	Administrative boundaries (Canton, municipalities)	.shp
swisstopo	Deep wells (depth > 500 meters)	.shp
swisstopo	Depth of geological units	.tif
swisstopo	Temperature of geological units	.tif
swisstopo	Heat flux	.shp
UNIGE	Atlas of Deep wells (depth > 500 meters)	.shp
UNIGE	Atlas of 2D Seismic lines 2020 (private)	.shp
UNIGE	Lithology of geological units	reports

Multi-criteria Analysis (MCA)

The integration of data includes several steps to produce a visualization of the most suitable areas (Fig 2). The workflow used consists of:

- Geoprocessing of raw vectors to produce clipped, difference, or intersected maps when necessary.
- Raster manipulations such as re-projection, rasterization of vector data, or extraction of data to produce new maps.
- Weighting of the data, i.e. give a weight to each parameter related to their importance in the analysis and their uncertainty.
- Proximity analysis on key parameters, i.e. "how close is the infrastructure from a potential prospect".
- Normalization of the data on a common scale
- Overlay analysis of the surface and subsurface data to produce the MCA maps.

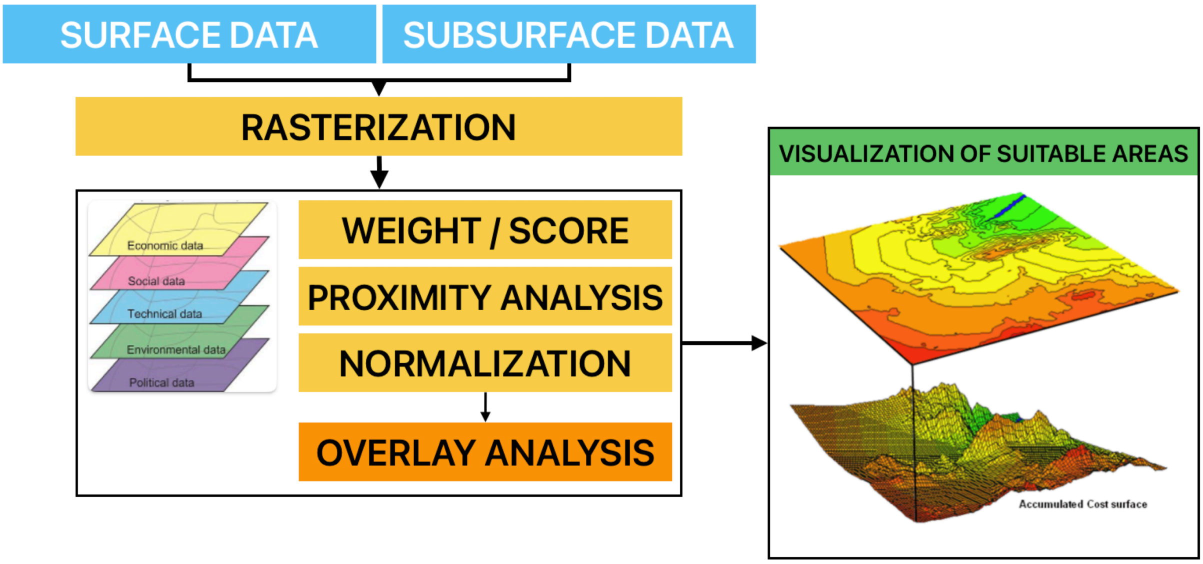

Figure 2 - Workflow used to perform the MCA in the context of DeCarbCH.

To perform the MCA, all vector data needs to be converted to raster format. To do so the "gdal:rasterize" algorithm was used (https://gdal.org/programs/gdal_rasterize.html).

Rasterization was performed using a set of fixed parameters:

Raster size units: georeferenced units.
Width/horizontal resolution: 100 m.
Height/vertical resolution: 100 m.
Output extent: 2485424.9917,2768423.9467,1109585.9740,1287413.9389
Nodata value: not set.
Output CRS: EPSG:2056 - CH1903+ / LV95.
Output format: Flot32 GTiff.

Buffer generation was done using the “native:buffer” QGIS algorithm (https://docs.qgis.org/3.34/en/docs/user_manual/processing_algs/qgis/vectorgeometry.html#buffer). Parameters used:

Distance: number of meters depending on dataset.
Segments: 5.
End cap: round.
Join style: round.
Miter limit: 2.

Proximity analysis was performed using the “gdal:proximity” algorithm. This analysis generates a raster proximity map indicating the distance from the center of each pixel to the center of the nearest pixel identified as a target pixel. Target pixels are those in the source raster for which the raster pixel value is in the set of target pixel values (https://gdal.org/programs/gdal_proximity.html). The following parameters were used:

Distance units: georeferenced units.
Maximum distance to be generated: depending on the dataset.
Value applied to all pixels that are within the -maxdist of target pixels: 0.
Nodata value: not set.

Raster calculation was performed using the QGIS “native:rastercalc” algorithm (https://docs.qgis.org/3.34/en/docs/user_manual/processing_algs/qgis/rasteranalysis.html#qgisrastercalc).
The parameters used were:

Expression: raster calculation formulas
Output extent: 2485424.9917,2768423.9467,1109585.9740,1287413.9389
Output CRS: EPSG:2056 - CH1903+ / LV95.

Before the final raster calculation is computed, all rasters are normalized mathematically on scale from 1 to 10 to illustrate the favorability. Normalization was either done in the raster calculator algorithm using the mathematical formula for normalization for custom range:

$$Rnorm = (b-a)*((x-Rmin)/(Rmax-Rmin))+a$$

Where a and b are the lower and upper ranges, Rmin and Rmax are the minimum and maximum values of the raster.
Otherwise, we normalized using the QGIS “native:rescaleraster” algorithm (https://docs.qgis.org/3.34/en/docs/user_manual/processing_algs/qgis/rasteranalysis.html#qgisrescaleraster).

Subsurface and surface characteristics

Geology of the reservoir units in the Swiss Plateau

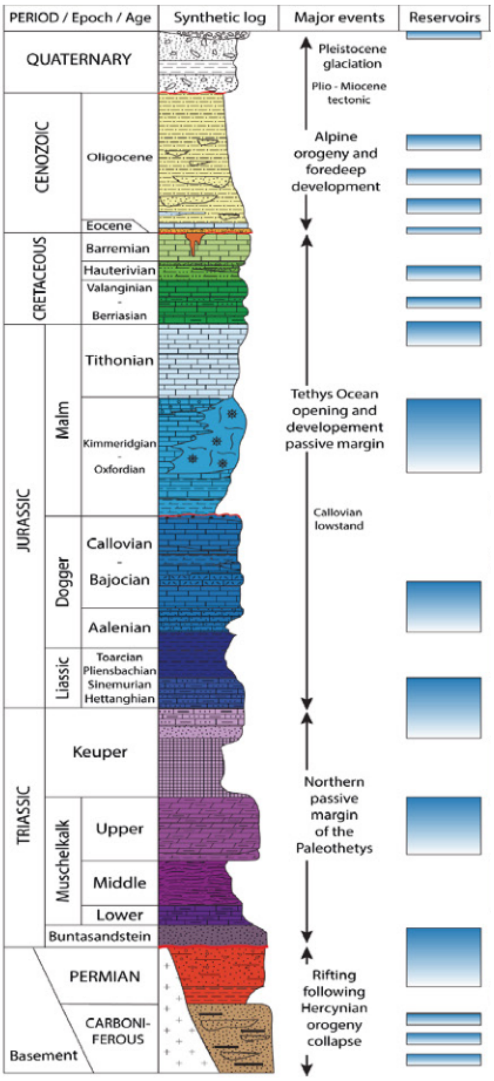

Figure 3 - Geological units and known reservoirs in the Swiss Plateau. Modified from Moscariello 2019.

The geology of the Swiss Plateau consists mostly of a thick Mesozoic sedimentary succession (Fig. 3), made of evaporites at the base and a succession of thick carbonates and marls succession formed at the southern margin of the European continent on the northern margin of the Tethys Ocean. The Mesozoic sequence was deposited on top of a Paleozoic crystalline basement with down-dropped graben filled with continental siliciclastic sediments of Permian and Carboniferous age because of the Variscan orogeny and rifting linked to post-orogenetic collapse. The top of the Mesozoic sequence (Lower Cretaceous in age) is marked by a regionally extensive erosional surface which formed during the general uplift of the foreland basin during the Alpine compression. Above this surface, Oligocene siliciclastic Molasse are overlain by heterogeneous Quaternary glacial and glaciofluvial deposits.

Fracture networks in the Mesozoic sequence seem to represent important features to guarantee good storage capacity although their connectivity is equally important to provide enough permeability to the geothermal system. Recent studies focused on characterization of Mesozoic reservoirs (Rusillon, 2018, Brentini, 2018, Makhloufi et al., 2017; Rusillon and Chablais, 2017, Ferreira De Oliveira et al., 2020; Makhloufi and Samankassou, 2019) indicate that matrix porosity and permeability vary considerably depending on primary sedimentary processes and especially secondary diagenetic overprint.

Based on current knowledge the Triassic and Jurassic series, mostly formed by carbonate successions intercalated with marls, show matrix porosity in the range of 2-5% with exceptions in the clastic Buntsandstein (Lower Triassic) reaching 10-15% (Rusillon, 2018). Matrix permeabilities varies between 0.01 and 1 mD (milli-Darcy) with exception in the Buntsandstein and dolomitized Muschelkalk (Middle Triassic) reaching 100 mD. Primary reservoir targets represented by high porosity/high permeability layers may be represented by the reef complex of the Upper Jurassic, Kimmeridgian age as demonstrated in the Munich area (Germany) in the Bavarian Molasse Basin (Lüschen et al., 2014) where a combination of karst and fracture can assure excellent reservoir properties. The Lower Cretaceous units, despite having higher lithological variability including coarser grain sizes associated with the development of more heterogeneous sedimentary environments at the time of deposition (i.e. tidal inlets) compared to the Jurassic series, the reservoir properties also show porosity <8% and permeability ranging between 0.001 and 10 mD. Reservoir properties improve considerably when considering the Cenozoic series consisting of both Eocene and Oligocene units which have not experienced the same burial history as the older strata (Schegg and Leu, 1996; Moscariello et al., 2019 a, b). These units may contain very effective reservoirs although continuity and extension may be an issue for the Eocene and Oligocene. On the other hand, reservoir extension and continuity for the Oligocene continental Molasse, while it is considered higher than the Eocene units, it is still controlled by the dimensions and connectivity of channelized bodies occurring within the sequence. Porosity and permeability in these units have values ranging between 5-35% and 1-1000 mD, respectively.

Depth and faults of the different reservoirs identified.

The temperatures of a given reservoir is in part controlled by its depth as temperature increases at a relatively consistent rate of around 25 to 30 °C/km in the subsurface. Depths of the main subsurface reservoirs has been mapped by extracting the top surfaces of each reservoir from the GeoMol model. The GeoMol model is the outcome of a collaboration between the Swiss Oil Company (SEAG), the National Cooperative Society for Radioactive Waste Storage (Nagra), the universities of Geneva, Fribourg, Bern, Basel, the Swiss Federal Institute of Technology in Zurich (ETHZ), and the industrial services of the City of St. Gallen.

Reservoir can be affected by faults playing a crucial role in geothermal systems. Faults can:

- act as conduits for fluids allowing geothermal fluids to migrate from deeper, hotter regions to shallower reservoirs.
- create or enhance permeability within the subsurface rock formations. When faults intersect with permeable rock layers, they can create fractured zones that act as reservoirs for geothermal fluids. These fractured zones provide pathways for the circulation of fluids, allowing for efficient heat extraction.
- can facilitate heat transfer within the subsurface. As hot fluids circulate through fractured zones along faults, they transfer heat to surrounding rock formations. This process helps to heat up reservoirs and maintain high temperatures, enhancing the productivity and longevity of geothermal systems.
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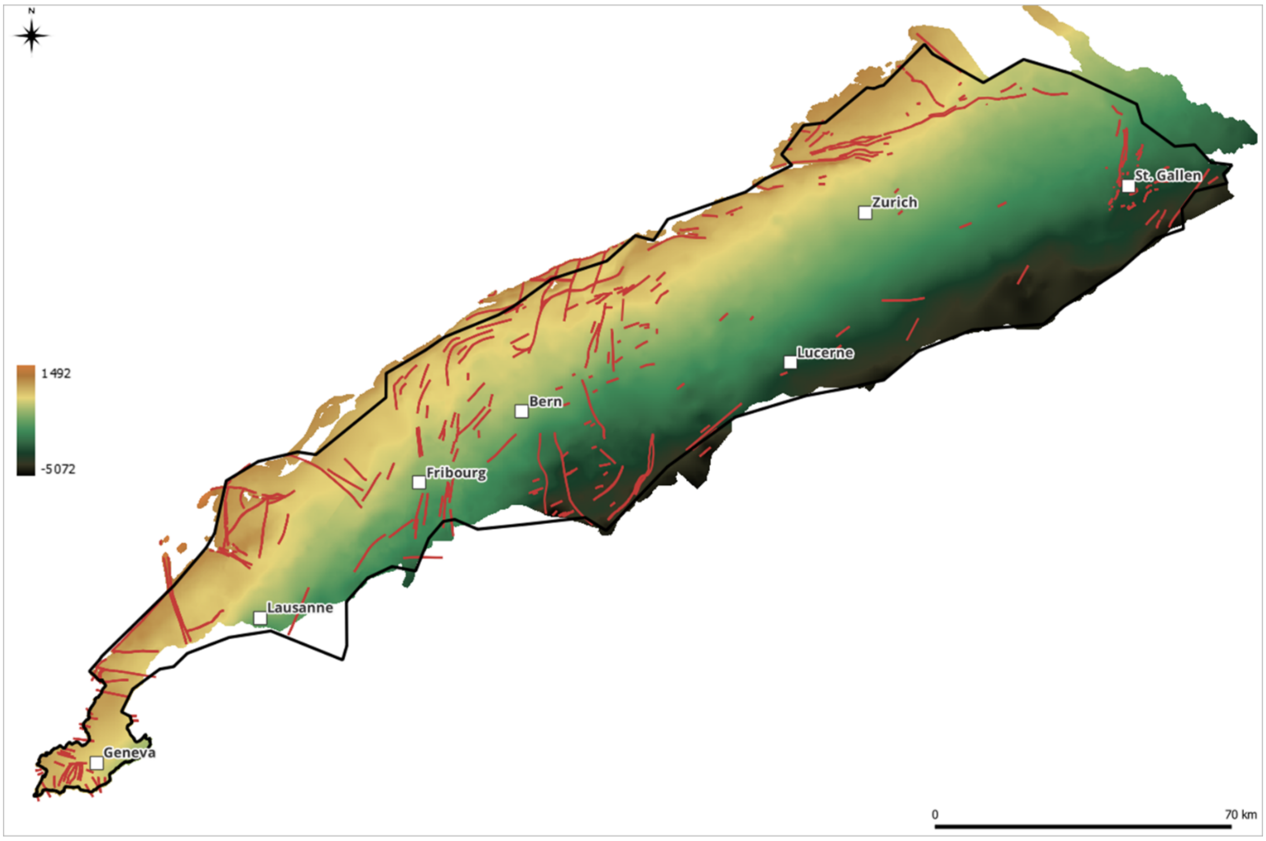

Figure 4 – Elevation above sea level of the base Cenozoic. Faults are displayed in red.

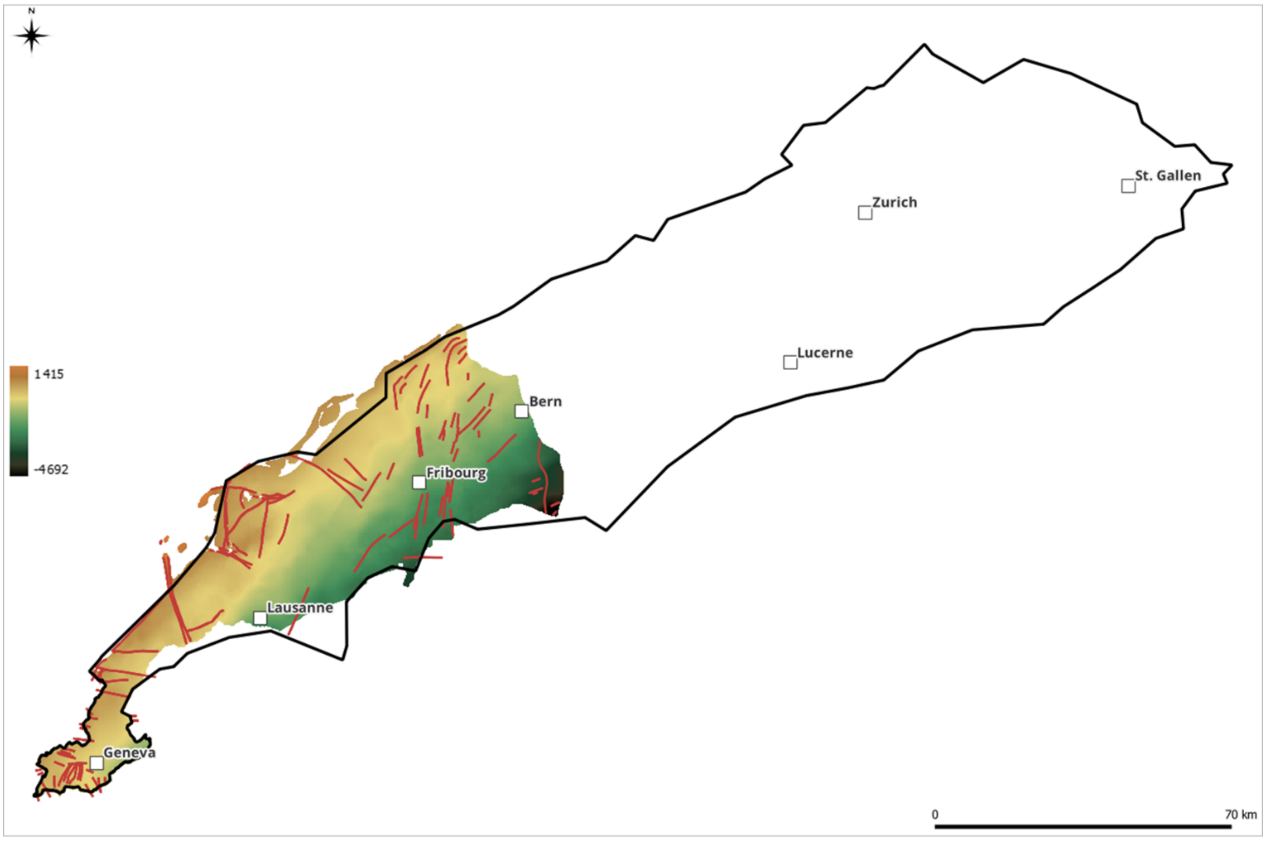

Figure 5 - Elevation above sea level of the top Cretaceous. Faults are displayed in red.

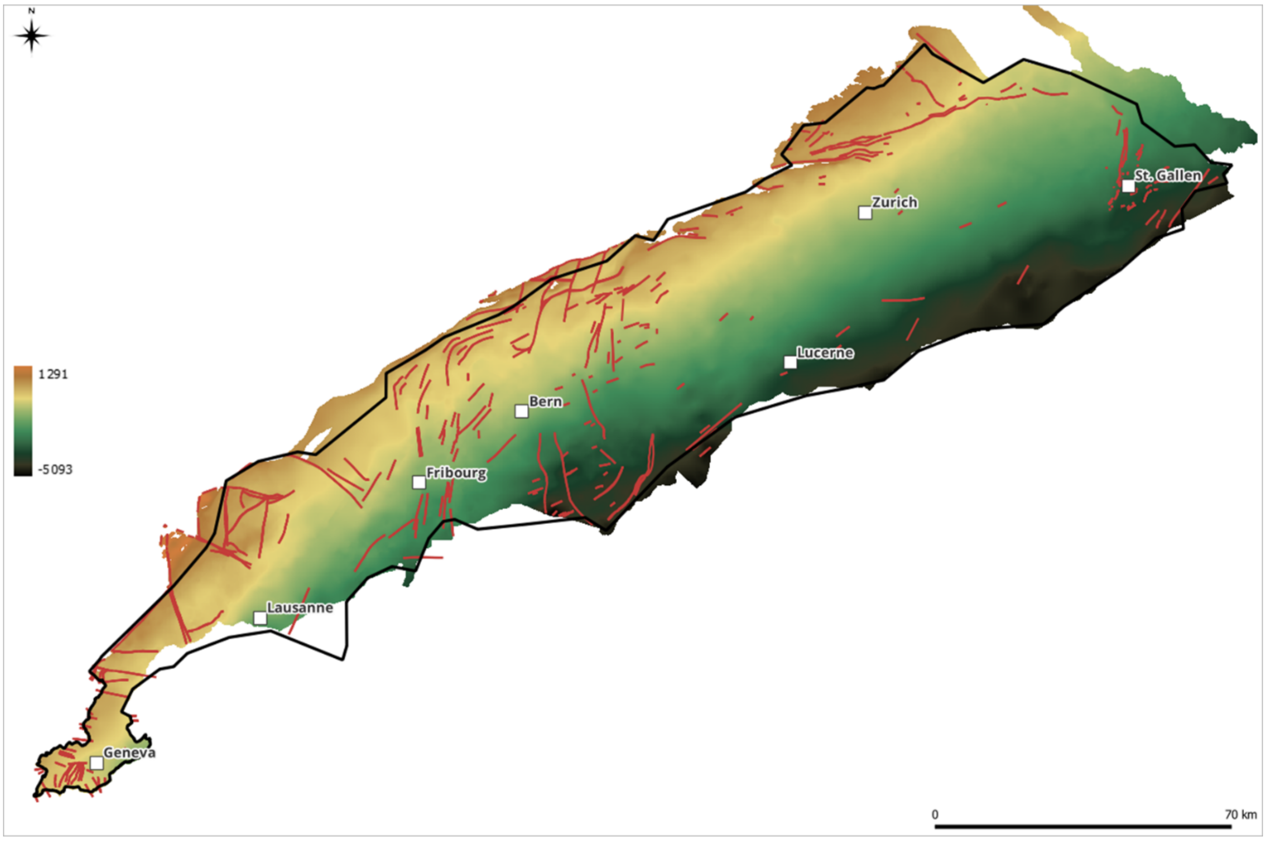

Figure 6 - Elevation above sea level of the top Upper Jurassic. Faults are displayed in red.

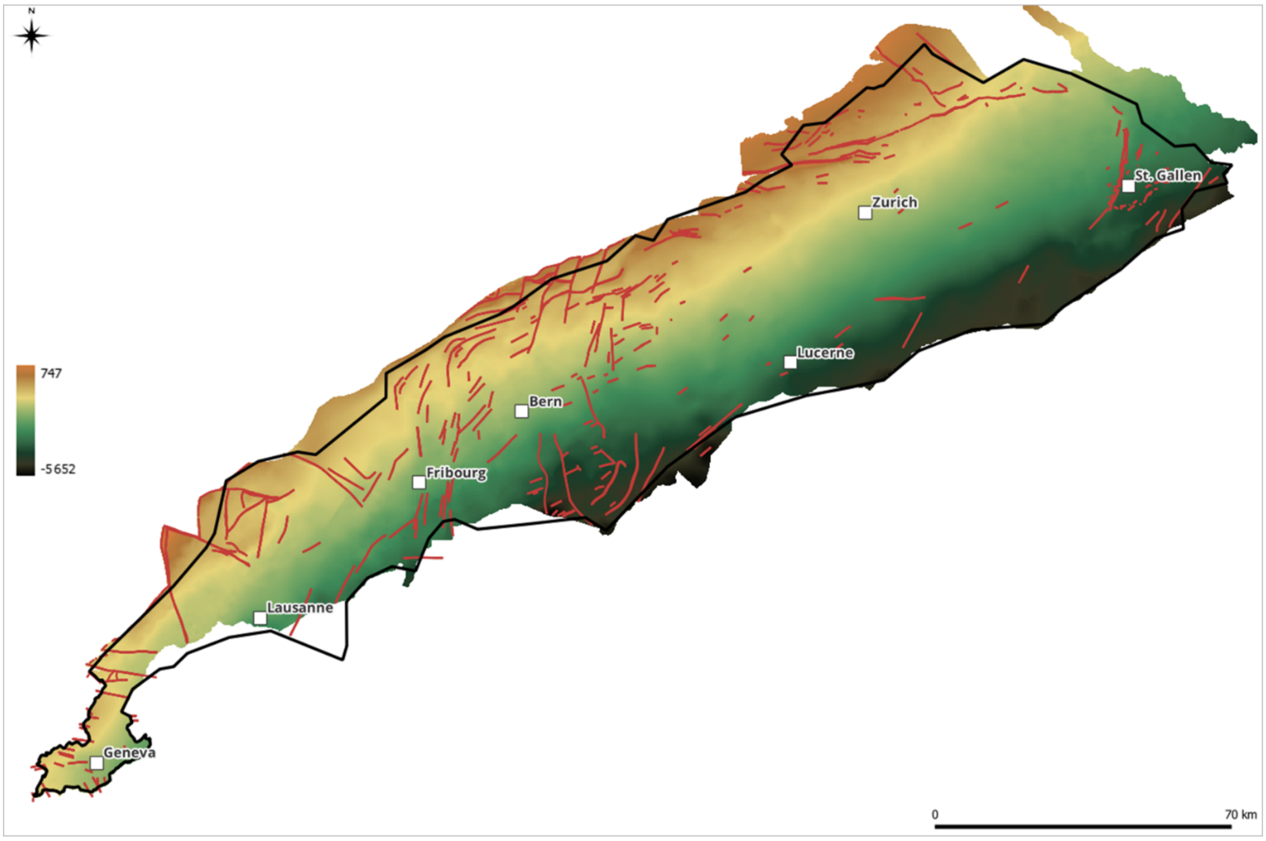

Figure 7 - Elevation above sea level of the top Middle Jurassic. Faults are displayed in red.

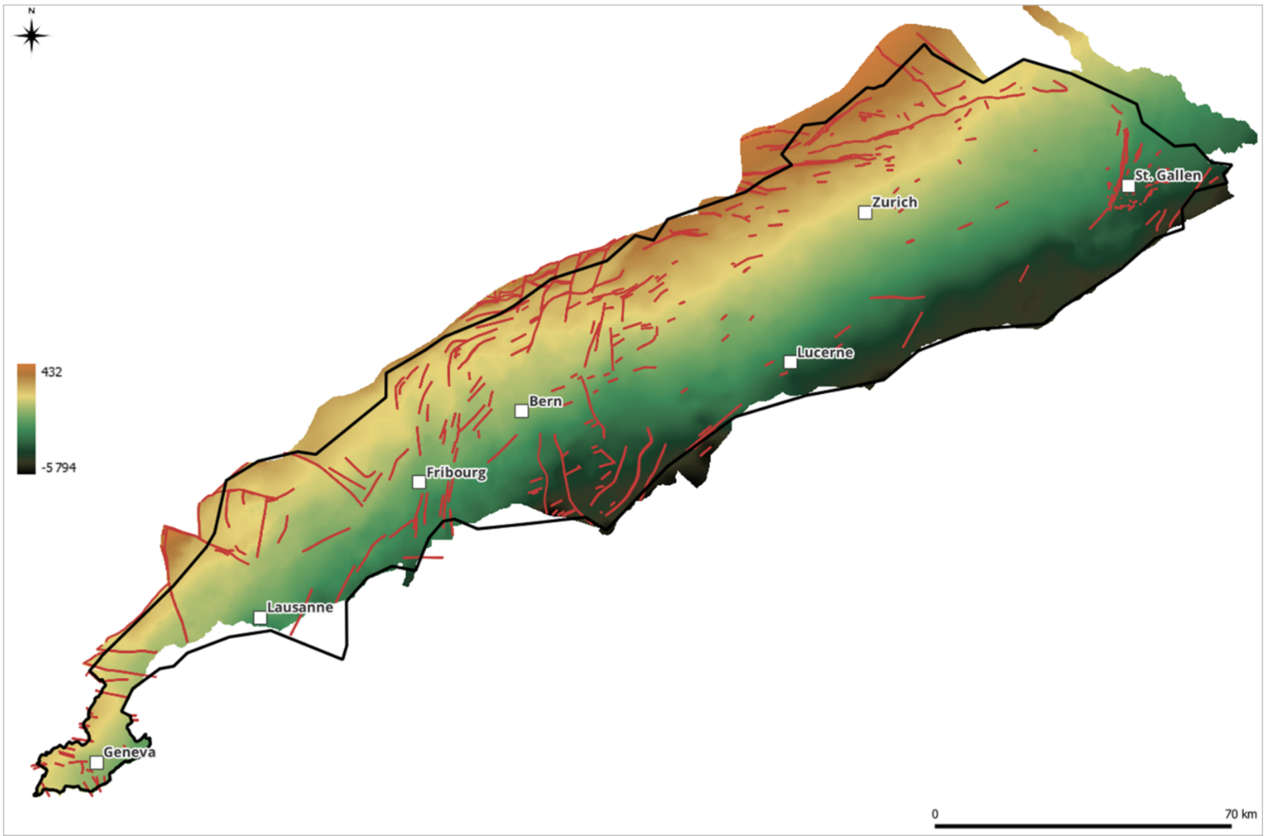

Figure 8 - Elevation above sea level of the top Lower Jurassic. Faults are displayed in red.

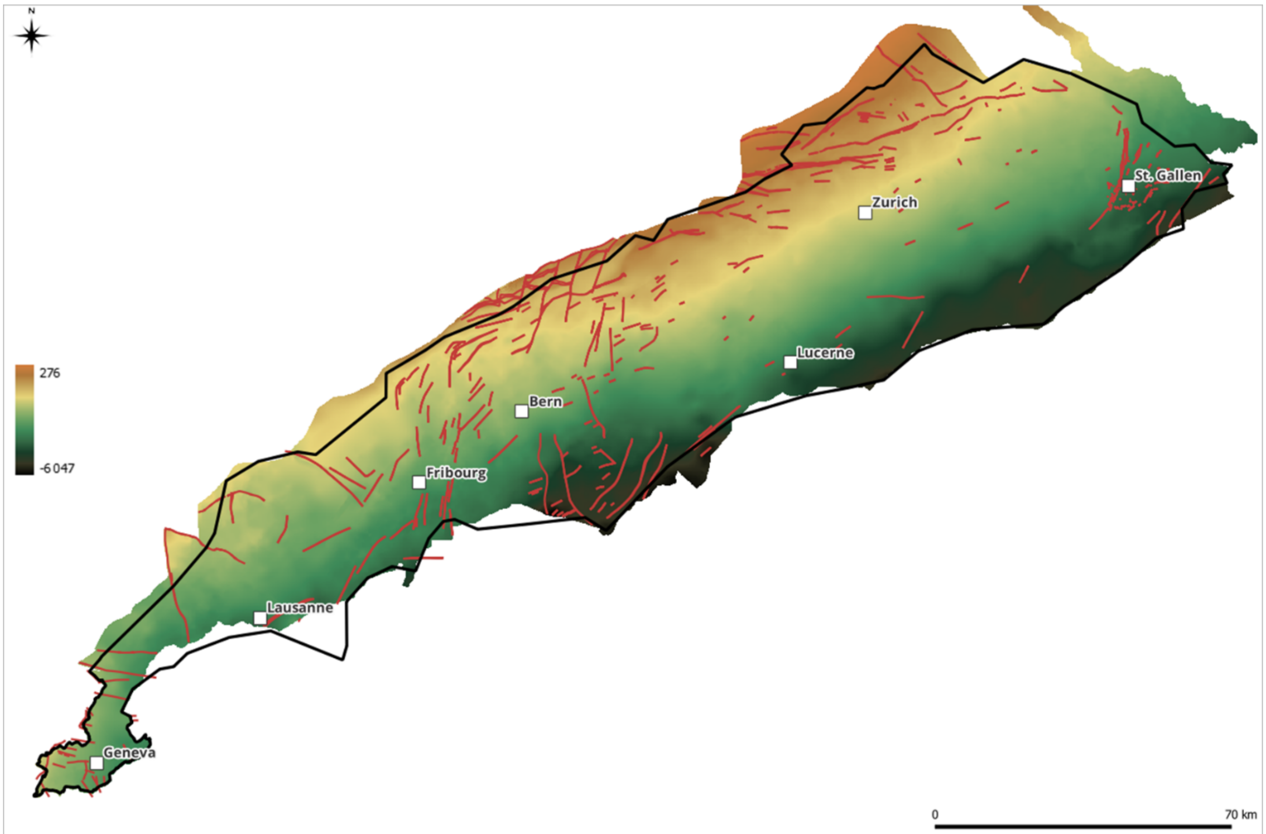

Figure 9 - Elevation above sea level of the top Middle Triassic. Faults are displayed in red.

In the context of DeCarbCH, the focus is made on shallow hydrothermal systems. Therefore, a cut off has been applied to the dataset to assess reservoirs with depths ranging from 0 to -1000 m.

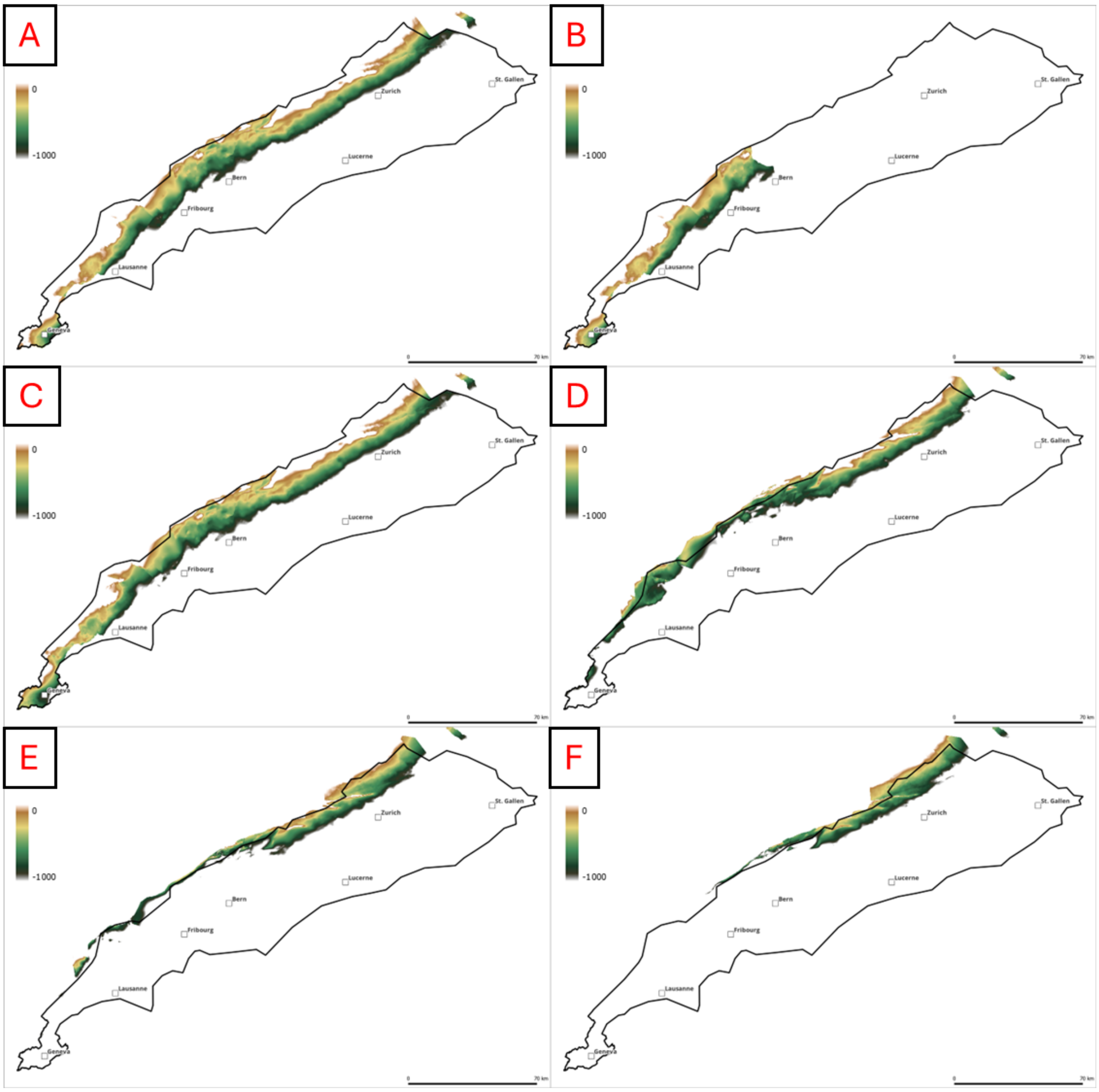

Figure 10 - Elevation from 0 to -1000 m in the different reservoirs identified. A: base Cenozoic, B: top Cretaceous, C: top upper Jurassic, D: top middle Jurassic, E: top lower Jurassic and F: top middle Triassic.

As shown in Fig. 10, the shallow part of the identified reservoirs is mainly localized in the northern part of the Swiss Plateau. This is due to the geological configuration of the Swiss Plateau where geological units are shallower towards the Jura and dip towards the Alps.

Temperature distribution in the subsurface.

In the subsurface, temperature distribution is governed by the Earth's geothermal gradient, which causes temperatures to increase with depth at an average rate of 25 to 30 °C/km. However, this gradient can be influenced by local geological conditions, including rock composition, thermal conductivity, and heat flow. Areas with higher heat flow, such as volcanic regions or tectonically active zones, may experience elevated temperatures at shallower depths. Additionally, hydrothermal systems, driven by the circulation of hot fluids through fractures and faults, can locally enhance temperatures in shallow geological formations. Surface conditions, such as seasonal variations and climate, can also impact temperature distribution near the Earth's surface but diminish with depth.

Temperature models are available in the GeoMol model but only for 3 geological units: the upper Marine Molasse, the upper Jurassic and the middle Triassic. To produce temperature maps for the reservoirs considered in this project we decided to apply a simple geothermal gradient model over the complete Swiss Plateau. Calculation of the temperature model follows the equation:
*12 + "depth of the reservoir" * 0.03*
This equation applies a geothermal gradient of 0.03 °C/m considering a mean surface temperature of 12°C.
For each map isotherms have been calculated. The isotherms at 30, 70 and 120°C are displayed in yellow, orange, and red respectively.

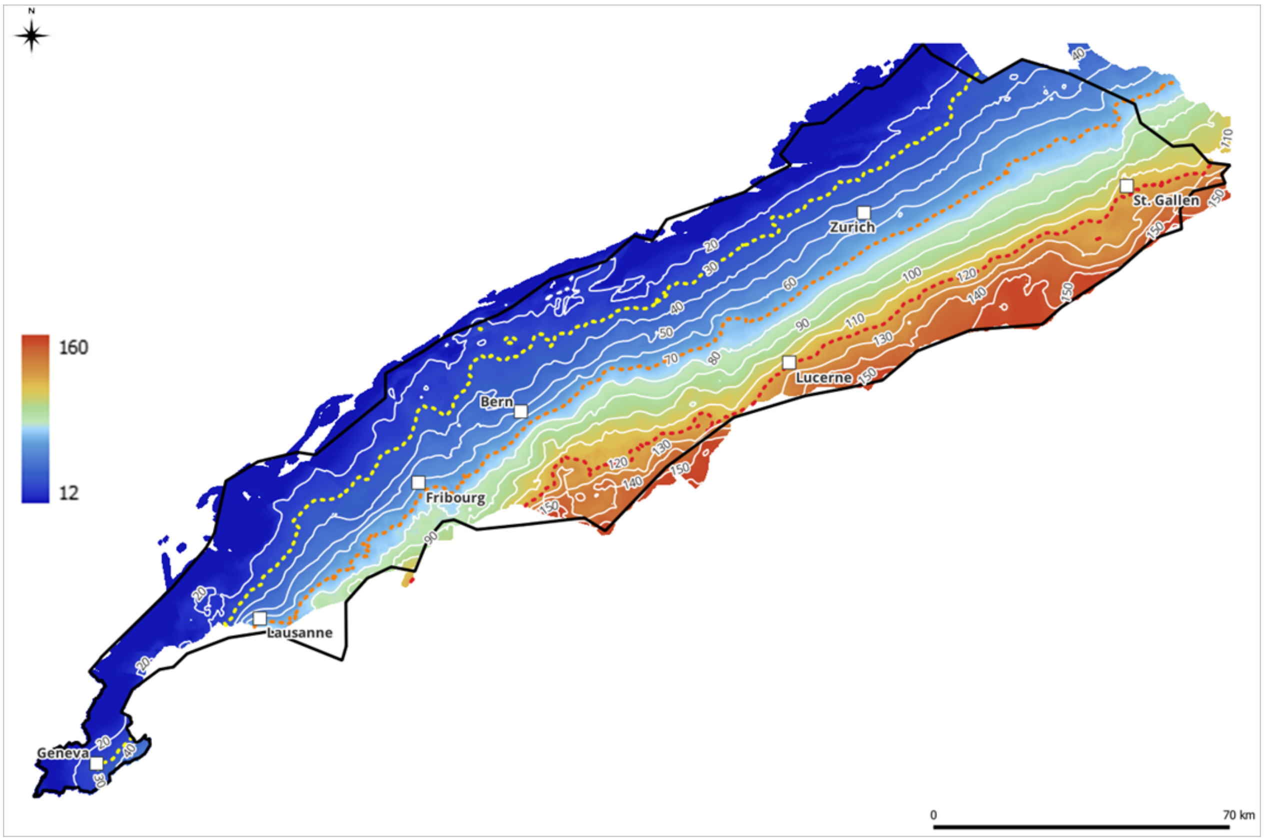

Figure 11 - Temperature distribution at the base of the Cenozoic (°C).

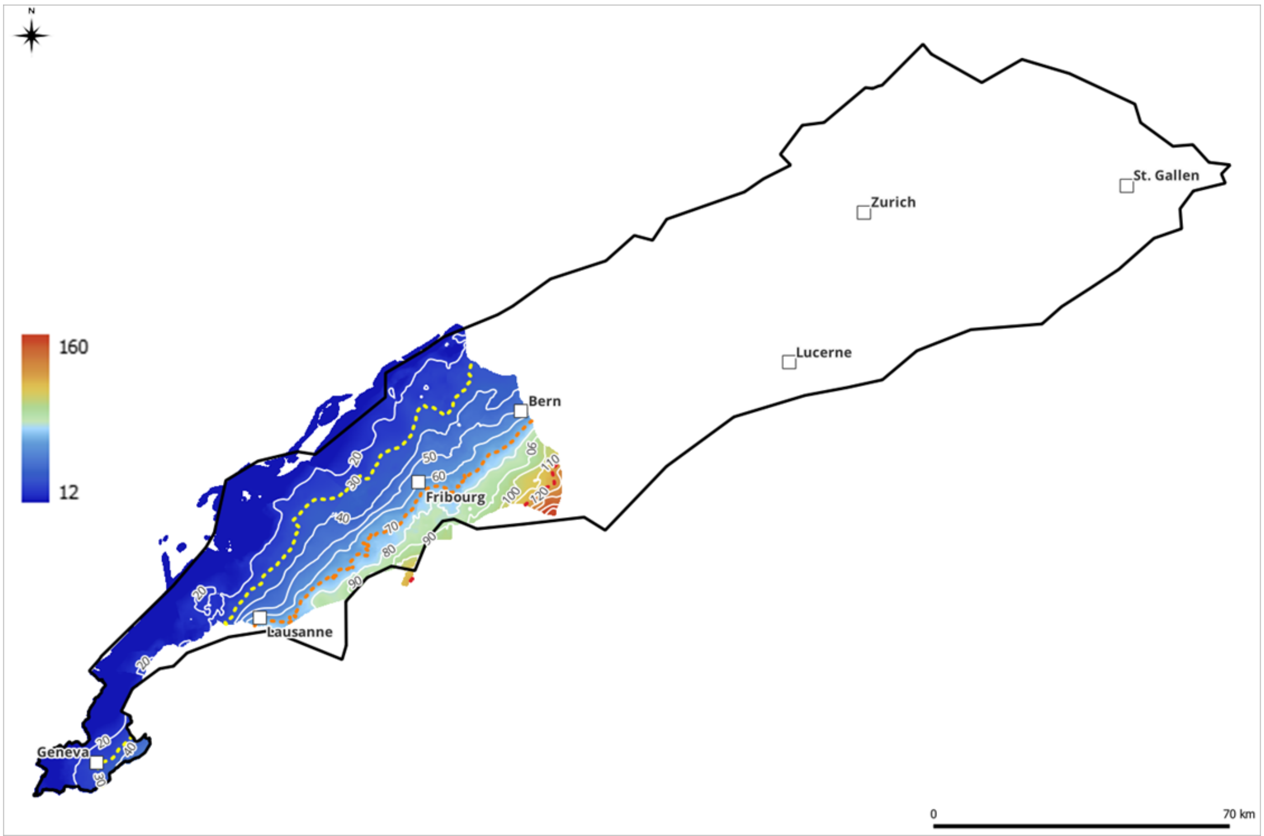

Figure 12 - Temperature distribution at the top of the Cretaceous (°C).

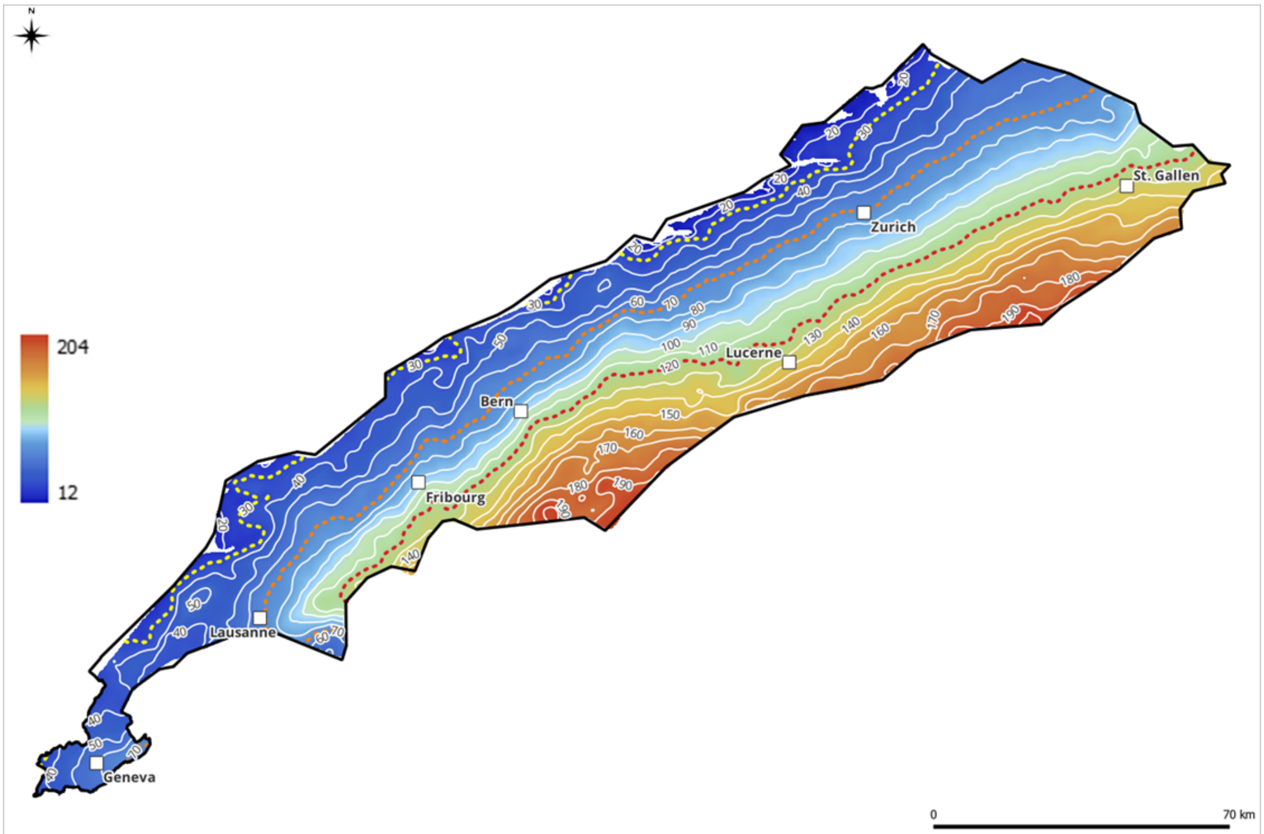

Figure 13 - Temperature distribution at the top of the upper Jurassic (°C), source: swisstopo, GeoMol temperature model.

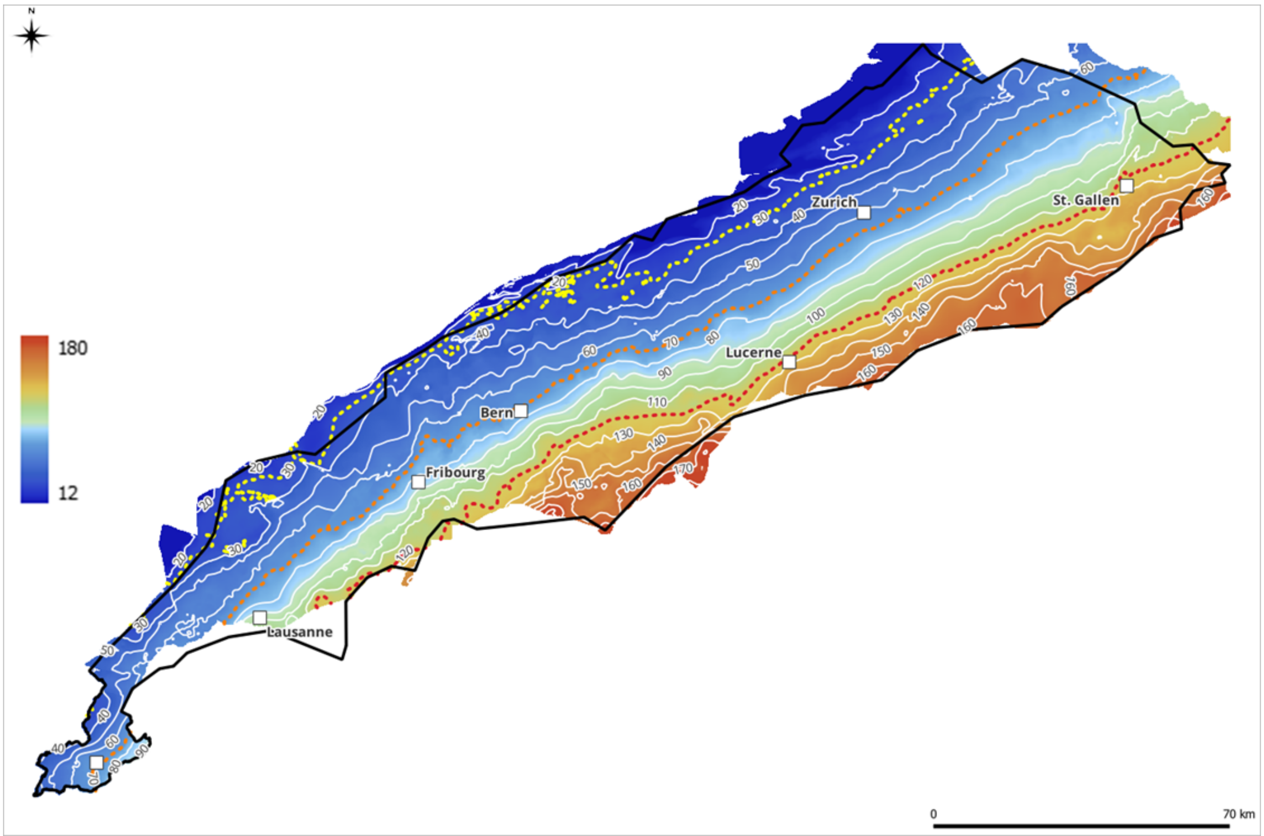

Figure 14 - Temperature distribution at the top of the middle Jurassic (°C).

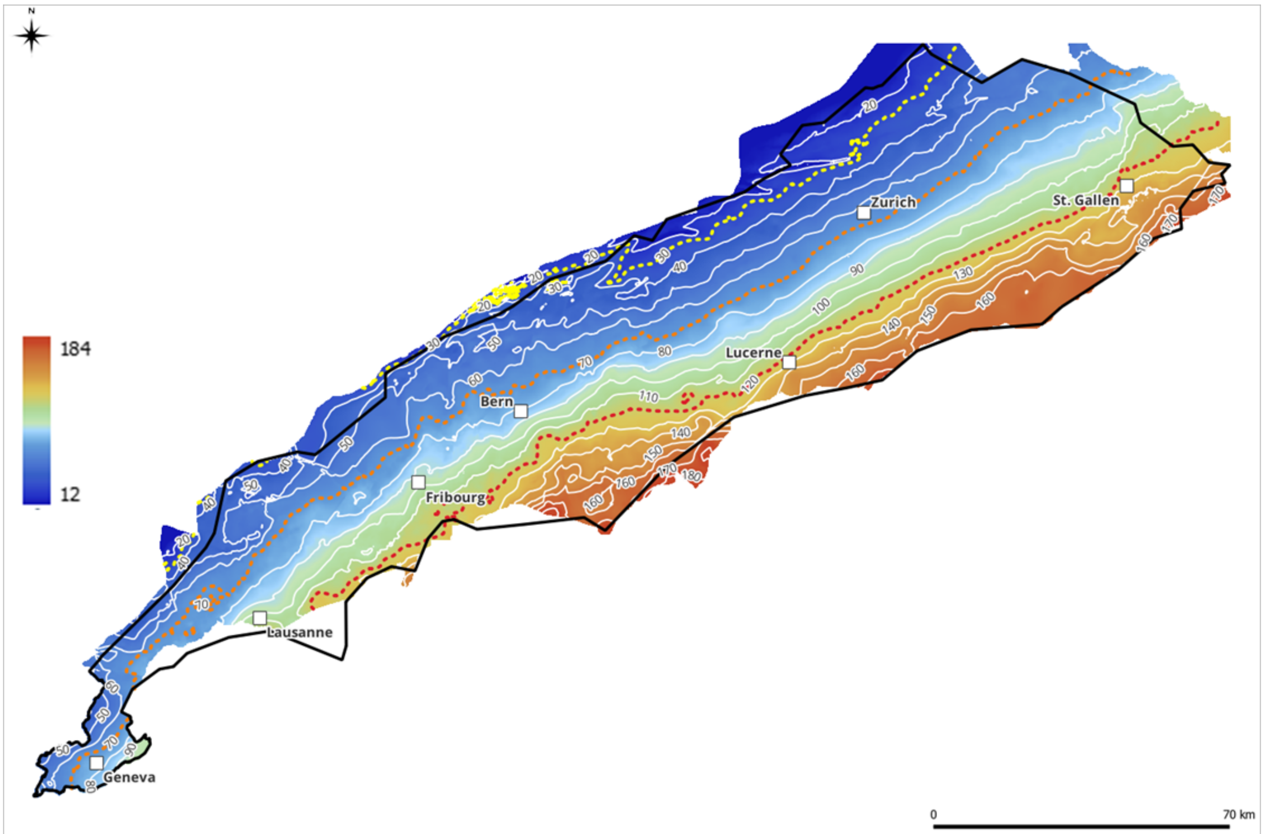

Figure 15 - Temperature distribution at the top of the lower Jurassic (°C).

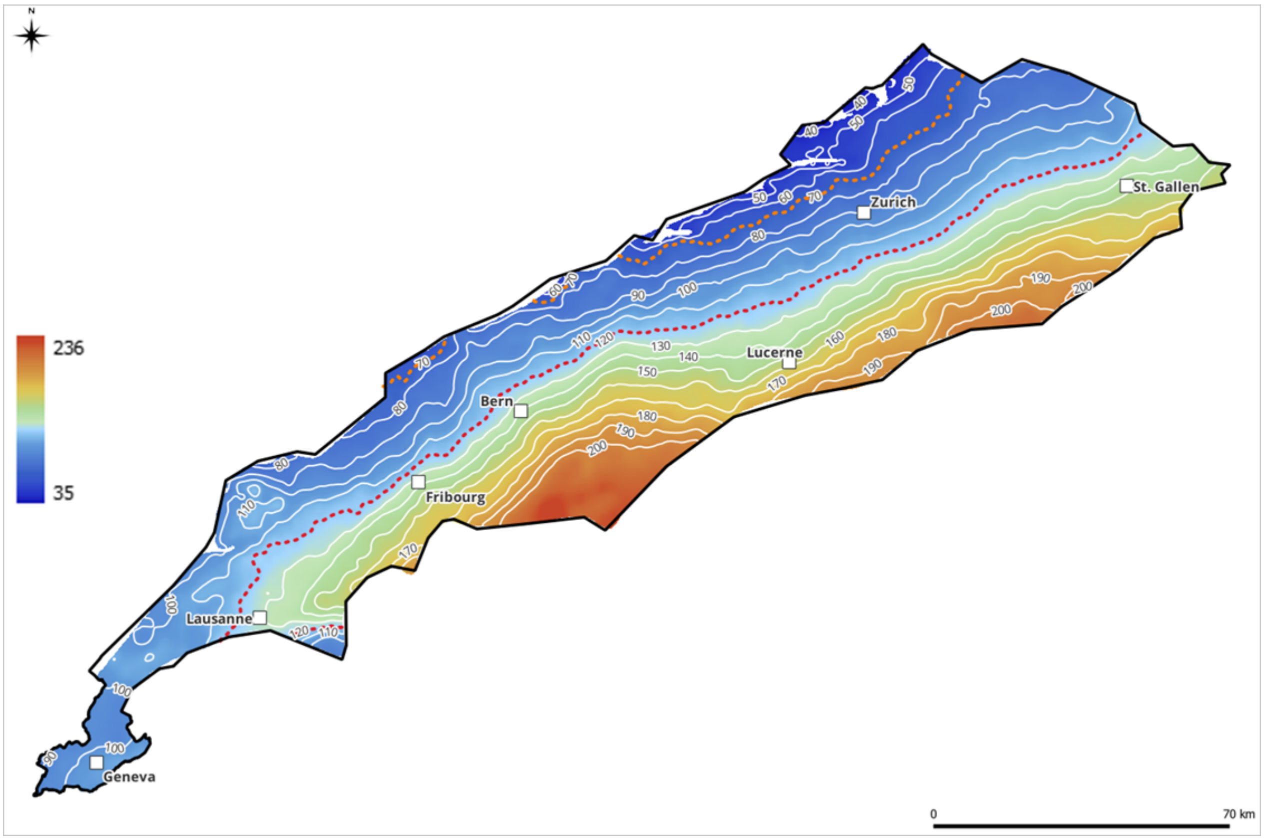

Figure 16 - Temperature distribution at the top of the middle Triassic (°C), source: swisstopo, GeoMol temperature model.

Temperature distribution across the different reservoirs directly relates to their stacking and increasing depth. The isotherms emphasized (30, 70 and 120°C) were chosen as they represent main application for geothermal use:

- Upon achieving 30°C, shallow geothermal systems coupled with heat-pumps can be implemented.
- At higher temperatures close to 70°C direct use of geothermal energy into district heating networks can be implemented.
- Above 100°C and especially at the 120°C threshold, power generation associated to direct use can be implemented.

Temperature maps are also available at threshold depths. As most of the reservoirs in the Swiss Plateau are represented by similar lithologies (mostly carbonates) and with low porosity/permeability, another way of exploring for suitable geothermal resources could be to focus on certain depths targets. As drilling cost increases with depths, focusing on a target shallow depth could help in reducing implementation costs while targeting suitable temperatures in shallow subsurface reservoirs.

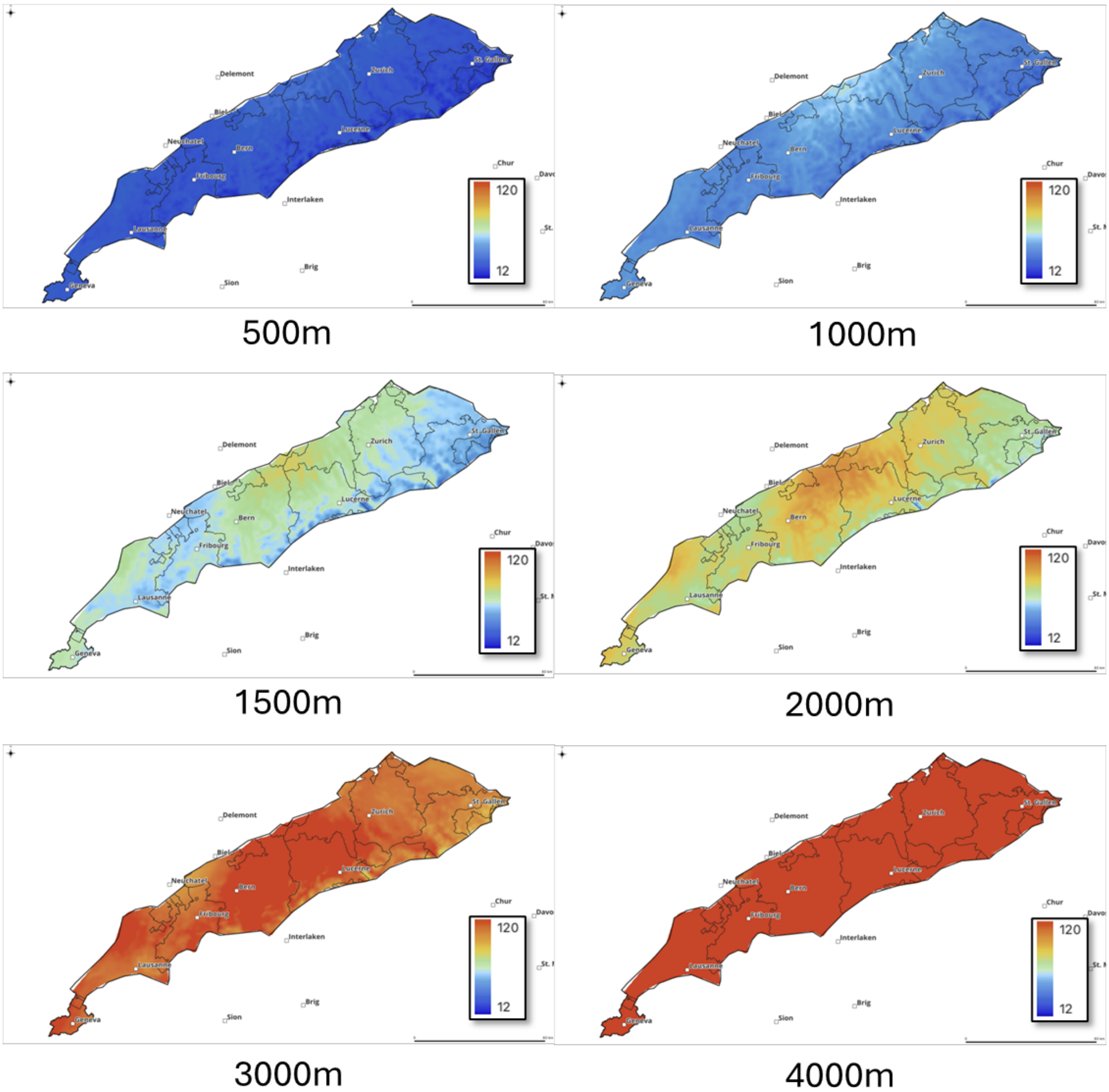

Figure 17 - Temperature distribution at given depths in the Swiss Plateau.

In Fig. 17, the legend has been normalized from 12 to 120 °C. Higher temperatures can be achieved at greater depths. The limit is set on the 120 °C threshold at which co-generation of power and heat can be implemented.

The maps at 1000, 1500 and 2000 m below ground level exhibits a temperature anomaly centered at the junction of Canton Bern, Canton Luzern and Canton Aargau. In this area, the temperature at a given depths is systematically higher compared to the mean temperatures in the Swiss Plateau. A similar anomaly can be observed in the northern part of Canton Vaud.

CO_2 producers in the Swiss Plateau.

STATENT[1] is a statistic data base of the Swiss Federal Government that provides central information on the structure of the Swiss economy (number of companies, number of establishments, number of jobs, number of full-time equivalent jobs, male-female employment, etc.). STATENT is the successor to the Enterprise and Establishment Census (RE), the last of which was conducted in 2008.
STATENT is based primarily on social insurance registers (AVS registers), which provide information on the number of companies, wages and jobs, and on the Business and Establishment Register (REE), which provides the basic structure of observation units. STATENT also integrates information available from other sources, such as the Enterprise and Establishment Register Update Survey (ERST), Employment Statistics (BESTA) and Profiling.

The STATENT dataset has been used as a proxy for CO_2 emissions by considering that a larger number of employees would indicate a large company with important energy needs. Moreover, the STATENT data set comes with industry types, making it relatable to consider energy intensive industries more susceptible to important CO_2 emissions.

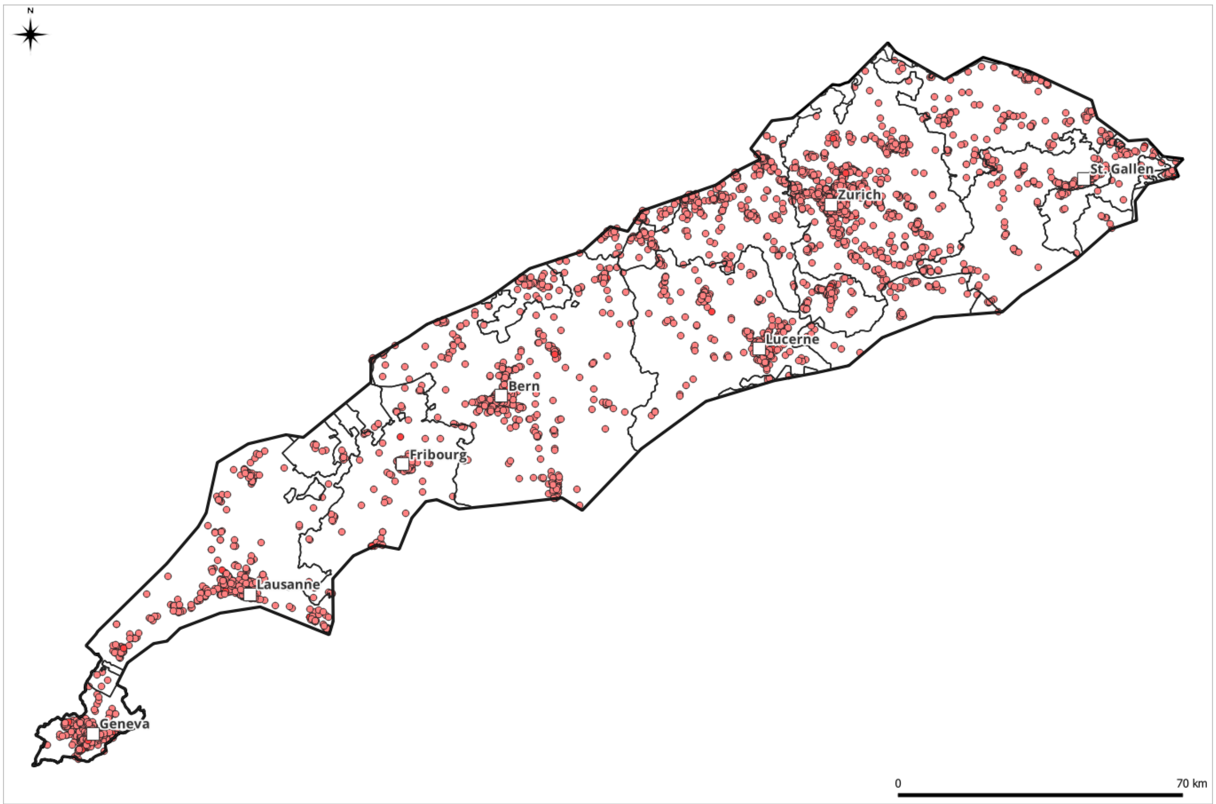

Figure 18 - STATENT data set. Industries with more than 100 employees are represented on the map.

[1] https://www.bfs.admin.ch/bfs/fr/home/statistiques/industrie-services/enquetes/statent.html

Another information than can be used is the heat and cooling demands for the industry. This data set is also derived from the STATENT data and is made available publicly by the SFOE.

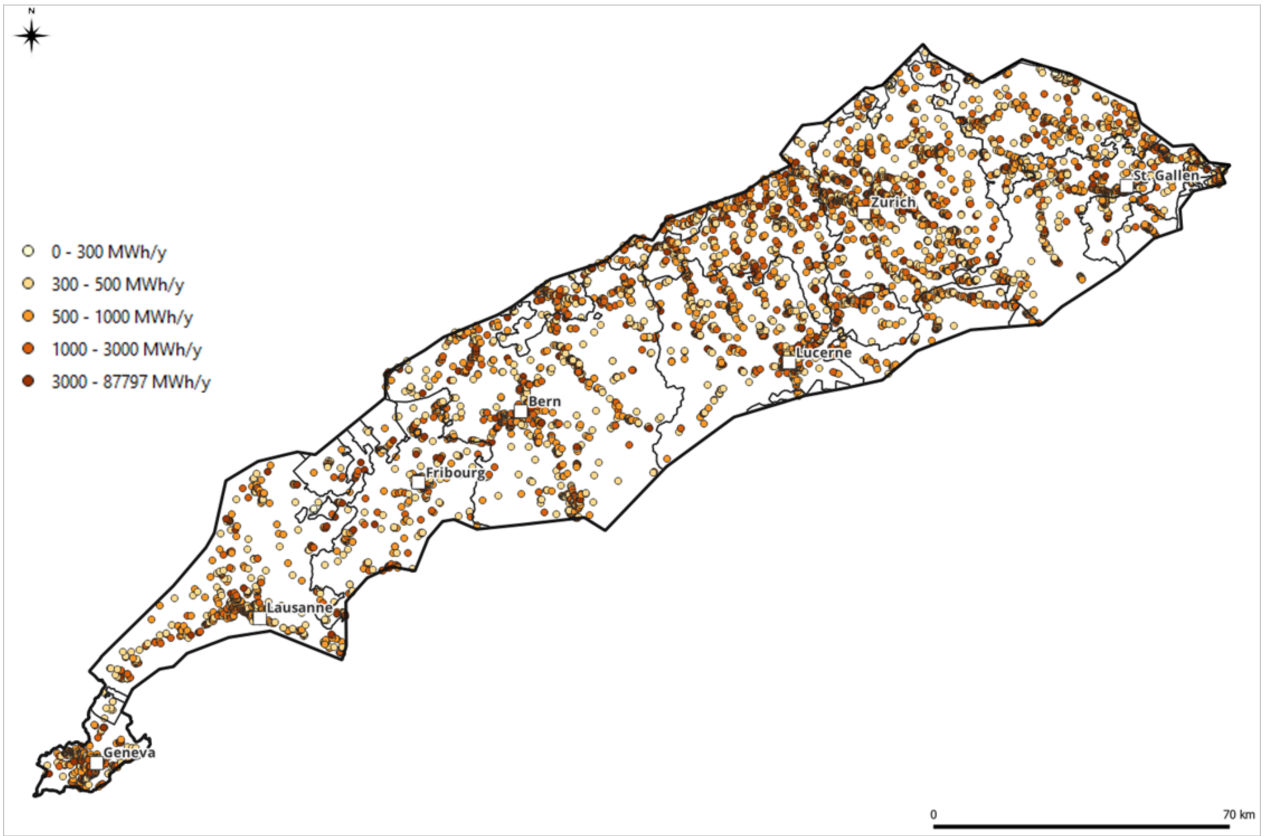

Figure 19 - Industrial heat demands in the Swiss plateau, source: https://www.bfe.admin.ch/waerme-kaeltenachfrage-industrie.

Multi-criteria analysis. Are there suitable areas where CO_2 emissions could be reduced with shallow geothermal?

In the context of geothermal energy planning, MCA can be used by integrating the various factors relevant to resource potential and environmental impact. In the context of this project these are:

- Subsurface Temperatures: subsurface temperature data is integrated to identify regions with high geothermal potential. Areas with elevated temperatures at accessible depths are prioritized for further exploration and development.
- Fault: fault serves as conduits for geothermal fluids and can enhance permeability in underground reservoirs. The MCA incorporates geological data to pinpoint areas where fault networks intersect with high-temperature zones, indicating favorable conditions for geothermal resource exploitation.
- Proximity to CO_2 Emitters: identified location emitting significant CO_2 emissions are integrated as a surface parameter delimiting where geothermal energy should be implemented into the energy demand. Integrating this data allows planners to target areas where geothermal energy deployment can directly offset carbon emissions, thereby maximizing environmental benefits.

Weighting the dataset.

In a multicriteria analysis, weighting the dataset involves assigning relative importance or significance to different parameters being considered. This process is crucial because it allows decision-makers to prioritize certain criteria over others based on their objectives, significance, uncertainty, or the specific context of the analysis.

In the context of DeCarbCH the following weight table was used:

Data	Weight
Temperature	10
Faults proximity	5
Lithology	5
STATENT – Industries > 100 employees	9

Some of the data acquired or produced was not used in the MCA. This corresponds to:

- Depths. As temperature is already a function of depth (by using the geothermal gradient calculation), using this data would be redundant.
- Energy demands. We chose to use the STATENT dataset provided as it is more recent than the publicly available dataset.
- Surface heat-flow. While this data has been used in previous studies, the large uncertainty related to the few data points used to produce the available heat-flow maps would induce an important bias in the analysis.

Proximity analysis.

A proximity analysis has been used on:

- The faults data set. We consider that faults can act as fluid conduits, but their effect is not limited to the fault line. Faults can generate fracture network impacting the host rock at a certain distance from the fault plan called "damage zone". While there is no consensus on the width of the damage zone, it is commonly assumed that its width ranges from 0 to 500 m on each side of the fault plane. We chose a 200 m buffer zone around the fault plane as representative a mean potential damage zone in the identified faults.
- Industry of more than 100 employees (Fig. 20). One of the limitations of geothermal energy is that the resource must be close to the consumer. In fact, as heat is transferred from the subsurface to the consumer, energy loss occurs. Therefore, we try to look for the shortest distance between potential geothermal energy sources and industrial needs. We defined the maximum distance as 5000 m from an industrial site. It means that if a geothermal energy source is further away than 5 km from a potential customer, it is deemed unsuitable.

Data integration in the MCA

All the vector data are rasterized using the same parameters. The grid is set to a resolution of 100x100 in order to stay consistent with swisstopo griding.
Rasters are normalized on a scale from 1 to 10 before being summed after application of their weights in forms of ratios.

The raster formula can be summarized as:
((Temperature * 10) + (Faults * 5) + (Lithology * 5) + (STATENT * 9)) * AREA/29

"AREA" is a simple raster used to delimit the area of computation, it has a value of 1 inside the delimitation of the Swiss Plateau and 0 outside. The 29 refers to the sum of the weights to produce a map normalized a scale from 1 to 10.

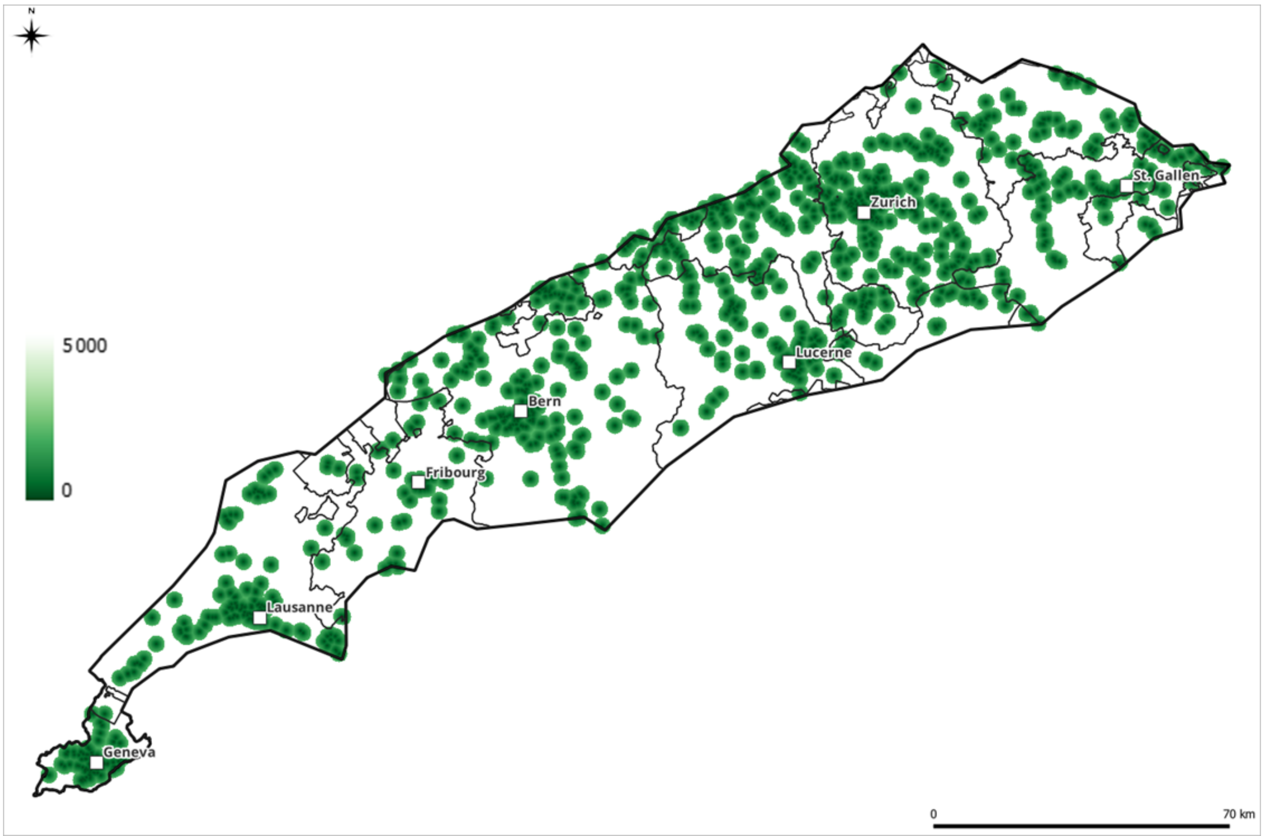

Figure 20 - Proximity (in meters) from industries with more than 100 employees. White areas represent location farther than 5 km from any industries with more than 100 employees.

Results for each geological potential reservoir.

The results of the MCA are presented in the form of "suitability" maps with a score ranging from 1 to 10. At a score of 1, the area is deemed to be of low suitability while an area with a score of 10 is considered as highly suitable.
Using the temperature, faults, lithology and STATENT data for all the identified reservoirs in the Swiss Plateau, is appears that in almost all cases the northern part of the Swiss Plateau is the least suitable. This is due to lower temperatures at depth, explain by the geological configuration of the subsurface units being shallower towards the Jura (and thus colder) and deepening towards the Alps (becoming hotter).

Areas with faults are always ranking better than areas without faults. This emphasizes the need for geological exploration and characterization of faults to assess their potential for fluid transfer.

The most suitable areas are defined as:

- South of the Swiss Plateau where the temperatures are higher at depths,
- Close to industrial demands and CO_2 emitters,
- If possible close to a fault which could potentially ensure geothermal fluid flow.

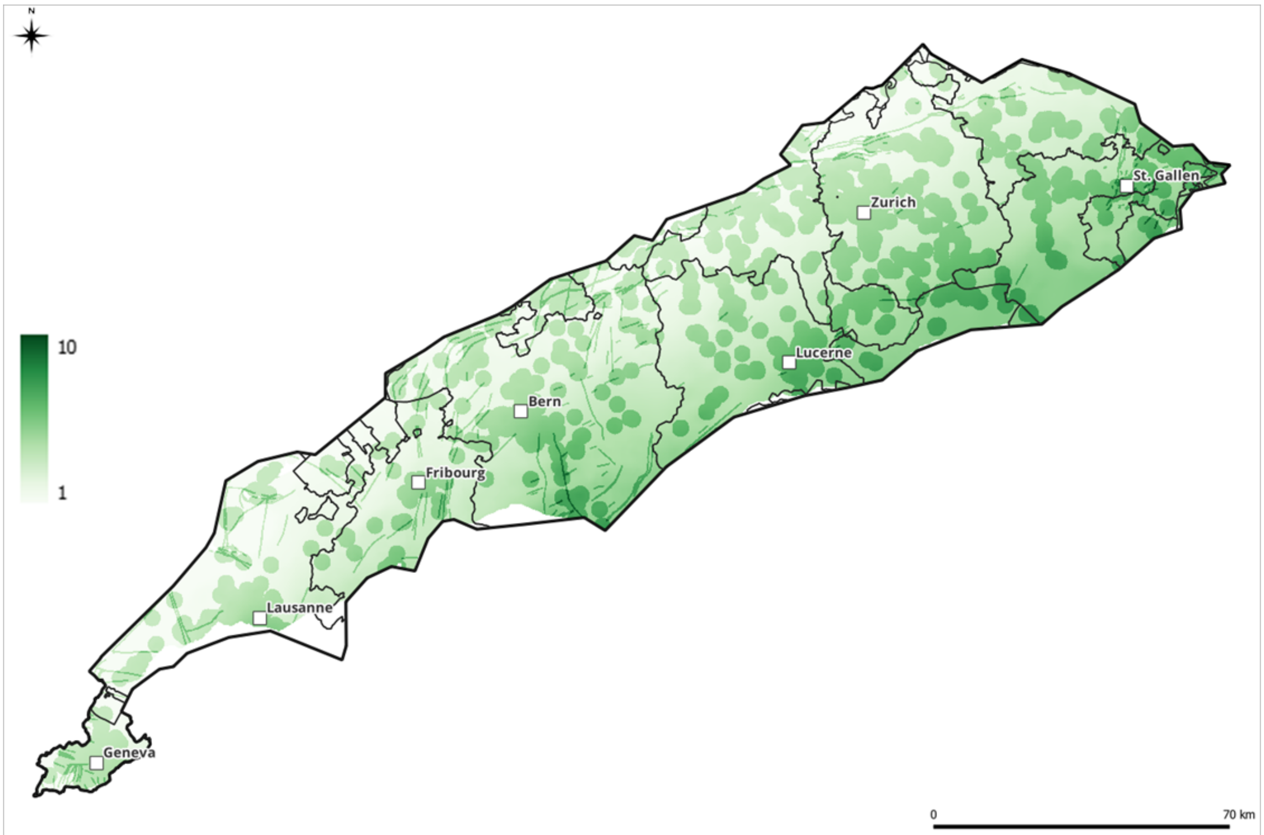

Figure 21 - MCA result for the suitability of the base Cenozoic.

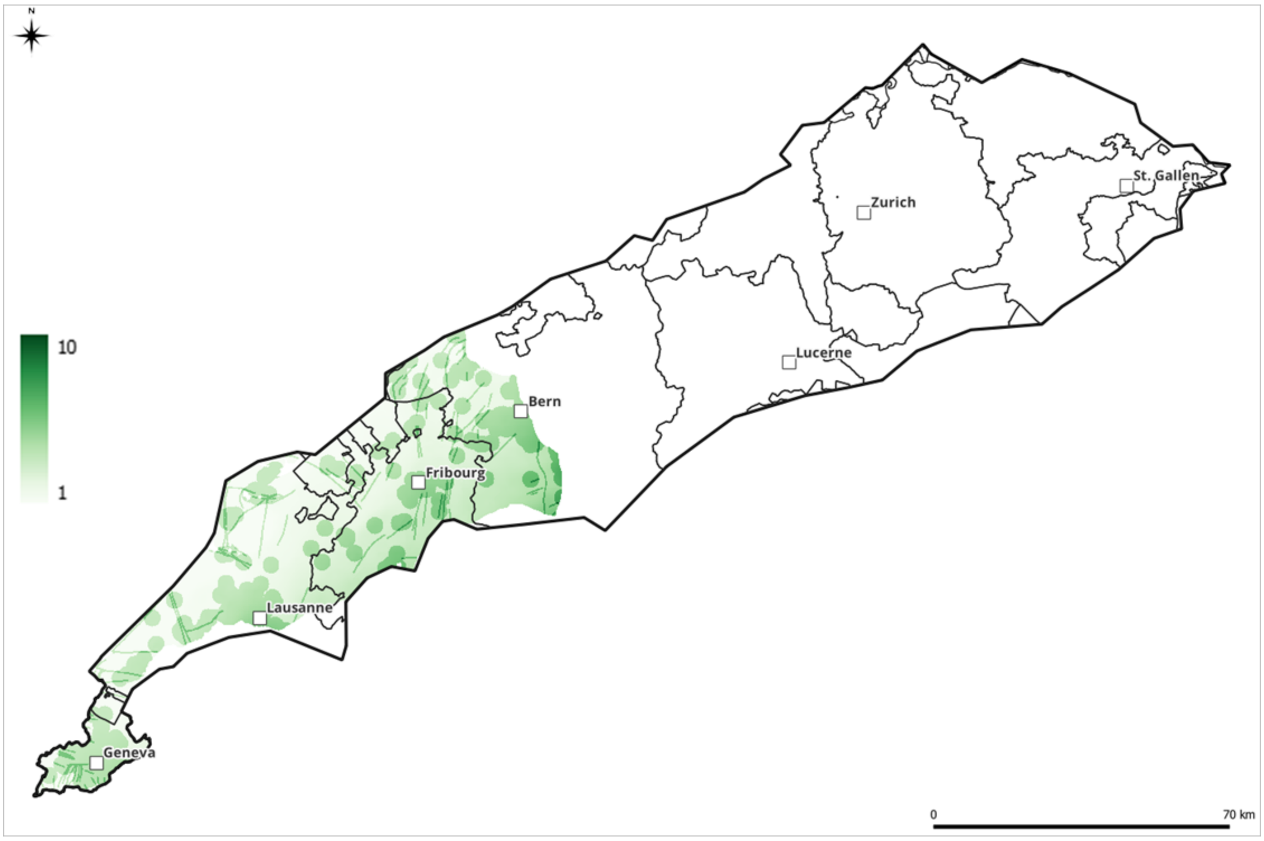

Figure 22 - MCA result for the suitability of the top Cretaceous.

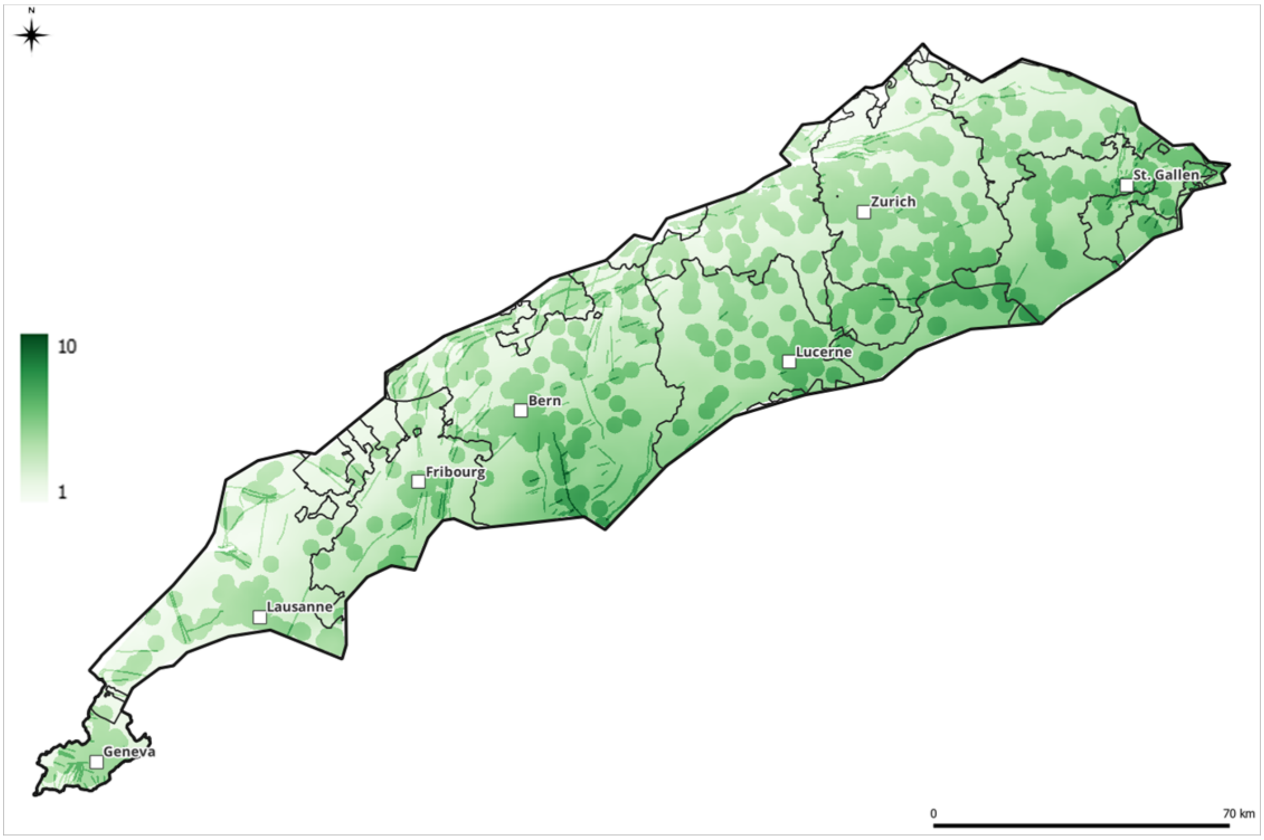

Figure 23 - MCA result for the suitability of the top upper Jurassic.

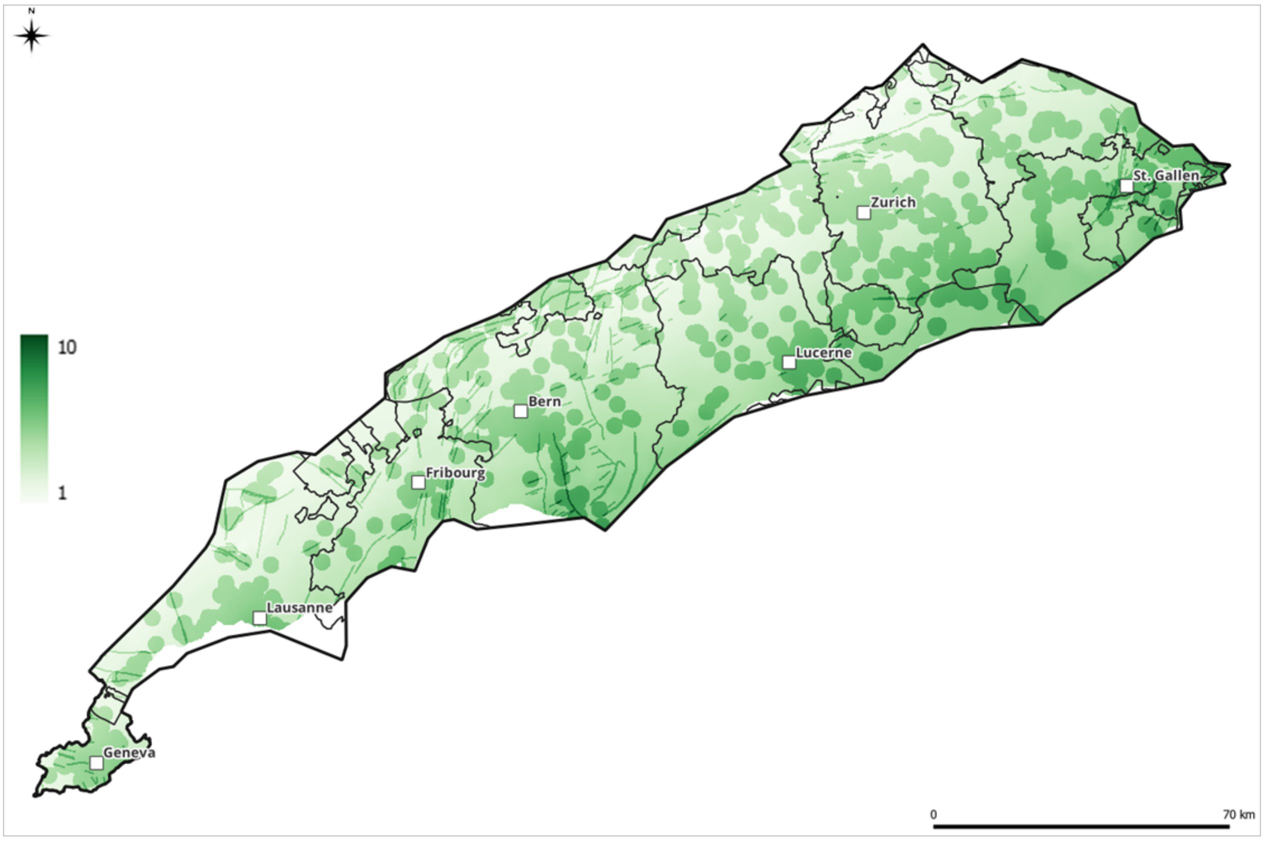

Figure 24 - MCA result for the suitability of the top middle Jurassic.

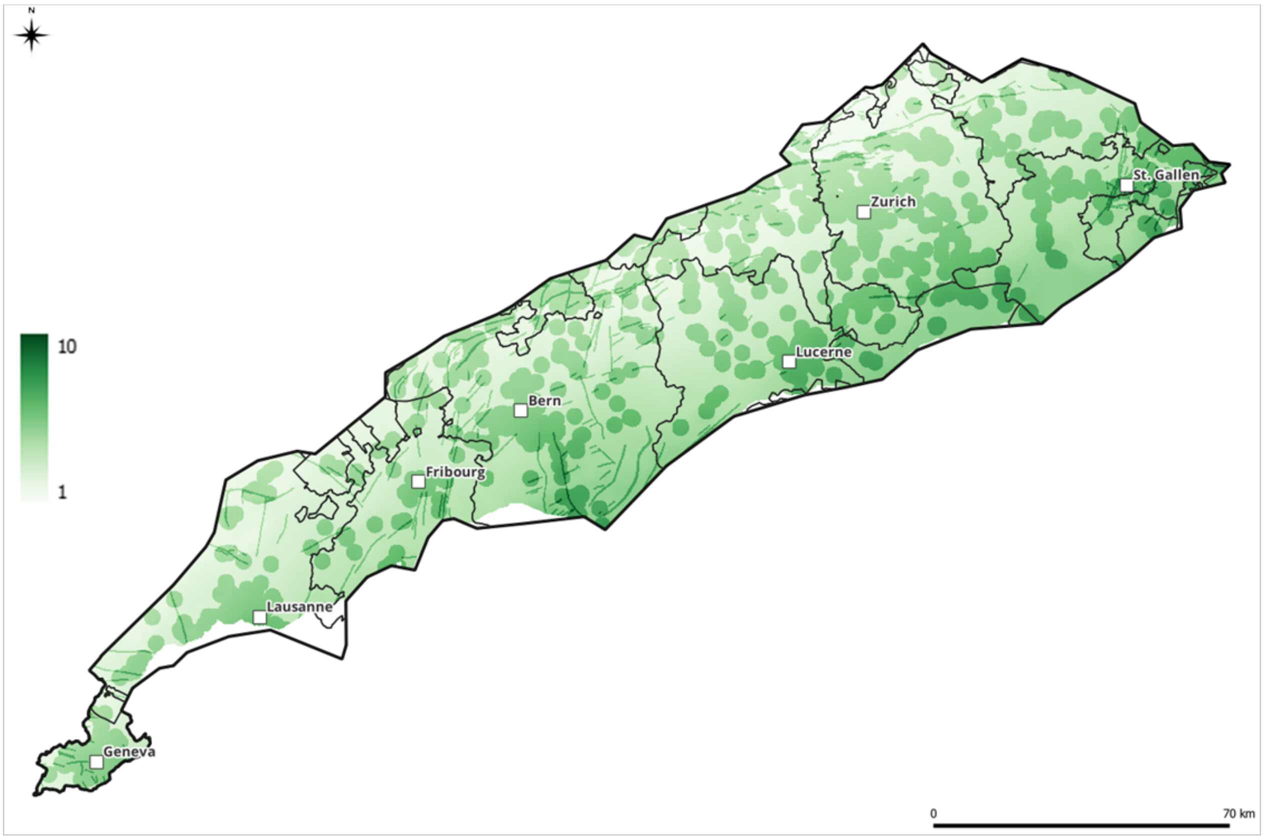

Figure 25 - MCA result for the suitability of the top lower Jurassic.

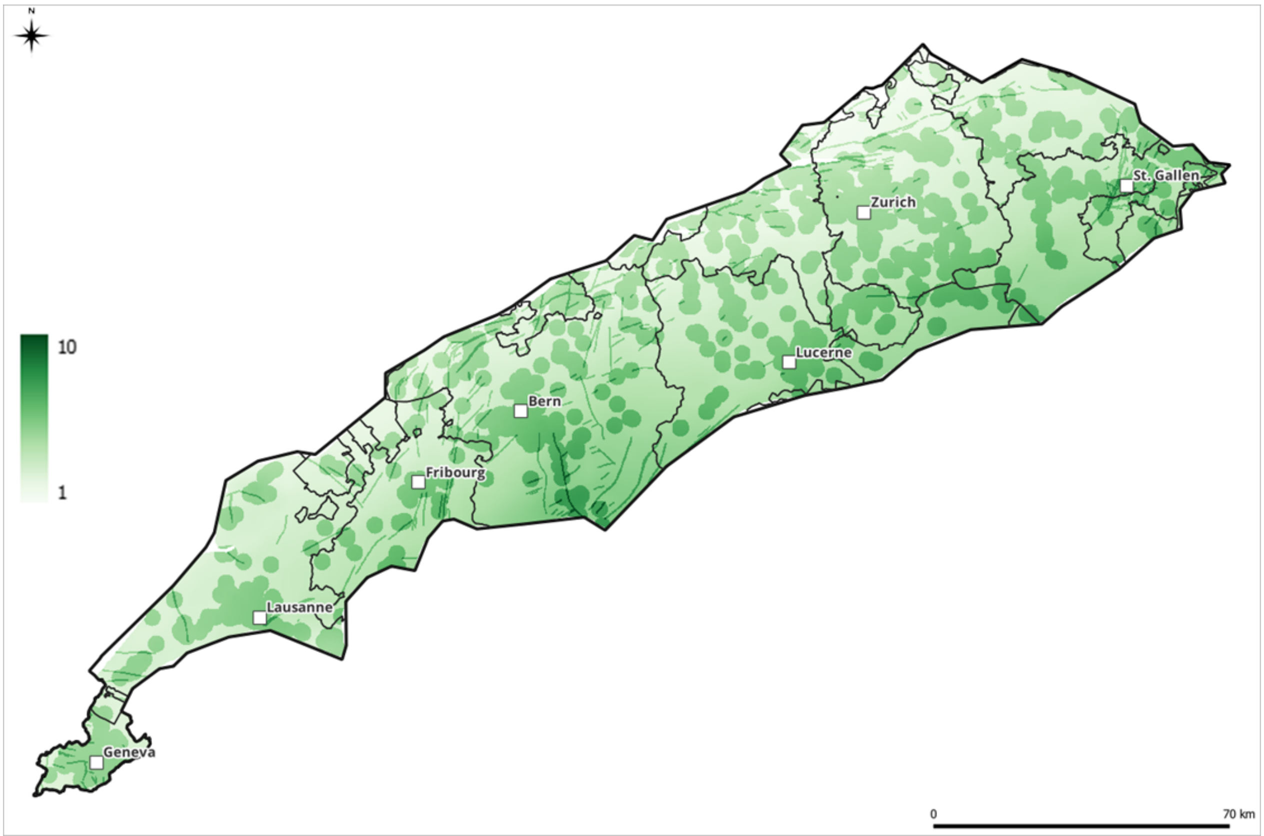

Figure 26 - MCA result for the suitability of the top middle Triassic.

Way towards a more economic approach.

The results of the MCA presented above emphasize the suitability of the southern part of the Swiss Plateau where potential geothermal reservoirs display higher temperature. However, targeting these reservoirs can be challenging both economically and technically. The deeper the resources, the highest the coast of reaching it. Furthermore, deeper wells can include several technical risks such as: well collapse, hydrocarbons occurrence, overpressure, loss of drilling equipment.

Shallow prospects are easier to target and reach with a lower economic impact. It has been done recently in the Canton of Geneva (exploration wells GEo_01 and GEo_02) where prospect have been explored at ~700 and ~1200 meters deep.

We propose to focus on three target depths where temperature data are available: 500, 1000 and 1500 m below ground level. In order to be economically viable, we will look for areas where the temperature is above the mean geothermal gradient (30°C/km) and could be used to implement either heat-pumps or direct use. Our selection is the following:

- Areas where the temperature is above 30°C at 500 m deep, Fig. 27.
- Areas where the temperature is above 50°C at 1000 m deep, Fig. 28.
- Areas where the temperature is above 70°C at 1500 m deep, Fig. 29.

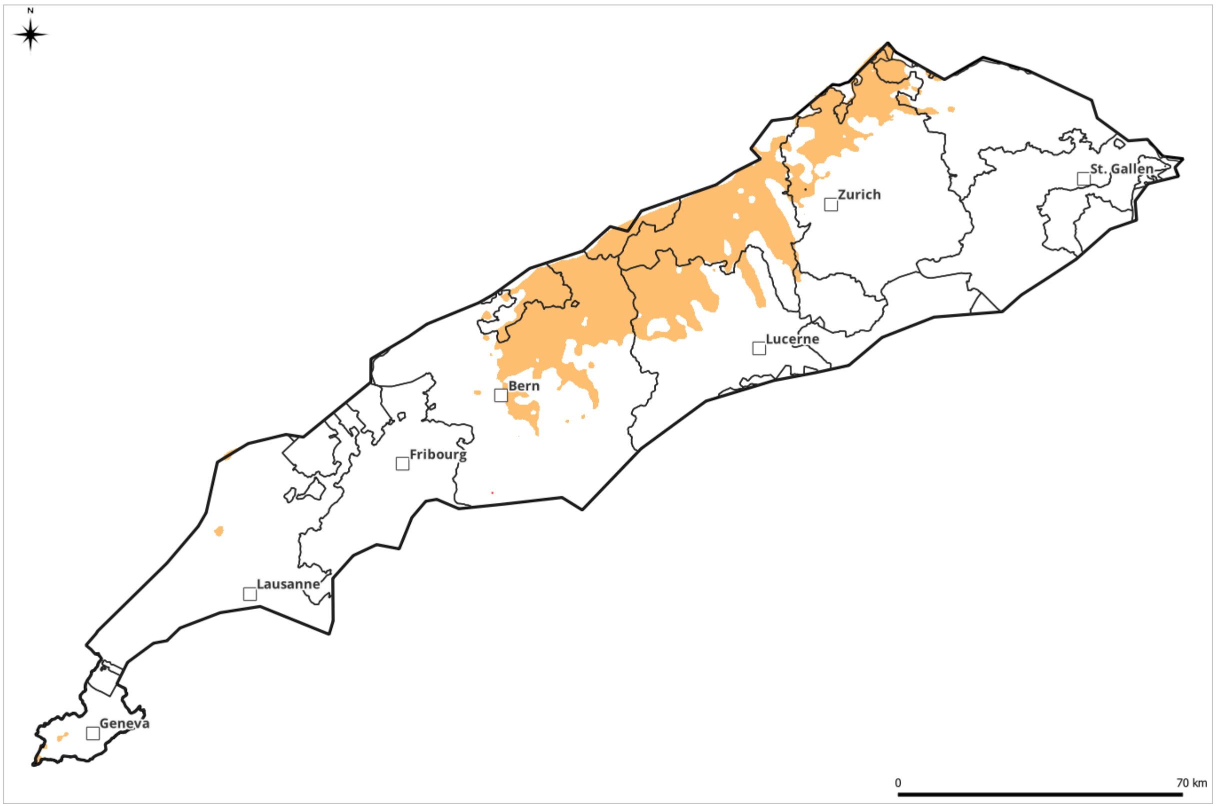

Figure 27 – In light orange, the area at 500 m deep where the temperature is above 30°C in the Swiss Plateau.

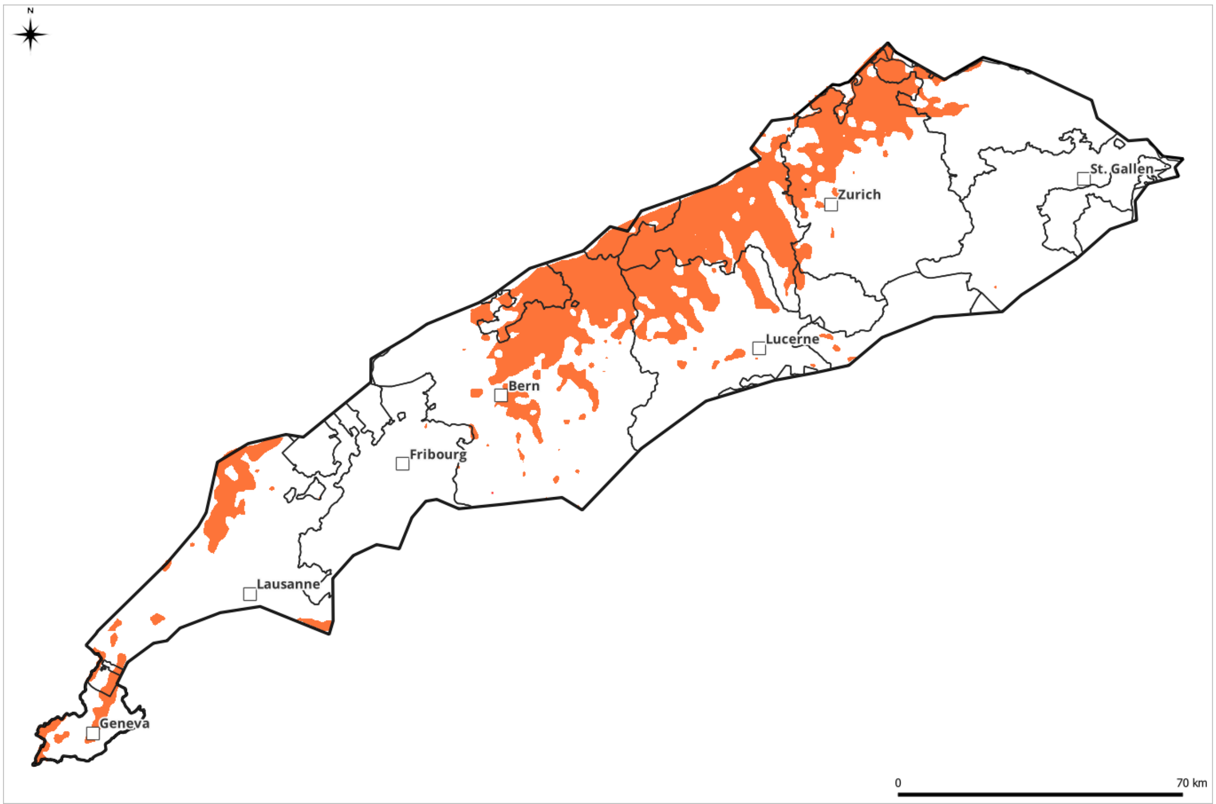

Figure 28 - In orange, the area at 1000 m deep where the temperature is above 50°C in the Swiss Plateau.

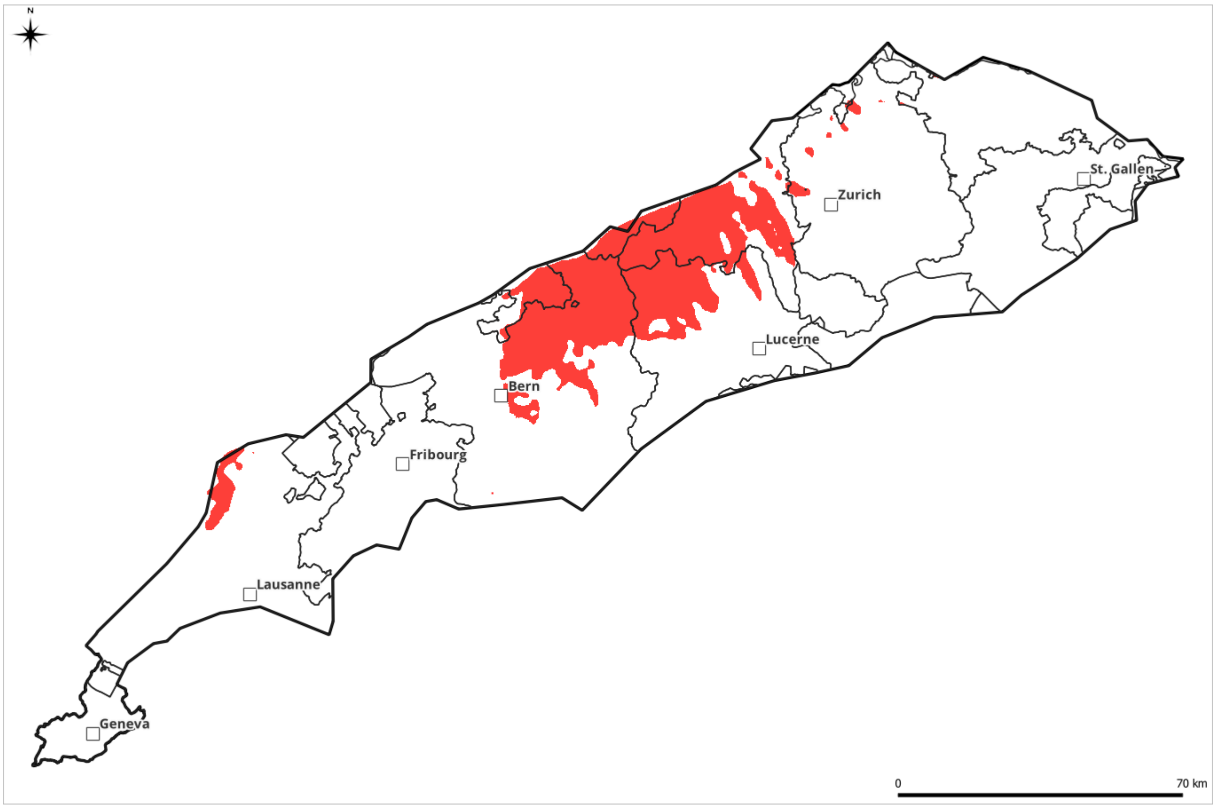

Figure 29 – In red, the area at 1500 m deep where the temperature is above 70°C in the Swiss Plateau.

Combing the three maps reveal that high temperatures could be reached in the northern part of the Swiss Plateau at relatively shallow depth (Fig. 30).

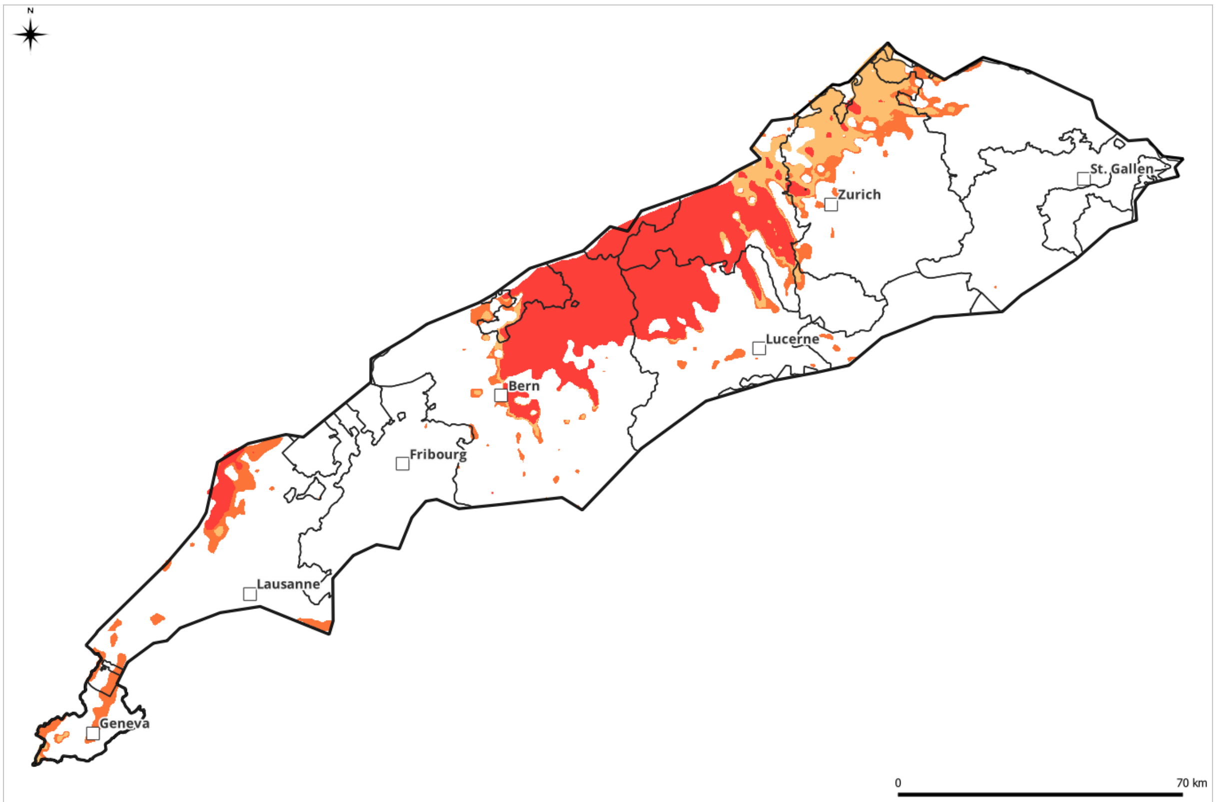

Figure 30 - Combination of the three shallow maps.

The MCA performed per geological reservoir was displaying the northern part of the Swiss Plateau as less suitable than the southern part due to colder temperatures. This was not related to the value of the temperature but rather in its distribution. In this case we are focusing on temperature related to use cases where the implementation at lower costs could be feasible.

We apply the same methodology using these temperature maps at given interval, integrating them with the STATENT dataset. While fault plane at given intervals are not integrated, they would be in a future work.

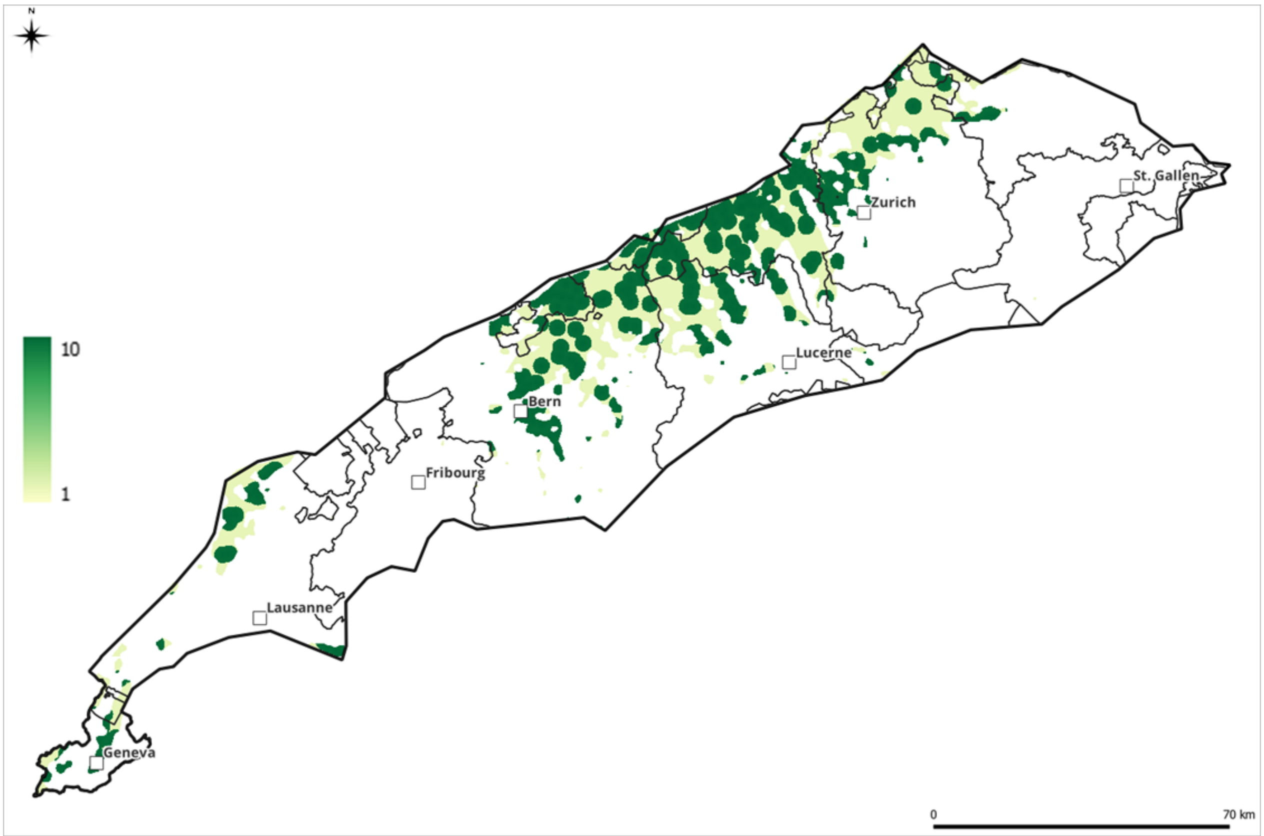

Figure 31 - Suitability of geothermal system above 30°C at 500 meters deep in the Swiss Plateau considering the location of CO_2 emitters.

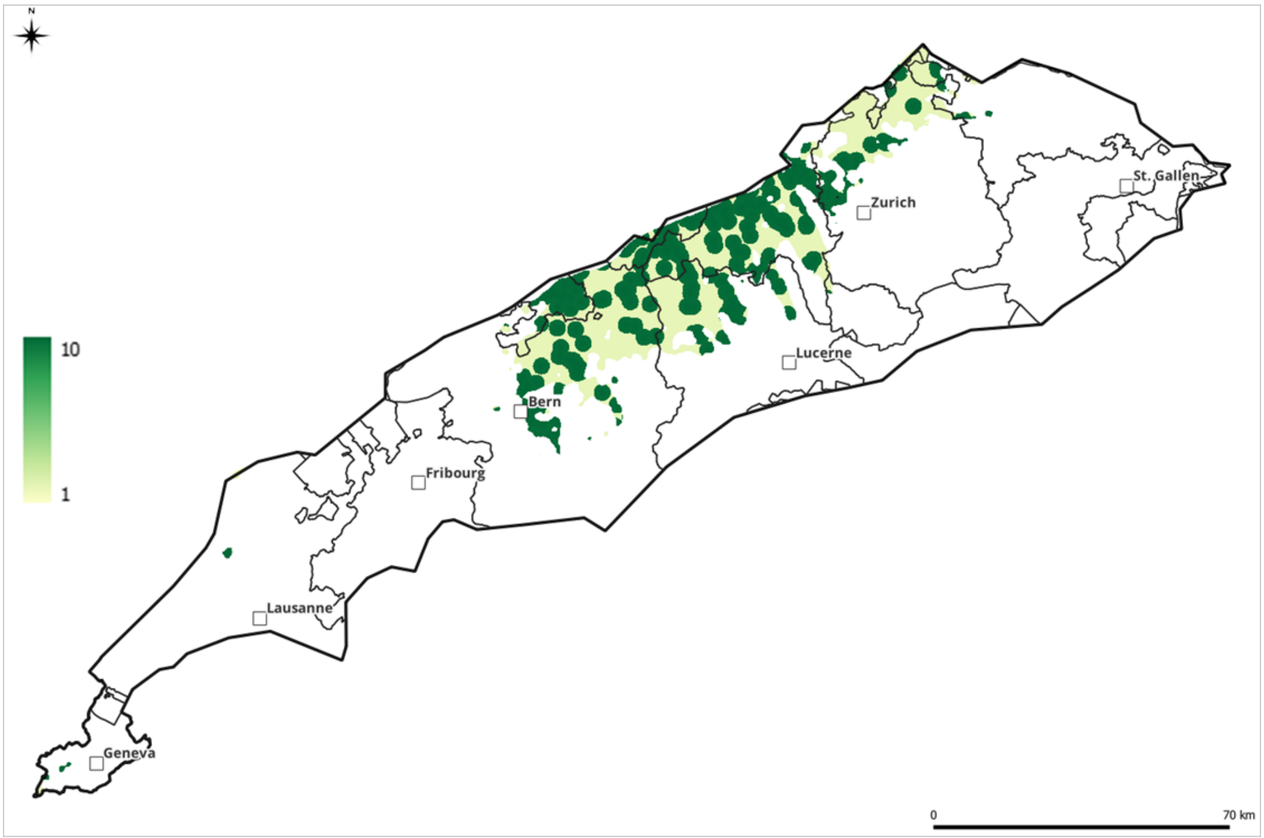

Figure 32 - Suitability of geothermal system above 50°C at 1000 meters deep in the Swiss Plateau considering the location of CO2 emitters.

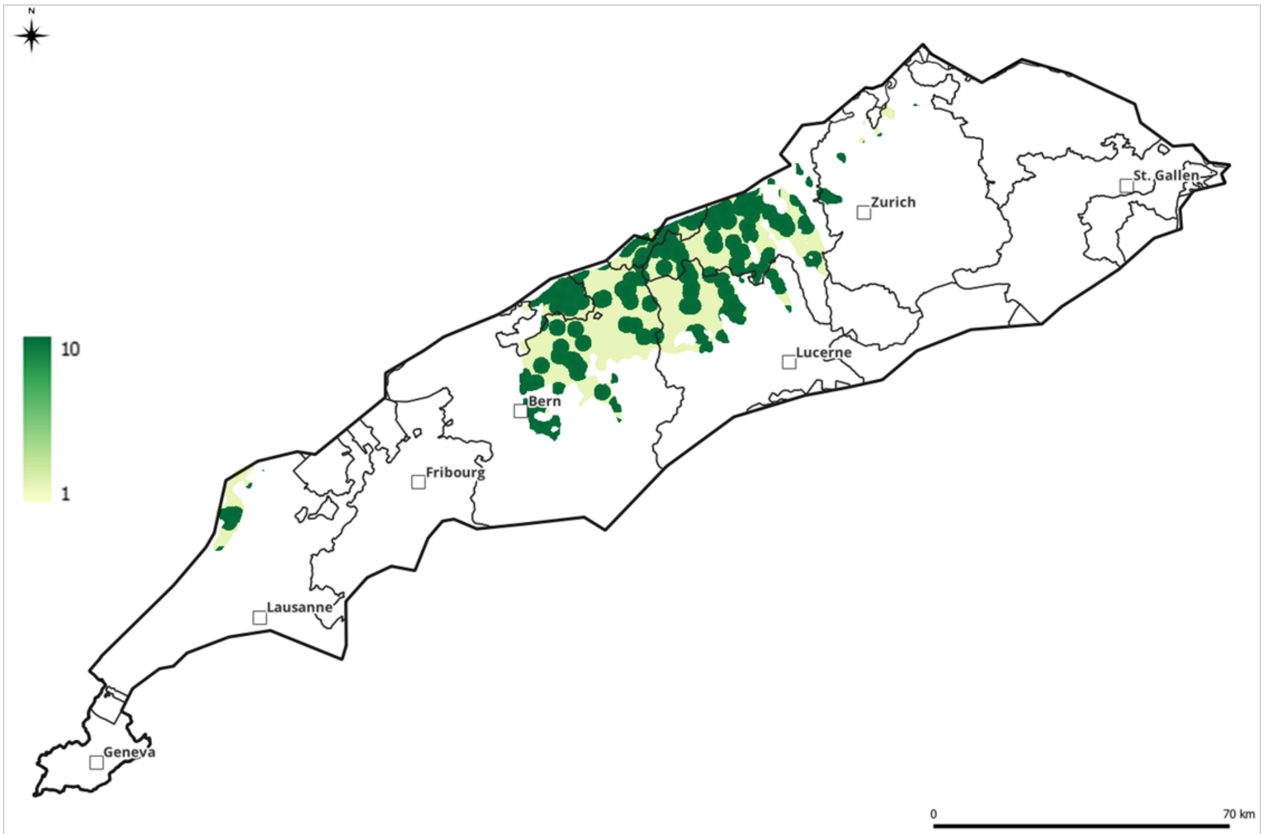

Figure 33 - Suitability of geothermal system above 70°C at 1500 meters deep in the Swiss Plateau considering the location of CO2 emitters.

Globally, the northeastern part of Canton Bern, the northern part of Canton Luzern and the western part of Canton Aargau represents three areas where suitable temperatures for geothermal application can be reached at shallow depths and bring to energy consumers.

Shallow geothermal systems in correlation with CO2 emitters are also observed in the Canton of Geneva and Canton Vaud, at 500 and 1500 meters respectively. The results observed in the Geneva Canton as already been confirmed by the GEothermies program and the ongoing exploration of geothermal resources in the last decade.

Conclusions and way-forward.

Switzerland, renowned for its commitment to environmental sustainability, seeks innovative solutions to reduce carbon emissions while ensuring energy security. Geothermal energy presents a promising avenue for achieving these objectives. Multi-Criteria Analysis (MCA) serves as a powerful tool in identifying suitable areas for geothermal energy development by integrating subsurface temperatures, faults, and the locations of high CO_2 emitters.

Switzerland boasts significant geothermal energy potential, primarily driven by its tectonic activity and geological characteristics. Switzerland's geothermal gradient varies across regions, with higher temperatures observed in areas with geological features conducive to heat accumulation. The tectonic setting that led to the presence of faults and geological structures, influenced the permeability and could be a source of circulation of geothermal fluids at different temperature ranges.

In this context, the MCA facilitates a systematic evaluation of Switzerland's geothermal resource potential, guiding the allocation of exploration efforts towards areas with optimal subsurface conditions. By considering multiple criteria simultaneously, planners can identify geothermal hotspots with high potential for CO_2 emission reduction. The results of this work can enable the strategic placement of geothermal facilities near CO_2 emission sources, minimizing environmental impact while maximizing carbon mitigation benefits.

For example, MCA could be applied to evaluate geothermal energy opportunities in regions such as Canton Bern, Canton Aargau, Canton Luzern, where subsurface resources and industrial heat demands coincide. By analyzing subsurface temperatures, fault distributions, and CO_2 emission profiles, the MCA is a tool for identifying suitable sites for geothermal systems implementation. The MCA offers a robust framework for optimizing energy planning in Switzerland and advancing CO_2 emission reduction objectives. As Switzerland continues its transition towards a low-carbon future, project such as the one presented here serves as a valuable tool for harnessing the benefits of geothermal energy while mitigating environmental impact and fostering energy resilience.

The work presented here can be further develop by implementing additional steps and datasets:

- The temperature models are based on old data, non-calibrated with more recent subsurface temperature data. It is important to update these models in order to have a better understanding of the distribution of heat in the subsurface.
- Reservoir characterization is heavily dependent on the study of subsurface samples. Unfortunately, few boreholes in the Swiss Plateau have been cored or the data is lost or privately owned. Access to additional data and further exploration of the Swiss Plateau could give new insights on the reservoir properties of the different geological reservoirs and their variability regionally. Efforts of detailed reservoir characterization thru sampling cores of deep geological intervals as it has been performed by NAGRA for their drilling recent campaign would strongly benefit the energy transition.
- Faults are important and major conduits for fluid migrations. However, in order to characterize as best as possible faults and their potential fracture networks, it is important to carry out detailed geophysical exploration (seismic acquisition). Recent efforts have been made in this regard (e.g. St Gallen, NAGRA blocks, and the newly acquired 3D seismic in the Canton of Geneva, the Éclépens region and Basel). Characterization and modeling of the fault system is often a complex and tedious task requiring an important resource commitments. Yet, the understanding and ability to predict fault and fracture systems at depth is paramount to make future projects viable and avoid disappointments such as La Côte, Yverdon-Les-Bains and Lavey-les-Bains.
- The STATENT data used to locate CO_2 emitters represent only a proxy. Real data form physical measurements or new data acquisition tailored to the quantification of CO_2 emissions would help in identifying where it is urgent to explore for geothermal energy production.

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