# Common Risk Segment mapping to de-risk geothermal exploration

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## ABSTRACT

The Swiss Ordinance of the Reduction of Carbon Emissions is at the core of Switzerland's climate policy. In this context, prospecting and developing geothermal resources has been promoted through financial assistance. The Swiss Plateau is known for manifestation of hydrocarbon seepages, indicating the presence of an active and intricate petroleum system with multiple geothermal plays. Over the past two decades, geothermal drilling in the region has frequently encountered oil and gas (e.g., Schlattingen-1, St. Gallen GT-1), leading to occasional environmental and anthropogenic incidents. These events have negatively impacted the public's perception and the economic viability of geothermal projects, both locally and nationally. To this end, a long-term project has been carried out by the University of Geneva (UNCONGEO) which aimed at assessing the potential presence of subsurface hydrocarbons in project areas to minimize risks such as environmental damage, operational setbacks, and resource losses during geothermal exploration activities.

To meet this objective, the initial key step involved gaining a comprehensive understanding of the active petroleum system in the Swiss Plateau. This process entailed identifying, characterizing, and quantifying the key elements and mechanisms responsible for the generation, migration, accumulation, and preservation of oil and gas in the subsurface.

Once the previous task was completed, Common Risk Segment (CRS) maps were created for the entire Swiss Plateau, highlighting the spatial distribution of geological risk associated with an active petroleum system within a broader petroleum play. These maps aim to assess the likelihood of encountering hydrocarbon accumulations in areas where deep geothermal wells (>0.5–1 km) might be drilled. CRS maps were developed for each of the main petroleum plays of the Swiss Plateau by evaluating the quality of key petroleum system elements (source rocks, reservoirs, and seals) through integration of existing data and petroleum system modelling results. Additionally, data availability and quality assessment maps were provided for each play element, offering insights into the type and quality of data used in the assessment. Furthermore, these maps highlighted data gaps where new acquisition is needed to accurately evaluate the risks for deep geothermal projects.

The CRS maps produced by this work are valuable tools for planners and decision-makers, offering an initial assessment of the risk of encountering hydrocarbons at depth. Further work will be realized to reduce the uncertainties related to the poor data coverage throughout the basin.

## 1. INTRODUCTION

Geothermal energy is increasingly recognized as a vital component of the global transition to sustainable energy systems, offering a reliable and low-carbon alternative to fossil fuels. In Switzerland, the Swiss Plateau, part of the Molasse Basin, is a region with significant geothermal potential due to its favourable geological conditions, including deep aquifers and high heat flow (Moscariello 2019). However, the development of geothermal resources in this area is not without challenges. One of the primary risks is the potential to encounter hydrocarbons during drilling, which can lead to operational complications, increased costs, and safety concerns.

Hydrocarbon exploration in Switzerland began a century ago in the search for local oil and gas resources (Bloesch 1920). By 2012, 37 deep wells had been drilled with Noville-1 being the last exploration well, in the Canton of Vaud. The exploration target evolved over time, moving from the Cenozoic to the Mesozoic and Permo-Carboniferous units. This change was driven by the integration of more advanced and high-resolution geophysical exploration tools, such as reflection to refraction seismic, and drilling technology, as highlighted by Greber et al. (1997) and Leu (2012). Despite numerous promising indications of oil and gas along the entire stratigraphic sequence, only one semi-commercial gas field, Entlebuch-1, was discovered in the 1980s. This well produced 2.65 billion cubic feet of gas in the upper Jurassic unit (Malm). More recently, a gas play was found in the Permo-Carboniferous deposits in the Weiach well (Ajuaba 2023) and in the

Noville-1 well (confidential report). However, hydrocarbon production will not occur in any of these wells.

In July 2013, a deep geothermal project in St. Gallen aimed at harnessing hydrothermal energy for district heating and electricity generation encountered an unexpected influx of overpressurized natural gas (approximately 90% methane) at a depth of 4,450 meters. This "gas kick" necessitated the injection of drilling mud and water to stabilize the well. Subsequently, a series of induced seismic events occurred, including a magnitude 3.5 earthquake that was felt across northeastern Switzerland. The seismicity was attributed to the destabilization of a nearby fault, likely facilitated by a hydraulic connection between the well and the fault zone. The presence of overpressurized gas, combined with injection operations, is believed to have contributed to the fault's reactivation (Zbinden et al 2020). To address these challenges, systematic risk assessment methods are crucial. Common Risk Segment (CRS) mapping, originally developed for petroleum exploration, has emerged as a powerful tool for evaluating geological risks in geothermal projects. CRS mapping assesses the likelihood of hydrocarbon presence by analyzing key geological elements such as source rocks, reservoirs, and seals.

The objective of this paper is to provide a comprehensive analysis of hydrocarbon risks in the Swiss Plateau, identify high-risk areas, and propose mitigation strategies to support safer and more efficient geothermal exploration. The study focusses on six petroleum plays: Cretaceous, Malm, Dogger, Lias, Muschelkalk, and Permo-Carboniferous. Each of these plays presents distinct geological characteristics that influence risk levels. By combining data from petroleum system modelling, well logs, seismic surveys, geological models, and geochemical analyses, this work aims to contribute to the growing body of knowledge on geothermal risk assessment. This research is part of the UNCONGEO program, which aims to evaluate the presence and potential distribution of hydrocarbons in the subsurface of the Swiss Plateau region.

## 2. METHODOLOGY

The CRS mapping methodology employed in this study is a structured approach adapted from hydrocarbon exploration, with a focus on leveraging GIS data for spatial analysis (e.g., Grant et al 1996, Scandizzo 2005, Lynch et al 2020,).

The petroleum system models reconstructed in this study are based on several assumptions. Subsurface data is scarce and scattered throughout the basin, necessitating interpolation and/or extrapolation. Therefore, uncertainties in the results presented must be considered. The most relevant uncertainties in terms of their impact on the modelling outcomes are:

- Distribution and properties of the source rocks, particularly the Permian and Carboniferous deposits, which is barely known.
- Fault location, geometry, activity timing, and sealing properties (e.g., degree of cementation, juxtaposition, transmissibility).
- Porosity and permeability properties throughout the entire basin.
- Geometry of the basin (traps).
- Lithology and sedimentary facies distribution of both source, reservoir, and seal rocks throughout the entire basin.
- Source rock thermal maturity state throughout the entire basin.
- Timing of thrusting phases (s) and magnitude and timing of syn- and post-orogenic erosion.

Five 2D thermal models were realised along key geological transects throughout the basin. These models were validated by calibration data (porosity, temperature, vitrinite reflectance) measured in wells. The modelling results provided an estimate of the thermal maturity of the potential hydrocarbon source rocks (Omodeo-Salé et al 2020). Additionally, the model estimated the potential hydrocarbon migration paths and the areas and stratigraphic units where hydrocarbon accumulations could occur along the sections. The geological sections and fault distributions used for modelling were extracted from the GeoMol 2021 project, a 3D geological model of the entire Swiss Plateau, realized by swisstopo (Allenbach et al 2017).

### 2.1 Play Definition.

A geological play represents the conceptual framework for identifying potential hydrocarbon accumulations. A play is characterized by the presence of essential petroleum system elements: source rock, reservoir, and seal, as well as the geological processes that allow hydrocarbons to accumulate. The definition of these plays is grounded in the stratigraphic framework of the basin, drawing from extensive literature data and previous geological surveys. The primary objective is to delineate the main hydrocarbon targets based on known stratigraphic sequences, tectonic settings, and structural features. Six geothermal plays were considered and named with respect to the main reservoir unit (Table 1).

**Table 1: Plays considered in this work to build the CRS maps of the Swiss Plateau. P-C. stands for Permo-Carboniferous.**

| Play | Reservoir | Seal | Source Rock |
|---|---|---|---|
| Cretaceous | Lower Cretaceous carbonates | Molasse shales | Posidonia shales and P-C. |
| Malm | Upper Malm carbonates | Lower Cretaceous or Molasse shales | Posidonia shales and P-C. |

| | | | |
|---|---|---|---|
| Dogger | Dogger carbonates | Lower Malm marls | Posidonia shales and P-C. |
| Lias | Lias and/or Upper Trias carbonates | Lias shales and marls and/or Dogger marls | Posidonia shales and P-C. |
| Muschelkalk | Muschelkalk dolomitic carbonates and Buntsandstein continental sandstone | Keuper and/or Muschelkalk evaporites | P-C. |
| P-C. | P-C. continental sandstone | Muschelkalk and/or Keuper evaporites | P-C. |

**2.2 Classes Definition.**

To define the risk associated with the presence of hydrocarbons in the subsurface, it is essential to assess the quality of the three elements composing a petroleum system (source rock, reservoir and seal). The quality assessment is based on the presence or absence of a series of properties, specific to each play element. Consequently, the knowledge of these properties was related to the availability of data. Based on the above, two types of important aspects were used to classify the data and information available: 1) petroleum system data availability and 2) petroleum system assessment.

The data availability classification defines for each petroleum system element the availability of data which are necessary to assess its quality and appropriateness to generate hydrocarbon in the case of the source rock, or to store hydrocarbons in the case of the reservoir, and to confine hydrocarbons in the cases of the seal. Based on these data, the assessment of petroleum system elements was carried out. The assessment also considers our interpretation of the quality of these elements, particularly in the case when data are not available. In this paper, only the system assessment will be presented.

The source rock assessment classes were defined on properties directly measured, when data are available, whereas, in the case there are no data for a specific area, data were extrapolated from the closest wells where data are available (Table 2). The properties considered were presence (i.e. occurrence), maturity and organic matter richness (TOC > 2%).

**Table 2: Yes/No table of the source rock data assessment classification. SR: Source Rock, TOC: Total Organic Carbon.**

| Class | SR Presence | SR Maturity | TOC > 2% |
|---|---|---|---|
| 1 | Y | Y | Y |
| 2 | Y | Y | N |
| 3 | Y | N | Y |
| 4 | Y | N | N |
| 5 | N | N | N |

The reservoir data availability classes were assigned based on the availability of data for each reservoir unit within a play. Data deemed essential for defining a reservoir's properties included the presence of GeoMol surfaces and faults within the unit, the occurrence of the unit in a specific well, and the availability of porosity data.

The reservoir assessment considers three key properties: the presence of the reservoir, its porosity (Phi), and its fractures. An effective reservoir is defined as having an average matrix or fracture porosity of over 15%. Since information on fracture porosity is scarce for fractured reservoirs, it was assumed that these reservoirs may have open fractures when nearby faults crossing the unit are oriented at ±45° to the maximum stress orientation ($\sigma 1$). The properties are assigned to the maps based on available measured data. In cases where complete data is unavailable, information is inferred and derived from the closest wells with available data (Table 3).

**Table 3: Yes/No table of the source rock data assessment classification.**

| Class | Reservoir Presence | Reservoir Phi > 15% | Reservoir Fractured |
|---|---|---|---|
| 1 | Y | Y | Y |
| 2 | Y | Y | N |
| 3 | Y | N | Y |
| 4 | Y | N | N |
| 5 | N | N | N |

Seal data availability classes were assigned based on the availability of data for each seal unit within a play. The essential data for defining a seal's properties include: the presence of the GeoMol surface for that seal unit, the presence of GeoMol faults in that unit, the occurrence of the seal unit in a specific well, and the availability of lithologic data.

The seal assessment considers the presence of the seal, its impermeability based on lithologies, and its integrity. A lithology is considered impermeable if it comprises >50% of impermeable facies (shales, marls). Regarding seal integrity, due to the lack of unambiguous data, it was assumed that the seal is not fractured when faults in the unit are oriented ±45° to the minimum stress orientation ($\sigma 3$).

**Table 4: Yes/No table of the seal rock data assessment classification.**

| Class | Seal Presence | Seal Integrity | Seal Impermeable |
|---|---|---|---|
| 1 | Y | Y | Y |
| 2 | Y | Y | N |
| 3 | Y | N | Y |
| 4 | Y | N | N |
| 5 | N | N | N |

The assignment of these properties throughout the maps was done considering the measured data when available. In the absence of data for a specific area, information was inferred and derived from the closest wells with available data (Table 4).

### 2.3 Common Segment Risk mapping.

QGIS was used to process and compile the acquired data. All algorithms and calculations were performed within QGIS.

The UNCONGEO database contains an exhaustive list of boreholes in the Swiss Plateau that reached a depth of at least 500 metres. It is estimated that borehole data remains reliable within 1.5 kilometres of the drilling site. It was assumed that the damage zone inherent to the fault extended 200 metres on each side of the fault plane. The extension of geological units was derived directly from the GeoMol geological model, which contains a selection of nine horizons across the study area corresponding to the Swiss Plateau. The source rock, reservoir, and seal extensions have been considered and represented as a classified vector file.

Each play element (reservoir, seal, source rock occurrence, and maturity) is represented by a vector map with values ranging from 1 to 5, corresponding to their assessment class. For the reservoir and seal components, the unit extent map and fault map are aggregated into a single vector map. Vector data is then converted to raster format using the gdal:rasterize algorithm in QGIS. The CRS map is computed by multiplying the following raster [1]:

SR_raster * Reservoir_raster * Seal_raster [1]

The CRS map is then normalised mathematically on a scale from 1 to 5 to illustrate the classification used. Normalisation was done in the raster calculator algorithm using the mathematical formula for normalisation for custom range:

$$R_{norm} = (b-a)*((x-R_{min})/(R_{max}-R_{min}))+a \qquad [2]$$

Where a and b are the lower and upper ranges, $R_{min}$ and $R_{max}$ are the minimum and maximum values of the raster.

The CRS maps classify the risks of encountering hydrocarbons during drilling in a given play. The level of risk is determined by the results of the raster multiplication. A score of 1 indicates the highest risk, meaning all play components are present and susceptible to forming a working petroleum system. Conversely, a score of 5 represents the lowest risk, where the play components may not be able to form a working petroleum system. The risk of encountering hydrocarbons in the subsurface is then classified as high (1), high to medium (2), medium (3), medium to low (4), and low (5).

## 3 RESULTS AND DISCUSSION

### 3.1 Source Rocks

In this study, it was assumed that all the plays defined for the Swiss Plateau share the same source rocks: the Posidonia Shales and the Permo-Carboniferous deposits. Consequently, the same source rock maps were generated for all the plays.

The Posidonia Shales source rock properties were reconstructed primarily based on the occurrence in wells and the geochemical analysis performed on core samples. The presence of the Posidonia Shales source rock is certain only when a well has been drilled deep enough to reach the Lias unit and when a detailed description of the lithologies crossed by the well is available. In such cases, its presence can be confidently inferred. However, when this information is not available, its presence remains unknown and can only be extrapolated from near wells where data is available.

The presence and geochemical characteristics of the Posidonia Shales were primarily reconstructed from well data and thermal modeling results. Their thermal maturity was assessed through 1D and 2D basin modeling along five geological sections, and these results were extrapolated across the Plateau. While direct geochemical data, such as Rock-Eval pyrolysis and vitrinite reflectance (VR), are available for a limited number of wells, particularly in the Vaud region and northeastern Switzerland, broader interpretations relied heavily on interpolation and model calibration. Areas with strong evidence of mature and organic-rich Posidonia deposits include the Essertines-1, Eclépens-1, and Weiach-1 wells. Based on available data, a source rock assessment map has been produced for this unit (Figure 2).

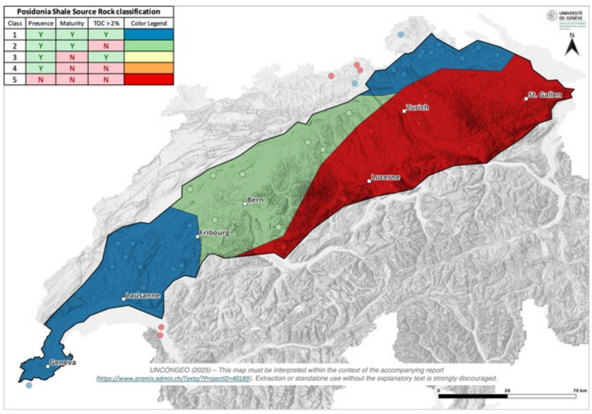


**Figure 2: Classification of the Posidonia Shale source rock based on the assessment of available data.**

The Permo-Carboniferous source rock properties were mostly reconstructed based on the occurrence of these rocks in wells and the geochemical analysis performed on core samples. We assumed that the Permo-Carboniferous source rock is present whenever a Permo-Carboniferous graben has been identified in the subsurface based on seismic and borehole data present in the literature. The maturity of the source rock is primarily assessed through thermal modelling results, while the TOC content is inferred from the presence or absence of thermogenic gas in the considered area (Figure 3).

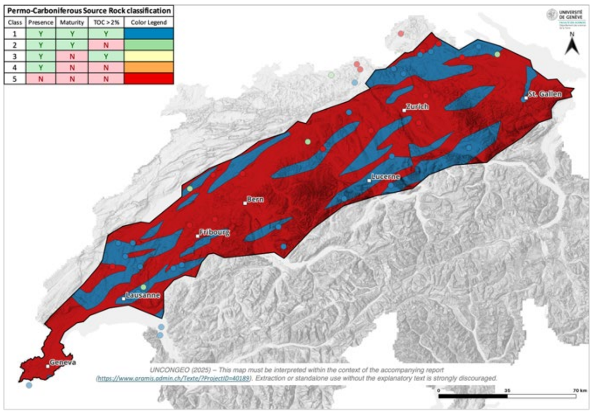


**Figure 3: Classification of the Permo-Carboniferous source rock based on the assessment of available data.**

### 3.2. Reservoirs

Reservoir units were evaluated for each geothermal play. The lower Cretaceous reservoir, primarily composed of fractured and karstified limestones and marls, is restricted to the western sector of the Plateau. Data for this unit are scarce, and porosity values are consistently below 15%, leading to low reservoir quality assessments across most wells. The spatial distribution of reservoir presence, degree of fracturing, and data confidence was mapped and synthesized into CRS interpretations. Despite limited porosity, localized fracturing enhances the geothermal potential, especially in areas such as Cuarny-1 and Eclépens-1.

The Malm reservoir, comprising micritic limestones and reefal facies, is more widespread and present throughout most of the Plateau. However, porosity data remain sparse and generally below the threshold considered favourable for reservoir quality. As with the Cretaceous reservoir, fracture networks are critical for permeability and plays such as Essertines-1 and Romanens-1 show enhanced potential due to documented or inferred fracturing. The Dogger reservoir, composed of oolitic limestones, similarly exhibits low porosity across the region, with fractured zones inferred in select areas. Presence assessments were often derived from seismic interpolation when stratigraphic units had not been directly penetrated.

The Lias play, where present, is formed by sandstone bodies of the Rhaetian and Early Jurassic age. Due to the heterogeneous nature of these clastic sequences, reservoir assessment was more variable, with sand-rich intervals rarely exceeding the porosity threshold. In several wells, the presence of potential reservoirs could not be confirmed due to lack of penetration or inadequate lithological descriptions. In the Mushelkalk play, the reservoir is represented by the Trigonodus dolomite and the Melser sandstones deposits, composing the Muschelkalk as well as the Buntsandstein of the early Triassic. Finally, the Permo-Carboniferous play reservoir is composed mainly of sandstones.

### 3.3 Seals

Seal integrity is a critical component in defining the containment capacity of petroleum systems. For the lower Cretaceous play, the seal is represented by the overlying Molasse units. These units vary in composition but frequently consist of impermeable shales and marls, with lithological descriptions available in many wells. Where lithological data were unavailable, the sealing capacity was inferred through extrapolation from nearby wells. General facies analysis indicates that areas with high proportions of marls and shales (e.g., Pfaffnau-1, Noville-1) offer favourable sealing conditions.

For the Malm play, seals comprise either interbedded argillaceous limestones within the Malm itself or the overlying Cretaceous and Molasse units, depending on local stratigraphy. In cases where the Malm unit is not capped by impermeable sediments, sealing integrity is significantly compromised, and risk levels are elevated accordingly. The Dogger play relies on the overlying lower Malm unit as its primary seal. Lithological characterizations—such as marls and calcareous shales—were generally favourable, although in many wells these facies were not directly encountered, necessitating reliance on extrapolated data.

For the Lias, the seal is represented by superimposed shales deposits, included in the same Lias unit and/or in the Dogger unit (Opalinus Clays). For the Muschelkalk and Permo-Carboniferous plays, the seal is represented by anhydrite and salt, alternated with shales and marls from the Keuper.

### 3.4 CRS maps

The lower Cretaceous play is present only in the western sector of the Swiss Plateau and presents mostly a medium risk of encountering hydrocarbons in the subsurface (Figure 4). Data and interpretations show that the quality of the lower Cretaceous reservoir is poor in most of the Plateau, while the quality of the Molasse seal is good in the central part and poor at the borders. Consequently, the resulting CRS map indicates that most of the Plateau displays a mediu to low risk. However, this risk increases to « medium to high » over the known Permo-Carboniferous grabens.

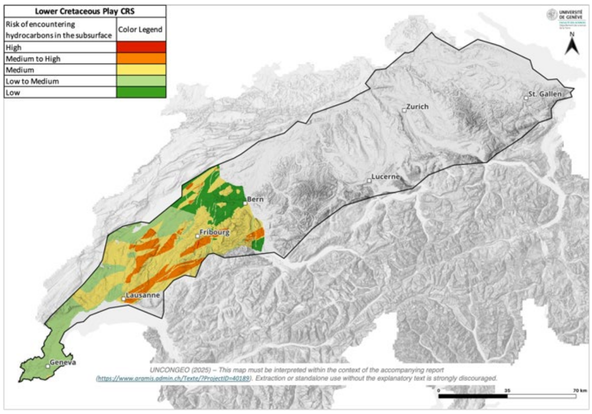


**Figure 4: Common Risk Segment map presenting the risk of encountering hydrocarbons in the subsurface for the lower Cretaceous play.**

In the Malm play, the western and central sector of the Plateau generally presents a medium risk of encountering hydrocarbons, which increases to high on top of the Permo-Carboniferous troughs. The south-eastern part of the Swiss Plateau exhibits the lowest risk (Figure 5).

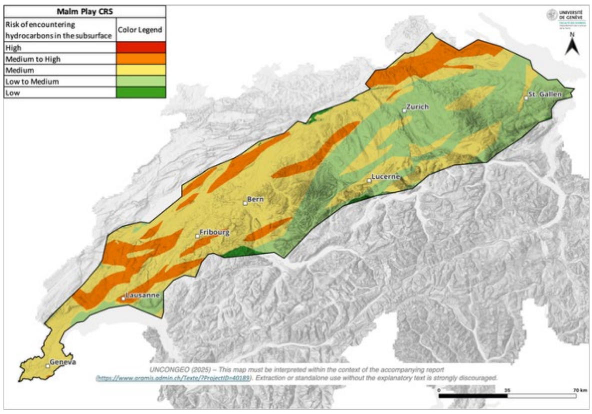


**Figure 5: Common Risk Segment map presenting the risk of encountering hydrocarbons in the Malm play.**

The overall poor reservoir properties of the Malm, Dogger and Lias reservoirs, coupled with the heterogeneous distribution of the Posidonia Shales source rocks results in similar interpretations for the CRS maps of both the Dogger (Figure 6) and Lias (Figure 7) plays. Overall, for the Jurassic plays, the south-eastern part of the Swiss Plateau exhibits low risk due to the non-deposition of the Posidonia Shales. Small differences are observed in the repartition and properties of the faults where the risk of encountering hydrocarbons can vary in function of their orientation regarding the stress field.

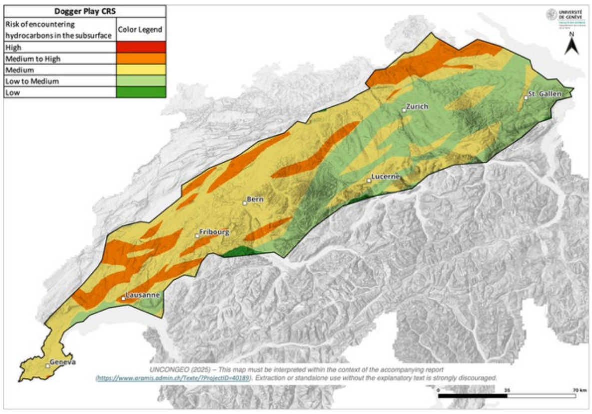


**Figure 6: Common Risk Segment map presenting the risk of encountering hydrocarbons in the subsurface for the Dogger play.**

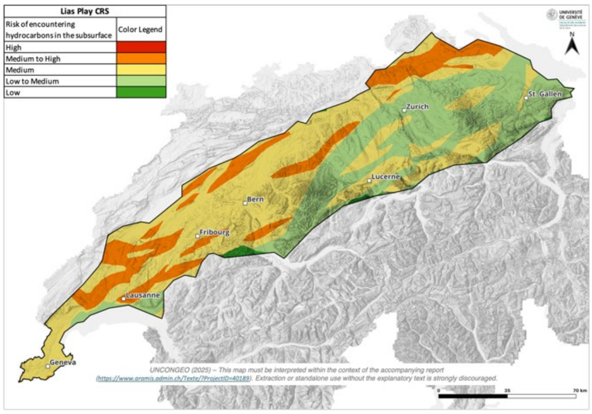


**Figure 7: Common Risk Segment map presenting the risk of encountering hydrocarbons in the subsurface for the Lias play.**

The CRS map for the Muschelkalk play is shown in Figure 8 presenting low to medium risk throughout the entire Swiss Plateau. Data and interpretations suggest that the quality of the reservoir (Muschelkalk and Bundsandstein units) is poor throughout the entire Swiss Plateau, with only a few areas exhibiting medium to high porosity. In contrast, the quality of the seal (Keuper and middle Muschelkalk units) is very good. Consequently, the resulting CRS map indicates a low to medium risk throughout the entire plateau. Medium to high-risk areas are located on the top of the Permo-Carboniferous troughs and in the vicinity of certain faults, where the risk is medium to medium-high.

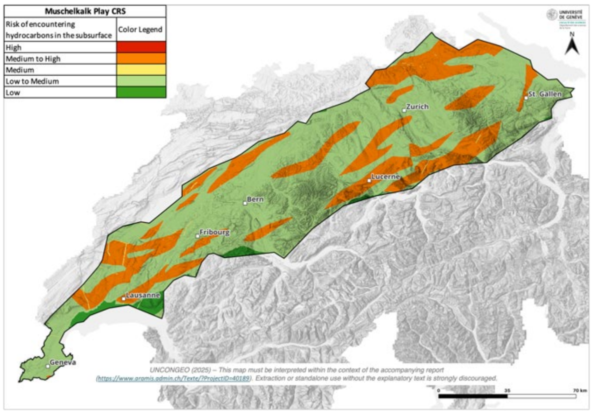


**Figure 8: Common Risk Segment map presenting the risk of encountering hydrocarbons in the subsurface for the Muschelkalk play.**

The Permo-Carboniferous play is present only in the areas where Permo-Carboniferous troughs are present. The CRS map of the Permo-Carboniferous play is shown in Figure 9. The risk to encounter hydrocarbons is medium to high in the areas where the Permo-Carboniferous troughs are located, and low to medium in the rest of the Plateau. Some areas affected by faults can present a medium risk of encountering hydrocarbons in the subsurface.

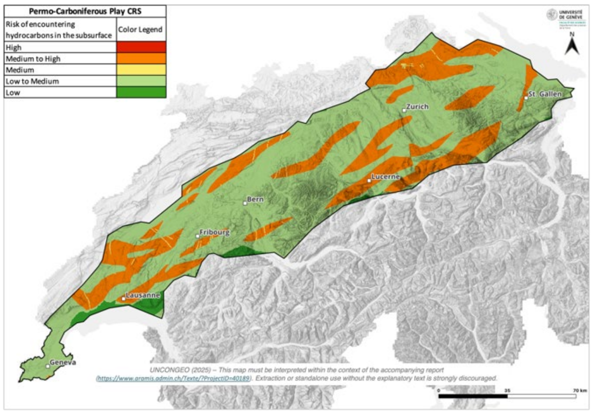


**Figure 9: Common Risk Segment map presenting the risk of encountering hydrocarbons in the subsurface for the Permo-Carboniferous play.**

### 3.5 Data occurrence and uncertainties

To visually represent the spatial distribution of the data used to build the CRS maps, a data occurrence map was produced (Figure 10). The data occurrence map was produced using borehole data, with an effective radius of 1.5 km around the drilling site: seismic data (2D and 3D), with an effective radius of 2 km on each side of the seismic acquisition.

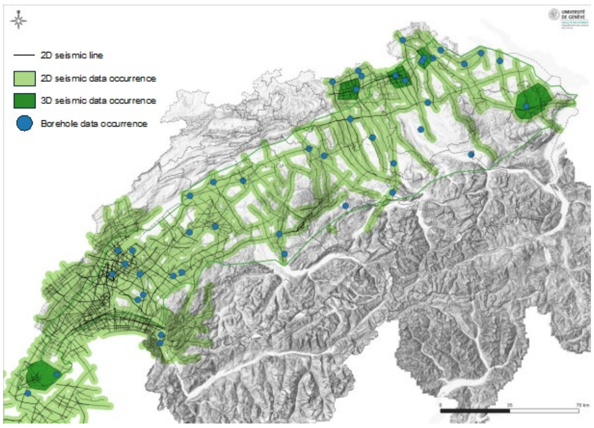


**Figure 10: Data occurrence illustrating areas with high data density contrasting with areas where data gaps are present.**

Occurrence refers to the visual representation of the spatial distribution of areas with sufficient data density where CRS maps have the less uncertainty. This map provides critical insights in defining areas of lower certainties. Geological uncertainty related to the lack of seismic or borehole data can arise primarily due to the absence of direct subsurface information, which is crucial for understanding geological structures, formations, and rock properties (e.g. reservoir porosity, seal integrity etc). Without accurate data inputs, geological models may rely on assumptions or extrapolations. This introduces uncertainties that can affect the reliability of predictions and decisions based

## 4. CONCLUSIONS

Common Risk Segment maps were produced, illustrating the spatial distribution of geological risk associated with hydrocarbons in the subsurface throughout the entire Swiss Plateau. These maps were created by integrating all the data and knowledge acquired during the petroleum system modelling. Source rock, reservoir, and seal quality assessment maps were obtained for each Play and then combined to create a final risk map. Data availability maps were also generated, indicating the occurrence and type of data used to build the assessment maps. These maps highlight the uncertainties in the calculated risk levels presented in the CRS maps due to identified data gaps.

The highest risk of encountering hydrocarbons in most plays is related to the location of source rocks. This risk can be high on top of Permian-Carboniferous grabens and in the west-northern sectors of the Plateau, where the Posidonia shale source rock is distributed. However, uncertainties in the distribution, properties, and thicknesses of these source rocks need to be considered. Fault zones also represent risk areas as hydrocarbons can migrate from the source rock/reservoir to the uppermost units. Understanding the cementation and stress state of faults is crucial to properly evaluating the risk in these areas.

Due to the general poor subsurface data coverage, the final CRS maps present uncertainties. This is due to: the extrapolation realized on scarce data in order to characterize the petroleum system at a regional scale and to our current level of knowledge of the basin's petroleum system. Therefore, special attention should be paid to the occurrence, density, and reliability of subsurface data in a specific area of interest. A poor data coverage could significantly increase the uncertainties on the risk evaluation. In most cases, further investigations and data gathering are necessary to improve our model and results on the potential presence of hydrocarbons in the subsurface.

This study's maps are valuable tools for planners and decision-makers. They allow for an initial assessment of the risk of encountering hydrocarbons at depth. These maps can then be used to propose mitigation measures, such as further subsurface studies, reprocessing of existing seismic data, and new data acquisition, to de-risk geothermal exploration activities, particularly in the vicinity of proposed drilling sites.

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