Heat production and storage in Western Switzerland: advances and challenges of intense multidisciplinary geothermal exploration activities, an 8 years progress report

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Heat production and storage in Western Switzerland: advances and challenges of intense multidisciplinary geothermal exploration activities, an 8 years progress report.

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ABSTRACT

A wide range of regional-and reservoir scale subsurface evaluation activities of geothermal energy resources and underground thermal energy storage potential have been carried in the Canton of Geneva area located in the Westernmost Swiss Molasse Basin. These activities promoted since 2012 through the 'GEothermie2020' program by the Canton authorities and SIG (Service Industriel de Genève), include both technical, regulatory and social acceptance aspects and it is aimed at implementing a nuclear-free 2050 energy strategy increasing the penetration of renewable energy sources into the energy system, and by reducing the energy consumption and the use of fossil fuels. A large data set of 2D seismic lines mostly acquired for hydrocarbon exploration carried out in the 70s and 80s, have been collected and in part re-processed. To this, additional new 2D seismic and new walk-around and walk-above VSP were acquired in selected wells in order to establish a better controls on velocity model and reservoir heterogeneity and thus set the basis for future 3D seismic acquisition. Newly-acquired gravity data, calibrated with the available deep boreholes have been integrated in a single data base which served as basis for establishing a sound subsurface stratigraphic model. The latter spans from the Permo-Carboniferous to the Cenozoic age, including potential geothermal reservoirs throughout the stratigraphic succession. The mapping of fault system and geochemical analysis of associated mineralisation has been carried out to identify deeply rooted lineaments which may connect the crystalline basement to shallower formations and thus be important conduits of geothermal fluids. Over the 8 years of exploratory study aimed at 1) identifying and assessing the geothermal play elements 2) identifying a number of most suitable subsurface targets for both heat direct-use and storage, using a play fairway analysis approach and 3) supporting further evaluation and risk assessment (including the possible undesired occurrence of hydrocarbons and induced seismic). The encouraging results of the first shallow exploration well confirm the preliminary positive evaluation of the geothermal potential of the region. However, subsurface uncertainties related to structural and stratigraphic compartmentalization and the variability of reservoir properties remain large and will be targeted by further data acquisition such as downhole geophysics, extended dynamic tests, and 3D seismic survey. These data, together with knowledge transfer from the more mature HC industry will provide the geothermal players with the necessary best practice, knowledge and workflows to accomplish successfully the exploratory of geothermal resources.

1. INTRODUCTION

The energy transition journey started by the Swiss Confederation with the definition of the Energy Strategy 2050 accepted in 2017 by the majority of the Swiss population. In this framework, two important measures have been put in place by the Federal Government through its Federal Office of Energy (SFOE) in order to provide financial support for the exploration and development of geothermal energy in Switzerland. The first measure aims at supporting Pilot & Demonstration projects covering up to 40% of the non-amortizable additional cost (i.e. costs beyond conventional technologies or systems). In this context, costs for the development, procurement and materials, construction optimization, operation, monitoring, documentation and communication are also included. This measure is available to companies, tertiary education sector (Universities, Universities of Applied Science, Federal Institutes), public entities etc. and there are no limits regarding project duration and financial scope of projects. The second measure is included in the new law (in force since January 1st 2018) aimed at reducing CO_2 emissions (aka 'CO_2 law'). According to this measure up to 60% of the prospection and exploration costs including surface data acquisition, procurement and materials, drilling operations, well testing and logging will be covered by the Confederation.

In Western Switzerland, the interest for moving the heat energy consumption away from fossil fuels towards greener geothermal energy started much earlier. The first geothermal exploration attempt in the Geneva area was made with the Thônex well drilled in 1993 following 10 years of preliminary studies (Jenny et al, 1995), which yielded commercially unsatisfactory results. In the Canton of Vaud the project in Lavey le Bains (https://www.agepp.ch/), started in 2005, where hot waters are already used for spa bathing, aims at combining heat and power from deep targets in the crystalline rocks is now entering into the exploration phase. Moreover the project 'Vinzel', at present about to enter in the execution phase, started back in 2006 and will aim at a 2'200 m target in the Mesozoic fractured carbonates (www.energeo.ch).

In 2014, 5 years before the Federal Energy Strategy 2050 become executive, the Canton of Geneva (CoG) established the basis for a long term energy strategy. The GEothermie 2020 program (Andenmatten Berthoud; 2014; Moscariello, 2016) was thus put in place by the CoG and the local energy supply company Service Industriel de Genève (SIG). Overall this cantonal program aims at three main strategic objectives 1) reduce greenhouse gases emissions and adapt to climate change; 2) reach the '2000 W Society' goals (Jochem, 2004) without nuclear energy; and 3) adopt a Cantonal concept of the environment by preserving and developing local natural resources. In this context a number of coordinated actions have been established by the CoG and SIG such as: a) control and reduce energy demand, b) develop local renewable energies, c) promoting mobility without fossil energy, d) plan energy infrastructures, and e) promote smart grids all aiming at both accelerating the ecological transition and developing geothermal energy.

Geothermal energy in the CoG is therefore one of the enabling tools, instrumental to drastically reducing the fossil fuel consumption (i.e. fuel and natural gas) which in 2014 served 92 % of the heat demand, the latter being the 52% of the total energy consumption (including biomass, gasoline, diesel, fuel, natural gas, hydroelectric and solar) of the CoG. According to the GEothermie 2020 program, the energy policy targets for the heat demand sector set for 2035 (Figure 1), aim at an overall decrease of 18% of energy consumption including a 42% decrease in fossil fuel. Renewable energy including geothermal energy would thus aim at an increase of 34% (Quiquerez *et al*. 2016). Currently, more than 50% of total final energy at Geneva is used to cover space heating (SH) and domestic hot water (DHW) demand (Figure 1). Despites the importance of the heating sector and the high heat demand density (Quiquerez *et al.*, 2016), only 10% of total thermal demand is covered by district heating networks (DH).

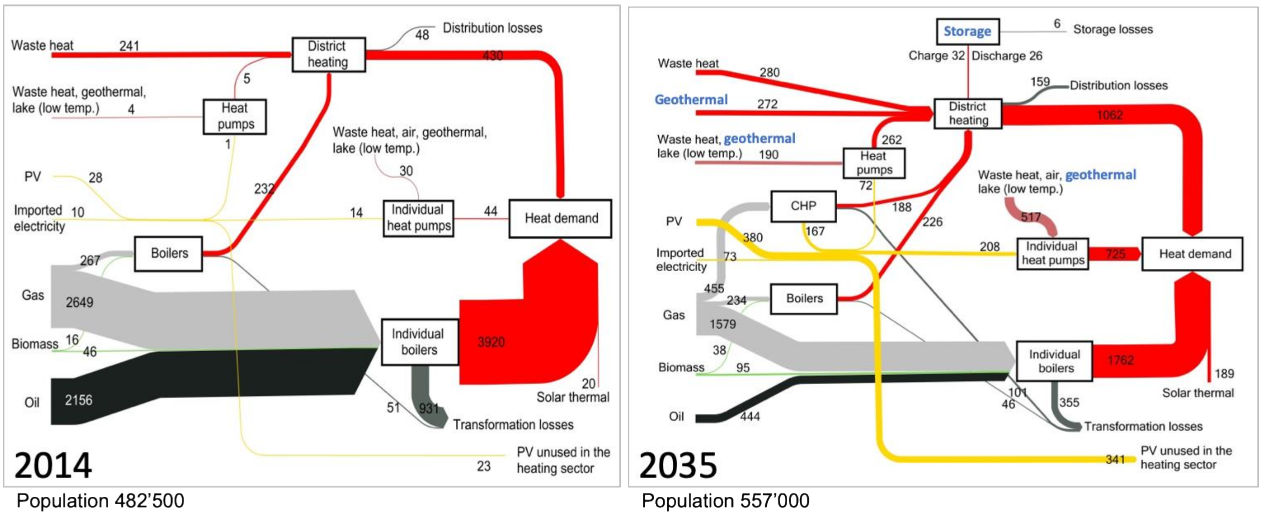

Figure 1: Heat distribution forecast for the Canton of Geneva in 2035 with a comparison to the situation in 2014 showing how geothermal energy will play an important role for district heating, heat-pumps and storage. The use of alternative source of energy in 2035 will reduce considerably the use of hydrocarbons (black and gray lines indicating Gas and Oil). Modified from Quiquerez et al., 2016.

In this paper, we will describe the progress made since 2014 in understanding the subsurface of the Canton of Geneva in the westernmost Switzerland. Over the 8 years of exploratory activities progress has been made to 1) identify and assess the geothermal play elements 2) identify a number of most suitable subsurface targets for both heat direct-use and storage, using a play fairway analysis approach and 3) support further evaluation of main subsurface uncertainties and the assessment of related risks and opportunities (including the possible undesired occurrence of hydrocarbons and induced seismic).

2. DATA

One of the first step of the GEothermie 2020 project aimed at collecting and harmonizing the large existing data set acquired in the past in the CoG and neighboring France (Brentini, 2018). These data consisted in lithological profiles and wireline logs from old hydrocarbon exploration wells (Fig. 2) mostly drilled in the neighboring France with a few deep hydrogeological and geothermal wells drilled in Switzerland. Moreover, the lithological sections established on outcrops located in the surrounding mountain areas (Jura, Salève, Vuache) since the 1950 have been compiled and their nomenclature and lithological subdivision made consistent with the Swiss Geological survey nomenclature and a new chronostratigraphic chart been proposed (Rusillon, 2018). In addition, once the compilation of all 2D seismic lines acquired over the years both for hydrocarbon and geothermal exploration was accomplished, selected lines were reprocessed improving noise signal ration and illumination of Mesozoic reservoir targets. New additional 2D seismic lines with optimized acquisition parameters were also specifically acquired in order to improve the coverage of the area of study. Over the last 8 years, a series of geophysical, hydrogeological and reservoir characterization studies have been carried out aimed at deep geological reservoir distribution and modeling (Clerc *et al.*, 2015; Guglielmetti *et al*., 2019; Guglielmetti *et al*., 2020b; Perozzi *et al*., 2020), reservoir property measurements (porosity/Phi, permeability/K, density, acoustic parameters such as Vp and Vs; Rusillon, 2018; Rusillon and Chablais, 2017; A. Zappone et al., comm. pers.), understanding the fault and fracture systems and their subsurface modeling (Mastrangelo and Charollais, 2018; Moscariello *et al.*, 2019b), quantification of fluid flow properties (TºC, flow rates, geochemistry; Guglielmetti *et al.*, 2020a), burial history, diagenesis (Rusillon, 2018; Makhloufi *et al.*, 2018), assessment of hydrocarbon potential generation (Moscariello *et al.*, 2019), and natural seismicity monitoring and ambient noise tomography (Ferreira Autunes, 2016; M. Lupi comm. pers.). All data described before form the basis of a complex data base (Brentini, 2018) whose structure and content is continuously updated with results generated from the ongoing research, including new data collection, carried out by Academia, SIG and various consultants involved in the GEothermie 2020 project.

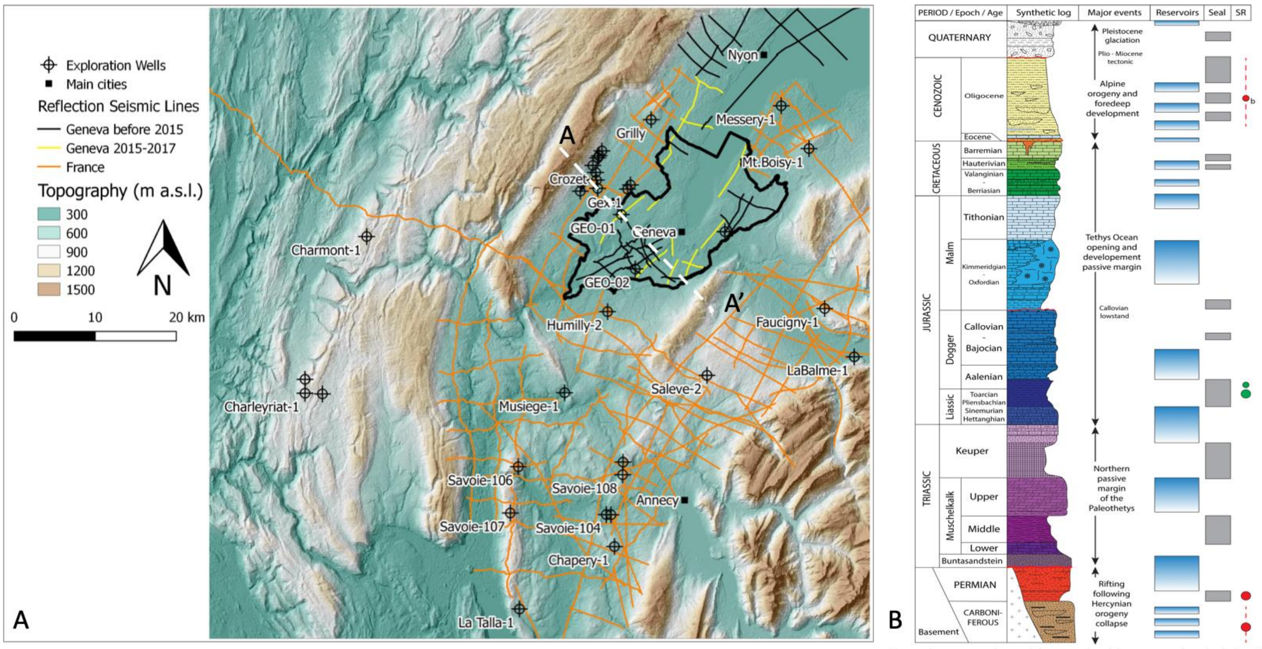

Figure 2: A) Geographic map of the western Switzerland and surrounding France with indication of wells and seismic lines available in the area of study. The A-A' trace refers to the cross- section of Figure 3; B) summary stratigraphy of the Swiss Plateau in the Geneva Basin area with indication of potential reservoirs (based on matrix properties), seals and hydrocarbon source rocks (SR). Triassic and Jurassic nomenclature includes stratigraphic subdivisions commonly used in the Swiss Plateau. SR large circle: major SR; small circle: minor SR; green: oil; red: gas; b: biogenic.

3. GEOGRAPHIC AND GEOLOGICAL SETTING

The Geneva Basin is located in the westernmost sector of the Swiss Plateau. It consists of a low relief area confined between the Salève Mountain to the SE and the folded Jura chain to the NW (Figure 2) resulting from the interplay between tectonic deformation associated with the Alpine foreland emplacement and the profound landscape modifications associated with Pleistocene glaciations and subsequent post-glacial processes (Moscariello, 2019). The geology of the basin, partly cropping out in the surround reliefs (Salève Mt. to the SE, the Vuache Mt to the SW and the Jura to the NW) consists mostly of a thick Mesozoic sedimentary succession (Figure 2), consisting 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 Palaeozoic crystalline basement with down-dropped graben filled with continental siliciclastic sediments of Permian and Carboniferous age as a consequence of the Variscan orogeny and rifting linked to post-orogenetic collapse (Figure 3). The top of the Mesozoic sequence (Lower Cretaceous in age) is marked by a regionally extensive erosive surface which formed during the general uplift of the foreland basin during the Alpine compression. Above the erosional surface, Oligocene siliciclastic Molasse are overlain by heterogeneous Quaternary glacial to glaciofluvial deposits. The generic stratigraphy of the Geneva Basin and surrounding area and synthetic geological profile across the Geneva Basin are shown in Figures 2 and 3 respectively. A short summary of the main stratigraphic element and their main paleogeographic and tectonic significance are summarized here below.

3.1 Variscan Orogeny and Post Variscan Rifting

The Geneva Basin lays over a crystalline basement resulted from the Palaeozoic Variscan orogeny (c.a. 480-250 Ma, Matte, 2001). The latter stages of this orogeny related to the continental collision between the Gondwana to the southeast and Laurentia-Baltica to the northwest, forming the supercontinent of Pangaea (Matte, 2001 and reference therein). After the main Variscan orogeny, the dextral translation of Gondwana and Laurussia and the reorganization of the asthenospheric flow patterns, caused the collapse of the orogeny and the thinning of the lithosphere and the setting of a transtensional and transpessional tectonic regime together with a strong regional thermal subsidence (Ziegler et al., 2004; Wilson *et al.*, 2004). In the Geneva Basin, predominantly NE-SW trending, elongated half-grabens in were created (McCann *et al.*, 2006). Sediments deposited during the Permian and Carboniferous could be found locally in these structures in the Humilly-2 well (Figure 2) in the Geneva Basin and other location in the Swiss Plateau (Madritsch *et al.,* 2018), which consists of mainly lacustrine and fluvial deposits eroded from the crystalline basements. Under the humid conditions in the Carboniferous times, coal beds were formed, intercalating with the above deposits. The top of the basement is characterized by an angular unconformity on which Triassic sediments were deposited (Signer and Gorin, 1995; Sommaruga *et al.*, 2017; Moscariello, 2016).

3.2 The Mesozoic sequence: evaporites and shallow marine carbonate platform

The Triassic series, unconformably overlying the basement and Permo-Carboniferous rocks, is generally divided into three intervals, namely, the Buntsandstein (continental sandstone), Muschelkalk (marly limestones, anhydrites and dolomites) and Keuper (anhydrite, salt and shale). The Early to Middle Triassic (Buntsandstein to Muschelkalk) marks a marine transgression which formed a shallow epicontinental sea. The later deposition of dolomites and evaporites (Late Triassic, Keuper) suggests a restricted marine condition with limited connection to the Tethys. The Keuper evaporites are commonly thought to represent an important décollement layer which served in the later formation of the Jura fold and thrust belt (FTB) (Sommaruga *et al.*, 2017).

The Jurassic sequence starts with a marine transgression, marked by the marly limestones deposited during the Liassic (Lower Jurassic) and the Dogger (Middle Jurassic) in a distal marine environment. In this period (Toarcian), anoxic condition occurred enabling the accumulation and preservation of organic matter-rich marine deposits. The Upper Jurassic (Malm) was characterized by an important regional marine regression after which shallow carbonate platforms, with the accumulation of massive limestone and patch reefs occurred.

The Early Cretaceous is characterized by a shallow and warm water environment, with several emersion-drowning episodes caused by low amplitude sea-level fluctuations. During this time, massive and bioclastic limestones with marly intervals were deposited. Subsequent wide marine transgression led to the deposition of pelagic chalk and limestones. These deposits were then completely eroded when the Geneva Basin came to emersion, which has caused the large-scale karstification in the Urgonian limestones.

3.2 The Cenozoic Alpine foreland: Molasse and Quaternary deposits

In early Cenozoic times (Eocene-Oligocene), the basement uplift associated with the Alpine orogeny genetically associated with the convergence of Eurasian and African plate exhumed the uppermost Mesozoic series. The latter is therefore marked by a major unconformity which was estimated to have removed ca. 1’500-2’000 m of sequence (Schegg and Leu, 1996, 1998). Karsts and fractures on the top Mesozoic were filled with Eocene lateritic sediments (Becker *et al.*, 2013) and some reworked Aptian-Albian sediments.

Sediments eroded from the rapidly uplifting Alps were deposited in the Geneva Basin, which was at a flexural foreland position at the time. In the Geneva Basin, the Lower Freshwater Molasse (LFM) which comprises alternations of sandstones and marls, directly onlaps the Early Cretaceous units or the Eocene lateritic sediments. The Upper Marine Molasse (UMM) and the Upper Freshwater Molasse (UFM) are not preserved in the Geneva Basin as they were either removed during the uplift of the Jura chain (Miocene-Pliocene) and/or the Pleistocene glacial advances (Signer and Gorin, 1995; Schegg and Leu, 1996; Charollais *et al.*, 2007) or not deposited in this area. The Oligocene Molasse deposits are in fact overlain by Quaternary glacial, glacio-lacustrine and lacustrine sediments which account for a period punctuated by several episodes of glacial progradation and retreat (Moscariello et al, 1998, Fiore *et al.*, 2011). Following the last Glacial Maximum (Moscariello *et al.*, 1998) the establishment of the present day fluvial network shaped the landscape to the present configuration (Moscariello, 2019).

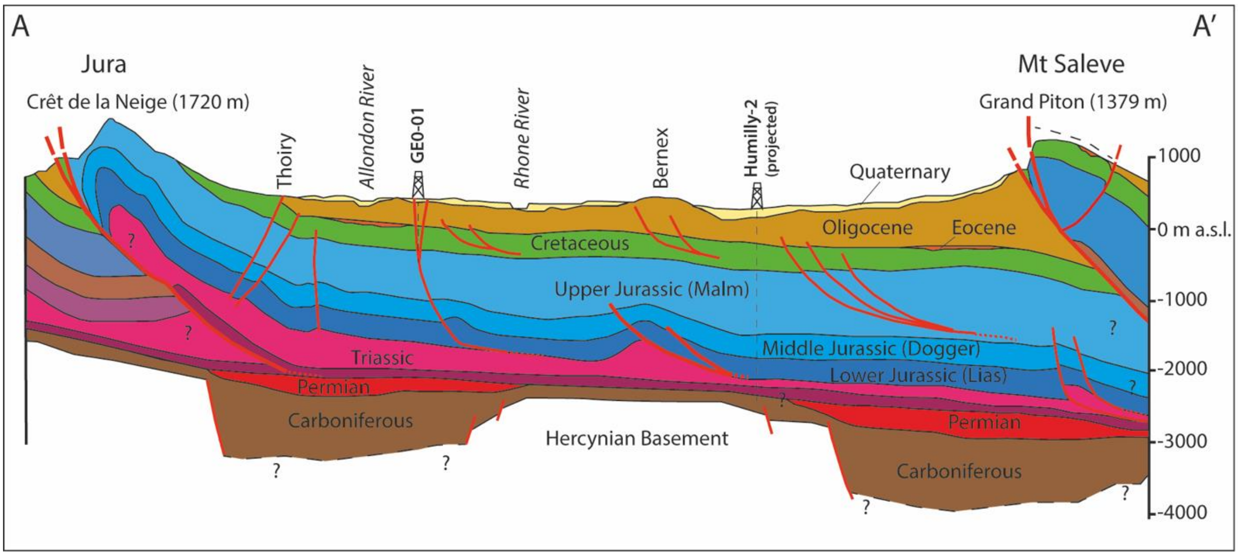

Figure 3: Geological section crossing the Geneva Basin from SE to NW summarizing the key stratigraphic and structural elements present in the basin. This section has been drawn from several 2D seismic lines and borehole data. See Figure 2 for A-A’ line trace.

4. GEO-ENERGY PLAY ELEMENTS

When exploring for geothermal energy in a sedimentary basin such as the Swiss alpine foreland, is very likely that other type of geo-energy resources such as hydrocarbons could be present in the subsurface. In Switzerland, several cases are known where both, shallow and deep geothermal wells (e.g. Schlattingen, St Gallen) encountered hydrocarbon accumulations. This often impaired and/or stopped the geothermal development or exploration activities and had negative impact on society’s perceptions influencing support for the transition towards green energy. For this reason, a comprehensive and holistic approach to subsurface geo-energy studies should be carried out considering the subsurface occurrence of all possible geofluids (water, gas, petroleum) which may be found at depth and play a conflicting role when it comes to geothermal exploration and development (Figure 4).

Positively, the well-established definition of a hydrocarbon play including the source rock, reservoir rock, seal rock and trapping mechanisms (Magoon and Dow, 1994), can be applied to geothermal exploration with play concepts which include the heat source, the reservoir rock and its heat/fluid storage capacity, and the aquiclude/seal rock. For both geo-energy the fluid migration or heat migration pathway is an additional element which is essential to understand and predict the likelihood of geo-energy occurrence in the subsurface, which is another parallel to hydrocarbon exploration concepts.

In the following paragraphs both geothermal and hydrocarbon play elements (Figure 4) will be discussed with respect the Swiss Plateau and specifically its westernmost region (Canton of Geneva).

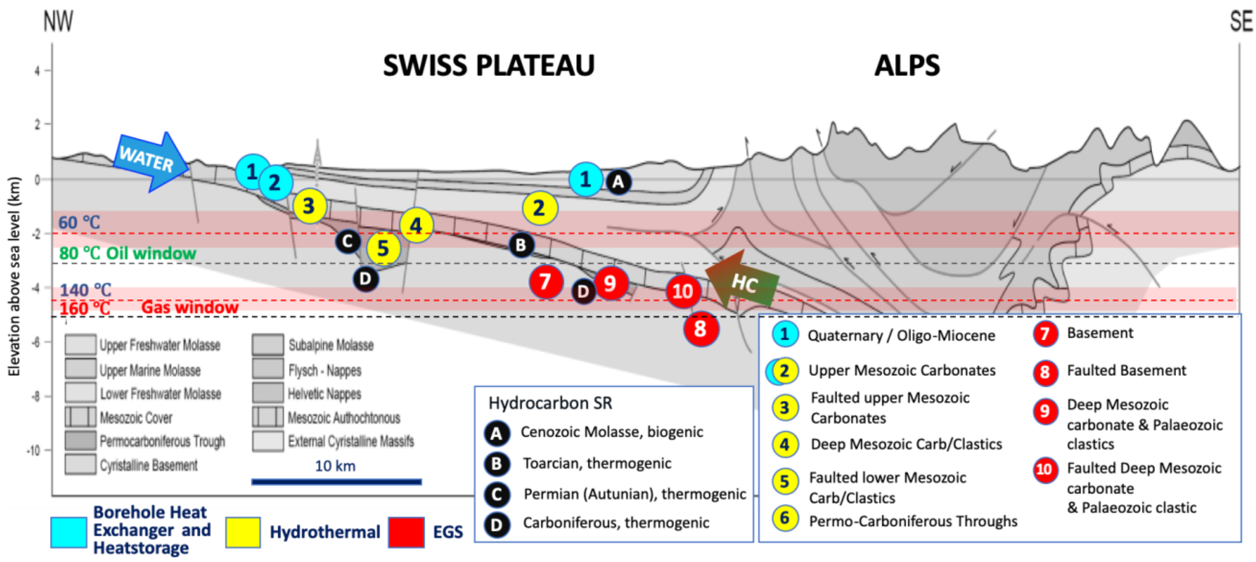

Figure 4: Summary of geothermal and hydrocarbon plays on an ideal cross section across the Swiss Plateau. The circles with numbers indicate the different geothermal plays and the type of geothermal energy utilization (borehole heat exchange, heatstorage, hydrothermal and enhanced/engineered geothermal systems. The arrows indicate the main direction of water circulation in the subsurface which is primarily opposite to the up dip migration of hydrocarbon

4.1 Geothermal Plays

4.1.1 Heat source and fluid flow

Based on a global scale perspective, comparing a large variety of geothermal systems (Moek, 2014), the geothermal processes in the Swiss Plateau, where no asthenosphere anomalies occur, are mainly conduction-dominated. The geothermal source is therefore associated with deep aquifers systems heated by a near normal heat flow which in the western Switzerland region are controlled by an average geothermal gradient of ca. 25–30°C/km. (Chelle-Michou *et al.*, 2017). The subsurface modelling of temperature distribution based on several wells in the area allowed the establishment of a number of positive and negative thermal anomalies interpreted as a result of heat advection caused by fluid circulation along faults and/or karst systems (Chelle-Michou et al., 2017). This indicates the great potential for low-enthalpy/low-temperature geothermal resources and the occurrence of advection-dominated potential targets.

Specifically, the pronounced topographic relief of the adjacent Jura mountain belt and the overall SE dipping strata as a result of the foreland foredeep located to the SE of the Geneva Basin (Figures 2 and 3), result in a groundwater flow and thermal gradient strongly influenced by large hydraulic heads which may cause artesian flows. The latter is the case of the GEo-01 borehole, an exploration well drilled in 2017 in the northwestern side of the Geneva Basin ca 5 km from the Jura first ridge. The well reached 745 m below ground floor (bgf) where it encountered fault-related fractured Upper Jurassic carbonates (Twannback Fm) which delivered 34°C warm water at artesian pressure (10 bars) and high-flow rates (50 l/s). On the other hand, the Thônex well, drilled in the southwestern part of the basin, in the foredeep location ca 20 km away from the Jura Mt, encountered the same stratigraphic units at ca. 1’822 m bgf which was tested together with deeper interval to a total depth of 2’420 m bgf. Despite the occurrence of three fractured intervals detected by bore hole image (BHI) tool, and the encouraging bottom-hole temperature of 88˚C, the well delivered 70°C warm water at very low-flow rates (3.8 l/s) during production tests. Based on stable isotope analysis on water samples, the origin of the fluids was proposed to be from the Jura reliefs and an underground residence time was estimated in the order of 10'000 to 15'000 years (Nawratil De Bono, 2011). Recent geochemical studies on water samples from boreholes and springs in the Geneva Basin (Guglielmetti, et al. 2020a) highlights that the deep water circulations have a meteoric origin and that during the circulation path, mixing processes between different end-members, including gas and hydrocarbon transport, provide geochemical facies which become more and more complex the longer is the residence time.

4.1.2 Geothermal Reservoirs

The comparison between the two well results described above, clearly attest for the complexity and variety of fluid circulation conditions occurring in the Geneva Basin subsurface. Occurrence of fracture network in the Mesozoic sequence seems 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) indicate that matrix Phi and K 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 Phi in the range of 2-5% with exceptions in the clastic Buntsandstein (Lower Triassic) reaching 10-15% (Rusillon, 2018). Matrix K varies between 0.01 and 1 mD (milli-Darceys) with exception in the Buntsandstein and dolomitized Muschelkalk (Middle

Triassic) reaching 100 mD. Primary reservoir targets represented by high Phi/high K layers may be represented by the reef complex of the Upper Jurassic, Kimmeridgian age (Etiollet Fm.; Rusillon, 2018) 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 Phi <8% and K ranging between 0.001 and 10 mD. Reservoir properties improve considerably when considering the Cenozoic series consisting both of the Eocene and Oligocene units which have not experienced the same burial history as the older strata (Schegg and Leu, 1996; Moscariello et al., 2019). These units may contain very effective reservoirs although continuity and extension may be an issue for the Eocene ‘Sidérolithique’ facies (Figures 2 and 3). 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. Phi and K in these units have values ranging between 5-35% and 1-1000 mD, respectively.

When comparing with outcrops from surrounding reliefs the Geneva Basin, reservoir properties values from borehole data show a large differences up to an one order of magnitude in K and several units of Phi. Ongoing analysis on stable isotopes (Sr, O, C) on bulk carbonate (S. Courgeon and E. Samankassou ongoing work), and vitrinite reflectance (S. Omodeo Salé, ongoing work) analysis on organic material derived from both outcrops and boreholes, demonstrates clearly the different burial history of the basin compared to the surrounding reliefs, casting doubts on the relevance of the use of outcrop data as a direct analogue of subsurface reservoir conditions.

As indicated above, the reservoir effectiveness of deeper Mesozoic units cannot rely only on primary matrix porosity. On the other hand, secondary porosity related to dolomitized and karstified intervals such as in the Muschelkalk or the upper Jurassic (i.e. Malm reef complex; Rusillon, 2018) could provide better reservoir property. Secondary porosity and permeability associated with fractures, as described above, provides therefore the necessary conditions for effective reservoir storage, connectivity and deliverability. From the experience of the GEo-01 and Thônex wells, the understanding of the nature of fracture, i.e their geometry such as spacing, orientation, continuity and type of filling, etc. is crucial for driving an effective exploration and development campaign. Related to this, the understanding of the genetic processes associated with the formation and timing of fracture networks is a fundamental step which still requires more investigation and study. The understanding of structural framework of the Geneva Basin has in fact evolved considerably in the last 8 years (Figure. 4) thanks to the increased coverage made by 2D seismic lines specifically acquired by SIG to image the CoG and surrounding French territory in support of the GEothermie 2020 project (Figure 2) and the more detailed interpretation work. From the common belief that regional low-angle to vertical strike-slip faults crossing the study area from SE to NW, likely associated with large fracture corridors (Figure 5), would represent the main structural features of the area, the accurate interpretation of 2D seismic resulted in a different view where by the structural framework would be instead characterized by shorter fault segments, both at high and low angle, oriented in both NW-SE and NE-SW directions (Figure 5). In particular, the occurrence of SE-verging low-angle fault planes with inverse slip, in some cases associated with thrust anticlines, is seen to be a prominent characteristic of the Geneva Basin subsurface (Figure 3 and 6). These latter faults, which can be detected at different stratigraphic levels where detachment surfaces can develop in conjunction with ductile lithologies (Figures 3 and 6) are responsible, together with regional transpressive faults such as the Vuache Fault (Figure 5) for the overall shortening and anti-clockwise rotation of the Jura FTB which occurr in the westernmost Swiss Plateau region (Affolter and Gratier, 2004; Moscariello et al., 2019b). This new model could have important implications for fluid-flow circulation in the subsurface for both geothermal and hydrocarbon fluids (see below). This alternative advanced model (i.e . 2019 in Figure 5) seems to be more appropriate and consistent with the available data, although many uncertainties still exist with respect to the spatial orientation and lateral continuity of these structural elements and their kinematic and temporal evolution. These parameters will have, in fact, a critical impact in predicting the nature of associated fracture network and thus, establish a solid predictive model to steer an effective exploration campaign.

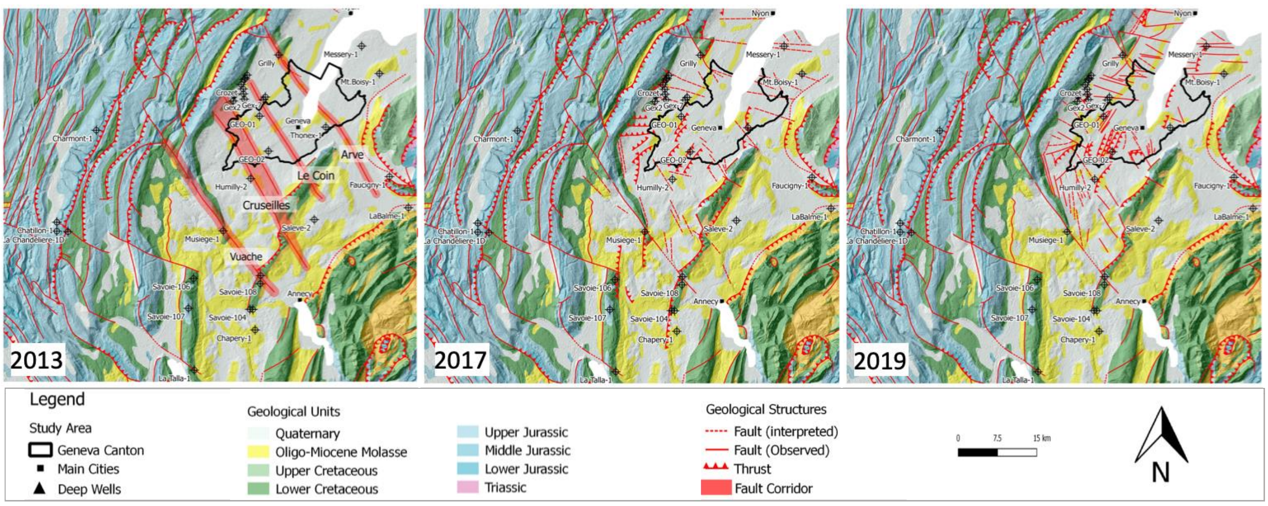

Figure 5: Comparison of fault distribution in the Geneva Basin area based on the different and evolving views over the last 8 years (2013, 2017 and 2019). A higher complexity than previously thought seems to characterize the subsurface which will have important implications for effectively exploring and developing geothermal resources.

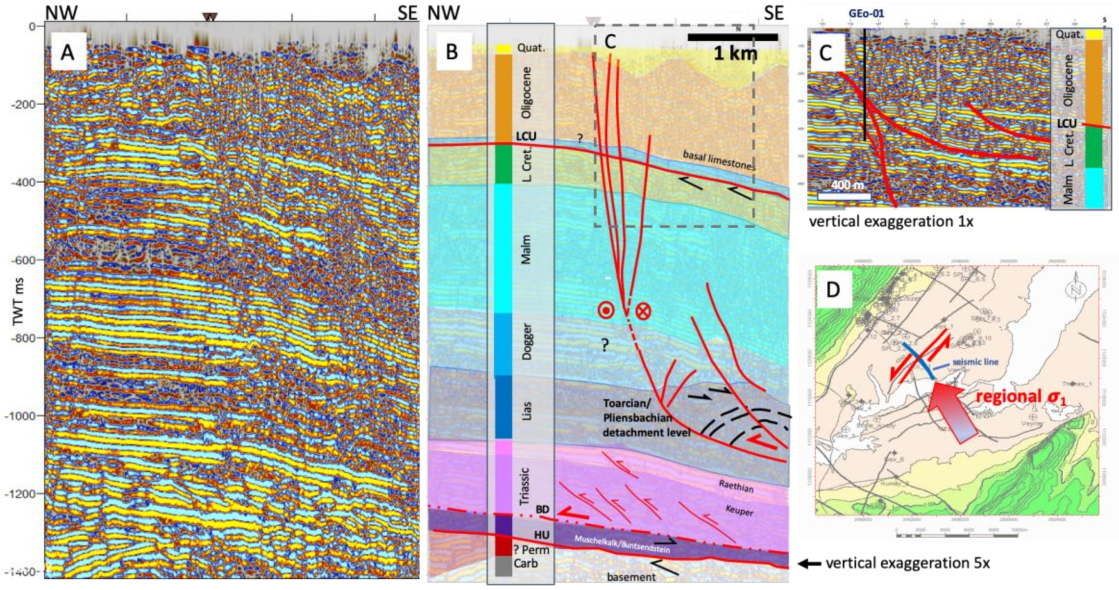

Figure 6: Example of structural deformation observed in the Geneva Basin subsurface. High lo low-angle inverted faults generates in correspondence of ductile shale-rich stratigraphic units (i.e. Toarcian or Pliensbachian shales and shale-rich units within the Lower Cretaceous interval) accommodate the shortening and rotation occurred in the Geneva Basin during the Alpine compression. A) 2D seismic profile (PreSTM – Relative Acoustic Impedance) and B) its interpretation (vertical exaggeration 5x). The little vertical displacement along the main fault can be explained by a strike slip movement along the fault plane itself which is consistent with the regional anticlockwise rotation. C) a detailed of the Lower Cretaceous interval affected by small offset low angle fault; D) tentative kinematic reconstruction of explaining faults and folds observed in seismic. LCU: Lower Cretaceous unconformity; BD: basal detachment; HU: Hercynian unconformity.

4.1.3 Geothermal Aquicludes/Seal

The current knowledge on reservoir quality and property distribution of the Mesozoic succession suggest that very little contrasting matrix properties exists in the overall strata which would enable a clear distinction between reservoir and aquicludes. The potential Mesozoic reservoirs have low Phi and K values (see above) which may not be able to ensure high connectivity and thus high water flow rates needed for geothermal exploitation. In addition, the shale-rich intervals existing in the Lower and Middle Jurassic (Pliensbachian, Toarcian, Oxfordian, Bajocian shales and marls) and the evaporites layers in the Upper Triassic (Keuper salt and anhydrites) represent basin-wide seals. Fault systems and associated fracture network cross cutting the basin stratigraphic succession provides therefore the connectivity needed to allow advective heat transport from the deeper to the shallower parts of the studied foreland basin, thus warranting continued optimism for geothermal exploitation.

4.2 Hydrocarbon Plays

4.2.1 Source rocks and migration

Several lithostratigraphic units which occur in the Swiss Plateau subsurface contain hydrocarbon source rock intervals. Typically they are from older to younger, the 1) Carboniferous coals; 2) Permian, Autunian lacustrine shales; 3) Lower Jurassic, Toarcian organic rich Posidonia shales (or Schistes Carton in the neighboring France), 4) Middle Jurassic, Aelenian Opalinus shales 5) Cenozoic, Rupelian shales in the Molasse units. On the basis of recent geochemical and vitrinite reflectance analysis performed on these source rock units (Schegg *et al*., 1999; Leu and Gautschi, 2014; Moscariello *et al.*, 2019b), the Autunian, Carboniferous and Toarcian source rocks represent the most prominent units which contains sufficient total organic carbon (4.3% TOC) and have reached thermal conditions enabling the generation of hydrocarbons (oil-window thermal conditions). But the Aelenian Opalinus shales, despite probably having reached the thermal conditions to expel hydrocarbons, have a very low TOC values (0.6 %). In the Molasse units in the Swiss plateau the Rupelian shales, probably absent in the Geneva Basin, can reach 4% TOC (Eichentopf *et al*., 2019) and represent, therefore, a fair hydrocarbon source rock if reaching the right burial depth. Organic material within the Molasse may also generate biogenic gas as often recorded in shallow boreholes drilled for both hydrogeological and heat pump installations (Moscariello *et al*., 2019a).

In the Westernmost Swiss region, similarly to the rest of the Swiss Plateau, the thermal conditions and source rock maturities vary depending on the location with respect of the foredeep. Closer to the Alpine front, where the burial of Mesozoic and Cenozoic reaches the maximum depth (3-4 km), the gas window or over maturity is likely to occur for the deeper Permo-Carboniferous source rocks. On the other hand, the source rock units located in the up-dip profile, affected by the forebulge uplift and here located at the foothills of the Jura FTB, may be immature or in the oil window (Figure 7). In the Geneva Basin, the foredeep is located at the front of the Salève Mt where a gravity anomaly (Guglielmetti *et al*., 2020b) and seismic data suggest the presence of a deeply buried Paleozoic graben, most likely filled with Permian and Carboniferous rocks (Figure 3). Geochemical analyses suggest that all source rocks contained in these units are located in the gas window (Moscariello et al., 2019b). The same rocks may be in the oil window up-dip to the NW, i.e., at the foothills of the Jura where the Permo-Carboniferous graben are structurally shallower (Figure 3; Mugnier *et al*., 1996).

Migration of hydrocarbon from the source rocks to the higher stratigraphic levels occurs up-dip, mostly following the regional trend i.e. from SE to NW. The most effective migration paths are likely represented by high-angle faults and associated fracture networks crossing the basin (Figure 7). Despite the uncertainties related to the understanding of the structural framework, most direct observations of hydrocarbon at surface (oil seepages or gas findings in shallow boreholes) have occurred in the northwestern sector of the CoG (Figure 7). This, together with biomarker analysis (Moscariello *et al.*, 2019b), provides an indirect evidence of the migration from the kitchen (Magoon and Dow, 1994) located in the foredeep situated at the NW foothill of the Salève Mt (Figure 3). In addition, detachment surfaces represented by the Toarcian (source rock) and Pliensbachian shales can be locally the origin of low angles thrust planes (Figure 6) which can provide preferential migration paths for hydrocarbon from deep to shallower layer, up to the surface (Moscariello *et al.,* 2019a).

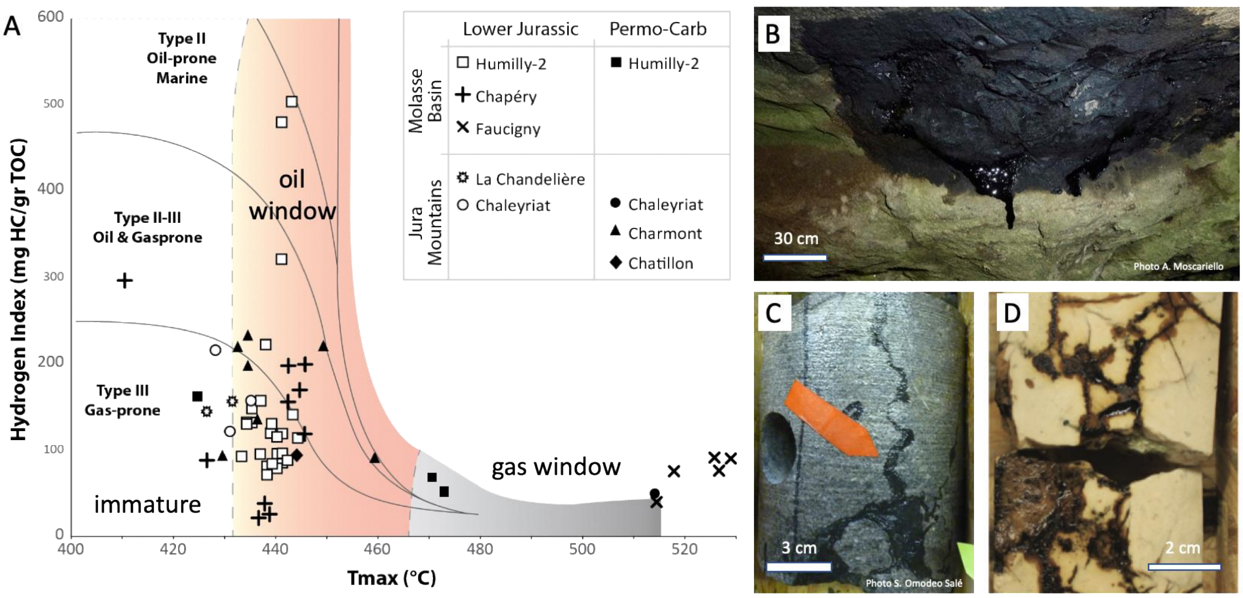

Figure 7: A) Hydrogen Index vs. Tmax graph outlining the kerogen types and level of maturity of the two main source rocks occurring in the Geneva Basin (modified from Moscariello et al, 2019b); B) oil seepage associated with fracture affecting the Oligocene Molasse sandstone (Roulavaz river, Allondon); C) oil impregnated limestones at a depth of ca. 1'850 m bgf providing evidence of deep oil migration across Middle Jurassic carbonates (well Humilly-2); D) oil impregnated fracture in the Urgonian limestones at a depth of ca 200 m bgf (Lower Cretaceous, well GEX-06)

4.2.2 Reservoirs units

As described before very few stratigraphic units may represent very high-quality (i.e. Phi 10-20% and K 100-1000 mD) matrix properties for geothermal reservoirs. Exception to this may be the Buntsandstein (Lower Triassic) and, if affected by secondary porosity, i.e.. development of diagenetic enhanced pore space and karstic cavities, a few carbonate units such as the Muschelkalk, Oxfordian carbonates, Malm reef complex (Figure 2). On the other hand, low matrix Phi and K values may be sufficient to be relatively effective for hosting gas accumulations. In this perspective, the Permo-Carboniferous sandstones could be considered potential tight gas reservoirs. In all cases, fracture network associated or not to fault zone may certainly improve reservoir quality although compromising at the same time the seal integrity (see below).

4.2.3 Trap and Seals

The uncertainties inherent with the detailed understanding on the subsurface geometry of lithostratigraphic units and fault pattern distribution, orientation and kinematics, still leaves doubts about the possibility of occurrence of effective subtle 4-way dip closures or fault-bounded 3- or 2-way-dip closures in the Jurassic and/or Triassic sequences. In the case of the Jura or Salève Mt., the regional dip and thrusting at the Lower – Middle Triassic level (Figure 3), can produce a viable reverse fault-dominated trap without folding at the relevant reservoir-seal interval while minor footwall drag can provide a viable trap sealed by an overlying thrust fault (Biddle and Wielchowsky, 1994). Stratigraphic traps may be associated with Buntsandstein and Permian and Carboniferous reservoirs within the graben.

Several stratigraphic units have the lithological characteristics (property and thickness) and lateral extension to be considered potential effective seals (Fig. 3) allowing hydrocarbon trapping. However, the large density of faults affecting the entire stratigraphic succession in the study area may have dramatically impaired the seal integrity and hence its retention effectiveness. The ineffectiveness of this important play element explains partly the long history of unsuccessful hydrocarbon exploration carried out between the 1960s and the 1980s in the Swiss Plateau and neighboring France.

5. SUBSURFACE UNCERTAINITIES, RISKS AND OPPORTUNITIES

Since the onset of the GEothermie 2020 program the understanding of the subsurface in the westernmost part of the Swiss Plateau has considerably improved. The study of vintage data, integrated with those provided by new geophysical and drilling campaigns has provided a better comprehension of important aspects of the subsurface such as the overall large-scale regional distribution of key lithostratigraphic units, the reservoir potential of possible key units such as the Malm reef complex, etc. On the other hand, these studies have also highlighted the knowledge gaps and the uncertainties related to various aspects which may impact negatively or positively, the effective exploration and development of geothermal resources.

The uncertainties related to the GEothermie 2020 program can be grouped in various categories referring to their technical, commercial organizational, economic, environmental, social, and political aspects. As far as the technical uncertainties are concerned, they include both subsurface and surface engineering aspects which are, at this point in time, not fully understood and mastered. Each uncertainty associated with a geo-energy project may lead to a risk or/and an opportunity which need to be assessed and ranked with respect to each specific project's objectives (i.e. data acquisition or drilling objectives i.e. stratigraphic calibration vs resource exploration etc.). Uncertainties, risks and opportunities are therefore linked to a specific project and may not be all relevant at the same time.

Considering the subsurface aspects, the geological uncertainties refer to the understanding of key reservoir aspects such as sedimentary, geometric and architectural characteristics controlling aquifer dimension and connectivity. Petrophysical uncertainties refer to those parameters which control fluid flow such as Phi and K related to both primary (sedimentary) and secondary (diagenesis, karst, and fracture) processes. Fluid-flow uncertainties refer to those related to the understanding of how temperature and fluids, both water and hydrocarbons, are distributed in the subsurface and those aspects which refer to the processes associated with the flow from subsurface to surface. Related processes associated with fluid production such as scaling, corrosion etc. are also part of those uncertainties which may have a strong impact on surface facilities (i.e. heat production and distribution systems).

Mitigation actions can be put in place to reduce the possible risk associated with each individual uncertainty. Specifically regarding the subsurface, these often consist of new data acquisition, provided that the financial investment is justified by the value added by the new acquired information and the perceived gravity of the possible associated risk. Equally important is the identification and development of more solid conceptual models based on relevant analogues from what are thought to be similar geothermal systems (i.e. Bavarian Upper Jurassic play, Paris Basin Dogger play).

A non-exhaustive list of key uncertainties and related risks and opportunities focusing on subsurface parameters which to date are considered the most critical ones is presented in Table 1.

The effective development of geothermal energy in the CoG by reducing subsurface uncertainties is critical as it will have a double importance in the future cantonal energy system: i) underground heat will be directly or indirectly (temperature upgrade by heat pump) injected on the DH; ii) available heat surplus on the DH could be stored into underground geological units (Koornneef *et al.*, 2019).

From a surface engineering and energy system point of view, in the 2035 scenario (see above, Fig. 1) the main uncertainty which may represent a major blockage in enabling direct integration of geothermal energy in the existing system, is the current level of the DH temperature. Today, in fact, the largest thermal network in the Geneva area operates on a 120°C/75°C regime, which, based on average geothermal gradient of 25-30°C/km (Chelle-Michou *et al.*, 2017) may require an underground exploitation at a depth of 2'000-2'500 m or deeper. In this case the geothermal fluid temperature would be below the DH return temperature, heat pumps will be required to supply the network, thus entailing an additional electrical consumption.

Underground thermal energy storage (UTES) integration is also constrained to DH temperature levels; however, other uncertainties must be taken into account. The UTES charging/discharging energy must be well constrained as the DH must be able to accept the extra energy from the UTES; charging energy must be available at relatively low cost in order to ensure the economic feasibility of the project, and energy losses and UTES efficiency must be evaluated during project phase. In addition, the use of UTES to increase the geothermal power at lower cost (e.g., the Dutch project described in Koornneef *et al.*, 2019) could be considered, in order to reduce DH costs (Salo *et al*., 2019) and increase the operating duration of renewable capacities.

6. CONCLUSION AND PERSPECTIVES

By 2035, the development of DH coverage is envisaged to supply more than 30% of total CoG heating demand, with at least 80% of it supplied by renewable energies (Fig. 1). The DH role is therefore key for renewable energy integration. After overcoming some technical, spatial and economic constraints (Quiquerez *et al.*, 2016), allow the geothermal energy at different temperatures to play an important role in the overall energy supply portfolio.

In this context the progress made over the last 8 year in investigating the subsurface in order to identify the best targets for geothermal energy exploration and production, using a play approach, have been remarkable. Yet, several key uncertainties specifically related to the subsurface (i.e. matrix vs fracture porosity magnitude, location and connectivity) are still being addressed by a series of initiatives which integrate the work of academia, industry and subsurface consultancy companies.

The strong and long-term commitment from the Canton of Geneva and local energy industry SIG, together with the Federal financial measures to support concrete actions toward a cantonal and national energy transition, have enabled the Geneva Basin to become a world class center of active international research and development in geothermal energy. A series of pilots and demonstration projects have been initiated and will be implemented in the course of the next 1-3 years including new stratigraphic and exploration wells, advanced geophysical surveys including downhole fiber optic installation, a large cross French-Swiss border 3D seismic survey, passive seismic monitoring, extended dynamic tests, water geochemical sampling, etc.

These new data leading to an improved knowledge of the Geneva Basin geothermal systems, together with the integration of innovative specific geothermal technical solutions (logging tools and well drilling and completion technology) with experience transfer from the more mature hydrocarbon industry will provide the geothermal players with the necessary best practice, knowledge and workflows to accomplish successfully the exploratory of geothermal resources. The years to come will therefore be very important for demonstrating the importance of geothermal energy in the overall energy demand of the CoG. The success of these ambitious project will set an positive example for the rest of Switzerland and neighboring France in demonstrating how the integration of several actors, including industrial, academic, economic, societal and political interests, can be aligned to move forward with concrete action towards an overall cleaner and renewable energy supply.

Category	Uncertainity	Level of Uncertainity	Risk	Opportunity	Mitigation action
Reservoir Geology	geometry and distribuiton of Quaternary aquifers	low	negative impact, i.e., contamination by deeper fluids of main freshwater resources hosted in the Quaternary units	suitable for Ground Source Heat Pump utilizations	Revision of the Quaternary 3D model by acquisition of new geophysical data (gravity, seismic, electric?)
	presence of porous sandstones in the Cenozoic Molasse	Medium	under- or overestimation of reservoir properties could lead to wrong conceptual model and consequent inadequate definition of drilling targets and type of production development (i.e. heat production vs storage)	suitable for heat storage	better image of subsurface (i.e. seismic)
	large karst occurrence	medium	drilling and logging, managing large water flow	high water flow rates	improve analogue model and imaging of top Cretaceous
	small karst occurrence	high	limited effective reservoir dimension	moderate to high water flow	improve analogue model and imaging of top Cretaceous
	dimension and geometry of individual Malm reef complex across the basin	medium	under- or overestimation of dimensions could lead to wrong conceptual model and consequent inadequate definition of drilling targets and production development (i.e. heat production, heat storage)	reef complex may be connected through fault and fracture network to larger deeper reservoirs. If isolated can be an excellet reservoir for heat storage	improve analogue model and imaging of top Jurassic
	large production from Dogger	medium	difficult to drill and log and, managing large water flow	high water flow rates	better image of subsurface, improve analogue model and imaging of Dogger
	production fromTriassic units	high	drilling and logging, managing large water flow, potentially high salinity fluids, scaling/corrosion problems	high water flow rates potentially favourable for large heat production	better image of subsurface (i.e. 3D seismic)
	production from Permo-Carboniferous	high	drilling and logging, HC occurrence, unknown presence of geothermal fluid	high temperatures potentially favourable for power production	better image of subsurface (i.e. 3D seismic), combined petroleum system and geothermal models
	production from fault-related fracture	low	drilling risk, induced seismicity depending on producing interval depth, faults can allow HC-rich deep waters upflow, fractures can be sealed	high flow rates and circulation of hot water from deeper subsurface	better image of subsurface (i.e. 3D seismic)
	fracture orientation	high	not efficient well design	not optimized production, learning on structural	borehole images acquisition, develop predictive model and upscaling at reservoir scale
	non connected (open) fracture network	high	low o no well deliverability	learning about subsurface	borehole images acquisition, develop predictive model
	dolomitiation not widely spread in the subsurface	medium	well deliverability negatively affected	learning about dolomite distribution in the subsurface	acquire cores on interval of interest
Petrophysics	not accurate Phi/K distribution	high	not accurate geological model and poor identification of well targets	learning about K/Phi distribution in the subsurface	acquire cores and Phi/K logs on intervals of interest; establish a sound analogue data base
	relevance of Phi/K from outcrop	high	not accurate geological model and prediction of well deliverability	learning about geometry and dimension considering paleogeographic setting despite different diagenetic overprint.	acquire cores and Phi/K logs on intervals of interest; establish a sound analogue data base
Fluid Flow	thermogenic gas saturation	medium	impaired well performance	learning about deep gas circulation in the subsurface and improving predictive model	improve gas migration and saturation predictive model i.e. migration paths
	geothemal gradient distribution	medium	existing estimate is inaccurate leading to wrong predictive modelS	learning from new data about deep fluid circulation and improving predictive model	improve predictive model integrating new results
	finding artesian flow	medium	impaired heat storage	high water flow rates and	improve predictive model integrating new results
	large hydrocarbon occurrence	low	drilling hazard manageable, permanent stop of drilling activities, possible negative social impact	learning from deep HC circulation in the subsurface and improving predictive model	improve predictive model by acquiring HC samples and better imaging/quantifying source rock within deep stratigraphic units
	small hydrocarbon occurrence	high	drilling hazard manageable, temporary stop of drilling activities	learning from deep HC circulation in the subsurface and improving predictive model	improve predictive model by acquiring HC samples and better imaging/quantifying source rock within deep stratigraphic units
	geochemical composition of deep geothermal waters	medium	mixing processes can occur between shallow and deep high saline brines, scaling/corrosion/precipitation/dissolution problems, Gas HC can be dissolved in deep fluids	constraining the geocemical composition of deep fluid to prevent environmental and technical impacts, learning from deep circulation in the subsurface and improving predictive model to assess the geothermal potential of deep targets	improve hydrogeological and geochemical models with repeated sampling campaigns, including new data from new wells when available, including production tests and monitoring P/T/chemistry evolution in surrounding areas

Table 1: Non-exhaustive summary table of uncertainties, risks and opportunities and their relative ranking related to geological, petrophysical and fluid-flow aspects.

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