Exploring for geo-energy resouces in the Geneva Basin (Western Switzerland) : opportunities and challenges

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Exploring for geo-energy resources in the Geneva Basin (Western Switzerland): opportunities and challenges

Andrea Moscariello [1]

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Abstract

A regional-scale evaluation of geothermal energy resources and subsurface heat-storage potential are being carried in the westernmost part of Switzerland and the nearby surrounding France (Haute-Savoie and Ain Departments) in the framework of the 'GEotherme2020' and Swiss national SCCER SoE programs. These activities are promoted by the Canton authorities and the Services Industriels de Genève.

A large data set of 2D seismic lines from different surveys and vintages have been collected, in some cases, reprocessed and integrated in a single data base with newly acquired seismic and borehole data. This forms the basis for the definition of the subsurface stratigraphy and the identification of regional variability of key geological formations. The latter span from the Permo-Carboniferous to the Cainozoic time period, including potential geothermal reservoirs such as the Palaeozoic and Triassic sandstones and several limestones intervals throughout the Mesozoic series.

A detailed mapping of fault systems is being carried out with specific focus on the deeply rooted lineaments which may allow connectivity between the crystalline basement and shallower stratigraphic formations. In particular, attention has been given to the lineaments controlling the Permo-Carboniferous extensional structures and their possible reactivation at later stages during the Alpine inversion and the present day tectonic regime as normal, inverse or transpressive faults.

Downhole temperatures from deep boreholes drilled in the study area suggest a gradient ranging between 25 and 30 °C/km. These data have been used in junction with regional and newly acquired Bouger-anomaly gravity maps, distribution of historical and recorded earthquakes epicentres and results of ongoing passive seismic monitoring.

The ongoing examination of these different data sets aims at definig both geothermal and hydrocarbon plays in support of further evaluation and risk assessment, including the possible undesired occurrence of hydrocarbons, of the regional geothermal potential. This will ultimately assists in the identification of a number of most suitable subsurface targets for both direct use of heat and heat-storage.

[1] Department of Earth Science, University of Geneva. Rue des Maraichers 13 - 1205 Geneva (Switzerland) andrea.moscariello@unige.ch

1 Introduction

Geological investigations aimed at exploring for geo-energy resources (i.e. hydrocarbon or geothermal) in the Western Switzerland started during the First World War (Heim and Hartmann, 1919) when increased prices for crude oil and its crude products rose the question of security of supply and risks associated with dependency on foreign countries (Widmer, 2016). At that time, oil-impregnated sandstones and asphalt deposits occurring in the area of Dardagny (Fig. 1) had already been described by J.-P. Horneca in 1769 and H.B. De Saussure in his famous «Voyage dans le Alpes» published in 1770 (cfr. Girard, 1913; Lagatola, 1935). These hydrocarbon were in fact extracted already in the 1870s when they were used mostly for heating and impermeabilization of roofs and Geneva lake's boats.

Several years later, in the 1960's early 70s, exploration wells were drilled France to the South and SE of the Canton of Geneva, in the neighbouring Haute Savoie region (France) essentially aiming at anticlinal structures (Humilly-2, Savoie and Faucigny wells, Fig. 1). They generally yielded disappointing results with very minor oil and gas shows within tight reservoirs in the Mesozoic carbonates. In the Geneva Basin, the Humilly-2 well reached the Carboniferous sandstones but no hydrocarbon discovery was made. At the beginning of the 1980's, a series of shallow wells were drilled in the Pays de Gex region (France) along the northwestern border with Canton of Geneva (CoG, Fig. 1). These wells aimed at testing oil accumulations which were found with high viscosity (14 °API) in Oligocene fluviatile sandstones and «Urgonian» Lower Cretaceous limestones. At that time, these accumulations were not considered commercial and all wells were abandoned. After these latest unsuccessful efforts the hydrocarbon exploration in western Switzerland and neighbouring France was almost abandoned[1] also as a consequences of more promising discoveries made in other parts of Europe (e.g. North Sea) where most of the industry interest was focused.

In the same period, the CoG promoted a series of geological studies to investigate the possibility to move the heat energy consumption away from fossil fuels towards greener geothermal energy. In 1993, following 10 years of preliminary investigations (Jenny et al, 1995), the first geothermal exploration well in the CoG was drilled (Thônex-1 well) which yielded commercially unsatisfactory results. Almost twenty year later, in 2014, 4 years before the Swiss Federal «2050 energy strategy» become executive[2], the 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 Services Industriels de Genève (SIG). Overall, this cantonal program aims at reducing greenhouse gases emissions and adapt to climate change; reaching the «2000 W Society» goals (Jochem, 2004) without nuclear energy; and adopting a Cantonal concept of the environment by both preserving and developing local natural resources (Quiquerez et al. 2016; Moscariello et al, 2020). In parallel to the GEothermie 2020 program other national (SCCER SoE[3]) and international projects (HEATSTORE[4] within the EC GEOTHERMICA framework program) were carried out and followed making the Canton of Geneva a real-scale field laboratory for geothermal exploration.

In this paper, we will describe the main geological features of the Geneva Basin and their relevance for geothermal exploration emphasizing those aspects which have improved the knowledge of the subsurface by implementing a multidisciplinary integration of existing and newly acquired data, information and knowledge. In particular this paper will address the geo-energy play elements and highlighting the most suitable subsurface targets for both heat direct-use and storage, using a play fairway analysis approach. The main subsurface uncertainties and leading to the identification of risks (including the possible undesired occurrence of hydrocarbons and induced seismicity) and opportunities will be also discussed.

[1] At the end of the 80s- and early 90s two more wells (La Balme-1 and Brizon-1, See Fig. 1) located at the front of the Subalpine were drilled also yielding disappointing results (Charollais et al., 1996). In the early 2000 in western Switzerland hydrocarbon exploration licences were then granted in the Canton of Neuchatel, Vaud and Geneva. These licences, today expired, were not followed by any actual exploration activity (seismic acquisition, wells etc.) with exception for the deep well Noville-1, located in the easternmost side of Lake Geneva.

[2] The «2050 energy strategy» was accepted by 58.2% of the population in a popular vote on May 21, 2017, and the new legislation came into force in 2018.

[3] http://www.sccer-soe.ch/en/home/

[4] https://www.heatstore.eu/

2 Data

One of the very first activity initiated in the context 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 (Fig. 2; Brentini, 2018). These data consisted in lithological profiles and wireline logs from old hydrocarbon exploration wells 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 ratio 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 understanding and modelling the deep geological reservoir distribution (Clerc et al., 2015; Guglielmetti et al. 2020a, b; Perozzi et al., 2020), and allowed the collection of 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 subsur-

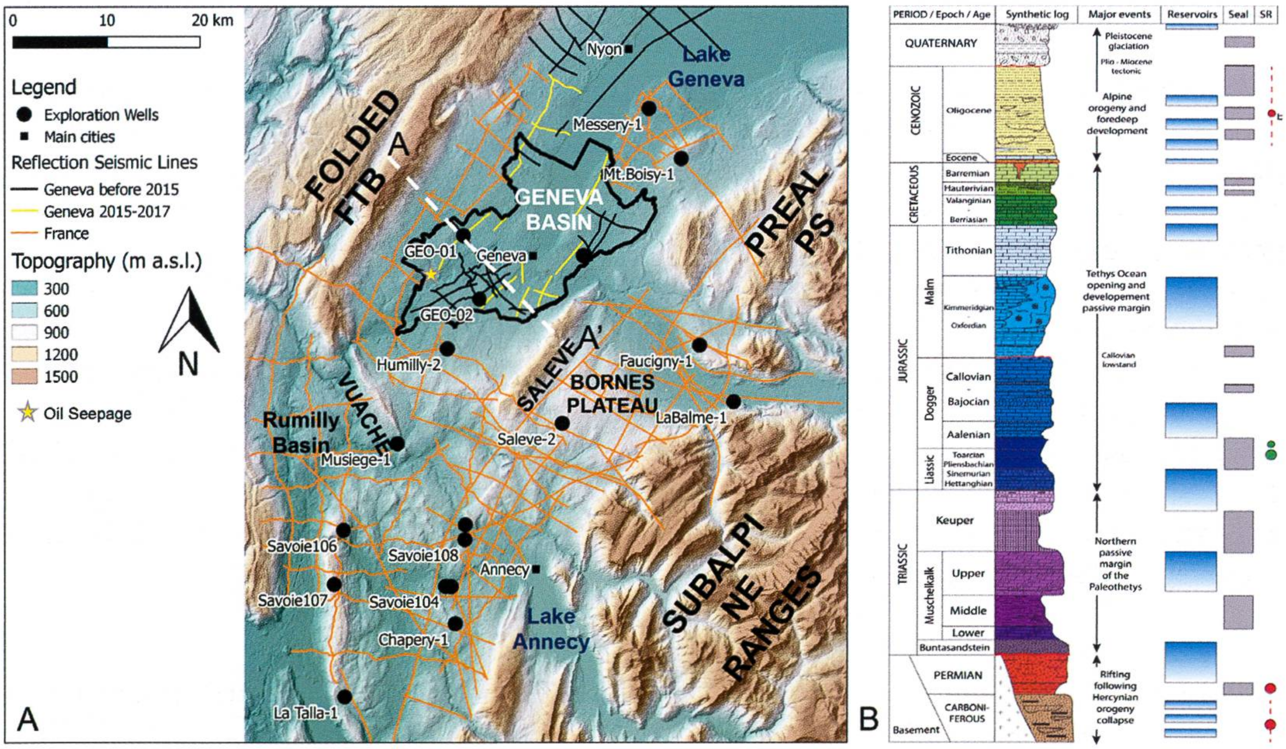

Fig. 1: A) Geographic map of the western Switzerland and surrounding France with indication of wells and seismic lines available in the area of study. The A-A' trace refers to the cross- section of Figure 3; B) summary stratigraphy of the Swiss Plateau in the Geneva Basin area with indication of potential 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.

face modeling (Mastrangelo and Charollais, 2018; Moscariello et al., 2019b), characterising of fluid flow in the subsurface and quantification of their properties (resistivity trends, T ºC, flow rates, geochemistry; Carrier et al., 2019; Guglielmetti et al., 2020a), burial history, diagenesis (Rusillon, 2018; Maklohufi et al., 2018), assessing the potential of hydrocarbon generation (Moscariello et al., 2019a), and monitoring natural seismicity and ambient noise tomography (Ferreira Autunes, 2016). 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.

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 (Fig. 1) 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 (Fig. 1), 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 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 (Fig. 3).

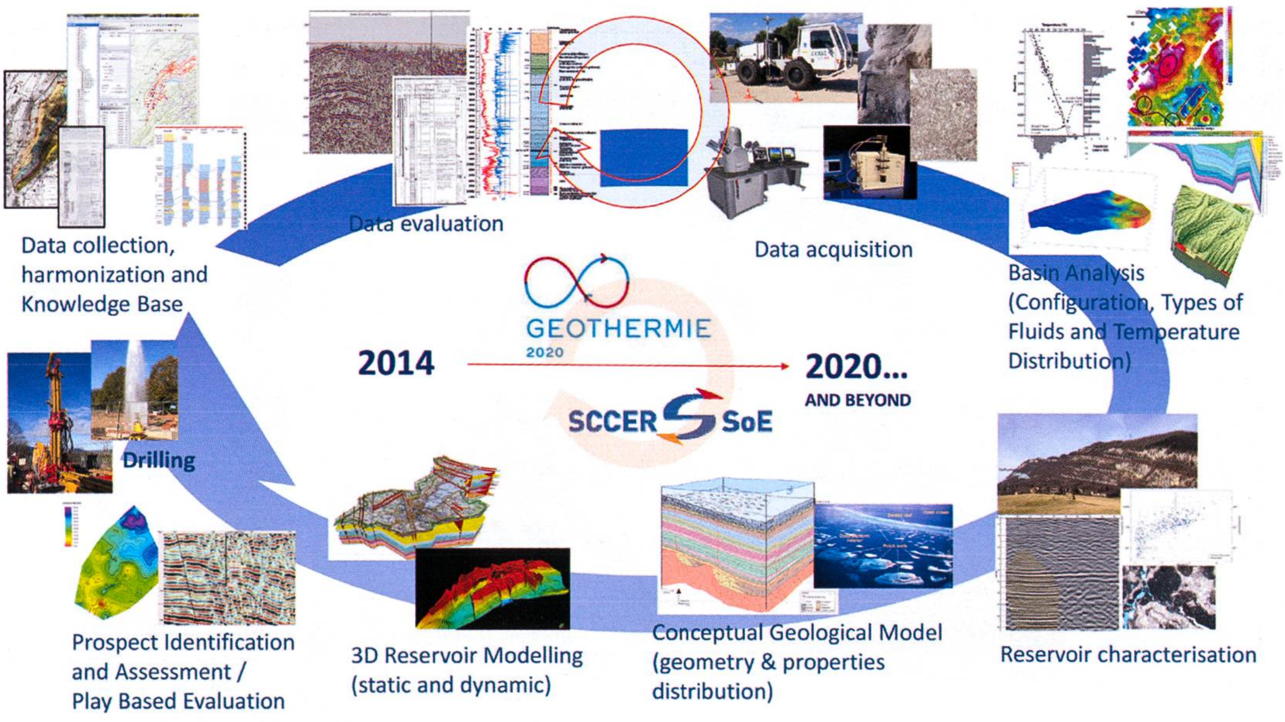

Fig. 2: Workflow and activities used in the geoenergy exploration phase aimed at the evaluation of geothermal resource potential. This workflow has been adopted to respond to the GEothermie 2020 program and the objectives of the large national swiss program SCCER SoE (Swiss Competence Center of Energy Research - Supply of Electricity) where fundamental research has been coupled to pilot and demonstration projects.

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. The generic stratigraphy of the Geneva Basin and surrounding area and synthetic geological profile across the Geneva Basin are shown in Figures 1 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 were created (McCann et al., 2006). Sediments deposited during the Permian and Carboniferous were found locally in these structures in the Humilly-2 well (Fig. 1 and 3) 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. No Permian sediments were observed yet in the Geneva Basin. However their occurrence is possible as these were found in the deeper subsurface in the surrounding region (i.e. Noville-1 well). 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).

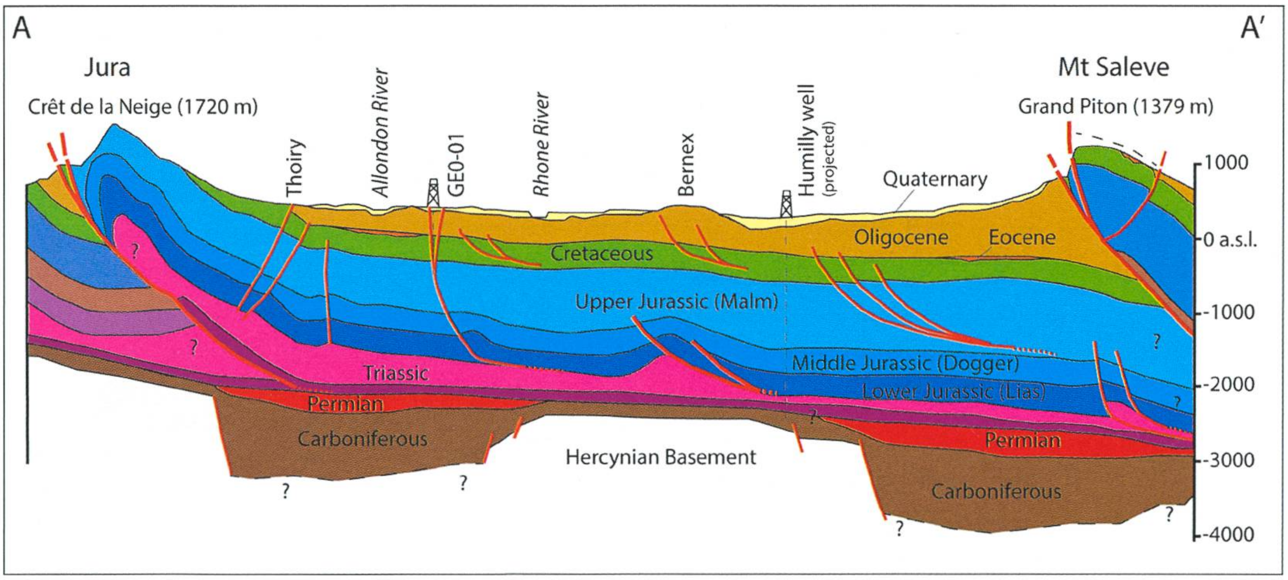

Fig. 3: Geological section crossing the Geneva Basin from SE to NW summarizing the key stratigraphic and structural elements present in the basin. This section has been drawn based on several 2D seismic lines and borehole data. See Figure 1 for the location of the A-A' trace.

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.

3.3 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 (Fig. 3). 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, 2020).

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 thus play a conflicting role when it comes to geothermal exploration and development (Fig. 4).

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 hyrocarbon and geothermal fluids their migration (hydrocarbon or hot water) pathway is an additional element which is essential to understand and predict the likelihood of geo-energy occurrence in the subsurface.

In the following paragraphs both geothermal and hydrocarbon play elements (Fig. 4) will be discussed with respect the Swiss Plateau and specifically its westernmost region (e.g. CoG).

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

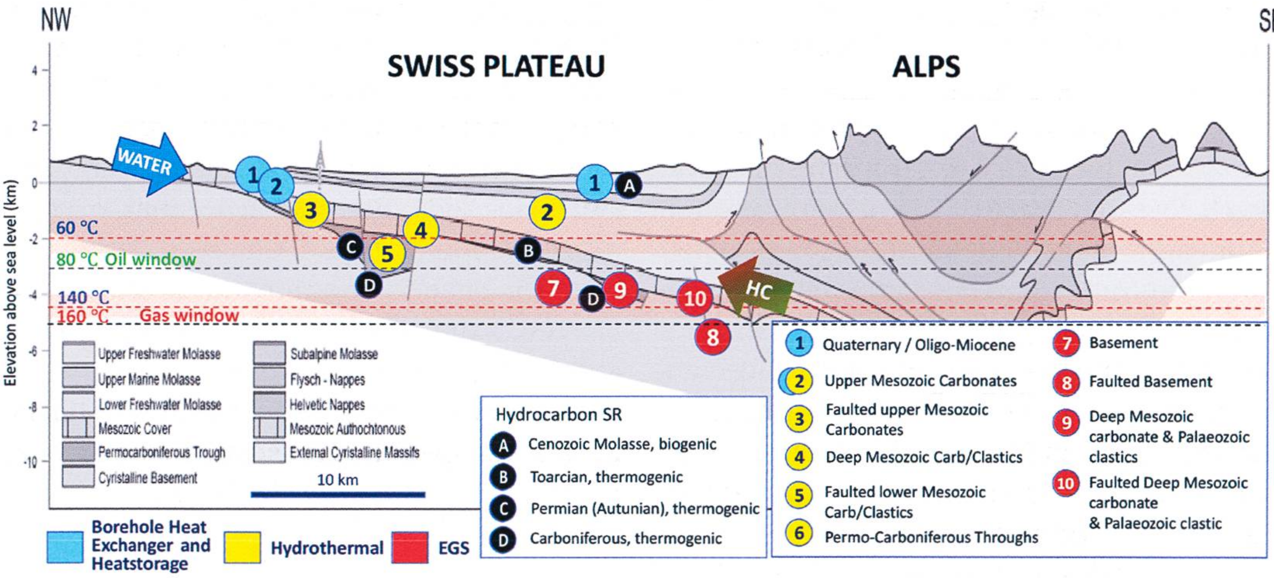

Fig. 4: Summary of geothermal and hydrocarbon plays on an ideal section across the Swiss Plateau. The circles with numbers indicate the different geothermal plays and the type of geothermal energy utilization (borehole heat exchange, heat-storage, hydrothermal and enhanced/engineered geothermal systems).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

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. Geochemical and fluid inclusions analysis associated with pervasive MVT-style mineralizations found in the Buntsandstein units at ca. 3000 m below ground floor in the Humilly-2 well, indicate temperatures of 140 °C suggesting a complex deep fluid circulation linked to different phases of the basin formation history (Chelle Michou et al., in prep).

Specifically, the pronounced topographic relief of the adjacent Jura mountain belt and the overall SE dipping strata caused by the foreland foredeep located to the SE of the Geneva Basin (Fig. 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-1 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 attests for the complexity and variety of fluid circulation conditions occurring in the Geneva Basin subsurface. 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 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 (Fig. 6) 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

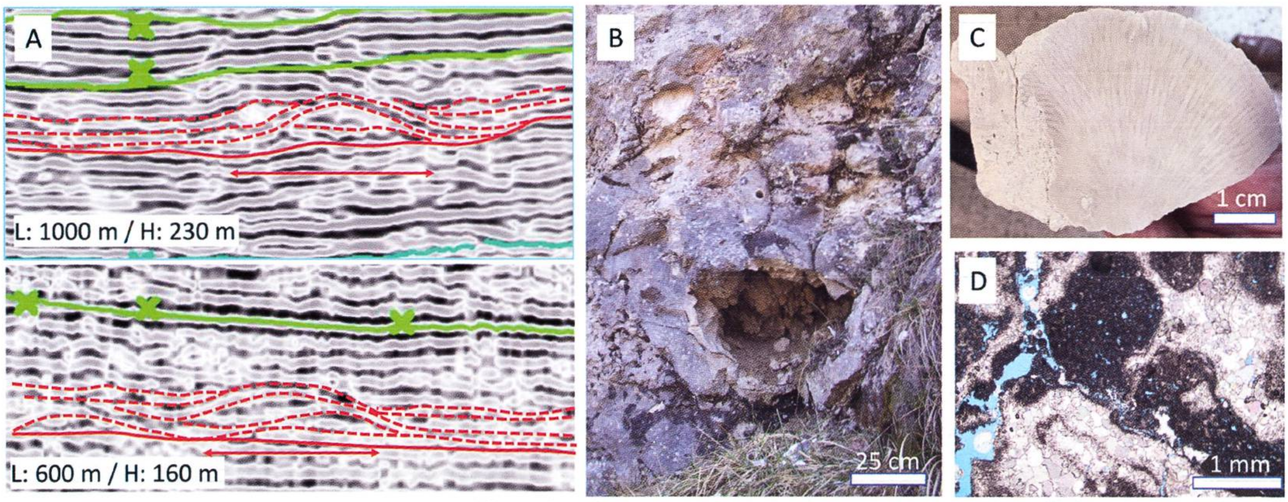

Fig. 5: Example of Kimmerdigian (Malm, Upper Jurassic) reef-complex reservoirs as they appear in A) 2D seismic in the subsurface of the Canton of Geneva (L and H indicates length and height, respectively), B) in outcrop (Prapont, Ain, France), C) hand-sample where specimens of ramose corals (Calamophyl- liopsis flabellum Michel) are well visible and D) thin section displaying carbonate reservoir with intrapar intraparticle porosity.

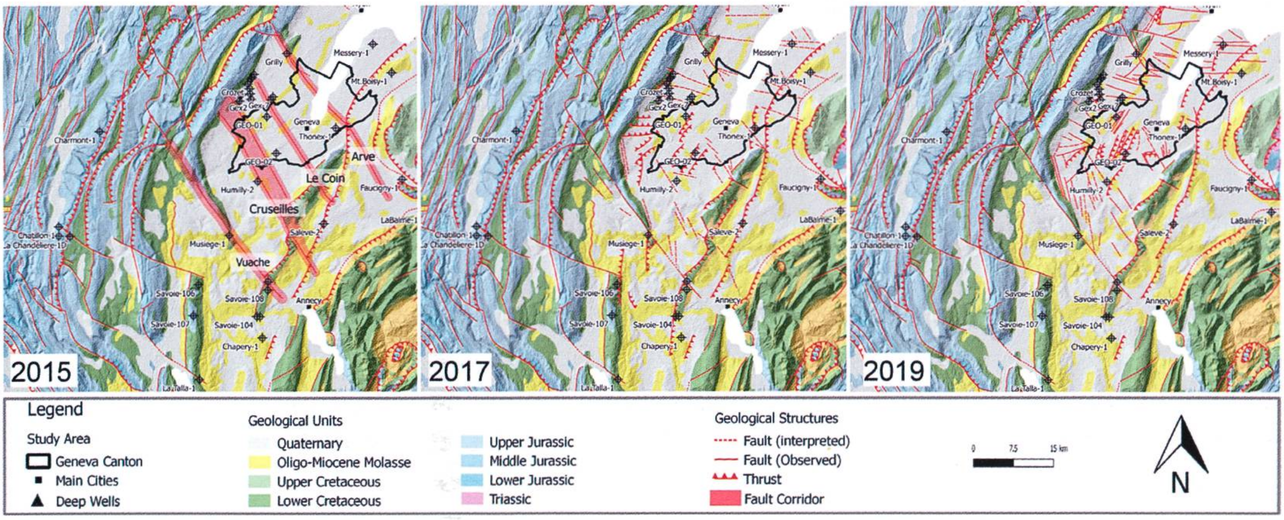

Fig. 6: Comparison of fault distribution in the Geneva Basin area based on the different and evolving views over the last 8 years (2013, 2017 and 2019). A higher complexity than previously thought seems to characterize the subsurface which will have important implications for effectively exploring and developing geothermal resources.

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 «Sidérolithique» and Oligocene «Gompholite» facies (Fig. 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 difference up to one order of magnitude in K and several units of Phi. Ongoing analysis on stable isotopes (Sr, O, C) on bulk carbonate (Courgeon, 2018 in Meyer, 2019), 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 ef-

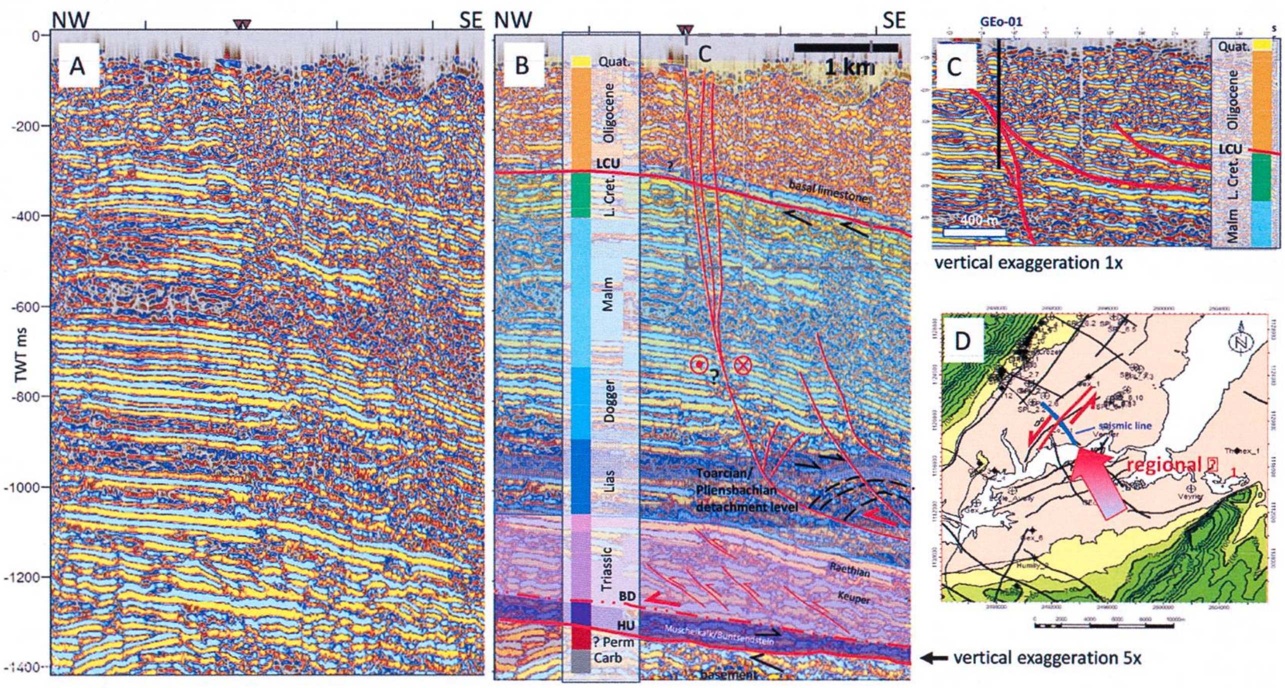

Fig. 7: Example of structural deformation observed in the Geneva Basin subsurface. High lo low-angle inverted faults generated in correspondence of ductile shale-rich stratigraphic units (i.e. Toarcian or Pliensbachian shales and shale- rich units within the Lower Cretaceous interval) accommodate the 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 generalized regional anticlockwise rotation. C) a detailed of the Lower Cretaceous interval affected by small offset low-angle faults/thrusts accommodating the overall of the alpine basin shortening; D) tentative kinematic reconstruction of explaining faults and folds observed in seismic. LCU: Lower Cretaceous unconformity; BD: basal detachment; HU: Hercynian unconformity.

fective reservoir storage, connectivity and deliverability. From the experience of the GEo-01 and Thônex-1 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 (Fig. 9). 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 (Fig. 6) 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 (Fig. 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 (Fig. 6), 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 (Fig. 6). 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 (Fig. 3 and 6). These latter faults, which can be detected at different stratigraphic levels where detachment surfaces can develop in conjunction with ductile lithologies (Fig. 7), are responsible, together with regional transpressive faults such as the Vuache Fault (Fig. 6), for the overall shortening and anti-clockwise rotation of the Jura FTB which occur in the westernmost Swiss Plateau region (Affolter and Gratier, 2004; Moscariello et al., 2019b). In the Vuache area, as a result of this latest deformational phase of generalized anti-clockwise rotation, West-WNW verging, low-angle thrust surfaces, characterized by ramp and flats geometry (Fig. 8), cut the vertical fault planes associated with the strike-slip system inherited from Mesozoic times (Meyer, 2000).

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 Fig. 6) 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 (Fig. 9).

4.1.3 Geothermal Aquicludes/Seal

The current knowledge on reservoir quality and property distribution of the Mesozoic succession suggests 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 (Fig. 3). Fault systems and associated fracture network cross cutting the basin stratigraphic succession (Fig. 3) 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 (Fig. 1). 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 ones containing sufficient total organic carbon (4.3% TOC) and having reached thermal conditions enabling the generation of hydrocarbons (oil-window thermal conditions). However, 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

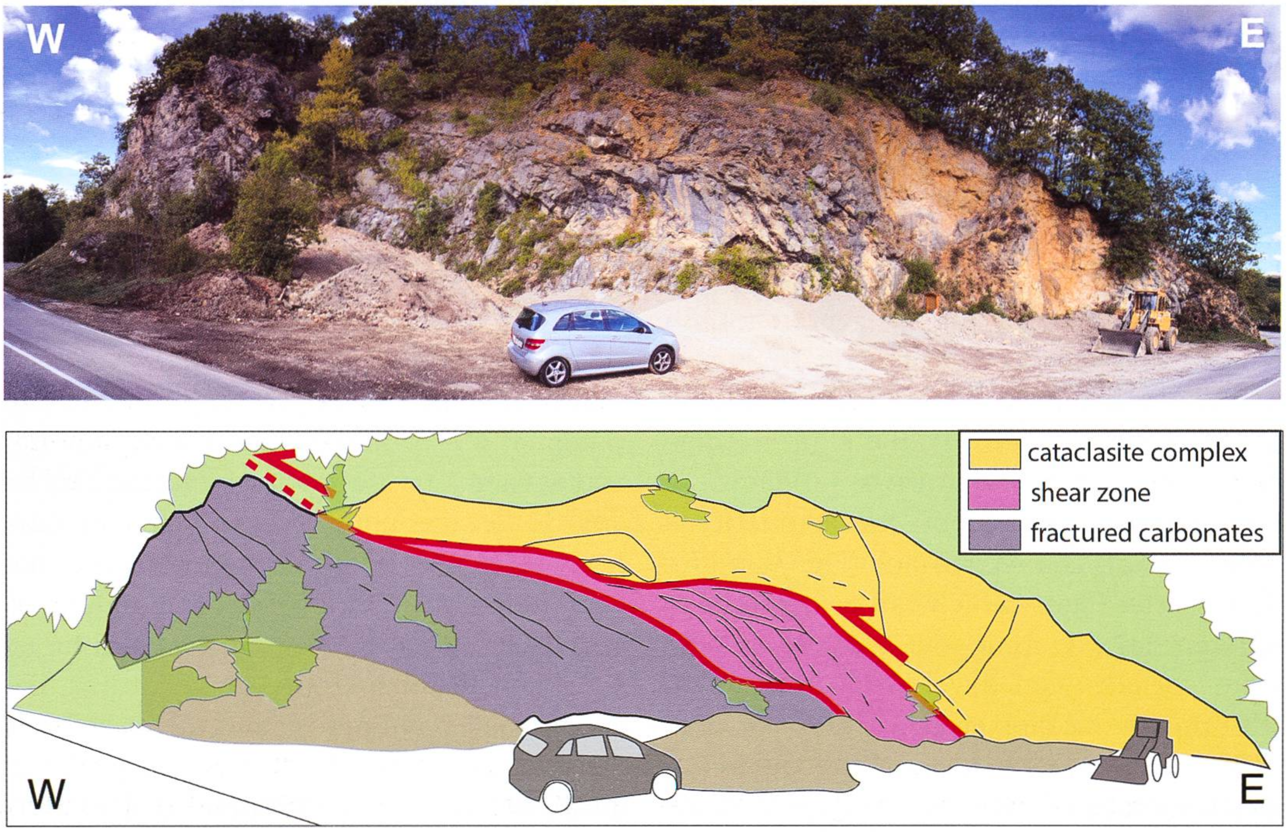

Fig. 8: Low-angle southwestern-verging thrust outcropping at the southern tip of the Vuache Mountain (Malpas, France). In this location the Vuache Fault complex has been described as left-lateral strike-slip regional fault (cfr Charollais et al., 2013). However, recent detailed observations revealed the occurrence of a clear low-angle shear zone with reverse kinematic indicators associated with a hydrothermally-altered cataclasite complex. These deformational features, occurring in other parts of the Vuache Mountain are likely associated with the anti-clockwise rotation of the Geneva Basin area, and seem to post-date the main left-lateral strike-slip event. Fractured carbonates consist of the Lower Cretaceous, 'Urgonian' facies.

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 (Fig. 10). 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 (Fig. 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 (Fig. 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 (Fig. 4). The most effective migration paths are likely represented by high-angle faults and associated fracture networks crossing the basin (Fig. 3). 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 (Fig. 1). 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 (Fig. 3). In addition, detachment surfaces represented by the Toarcian (source rock) and Pliensbachian shales can be locally the origin of low angles thrust planes (Fig. 7) which can provide preferential migration paths for hydrocarbon from deep to shallower layer, up to the surface (Moscariello et al., 2019a).

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 (Fig. 1). 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 (Fig. 5). 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 with 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 leave 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 (Fig. 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 grabens.

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 uncertainties, risks and opportunities

Since the onset of the exploration activities promoted by the GEothermie 2020 program, the understanding of the subsurface in the Geneva Basin has considerably improved. The study of vintage data, integrated with those provided by new geophysical and drilling campaigns (Fig. 2) 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 (Moscariello et al., 2020). 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 threat 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, threats and opportunities are therefore linked to a specific project (i.e. a well defined choice) 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). The integration of different independent analytical and multi-disciplinary study approaches and implementation of dedicated industry-standard workflows (Fig. 9) will be able to assist in accelerating the understanding of the subsurface thus leading to the maturation of geothermal development plans.

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 district heating (DH); ii) available heat surplus on the DH could be stored into underground geological units (Koornneef et al., 2019, Moscariello et al., 2020).

6 Conclusions and perspectivies

The exploration of the subsurface in Switzerland has been steadily progressing over the years starting in the 1920s motivated by hydrocarbon exploration, then feasibility studies for underground nuclear waste material and lately by geothermal potential assessment (Fig. 11). Despite the acceleration of data acquisition occurred over the last 10 years (2D and 3D seismic and new wells in NW Switzerland and partly in the CoG), the large mapping effort by the Swiss Cantons and Federal geological survey office (swisstopo) with the project Geomol (Allenbach et al., 2017), the level of understanding of the

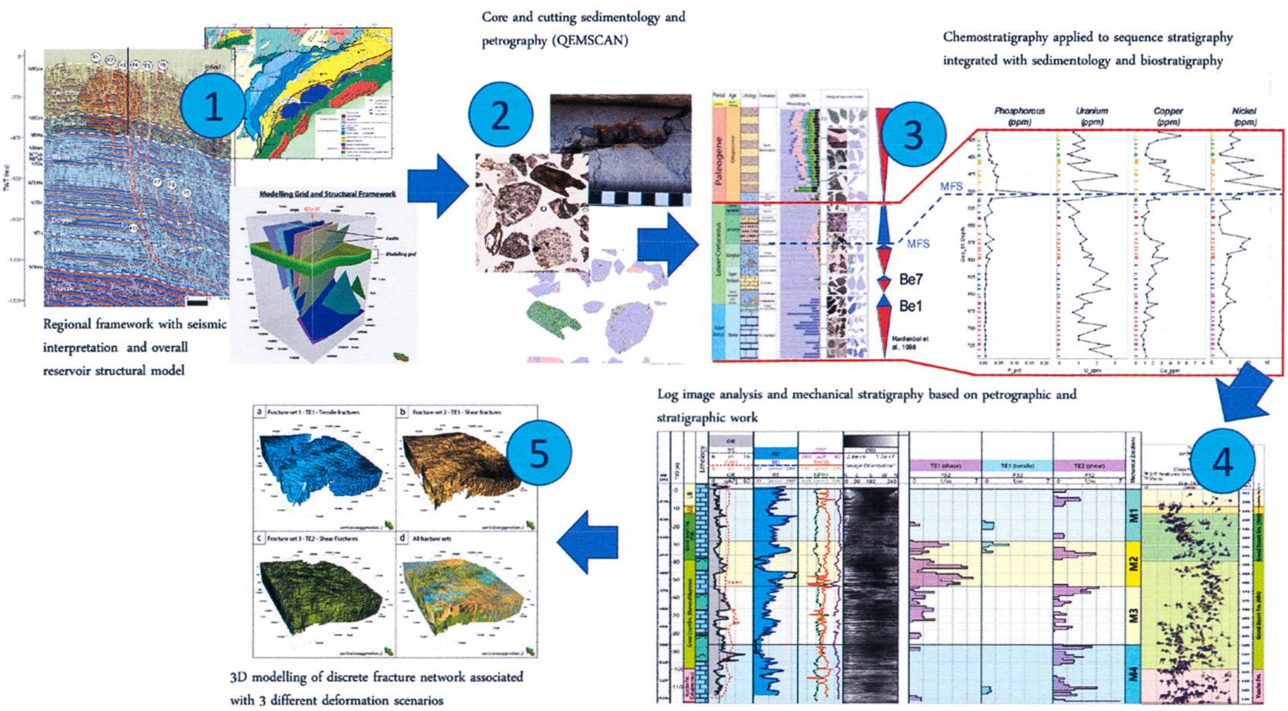

Fig. 9: Integrated workflow deploying a multi-scale approach to model fractured reservoirs around the GEo-01 well (see Fig 1 for location) starting from 1) the structural seismic interpretation and fault modelling, 2) sedimentological and stratigraphic analysis of the reservoir intervals using 3) quantitative petrography (QEMSCAN) and chemostratigraphy, 4) petrophysical analysis and bore-hole image interpretation and 5) discrete fracture modeling conditioned by local and regional constraints (images extracted from original work carried out by Lo, 2019; Ferreira de Oliveira et al., 2020; Eruteya et al., 2020).

Swiss deep subsurface remains still scattered and insufficient to guarantee a successful implementation of geothermal exploration across the Swiss Plateau. Despite this, in the CoG, the Geneva State authorities and SIG are committed to improve considerably the understanding and quantify the subsurface geothermal potential by conducting a structured and step-wise approach exploration strategy which will enable to meet the 2035 targets. By this date, the development of DH coverage in the CoG is envisaged to supply more than 30% of total heating demand, with at least 80% of it supplied by renewable energies. The DH role is therefore key for renewable energy integration which, together the use of geothermal energy at different temperatures could play an important role in the overall energy supply portfolio (Quiquerez et al., 2016).

In this context the progress made in investigation the best 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 CoG 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 exploration 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 parties, can be aligned to move forward with concrete action towards an overall cleaner and renewable energy supply and use.

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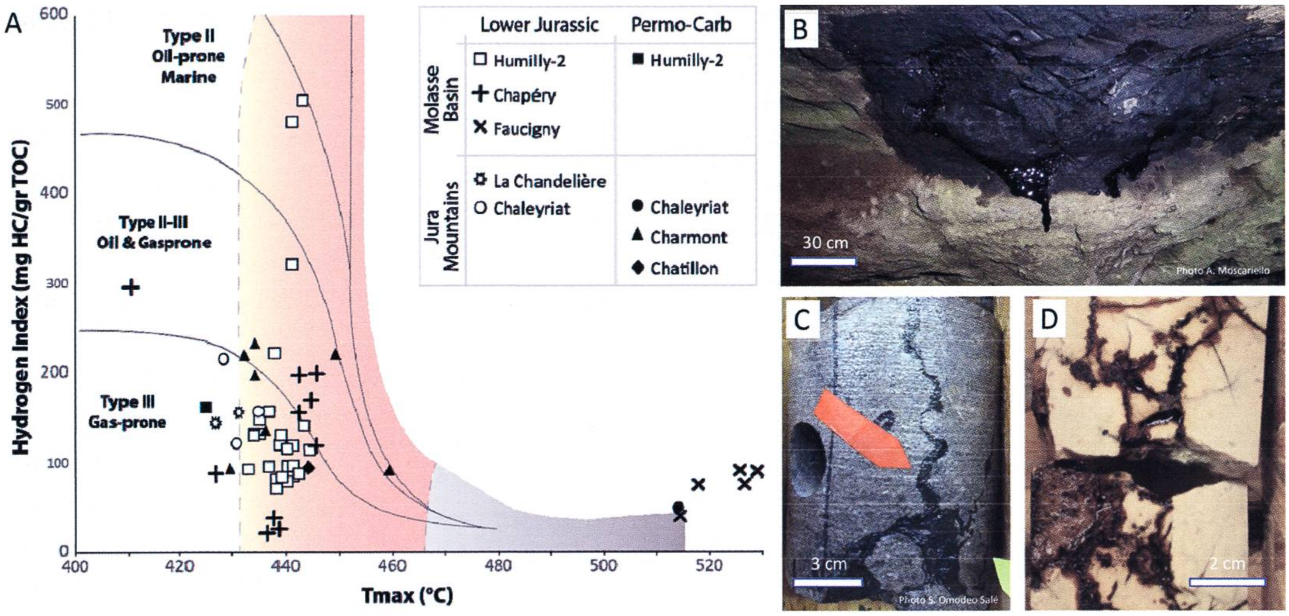

Fig. 10: A) Hydrogen Index vs. Tmax graph outlining the kerogen types and level of maturity of the two main source rocks occurring in the Geneva Basin (modified from Moscariello et al, 2019b); B) oil seepage associated with fracture affecting the Oligocene Molasse sandstone (Roulavaz river, Allondon); 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).

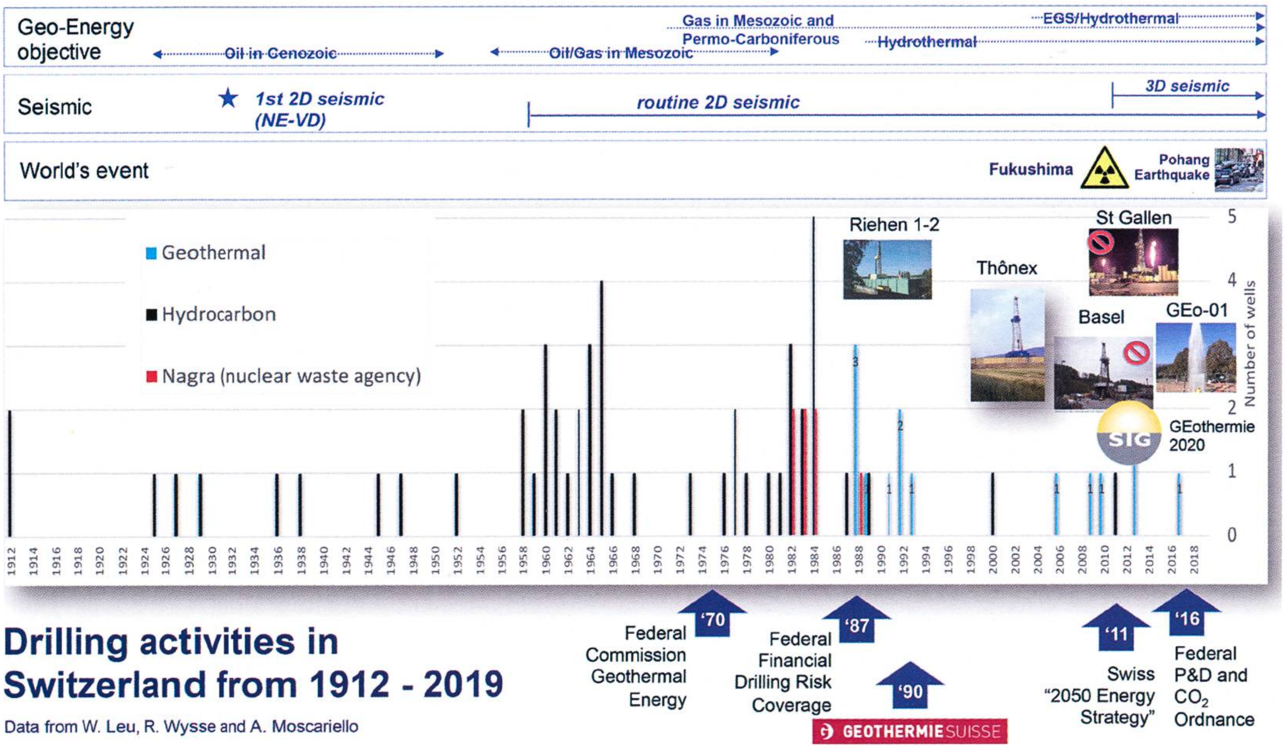

Fig. 11: Drilling activities in Switzerland aimed at geo-resources (hydrocarbon and geothermal) and nuclear waste disposal exploration. Compilation based on information from W. Leu, R. Wyss and this work. The critical moment in the «geothermal geo-energy journey» has been in 2016 when two important measures have been put in place (P&D and CO2 Ordnance) by the Federal Government through its Federal Office of Energy (SFOE), which aim at providing financial support to the exploration and development activities related to geothermal energy in Switzerland.

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