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Detailed Structural and Reservoir Rock Typing Characterisation of the Greater Geneva Basin, Switzerland for Geothermal Resource Assessment

Nicolas Clerc, Elme Rusillon, Andrea Moscariello, Philippe Renard, Sabrina Paolacci and Michel Meyer

University of Geneva, Department of Earth Sciences, 13 rue des Maraîchers 1205 Geneva, Switzerland

Nicolas.Clerc@unige.ch; Elme.Rusillon@unige.ch

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ABSTRACT

A large, multistage program (GEothermy 2020) for developing the deep geothermal energy resources of the trans-border (Swiss-French) Greater Geneva Basin was initiated in 2013 by the State of Geneva (Switzerland).

In this framework, two PhD research projects have been set up to study the subsurface geology of the region focusing on both geothermal and hydrothermal energy prospection. The first project aims at characterizing facies distribution, petrophysical and thermal properties of the sedimentary sequence ranging from Permo-Carboniferous to Lower Cretaceous units. The second project investigates the basin structural evolution, fault-related fractures and their geometrical characteristics and properties. This information is being integrated in 3D geological models at both regional and local scale, derived from 2D seismic lines and wellbore data.

Detailed rock typing description from petrophysical measurements and laboratory analyses of core and outcrop samples (facies and micro-facies description; geochemical, petrophysical and thermal properties) are being carried out in order to assess the lateral variations of facies and their reservoir properties. Fracture analyses and laboratory tests from outcrops and core samples are also being performed in order to develop mechanical-stratigraphic models of target reservoir units.

Regional facies mapping based on the reconstruction of depositional environment evolution through time, as well as insights on structural evolution of the basin will help to enhance the understanding of the distribution of productive reservoir facies and fractured zones within the study area. These elements will be key geological parameters for the successful development of geothermal energy in the Greater Geneva Basin.

1. INTRODUCTION

The study area covers the Greater Geneva region, a Swiss-French transnational zone located at the southwestern extremity of the North Alpine foreland molasses basin. The Greater Geneva Basin extends over about 2’200 km^2 from the southwestern part of Lake Geneva nearby the city of Nyon (Switzerland) toward the city of Annecy in France (Fig. 1). Over this region, the basin is limited in the Northwest by the internal chain of the Jura Mountains and to the Southeast by the thrusting front of the Alpine units (Fig. 1).

The “GEothermy 2020” program is a transnational program that has been launched recently in collaboration between the Geneva State and neighboring French authorities. It aims at characterizing the Greater Geneva Basin geology and investigating its deep geothermal potential. This multi-phase program implies successive stages of investigation including the gathering, assessment and general interpretation of existing subsurface data (2D seismic; well-logs and core samples) in 3D geological and structural models. The two complementary PhD research projects described in this paper mostly rely on the early phases of the “GEothermy 2020” program. They aim at gathering consistent dataset and gaining solid knowledge about the deep subsurface geology of the Greater Geneva Basin in order to produce informed recommendations to enable the planning of subsequent phases of the program.

The first project focuses on seismic-based 3D geomodelling and analysis of basin structural evolution, fault-related fractures and their geometrical characteristics and properties. Fracture analyses from outcrops and core data, coupled with basin-scale structural framework and lateral variations will lead to the establishment of a mechanical stratigraphy for key reservoir horizons. The second project focuses on characterizing facies distribution, petrophysical and thermal properties of the sedimentary sequence ranging from Permo-Carboniferous to Lower Cretaceous units. The study encompasses well logs and cores investigation for detailed petrophysical analysis, a micro-facies study using both conventional and automated QEMSCAN petrographic analysis, diagenetic study by optical cathodoluminescence and sediments provenance analyses (QEMSCAN combined with ICPMS). Furthermore, it will allow us to identify pore distinctive features and highlight paragenetic sequences of sedimentation and diagenesis. Both these outputs will be ultimately used to build a predictive model of reservoir characteristics across the Greater Geneva Basin.

2. GEOLOGICAL SETTINGS

The Greater Geneva area has been extensively studied over the past on various geological aspects. Some of the most recent integrated studies include a report on the geothermal potential of the Geneva region (PGG) delivered to the Geneva State authorities in 2011 and an academic regional seismic interpretation study (Paolacci, 2012).

2.1 Paleoenvironmental Context and Lithostratigraphy

The Greater Geneva Basin consists of a thick sedimentary cover of Mesozoic age, principally composed of carbonate and marl formations, overlying a crystalline basement often incised by depressions filled with Permo-Carboniferous sediments. The top of the Mesozoic series forms an erosive and highly karstified surface, overlain by siliciclastic Tertiary Molasse sediments of Late Oligocene to Early Miocene age, thinning out toward the foothills of the Jura Mountains in the Northwest (Fig. 2). The Molasse deposits are finally overlain by Quaternary sediments of principally glacial to fluvioglacial origin that locally reach important thickness.

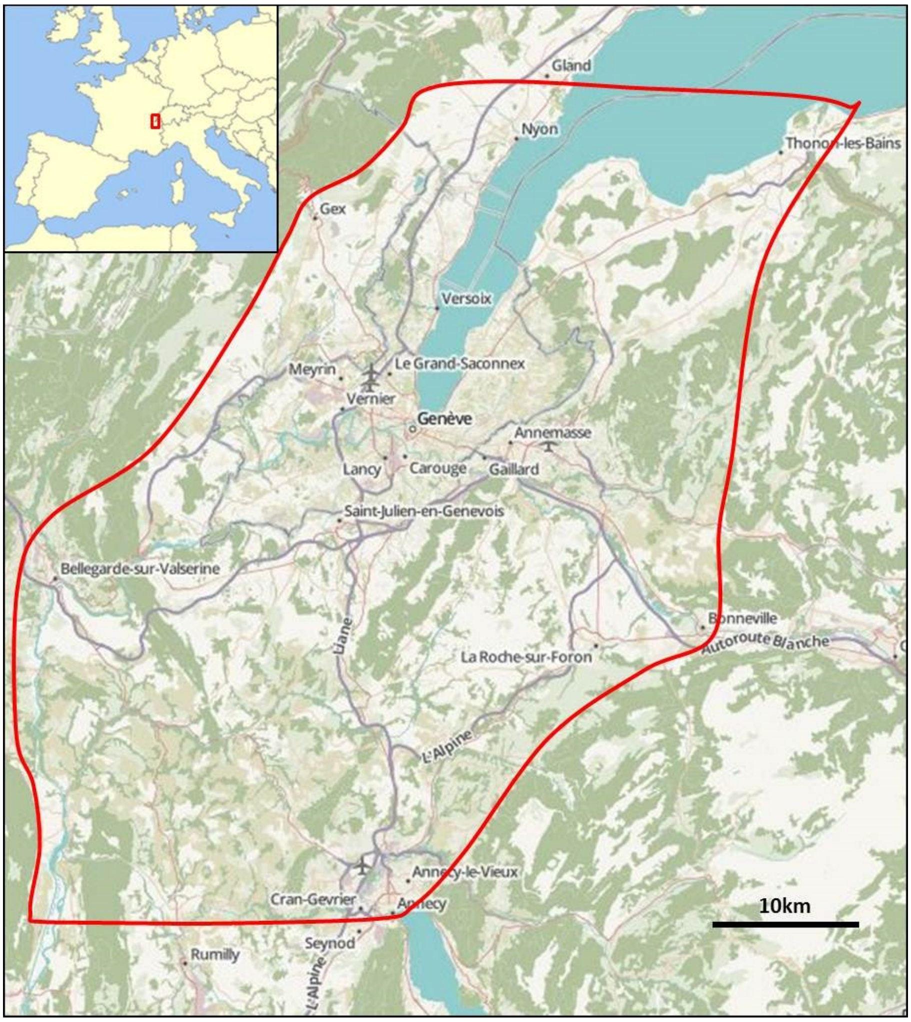

Figure 1: Location of the study area over the transnational Swiss-French Greater Geneva Basin (modified after ©OpenStreetMap contributors and commons.wikimedia.org).

The following detailed description of the lithostratigraphy mainly refers to Charollais et al (2013) and Sommaruga (1997), who already compiled several publications on the regional geology of the study area. The basement *sensu stricto* is composed of pre-Carboniferous magmatic and metamorphic rocks (mainly gneiss). Its morphology dips gently to the S-SE (1°-3°) and shows irregularities inherited from Paleozoic structural patterns (lineaments, half-grabens) (Gorin et al, 1993). These structures locally preserve the Permo-Carboniferous sediments originated by hercynian orogens erosion, comprising continental sandstones, breccia, silts, bituminous shales and coal beds (mainly lacustrine and river deposits). The crystalline basement and these continental deposits form the basement *sensu lato*. Some lineaments (see subsection 2.3) affect the whole stratigraphic column and seem to be associated to certain basement trends. In different places, they influence the thickness and distribution of sedimentary facies as observed by several authors in Liassic and early Dogger deposits (e.g. Meyer et al, 2000 and references therein).

The Triassic is generally characterized by evaporites associated with the development of an epicontinental shallow water sea controlled by variable connexion conditions with the Tethys Ocean. The Triassic sedimentary sequence can reach 1’000 m of thickness in the internal folds and thrusts of the Jura Mountains, but is less than 500 m in the Swiss North Alpine foreland basin. It is usually divided into 3 intervals according to the Germanic classification: the Buntsandstein mainly composed of continental sandstone with basement components; the Muschelkalk recording the first marine transgression showing successively marly limestones, evaporites and dolomites; and the Keuper comprising two intervals Lettenkohle and Raethian. The first Lettenkohle interval is composed of lignite and dolomite and characterized by evaporites (gypsum and halite) with clay intervals. This unit worked as a decollement layer for the Jura Mountains and Mount Salève (Fig. 2). Finally, the Raethian is composed of shales overlain with a sandstone unit enriching upward in carbonate components. The uppermost boundary is not yet clearly defined in this sandstone interval, which is sometimes attributed to the Hettangian (Meyer et al, 2000; SNPA report, 1969).

A rapid marine transgression occurred in the Liassic. The predominant depositional facies is then characterised by bioclastic muddy limestones to dark homogenous marls corresponding to a distal marine environment. The Dogger also developed in a deep water environment and the Aalenian are sometimes difficult to distinguish from the underlying Liassic. The latter shows intercalated marls and crinoidal limestone with quartz-detritic input in the upper part. These are general trends in the Geneva Basin sedimentation. Nevertheless, facies variations were observed at a larger scale separating a shallower environment area in the Northwest and a deeper and low-energy environment area southeastward. The limit between the two areas was not stationary but apparently kept a general ENE-WSW orientation. When present, the Callovian interval is composed of a thin condensed iron-rich oolithic limestone. The Malm is characterized by shallower platform deposits starting with marly and micritic limestones ("Calcaires Pseudo-lithographiques") in the Oxfordian. Biohermal reef facies developed mainly during the Kimmeridgian-Thitonian interval such as oolithic limestone, peri-reefal deposits, coral limestone, bioturbated and dolomitised lagoonal limestone and calcarenites. The last Jurassic stage is the "Purbeckian" which is generally more argillaceous than the underlying Malm deposits. The late Jurassic is characterized by a widespread regression as shown by the occurrence of emersive facies with vegetation evidences and dinosaur's tracks. At that period, proximal platform depositional environments similar to actual Bahamas conditions were predominant.

Looking at the whole basin, the Lower and Middle Jurassic sequences become thinner towards the East of Lake Geneva and from the Mount Salève towards the Alpine front respectively (Signer & Gorin, 1995). This could be related to the distal platform boundary, also mentioned by Charollais et al. (1996) who observed transitional facies from external platform to basinal environment in the wells Faucigny-1, La Balme-1 and Brizon-1 (Fig. 5) located close to the Alpine front in the Arve valley (Fig. 3).

In the Early Cretaceous, a shallow and warm water environment prevailed with small amplitude sea level fluctuations and temporarily local lands emerging. Berriasian deposits are mainly fine grain/bioclastic limestone ("Calcaires de Toiry") and fine quartz-rich bioturbated limestone ("Calcaires de la Corraterie") alternating with organic-matter-rich marls. After a short emersion, a deepening upward trend is observed in which a marly formation appears in the Hauterivian ("Marnes d'Hauterives"). A thick interval of bioclastic limestone ("Calcaires urgoniens") is developed in the Barremian, largely karstified. At the end of the Cretaceous, the Greater Geneva Basin came to emersion and the remaining Late Cretaceous sediments, if they existed, were totally eroded (Sommaruga, 1997). Nevertheless, these latter were apparently recognized in some karsts infills.

In the Early Tertiary, a warm and subequatorial climate accelerated erosion of the Cretaceous sequence. Red, lateritic deposits called "Siderolithique" and dated from the Eocene often fill the "Urgonian" karsts pockets, fractures and sinkholes.

The Mesozoic sequence outcrops in the Jura Mountains, Mount Salève and Mount Vuache (Fig. 3), but it is covered in the basin by a thick interval of detritic Alpine Tertiary sediments called "Molasse" (sandstone and marls) and Quaternary formations, mainly from glacial and fluvioglacial origin.

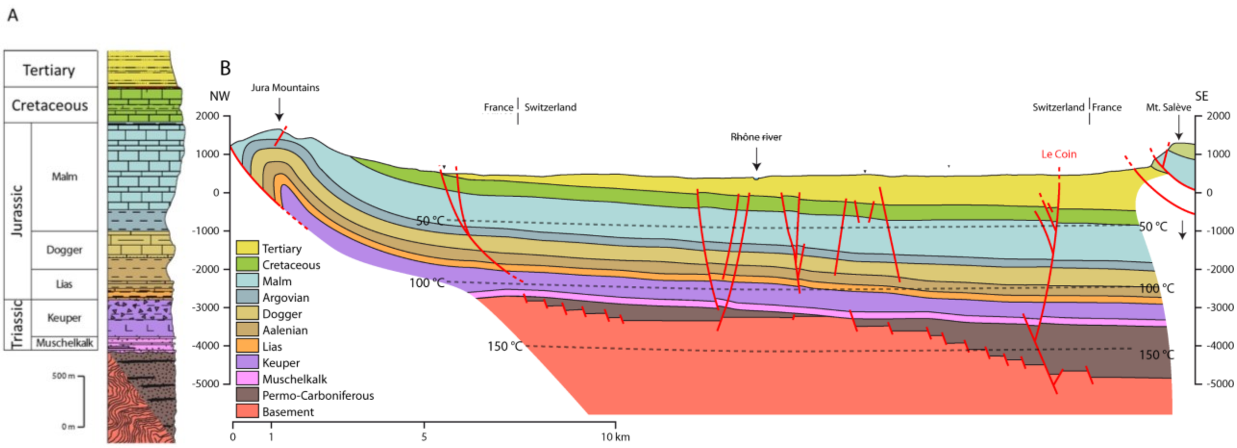

Figure 2: Synthetic stratigraphic log (A) and geological cross-section (B) across the Greater Geneva Basin (modified after PGG report, 2011). Refer to Figure 3 for profile location.

2.2 Principal Deep Geothermal Reservoir Units

Various studies have been carried out on the principal reservoirs in the Greater Geneva Basin, highlighting typical lithologies and characteristics required for a potential reservoir rock in the area: porous sandstone, karstified limestone, reef or peri-reefal deposits, dolomitised limestone altered by dissolution, fractured limestone, brecciated zone (Hugot, 1983; Service Cantonal de Géologie, 1979; PGG, 2011; Paolacci et al., 2013). This section focuses on the intervals which meet these criteria.

The Permo-Carboniferous sediments held in half-graben could be an interesting reservoir for deep geothermal production because of its tectonic and lithological predispositions, but is still poorly understood and documented (only 4 wells reached this layer). The overlying sandstone from the Buntsandstein formation was described as an aquifer in 3 wells, with good matrix and fracture porosity. But estimated permeability remains apparently low (flow rate $\leq$ 2 l/s; hydraulic conductivity$\approx$7.7*10-6 m/s) to be interesting for geothermal exploitation.

Only the upper part of the Muschelkalk indicates porosity higher than 5%, but permeability seems low except when the rock is fractured or karstified (Signorelli et al., 2004) as observed in the northern part of Switzerland where geothermal heat is already used.

Bioclastic and oolithic limestones from the Dogger are potentially porous facies. Their deeper position compared to the Malm could host high temperature fluids. Drilling mud losses were observed in this layer in 2 wells and tests produced between 0.1 and 0.5 l/s of mineralized water. The permeability is close to 0.05 mD in massive intervals and exceeds 15mD in fracture zones. In the Paris basin, the main oolithic intervals in the Dogger have been used for geothermal heat production for more than 40 years. However, several tests conducted in the same formation in the Jura Mountains revealed important lateral and thickness variations as well as changing fracture and permeability patterns. These heterogeneities could limit the potential of this reservoir.

Malm limestones of the Middle Oxfordian, Kimmeridgian and Thitonian represent the main aquifer of the Mesozoic sequence in terms of volumes. This is also the main Bavarian Basin aquifer, which has produced geothermal energy for several years. In the Jura Mountains, this interval constitutes the crest of the internal folds which facilitates aquifer recharge. Similarly to the Dogger aquifer, facies and thickness variability is high in the Malm. The coral reef environment is associated with better reservoir properties and its distribution is still under investigation. Signorelli et al. (2004) reported that the whole Malm interval could be highly fractured and karstified which was confirmed by mud loss in the Kimmeridgian interval of the well Humilly-2 (Fig. 5). However in Thônex-1 well, disappointing flow rate was encountered in the Malm and revealed that the geothermal reservoir could display important porosity but low permeability and poorly connected fractured zones (Vuataz & Giroud, 2010).

The entire Early Cretaceous interval is considered as a regional aquifer except in its Hauterivian marls. The “Calcaires urgoniens” Formation, which forms the top of the Mesozoic sequence, is the shallowest reservoir, but it could reach interesting temperatures where covered by thick Molasse and Quaternary deposits. Also, this layer thickens towards the Alpine front and shows facies variations from bioclastic to pseudo-oolithic limestone, sometimes slightly dolomitised which can locally improve reservoir properties. The “Calcaires urgoniens” Formation is already exploited for thermal baths (Divonne-les-Bains) with several sources of relatively high flow rates. It is intensely karstified, but the well Thônex-1 revealed that main open fractures and karsts are plugged with “Sidérolithique” sandstone causing low permeability.

2.3 Tectonic and Structural Settings of the Basin

The Greater Geneva Basin is geographically encompassed between the internal reliefs of the Jura arc Mountains in the Northwest and the front of the Alpine thrusts at the Southeast of the Bornes Plateau (Fig. 3). This overall NW-SE shortening is laterally accommodated by a series of major NW-SE wrench fault systems and internally absorbed by the intra-basin Salève thrust anticline and its southern continuation, and by low-relief undulations in the Mesozoic sedimentary cover. In the SSW continuation of the Greater Geneva Basin, toward the city of Annecy (Fig. 1), the present-day maximum horizontal stress rotates toward a more E-W direction, consistent with the maximum horizontal shortening direction in this region (Sambeth & Pavoni, 1988). Gorin et al. (1993), Signer & Gorin (1995) and Paolacci (2012) carried detailed seismic-based investigations on the structural scheme of the Geneva Basin and Bornes Plateau as summarized below.

The thrusting front of the Subalpine and Prealpine units, the Salève thrust anticline and the internal reliefs of the Jura Mountains are intimately linked with the presence of SW-NE striking Permo-Carboniferous lineaments. On seismic data, the Permian sandstones show a relatively transparent facies whereas the underlying Carboniferous interval is characterized by discontinuous high-amplitude negative reflections interpreted as coal-bearing sediments. The crystalline basement is difficult to identify from seismic data and is interpreted as the transparent to chaotic seismic facies that is locally visible below the Carboniferous reflections. The existence and location of these Permo-Carboniferous half-graben (Fig. 2) is therefore evidenced by the varying depth of the base of these coal-bearing reflective Carboniferous sequences with respect to the base of the Mesozoic interval (Fig. 4): crystalline basement highs sitting where the Permo-Carboniferous reflectors get closer to the Mesozoic base as opposed to the Permo-Carboniferous graben in which the coal-bearing reflective layers appear deeper.

In the South of the Greater Geneva Basin (Bornes Plateau), a SW-NE trending Permo-Carboniferous half-graben dips southeastward. Its Southeast limit is delineated by major northward downfaulting of basement, which has been reactivated as a reverse fault by the compressive Alpine tectonic phase. This ended up in the formation of a basement high on which sits the frontal thrust of the Subalpine units. In the center of the basin, the front of the Salève thrust anticline corresponds to the southern limit of a Permo-Carboniferous half-graben, deeper than 4’000 m, with SW-NE striking, also characterized by a succession of normal basement faults with down thrown blocks located to the North. The basement high underlying the Salève ridge probably resulted from the reactivation of these basement faults bordering the Permo-Carboniferous basins at different periods of time since the Palaeozoic. The Permo-Carboniferous half-graben located at the front of the Subalpine units and underneath the front of the Salève thrust anticline hosts structural lows at the top of the Mesozoic interval (Fig. 3), filled by thicker Tertiary Molasse deposits. The existence of another SW-NE trending and northward thickening Permo-Carboniferous graben is also suggested along the southern limit of the internal Jura Mountains. Its southern extension corresponds to basement-involved reverse faults, suggesting an inversion of this Permo-Carboniferous basin during the Alpine compressional phase. This interpretation is in line with similar observations further West (Philippe, 1994) and further East (Pfiffner, 1994).

From West to East, the northern part of the Greater Geneva Basin is affected by four major NW-SE trending wrench fault systems respectively called the Vuache, the Cruseilles, Le Coin and the Arve wrench fault zones (Fig. 3). These accidents link the Subalpine units with the Jura Mountains across the Bornes Plateau, the Salève ridge and the Geneva Basin. Whereas the Vuache fault zone can be followed on surface landscape along the Mount Vuache and the southwestern continuation of the Mount Salève chain, the surface manifestations of the Cruseilles and Le Coin wrench fault systems are only observed in the Jura and Salève mountains where they offset the outcropping Mesozoic units. Their continuation across the Geneva Basin and the Bornes Plateau is revealed on the 2D seismic data (Gorin et al., 1993; Signer & Gorin, 1995), (Fig. 4).

The Vuache fault is a major sinistral wrench fault zone, which has been studied by many authors over the last decades (e.g. Charollais et al., 2013 and references therein). Combined with a transpressional movement of the basin, it gave rise to the Mount Vuache (Fig. 3). The early occurrence of the Vuache fault in the Alpine orogeny history played a crucial role in the structural evolution of the basin and its neighboring tectonic regions, with the northeastern compartment being rapidly decoupled from its southwestern counterpart (Meyer, 2000). Seismotectonic investigations in the Geneva Basin area revealed that the sinistral movement of this fault system is still active nowadays (Sambeth & Pavoni, 1988). According to certain authors, (Blondel, 1984;

Signer & Gorin, 1995), the geographical occurrence of this wrench fault system is related to basement faults. More particularly, the eastern flank of the Mount Vuache seems to correspond to an eastward downthrowing basement fault delineating a 3'000 m deep Permo-Carboniferous half-graben. This latter extends eastward in the Geneva Basin up to the Cruseilles wrench fault system, which in turn corresponds to the transition to another NW-SE trending basement high (Signer & Gorin, 1995). It is therefore assumed that both the Vuache and the Cruseilles wrench fault systems are related to ancient normal basement faults bordering Permo-Carboniferous basins, which were reactivated and propagated in flower structure patterns through the overlying Mesozoic cover during the Alpine compression. At top Mesozoic level, the Vuache and Cruseilles wrench fault zones delimit a NW-SE depression (structural low on Figure 3), an important depocenter where the oldest Tertiary Molasses deposits of the Geneva basin are restricted (Gorin et al., 1993; Signer & Gorin, 1995). A similar structural low at top Mesozoic level is also identified between the Cruseilles and Le Coin wrench fault zones.

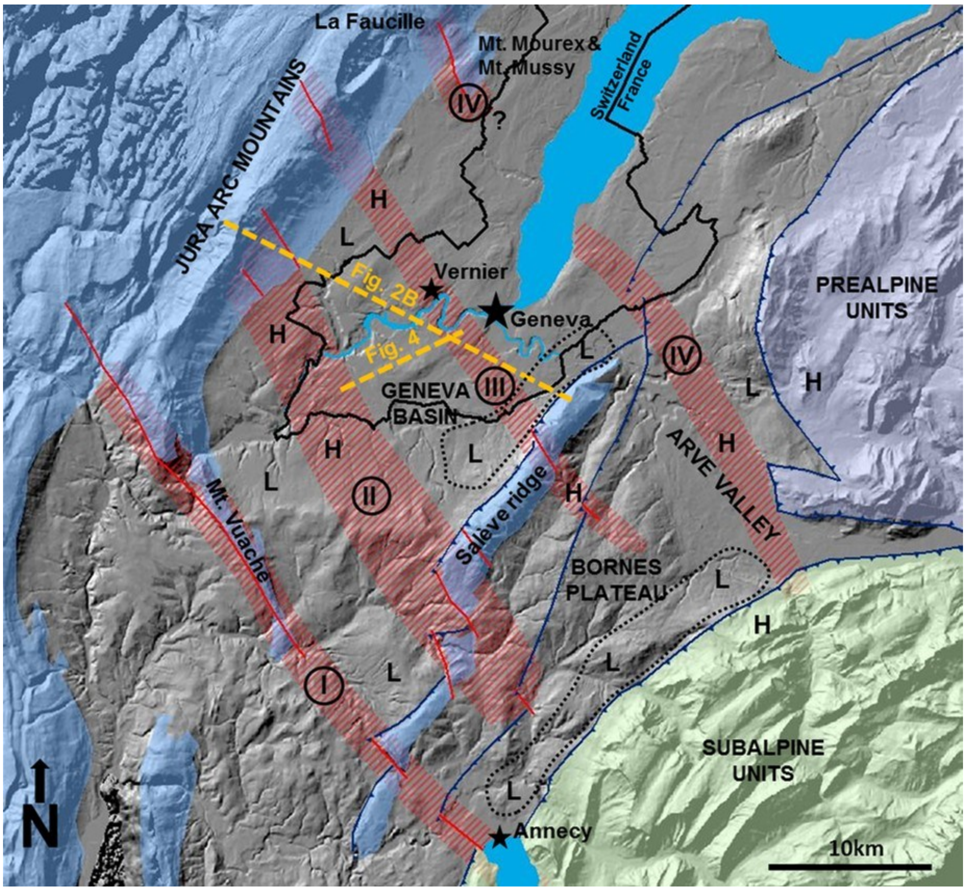

Figure 3: Mesozoic-Cenozoic structural scheme of the Greater Geneva Basin illustrating: a) SW-NE Mesozoic lows associated with underlying Permo-Carboniferous basins at the front thrust of the Salève ridge and Subalpine/Prealpine units. b) Zones affected by the NNW-SSE trending wrench fault systems crossing the Geneva Basin and Bornes Plateau: (I) Vuache; (II) Cruseilles; (III) Le Coin; (IV) Arve. c) Top Mesozoic structural highs (H) and lows (L) associated with underlying Permo-Carboniferous tectonics. Figure after Signer & Gorin, 1995.

Le Coin wrench fault zone (Fig. 3) is also interpreted as a sinistral system, expressed on the seismic data as a flower structure in the Mesozoic interval of the Bornes Plateau (Signer & Gorin, 1995). North of the Salève Mountain, its link across the Geneva basin with its expression in the Jura Mountains is less obvious due to lack of seismic data, but is supported by the presence of important NW-SE trending faults observed in Tertiary Molasse outcrops near the Rhône River in Vernier (Fig. 3) (Rigassi, 1956; Angelillo, 1987 in Signer & Gorin, 1995). In both the Bornes Plateau and at the piedmont of the Jura Mountains, the Le Coin wrench fault zone is possibly related to a deeper basement fault (Paolacci, 2012). Further to the West, evidences regarding the northward persistence of the Arve wrench fault zone across the Geneva Basin are more hypothetical due to the absence of seismic data. Various authors have attempted to correlate it with the La Faucille fault zone, Mount Mourex and Mount Mussy structures (Fig. 3) as well as with strike slip fault evidences detected on shallow reflection seismic data within the thick quaternary infill of Southwest Lake Geneva and with NW-SE surface lineaments observed in the southern side of the lake. Northeast of Mount Salève, recent 2D seismic data highlight a 2-2.5 km width chaotic zone affected by series of subvertical faults forming a flower structure across the Mesozoic, which is interpreted as the signature of the Arve wrench fault zone. Some of these faults visibly extend in the underlying Permo-Carboniferous sediments, with unclear but possible continuation in the crystalline basement (Geo2X, 2011). Further to the South, in the Arve Valley (Fig. 3), the Arve wrench fault zone also appears on the seismic data as a flower structure in the Mesozoic (Signer & Gorin, 1995).

Finally, in addition to the SW-NE and NW-SE basement-related tectonic lineaments discussed above, seismic data also shows a series of "low relief anticlinal and synclinal flexures" within the Mesozoic and Cenozoic cover of the Geneva Basin displaying SW-NE axis. These structures, probably inherited from the late Alpine orogeny (Miocene – Pliocene), often underlie the molassic hills characterizing in some places the surface topography of the Geneva Basin (Signer & Gorin, 1995). These undulations and their impact on the Quaternary infill of the basin had also been highlighted with gravity data (Poldini, 1963; Olivier et al., 1983).

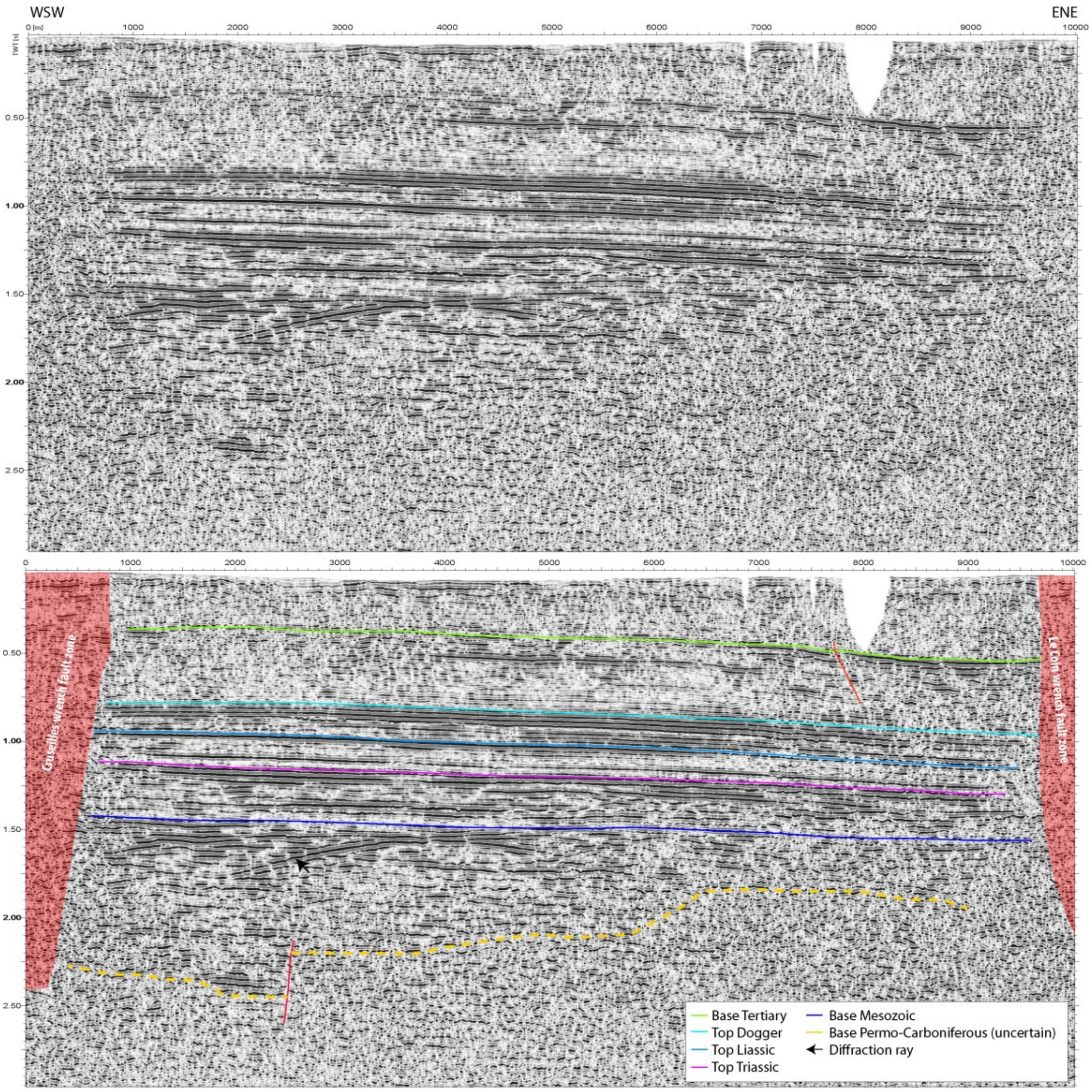

Figure 4: WSW-ENE oriented seismic line located between the Cruseilles and Le Coin wrench fault zones (discontinuous chaotic zones), highlighting the difference in seismic signature between the discontinuous high-amplitude reflection of the coal-bearing Carboniferous layers and the transparent to chaotic seismofacies of the crystalline basement. Refer to Figure 3 for localization.

3. WORKING DATASET

Deep wells provide valuable data to investigate buried sediments forming potential deep geothermal reservoirs. Thousands of wells were drilled in the Greater Geneva area for hydrogeological purposes, but only a few reached the Mesozoic sequence. These wells were mostly used for hydrocarbon exploration between the 50's and the 80's. Since then, exploration decreased as no profitable hydrocarbon accumulation was found in the area, while the interest for the deep subsurface slowly shifted toward its geothermal potential (well Thônex-1 drilled in 1994).

Thirty-six wells in France and seven in Switzerland were selected for rock typing investigations (Fig. 5). Few wells were also selected around the study area to confirm correlations across the basin. Most of the wells are located in the Molasse Basin (transborder area), and a third of the wells is situated in the Jura Mountains where the Mesozoic sequence is uplifted, allowing us to investigate the deeper and older sequences. Three wells are located in the Arve valley, close to or in the Subalpine units where the outer carbonate platform boundary is highlighted (Charollais et al., 1996).

The well data set comprises reports, logs and cores. Lithological descriptions and e-logs including caliper, spontaneous potential, gamma-ray, sonic and resistivity data are available. The most recent wells also include density, porosity and photoelectric factor measurements. Within this large well dataset, the data quality differs significantly from the oldest to the most recent, which complicates the data processing and analysis (digitalisation, petrophysical measurements and interpretation). Common problems with old data logs in paper format are faded and imprecise curves, errors or missing data in scale and headers. Additionally, the wells selected were usually cored, but only few of these cores are currently available. Original core descriptions exist for most of them, however, a consistent approach in facies and stratigraphic description is often missing. In order to recognize and understand lateral fluctuations of synchronous sedimentary deposits, the available core material was reviewed to ensure consistency and homogeneity of descriptions and interpretations. For this purpose, 14 cored wells were selected, geographically distributed along a N-S transect across the Greater Geneva Basin. Cores were described in the potential reservoir intervals, sometimes extended to overlying and underlying geological units for a better understanding of the sedimentary sequence. Plug samples were taken in each different facies. Fault mineralisation and organic matter-rich intervals were also sampled separately in order to analyse the Rock-Eval pyrolysis and fluid inclusions, which could help to understand the burial history of the basin.

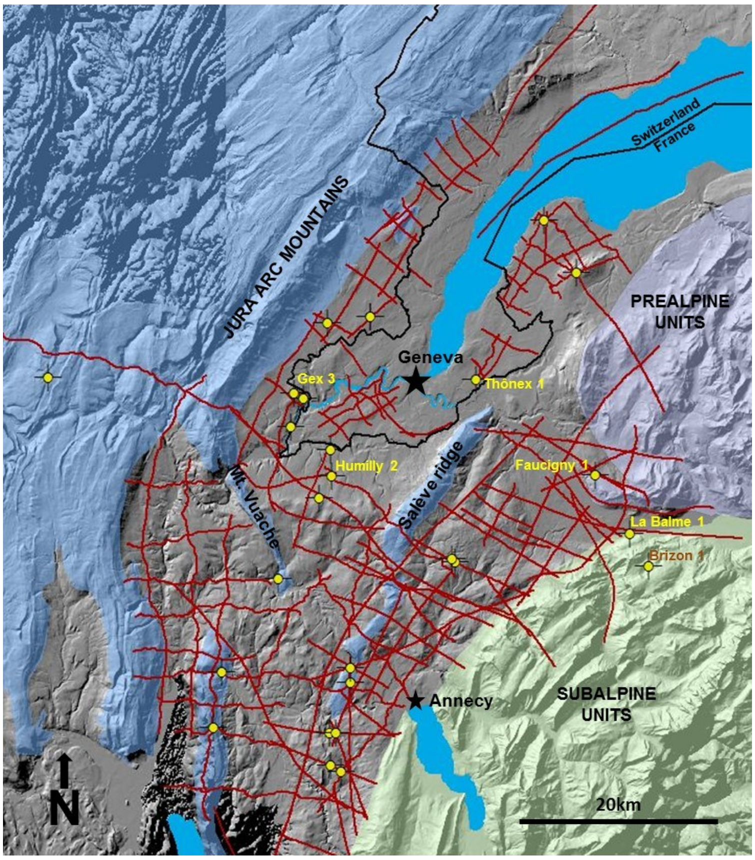

Figure 5: Distribution of 2D seismic data and wells reaching Mesozoic and/or deeper units across and nearby the Greater Geneva Basin.

About 1’500 km of 2D seismic lines are available over the study area (Fig. 5), most of them (about 1’300 km) located on the French territory and about 185 km covering the Swiss area. The French data comes from 8 different acquisition campaigns, mostly for hydrocarbon exploration, undertaken from 1957 to 1990. Post-1965 lines (1’200 km), for which raw field acquisition data could be recovered in digital format, were recently reprocessed either as post-stack time migration or as pre-stack time migration (PostSTM and PreSTM) when possible, depending on their age. The quality of the reprocessing is generally good but remains constrained by acquisition parameters used 20 to 40 years ago. Pre-1965 lines (57 km) were only recovered in paper format. They are therefore simply vectorized and harmonized, and still carry the processing quality of that time. The Swiss seismic data corresponds principally to 3 acquisition campaigns undertaken from 1987 to 2010, plus a selection of unitary lines issued from earlier acquisition campaigns (1972-1977) to complete the seismic dataset toward the Northeast of the study area. With the exception of 2 lines of the 2010 campaign that aimed to specify the deep subsurface around the geothermal well of Thônex-1 (Fig. 5), available in digital format, the Swiss seismic acquisition campaigns were acquired for hydrocarbon exploration purpose and vectorized from recovered paper copies (Paolacci, 2012).

Finally, the topographic landscape (Mount SalèvFe and Jura Mountains, Fig. 3) surrounding the study area is rich in Mesozoic outcrops (down to the Early Jurassic intervals), therefore allowing easy access for stratigraphic measurements, facies description and sampling.

4. METHODS

Rock typing was never carried out in the Greater Geneva Basin before and requires several petrophysical and geochemical analyses, as well as sedimentological expertise to be completed. First, a log-based petrophysical analysis is being performed. Main available logs were provided in paper scan format and were digitalized in order to be incorporated in petrophysical and modelling software. When existing in well reports, petrophysical measurements such as porosity and permeability were indexed and compared with further logs investigations.

Secondly, 14 cored wells were described to provide a coherent facies description throughout the basin. More than 200 plug samples were collected representing every different facies encountered. Porosity and permeability are being measured on each whole sample with the AP-608 automated porosimeter-permeameter (Coretest Systems, Inc.) at the University of Geneva and will also be compared and added to the “rock properties database”. Thin sections will then be derived from plug samples in order to carry out a sedimentological micro facies analysis, or to complement the existing ones when reports are incomplete or highlight discrepancies. A diagenetic study with optical cathodoluminescence (CL 8200 MK5) is also needed for further cement characterization. This approach will allow specifying the stratigraphy, paleoenvironments and facies lateral variations. Furthermore, it will permit to detail pore distinctive features and finally determine paragenetic sequences. Micro-facies will also be analysed using QEMSCAN technology available in the University of Geneva, and compared with the classical analysis under the microscope. Finally, ICP-MS geochemical analyses (metal distribution) coupled with investigations on heavy minerals using QEMSCAN will lead to outline possible stratigraphic intervals and sediment provenance in order to improve stratigraphic and facies correlations and enhance the understanding of the paleogeography at the time of deposition. Finally, thermal specific measurements (thermal transmissivity, conductivity and capacity) are also planned to complete rock properties investigation.

Outcrops are essential to understand complex structures and lateral facies variations in complement to the well data that provide punctual information from the subsurface. In order to enhance the data set and confirm interpretations, outcrops showing analogue structural pattern and reservoir facies will be investigated.

Seismic interpretation of key Mesozoic units and underlying Permo-Carboniferous graben is achieved over the entire study area to build a consistent structural 3D model at the Greater Geneva Basin scale. While the 2D seismic data available generally poorly image the Permo-Carboniferous graben, its delineation (especially between 2D seismic lines) might be reinforced by the use of gravimetry data. The first compilation of residual gravity anomaly maps generated from existing data has shown encouraging results, not only at imaging large anomalies associated to Permo-Carboniferous graben and/or thick Quaternary infills, but also at highlighting smaller-scale gravity effects associated to the major wrench fault systems across the basin (reduced bulk densities in brecciated or higher fracture intensity zones). With an appropriate depth-constrained structural model of the Mesozoic, Cenozoic and Quaternary intervals, along with accurate layer density values and distribution, the stripping of all known gravity effect allows to interpret the resulting misfit as the discrepancies between the gravity model response and the measurements (Altwegg et al., subm.). This approach can help improving the characterization of the Permo-Carboniferous grabens and fault zones geometries.

In order to assess adequately the present-day facies distribution with respect to their initial depositional environment, it is important to account for a proper understanding of the structural basin evolution through time. As part of his work, Meyer (2000) carried out graphical structural restoration of the same region to correlate and retrieve relative depositional paleogeography of Kimmeridgian reefs facies observations from different major fault compartments. He established that the Geneva basin underwent important shortening (up to 20 km along the Vuache fault) during the Alpine compressional phase, implying multi-kilometric relative displacements between the major fault block compartments. As a consequence, certain facies originally deposited in neighbouring positions can be distant by several kilometres nowadays. In a geological modelling context, this type of consideration has a certain impact on lateral facies and facies-related properties variations, especially across principal tectonic lineaments. Despite a relatively poor deep well coverage over the study area, particular attention is addressed to this question.

Geomechanical and fracture stratigraphy analysis (Laubach et al., 2009) is conducted on key outcropping reservoirs with photogrammetry method as well as from available borehole and core data. Additionally, a separate study on fracture dating from geochemical and mineralogical analysis of fracture infill minerals is currently held at the University of Geneva, Switzerland. Both of these aspects: facies-restricted geomechanical layering and timing of the different fracture families, coupled with structural restoration, should allow estimating zones of particular stress and strain build-up across the basin during its structural evolution, and hence predict areas of potential higher fracture intensity with enhanced permeability in target geothermal reservoirs.

All these findings will then be integrated in both regional and local 3D geological models, built at various scale and resolution depending upon their sizes and objectives. Regional larger scale models will provide the “big picture” of the area in terms of tectonics (major faults and thrusts geometries and fault-bloc compartments), facies and facies-related properties (petrophysical, structural and thermal) distribution. Smaller-scale, higher-resolution models will further specify local areas, previously identified as potential candidates for further investigation (geophysics, exploratory drilling) for deep geothermal energy development.

5. PRELIMINARY RESULTS AND OBSERVATIONS

The cores described were selected according to their availability and along a N-S transect across the basin. It allowed us to identify lateral facies variations at different stratigraphic levels. Firstly, the Muschelkalk shows heterolithic sediments (dolomitic sandstone and clay-rich laminations) in the northern part of the basin whereas cleaner dolomite (with anhydrite nodules) becoming richer in clay lamination towards the top is observed in the South. In the Raethian, a higher carbonate percentage was found towards the South. This is interpreted as an estuary complex depositional environment, getting more proximal to the North. This trend corresponds to progradation/retrogradation direction of the carbonate platform. This observation is less evident in the Dogger and the Malm intervals, although they show several different facies. Within the Cretaceous sequence, the “Calcaires urgoniens” Formation is well represented in the Gex-3 well and surrounding wells (Fig. 5). Here it shows remarkable karsts with breccia and Sidérolithique sandstone infill, as describe in the Thônex-1 well final report (Géologie-Géophysique & Géoproduction Consultants, 1994), but also hydrocarbons occurrence in the fractures (Fig. 6).

Currently, seismic interpretation and coarse 3D modeling work is ongoing over the Greater Geneva region. This initial phase is achieved in collaboration with the French Geological Survey (BRGM), in the framework of the European GeoMol project to which our research is associated. This project, driven by the European Territorial Cooperation, consists in a large scale 3D subsurface mapping of the Tertiary and Mesozoic units across the northern Alpine foreland basin, which extends from its southwestern extremity in the Savoy-Geneva region (our study area), through Switzerland, South Germany, Austria, up to its easternmost termination in Czech Republic. This international participative effort aims at harmonizing key depth horizons and assessing the geopotentials (deep geothermal energy, storage capacity) of the deep subsurface, as well as its use and sustainable management.

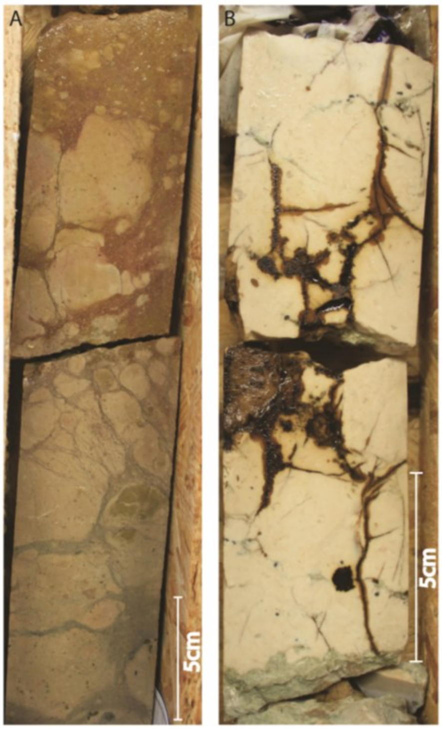

Figure 6: Well Gex-3, "Calcaires urgoniens" Formation: karst filled with breccia (A) and oil-filled fractures (B). Refer to Figure 4 for well location.

6. CONCLUSIONS

The Greater Geneva Basin is considered to have a large potential for geothermal exploration and exploitation which developed during the complex sedimentary and tectonic history of this region.

During its structural evolution, the Greater Geneva Basin underwent an important NW-SE shortening, which was laterally absorbed by NW-SE wrench fault zones as well as by low-reliefs intra-basin flexures of the Mesozoic cover. The "Vuache", "Le Coin", "Cruseille" and the "Arve" wrench fault zones represent the principal structural lineaments linking the Subalpine units with the Jura Mountains across the Geneva Basin and Bornes Plateau. While seismic data suggest that they originate from ancient basement faults reactivated during the Alpine orogeny, these lineaments propagate through the Mesozoic and Cenozoic sequences in flower structure patterns. These wrench fault zones represent potential higher-intensity fracture zones with associated enhanced permeability conditions, which give them special interest as potential geothermal reservoirs. The crystalline basement is incised by Permo-Carboniferous half-grabens located below the thrust front of the Subalpine units and Salève thrust anticline respectively. These half-grabens are delineated by ancient normal faults, which were reactivated in reverse motion during the Alpine compression, creating structural highs on which these thrust fronts developed. Similarly, the first internal folds of the Jura Mountains correspond to the position of an inverted Permo-Carboniferous graben. Structural highs and lows at the top Mesozoic also find their origin within the underlying Permo-Carboniferous structures.

In the area, the top Cretaceous represents an important erosive surface showing important karst development. Main potential reservoirs consist in Permo-Carboniferous sandstones, upper Muschelkalk, Dogger limestones, reefal Malm and karstified Upper Cretaceous unit. The Tertiary Molasse formations are known for their aquifer properties, but are not considered as key geothermal reservoirs targets due to their relatively shallow depths.

Overall, the ongoing studies in the Greater Geneva Basin on deep geothermal potential allowed us to gather and compile for the first time ever an almost complete data set of the existing subsurface data and knowledge regarding the area. 1'500 kilometres of 2D seismic lines issued from various acquisition campaigns, along with 43 deep wells equipped with core and log measurement data constitute the main initial data set. Along with complementary observations, this is being used for detailed structural basin analysis and reservoir rock type investigations. Results will be integrated in multi-scale 3D geological models, which will serve as an important decision tool for further investigations and development of deep geothermal energy in the Greater Geneva Basin.

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