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Rock typing, structural characterization and stratigraphy harmonization in support of geothermal exploration in the Greater Geneva Basin (Switzerland)

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ABSTRACT

A multi-phased program aiming at assessing and developing medium and deep geothermal energy resources in the trans-border (Swiss-French) Greater Geneva Basin is being developed since 2012. In this framework, a detailed subsurface study focused on both structural and reservoir rock typing is being carried out to identify and characterize potential geothermal reservoirs.

This paper presents the first results on the structural analysis and reservoir assessment of the Greater Geneva sedimentary sequence, in a coherent stratigraphic framework. It specifically focuses on the Kimmeridgian stratigraphical unit that appears to be the most promising target for geothermal energy production.

1. INTRODUCTION

During the last decades, interest for the development of deep geothermal energy has raised in Switzerland, not only for electricity generation, but also for heat/cold production to serve heating/cooling of greenhouses and buildings.

The GEothermie 2020 geothermal exploraiton program, promoted by the State of Geneva and the Services Industriels de Genève (SIG), covers the Geneva Canton area and the surrounding French municipalities. This multi-phased program aims at validate the outcomes of a preliminary study (PGG, 2011) focused on the geothermal potential of the trans-border Greater Geneva Basin (GGB) and further investigate the medium to deep subsurface in order to quantify the resources and ultimately leading to their development by 2020.

Although this initial study demonstrated that potential medium to deep aquifers reside in the basin, it also pointed out the lack of integrated geological study and detailed reservoir assessment. Since the unsuccessful hydrocarbon exploration campaigns between the 50's and 80's, only the shallow subsurface sedimentary cover has been widely investigated for hydrogeological purposes. Only in 1994, a geothermal well, Thônex-1 (figure 1) was unsuccessfully drilled South-East of the Geneva State (Jenny et al., 1995) as it encountered low porosity reservoir with low flow rates, highlighting the difficulty to predict reservoir quality at depth.

At regional level, the stratigraphy of Mesozoic units was also never completely homogenized across the basin and showed large inconsistencies complicating basin-scale correlation and thus understanding both facies and architectural changes. Furthermore, to date no integrated database exists to collect and manage both shallow and deep subsurface data, for different purposes and type of users.

In order to get a more detailed and consistent characterization of the subsurface geology, and manage the current and future data acquired, numerous complementary PhD and Post Doc projects were initiated at the Department of Earth Sciences of the University of Geneva. This paper discusses on-going work of three of them, whose objectives are: (1) to analyse the basin structural evolution, fault systems development, their characteristics and relationships through seismic-based 3D geomodelling, in order to provide 3D geometrical models of target geothermal aquifers and identify fault-related enhanced permeability zones in the basin (2) to assess the distribution, geometry, sedimentology and petrophysical properties of potential reservoir units, using well data and outcrop analogues; to characterize rock types in the target reservoir units as input for population of 3D structural models (3) to review and harmonize the stratigraphy from both field observations and regional literature research, and attempt to synchronize it with respect to the new official Swiss stratigraphic framework (Morard, 2014). The building of a consistent database that centralises the homogenized geological information, as well as facilitates correlation work across the basin and Swiss Plateau scale will follow.

Overall, these 3 projects aim at establishing a comprehensive geological understanding of the deep subsurface through the integration of large quantity of sparse existing information, knowledge and newly acquired data using modern interpretation tools, workflows and data management approaches. This enables to target the best geothermal reservoirs in the GGB, and to provide informed recommendations for future exploration steps. The paper especially focuses on the Kimmeridgian reservoir unit that based on current observations and measurements, appears to be the most promising interval for geothermal production.

2. GEOLOGICAL SETTINGS

2.1 The Greater Geneva Basin (GGB)

The GGB covers a Swiss-French transnational zone located at the southernmost extremity of the North Alpine foreland Molasse basin. It is limited to the north-west by the internal chain of the Jura Mountains and to the south-east by the thrusting front of the Alpine units. Whereas in this paper we focus on the basin surrounding the Geneva region, the study area (about 2200 Km^2) extends from the city of Nyon (Switzerland) to the region of Rumilly basin (France) and encompasses the Bornes Plateau in front of the subalpine units (figure 1).

2.2 Tectonic and structural context

The GGB sedimentary cover consists of a thick Mesozoic and Cenozoic succession (3000-5000 m), which overlays a crystalline Variscan basement dipping gently to the S-SE, locally affected by paleo-graben or half-graben structures filled with siliciclastic Permo-Carboniferous sediments (Signer & Gorin, 1995; Paolacci, 2012; Clerc et al., 2015). In response to the alpine compression, the Mesozoic and Cenozoic sedimentary cover of the GGB underwent some shortening displacement associated with rotational motion, likely decoupled from the basement by a decollement surface occurring in Middle and Upper Triassic evaporites at the base of the Mesozoic sequence (Guellec et al., 1990; Affolter and Gratier, 2004; Arn et al., 2005). This shortening was absorbed through the structuration of the fold and thrust reliefs of the Jura arc mountains during the late Miocene and Early Pliocene (Meyer, 2000; Homberg et al., 2002; Affolter and Gratier, 2004). This deformation was laterally accommodated by a set of strike-slip fault systems. Among them, the most important left-lateral regional Vuache fault (figure 2), inherited from former tectonic regimes (Blondel et al., 1988), played an important role in the structuration of the GGB and in the distribution of Tertiary sediments.

According to the “thin-skin” (or “distance push”) model, were the Molasse basin and the Jura developed over a moving basal decollement layer (Sommaruga, 1999 and references therein), no direct morphogenetic connection should be expected between the basement faults and those ones observed in the overlying Mesozoic-Cenozoic overburden. However, inherited basement reliefs and normal faults bounding Permo-Carboniferous troughs might have played a role in the nucleation of the Mesozoic north-westward thrusts present in the SE sector of the Geneva basin and Bornes Plateau (Gorin et al., 1993; Signer & Gorin, 1995).

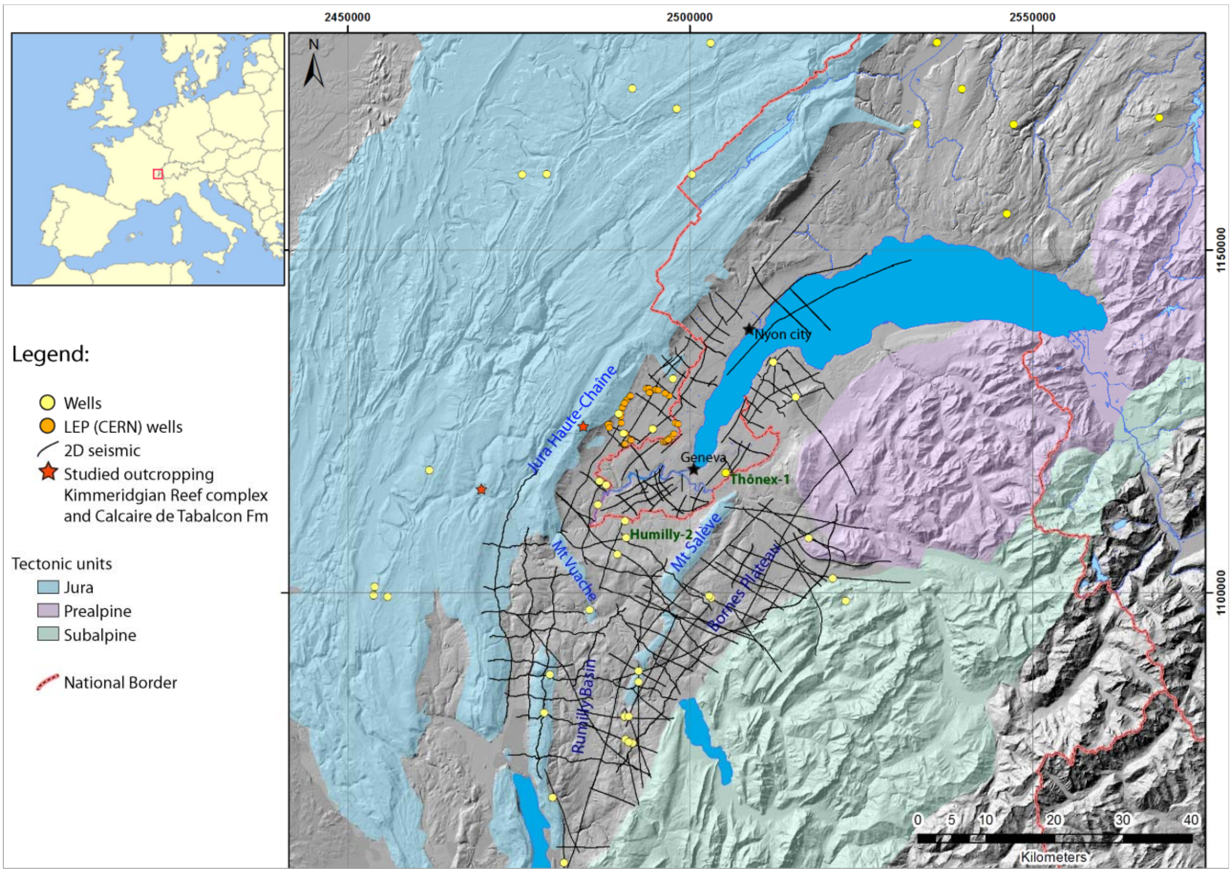

Figure 1: The Greater Geneva Basin (GGB) showing tectonic units, 2D seismic profiles and key locations discussed in the text.

As a result of this structuration, the GGB can be divided into 3 main structural compartments corresponding to Cenozoic paleogeographical domains (figure 1): (1) the Geneva basin *sensu stricto*, bounded by the Mount Salève, Mount Vuache and the Jura Mountains (2) the Bornes Plateau and (3) the northern part of the Rumilly basin (Berger, 2005; Morend, 2000; Charollais et al., 2013).

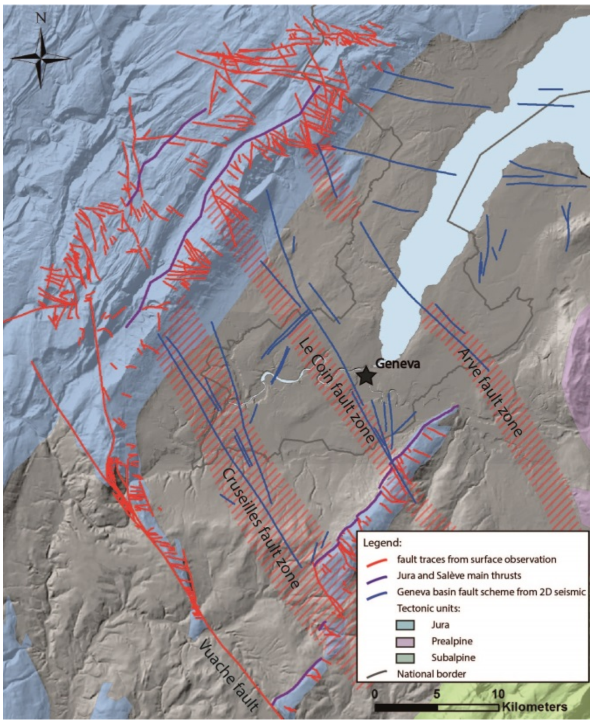

Figure 2: Schematic map of the Geneva basin with location of four main strike-slip fault zones (red, blue lines and dashed areas).

At present, a detailed study of the structural setting of the Geneva Basin *sensu stricto,* is being carried out. In this region, in addition to the Vuache fault described above, three other NW-SE striking left-lateral wrench fault systems/corridors affect the basin. They are known from SW to NE as the Cruseilles, Le Coin and the Arve fault zones respectively (figure 2). The surface expression of Cruseilles and Le Coin faults can be recognised on outcropping Mesozoic units in Mount Salève (Charollais et al., 1998). Unlike the Vuache fault, which can be traced on surface landscape for several kilometres from the Annecy region to the Jura Mountains (figure 1), no obvious connection of the Cruseilles, Le Coin and Arve systems can be drawn with good certainty from one side to the other of the Geneva Basin. For this area, whilst the above described large-scale tectonic framework is generally accepted, different interpretation exists concerning the fault locations, their lateral extensions and connections, mainly due to the availability of subsurface data.

In this work, a complete seismic dataset including reprocessed old 2D lines and newly acquired high-resolution 2D seismic data enabled us to perform a complete detail structural analysis of the Geneva Basin aiming to build a 3D-geological subsurface model. The interpretation of this new dataset allows the fine-tuning of existing interpretations (e.g. location of main fault zones) as well as better delineating their continuations across the study area which occurs as series of subvertical individual faults (often affecting most of the Mesozoic sequence) with associated smaller-scale sets of conjugates (figure 2). Upward extension through the Cenozoic interval of the most important faults often appears on 2D seismic as flower structures as already outlined by Signer and Gorin (1995) and Paolacci (2012). This subsurface expression is consistent with geometry observed for the Le Coin fault system at surface (Angelillo, 1987; Charollais et al., 2007).

2.3 Paleoenvironmental and stratigraphic frame

The sedimentary succession in the GGB formed principally during the Mesozoic and the Cenozoic time period (figure 3). The Mesozoic unit is mainly composed of carbonates and marls, except for the Triassic. During the latter, thick evaporitic series developed first, while the area was flooded by an epicontinental sea partially connected to the Tethys Ocean. This ductile layer played a key role in thrust formation and decollement during the Alpine orogeny (see section 2.2).

The Jurassic era is marked by a rapid transgression during its early stages (Liassic) and two successive regressive trends during the Middle and Late Jurassic (Dogger and Malm). Open marine depositional environments developed during the Liassic, Aalenian and Oxfordian (figure 3). The following Bajocian and Bathonian strata are typically characterized by crinoid-rich bioclastic limestone. The depositional pattern changed during the Kimmeridgian, where numerous patch reefs grew on pre-existing structural highs. Accordingly, for the entire Jurassic period, the inherited paleotopography influenced biotope and hydrodynamic factors controlling facies distribution (Meyer, 2000 and references therein; Piuz, 2008). At the end of the Tithonian, inter-reef depressions were sealed by prograding tidal deposits (Meyer, 2000).

The Lower Cretaceous units are characterized by oolithic and bioclastic limestones as a response to small amplitude sea-level fluctuations (Charollais et al., 2013 and references therein). The Upper Cretaceous instead is missing as a result of Early Cenozoic compressional deformation of the Alpine foreland that exhumed the Mesozoic strata. The subequatorial climate accelerated erosion and karstification of the Cretaceous sequence and created a large unconformity. Cretaceous karsts and fractures were subsequently filled by lateritic sediments (locally known as '*Siderolithic*').

The Cenozoic units mainly consist of marine and continental siliciclastic deposits forming the Oligo-Miocene Molasse. In details it can be subdivided in the Subalpine Molasse composed of thrusted and folded Lower Marine Molasse (LMM) and Lower Freshwater Molasse (LFM) and undeformed Molasse made of both LFM and Upper Marine Molasse (UMM). While in the Bornes Plateau LMM and LFM occurs, in the Rumilly Basin the LFM is overlaid by the UMM. On the other hand, the latter is not recorded in the Geneva Basin (Signer and Gorin, 1995), suggesting that transgression at that time (Burdigalian-Aquitanian) came from the SW. Finally, Quaternary glacial and post-glacial episodes finished to shape the current landscape.

2.4 Stratigraphy harmonization

During the past century, numerous field studies were conducted to understand the nature and stratigraphy of the Geneva Basin. The resulting regional geological maps show large heterogeneities and discrepancies as a result of different interpretations carried out through time by different authors. Stratigraphical correlations and the definition of lateral continuity of reservoir geological units are thus difficult at basin scale.

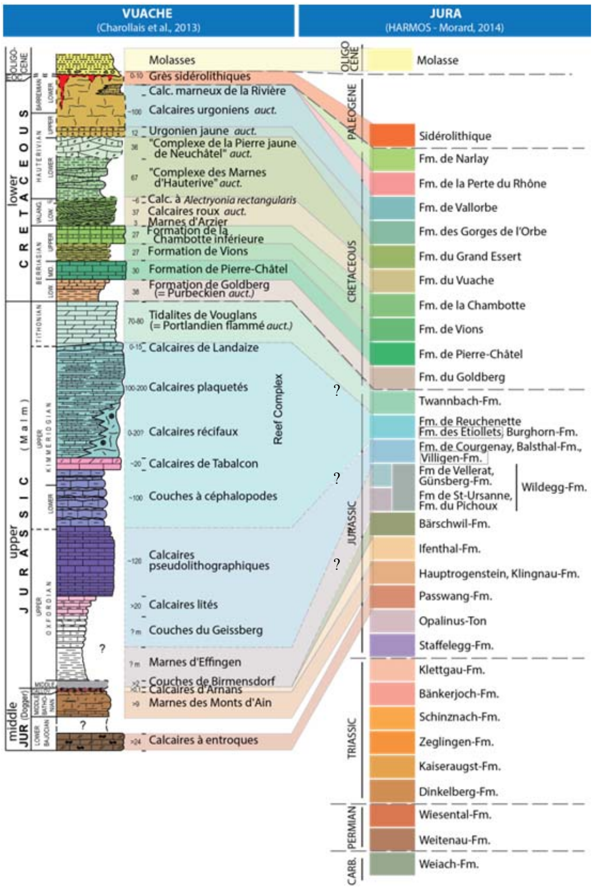

Figure 3: Stratigraphic column of the Mount Vuache (after Charollais et al., 2013) and comparison with HARMOS stratigraphy.

The GEothermie 2020 Program has raised the importance of harmonizing and correlating these data in order to understand better the GGB subsurface geology. For this purpose, the first step was to analyse, compare and compile numerous previous works done over several generations and then to connect the different definitions, interpretations and stratigraphic associations peculiar to each author. Resulting harmonized data improves the ability to understand the subsurface stratal geometry, which is necessary to describe and quantify lateral reservoir variations both at local and regional scales.

At national scale, the Swiss geological survey (Swisstopo) was confronted to the same problem. To solve this issue, harmonized lithostratigraphy with standard legends was developed for the Geological Atlas of Switzerland 1:25'000 (Swisstopo) (figure 4). This program called HARMOS, involved groups of experts with the aim of harmonizing at national level the startigraphic nomenclature (Morard, 2014; Strasser et al., 2016) which will be of guidance for each Swiss States and Cantons, such as the State of Geneva, currently discussed and implemented this new approach. At the moment, the stratigraphy presented in figure 3 and used for the elaboration of the new geological map of the Vuache and Musièges Mountains serves as reference (Charollais et al., 2013).

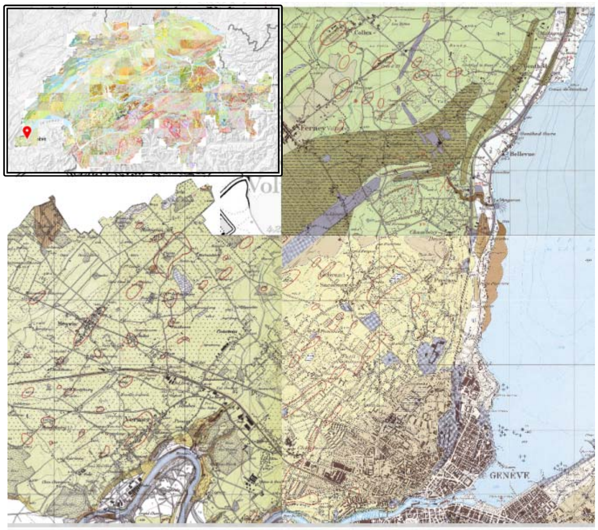

Figure 4: Geological maps from the Geological Atlas of Switzerland (1:25'000) in Geneva area (https://map.geo.admin.ch).

3. MATERIAL AND METHODS

Three different sources - 2D seismic lines, wells, and outcrops - provide most of the data used to study the GGB deep subsurface.

The seismic dataset available in the GGB consists of 1610 km of 2D seismic lines (1385 km and 225 km over the French and Swiss territories respectively). These data are of various vintage (ranging from 1957 to 2015) and quality. Most ancient seismic lines, originating from hydrocarbon exploration campaigns, were either digitized or reprocessed. This comprehensive dataset is used to define the structural framework of the study area, the associated uncertainties and elaborate a series of 3D geological subsurface models. The Humilly-2 well, located at the center of the study area (figure 1) crosses the entire Cenozoic and Mesozoic series down to the underlying Permo-Carboniferous sediments. Being equipped with time-depth pair data, it serves as a main reference well to anchor the seismic data and depth-calibrate the key stratigraphic horizons.

All the wells reaching at least the Mesozoic units were selected for further investigations in the GGB and its surroundings (37 in France and 8 in Switzerland: figure 1). Well reports and logs were collected and digitized. All relevant information on reservoir parameters and stratigraphy were extracted, quality checked and organized in a local database. Cores available were described and sampled. Microfacies and cathodoluminescence analysis on thin section was performed (conventional optical microscopy and CL 8200 MK5), as well as porosity (Phi), permeability (K) and density measurement on plug samples (AP-608 automated porosimeter-permeameter). Modal mineralogy and geochemical analysis using QEMSCAN and ICP-MS technologies were also carried out on core and cuttings samples from the reference well Humilly-2. On this latter only, P and S-wave velocity were also measured on plug samples (ETH Zurich), to help calibrating the seismic velocity model and characterizing the porosity in carbonates.

Recognition of the stratigraphical units was performed on the field to subsequently better discriminate the formations on space-limited core material. Mesozoic units ranging from the Keuper (Upper Triassic) up to the Lower Cretaceous (figure 3) in fact outcrop around the GGB in the Jura Mountains, Mount Vuache and Mount Salève (figure 1). In the targeted reservoir formations, a detailed sedimentological and petrophysical study using similar methods used on core samples was also performed. To date, two outcrops were studied in the Kimmeridgian *Reef Complex* unit and *Calcaires de Tabalcon* Formation in the Jura Mountains (St-Germain de Joux and Le Reculet, see figure 1 for location).

To constrain and understand better the stratigraphy of the GGB, nearly 50 diplomas and 10 PhD theses of the University of Geneva were consulted, enhanced by an extensive published literature search. A large work on collecting and digitizing these data was accomplished and numerous correlations sheets and stratigraphic logs were generated.

4. RESULTS ON RESERVOIR FACIES AND PROPERTIES

Previous researches, literature review and new measurements on reservoir properties highlight different potential geothermal reservoirs in the GGB sedimentary succession (figure 5). They are described in this chapter according to their current stratigraphical position (figure 3 left).

4.1 Triassic: Buntsandstein and Muschelkalk

Siliciclastic sandstone unit from the Buntsandstein shows porosity between 10-15% and variable permeability usually up to 1mD. In thin section, inter-particle pore type is observed only. Therefore, measurements variability depends on two factors: inter-particle calcite cement growth between grains and the shale content. At a larger scale, despite fractures enhanced matrix reservoir properties, well production tests recorded too poor reservoir qualities for geothermal exploitation (flow rate ≤ 2 l/s; hydraulic conductivity ≈ $7.7*10^{-6}$ m/s)(PGG, 2011).

The Muschelkalk unit appears to have moderate to low reservoir quality (porosity<10%) in the GGB, while it appears to be one of the best potential reservoirs for geothermal energy production and CO_2 storage in the northern margin of the Swiss Molasse Basin (Signorelli et al., 2004; Chevalier et al., 2010). The permeability shows a wide range of results (0.01 – 1 mD).

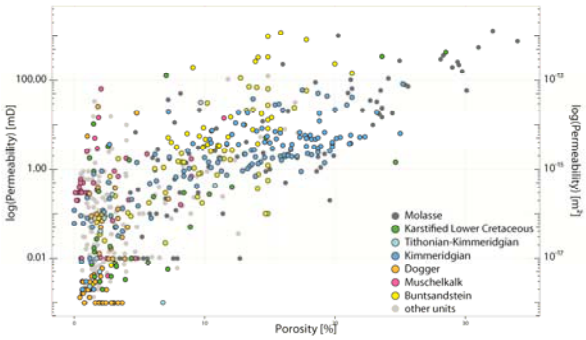

Figure 5: Porosity versus permeability measurements, illustrating different potential reservoirs in the GGB sedimentary succession.

4.2 Middle Jurassic (Dogger)

Three bioclastic intervals were investigated in the Bajocian and Bathonian, belonging respectively to the formations *Calcaires à entroques et polypiers*, *Calcaires échinodermiques supérieurs* and *Calcaire terreux*. The microfacies analysis and poroperm measurements revealed that these formations are composed of crinoid-rich pack/grainstones (porosity<5%). Similarily to the Muschelkalk unit, the permeability is highly variable (0.001-1 mD).

Based on regional knowledge, the Middle Jurassic unit was expected to show aquifer qualities. To the north-east of the GGB, the Bathonian *Grande Oolithe* Formation in the Jura Mountains is considered as a local karstified and fractured aquifer (Boem et al., 2006). Furthermore, the same stratigraphic interval shows excellent matrix reservoir properties in the center of the Paris Basin, where geothermal energy has being produced successfully from the Dogger for more than 40 years (Lopez et al., 2010; Makhloufi et al., 2013). The *Grande Oolithe* Formation does not extend to the Geneva area where the synchronous regional deposits relate to a deeper depositional environment. It reveals a different carbonated production, showing high-energy crinoid-rich environment (rather than oolithic shoals), with poor reservoir qualities described above. Fracture-enhanced permeability could improve reservoir properties in this unit.

4.3 Upper Jurassic: The Kimmeridgian *Reef Complex* and *Calcaires de Tabalcon*

The *Reef Complex* unit includes two main concomitant but distinct facies influencing the reservoir characteristics (figure 6c): (1) boundstone, rudstone and pack/grainstone patches, rich in reef-builder organisms such as corals, stromatoporoids, sponges and microbial crusts (*Calcaires récifaux*) interpreted as patch reefs and peri-reefal deposits (2) platy wackestone (*Calcaires plaquetés*) deposited in lagoonal environments. These two facies overlay the *Calcaires de Tabalcon* Formation, which is formed by bioclastic thrombolithic packstone often dolomitized and interpreted as reef front deposits. This formation is laterally more continuous than the *Reef Complex*.

Phi and K measurements reveal promising reservoir qualities in the reefs and coarse peri-reefal deposits. Porosity values range mostly between 10-20%, and permeability reaches commonly 1 mD. Microfacies analysis of the core material revealed micro-porosity and vugs in reef and peri-reefal deposits, while moldic, intra- and inter-particle, macropores are also observed in the outcrop samples of the same facies (Fookes, 1995; Chatelain and Grosjean, 2004; this study).

The diagenetic evolution is different between the surface and subsurface samples, leading to wider pore type diversity in the first setting. In the second one, moldic dissolution features and intra/inter-particle pores are systematically filled with calcitic cement. However, SEM images suggest that micropores are preserved in the micritic part, and micro-inter-crystalline porosity also remains in partially cemented molds.

Dolomitization also influences the petrophysical properties, particularly in the *Calcaires de Tabalcon* Formation. No core data are available in this unit, but cuttings description highlights vuggy sucrosic dolomitic layers in the western part of the basin, that were also recognized and sampled in Jura Mountains outcrops (figure 6a). Porosity values in these layers are between 10-15% and permeability can reach 35 mD. Dolomite rhombohedra were also observed in the *Reef Complex* unit, and could potentially create inter-crystalline porosity enhancing the reservoir quality, especially in mud-dominated fabrics (Lucia, 1995).

Vertical heterogeneities along this pure-carbonate interval are also highlighted in the petrophysical logs. In the Geneva Basin *sensu stricto*, only Humilly-2 and Thônex-1 wells cross the Kimmeridgian unit, where several porous intervals separated by tight barriers can be recognised.

4.4 Lower Cretaceous: karstic reservoir

At the top of the Mesozoic sequence, karst cavities and enlarged fractures associated to the major Tertiary erosional discordance are observed. These karsts affects principally the massive *Calcaires urgoniens* Formation but are observed to extend at least down to the *Pierre-Châtel* Formation (figure 3). The scattered Phi / K values are usually related to the karst infill, which is composed of continental sandstones and clays (‘*Siderolithic*’). The position and extension of these karsts are still uncertain across the subsurface, but further geophysical studies are currently carried out to constrain better their spatial distribution and impact on upper Mesozoic units, and to detail lithological characteristics of the sedimentary infill.

Several wells existing in the region attest that the Lower Cretaceous can be an artesian aquifer. Two recent wells located at the foothill of the Jura Haute-Chaîne were drilled in spring 2016 for drinking water exploration and exploitation. They showed flow rates of respectively 30 m^3/h and 50 m^3/h in the karstified Cretaceous unit (SEMM logging report, 2016; CCPG and Hydroforage report, 2016). In Divonne-les-bains, two shallow wells (~100 m) have supplied thermal bath for many years, producing 90 m^3/h of thermal water at a temperature of 14.4°C from the same unit (PGG, 2011). This confirms this karstified reservoir as a promising target for low enthalpy geothermal applications. Indeed, flow rates are high, but water temperature remains low (~15°C) due to their shallow depth production.

5. DISCUSSION ON THE KIMMERIDGIAN RESERVOIR

Results show that the Kimmeridgian *Reef Complex* unit and *Calcaires de Tabalcon* Formation represent the best potential reservoirs in the GGB for low enthalpy applications. However, lateral and vertical heterogeneities observed in this unit from surface analogs remain challenging to propagate through the subsurface. Detailed investigation on outcrop analogues, rock typing and seismic facies identification help the understanding of petrophysical property distribution of this complex reservoir unit across the basin.

5.1 Lateral variations

Several outcrops in the study area allowed the development of a robust conceptual depositional model for the Kimmeridgian *Reef Complex* unit (Meyer, 2000; figure 6c). Microfacies identified in the well samples can be related to the depositional environments described in that conceptual model, where muddy lagoonal facies often surround coarser patch reefs, forming potentially permeability barriers. However, the underlaying *Calcaires de Tabalcon* Formation, with good reservoir properties and laterally more continuous than the *Reef Complex* unit, can play a key role in connecting the overlying isolated reservoir bodies of Kimmeridgian patch reefs.

In the Bavarian basin, geothermal energy is successfully produced in comparable reservoir settings (reef-related facies pattern, paleogeographical domain, diagenetic alteration and age of the formations targeted) (Böhm et al., 2013; Homuth et al., 2014; Homuth and Sass, 2014; Steiner et al., 2014). Consequently, the Upper Jurassic reservoir units of the Bavarian Basin could be considered as reservoir analogue to the same units in the GGB.

As described in section 4.3, diagenesis also influences widely the reservoir qualities of the Kimmeridgian unit in the GGB. Southeastward migration of the patch reefs following the general regressive trend in the northern Alpine Tethyan margin during the Late Jurassic influenced not only the distribution of reef bodies through time, but also their diagenetic evolution. A NW-SE diagenetic trend was in fact recognized in the Kimmeridgian unit between the Jura Mountains and Mount Salève (figure 1), showing highly porous dolomitic intervals in the western part of the basin that becomes tighter to the south-east. This diagenetic imprint affects also rock mechanical properties, enhancing or decreasing permeability in fracture zones. This diagenetic gradient could thus explain why high permeable zones in Humilly-2 well were recorded (mud losses), while Thonex-1 geothermal well revealed poorly connected fractures and disappointing reservoir qualities (Vuataz and Giroud, 2010).

5.2 Upper Malm unit and Kimmeridgian reservoir from 2D seismic

Where present, the Purbeckien marls of the Lower Cretaceous (*Goldberg* Formation) (figure 3) allow the distinction between the Cretaceous and the Upper Jurassic limestones, which the Upper Malm unit generally displays a relatively transparent seismic facies with discontinuous subparallel reflectors. Often it becomes chaotic, probably affected by small-scale and unit-bounded discontinuities (figure 6b). This seismic interval is associated with the massive Tithonian and Kimmeridgian limestones, as well as, (where calcareous), the Uppermost Oxfordian deposits known as the *Calcaires Pseudolithographiques* Formation (figure 3). Toward the East of the Geneva Basin, these Upper Oxfordian limestones evolve to deeper facies (Wernli, personal communication) and its seismic facies smears with the underlying upper Oxfordian marls.

Within the Upper Malm sequence, a thin interval of higher-amplitude and more continuous reflectors can be identified. Based on the Humilly-2 reference well, this signature can be attributed to the Upper-Kimmeridgian interval (figure 6b). This includes the coeval *calcaires récifaux* and *calcaires plaquetés* Formations of the *Reef Complex* unit described in section 4.3. Although known on surface as an extensive marker across the basin, the underlying *Calcaires de Tabalcon* Formation is relatively thin (20-30m) in the southwestern part of the Geneva Basin (Charollais et al., 2013; Donzeau et al., 1997) whereas it reaches 80m in the Thônex-1 well toward the southeast of the Geneva Basin. Its seismic signature is included in the Kimmeridgian interval.

At various places in the Geneva Basin, dome-shape type of structures with irregular internal reflection patterns can be recognized on 2D seismic records, surrounded by onlapping reflector geometries (figure 6b). According to their size (comparable with surface outcrop observations) and stratigraphic position, these objects are tentatively interpreted as the Kimmeridgian reef buildups (*Calcaires récifaux* Formation), onlapped on their flanks by the lagoonal deposits of the coeval *Calcaires plaquetés* Formation.

5.3 Rock typing workflow

Defining rock types from well data and outcrop measurements helps propagating and predicting reservoir properties in 3D geological models. Different rock typing schemes were developed in the literature, focusing either on depositional facies, pore types, electrofacies or flow dynamic properties, but only few opted for an integrated approach. Skalinski and Kenter (2015) give an overview of these different methodologies and established their own workflow for hydrocarbon reservoir assessment that combines “geological processes, petrophysics and Earth modelling aspect”.

A similar approach adapted to geothermal prospection and to the dataset available is being elaborated for this study, based on Makhloufi (2013) and Skalinski and Kenter (2015). Depositional rock types are first identified from the core material and outcrop analogues, and then extrapolated to conceptual depositional models. Afterwards diagenetic history and pore types are characterized. Their relationship with petrophysical properties (porosity/permeability, thermal capacity and conductivity) is analysed in order to understand whether depositional or diagenetic attributes dominate flow parameters. Multivariate statistical analyses are then performed to help discriminating rock types, and also to understand if depositional rock types are linked to specific log signals. This approach will help propagating rock types along wells where no core material is available, and consequently to constrain better their distribution in 3D models.

This step by step approach is designed to integrate geological and petrophysical attributes at different scales (core, log), and understand better their spatial distribution.

6. DATA MANAGEMENT

Management of subsurface data is often regarded as less important than the interpretation and understanding of the data themselves. However, in order to ensure a sustainable use and management of their resources, State institutions need a strong and secure infrastructure where surface and subsurface data will be collected and stored. This can only be achieved with homogenized and structured datasets.

In this respect, the State of Geneva has its own geographical information system, the SITG (Système d'Information du Territoire Genevois). It offers a wide selection of data on different themes through interactive accessible maps and downloadable data. However, access to deep geological information is not sufficiently developed to date as only shallow borehole geology information is organized and accessible.

Within the framework of the GEothermie 2020 program, the opportunity to improve the subsurface knowledge by collecting new data in the area, both in two and three-dimensions becomes a reality. A large work, also based on the learning acquired from several other European geological surveys, is currently being executed on the development of a more complete database and new IT platform in order to address these needs.

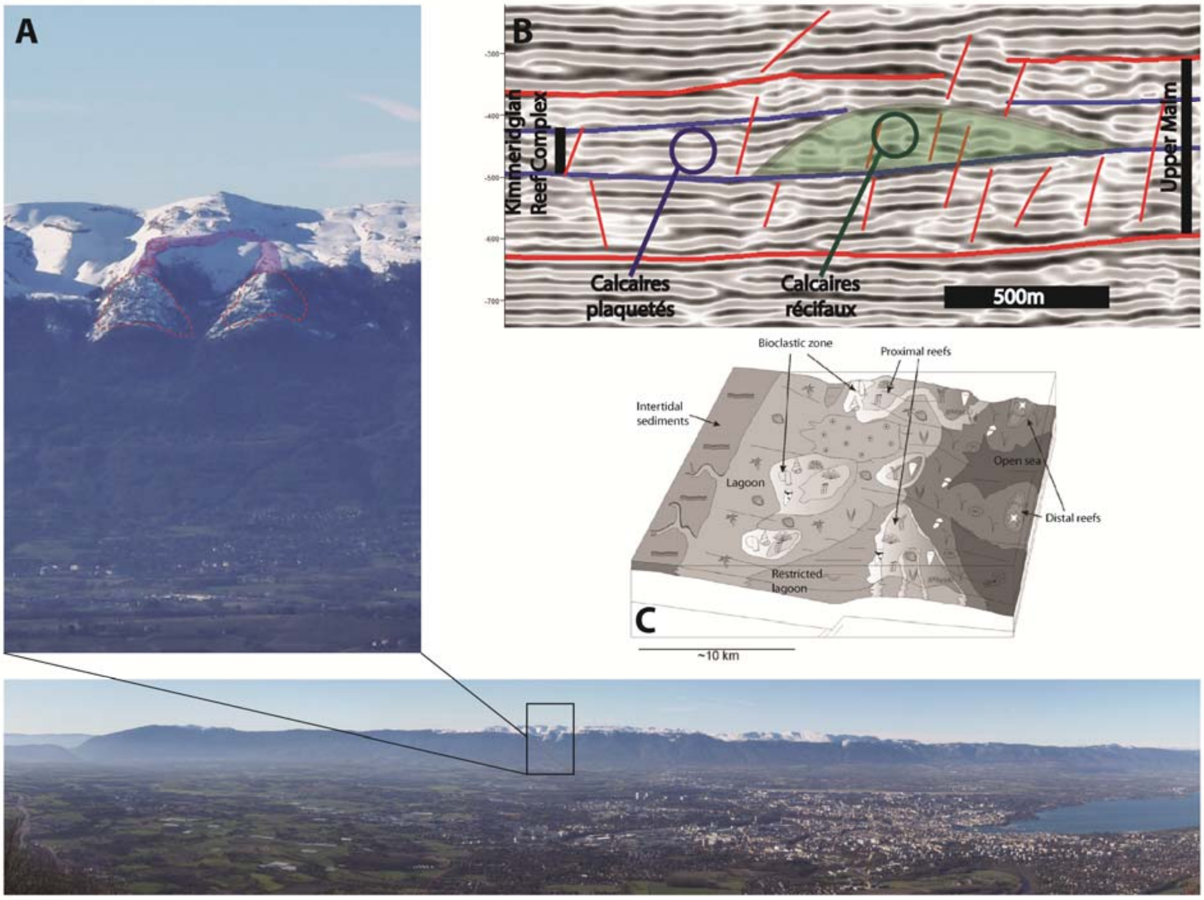

Figure 6: The Kimmeridgian *Reef Complex* (*RC*) unit and *Calcaire de Tabalcon* (*CTab*) Formation: A) on outcrop in the Jura Haute Chaîne (le Reculet: *RC* in red, *CTab* in purple) B) on 2D seismic C) conceptual model from Meyer (2000)

Concerning 3D model products, the State of Geneva acquired in 2014 the GST (Geosciences in Space and Time, Gabriel et al., 2015) platform. It offers an interface on internet (ge.ch/sitg/geologie3D) to operate and visualize 3D models as well as to generate virtual boreholes and cross-sections across these models. The integration of this visualization platform with the future interactive database system is currently planned in order to be able to distribute or share parts of 3D geological models with external parties.

7. CONCLUSIONS AND OUTLOOKS

This study provides new insights on the structural framework, the reservoir assessment and the stratigraphic framework of the GGB. Data management issues are also addressed, since this project generates numerous data of various natures. The main conclusions of this ongoing integrated work can be summarized as follows:

- Structural characterization using all available 2D seismic dataset confirms the existence of four major NW-SE wrench fault zones across the Geneva Basin, and reveals the presence of complex associated and conjugate fault systems. Nevertheless, uncertainties remain regarding the horizontal extension, connection and precise orientation of certain fault interpretation due to the geographical coverage and 2D character of the seismic dataset. A clear mapping and understanding of the relative motion and timing of these systems will help constraining their interpretation and lead to the identification of fault-related enhanced permeability (higher fracture density) zones across the basin. Along with the outcomes of the reservoir properties analysis, this will allow the identification of potential targets for future geothermal exploration drilling.
- The sedimentology and petrophysical attributes of the GGB subsurface sequence, indicate the Kimmeridgian *Reef Complex* unit and *Calcaires de Tabalcon* Formation as the most promising reservoir in the area. However, heterogeneities linked to depositional trends and diagenetic imprints complicate the reservoir property propagation through the subsurface: microporous patch reef bodies overlay a more continuous layer in which strong dolomitization increases the reservoir quality. High-K fracture zones may improve also fluid circulation, but a diagenetic cementation trend seems to seal such structures to the south-east of the study area.
- Specific rock typing definition workflow has been established to manage reservoir heterogeneities and ease the distribution of petrophysical properties in 3D models.
- Kimmeridgian reef buildups are tentatively interpreted on 2D seismic as being responsible for

the dome-shape structures observed across the basin. Whereas their size (similar to outcrop observations), stratigraphic position and presence of onlapping reflector geometries on their flanks support such interpretation, this latter can also get biased by the presence of numerous (subseismic) unit-bounded fault discontinuities that commonly affect the massive limestones of the Upper Malm and Cretaceous units. However, as they are identified as key potential targets from petrophysical measurements, continued attention will be given to the 3D mapping and seismic facies signature distribution of the Kimmeridgian interval.

- The complete understanding and harmonization of regional stratigraphy is a key issue to design properly sedimentary body distribution through the subsurface. The final goal is to create composite logs for each surrounding region and then to define homogenized stratigraphic succession for the GGB.
- Direct correlations with the HARMOS program are not exhaustive for all geological periods, in particular for the Jurassic. Important differences between local stratigraphic nomenclature and this new system exist and are further investigated.
- The development of an intelligent and interactive system for data management holds an important place, especially for such large-scale projects involving growing numbers of stakeholders.

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