Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Application of Chemostratigraphy and Petrology to Characterize the Reservoirs of the Mesozoic Sequence Crossed by the Geo-01 Well: Potential for Direct Heat Production and Heat-Storage

Ferreira De Oliveira G.[1], De Haller A. [1], Guglielmetti L. [1], Makhloufi Y. [1], Moscariello A[1].

1: University of Geneva – Earth Sciences Department. Rue des Maraîchers 13, 1205 Geneva (Switzerland)

gustavo.ferreira@etu.unige.ch

Keywords: Low Cretaceous, Geochemistry, Geothermal reservoirs, GEothermie2020.

ABSTRACT

The sedimentological and geochemical properties of the Mesozoic sedimentary sequence outcropping in the Geneva Basin have been characterized in several studies in the last decade; however, there is a lack of understanding of such properties in the subsurface. Therefore, in order to investigate the Geneva Basin subsurface, a first explorative well (Geo-01) has been drilled in the context of the GEothermie 2020 Program. The target of interest ranges from the Upper Jurassic to the Lower Cretaceous geological units. This sedimentary sequence is composed mainly of carbonate rocks intercalated with thin layers of marls and shales, so the local stratigraphy can be characterized by the variation in concentration of specific groups of chemical elements (eg. major and rare earth elements). The application of chemostratigraphic tools was used to define geochemical zonations of the principal formations crossed by the GEo-01 well. Finally, a regional correlation is proposed using the geochemical data from two other wells (Crozet and Grilly) located near to the study area. Extending this chemical zonation, a chemostratigraphic correlation was produced between the investigated wells.

1. INTRODUCTION

During the last years, geothermal energy has attracted great interest in the Swiss territory. Many investments have been made in order to develop geothermal exploration throughout the country. In a context of high demand for clean generation of electricity and heating/cooling, the State of Geneva and the *Services Industriels de Genève* (SIG, water and energy utility of the Geneva Canton), developed the *GEothermie 2020* geothermal exploration program. This multi-phased program aims at validating the results of a preliminary study (PGG, 2011), and furthermore investigating the medium to deep subsurface of the Geneva Basin (GB). The first exploration phase of the project was able to prove that geothermal potential exists in the Mesozoic and Cenozoic series of the GB ((Clerc *et al*., 2015; Makhloufi *et al*., 2018; Moscariello, 2016; Rusillon, 2018; Moscariello *et al*., 2020), although the reservoir quality can exhibit important lateral variability.

In this context, the second exploration phase led to the drilling to the first medium-depth exploration well of the *GEothermie* 2020 program. The well GEo-01, was thus drilled with the purpose of exploring, identifying and characterizing the geological and hydrogeological conditions of the Upper Mesozoic units. The GEo-01 well went through 407 meters of Oligocene Molasse, 241 meters of Lower Cretaceous limestones and reached the Upper Jurassic (Tithonian) limestones at a final depth of 745 meters below ground floor. Hot water was found at 744 meters depth. This water naturally rises to the surface at a temperature of 33 °C with an artesian flow rate of ca 50 l/s.

A complete petrographic, mineralogical and geochemical characterization has been performed using QEMSCAN analysis and optical microscopy, coupled with a whole-rock (cuttings) down-hole geochemical profiles obtained by ICP-MS. This was aimed to have a better understanding of the composition and repartition of the sedimentary facies and to help correlate the stratigraphy of GEo-01 with other reference wells in the GB (Humilly-2; Thônex-1; Grilly; Crozet).

The comparison of the sedimentological and geochemical aspects enabled us to establish a correlation between the different wells, thus providing new information on the distribution and continuity of the units studied in the GB. As the strike-slip fault systems and associated fracture corridors crossing the study area are considered the main structural features potentially enhancing reservoir porosity and permeability, we have studied key seismic reflection lines close to GEo-01 and the image logs from the well to characterize the fault and fracture systems (Lo, 2019), as well as the role of lithological heterogeneity in these structures.

This study provides new insight on the subsurface in an area of great interest for the *GEothermie2020* program the GB. The integration of previous knowledge and these new results have provided key data that can be used both as input in the 3D geological numerical modeling ongoing efforts which in turn will assist the decision making process that will shape the future geothermal exploration program in the Geneva Basin.

2. GEOGRAPHICAL SETTING

The Geneva Basin is located at the southernmost extremity of the North Alpine foreland Molasse basin and covers part of the French and Swiss territory. The area extends across the French-Swiss border including a large study area (ca 2200 Km^2) spanning from the city of Nyon (Switzerland) to the region of Rumilly (France). The internal chain of the Jura Mountains limits the basin in the north-west while the thrusting front of the Subalpine units limits the south-east part (Figure 1).

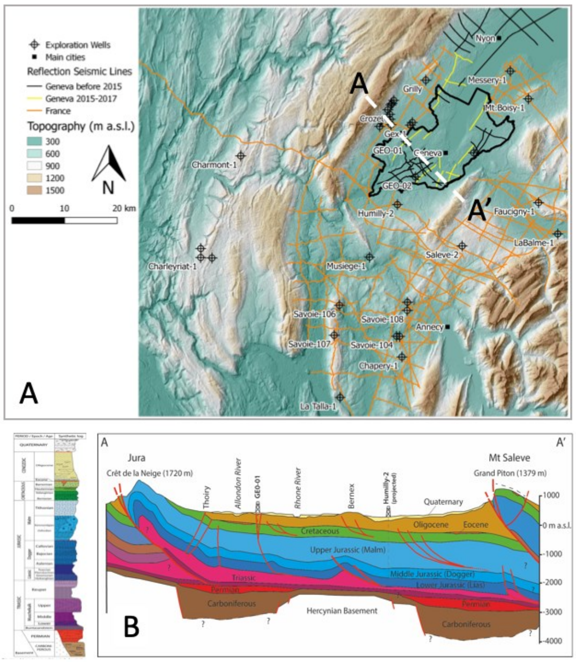

Figure 1- – A) The Geneva Basin and surrounding region with location of main boreholes and 2D seismic lines acquired to date. The main wells used in this project (Geo-01, Crozet, Grilly, Humilly-2 and Thônex-1) are also indicated; B) Simplified stratigraphic columns and NW-SE geological cross-section (AA') showing the principal stratigraphic and tectonic features of the GB (drawings modified from Moscariello *et al*., 2020)

3. TECTONIC AND STRUCTURAL CONTEXT

The GB sedimentary sequence is composed by thick Mesozoic and Cenozoic succession which can reach between 3000-5000 meters. This sedimentary cover overlays a crystalline basement formed during the Variscan and is dipping gently to the S-SE affected by paleo-graben or half-graben structures filled with siliciclastic Permo-Carboniferous sediments (Clerc *et al.*, 2015; Moscariello *et al.*, 2020; Signer & Gorin, 1995).

During the Alpine compression, those sediments experienced a shortening with an overall NW-SE orientation accommodated by series of major NE-SW fault corridors (Figure 2a) and low-relief undulations in the Mesozoic layers. This shortening is possibly associated with rotational motions, which decoupled the sedimentary succession from the basement by a decollement surface in the occurring in Middle and Upper Triassic evaporites at the base of the Mesozoic sequence. This shortening was absorbed by the formation of the fold and thrust reliefs of the Jura arc mountains during the Miocene and Early Pliocene. A set of strike-slip faults was developed by the laterally accommodation in response to this deformation. The most morphotectonic prominent and important strike-and slip fault in the area has a NW-SE orientation and in the landscape is represented by the Vuache Mountain (Figure 2a) (Charollais *et al*., 2013). The Vauche fault crosscuts the entire basing and played an important role in the structuration of the GB and the distribution of the Tertiary sediments. Inherited reliefs and normal faults bounding Permo-Carboniferous throughs might have played a role in the Geneva Basin and Bornes Plateau. (Gorin, *et al*., 1993; Signer & Gorin, 1995)

Based in this structuration, the area of study can be subdivided into three main structural compartments: (1) The Geneva Basin, bounded by the Mount Salève, Mount Vuache and the Jura Mountains, (2) the Bornes Plateau and (3) the northern part of the Rummilly Basin (Figure-1a) (Charollais *et al*., 2007, 2013).

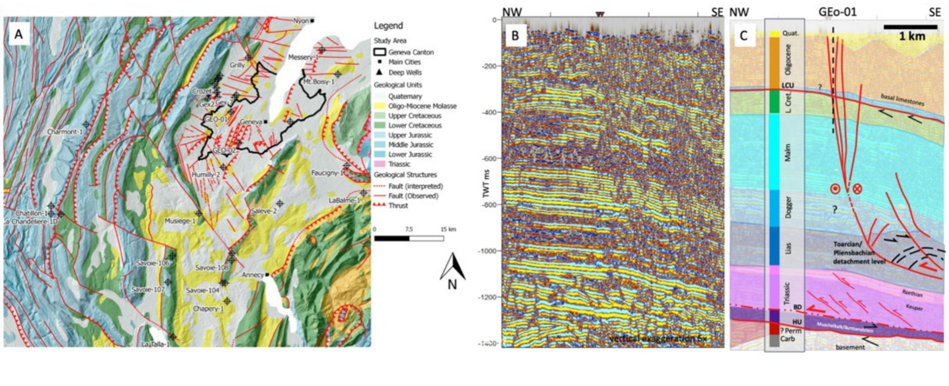

Figure 2 – (A) Simplified geological map based on 1:100'000 scale, with indication of principal structural features in the Geneva Basin as interpreted in the context of the *GEothermie 2020* project (Moscariello *et al*., 2020). B) NW-SE 2D seismic profile (PreSTM – relative acoustic impedance) and C) its interpretation passing through the Geo-01 well. (modified from Moscariello *et al*., 2020)

4. Paleoenvironmental and stratigraphic framework

The Geneva Basin is composed by a thick sedimentary sequence of Mesozoic age, principally consisting of carbonates and marl formations, overlying a crystalline basement which formed during the Variscan (Hercynian) orogeny. This oldest unit results from the collision between the Gondwana (South) and Laurasia (North) continents (Sommaruga, 1997). The development of the North Atlantic and the Tethys ocean from the end of the Carboniferous until the Triassic originated extensional features in the basement of Western and Central Europe. In the GB these low angle normal faults and half grabens with a SW-NE trending are filled with Permo-Carboniferous siliciclastic sediments (Figure-1c) eroded from the surrounding topographic highs (eg. Vosges, Serre, Morvan, Massif Central, Bohemian Massif). The Basement *sensu* lato, formed by crystalline basement and the mainly continental deposits, is underneath Triassic sediments and this contact is marked by an angular unconformity (Signer & Gorin, 1995).

At the beginning of the Mesozoic, the breakup of the Pangea mega continent reactivated late Hercynian crustal discontinuities. During the Lower Triassic rifting phase, an epicontinental shallow water sea was formed by a marine transgression coming, partly from the North (Germanic Basin), but mainly southeastern Paleothetys (Sommaruga, 1997).The type of sedimentation was controlled by the connection with the Tethys Ocean. In transgression periods, carbonates were precipitated in flooded lowlands, whereas continental clastics and evaporites were formed under restricted water circulation (Disler, 1914). Those units worked as decollement layer for the Jura Montains and Mount Salève (Clerc et al., 2015). The thickness of the Triassic sediments in the studied area is variable because of tectonic thickening, thinning and doubling of strata.

The Lower Jurassic stills influenced by the marine transgression of the Late Triassic, and later, during the Middle and Upper Jurasssic, two successive regressive trends affected the Jurassic series. From the Hettangian until the Toarcian, the basin experienced open-marine conditions, that shifted to shallower conditions during the Bajocian and Bathonian (Makhloufi *et al*., 2018). During the Kimmeridgian patch reefs developed on top of pre-existing structural highs (Meyer, 2000). The sealing of inter-reef depressions by prograding tidal deposits followed during the Tithonian, with the local occurrence of immersive facies (Strasser, 1994).

In the Early Cretaceous, the progressive break up of Pangaea intensified mid-oceanic spreading and crust formation, increasing rapidly the volcanic activity on land and in the sea. This phase of particularly intense tectonic activity affected life, the environment, climate, sea level and sedimentary dynamics (Föllmi, 2012). Overall, the Lower Cretaceous is characterized by recurring, similar, stacked lithologies because of cyclic variations of environmental conditions in relatively shallow water, induced by small amplitude sea-level fluctuations (Strasser & Hillgärtner, 1998). At this time an incursion covered the southern Jura. A shallow and warm water environment was stablished with a small amplitude sea level fluctuations and temporarily local lands emerging (Donzeau et al., 1997). The Berriasian deposits are mainly composed by fine grain/bioclastics limestone and fine quartz-rich bioturbated limestone alternating with marls rich in organic matter (Strasser *et al*., 2016). The Lower Barremian is characterized by yellowish oolithic limestone with intercalations of marls at the top and the Upper Barremian composed by very resistant limestones, oolithic at its base and grading into recrystallized limestones at the top (Urgonian facies). The Aptian and Albian periods are marked by successive emersion and drowning episodes, influenced by an intensified greenhouse climate condition (Föllmi, 2012). Afterward, in a transgressive phase, pelagic chalk and limestones were deposited over the entire area (Brentini, 2018). Lacustrine to marine sediments (glauconitic sandstones) rich in siliciclastic material are present infilling topographic depressions.

By the end of the Cretaceous, the GB emerged and the Late Cretaceous sediments were totally eroded (Sommaruga, 1997) and the remaining part preserved in some karst pockets, which formed during the subaerial exposure of the Cretaceous sequence.

The intensified tectonic activity linked to the convergence of the African and Eurasian plates, during the early Cenozoic, exhumed the Mesozoic strata (Schegg & Leu, 1998). A warm and subequatorial climate accelerated erosion of the Cretaceous sequence, creating a major unconformity at the top of the Mesozoic sequence. Lateritic deposits from the Eocene, called "Sidérolithique", often infills karsts features, fractures and sinkholes.

During the Oligocene-Miocene the uplifting of the Alps originated the "Molasse Basin", that is characterized by detrital Cenozoic sediments coming from the alpine realm and deposited in a peri-foreland basin. In the Geneva Basin, the Molasse is divided in three paleozoogeographical domains: The Bornes Plateau, the Geneva Basin and Rumilly Basin (Charollais *et al*., 2007). The Molasse succession comprise four major lithostratigraphic units: The Lower Marine Molasse (LMM), Lower Freshwater Molasse (LFM), Upper Marine Molasse (UMM), and the Upper Freshwater Molasse (UFM). The Bornes Plateau contains the LMM and LFM. Those units were folded and thrusted during the Alpine orogeny forming the sub Alpine Molasse. In the Geneva Basin only the LFM which is directly superposing the eroded Cretaceous sediments or the Eocene lateritic units is preserved. In the Rumilly Basin the LFM is overlain by the UMM, which is present only in this domain and formed by a transgression from the SW. In the Geneva Basin, ca 1500-2250 m of LFM and UMM are missing due to a post-Molasse erosion (Schegg & Leu, 1998).

Several glaciations marked the Quaternary in the Geneva Basin. During this period, the retreat and progradation of the Rhône Glacier generated a sedimentary record related to glacial, glacio-lacustrine, and lacustrine environments (Moscariello *et al.*, 2018).

5. MATERIALS AND METHODOLOGY

The samples used in this study were provided by the *GEothermie 2020* program during the drilling phase of the GEo-01 well. In total, 163 samples from the Mesozoic succession were taken along the well, and 54 of them were selected for geochemical analyses based on the stratigraphic level of interest. In addition, the Molasse interval was previously studied by Pierdona (2018) where 33 levels of interest were added to the present work to complete the entire sedimentary sequence (87 samples in total). To provide a regional correlation between the Lower Cretaceous facies, two other wells were selected and analyzed. The Grilly and Crozet wells are in the French part of the GB and they were realized for the exploration of underground water in the region. These wells, although shallow, cross the Lower Cretaceous formation that can be found in deeper parts in the basin. For the Crozet well and the Grilly well, 21 and 25 samples were selected, respectively.

To carry out a detailed stratigraphic and facies analysis of the Lower Cretaceous/Upper Jurassic inside the GEo-01 well, this project proposes a new type of study using inorganic geochemical analysis that give us the rock's chemical signature which can be then used to perform stratigraphic study (chemostratigraphy). This approach, unlike the conventional tools as the electric logging and biostratigraphy, allows a more refined and quantitative analysis of the samples. The zonation of a sequence in terms of its chemical characteristics is based on changes in the geochemical composition (variations in their major and trace element) concentrations.

Two different types of analysis were used to obtain the necessary geochemical data: the automated Quantitative Evaluation of Minerals by SCANning electron microscopy (QEMSCAN) to a mineral and textural characterization and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) to elemental composition.

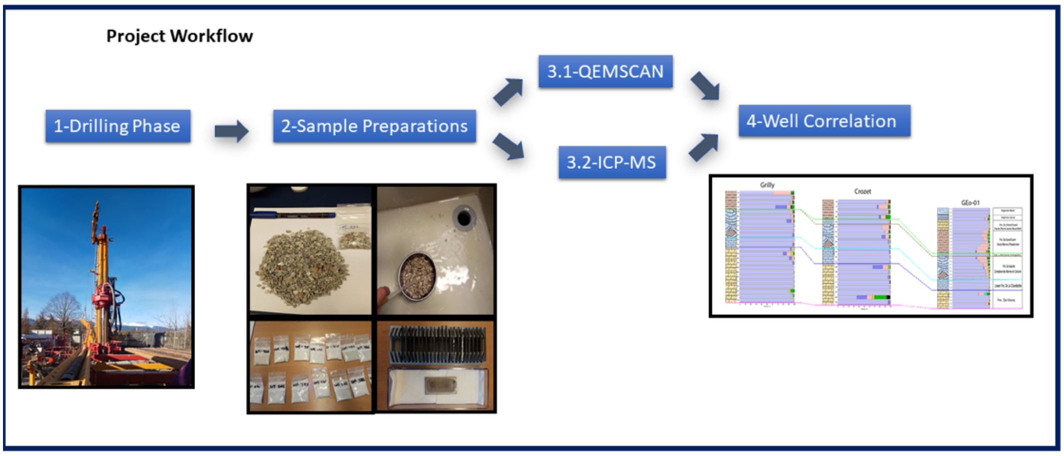

Figure 3 – Workflow of the present work showing some pictures of the specific processes.

Automated mineral and textural characterization were performed using a FEI QEMSCAN® Quanta 650F facility installed at the Department of Earth Sciences (University of Geneva, Switzerland) on a set of 87 carbon-coated polished thin sections of rock cuttings (**Error! Reference source not found.**). Sample preparation method (adapted from Zanoni *et al*., 2016) included washing of ditch cuttings have been which were then hand-picked to remove remnants of drilling mud (Figure 3) before thin section preparation. QEMSCAN analyses were performed with a 15kV acceleration voltage and a probe current of 10 nA. The X-ray acquisition was 10'000 counts per pixel using a point-spacing grid of 10µm. The scanned thin section surface was around 14x20 mm where the mineral phase identification was made thanks to a the combination of back-scattered electron (BSE) contrast and EDS spectra giving information on the elemental composition (Gottlieb *et al*., 2000). A mineral name was then assigned to each acquisition point by comparing its X-ray EDS spectra to a library of known spectra initially provided by the manufacturer and improved in-house using a variety of natural standards. QEMSCAN® data processing was performed using the FEI iDiscover software. Then, for each sample, the QEMSCAN software provides a mineralogic maps (**Error! Reference source not found.**).

Samples for ICP-MS and QEMSCAN analyses in the GEo-01 were taken from the same stratigraphic intervals. Inductively Coupled Plasma Mass Spectrometry or ICP-MS is an analytical technique used for elemental determinations. The whole-rock compositional data for ten major elements and thirty-seven trace elements (including REEs) was acquired by ICP-MS in 54 samples that were sent to and analyzed by Bureau Veritas laboratory (Vancouver, Canada). After interpreting all the obtained results, a correlation between the 3 wells was performed to obtain the lateral continuity of the different facies that composes the Lower Cretaceous of the GB (Figure 5).

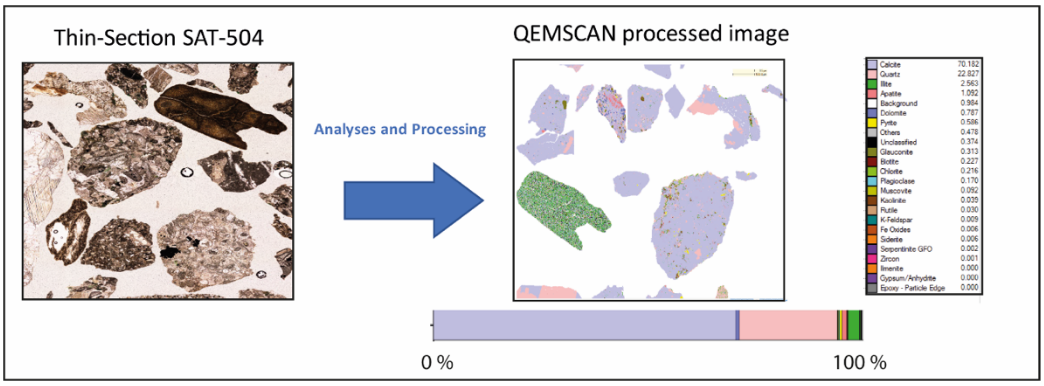

Figure 4 – Scheme showing the results of petrography and QEMSCAN analyzes obtained on the Sat-540 (540m) sample. After the preparation of the thin sections, the samples were analyzed, and the results were processed using the FEI iDiscover software. Note that after processing, the software provides us with a mineral map with the volume of each mineral in percentage. A bar chart is also provided by the software showing the volume percentage of each sample.

6. RESULTS AND INTERPRETATIONS

6.1 QEMSCAN RESULTS

Underlying the Lower Cretaceous Sediments there is a package of sediments (628-745m) that, although rich in calcite, contain a large amount of dolomite (Figure 5). This increase in dolomite followed by a decrease in calcite marks the transition between Cretaceous and Jurassic. A second sequence overlying this first package, with a thickness of 208 m (412-620m) is dominated by a high content of calcium carbonate (Figure 5). The QEMSCAN analyses display limestones rich in calcite with presence of quartz, illite, pyrite, phosphatic shells remains and glauconite in variable proportions. This sequence corresponds to the Lower Cretaceous and can be divided into different mineralogical facies according to the compositional variations mentioned above. Four different cycles can be recognized throughout the Lower Cretaceous sequence on the basis of the increase in the % of quartz which is always followed by an increase in illite and glauconite (Figure 5). The last sequence of sediment corresponding to the Oligocene Molasse sequence extends for 374 meters (38 – 412m) along the well and it is composed basically of an intercalation of siliciclastic rocks that vary between shales and sandstones (Figure 5). Mineral maps and mineralogic proportions exhibit a high quantity of quartz (average of 19%) and phyllosilicates (average of 8.3% in illite and 0.4% in biotite) in this entire package (Figure 5). However, from the compositional point of view, the main characteristic that differentiates these sediments is the presence of minerals such as plagioclase, feldspar, serpentinite, iron oxides and heavy minerals.

The other two wells (Grilly and Crozet; Figure 1) were drilled geographically closer to the NW border of the basin at the foothills of the Jura Mt, so in a slightly different context than the GEo-01 well. Despite reaching a maximum depth of 248 meters, the Grilly and Crozet wells presented in their samples carbonate sediments intercalated with marls and detrital levels (Figure-5).

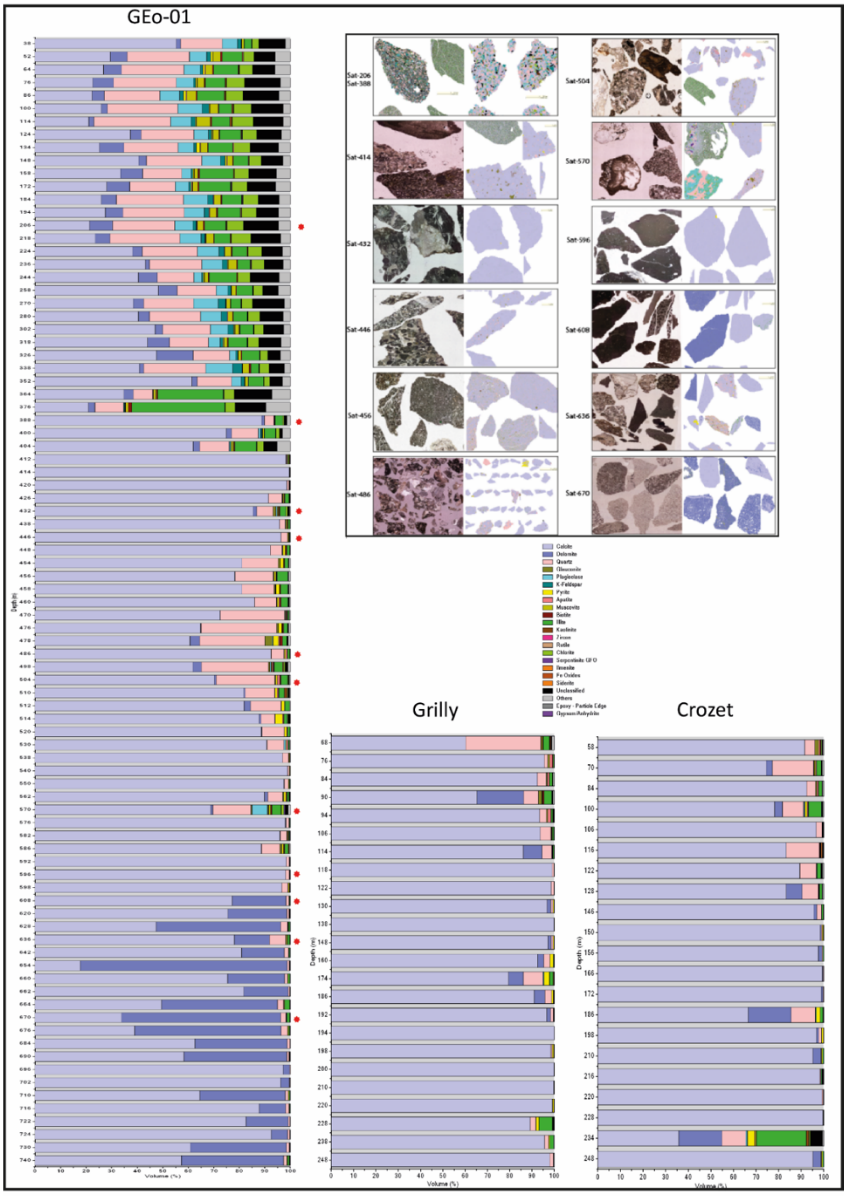

Figure 5 – Comparison between the results obtained by QEMSCAN analyses in the three studied wells (GEo-01, Grilly and Crozet). In the graphs, each sample is represented by a bar showing the volume of each mineral as a percentage of area. The inset at the top right, provides examples of thin sections and their respective QEMSCAN mineralogical maps for the most significative lithology crossed by the GEo-01 well (location of samples is indicated by red dots).

6.2 ICP-MS RESULTS

Along the Lower Cretaceous sequence, the results show a very low concentration in K, Ni, and Al in the sections dominated by pure limestones (rich in Ca). K, Ni, and Al are present in high concentrations in the marly beds found intercalated within the limestones (Figure). All these three elements display slight variations along the vertical profile of the borehole. These variations trends to be accentuated between 515 and 450 m, exhibiting a increasing in those elements. This pattern can be observed again between 560m and 600m, but with slightly lower values. Going deeper into the well, already entering the sedimentary deposits of the Jurassic period, the sediments do not present great variations in the majors, REEs and immobile elements. This sequence can be divided into two sedimentary units. The first package extends between 655m and 695m (Figure), showing a slightly higher concentration of elements such as K, Na, Al and Ti. Entering in the second package (696m – 744m), these elements have slightly lower concentrations. This variation in the concentration of these elements, although not so prominent, suggests changes in the lithofacies formed during this period. In addition, two elements showed interesting results throughout the Jurassic sedimentary section. Looking at the majors' elements Ca and Mg, we can observe a mirrored pattern between both (Figure). As the concentration of Ca decreases towards the top of the Jurassic sedimentary sequence, the Mg concentration increases at a similar rate. In the case of GEo-01, vertical profiles of Cu, U and P generally follow the variations seen in the major's elements, usually associated with debris-rich levels. Despite of this, they share a very characteristic signature between 500 and 510 meters. At this level a large spike was observed caused by an enrichment in these elements.

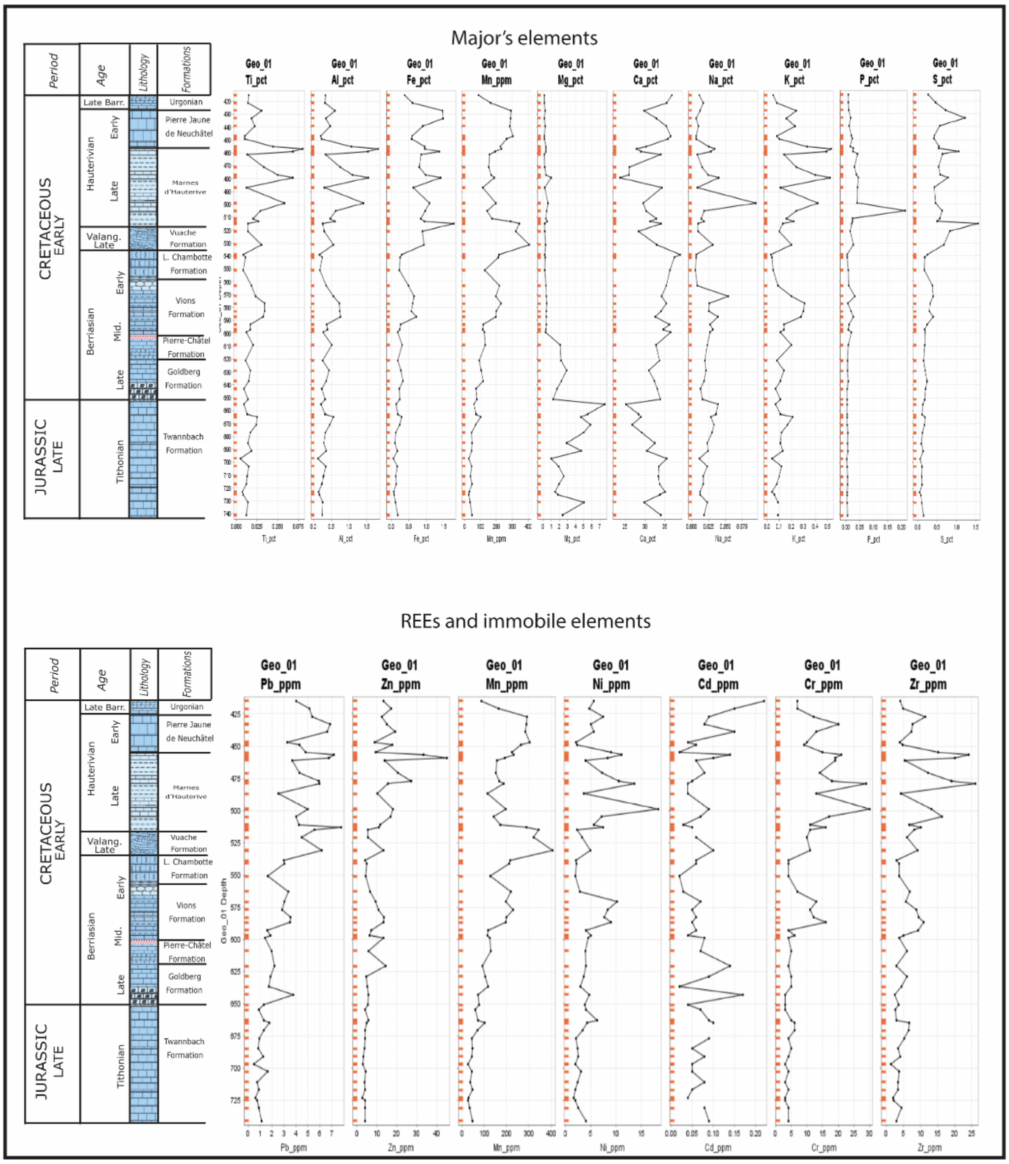

Figure 6 – Results obtained by ICP-MS. The upper image shows the GEo-o1 lithostratigraphic column modified from the cutting samples description provided. To the right, the vertical concentration (%) profiles of the main major's elements for the present study are shown. The lower image shows the vertical concentration profile of REEs and immobile elements.

7. DISCUSSION

During the last century a great effort has been made in several research domains to understand better the stratigraphy of the Swiss region. The large number of studies by different authors have led to discrepancies and heterogeneities in regional geological maps, making stratigraphic correlations and the definition of the lateral continuity of the main geological units extremely difficult. Therefore, a national stratigraphic harmonization was proposed by Swiss Geological Survey (Swisstopo) with the HARMOS program. Groups of experts (Morard, 2014; Strasser *et al*., 2016) provided a new regional stratigraphy using numerous previous works, reviewing and correlating all this data in a harmonious and more comprehensive way, which will be of guidance for each Swiss States and Cantons, such as Geneva.

Based on the works of Strasser *et al*., (2016), Charollais *et al*., (2013), Russilon (2018) and Brentini (2018), the present study was able to distinguish the main lithofacies and substrate formations of the Geneva Basin, proposing a revised stratigraphic column of to GEo-01 well using the results obtained with the QEMSCAN and ICP-MS analyses (Figures 7 andf 8). Throughout the GEo-01 well, the mineralogical content provided by QEMSCAN allowed the recognition of one sedimentary formation in the Upper Jurassic plus ten other units belonging to the Lower Cretaceous.

At the botton of the GEo-01 well it was found a sedimentary package containing carbonates with high dolomite content (740m - 628m). These sediments represent the Upper Jurassic of the Geneva Basin and are described in the new stratigraphic framework (Rusillon, 2018) as Twannbach Formation. This formation represents the Tithonian age and is generally characterized by biomicritic limestone deposited in a calm, subtidal and lagoonal environment (Makhloufi, 2018). The strong dolomitization of these sediments evidenced by the results serves as an indicator of the boundary between the Upper Jurassic and Lower Cretaceous sediments (Figure 8).

Overlying the Tannbach Formation, it was recognized the Goldberg Formation (608m-620m). This formation, first defined as "Purbeck Facies " (Strasser *et al*., 2016), is characterized by an alternation of limestone beds and marls. Depending on the geographical location, the facies of Goldberg Formation varies a lot, been dominated by marls into morphological depressions (Strasser, 2016). The presence of dolomite in these sediments also helped to stablish the limit between this formation and the Pierre Châtel formation right above (Figure 7). The boundary between these two formations is always described in the literature (Tresch & Strasser 2010 and see Rusillon, 2018 for review) as a sharp transgressive surface. This specific feature has also been observed in the description of cutting samples provided by the mudlogging contractor (Hydrogeo) and it is confirmed by a drastic change in the mineralogical composition of these sediments.

The Pierre Châtel Formation is usually dominated by beds of bioclasts and oolitic grainstones with local marginal layers (Steinhauser & Charollais 1971; Rusillon, 2018). Therefore, the sediments of this formation are marked by a high content of calcite and low content of quartz and debris, constituting a level of 'massive limestones' (Figure 8). Overlying the Pierre Châtel Formation were found sediment layers rich in quartz sands, hydroxides, iron oxides, and organic matter (depth). Those minerals are found in different facies which include, claystones, sandy marls, sandy marly limestones and oolitic and bioclastic limestones. These sedimentary facies correspond to a coastal/shallow marine depositional environment, characteristic of the Vion Formation (Charollais *et al*., 2013; Strasser *et al*., 2016; Rusillon, 2018). At the top of the Late Berriasian, it was found the lower part of the Chambotte Formation. In the Swiss Jura realm, the upper part of this formation is missing and just the lower part (Subzone Otopette) is present (Charollais *et al.,* 2008). This formation is generally made up of massive, whitish limestone complex (high calcite content and low quartz content). The facies contain ooids and bioclasts deposited in a shallow marine environment with lagoons and high-energy shoals (Strasser, 2016).

Representing the Valanginian time interval, is the Vuache Formation. Also known as "Complexe des Marnes and calcaires roux ", the Vauche Formation consists mainly of reddish limestones ("Calcaires roux"), marls ("Marnes d'Arzier") and pure limestones ("Alextryonia rectangularis") at the top of the sequence (Rusillon, 2018). Confirming observations made by Strasser *et al*., (2016) this formation has some local levels enriched in glauconite (498m) associated with the sedimentary record of possible storm events. At the top of the sequence, a pure limestone was found representing the facies of "Alextryonia rectangularis".

Composing the Lower Hauterivian sequence, is the Grand Essert Formation. This formation is divided into two different sedimentary facies, "Marnes d 'Hauterive” (Hauterive marls) at the base and ‘Pierre Jaune de Neuchâtel’ at the top (Strasser *et al.,* 2016). The lower part is recognizable for its high detrital quartz content in the marls layers and grains of quartz and glauconite in the limestone beds. The upper part was defined from the content of detrital quartz and glauconite in the limestone. Levels with higher amount of calcite and slightly lower amount of detrital quartz and glauconite mark the boundary between the two facies (448m).

Closing the Cretaceous sedimentary sequence are the Barremian deposits of the Urgonian carbonate platform. This package can be divided into 2 different facies, the Urgonian Jaune (yellow Urgonian) in the base and Urganian Blanc (white Urgonian) at the top (Arnaud-Vanneuu & Arnaud, 1990). The base is characterized by an enrichment in minerals such as detrital quartz, illite and glauconite, while the upper part is characterized by a pure limestone with almost 100% of calcite. Directly overlapping the lower Cretaceous sedimentary sequence and separated by a large regional discontinuity lay 374 meters of siliciclastic deposits. These represent the Oligocene Molasse (Pierdona, 2018) succession generally characterized by sandstones intercalated with shales and, toward the base, some local freshwater limestones that formed in restricted lake basin during the formation of the foreland basin (Charollais *et al*., 2013).

Using the results of ICP-MS analysis, a chemostratigraphic study (Ratcliffe *et al*., 2007) of the Mesozoic sediments crossed by the GEo-01 well was conducted. Following the formations described with the QEMSCAN data it is here proposed a geochemical zonation defining them as chemostratigraphic units.

The Upper Jurassic is generally characterized by carbonates showing a high Mg content followed by a reduction in Ca content (Figure 8). Variations in Ca and Mg content within the Twannbach Formation show possible changes in facies or dolomitization processes. The recent work from Makhloufi (2018) points out different stages of dolomitization in the Twannbach formation. Therefore, looking at the respective values in more detail, this formation can be divided into two chemostratigraphic units, Unit 1 (740-710m) and Unit 2 (702m-628m).

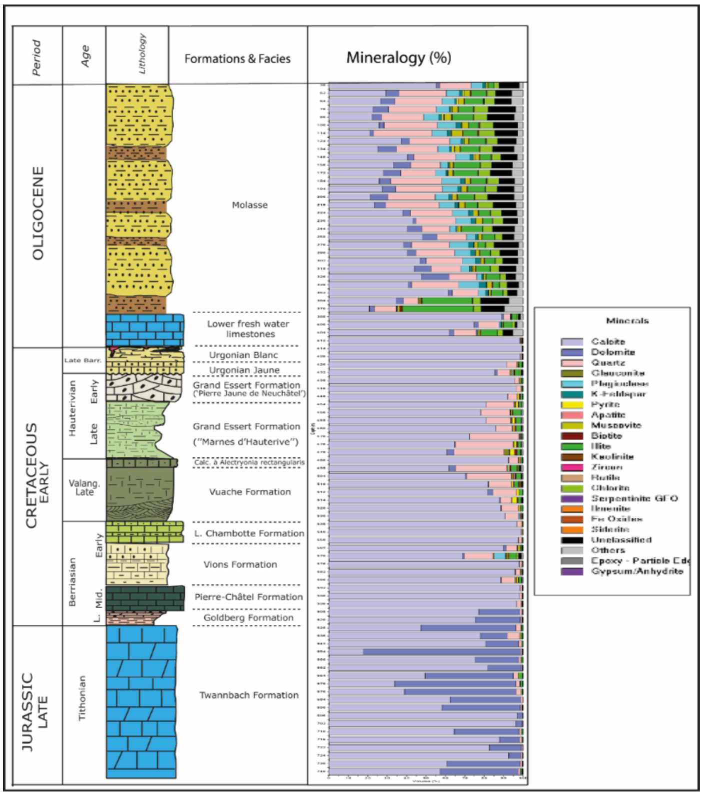

Figure 7 – Litho-stratigraphic subdivision derived from the interpretation of the QEMSCAN analysis results. The chrono-stratigraphic interpretation is based on Strasser *et al.* (2016), Charollais *et al*. (2013), Rusillon (2018), Brentini (2018).

Above the upper Jurassic, the formations belonging to the Berriasian (620m-538m) were analyzed, thus proposing 4 chemostratigraphic units. The Lower Berriasian is represented by the Goldberg Formation, where the major (except for Ca and Mg), REEs and Iimmobiles elements show low values (Figure 8) defining the chemostratigraphic unit 3 (620m-608).

In the carbonates of the Pierre Châtel formation, which represent the middle Berriasian, were observed, except for Ca, low and constant values of Major's elements and REEs and mobiles. This characterized the chemostratigraphic unit 4 (598m-592), which reflects pure carbonates with almost 100% calcite (Figure 8). The Early Berriasian was divided into two different formations, which later allowed the definition of two chemostratigraphic units (Units 5 and 6).

Furthermore, at the base, the Vion formation is characterized by an increase in the concentration of major elements such as K, Al, and Ti (Figures 6 and 8), which is also followed by an increase in the concentrations of REEs and immobiles elements. These values are associated with the presence of quartz sands, hydroxydes and oxydes. Based on these characteristics this formation was defined as the Unit 5. Closing Early Berriasian, the Lower Chambotte Formation is described consisting of pure limestones presenting a high concentration of Ca followed by a low decrease of major's and REEs and immobile elements, being defined as the Unit-6.

Representing the Valanginian, it was described the Vuache Formation. This formation is characterized by high Ca content in the base that decrease towards the top. On the other hand, an enrichment of major's elements toward the top is noted. This characteristic is probably linked to the increase in the amount of detrital sediment input and the presence of marl levels towards the top. At the top of this formation, a thin layer of limestones (1 meter thick) is observed by high Ca content and low major element concentrations (486m). This facies is called 'Alextryonia rectangularis', and marks the top of the Vuache Formation and hence the end of the Valanginian in the Geneva Basin (Figure 8). This entire formation was classified as a single chemostratigraphic unit (i.e Unit 7).

The Hauterivian deposits are represented by the Grand Essert Formation (478m-454m). This formation has been divided into two different facies which have totally different geochemical characteristics. The Late Hauterivian facies are called "Marnes d'Hauterive". This sediment package featured levels of a high content of major's and REEs and immobile elements. These pics characterize the Unit 8 and are probably linked to the presence of debris-rich sediment and marls layers (Figure 6).

The top of the Grand Essert Formation is represented by the 'Pierre Jaune de Neuchâtel' facies. This sequence is composed of clean limestones with high Ca content, followed by low concentrations of major, REEs and immobile elements, characteristics that allowed this sequence to be defined as the Unit 9.

Closing the Mesozoic sedimentary sequence were described sediments belonging to Late Barremian, the Urgonian facies (432m-414m). This sequence showed low levels of Ca at the base (Urgonian Jaune) that increases towards the top (Urgonian Blanc). This variation is followed by an impoverishment in major , REEs and immobile elements. These geochemical characteristics are linked to the establishment of a carbonate platform during this period (Arnaud-Vanneuu & Arnaud, 1990). This also gives to this unit specific characteristics that allowed its definition as the chemostratigraphic Unit 10.

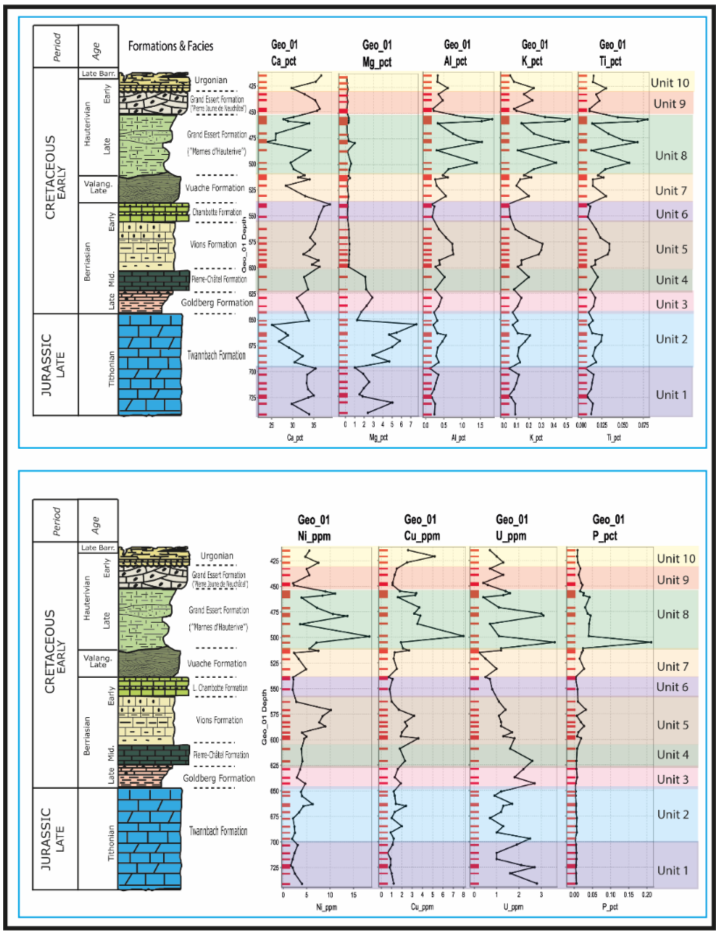

Figure 8 – Diagrams showing the interpretation of the results obtained by the ICP-MS analyses. The top diagram shows the stratigraphic column proposed by the present work, correlated with vertical variation of the major elements used for the definition of the chemostratigraphic units. The lower diagram shows the main REEs and immobile elements used to define the 10 chemostratigraphic units along the GEo-01 well.

According to the compilation of studies proposed by Hardenbol *et al.*,1998, the application of sequence stratigraphy in various outcrops in western Europe revealed that the Cretaceous of this region is characterized by a transgressive-regressive major cycle. The Cretaceous rocks crossed by the GEo-01 well encompasses only the Lower Cretaceous stratigraphic succession, thus having high and low-frequency transgressive-regressive cycles facies comprised in the transgressive phase of the Cretaceous major transgressive-regressive cycle (Strasser & Hillgärtner, 1998). Compiling all the results and interpretations, it was proposed an interpretation of the sedimentary facies found applying the sequence stratigraphy (Figure 9).

Throughout the Lower Cretaceous sedimentary sequence, four transgressive cycles were identified, separated by three other regressive cycles. Transgressive cycles were characterized by depletion trends in vertical mineralogy profiles, followed by a enrichment of specific elements such as Cu, U and P. In another hand, the regressive cycles are characterized by an enrichment in detrital sediments evidenced in the vertical profile of mineral content, accompanied by an impoverishment in Cu, U and P. Using the P content, it was possible to identify a condensed bed, which is marked by a high phosphate content. This condensed bed is observed throughout the Helvetic domain and marks the period of maximum flooding of the existing carbonate platforms (Föllmi *et al.*, 2007).

Finally, a correlation between the wells GEo-01, Crozet and Grilly was elaborated in order to recognize the Lower Cretaceous facies in different locations of the Geneva Basin and to verify the continuity and geometry of these sedimentary packages. Using the present description of sedimentary facies in reference well GEo-01, it was possible to establish a correlation between the three wells. In Crozet and Grilly wells it was identified all sedimentary facies ranging from the Upper Berriasian (Vions Formation) to the Lower Hauterivian (Grand Essert Formation - Marnes d'Hauterivian), except for the Valanginian Facies "Calcaires a Alectryonia Rectangularis", which was not identified at Grilly well (Figure 10).

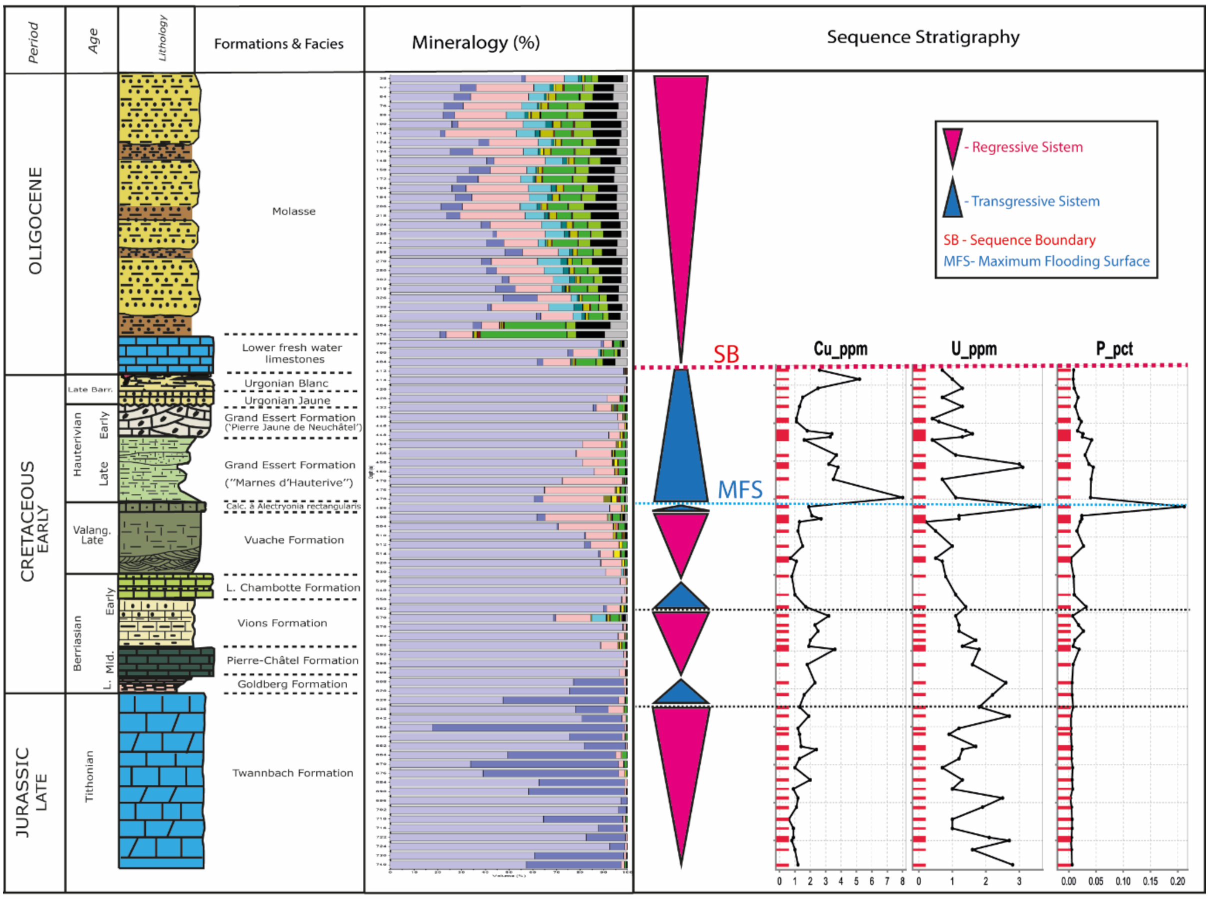

Figure 9 – Lithological and QEMSCAN derived mineralogical log of the GE0-01 well and sequence stratigraphic interpretation based on both mineralogy and geochemical data. The MFS at the top Valanginian is well identified with Cu, U and P increase.

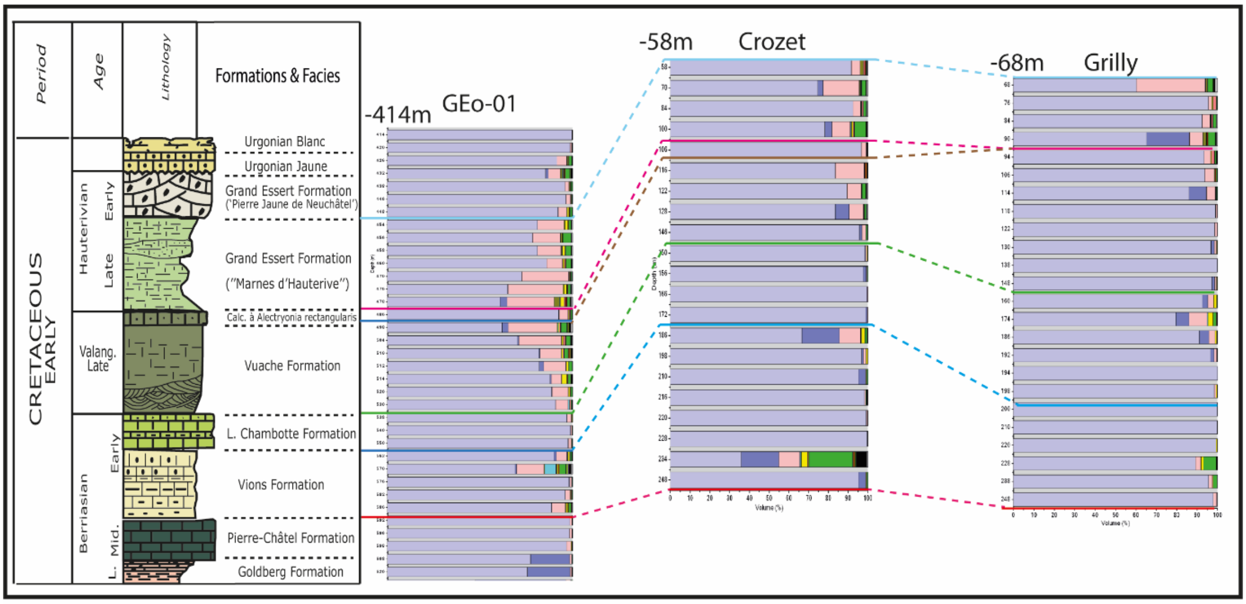

Figure 10 – Proposed stratigraphic correlation for the GEo-01, Crozet and Grilly wells. The continuity of the various Formations forming the Lower Cretaceous succession has been detected based on QEMSCAN mineralogy.

8. CONCLUSIONS

This study demonstrates the importance of mineral analysis and whole rock geochemistry as very effective tools to support exploration studies in poorly known sedimentary basins. In the present project, the main stratigraphic units of the Lower Cretaceous of the Geneva Basin, which contain important reservoir targets for geothermal resources usage (heat production and storage), have been better characterised in their vertical and lateral compositional heterogeneity. Mineralogical and geochemical variations do in fact exist along the sedimentary sequences that make up the Geneva Basin, thus enabling the effective application of a chemostratigraphic approach.

The Mesozoic sequence in the Geneva basin is composed basically by interlayers of different carbonate rocks, which, in absence of core and detailed and time-consuming petrographic and biostratigraphic studies makes it difficult to recognize the main sedimentary facies composing them. However, by using QEMSCAN and ICP-MS, the present study was able to analyse a large number of thin-sections in a relatively short time, recognizing and characterizing the main formations crossed by the GEo-01 exploratory well, giving each one a chemostratigraphic signature. This allows a stratigraphic correlation between different wells in the same basin setting and geological context.

AKNOWLEDGMENTS

The Services Industriels de Genève and the Canton of Geneva are warmly thanked for the continued financial support provided to the Department of Earth Sciences and Environmental Sciences/Institut Forel of the University of Geneva to promote the research on subsurface characterization ad geothermal systems of the Geneva area in the framework of the 'GEothermie 2020' program. This paper is a contribution to the Swiss national program SCCER SoE funded by the SNF and Innosuisse, the project GECOS supported by Innosuisse, SIG and Geo2x, the EC funded GEOTHERMICA/HEATSTORE program and the UNCONGEO project supported by swisstopo, Swiss Federal Office of Energy Canton of Geneva and Canton of Vaud.

REFERENCES

Brentini, M.: Impact d'une donnée géologique hétérogène dans la gestion des géo-ressources : Analyse intégrée et valorisation de la stratigraphie à travers le bassin genevois (Suisse, France). *Terre & Environnement* ***140*** (2018), 230 pp.

Charollais, J., Weidmann, M., Berger, J.-P., Engesser, B., Hotellier, J.-F., Gorin, G., Reichenbacher, B., and Schäfer, P. (2007). La Molasse du bassin franco-genevois et son substratum. *Archives des Sciences,* ***60***, pp.59–174.

Charollais, J., Wernli, R., Mastrangelo, B., Metzger, J., Granier, B., Martin, M. Saint, & Weidmann, M. (2013). Présentation d'une nouvelle carte géologique du Vuache et du Mont de Musièges. *Archives Des Sciences*, ***66***, pp.1–63.

Clerc, N., Rusillon, E., Moscariello, A., Renard, P., Paolacci, S., & Meyer, M. (2015). Detailed Structural and Reservoir Rock Typing Characterisation of the Greater Geneva Basin, Switzerland, for Geothermal Resource Assessment. *World Geothermal Congress 2015, Melbourne, Australia*, (April), ***11***.

Disler, K. (1914). Stratigraphie und Tektonik des Rotliegenden und der Trias beiderseits des Rheines zwischen Rheinfelden und DAugst. In *Verh Naturf Ges Basel*.

Donzeau, M., Wernli, R., Charollais, J., and Monjuvent, G. (1997). Notice carte St-Julien- En-Genevois, carte au 1/50000, feuille 653. *Bureau de Recherches Géologiques et Minières*, *brgm edition.*

Föllmi, K. B. (2012). Early Cretaceous life, climate and anoxia. *Cretaceous Research*.

Föllmi, K.B., Bodin, S., Godet, A., Linder, P. and Schootbrugge, B. V. D. (2007). Unlocking paleo-environmental information from Early Cretaceous shelf sediments in the Helvetic Alps: stratigraphy is the key!. *Swiss journal geosciences,* ***100***, pp. 349–369.

Gorin, G., Signer, C., & Amberger, G. (1993). Structural configuration of the western Swiss Molasse Basin as defined by reflection seismic data. *Eclogae Geologicae Helvetiae*, ***86***(3), pp. 693–716.

Gottlieb, P., Wilkie, G., Sutherland, D., Ho-Tun, E., Suthers, S., Perera, K., Jenkins, B., Spencer, S., Butcher, A., Rayner, J. (2000). "Using quantitative electron microscopy for process mineralogy applications". *Journal of the Minerals, Metals and Materials Society,* ***52(4)***, pp 24-25.

Hardenbol,J., Thierry, J., Farley, M. B., Jacquin, T., De Graciansky, P.-C., & Vail, P. R. (1998). Jurassic sequence chronostratigraphy. *SEPM Special Publication,* ***60***, chart.

Lo H.Y. (2019). *Discrete Fracture Network Modelling in the Geneva Basin (Lower Cretaceous Carbonates): Implication for Geothermal Exploration.* MSc Thesis, Department of Earth Sciences, University of Geneva, 135 pp.

Makhloufi, Y., Rusillon, E., Brentini, M., Moscariello, A., Meyer, M., & Samankassou, E. (2018). Dolomitization of the Upper Jurassic carbonate rocks in the Geneva Basin, Switzerland and France. *Swiss Journal of Geosciences*, ***111***(3), pp.475–500.

Morard, A. (2014). Correlations beyond HARMOS: how, where, why?. In *Swiss Geoscience Meeting 2014*, *Lausanne, Switzerland*.

Meyer, M. (2000). *Le Complexe récifal kimméridgien-tithonien du Jura méridional interne (France), évolution multifactorielle, stratigraphique et tectonique*. Thèse de doctorat: Univ. Genève, 2000 - Sc. 3170 – 2000.

Moscariello, A. (2016). Geothermal exploration in SW Switzerland. *European Geothermal Congress 2016,* ***9****, Strasbourg, France*.

Moscariello, A., Clerc, N., Pierdona, L., & De Haller, A. (2018). Exploring the interface between shallow and deep geothermal systems: new insights from the Mesozoic-Cenozoic transition. *16th Swiss Geoscience Meeting Bern*.

Moscariello A., Guglielmetti L., Omodeo-Salé S., De Haller A., Eruteya O.E., Lo H.Y., Clerc N., Makloufhi Y., Do Couto D., Ferreira De Oliveira G., Perozzi L., De Oliveira F., Hollmuller P., Quiquerez L., Nawratil De Bono C., Martin F., Meyer M.:

Heat production and storage in Western Switzerland: advances and challenges of intense multidisciplinary geothermal exploration activities, an 8 years progress report. Proceedings World Geothermal Congress, Reykjavik, Iceland , (2020), 12 pp.

Pierdona L. (2018). *Chemical stratigraphy and petrography of the Molasse in the Geneva Basin.* MSc Thesis, Department of Earth Sciences, University of Geneva, (2018), 131 pp.

Rusillon, E. (2018). *Characterisation and Rock Typing of Deep Geothermal Reservoirs in the Greater Geneva Basin*. Terre & Environnement, ***141***, 252 pp.

Schegg, R., & Leu, W. (1998). Analysis of erosion events and palaeogeothermal gradients in the North Alpine Foreland Basin of Switzerland. *Geological Society, London, Special Publications*.

Signer, C., & Gorin, G. (1995). New geological observations between the Jura and the Alps in the Geneva area, as derived from reflection seismic data. *Eclogae Geol. Helv.*, ***88/2***, 235–265.

Sommaruga, A. (1997). Geology of the Central Jura and the Molasse basin: New insight into an evaporite-based foreland fold and thrust belt. *Mémoires de La Société Neuchâteloise de Sciences Naturelles*.

Strasser, A. (1994). Milankovitch Cyclicity and High-Resolution Sequence Stratigraphy in Lagoonal-Peritidal Carbonates (Upper Tithonian-Lower Berriasian, French Jura Mountains). *International Association of Sedimentologists Series*, ***19***, 285–301.

Strasser, A., Charollais, J., Conrad, M. A., Clavel, B., Pictet, A., & Mastrangelo, B. (2016). The Cretaceous of the Swiss Jura Mountains: an improved lithostratigraphic scheme. *Swiss Journal of Geosciences*, ***109***(2), (2016), 201–220.

Strasser, A., & Hillgärtner, H.. High-frequency sea-level fluctuations recorded on a shallow carbonate platform (Berriasian and Lower Valanginian of Mount Saleve, French Jura). *Eclogae Geologicae Helvetiae*, ***91***(3), (1998), 375–390.

Steinhauser, N., & Charollais, J. (1971): Observations nouvelles et réflexions sur la stratigraphie du «Valanginien» de la région neuchâteloise et ses rapports avec le Jura méridional. - Géobios 4/\, 7-59.

Tresch, J., & Strasser, A. (2010). History of a Middle Berriasian transgression on the Jura carbonate platform: Revealed by highresolution sequence- and cyclostratigraphy (Switzerland and France). International Journal of Earth Sciences, ***99***, 139–163.

Zanoni, G., Šegvić, B. and Moscariello, A. (2016). Clay mineral diagenesis in Cretaceous clastic reservoirs from west African passive margins (the South Gabon Basin) and its impact on regional geology and basin evolution history. *Appl. Clay Sci.,* ***134***, pp. 186-209.