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ABSTRACT

Several activities ranging from subsurface data analysis, new data acquisition, database infrastructure design and policy making are ongoing in support of the large geothermal exploration effort in the framework of the 'GEothermie 2020' program in south-western Switzerland (Canton of Geneva). The step-wise approach strategy defined by the main project stakeholders aims at acquiring knowledge of the underground geothermal potential while ensuring continue support form public and political parties. The subsurface characterisation study carried out to date mostly by the University of Geneva is delivering encouraging results in support of future identification of drilling locations based on a detailed multidisciplinary study of the entire stratigraphic succession of the Geneva Basin underground. These will allow to meet both exploration requirements (i.e. reduce subsurface uncertainties) while responding to energy policy targets (increase use of sustainable energy source and increase energy efficiency).

1. INTRODUCTION

Energy supply, demand and security are amongst the key political and social issues of our time. In addition the increased environmental concerns related to the use of conventional energy sources such as fossil fuel and nuclear have led national and international communities to address the important aspects of energy transition to more sustainable and environmental friendly energy sources. Geothermal energy represents one of the main alternative sources of energy, which, despite its exploitation is known for over a century in several regions of the world (Italy, Island, California), only during the last decade is receiving a large degree of attention from society, politicians and investors.

This paper intends to provide an overview of the energy issues in Switzerland and more specifically present the technical approach implemented within the "*GEothermie 2020*" Program established to outline the technical and commercial feasibility of geothermal exploration and exploitation in the Geneva Canton, located in south-western Switzerland.

2. THE SWISS ENERGY CHALLENGE

Switzerland, despite its small dimension compared to other countries in Europe, has a high-energy consumption where, however, renewables represent a considerable part. In 2014, the share of renewable energy sources of energy final use consumption was 21.4% against 78.6% of non-renewables. As per electricity, with 9,052 kWh per person Switzerland is ca. 22% above the European Union's average consumption (year 2008). About 60% of Switzerland's electricity generation (corresponding to a share of 55.8% final user consumption) comes from renewable sources, most of it from hydro (56.4%), while non-hydro renewables supplied a small contribution of 3.8%. Nuclear contributes 37.9% to the countries electricity production and only about 1.9% is generated by fossil-fuel-based thermal power stations (SFOE, 2015). On the other hand, heat production from renewable sources corresponds to ca. 19% of total final use consumption (SFOE, 2015). Out of this, geothermal energy corresponds to ca. 26.4%, representing still a small but considerably growing percentage of the Swiss renewable energy portfolio. Over the last 22 years a series of deep geothermal projects (Riehen in 1994, Thonex in 1996, Basel in 2009, Schlattingen in 2011 and St Gallen in 2013) were attempted aiming at both deep enhanced geothermal systems and hydrothermal resources, in most cases without delivering the expected results. Moreover, man-made accidents such as induced seismicity associated with drilling and completion operations (Basel and St Gallen wells) generated a public concerns which undermined the future of geothermal exploration in Switzerland.

Enhanced interest for geothermal energy was revitalised when energy related issues became a main topic of public and political debate after the March 2011 accident at Fukushima Daiichi accident. This led to a referendum whose outcomes supported the Swiss energy transition and nuclear phase out by 2035. In this context, major initiatives to promote the identification and quantification of alternative sources of energy to nuclear energy, were promoted at federal level by the Swiss National Funds and Commission for Technology Innovation. This process led in 2014 to the establishment of a nation wide research and pilot & demonstration program known as Swiss

Competence Centers for Energy Research (SCCER) dedicated to a variety of energy topics such as innovative and sustainable research in the areas of geo-energy and hydropower (SCCER-Supply of Energy, http://www.sccer-soe.ch).

In the same period the Geneva Canton started an independent substantial reflection on local energy consumption whose finding highlighted the excessive use of conventional energy sources, inadequate level of energy efficiency and a strong dependency from resources outside the Geneva area. A review of the modes of supply, processing and use of energy led the Canton of Geneva to adopt officially an energy policy in the Constitution. In particular, the ambitious objectives to achieve a nuclear energy-free *'society at 2000 Watts'* (Jochem, 2004) as quickly as possible, were set, requiring a considerable reduction in energy consumption per capita. Based to this objectives, out of the 2000 Watts, 1500 Watts were to be generated by renewable sources against 500 Watts from fossil energy. In this context, the development of renewables is therefore a clear priority and geothermal energy offers particularly interesting potential.

2.1 Electricity vs. Heat in Switzerland

Following the decision of the Swiss Federal Council and the Parliament to adopt the Energy Strategy 2050 and its long-term energy policy, a step-by-step withdrawal from the use of nuclear energy is being implemented. Switzerland is therefore required to provide almost 40% percent of its domestically produced electricity from renewable energy sources (i.e. hydropower, geothermal, etc.). To face this challenging task the SCCER-SoE is one of the measures that have been put in place to achieve this goal by 2050. It focuses on electricity that can either be produced flexibly or continuously to meet base-load demand which would require a capacity of 20 megawatts electric installed every year from 2025 to 2050 (Giardini, 2016).

On the other hand, heat is one of the most required types of energy today. About 50% of the total energy consumed in Switzerland is needed to heat buildings, to provide domestic hot water, and to supply heat to industrial processes. Approximately 86% of the required heat is generated by the burning of fossil fuels, with the remainder produced from electricity. Households and services use about 92% of their total energy needs for heating buildings and water, while industry uses about 92% of their total energy requirement for generating process heat (SFOE, 2014). Heat Storage provides several solutions to reduce the CO_2 footprint of industrial processes and civil uses by means of storing waste heat deriving from industrial processes (such as waste-to-energy plants).

Geothermal energy is therefore an appealing alternative to conventional non-renewable energy sources whose potential and effectiveness in responding to both heat and electricity requirements are being addressed by a multitude of R&D and political initiatives at federal, cantonal and town level.

3. THE GEOTHERMIE 2020 PROGRAM

In 2014, after a preliminary phase of consultation between political, technical and administrative parties the State and Canton of Geneva and the local main energy supplier SIG (Services Industriels de Genève) launched the *'GEothermie 2020'* program aiming at developing in a short to medium time frame, a strategic roadmap to supply geothermal energy to the entire Canton (are of 282 Km^2 and ca 482'500 inhabitants). This large project, with an overall an investment envelope of 20 millions of CHF, consists of three main phases (figure 1). The first phase will be dedicated to both preliminary and detailed investigation where collection and examination of existing data will be followed by more in depth study when new data sets will acquired and interpreted (e.g. 2D / 3D seismic, shallow boreholes, etc.).

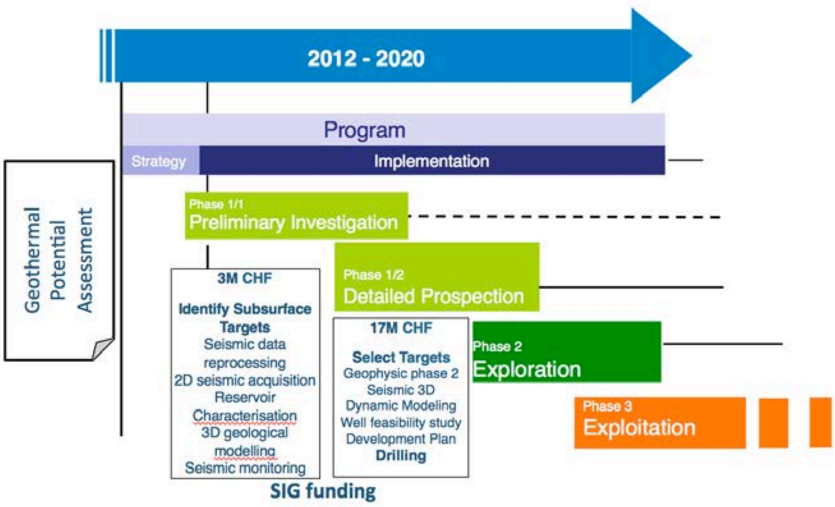

Figure 1: Geothermal potential assessment journey of the Geneva Basin currently implemented for the *'GEothermie 2020'* programme (modified after Andenmatten Berthoud, 2014).

This phase will be followed by the exploration and then energy exploitation phases. The first phase, aims to prove the technical and commercial feasibility of geothermal energy exploitation in the Canton and is mainly led and funded by SIG in partnership with the Department of Earth Science of the University of Geneva and a variety of third parties consultants. The detailed roll out of the subsequent phases including the planning and execution of exploration wells and energy production and distribution, will depend on the outcomes and recommendation of the first phase.

3.1 What are the options ?

Geothermal energy exploitation in Switzerland and in particular in the Geneva Canton is not a novelty. Shallow (100-200 m, figure 6) vertical geothermal probes designed to heat and cool domestic and industry buildings have been implemented successfully over the last 25 years providing in the Canton of Geneva heat in the excess of 1,200 GWh/year corresponding to ca 20% of the Current cantonal demand of heating energy (PGG, 2011). Significant implementation with exponential trend of this technology is ongoing suggesting the installation of shallow geothermal wells will pass the 5,000 units in Geneva by 2030.

On the other side, medium to large depth wells exploiting higher temperatures and thus attaining more energy potential (heat and electricity) are not yet in operation. However, the result of an old deep well drilled with a hydrothermal objective in 1996 (Thônex 1) and the review of available data suggested considerable potential for geothermal exploitations at larger depth (PGG, 2011). On this framework, the strategy adopted by the *‘GEothermie 2020’* projects aims to develop a step-by-step approach whereby the uncertainties and risks associated with deep geothermal wells (see Basel and St. Gallen examples) will be mitigated by a careful gradual improvement of knowledge of the underground, first passing through the exploration of geothermal resources at shallow depths and subsequently at greater and greater depth. This strategy will thus ensure a continue and gradual learning of the subsurface and its geo-energy diversity and potential while minimising risks of technical failure and ensuring sustained society, political and investor support.

3. THE GENEVA BASIN

The study area is located at the southernmost extremity of the North Alpine foreland Molasse basin. The area specifically concerned by the *‘GEothermie 2020’* program focuses in the Swiss territory. However, the ongoing geological study extends naturally 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) encompassing the Bornes Plateau in front of the Subalpine thrust front (figure 2). The area 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. The 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).

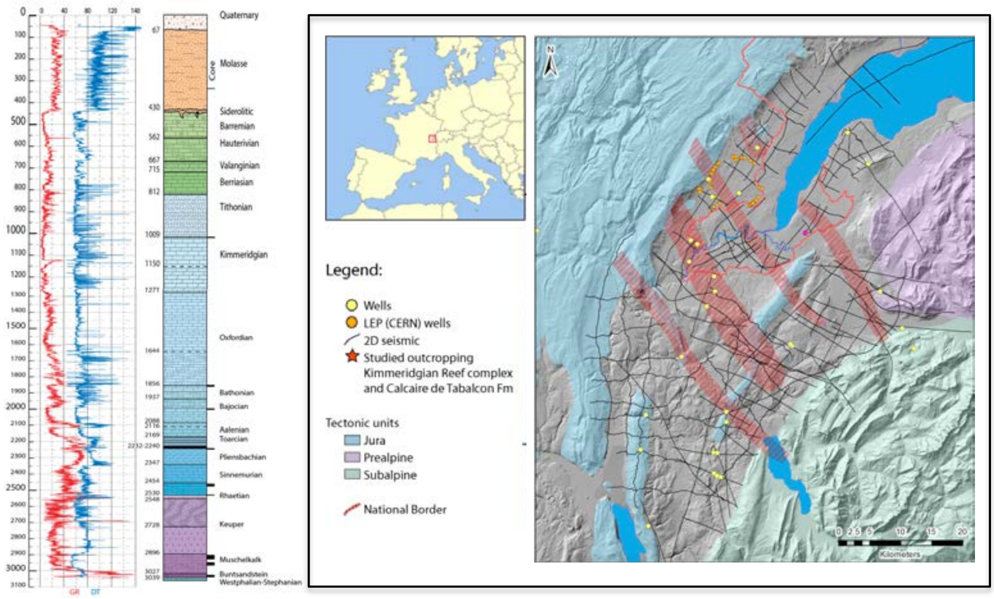

Figure 2: Simplified tectonic map of the Geneva Basin area with indication of 2D seismic and well data used in the feasibility study. The stratigraphic column of the Humilly-2 well is also shown displaying the complete known stratigraphic column.

In response to the alpine compression, the Mesozoic and Cenozoic sedimentary cover experienced 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 & Gratier, 2004). 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 & Gratier, 2004). This deformation was accommodated by a set of strike-slip fault systems and associated fracture corridors cutting the Geneva Basin in a NNW-SSE direction (figure 2).

3.1 Stratigraphic highlights

Several stratigraphic units occur in the sedimentary succession of the Geneva Basin subsurface (figure 2). The older known unit encountered in the Humilly-2 well (figure 2) consists of siliciclastic sandstones of Permo-Carboniferous age overlaid by similar lithologies of lower Triassic (Buntsandstein). These have porosity between 10-15% and variable permeability usually up to 1mD (Rousillon et al., 2016). On the basis of the few data available, the overlying Muschelkalk carbonates unit appears to have moderate to low reservoir quality (porosity <10%). This unit on the other hand is considered to have high potential reservoirs qualities 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), giving some hopes for similar characteristics in the south-western Switzerland. Both Buntsandstein and Mushenkalk porous rocks are overlain by ca. 250 m thick salt and anydrithes succession. This may provide an ideal confining unit although often heavily deformed by the *decollement* during the Alpine compression. The Lower Jurassic includes carbonates passing upwards to a marls and organic reach shale intervals (Toarcian) which constitute an active petroleum source rock (Do Couto and Moscariello, 2016). The Middle Jurassic reservoirs consisting of heterogeneous carbonate units rich in bioclastic, oolitic and clastic components and are overlying by marly carbonates. These units displays generally low porosity (< 5%) but are known elsewhere in the Swiss Plateau region to host karst and fracture systems and intervals with higher matrix porosity. These stratigraphic intervals are exploited successfully in the Paris Basin for more than 40 years (Hungemach, 2001). The Upper Jurassic units (Kimmeridgian) consisting of massive reef complexes and underlying stratified carbonates are currently considered the most promising reservoir target as indicated by reservoir properties data from old wells and observations based on outcrops. These units, visible in seismic can be targeted by individual wells and might deliver high-water discharge rates as it has been demonstrated in similar geological setting in the Munich area (Homuth et al., 2015) and the St. Gallen well (Wolfgramm et al., 2015). Lower Cretaceous units separated from the overlaying Tertiary (Eocene?) clastic sediments by a ca. 75 Ma stratigraphic hiatus, known in the region as Urgonian consist of thickly stratified carbonate often presenting large karstic cavities. This unit represent a key shallow reservoir which play an important role in connecting, through karst, fracture and fault systems, the surface water circulation with the deep subsurface. On this respect, the strike-slip fault systems and associated fracture corridors crossing the study area are indeed considered the main structural features potentially enhancing reservoir porosity and permeability, hence the quality of deep reservoir units. The entire Mesozoic succession is overlain by the Oligocene Molasse clastic units which varies in nature (marine or continental) depending on the location (Rumilly Basin and Bornes Plateau) as a consequence of complex, likely tectonically controlled, paleogeographic evolution (Moscariello et al., 2014).

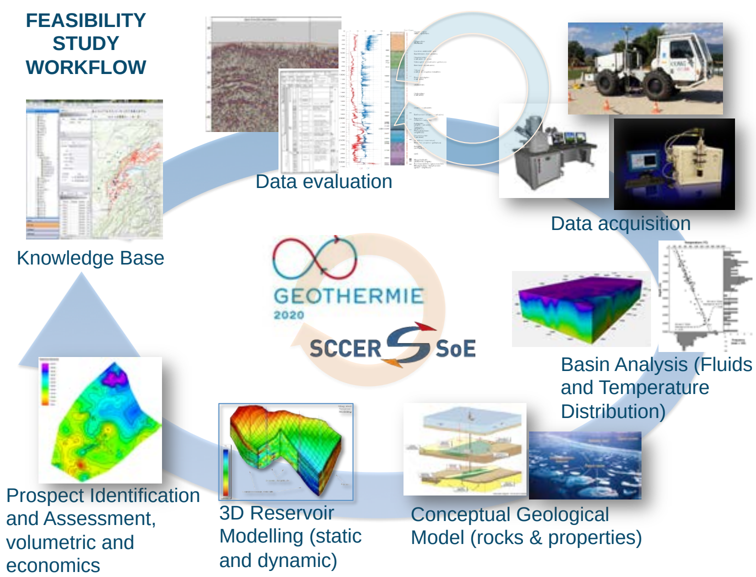

Figure 3: Feasibility study workflow implemented at the University of Geneva in support of the '*GEothermie 2020*' programme

4. THE GEO-ENERGY JOURNEY WORKFLOW APPLIED TO GEOTHERMAL EXPLORATION

The work carried out in Phase 1 of the *'GEothermie 2020'* program has been first dedicated to establish a sound and reliable database (figure 3). This consisted in collecting all vintage 2D seismic lines acquired by various hydrocarbon companies through the 50s and 80s in the Geneva Canton and nearby France and well logs of deep boreholes which were drilled for both petroleum exploration, deep hydrogeological prospection and geotechnical support for the construction of the Large Electron–Positron Collider (LEP) built at CERN, near Geneva (figure 2). Most of data have been digitized and quality checked and when possible reprocessed to enhance signal/noise ratio. In addition, new 2D seismic data have been acquired in order to increase the density of subsurface information and rock samples have been sampled from both vintage cores (where available) and outcrops of equivalent stratigraphic units present in the deep subsurface, which exists in the surrounding region of the Geneva Basin. Integrated data analysis and evaluation represents a large portion of Phase 1 efforts. This is being carried out by an interdisciplinary teams of Post Doctoral researchers, PhD and MSc students at the University of Geneva representing several disciplines including seismic interpretation, structural and sedimentary geology, mineralogy, inorganic and organic geochemistry, petrography and diagenesis, micropaleontology, petrophysics, passive seismic geophysics, fluid-flow dynamics, data base management.

The results generated during this step are being used to develop several alternative conceptual geological models of the subsurface which aim at capturing both the best available knowledge to date as well as the uncertainties associated with data quality (e.g. old and incomplete e-logs) and data continuity issues (e.g. 2D seismic line spacing). These models will enable the identification of a portfolio of geothermal prospects, which will be then screened and ranked according to surface engineering, economic and commercial criteria prior to move in to the drilling execution phase.

4.1 Geothermal prospectivety

The outcomes of the ongoing feasibility study (Phase 1 of the *'GEothernie 2020'* programme) need to respond to two key questions, which are summarised as follows:

1) Is there a sufficient geothermal gradient, which can ensure profitable exploitation of geothermal resources?
2) Is there sufficient permeability at depth to ensure sustained inflows into producing wells?

Historically, hydrothermal sources associated with mineral-rich hot springs (up to 23°C at surface) have been known in the Geneva Basin since the XVth century.

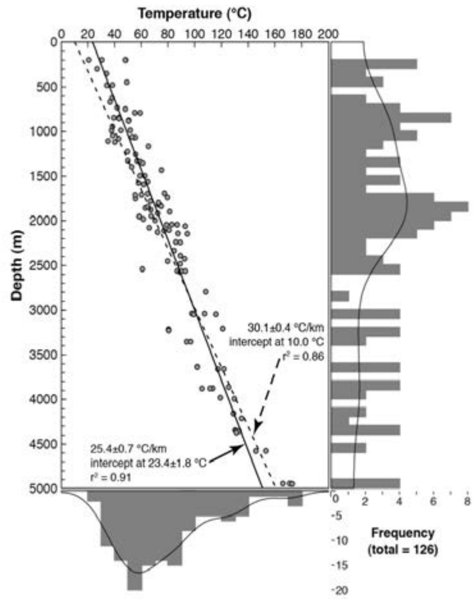

Figure 4: Average thermal gradient (corrected BHT) of 25.4 °C/km of the Geneva Basin area (from Chelle-Michou et al., 2016)

A number of warm water springs are located along the Salève Mountain (the village of Etrembières), the Usses river (La Caille bridge) and Mandallaz Mountain (hamlet of Bromines). The warm water springs located in Bromines, following the most recent earthquake associated with the Vuache fault reactivation (1996, M_L:5.3), recorded an important increase in discharge indicating a likely connection between hot-spring and shallow fault system rooted at 2-3 km depth (Thouvenot et al., 1998).

The first key question, regarding the geothermal gradient has therefore been addressed by an inventory of surface manifestations of hot water together with a detailed review 26 wells and more than 100 bottom hole temperatures (BHT) in almost 15 different stratigraphic units (Chelle-Michou et al., 2016). On the base of this work a best fitting polynomial curve indicate an average gradient of ca. 25.4°C/km (figure 4) and a number of temperature anomalies at different stratigraphic intervals suggesting fluid mixing and possibly convection (figure 4). Despite the solid statistical work to define this gradient (Chelle-Michou et al., 2016), uncertainty still exists as majority of BHT data derives from old wells (60s-70s) drilled for hydrocarbon exploration. Possible errors in measurements associated both with use of old technology and non-adequate procedures to attain equilibrium BHT may characterise the analysed data set therefore leaving a margin of uncertainty in the definition of geothermal gradient.

Higher level of uncertainties exists regarding the reservoir characteristics at depth and in particular the permeability distribution and effectiveness of reservoir connectivity. As indicated above, several stratigraphic units ranging chronologically for Triassic to the

Cretaceous have been identified as potential aquifers. However, direct observations from the subsurface (core and cuttings) are still statistically non representative for the entire basin and therefore not sufficient to draw final conclusions on reservoir distribution and quality. In core samples reservoir permeability is controlled by a variety of pore types ranging from a) vuggy sucrosic dolomitic porosity, b) micro-porosity and vugs in reef and peri-reefal facies, c) micropores preserved in the micritic carbonates, d) micro-inter-crystalline porosity in partially cemented molds (Figure 5). On the other hand, for instance, moldic, intra- and inter-particle macropores have been observed for reef and peri-reefal facies at larger outcrops scale (Rusillon et al., 2016). The diagenetic overprint largely variable at basin scale, adds another level of complexity in developing a predictive understanding of the lateral variability of reservoir properties. However, preliminary observation specifically on the Kimmeridgian reef complexes shows that diagenetic trends, likely controlled by the facies paleogegraphic distribution can be identified (Rusillon et al., 2016).

In addition to primary and secondary matrix porosity as described above, mud losses data from some of the examined wells indicate that permeability is also likely controlled by the occurrence of fractures. Fracture network are most likely associated with the NW-SE wrench fault zones crossing Geneva Basin (Clerc et al., 2015; Rusillon et al., 2016). Seismic interpretation focusing on these large fault zone coupled with outcrop observation at the basin margin, reveals the presence of complex associated and conjugate fault systems whose horizontal extension, connection and precise orientation in the subsurface, in some cases remain highly uncertain due to the discontinuous data set. To date, lack of dip meter, bore hole images and breakout data from deep stratigraphic intervals makes difficult to have a precise understanding of fracture type orientation spacing etc. Ongoing detailed structural investigation at outcrop scale and passive seismic monitoring on some of these large structural features will allow the better understanding of their current kinematics and strain characteristics (M. Lupi, personal communication).

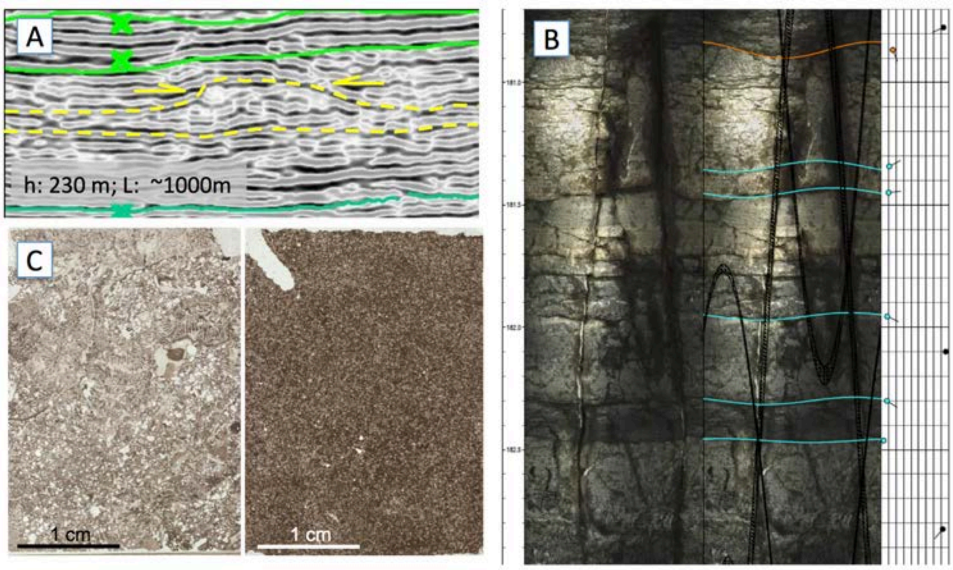

Figure 5: Reservoir properties such geometry and porosity at different scales from the Geneva Basin area: A) reef and peri-reefal facies in seismic from Kimmeridgian stratigraphic unit, B) karts-enhanced fractures developed in tight shallow Cretaceous carbonates (digital bore hole image, SEMM, 2016), C) texture and porosity characteristics at thin-section scale of two different carbonate reservoirs from the Geneva Basin.

3. PERSPECTIVES

The geothermal exploration in western Switzerland is at present in a crucial phase where large efforts are made on several fronts in order to prepare the following exploration and exploitation phases.

1) Further data acquisition campaigns (geophysical acquisition) and reservoir characterization studies including laboratory analysis and outcrop-based research, designed to address some of the key subsurface uncertainties mentioned above are being implemented. At the same time, a number of activities promoted by SIG are trying to couple immediate business interest while improving the knowledge of the subsurface. In this context few shallow depth wells will be drilled in the near future to respond to specific heat demand of industrial and large office building infrastructures. With the same approach, a heat storage project is being designed to capture and sequestrate excess heat produced (50–150 GWh/year range) by the large Geneva Canton incinerator. This project will be targeted at a depth not exceeding 1500-2000m (figure 6) where underground thermal energy storage (UTES) can be developed to sustain the increasing

need of heat during the cold months of the year.

During this first UTES project in the Canton of Geneva beside providing an opportunity to respond to energy demand it will represent the opportunity to: a) acquire new subsurface data such as core and logs to decrease uncertainities in reservoir characterization, b) develop an optimized exploration strategy in terms of geophysical data acquisition, c) produce a tool able to manage several geophysical datasets (seismic, MT and gravity) under a unique workflow which can be later applied to future geothermal projects in Switzerland and abroad.

UTES coupled to future development of geothermal energy for power production will contribute therefore to optimise the production of geothermal energy broadening its commercial offer and improving its environmental and economical sustainability.

2) Collection, organization and storage of subsurface data and knowledge are of primary importance in order to allow accessibility and then use of underground data. This is crucial to enable further assessment of all subsurface resources potential and support key investment decisions in agreement with the energy policy of the Canton. On this topic, the Canton of Geneva in collaboration with swisstopo (Swiss geological survey agency), is designing a new database infrastructure which will respond to the Cantonal requirements and regulations.

3) An active long-term seismic monitoring campaign with the installation of a dense network of locally managed seismographers integrated with the national seismographer network has been initiated to establish a base-line of background seismic activity in the Canton of Geneva. This is of primary importance in view of designing possible well completion practices (e.g. stimulation) in medium to deep geothermal boreholes and at the same time to understand better the kinematics of fault systems crossing the Geneva Basin.

4) Drafting a law regarding the exploration and exploitation of subsurface resources is being drafted at the Department of the Environment, Transport and Agriculture (DETA) of the Canton of Geneva. This text aims to ensure an adequate legal framework in preparation of future sustainable exploitation of underground resources by regulating future access and use of data and underground resources by public and private investors.

5) An active communication strategy with local population and neighbouring France administrations to share and engage them on a) the ambitious targets of both Canton and National energy strategy and more practically b) on the '*GEothermie 2020*' program. Public meetings and press releases in occasion of key important steps of the program have been and will be organised in order to ensure a full understanding of the various activities of the overall exploration program, especially prior seismic acquisition and drilling campaigns where the impact on local territory is greatest. Gaining and maintaining stakeholder support is in fact one of the most critical success factor in order to achieve the goals of the '*GEothermie 2020*' program.

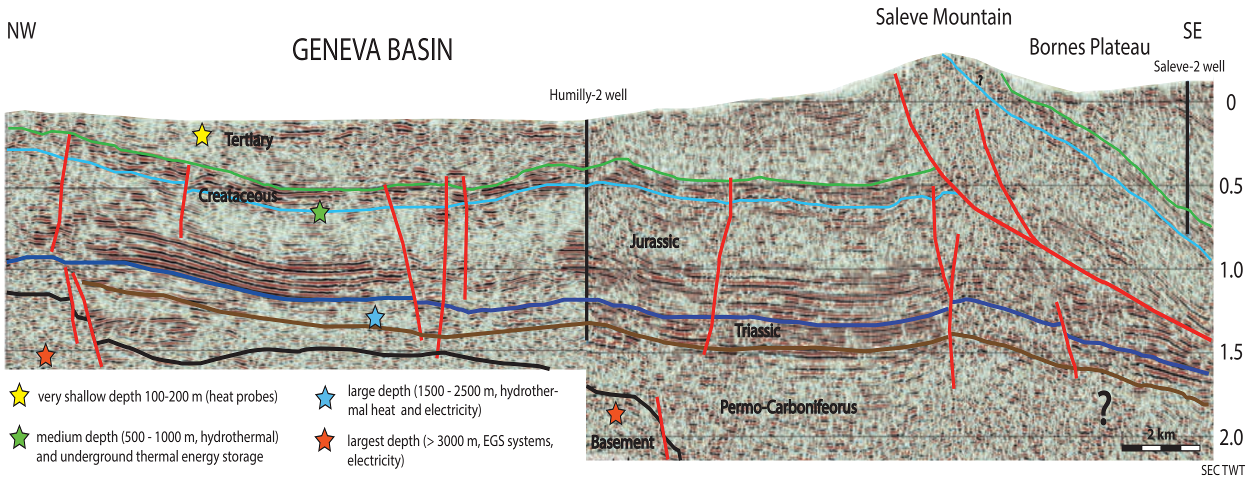

Figure 6: Seismic cross section across the Geneva Basin with indication of main stratigraphic units and indicative location of key reservoirs at different depths for different exploitation of energy resources (heat or electricity).

3. CONCLUSIONS

The Geothermal exploration in south-western Switzerland, specifically in the Geneva region, is part of the overall future energy plans for the Canton and City of Geneva. Geothermal is a local energy source, clean, renewable and continuously available. Its development is a priority of the cantonal policy to reduce the consumption of fossil resources and increase the Canton's energy independence.

Different immediate uses for geothermal energy, especially heat, are emerging: new residential areas (neighbourhoods already built or in refurbishment), large office buildings, agricultural activities (orchards, fruits and vegetables greenhouses), industrial processes. These opportunities supported by strong political and local industry commitments to meet Cantonal energy policy, are driving the exploration in search of underground resources for heat production. Future developments of geothermal exploration will move drilling targets into deeper underground to evaluate the potential for electricity production.

Yet, several uncertainties remain in understanding fully the complexity of the subsurface and its geothermal potential. The preliminary data carried out in the framework of the 'GEothernie 2020' project are however encouraging and help to establish a sound knowledge base for future important decisions. The step-wise approach implemented by SIG and the Canton of Geneva is a strategic way forward to ensure success while minimising risks and at the same time, guarantying crucial public support.

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