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3-D Static Model to Characterize Geothermal Reservoirs for High-Temperature Aquifer Thermal Energy Storage (HT-ATES) in the Geneva Area, Switzerland

Eruteya, O.E., Guglielmetti L., Makhloufi,Y., Moscariello A.

Department of Earth Sciences, University of Geneva, Geneva, Switzerland

Email: Ovie.Eruteya@unige.ch

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ABSTRACT

In the framework of the GEOTHERMICA ERA-NET co-funded project-HEASTORE, one of the main challenges related to assessing the technical feasibility and sustainability of High Temperature (~25°C to ~90°C) Aquifer Thermal Energy Storage (HT-ATES) is subsurface characterization. In this study, we aim to develop a 3-D geologically robust static model in order to characterize the subsurface at the GEo-01 geothermal exploration borehole and possibly identify candidate intervals suitable for HT-ATES within the Lower Cretaceous Carbonates in the Geneva Area. In order to achieve this, we analyzed a suite of subsurface datasets encompassing two-dimensional seismic reflection data integrated with petrophysical data and well report from the GEo-01 well recently drilled in the framework of the Geothermie2020 program and other proximal boreholes. Seismic interpretation reveals a well-developed flower structure deforming the Mesozoic and parts of the Cenozoic sediments. Petrophysical analysis suggests the Lower Cretaceous Formation is tight, generally characterized by low porosity and permeability values. However, the presence of fracture networks and faults deforming a substantial part of this unit may promote localized fluid circulation. Three candidate horizons have been identified as potential Lower Cretaceous targets (CT) suitable for HT-ATES in fractured intervals characterized by tested water outflows and devoid of hydrocarbon impregnation: (1) Grand Essert Fm / Pierre Jeune de Neuchatel + Marnes d'Hauterives Fm [CT1], (2) Vuache Fm - Chambotte- Chambotte inférieur [CT2] and (3) Goldberg Fm [CT3]. The 3-D static model developed in this study will be used as input for numerical heat flow and predictive THMC models for the Geneva Basin. Importantly, our findings highlight the need for subsurface data augmentation in the Geneva Basin. It also shed light on the implication of the subsurface manifestation of hydrocarbons as geohazard to heat storage and other geo-energy related projects at large.

1. INTRODUCTION

The deployment of renewable energy sources for both power and heat production is accelerating in Europe, a trend that will continue. However, the variations in both the availability and demand for energy and their integration into the existing energy infrastructure raise challenges in terms of operational variability and balancing. Peak shaving and heat storage can help to balance demand and supply to make better use of infrastructure and assets. Thermal energy storage can, for example, be implemented in heating networks in the form of Aquifer Thermal Energy Storage (ATES) to support the use of surplus heat from industry and the implementation of renewable heat sources. ATES involves the temporal storage of sensible heat and cold in the subsurface through the injection and withdrawal of groundwater (Dickson et al. 2009). Furthermore, ATES system may be employed as an auxiliary energy back-up system for storing surplus energy for later utilization usually during periods of peak demand (Bloemendal et al., 2014; McCartney et al., 2016). ATES has been gaining widespread attention based on its low carbon footprint and low thermal emissions when compared to other energy systems. This invariably results in a reduction of the overdependence on other conventional heating and cooling sources thereby reducing cost and the emission of climate-forcing gases which have an implication on global warming.

The successful development of an efficient ATES system is challenging as any geo-energy project where understanding and 3D modelling of the subsurface is of primary importance (Moscariello, 2016). Specifically, an ATES project requires detailed subsurface characterization of the proposed storage site, modelling and simulation of different storage scenarios to meet the envisage energy demand. This is critical for a comprehensive understanding of the geothermal plume behaviour over a given storage episode. Moreover, a geologically-realistic model is necessary to predict the interaction of subsurface elements, especially the structural framework (faults system) and even geobodies such as channels system with the thermal plume. Some of these elements may adversely promote early thermal breakthrough and may contribute towards thermal pollution of subsurface potable water, and in the extreme possible discharge of groundwater into surface water bodies (Possemiers et al., 2015). Most ATES models are typically built using simplistic grids that do not represent the true geological complexity of the subsurface at the storage site. The uncertainties in the nature of subsurface are mostly attributed to the paucity or unavailability of the dense network of subsurface geophysical datasets upon which the model is to be developed.

This study is being carried out under the framework of the GEOTHERMICA ERA-NET co-funded project-HEASTORE project and focuses on the development of a static geothermal model for the development of HT-ATES system in Geneva Basin situated in the Western Swiss Plateau (Figure 1). A recently drilled geothermal exploration borehole (GEo-01) by SIG (Services Industriels de Genève) in the framework of the Geothermie2020 program, targeting fault system in the Lower Cretaceous carbonate in the study area provides data to assess the potential for geothermal applications including high-temperature ATES. Therefore, the objectives of this study are tripartite; (1) develop a structural and stratigraphic framework for the study area (2) construct a robust static geothermal reservoir model (1.5 km x 1.5 km x 1.1 km) (3) identify potential candidate(s) horizons within the Cretaceous suitable for ATES. This was achieved based on the integration of geological, geophysical and petrophysical dataset encompassing seismic reflection datasets, borehole logs and cuttings, and sedimentological dataset from the drilling reports. The model developed in this study will serve as the foundation for future fracture network modelling, numerical thermo-mechanical and geochemical modelling of the ATES system.

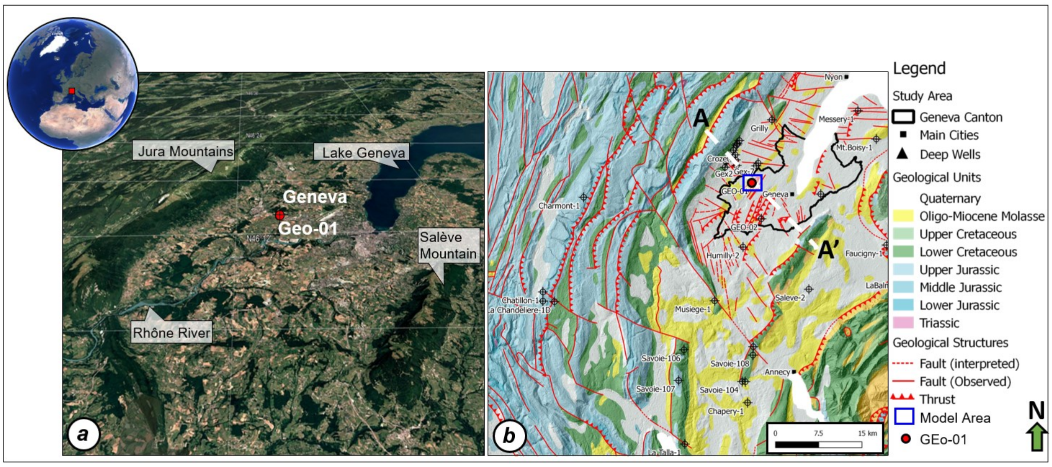

Figure 1. (a) Location of the study area in the Geneva Basin, Switzerland. (b) The structural situation of the Geneva Basin indicating the fault systems (Modified from Moscariello et al., 2020)

2. GEOLOGIC SETTING

The study area is in the Geneva Basin (hereafter GB) in the south-westernmost portion of the Swiss Molasse Basin (Figure 1). The GB is limited to the NW by the Jura Mountains and to the SE by the Salève Mountain. Importantly, the Jura Mountain has been identified as a source for recharging the subsurface aquifers systems in the GB (Murault, 2000) (Figure 2). The configuration of the GB is typified by a 2000-3000 m-thick Mesozoic and Cenozoic succession overlaying a Paleozoic crystalline basement that evolved during the Variscan orogeny (Figure 2). Subsequent to this orogenic episode an extensive rift system developed in the GB resulting in the evolution of a series of SW-NE trending half-graben structures infilled by Permo-Carboniferous sediments - mainly fluvial to lacustrine deposits with some intercalation of coal seams (Gorin et al., 1993, Signer and Gorin 1995; Clerc et al., 2015; Moscariello et al., 2019).

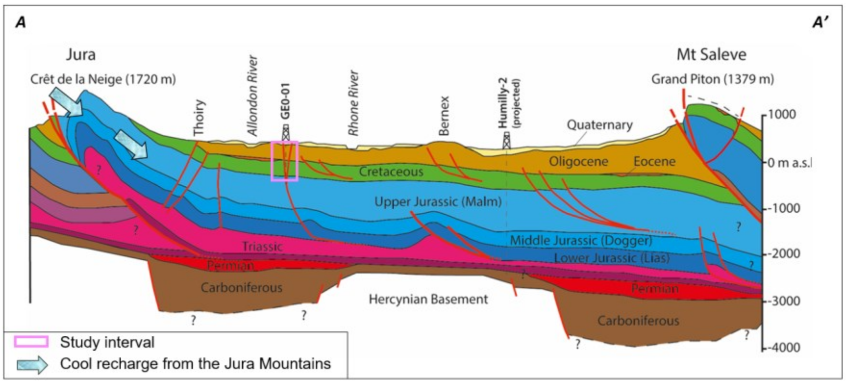

Figure 2. Configuration of the Geneva Basin indicating the present study interval in the uppermost basin fill (Modified from Moscariello et al., 2020). See Figure 1b for location.

The structural and stratigraphic evolution of the Mesozoic and Cenozoic unit in the GB is modulated by the underlying SW-NE trending half-graben structures and NNW-SSE basement related lineaments (Figures 2 and 3). The NNW-SSE trending lineaments are strike-slip fault zones - Vuache, Cruseilles, Le Coin and Arve fault zones. On a seismic reflection profile, these faults are expressed as wrench faults (Signer and Gorin, 1995). Importantly, these fault zones have been active since the Permo-Carboniferous to recent (Signer and Gorin, 1995). Ongoing hydrothermal exploration activities in the Geneva Basin target these fault zones.

Lower Jurassic deposits show marly carbonates and shales while the Middle Jurassic, alternating bioclastic carbonates and muddier facies testify to a transitional, shallower environment in the carbonate ramp when compared to the underlying unit. The Upper Jurassic unit shows an overall regressive trend, ending at the beginning of the Cretaceous. From the Middle Kimmeridgian until the Lower Tithonian, a coral-microbial patch reef system developed on a large, shallow carbonate platform. The strong diagenetic imprint and numerous fractures evidence a high heterogeneity within this unit but also promising reservoir properties (Makhloufi et al., 2018).

The Cretaceous unit is the main focus of this study and has been substantially eroded resulting in the absence of the Upper Cretaceous. The Lower Cretaceous series was deposited in a shallow and warm water environment characterized by a low amplitude sea-level fluctuation resulting in several episodes of emersion-drowning of the carbonate platform. This resulted in the deposition of a stacked system of alternating limestone and marly limestone layers characterized by tight and shallow carbonate facies. Importantly, this unit display excellent aquifer/reservoir properties characterized by the localization of abundant fracture networks and karst system (karstification been prominent in the Urgonian limestones) arising from the erosion of this unit. Uplift of the basement arising from the convergence between the Eurasian and African plates resulted in the exhumation of the Mesozoic succession (Trumpy, 1980; Karner and Watts, 1983). The ensuing sub-equatorial climate during this time promoted erosion of the top Cretaceous unit resulting in the development of a major unconformity. Fractures and karst features are common occurrences atop the Mesozoic series and are filled by some reworked Aptian-Albian sediments and some lateritic deposits (Hooker and Weidmann, 2007; Becker et al., 2013).

The Oligocene Lower Freshwater Molasse (USM) is composed of alternated sandstone and marlstone. This unit onlaps the Early Cretaceous unit or the lateritic Eocene sediments. Importantly, the Upper Marine Molasse (OMM) and the Upper Freshwater Molasse (OSM) are missing in the GB due to erosion during glacial advancement (Signer and Gorin, 1995; Charollais et al., 2007) (Figure 3). The topmost unit of the GB consists of Quaternary to recent sediments overlying the Molasse deposits. During the Quaternary several episodes of glaciation prevailed in the GB as recorded by the presence of glaciogenic sediments and tunnel valley systems incising the uppermost Molasse unit arising from the advance and retreat of the Rhone Glacier and its related glaciers (Moscariello, 1996; Moscariello et al., 1998; Fiore et al., 2011). During the Glacial maximum, about 1000 km of ice (Rhone and Arve Glaciers) covered the GB.

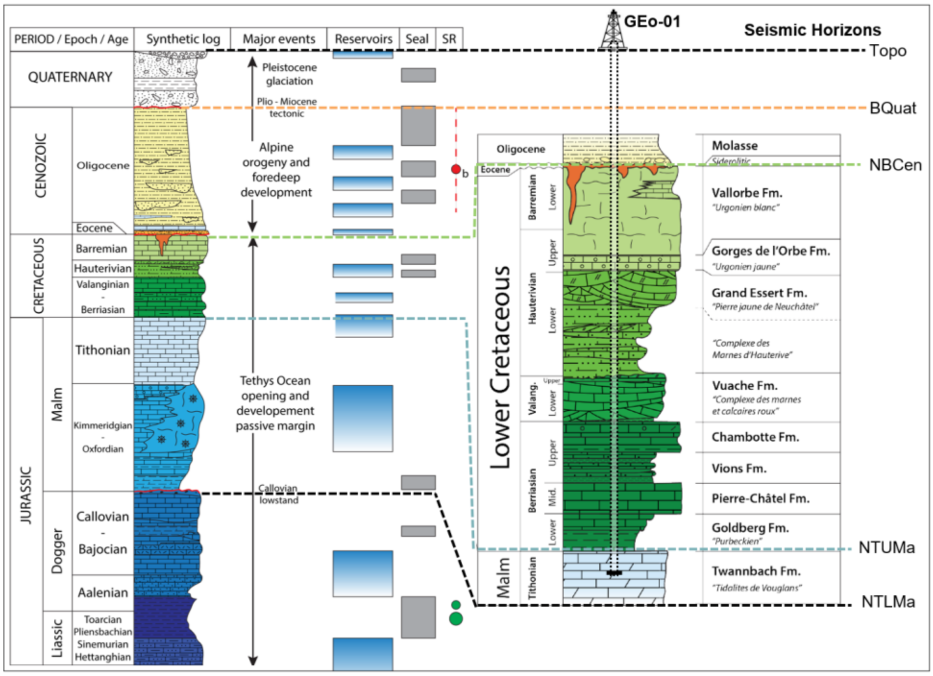

Figure 3: Lithostratigraphy of the Geneva Basin (modified from Moscariello et al., 2020). Key seismic horizons mapped in this study are indicated here and the formation depth of the Geo-01 well.

3. DATASET AND METHODS

In order to develop a geologically realistic static model, we analysed a suite of subsurface dataset consisting of seismic reflection dataset, borehole, sedimentological information from drilling report and a regional subsurface model- GEOMOL project (Figure 4).

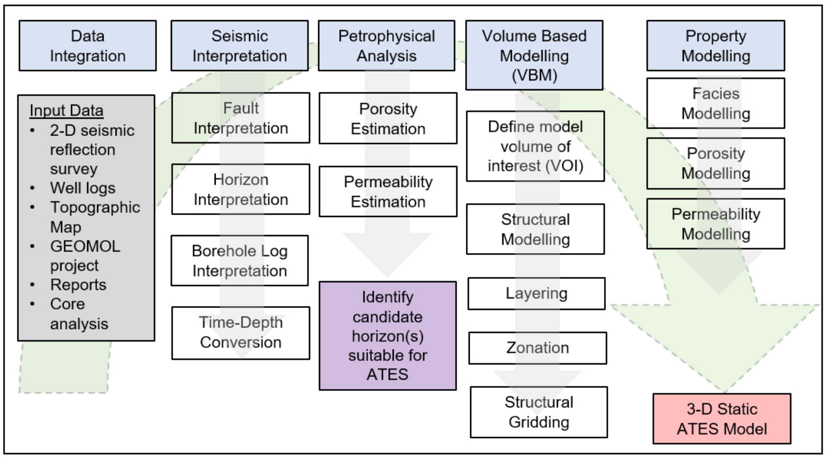

Figure 4: Workflow developed for this study.

3.1. 3.1. DATASET

3.1.1 2-D Seismic Reflection Data

The 2-D seismic reflection dataset available consists of two recently re-processed lines (15SIG_008, GG87-02) (Figure 5a). The seismic data is zero phased and a positive polarity for example transition from the Molasse (siliciclastic) to the Lower Cretaceous is represented by a hard kick and appears as a peak in the seismic data. The seismic reflection dataset is located close to the GEo-01 borehole (Figure 5a). Processing workflow is confidential and not available due to proprietary reasons.

3.1.2 Regional Subsurface Model - GEOMOL Project

GEOMOL project is a 3-D geological model of the Swiss Plateau created from the analysis of a large dataset of 2-D and now recently 3-D seismic reflection surveys, shallow and deep boreholes, geological sections and topographic maps. (https://www.swisstopo.admin.ch/en/knowledge-facts/geology/geological-data/3d-geology/deep/geomol.html). We extracted key stratigraphic surfaces within our volume of interest from the GEOMOL v 2016 project (available online at https://ge.ch/sitg/). Similarly, the velocity model from GEOMOLv2016 was employed for time-depth conversion.

3.1.3 Borehole Data- GEo-01 Geothermal Exploration Borehole

The principal borehole analysed in this study is the GEo-01 borehole drilled by SIG (Services Industriels de Genève) in 2018 for geothermal exploration in the Geneva Basin. The GEo-01 borehole was drilled to a measured depth of 733.16 m, with cuttings recovered for the entire interval, however, only the first 533 m was logged. Borehole logs available from GEo-01 include gamma-ray, spontaneous potential, sonic, calliper, resistivity, density, neutron and detailed well report identifying faulted and faulted intervals, hydrocarbon impregnated intervals and key formation tops.

3.2. METHODOLOGICAL WORKFLOW

3.2.1 Seismic Interpretation

All interpretations and modelling were performed using Schlumberger's Petrel 2018 seismic interpretation software and guided by previously existing tectonostratigraphic framework of the Geneva Basin (e.g. Clerc et al., 2015). A classical seismic interpretation technique was performed involving mapping of five key stratigraphic horizons of interest - Topography (Topo), Base-Quaternary (BQuat), Base Cenozoic/ Base Molasse (Bcen), Base Cretaceous (NTUMa) and Base Malm (Upper Jurassic) (NTLMa) (Figure 3). Faults were mapped as vertical to sub-vertical zones of discontinuity in the seismic reflectors in the seismic dataset. Since we analysed 2-D seismic profiles, fault planes were established by connecting the most likely faults intersections on the seismic profile. In order instances where this could not be achieved due to non-intersecting seismic lines, we opted for a knowledge-driven interpretation by extending the fault plane along a preferred direction based on the geological context and literature (e.g. Clerc et al., 2015; Moscariello et al., 2020). The faults networks and key horizon interpreted were converted from time to depth on the fly using the velocity model in the GEOMOL project in order to generate a structural model for the study area (Figure 4). However, during the quality control process, minor adjustments were made to the interpretations based on the formation tops available from GEo-01 borehole.

3.2.2 3-D Static Model Development

We used a volume-based modelling approach embedded in Petrel to develop the 3-D static model. Earlier structural and stratigraphic interpretation were inputted in a predefined volume of interest (VOI) (1.5 km x 1.5 km x 1.1 km) representative of the model boundary and from the topography to the base model (Figure 4). Subsequently, fault framework and layering, zonation and structural gridding were performed. Property modelling involving facies modelling and petrophysical modelling was performed based on the assumption that lithofacies are homogenous and petrophysical properties are homogenous laterally but will vary temporally at the scale of the different formations or aquifers encountered by the GEo-01 borehole. This approach is reasonable based on the availability of only one borehole within the study area, therefore further geostatistical modelling may lead in erroneous model development. Porosity and permeabilities values were difficult to derive from the borehole log in the Geo-01 since the entire interval was not logged. Furthermore, calliper logs reveal the deterioration of borehole conditions which indeed will lead to spurious log-derived petrophysical estimates (Figure 6). To remedy this, we relied on petrophysical measurement from wells elsewhere in the Geneva Basin penetrating the similar formation. This measurement has been derived from core plugs from the Gex borehole and Humily-2 borehole (Rusillon and Chablais, 2017). The grid was then populated with this petrophysical property per storage interval and non-storage interval.

4. RESULTS AND INTERPRETATIONS

4.1. SEISMIC STRATIGRAPHY AND LITHOLOGICAL DESCRIPTION

The study area was divided into four major seismic units (SU) based on variation in amplitude and frequency of the seismic reflectors reflecting changes lithology and density of the subsurface formation. We focus only on the Malm until the Quaternary (Figure 5).

Late Jurassic (SU-1): This unit is the basement for the interval of interest in this study. The upper part consists of continuous high amplitude reflections while the lower unit consists of low amplitude semi-transparent to chaotic facies reflections. This unit is bounded at the top by Near Top Upper Malm horizon. The lithology consists of this unit is characterized by limestone and dolomite interval as penetrated by the GEo-01 borehole (Figure 6).

Lower Cretaceous Unit (SU-2): The Lower Cretaceous is the unit of interest for the ATES. This unit is bounded by the Base Cenozoic Horizon and Near Top Upper Malm horizon. The reflectors are continuous high amplitude to semi-continuous reflectors in areas affected by deformation related to faulting. Thickness appears to be uniform. The GEo-01 well reveals this unit is predominantly carbonate dominated, consisting of massive limestones unit with occasionally marly intervals (Figure 6).

Molasse Unit (SU-3): The Molasse unit is bounded by the Base Quaternary and Base Cenozoic Horizon. The Molasse sediments onlaps the underlying Cretaceous rocks (Figure 5). This unit is characterized occasionally by continuous but mostly semi-continuous by low to high amplitude reflectors. Thickness within the study area increases toward the southeast. The Molassic sediments here consists predominantly siliciclastic sediments comprising of intercalated sandstones, marl and marly sandstone. The upper part consists of marl and sandstone (freshwater Mollasse) while the lower section consists of marl, sandstone, limestone and (lower Molasse) and gompholites at the very base of this unit (Figure 6).

Quaternary Unit (SU-4): The Quaternary unit is bounded by the Base Quaternary and the Ground Level horizon (Figure 5). This unit is characterized by the semi-transparent facies and some chaotic reflectors (Figure 5). The Base Quaternary is characterized by depressions incising into the upper part of the underlying Molasse unit. This is interpreted as a part of the Quaternary tunnel valley systems developed from the advance and retreat of glaciers (*sensu* Moscariello, 1996; Moscariello et al., 1998; Fiore et al., 2011; Wildi et al., 2014). The transparent seismic facies infilling this valley are characteristics of glaciogenic sediments. The thickness of this unit is higher in a region characterized by the incisions. In GEo-01, this unit consists of sandy gravel in the upper c. 2 m and moraines till the base Quaternary (Figure 6).

4.2. STRUCTURAL INTERPRETATION

Seismic line GG 87-02 reveal a prominent flower structure cross-cutting the Dogger, Malm, the Lower Cretaceous carbonates and part of the Lower Molasse sediments (Figure 5). This flower structure consists of four NW-SE dipping strike-slip faults and two NE-SW dipping strike-slip faults (Moscariello et al., 2019a). Some of this fault accommodate small vertical throw that affects the Lower Cretaceous carbonates. In another plausible interpretation, we introduce a thrust fault with a decollement in the Malm and deforming the Lower Cretaceous carbonates and shorter faults (Figure 5). Similar structural trends have been documented in the Geneva Basin (Gorin et al., 1993, Signer and Gorin 1995; Clerc et al., 2015). We suspect some traces of the first two northwesternmost faults on line GG 87-02 can be traced on the other line promoting the established of the fault planes and deducing a SW-NE trend for both faults. Based on this and knowledge of the geological setting together with synthesis from the literature, we hypothesize this trend for the remaining faults. Importantly, many smaller-scale deformations are mappable in the Cenozoic sediment, however, due to the chaotic nature of the seismic facies here, they are difficult to establish (Figure 5).

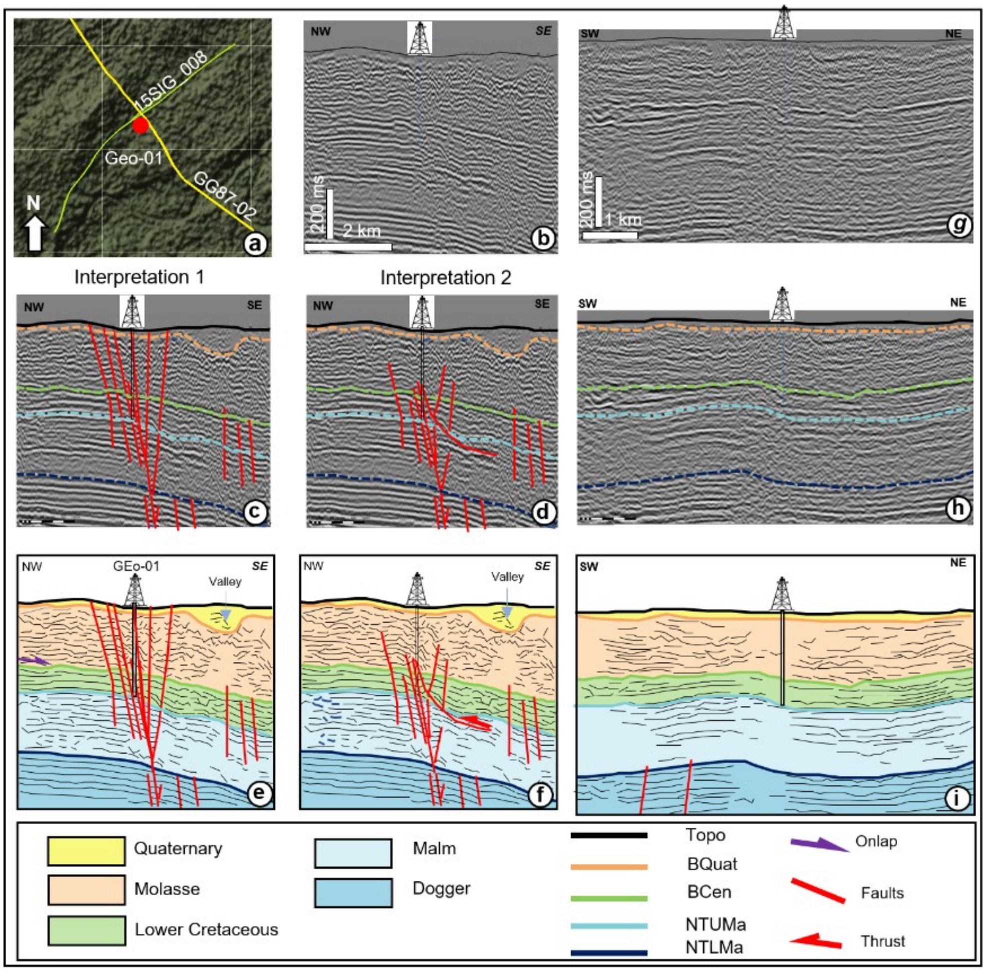

Figure 5: (a) Location of the seismics lines and Geo-01 well. (b-i) NW-SE and SE-NW seismic profile showing the subsurface structural situation around the Geo-01 borehole. Two plausible interpretation is presented for line GG 87-02 with a major difference being the introduction of a thrust fault in Interpretation 2 and shorter fault height.

4.3. LITHOFACIES AND PETROPHYSICAL CHARACTERS OF THE LOWER CRETACEOUS UNIT

Integration of the well logs and drill cutting analysis and sedimentological analysis provided in the drilling/logging reports resulted in the identification of different lithofacies in the Lower Cretaceous interval (Figure 6). Most of the units are carbonate facies consisting of an alternation bioclastic limestone, peloidal bioclastic limestone, Marly limestone, Oolitic limestone, Oo-bioclastic limestone, Micritic limestone and Ooid-Peloidal bioclastic limestone. However sandy marl and marl occurs in the upper and lower segment of the of the Grand Essert Formation (Figure 6).

Log-derived petrophysical properties such as porosity and permeability are not reliable from GEo-01 since the calliper log reveal borehole deterioration over a large section of the well bore (Figure 6). In order to achieve a robust estimate of this key petrophysical parameters, we compile values of core plug measurements from borehole penetrating similar formation in wells close to the present study area in the Geneva Basin. Generally, the entire Cretaceous intervals can be classified and tight having low porosity and permeability values ranging between 0.36 - 6.97% and 0.002 - 0.107 mD (Rusillon and Chablais, 2017). However, the presence of faulted and fractured intervals and even karstification is prevalent in some of the formations which may promote localized enhancement in the petrophysical properties (Figure 6). In this study, we used a porosity value of 2 % for the Cretaceous unit, however, intervals with an aquifer was assigned a porosity value of 20%. A permeability value of 0.02 mD was assigned to the Cretaceous units while a value of 10 mD was used for intervals with an aquifer.

4.4. IDENTIFICATION OF POTENTIAL CANDIDATE HORIZON FOR ATES IN THE LOWER CRETACEOUS UNIT

Several factors such as the sedimentary facies association, presence of faults, karst and fractures networks and importantly the occurrence of bitumen and light oil shows and the water flow from the aquifer were considered during the selection of potential candidate storage interval in the study area (Figure 6). In this study, we have discounted promising intervals with proven evidence of aquifer characterized by significant water outflow but less than 10 m thick and also evidence of hydrocarbons (Figure 6).

Following this, we have identified three candidate horizons in the Lower Cretaceous carbonates for HT-ATES development.

Cretaceous Target 1 (CT1): 10 m thick horizon in the Grand Essert Fm / Pierre Jeune de Neuchatel + Marnes d'Hauterives Fm. This interval is characterized by Bioclastic sandstone rich in peliods and bioclasts (Figure 6).

Cretaceous Target 2 (CT2): 12.5 m thick interval in the uppermost part of the Vuache Fm - Chambotte- Chambotte inférieur. This interval is characterized by bioclastic sandstones, rich in peloids and bioclasts. Fractures are also present and white calcite veins (majority <5mm) (Figure 6).

Cretaceous Target 3 (CT3): The deepest horizon is a 25 m thick interval within the Goldberg Fm. The upper 13 m consists of bioclastic limestone while the lower 12 m is characterized by Oopeliodal limestone. This interval is faulted and fractured (Figure 6).

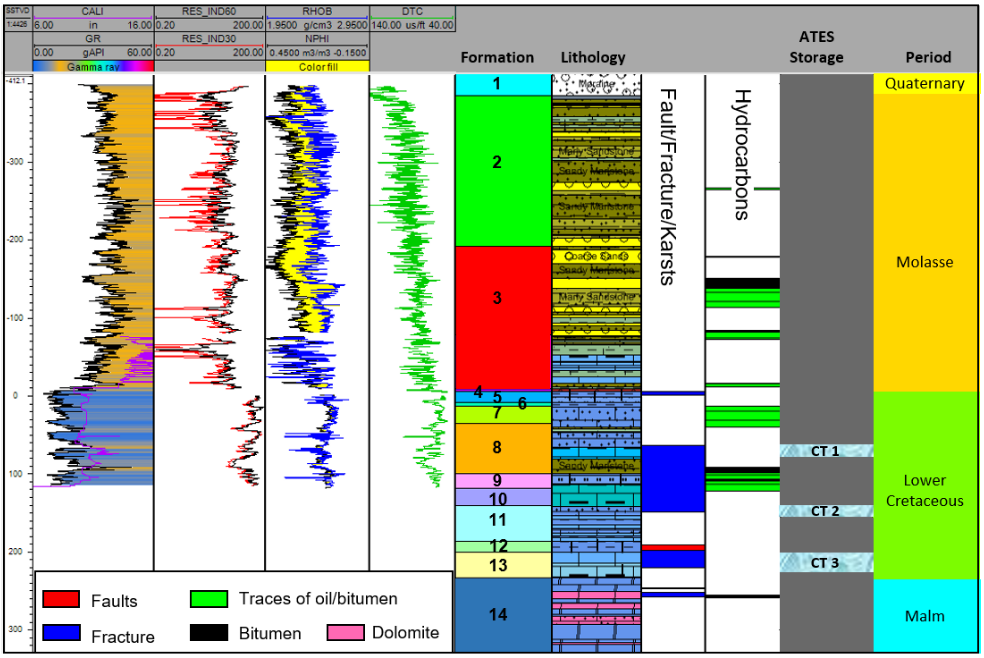

Figure 6: Geo-01 log interpretation panel. The candidate intervals identified for ATES are CT1, CT2 and CT3. 1-Colluvium and anthropic material and Glacial deposits ("würmian"), 2-Marnes et grès bariolés, 3-Lower freshwater limestones (Lower Freshwater Molasse), 4-Gompholite, 5-Vallorbe Fm. Blanc Urgonian, 6-Gorges de l'Orbe Fm Jaune Urgonian, 7-Grand Essert Fm.Pierre Jaune of Neuchâtel, 8-Grand Essert Fm. Hauterive Marls, 9-Vuache Fm, 10-Chambotte Fm., 11-Vions Fm., 12-Pierre Châtel Fm(& Goldberg?), 13-Goldberg Fm. and 14-Twannbach Fm.

4.5. 3-D STATIC HT-ATES MODEL DEVELOPMENT

Since the GEo-01 borehole encountered aquifers in the Lower Cretaceous fractured Carbonate rocks the temporal limit of the model was set at a level within the Malm (Figure 7). Spatial coverage of 1.5 km x 1.5 km over the study site was deemed sufficient to understand the fate of the thermal plume, boundary condition and contain any envisaged injector-producer well configuration/geometry during future dynamic simulations. Moreover, it would only be realistic to limit our model to this size based on the density of the datasets available for analysis and uncertainties related issues (Figure 5a). For simplicity, we modelled only four faults out interpretation 1 (Figure 5c). The faults were extended to occupy the 1.5 km^2 model boundary (Figure 7a) in a preferred SW-NE direction (Figure 7b). The dip of the faults was left undisturbed as those interpreted in the seismic profile (Figure 5c). Similarly, the top and bottom level of the faults were the same as those interpreted on the seismic lines but terminated by the boundary (Figure 7b). The for Cretaacous interval the model consists of 7 layers includes target horizons CT1, CT2 and CT3. Porosity and permeability values were assigned to the grid developed (see section 4.3).

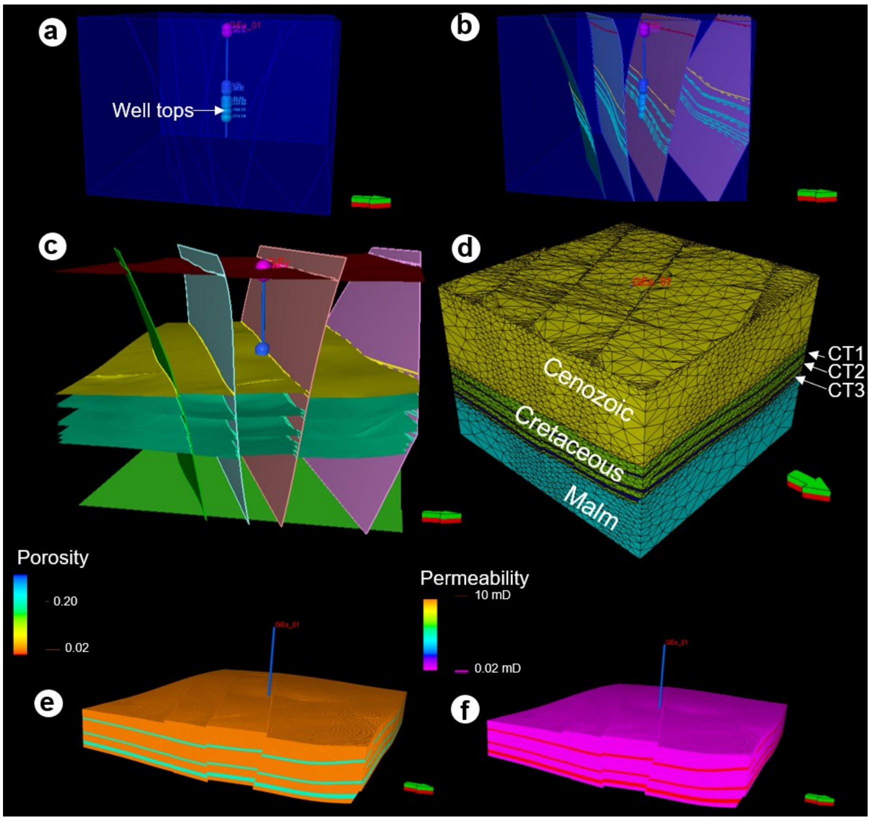

Figure 7: (a) Volume of interest (b) Faults interpreted (c) Fault and Horizons interpreted (d) Layering with the three candidate intervals for HT-ATES CT 1, CT2 and CT3. (e) Porosity model (f) Permeability model.

5. DISCUSSIONS

5.1. UNCERTAINTIES ASSOCIATED WITH THE 3-D STATIC MODEL DEVELOPMENT

Associated with 3-D subsurface modelling is the problem of incomplete knowledge of the subsurface (Siler et al., 2019). The robustness of the 3-D static model developed here is modulated by the integration of the subsurface dataset, their interpretation and associated uncertainties (Moscariello, 2016; Schweizer et al., 2017). A major factor contributing to this uncertainty is the density of the subsurface dataset (2-D seismic reflection survey, borehole dataset) analysed in this study (Figure 5a). Moreover, each of this dataset analysed is associated with some uncertainties related to its acquisition technique and data processing (Siler et al., 2019). This has a ripple effect on the understanding of the structural configuration of the study area and the final model geometry (Figure 7). In the 3-D static model developed in this study, the farther the distance from the input dataset the greater the uncertainty in constraining the subsurface geology configuration. Following this, interpretation and modelling is more robust and better constrained near the GEo-01 well.

Importantly, worth mentioning unequivocally is the ambiguous nature of seismic interpretation. This is more pronounced in fault interpretation and modelling (number of faults, fault orientation, fault length, fault height and type of fault contact in relation to a fault network) (Cherpeau et al., 2010; Julio et al., 2015; Røe et al., 2014) compared to horizon interpretation. A dual fault interpretation is presented in this study to capture part of this uncertainty (Figure 5). Indeed, both fault interpretation and model presented here is geologically realistic and likewise plausible based on the tectonostratigraphic evolution of the study area (e.g. Gorin et al., 1993, Clerc et al., 2015; Moscariello et al., 2020). In this study, significant uncertainty is expressed in the length of the faults mapped and direction of the fault plane since this cannot be deduced based on the low density of the 2-D seismic profile analysed here (Figure 5a). The direction of the faults modelled here has been guided by the first two NW fault interpretation (Figure 5c). Yet the extrapolation of this direction is based on a knowledge-driven hypothesis which would be tested when 3-D seismic data becomes available in the Geneva Basin in a few years' time. The geometry of these faults mapped will ultimately have an implication on the performance of the ATES system in terms of storage volume and aquifer properties and any further discrete fracture network modelling. A major issue is a difficulty in mapping faults in the Molasse and Quaternary unit based on the chaotic nature of the seismic reflections (Figure 5).

Any perturbation in the subsurface configuration of the study area not captured by our interpretation due to the nature of the input dataset may also affect the dip and azimuth of key surfaces and storage intervals. This has implications on the thickness variation of the potential storage targets in the Lower Cretaceous, also in the estimation of the storage capacity of the ATES system and ultimately in understanding the fate of the geothermal plume. We believe the regional surfaces provided by the GEOMOL project ameliorates the uncertainty in the stratigraphic interpretation of the major units. Furthermore, the availability of formation tops from the GEo-01 borehole allowed a local refinement of the interpretation derived from the GEOMOL project (Figure 7a). Since we interpreted 2-D seismic profiles it was almost impossible to deduce lateral and temporal changes in seismic facies characteristic of different formations in areas distal to the input dataset. Only the GEo-01 well was available within the 1.5 km^2 area introducing uncertainty during the facies modelling. Here, we assumed mostly a lateral homogeneity in the seismic facies and sedimentary in each formation or aquifer within the model boundary. While this may be far for the subsurface reality, we do not expect much variation in the Lower Cretaceous since the carbonate facies may have little variation based on the scale of our model

The (over)simplification of the facies model presented here assume localized homogeneity, this may affect the distribution of porosity and permeability with further implication on the behaviour of the geothermal plume. Importantly, the borehole logs available did not cover the entire interval due to hole stability problem, leaving the evaluation of the unlogged intervals to be on the analysis of the borehole cutting recovered (Figure 6). While analysis of the drill cuttings is a robust methodology for characterizing facies, only their advanced analysis proffers a good match with log data in order to provide direct correlation with subsurface formation penetrated (Salim & Lagraba, 2018). Yet some bias cannot be totally neglected which may arise due to the drilling strategy and mixing of drilling samples may occur at deeper levels resulting in the obscuring of primary lithology (Fowler & Zierenberg, 2016).

5.2. IMPACT OF 3-D STATIC MODEL CONFIGURATION, PETROPHYSCIAL AND FACIES PROPERTIES ON HT-ATES SYSTEM – LOWER CRETACEOUS UNIT

The impact of the geological features modelled in this study on HT-ATES depends explicitly on the way it has been represented in the 3-D static model built in this study (*sensu* Shekhar et al., 2014). Invariably it is related to the hypothesis and assumptions made to arrive at the closest match to the subsurface reality. For any geothermal development, the structural configuration related to the geohistory manifested as faults system and fracture network is perhaps the most important in order to unravel the nature of the subsurface fluid flow. Faults are crucial structures for the transport of fluids, solute and energy (Lopez and Smith, 1995). The strike-slip faults related to the flower structure mapped here affects the Upper Jurassic, Lower Cretaceous and the lower part of the Molasse creating a structural complexity and potential damage with the possibility of fracture enhancement and flow within this region (Figure 5). Normal fault systems and strike-slip faults occupying in extensional and transtensional domains serve as a conduit for fluid flow also in non-magmatic geothermal systems as is the case of the present study area (*sensu* Moeck 2014; Moeck and Beardsmore 2014). Yet, the ability of these fault planes to serve as pathways for fluid plumbing is strongly controlled by the stress conditions along with the different stratigraphic units, lithofacies, fault displacement and temperature (*sensu* Bjørlykke, 1993; Knipe & McCaig, 1994, Yielding et al., 2016). Indeed, fault stress analysis has not been conducted in this study, however, faults in predominately carbonate formation such as the Lower Cretaceous Unit is often thought to be conduits for fluid flow due to their brittle nature (Yielding et al., 2016). These faults may be a low permeability fault rock system due to the possibility of fault healing related to the chemical reactivity of carbonates even after their reactivation (see Yielding et al., 2016). Favourable fault transmissibility here will occur in areas where these faults have enough displacement and juxtapose different lithofacies within the Lower carbonate rocks. In all this fault may have an implication in preferentially promoting the upwelling of the geothermal fluids thereby reducing the efficiency of any HT-ATES system development here. The dip of the faults mapped here are high and may influence fluid circulation at depth (*sensu* Grasby and Hutcheon 2001) while faults properties such as the length, depth, thermal conductivity, lateral gradient in heat flow and fault rock permeability will determine whether the thermal regime along these fault planes at the Cretaceous level is governed by advection or convection (sensu Lopez and Smith, 1995).

The carbonates in the Lower Cretaceous unit were deposited in a shallow water environment with lithofacies within the main target storage horizon either micritic limestone or bioclastic limestone. Petrophysical analysis on core samples within these intervals reveals a tight reservoir system with very low permeability and porosity however with intervals characterized by fractures and karsts and faults (Figure 6). Fractures and faults any fault depending on their properties may enhance flow within the aquifer, however, a major problem then will be injectivity into this tight carbonate system in the absence of the later. Lateral connectivity between this aquifer will depend on the facies variability. Since a minimal facies variability is expected within the study area storativity may be enhanced. This hypothesis of facies homogeneities is supported by the acoustic property of the Lower Cretaceous in the study area showing a little variation on seismic data except in highly deformed area. Other potential issues related to injectivity into this tight carbonate system is a potential for formation damage. This may arise and have an implication on the spatio-temporal mobility of the injected fluids.

5.3. IMPLICATION OF HYDROCARBON OCCURRENCE IN THE STUDY AREA ON HT-ATES

The GEo-01 borehole encountered hydrocarbons in some parts of the Molasse and the Lower Cretaceous unit (Figure 6). This is not unique in the Swiss Plateau as other Geothermal exploration boreholes - St Gallen GT-1 and Schlattingen likewise encountered hydrocarbons (Moscariello et al., 2020). Furthermore, gas seeps and bitumen seep have likewise been documented in outcrops (Leu and Oester, 2012) pointing towards an active petroleum system (sensu Magoon and Dow, 1994). However, the generation and migration of hydrocarbons in the Swiss Molasse Basin are still not completely understood and currently under investigation (Schegg et al., 1999; Moscariello et al., 2019b). In this study, potential candidate storage horizons with the manifestation of light oil and heavy oil (bitumen) and even oil shows as documented in the drilling report have been discounted during the selection of suitable intervals for ATES (Figure 6). Indeed, the injection of hot water into hydrocarbon-rich or bitumen impregnated intervals in the Lower Cretaceous will ultimately reduce the oil viscosity and mobility ratio resulting in enhanced oil recovery (sensu Prats, 1986; Bousaid, 1991; Jabbour et al., 1996 and Okasha et al, 1998). A major concern and uncertainty are the possibility of the thermal plume bypassing the target storage intervals into hydrocarbon-rich non-storage intervals since both intervals are stacked in the study area (Figures 6 and 7). This scenario is plausible since the Lower Cretaceous unit is highly faulted and fractured (Figure 6). These faults systems and fracture network depending on their hydraulic behaviours may act as either high-permeability conduits for channelling these hydrocarbon-contaminated-water to the storage intervals and even towards shallower siliciclastic molassic intervals where they may be sequestered or rather behave as barrier or mixed conduit-barrier system (sensu Aydin 2000; Bense et al. 2013; Caine et al. 1996; Faulkner et al. 2010). Without these deformation pathways, the likelihood of cross-strata or cross formational geothermal fluids breakthrough is limited since the porosity of the Mesozoic series and even the molassic sediments is low (Brink et al., 1992; Kälin et al., 1992) and characterized by a complex mix of sediments (Schegg et al., 1999). Therefore, the occurrence of hydrocarbons remains a potential risk for the successful development of ATES in this portion of the Swiss Molasse Basin. Considering this, some authors have suggested the possibility of co-producing the geothermal and hydrocarbon resources in the Swiss Molasse Basin (Moscariello et al., 2018).

5.4. CONCEPTUAL MODEL EVALUATING THE FATE OF THE HT-ATES POTENTIAL OF THE STUDY AREA

Based on the configuration and petrophysical property of the 3-D static model developed here and synthesis of information from literature, multiple HT-ATES exploration scenarios and hypothesis on the long-term fate of the injected fluids in the Lower Cretaceous candidate intervals can be tested. Here, we consider the GEo-01 well as injector only and the location of a second well that will compose the doublet potentially in future operation will be defined by the dynamic reservoir modelling (Birdsell & Saar, 2020; Mindel & Driesner, 2020). Despite being based on a simplified structural model, we can anticipate that the fate of the seasonally injected fluids, assuming a relatively homogeneous (lithofacies) storage horizon CT3, will be mostly controlled by petrophysical properties assigned to this aquifer. This interval is a tight system characterized by low porosity, low permeability, but with karst and fractured networks associated with brittle structures that locally dramatically increase porosity and permeability (Figure 6). Here the fault networks modelled results in natural upwelling of groundwaters, and, in case of injection of hot water, this natural process can be further enhanced by buoyancy due to the temperature differential between injected fluid and ambient-aquifer condition (Figure 8). This hypothesis of the preferential migration of fluids upwards along the fault system here does not consider pressure gradient that will be generated by the installation of doublet system where the second well will serve a cold groundwater extraction well during storage cycles. However, the presence of a highly conductive fault zone controlling the natural artesian flow observed at GEo-01 might reduce the likelihood for the development of an efficient HT-ATES system considering an extended period of thermal storage. Drilling report corroborates a fault-controlled system in the vicinity of the GEo-01 well, with a high-velocity flow at the wellhead recording a similar temperature as the aquifer temperature (Chablais, 2019). The natural recharge of the system here is from the Jura Mountain chains (Figures 1, 2 and 8) and circulation at depth is related to the hydraulic gradient. The faults encountered in the Lower Cretaceous are most likely open faults, laterally confining and vertically promoting localized fluid circulation. Since no aquifer was encountered in the Oligocene Molassic sediments, albeit deformed and characterized by faults extending from the Lower Cretaceous, we suggest this unit seals the entire system. The lithofacies property of the Molasse especially the increase in the shaliness may have downgraded the plumbing capability of the faults here (Figure 6).

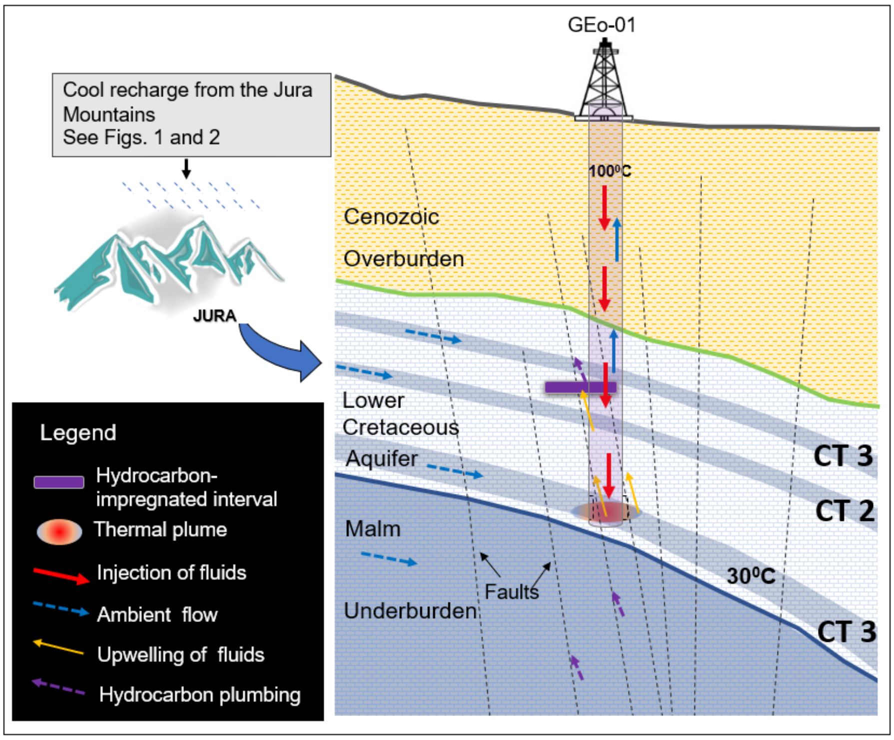

Figure 8: Conceptual model showing the fate of the thermal plume based on the GEo-01 well assuming high-temperature fluids are injected in the thickest and deepest aquifer CT3 in the Grand Essert formation.

6. CONCLUSIONS

In this contribution, we present the workflow for the development of a geologically realistic 3-D static model for an HT-ATES based on the integration of a suite of subsurface geophysical dataset around the GEo-01 geothermal exploration borehole recently drilled in the Geneva Basin. Start-of-the- art volume-based modelling technique has proved successful in developing a stable and robust 3-D static model when combined with knowledge-driven modelling decisions to ameliorate for areas with low data density inputs. However, uncertainties remain especially in the fault geometry and modelling and facies distribution which was assumed to be homogenous in this simplistic case presented here. Petrophysical analysis suggests the Lower Cretaceous formations are tight, generally characterized by low porosity and permeability values (Moscariello et al., 2020). This study highlights how the presence of a karstified, faulted and fractured intervals in the Lower Cretaceous locally enhance porosity and permeability allowing large groundwater flows, making the well suitable for direct uses and only in a second instance favourable for storage. Additionally, the manifestation of light hydrocarbons and their heavier counterpart have resulted in discounting some, albeit thinner, potential candidate storage interval in the Lower Cretaceous - since any HT-ATES develop here may reduce the oil viscosity and promote oil mobility resulting in enhanced oil recovery. Therefore, the subsurface manifestation of hydrocarbon in the Lower Cretaceous remains a potential risk worth considered during further numerical modelling and development of HT-ATES system and other geo-energy related projects in the Geneva Basin. Finally, three potential candidate horizons have been selected for HT-ATES in fractured intervals in carbonate-dominated Lower Cretatacoeus unit characterized by tested/confirmed water outflows: (1) Grand Essert Fm / Pierre Jeune de Neuchatel + Marnes d'Hauterives Fm [CT1]; (2) Vuache Fm - Chambotte- Chambotte inférieur [CT2] and (3) Goldberg Fm [CT3]. The structural situation of the study area, especially the occurrence of a potential damage zone may have implications on the evolution and fate of the thermal plume in any of the candidate storage interval. While the faults networks associated with the flower structure modelled here may serve as lateral traps and may promote a preferential vertical accent of the thermal plume, resulting in an irregular thermal plume geometry. All this remains hypothetical and explicitly depends on the fault-rock properties modulated by different aspects of basin geohistory, lithofacies, stress and fault displacement and the behaviour of the fracture networks in the Lower Cretaceous series. This is beyond the scope of the present study and will be considered as future directions. In the future development of HT-ATES system in the study area, compromise is to be made between developing the deeper thicker aquifer target system (CT3) versus the thinner shallow aquifer targets (CT1 and CT 2) as the deeper target will pose higher exploration and development costs. Yet a multi-horizon development strategy based on seasonal and long-term energy demand may be employed. Presently, in an ongoing application, the 3-D static model presented here is been employed as input for numerical heat flow and predictive THMC models for the Geneva Basin. Finally, the 3-D static model will be refined and updated when the envisaged 3-D vertical seismic profile survey and 3-D seismic reflection Survey over the study area becomes available. This would permit testing the validity of our mostly knowledge-driven fault model presented here. Until then, the model presented here is only the first attempt of a finer-scale representation of the subsurface geology with requisite characteristics and parameters for understanding the development of an ATES system in the Geneva Basin. Importantly, our findings highlight the urgent need for subsurface data augmentation in the study area, especially in the light of ongoing and future geothermal exploration campaign in the Geneva Basin.

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