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A revised structural framework for the Geneva Basin and the neighboring France region as revealed from 2D seismic data: implications for geothermal exploration

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Abstract

A new structural geological model of the Geneva Basin and neighboring France region has been generated based on a detailed interpretation of an extensive 2D seismic data set originated from a variety of surveys acquired over a period of ca 60 years and calibrated with numerous wells drilled in the past for hydrocarbon exploration. This new model reveals a much higher degree of structural complexity of the study area compared to what previously assumed. The study area can be subdivided in two main sectors characterized by a different orientation of strike-slip fault lines. The first sector located to the south including the Rumilly and Bellegarde Basins, Bornes Plateau and the southern part of the Geneva Basin is characterized by faults with an overall NNW-SSE direction. In this sector the regional continuous deeply-rooted NW-SE trending left-lateral strike slip faults previously thought to cross-cut the entire Geneva Basin parallel to the Vuache fault and respectively known as the Cruseilles fault, Le Coin fault and the more hypothetical Arve fault seem to be instead characterized by a much higher level of segmentation and lateral discontinuity. The Vuache fault remains however one of the major regional continuous line which most likely operated since Mesozoic time with different kinematics. The second sector, dominated by WNW-ESE to E-W-trending strike-slip faults, includes the northernmost part of the study area encompassing the northern part of the Geneva Basin and the Jura chain foothill. The two zones are separated by a ca 5 km-wide convergence zone characterized by a number of West-verging low-angle thrust planes affecting the geomechanically more brittle (calcareous prone) upper Mesozoic sequence and mostly rooted in the Oxfordian shales ad marls at the base of the calcareous Malm. In the western corner of the Geneva basin, the hinge zone between the Jura Haute Chaîne and the Vuache Mountain has developed important arcuate reverse faults affecting the entire meso-cenozoic series. The recognition of a different style of fault systems with variable orientation and rooting depths allows a better conceptual understanding of the subsurface, which can ultimately guide the definition of different geothermal plays.

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1 Introduction

Successful subsurface geo-energy (i.e. geothermal, hydrocarbons) exploration and development relies on the degree of understanding of the key geological elements such as reservoir distribution and structural framework which drive fluid-flow circulation and accumulation. An accurate understanding of these elements whose distribution and extension is often inferred from spatially discontinuous data points of variable quality (i.e. sparse and different vintages of wells and 2D seismic lines), will be the basis for developing sound conceptual subsurface geological models. The latter will be the fundamental basis for building 3D geo-cellular geological models, which will be then used for volumetric estimate, fluid-flow dynamic predictions and ultimately economic assessments of development of geo-energy project (Moscariello, 2016). In the context of the geothermal exploration in deeply buried sedimentary basins such as the Swiss Molasse Plateau, the definition of reliable structural framework is especially important as this is likely to determine and control the circulation (recharge and upwelling) of geothermal water. In the Geneva area, the ongoing geothermal prospection and exploration activities started in 2014 in the framework of the «GEothermies» program (formerly called «GEothermie 2020») promoted by the Canton of Geneva and the local public utility company Services Industriels de Genève (SIG), has initiated a large number of activities which addressed several aspects of the subsurface characterization (Moscariello et al., 2020). These ranged from data base and stratigraphic nomenclature harmonization (Favre, 2018; Brentini, 2018), reservoir properties characterization of specific stratigraphic units (Makhloufi et al., 2018; Rusillon, 2018), the assessment of potential risk of hydrocarbon occurrence at depth (Moscariello et al., 2020a) and a vast effort of re-interpretation of a large number of vintage, partly reprocessed and newly acquired 2D seismic data. This paper presents the main results of the structural interpretation derived by an accurate seismic interpretation offering a revised model of the general tectonic framework of the Geneva Basin and the neighboring France region (Bornes Plateau, Bellegarde and Rumilly Basins). More particularly this paper focuses on the Geneva Basin and will discuss briefly the significance and implications of this new model for geothermal exploration.

2 General settings and context of the study

This study focuses on the Geneva Basin (GB) and neighboring France forming the transnational Swiss-France southwestern termination of the north-alpine foreland Molasse Basin. Toward the NE, the study area opens and connects to the rest of the Swiss Molasse basin, whereas it is restricted on the W and NW by the Jura arc internal reliefs that bends from a NE-SW direction in the Geneva Basin to a N-S direction further west. The fronts of the subalpine and prealpine units limit the study area to the South and West respectively. The latter is affected by well-developed thrust anticline structures and cross-cut by the regional-scale Vuache fault. These elements separate the study area into 4 individual sub-basins: the Geneva Basin, the Bornes Plateau, the Bellegarde Basin and the Rumilly Basin (Fig.1).

2.1 Data and Methods

This work is based on the interpretation of 2D seismic data originated by various seis-

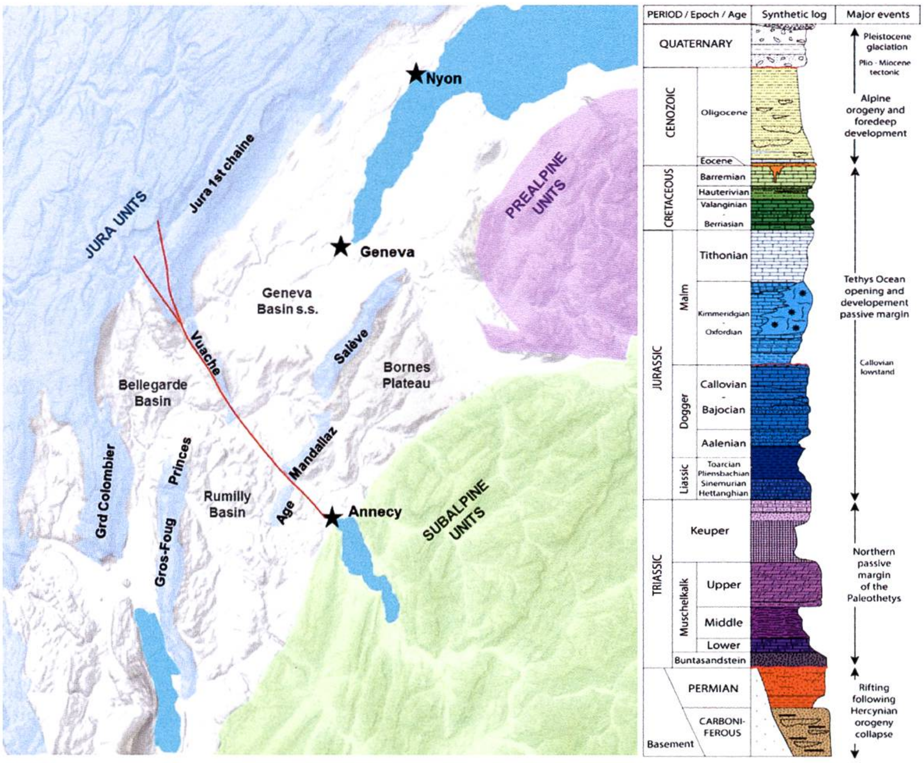

Fig. 1: Location map of the study area with key location names and principal tectonic units. Right: Stratigraphic column of the study area with the specific reference to the Geneva Basin for the Cenozoic section (modified after Charollais et al., 2013; Rusillon, 2018; Brentini, 2018; Moscariello, 2019).

mic surveys acquired between 1957 and 2015. Within the study area, the 2D seismic data reaches a total length of more than 1600 km, forming the most complete 2D seismic dataset existing at the time the model was built in 2018 (Fig. 2). Since then, additional 2D seismic has been acquired in 2018 and 2020 but was not considered in this work. This seismic dataset will keep growing, including a full 3D survey in Geneva planned for 2021. This will allow continuous improvements of the understanding of the deep subsurface architecture and will keep nourishing other ongoing interpretation works following both operational and academic goals.

Except over the southwestern extremity of the lake as well as over the most urbanized areas of Geneva and surroundings cities, this seismic dataset offers a relatively good coverage of the study area, although line quality varies between the various acquisition campaigns.

Seismic data in digital (SGY) format derived both from reprocessed and digitized raw material was analysed and interpreted using

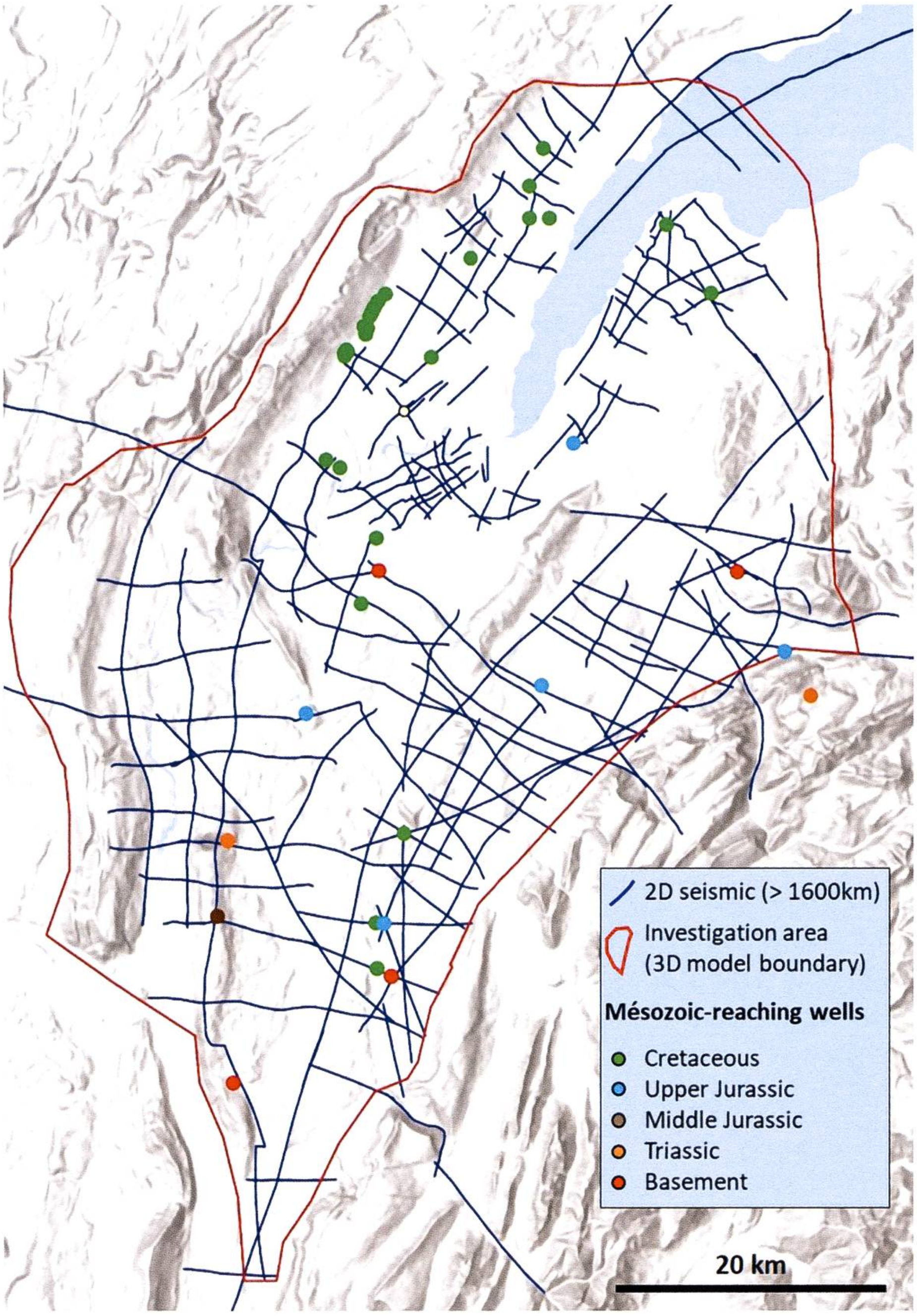

Fig. 2: Map view of the 2D seismic and Mesozoic well data used in this study.

Petrel interpretation and modeling software (Schlumberger, 2013 then 2017 version). The 2D seismic lines were time-shifted in order to minimize misties at line intersections and constitute a coherent dataset prior to interpretation. For this purpose, the time-depth pairs of the Humilly-2 well were used to time-adjust the reference seismic line 88SVO7 based on recognized key seismic reflectors. The seismic datum used for this work was established at 500 m.

In addition to the Humilly-2 well, this work benefited from other 42 wells reaching the Mesozoic units. Among them, 3 to 4 other wells (depending on the horizon considered) with check-shot data were used to tie the seismic away from the reference well Humilly-2 and thus ensuring a consistent stratigraphic and structural interpretation. They also served to establish the interval velocity maps used to compute the velocity model that served to depth-convert the interpreted horizons and fault surfaces. Remaining wells were used to constrain the horizons in the depth-domain. The stratigraphic nomenclature as well as the stratigraphic tops used across the area resulted from the combination of a detailed revision of literature and original analytical work which led to a deeply revised stratigraphic scheme for the region (Brentini, 2018; Rusillon, 2018). The current structural interpretation and modelling exercise evolved and continued from that initially carried out in the context of the GeoMol-CH project (Clerc, 2016; Allenbach et al., 2017). Current results over the Geneva region have been used to update the swiss GeoMol project. In this context, the key interpreted horizons were the Base Cenozoic (BCen), Top Upper Malm (TUMa) the Top Lower Malm (TLMa), Top Dogger (TDo), Top Lias (TLi), Top Keuper (TKeu), top Muschelkalk (TMus) and base Mesozoic (BMes). Seismic horizons discontinuity and offset, where not believed to be associated with acquisition and processing issues, were used to infer the occurrence of faults. Despite the difficulties and uncertainties associated with structural interpretation using sparse 2D lines, each fault correlation between 2 or more seismic lines was based using mainly their similar aspects in width, offset and vertical extension. In some places, the fault correlation and orientation inferred from 2D seismic line-to-line interpretation were mostly driven by contextual arguments based on a-priori knowledge and understanding of the overall tectonic regional framework.

In addition to seismic and well data, the subsurface interpretation work was both guided, questioned and quality-checked based on the structural maps, sketches and descriptions issued from various publications, reports and geological maps (Arn et al., 2004, 2005; Donzeau et al., 1997; Kerrien et al., 1998; Charollais et al., 2007; Charollais et al., 1998).
Given the large extension of the study area, the regional scale purpose of this study (i.e. modeling the main fault elements at regional scale in the 3-dimensional space) and the high variability of data quality and density, a detailed fault architecture modeling in 3D was not envisaged. The structural interpretation focused only on the key structural features that could be identified and mapped in 3D, implying for 3D modelling purpose a necessary simplification of the reality. An example of this is reported in Chapter 3.1.1.

2.2 Stratigraphy

The sedimentary cover consists in a thick succession (up to about 5000 m) of Mesozoic and Cenozoic units overlying a basement, whose erosive top surface records a regional dip of 1-3° (also affecting the Mesozoic cover) in the S-SE direction (Gorin et al. 1993 and this work). The basement, penetrated by few wells just outside the study area (Rusillon, 2018), is most likely made of crystalline rocks of Variscan age, deeply structured by graben or half-graben filled with Permo-Carboniferous sediments (Signer et Gorin, 1995 ; Paolacci, 2012; Moscariello, 2019).

The Mesozoic sedimentary interval spanning from the Triassic to the Lower Cretaceous is bound by the basal regional Hercynian unconformity and capped by an extensive Alpine unconformity, which is variably affecting the preservation of the Cretaceous sequence across the area. The Triassic rocks, not outcropping in the study area, are represented by the German stratigraphic units consisting of the siliciclastic Buntsandstein, dolomitic and evaporitic Muschelkalk, then varying alternance of evaporitic and dolomitic to marno-dolomitic sequence, up to the Rhaetian shales «argiles à esthéries» and «grès blond» sandstones that terminate the Triassic interval (Rusillon, 2018 & Brentini, 2018). The transition between the Triassic to the Jurassic sequence reflect the change in sedimentation evolving from a relatively stable continental and marginal shallow-water, marine environment (Triassic) to the marine platform developed in a passive margin, affected by the opening of the Thetyan ocean (Jurassic). Overall, the Jurassic sequence records a transgressive trend (Haq, 2017) ending with a short-lived regression (Tithonian) mostly dominated by carbonates deposition accumulated in different depositional environments such as shallow to deep platform environments, reef and peri-reefal (lagoonal) settings, tidal (wave-dominated) systems (Rusillon, 2018 & Brentini, 2018). The variations of relative sea-level changes which controlled the development of different environment of deposition were genetically associated with the interplay between tectonic and eustatic cycles. Very similarly, the Lower Cretaceous sequence preserved in the region is also dominated by carbonate sedimentation but marked by an increase in intercalation of siliciclastic material likely associated with the nearby development of a subaerial landscape during the lowermost Cretaceous regional sea-level fall in the Valanginian; (Haq, 2014). A approx. 72 million years hiatus separates the youngest Cretaceous rocks preserved in the Geneva region (Aptian age; Brentini, 2018; Rusillon, 2018) and the overlying older Cenozoic rocks represented by the Siderolithic of an estimated upper Eocene age (Charollais et al., 2007). This long-lasting subaerial exposure resulted in the development of an erosive and deeply karstified surface at the top of the Mesozoic series. This karst system, along with compartmentalization of tectonic origin, undoubtedly plays a key role in the hydrogeological drainage of the Cretaceous and Jurassic limestones across the basin.

The missing stratigraphic section in the study area of an estimated thickness of 1500-2000 m (Schegg and Leu, 1996; Schegg et al., 1997) was caused by the non-deposition and/or erosion related to the subaerial emersion associated with the Alpine orogeny.

In the Geneva Basin, the Cenozoic interval consists only of Lower Freshwater Molasse deposits (LFM) of Oligocene-early Miocene age. The overlying Upper Marine Molasse (UMM) is found only in the Bellegarde and Rumilly basins, to the West and SW of the Vuache fault (Charollais et al., 2007; Paolacci, 2012). In the Bornes Plateau, the thrusted subalpine Molasse is present at the front of the subalpine units (Charollais et al., 2007; Paolacci, 2012). It evolves northwards, in front of the prealpine units and continues into the lake, where it was mapped on lacustrine seismic data (Dupuis, 2009).

2.3 Tectonic settings

In response to the alpine compression in late Miocene – early Pliocene, the Meso-Cenozoic cover underwent a displacement and shortening detached from the basement through a regional decollement layer, which occurs in the Triassic evaporites at the base of the Mesozoic series (Sommaruga et al., 2017). This

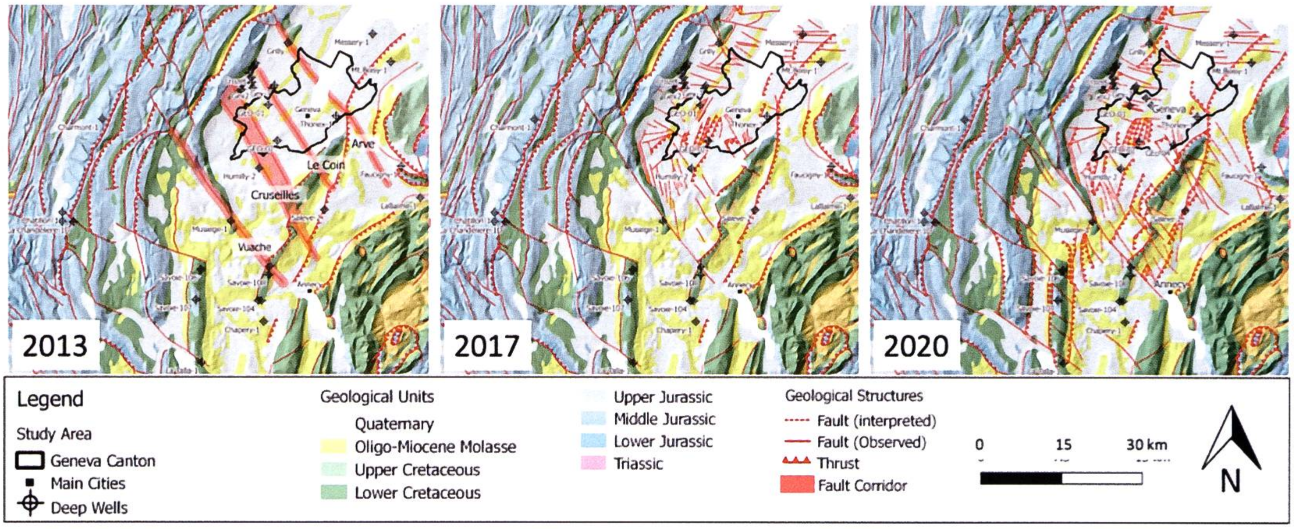

Fig. 3: Comparison of fault distribution in the Geneva Basin area based on the different and evolving views over the last decade. 2013: synthetic view of the basin-scale wrench fault systems suggested by previous interpretations including 1:500'000 geological map of Switzerland (Clerc et al., 2015 and references therein). 2017: unpublished intermediate view from ongoing interpretation already highlighting more discontinuous objects in the Geneva basin. 2019: current interpretation proposed in this paper. Figure modified after Moscariello (2019) and Moscariello et al. (2020a).

situation, which was also observed in the study area (see later), can be described by the «thin-skin» or «distant-push» model which was proposed to explain the tectonic evolution of the foreland Molasse Basin and the Jura arc during the last deformation phase of the Alpine orogeny (Buxtorf, 1916; Laubscher, 1961; Burkhard, 1990; Burkhard and Sommaruga, 1998; Sommaruga, 1997, 1999).

The reconstruction of the tectonic evolution of the Northern Alpine foreland region has been the focus of several research addressing different aspects and scale of structural elements (Laubscher, 1961, 1985, 1992; Burkhard, 1990; Gehring et al., 1991; Wildi et al., 1991; Burkhard and Sommaruga, 1998; Thouvenot et al., 1998; Hindle and Burkhard, 1999; Kastrup et al., 2004, Homberg et al., 1997, 1999, 2002; Affolter and Gratier, 2004; Baize et al., 2011; Ibele, 2011; Charollais et al., 2013; Moscariello, 2019; Cardello, et al., 2020; Polasek, 2020 amongst others) using mostly field observations i.e. geological and detailed structural mapping, paleomagnetic and seismologic data, modeling approaches etc. In the study area 2D seismic data have also been used (Gorin, 1989, 1992; Signer, 1992; Gorin et al. 1993; Signer and Gorin, 1995; Paolacci, 2012; Clerc, 2016; Allenbach et al., 2017) to reconstruct the structural framework of the Geneva Basin and surrounding regions taking advantages of the increasing coverage of geophysical data.

3 Description of the revised fault scheme

Following a detailed interpretation work of 2D seismic data, a revised vision of the regional structural framework is proposed here (Fig. 3 & 4). Whereas it images the major structures of this region, the main contribution of this study resides in the fine re-interpretation of the intra-basin fault scheme, especially in the Geneva Basin. This new model deviates from previous long-lasted model, which suggested the occurrence of regional strike-slip faults cross-cutting the entire Geneva Basin, with an NW-SE orientation parallel to the Vuache fault (Clerc et al., 2015 and references therein). These large faults were known, from West to East, as: 1) the Cruseilles fault zone, 2) Le Coin fault zone and 3) the Arve fault zone, although that latter always remained more hypothetical (Fig. 3-left). Over the last few years, continuing investigations hold in the framework of this ongoing PhD study, including that published in the initial version of the swiss GeoMol project (Clerc, 2016; Allenbach et al., 2017) gradually highlighted a different, more detailed and more complex fault scheme in the Geneva and neighboring basins. In the proposed interpretation (Fig. 4), one can see that both Cruseilles and Le Coin fault zones are preserved and confirmed by the seismic data where initially known from geomorphological and outcrop signatures (across the Salève ridge), but are no-longer extrapolated across the Geneva basin to connect to the first Chaîne. The following sections discuss the principal structural features known, observed and/or reinterpreted across the study area.

3.1 Strike-slip fault system

According to this interpretation the presence of two main strike-slip fault systems, respectively oriented NNW-SSE and WNW-ESE to E-W is highlighted across the study area.

The first system, oriented NNW-SSE as the Vuache fault (see later), dominates in the

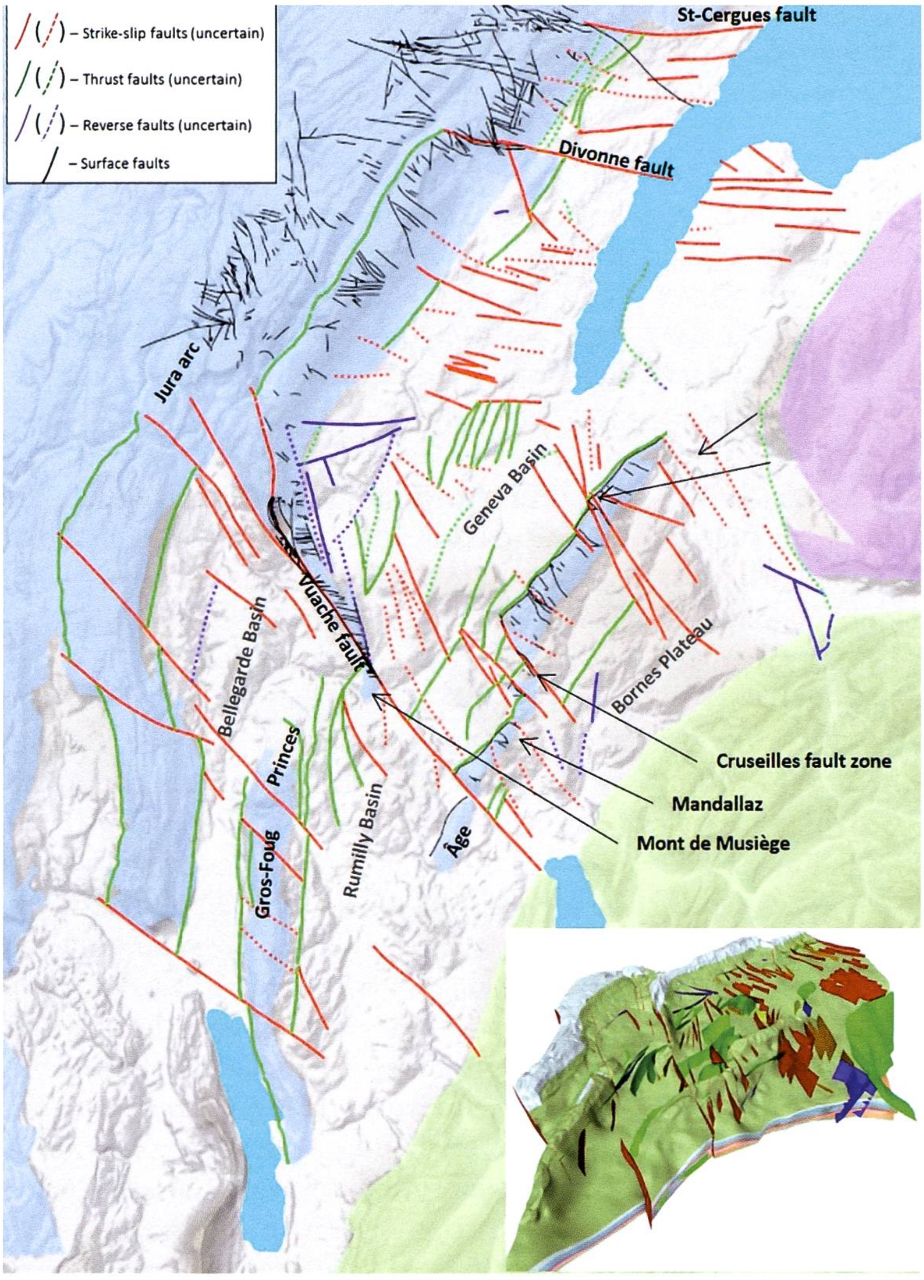

Fig. 4: Map view of the new regional structural model of the study area. Faults are distinguished on the basis of their types and their degree of confidence: red: strike-slip; purple: reverse; green: thrust. Black lines refer to surface lineaments and faults derived from geological maps. Lower right: oblique view of the 3D regional model (Mesozoic units only).

southern part of the study area, including the Bellegarde and Rumilly Basins, Bornes Plateau and southern corner of the Geneva Basin (Fig 4). As a whole, these faults record a general left-lateral movement, as clearly indicated by the geomorphologically visible offset associated with the Cruseilles and Le Coin fault zones that segment the Mandallaz – Salève Mountain ridge. At regional scale, these NNW-SSE oriented faults are either formed by long and aligned fault segments, such as those crossing the Bellegarde and Rumilly basins, or shorter and clustered fault segments like in the Cruseilles and Le Coin fault zone cases. The Arve fault zone, passing through the homonymous valley, is also formed by clustered segments although its occurrence has a much higher degree of uncertainty due to poorer seismic data coverage in this zone.

The second strike-slip system, oriented E-W, is mainly observed in the northern part of the study area coherently on both shores of the Leman lake. In the Nyon region (Fig. 4), the strike-slip faults interpreted on seismic data show good coherency with those mapped on outcropping Mesozoic units in the Jura Mountain as well as with those interpreted on the 1:25'000 geologic map of Nyon (Arn et al., 2004 and 2005). In this region, whereas some of these lineaments might, for some authors, display individually a left-lateral movement, this E-W strike-slip fault system shows an overall right-lateral movement (Arn et al., 2005). This system is interpreted as continuing along the Jura footwall, where it progressively adopt a WNW-ESE orientation. This is supported by many geomorphological lineaments of similar orientation in the Jura Haute Chaîne and by the outcomes of recent fine-scale structural analysis on high-resolution DEM and field observations (Cardello et al., 2020; Polasek, 2020).

Generally, most of the strike-slip faults identified on the 2D seismic data have been interpreted and modelled as subvertical structural features affecting the entire Meso-Cenozoic stratigraphic succession. Pronounced vertical offsets affecting these strike-slip faults are rarely observed. Where observed, along some of the most important lineaments, such vertical offset are thought to results mainly from horizontal displacement and juxtaposition of terrains of different elevation. At depth, these strike-slip lineaments do not root deeper than the regional decollement level, corresponding in this area to the Triassic Keuper evaporites (Sommaruga et al., 2017). Indeed, such a thin-skin model implies a complete decoupling of the Meso-Cenozoic sedimentary cover from its basement and Lower autochtonous triassic unit. This model excludes any direct morphogenetic connection between basement faults and those observed and described here within the sedimentary cover. This does not exclude, however, that indirectly, certain features such as major thrust faults in the sedimentary cover would have nucleated above remnant basement reliefs, themselves associated with basement faults.

Within the Cenozoic Molasse interval, the trace of these strike-slip faults on the 2D seismic data is often less obvious compared to the underlying massive calcareous series. This is due on one hand to the fact that the Lower Freshwater Molasse seismic facies displays very discontinuous reflectors due to the complex architecture and sedimentary facies distribution characterizing these continental deposits. On the other hand, the quality of some of the 2D lines across this interval does not allow the unambiguous identification of faults and their sense of movement. In summary, whereas these strike-slip features are well expressed and limited in space across the mechanically competent Mesozoic limestone series, through the Cenozoic interval they tend to propagate as more complex patterns often displaying asymmetrical flower structures ultimately resulting in relatively wide fault zone corridors (Clerc, 2016). In certain cases, for strike-slip faults recording important horizontal displacement such as the St-Cergues fault, the development of fault corridors is not restricted to the Cenozoic interval, but affects the entire Meso-Cenozoic series.

3.1.1 The Vuache fault and the Vuache Mountain

The geometry and cinematic evolution of the Vuache fault has been well described by various authors (Charollais et al., 1983; Blondel et al., 1988; Guellec et al., 1990; Wildi et al., 1991; De l'Harpe, 1996; Donzeau et al., 1998; Charollais et al., 2013, Moscariello, 2019) and constitutes a central feature in the study area. This fault, which displays strong morpho-tectonic evidence with the Vuache Mountain relief (Charollais et al., 2013; Moscariello, 2021), played an important role in the structural evolution of the region. This fault is a major NNW-SSE left-lateral strike-slip that extends across the Molasse Basin linking the Jura arc to the front of the subalpine units in the Annecy region (Fig. 4). Its possible extent further SE, within the subalpine domain cannot be ruled out. In the Mont-de-Musiège area, at the southern extremity of the Vuache Mountain, the horizontal offset is in the order of 10 km and decreases gradually toward the NW, where this displacement is absorbed by the fold and thrusts structures of the Jura (Meyer, 2000). Along the Vuache Mountain as well as across the first structures of the Jura, the Vuache fault records a transpressive movement (Blondel et al., 1988; Wildi et al., 1991; Charollais et al., 2012).

Several studies suggest a polyphasic origin of this fault and discuss its impact on the regional tectonic history. The analysis on fault mirrors present in the Vuache Mountain (Blondel et al., 1988) indicate that this relief would result from a multiphase deformation, already active during the compressive phase that occurred during the Eocene, at the beginning of the subduction of the European margin. This deformation and generation of an early Vuache Mountain as a geomorphic barrier between the Geneva Basin and the Rumilly and Bellegarde Basins would have continued during the extensive period associated with the rifting of the Rhine and Bresse grabens in the Oligocene (Homberg et al., 2002), as well as in the early Miocene, as suggested by the contrasting difference in the preserved Molasse sedimentary record on either sides of the Vuache Mountain: absence of Upper marine Molasse (UMM) on the Geneva Basin side although present in the Rumilly and Bellegarde basins conformably overlying the Lower Freshwater Molasse (LFM) (Paolacci, 2012). In addition, the prominent activity of the Vuache fault during the Cenozoic time could have been associated with pre-existing mechanically weak zones of the upper crust associated with the evolution of the passive European margin during late Jurassic and Cretaceous time. On seismic data, the Upper Malm unit across the Vuache fault zone shows a clear change in thickness suggesting a higher accommodation space to the E-NE sector compared to the W-SW (Fig. 5). This statement remains valid once the fault restored by the 10 km lateral displacement mentioned above, as revealed by the thickness maps computed from the 3D geological model. Moreover paleogeographic reconstructions on sedimentary facies after such structural restoration suggest abrupt changes in bathymetry between its eastern and western compartments (Charollais et al., 1983; Donzeau et al., 1997; Meyer 2000).
More recently, the Epagny earthquake of magnitude ML 5.3 in 1996, associated with the Vuache fault, whose epicenter was located at ca. 2 km depth (Baize et al., 2011) indicates that nowadays, the deformation of the sedimentary cover operates in a decoupled manner from its basement. Along with seismic evidence of large-scale thrust faults

rooting in the Triassic decollement level (see chapters 3.2, 3.5 and Fig. 6), this support the thin-skin model vision adopted in this work and described earlier.

Recent interpretation of the Vuache fault from 2D seismic profiles cross-cutting the fault SE of the Vuache Mountain (Fig. 5) highlights a high-degree of complexity including the development of intermediate decollement surfaces. In fact, evidence of low-angle faulting associated with the development of local decollement level within the shallower stratigraphic intervals have been observed across the study area (see chapter 3.6; Moscariello, 2019). For the Vuache fault case this observation seems to be corroborated by geochemical isotopic analysis of calcite cements associated with the Vuache fault zone where relatively low temperatures of paleo-geothermal fluids (ca. 70ºC) would attest for a shallower circulation network (Cardello, 2017). This geometrical complexity while observable in 2D seismic, cannot be modelled in the 3-dimensional space with the current sparse seismic dataset.

3.2 The Jura first Chaîne

Although poorly imaged due to the absence of 2D seismic data across the Jura first Chaîne, evidence of thrust and backthrust faults can be observed at the foothill of the Jura first Chaîne, which along with the Plateau de Retord and Grand-Colombier above the Bellegarde basin, delineate the northwestern and western limit of the study area.

On the Geneva Basin side, only the base of the main thrust of the Jura Haute-Chaîne that develop northwest above the synclinal of the Valserine (Fig. 6 B, C and D) is visible on seismic, along with modest evidence of associated backthrusting. This important thrust fault is interpreted by Arn et al. (2004, 2005) as disappearing northeastward against the Divonne strike-slip faults and the associated Mont Musy – Mont Mourex structure (Fig. 4). This would be then replaced, further northeast in the Nyon region, by a series of thrusts oriented toward the SE. Whereas the absence of a main NW-verging basal thrust in this region could be considered, these latter SE-verging thrust faults are confirmed by

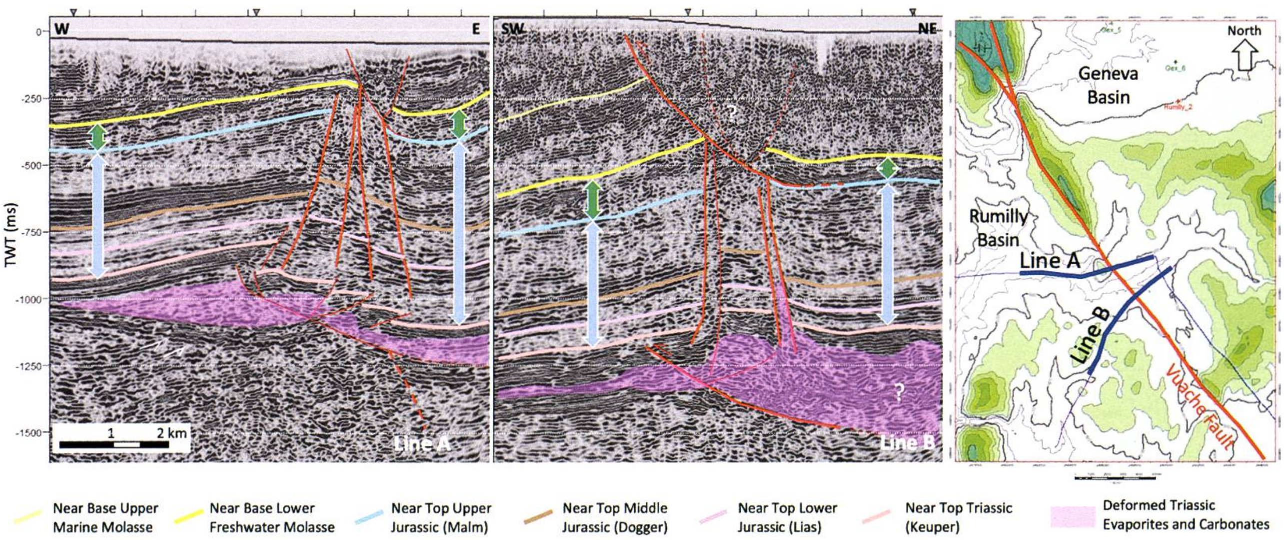

Fig. 5: Interpreted 2D seismic profiles across the Vuache fault which in the subsurface correspond to a 1 – 1.5 km wide fault zone. Low angle thrusts, rooted at the base of Triassic evaporites are responsible for the displacement of the Geneva Basin to the West and SW. The different in stratigraphic thickness on the two sides of the fault attest for an important and complex role of this structural element since early Jurassic time. Shallower detachment corresponding to marly layers at the base Cretaceous (i.e. Goldberg Fm) may be responsible for the most recent deformation affecting the Vuache fault zone.

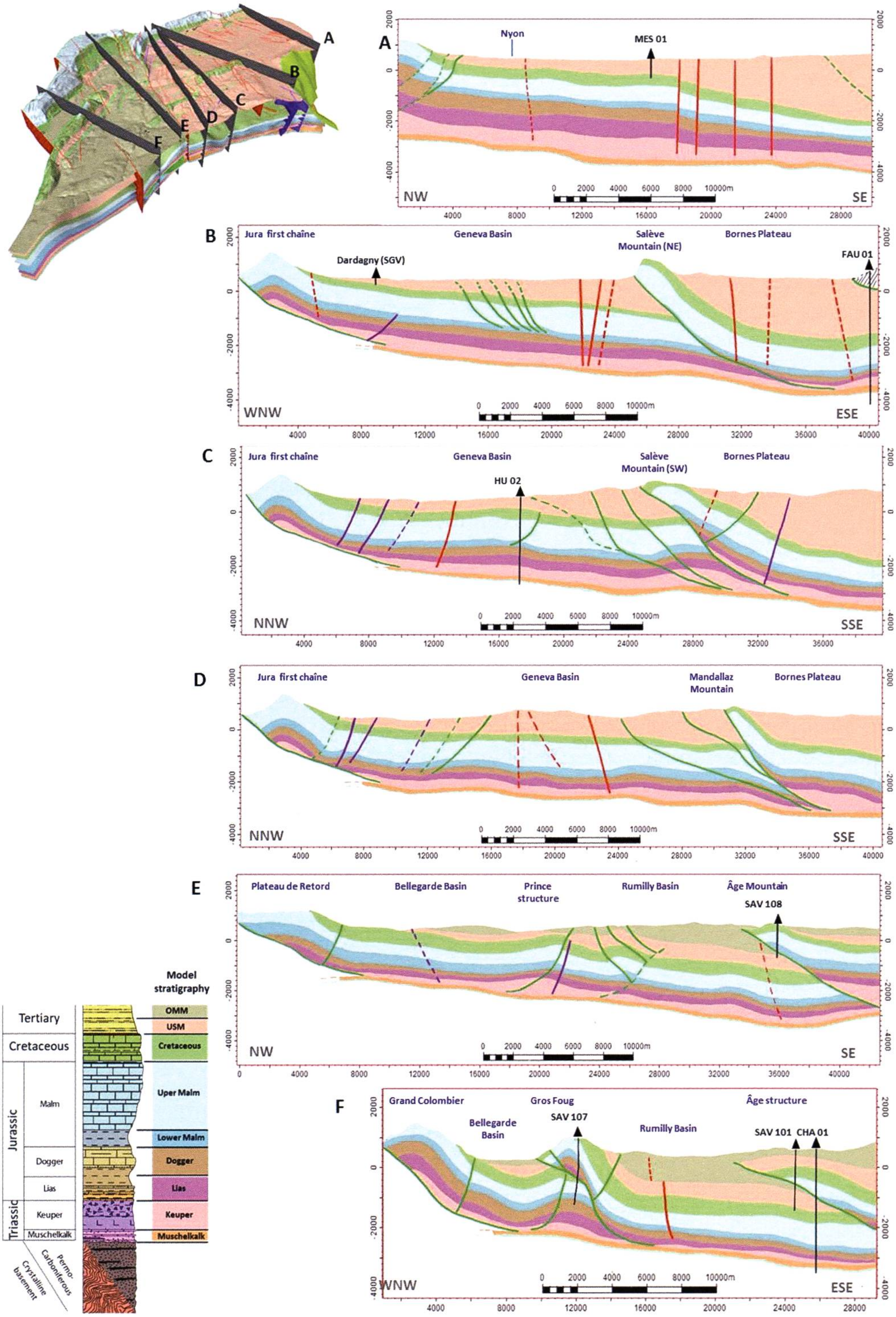

Fig. 6: Series of key regional cross-sections extracted from the 3D structural model of the study area. The main tectonic features discussed in the text are highlighted. The location of the profile is indicated in the inset figure at the top left. The stratigraphic layers indicated in the cross section correspond to the seismic horizons mapped for this work.

the 2D seismic data, (Fig. 6 A), segmented by important E-W strike-slip faults well developed in this region (Fig. 4). This right-lateral E-W strike-slip faults system, which extends along its foothill, gives the Jura first Chaîne a clear transpressive origin in the Geneva Basin area.

southwest of the Vuache, the Plateau de Retord and Grand-Colombier reliefs, that forms the western limit of the Bellegarde Basin (Fig. 1) are characterized by a large thrust fault verging toward the West and NW and rooting on the Triassic decollement layer (Fig. 6 E and F). The latter is segmented by important NW-SE left-lateral strike-slip faults and affected by backthrust faults, similarly to most major thrust anticline structures in the study area.

3.3 The Mandallaz – Cruseilles – Salève zone

Good-quality seismic profiles oriented perpendicular to the axis of the Salève Mountain ridge in its southwestern end and crossing the Mandallaz Mountain, provide a relatively clear subsurface image of these structures helping the three-dimensional structural interpretation of this region. However, the complex Cruseilles fault zone impacts the quality of the seismic data and account for important structural complication relatively tricky to infer from existing 2D data. In addition to a main thrust plane, along which most of the shortening occurs, several other thrust planes are also detectable toward the Geneva Basin (Fig. 6 C and D).

On the southwestern flank of the Salève Mountain, the seismic reveals at least one backthrust plane extending toward the Bornes Plateau (Fig. 6C). Other evidences for additional backthrusts structures appearing closer to the southern flank of the Salève are documented by Mastrangelo et al. (2013), who suggest their existence from the presence of «kink» structures in the outcropping Cretaceous units associated with important dip angle variations observed in nearby Oligocene Molasse beds. Unfortunately, at such shallow depths and proximity to the main anticline structure, the seismic data quality is not sufficient to recognize these proximal backthrust faults and understand their geometry at depth. On the Mandallaz Mountain relief, however, no clear backthrust fault has been observed from the seismic data (Fig. 6D).

Thrust plane signatures between the Salève and Mandallaz Mountains are relatively similar and do extend across the Cruseilles faults zone, although strongly segmented by the numerous strike-slip faults that characterize this area (Fig. 4). This tends to support the hypothesis that both the Salève and Mandallaz Mountains used to belong to a same structural ridge, which was then segmented by the Cruseilles fault zone slightly before achieving its final state. Indeed, the ca 5 km southeast offset position of the Mandallaz Mountain axis compared to the Salève Mountain, its lower elevation relief and absence of associated backthrust signatures (that develop at latest stage of thrust anticline formation) account for the fact that at a certain point, once segmented by the Cruseilles faults the Mandallaz Mountain thrust anticline stopped its evolution whereas the structuration of the Salève Mountain continued towards its current shape, elevation and farther basinward position.

3.4 The Âge Mountain

On both geographical and geomorphological points of view, the Âge Mountain seems to form the occidental termination of the Salève Mountain ridge, crosscut by the Vuache fault that generates an apparent c.a. 2km left-lateral offset. In reality, the Âge Mountain shows a different internal geometry compared to the Mandallaz Mountain that, as described above genetically belongs to the Salève Mountain ridge structure. This argues strongly in favor of their independent respective structuration origins and points to the existence of the Vuache fault in the late Miocene, at the time of the structuration of the Jura (Meyer, 2000).

The thrust at the base of the Âge Mountain is not revealed on surface and therefore only identifiable on 2D seismic data, where it seems to disappear at shallow Cenozoic depth. This consists of a relatively low-angle thrust that flattens and extends southwestward, further away than the outcropping Mesozoic units that form the Âge Mountain relief on surface. While identifiable from 2D seismic data as the transition to a relatively chaotic allochthonous compartment, the trace of this low-angle thrust is further confirmed by the funding of the hydrocarbon exploration wells (Fig. 3) that penetrated this structure (Fig. 6 E and F). If, from seismic data, evidence for higher tectonic complexity leading to thickness variations (thickening of the Cretaceous) seems to affect the allochthonous compartment of the structure, such smaller-scale features cannot be correlated and therefore modelled in 3-dimensions. Nevertheless, these complications are confirmed in the lithostratigraphy description of the aforementioned wells that report a large abundance of faults, breccia and repetitions of stratigraphic intervals in the allochthonous compartment toward the apex of the structure.

3.5 The Gros-Foug and Montagne des Prince structure

The occurrence of a basal thrust plane below the Gros-Foug Mountain structure has been proposed in the past (Wildi and Huggenberger, 1993) to explain the existence of important hidden volumes identified in restoration exercises. The available good-quality 2D seismic profiles available in this region allow us to confirm this and provide a clear interpretation image concerning the main tectonic features behind this relief.

The Gros-Foug Mountain is an anticline structure characterized by a very steep thrust fault evolving westward that seems to decapitate another deep and steep reverse fault (or straighten up ancient thrust fault) verging eastward (Fig. 6F). It is also affected by at least one important backthrust fault, well marked on most seismic lines with identifiable displacement. The steepness and narrowness of this structure compared to other thrust anticlines across the region, has to be related to the thickness of Triassic evaporites present at the base of sedimentary cover and their role as lubricant layer for the regional decollement. Major change of the Jura fold axis direction that occurs in this region may be in fact controlled by the distribution of the Triassic salt basin (Affolter and Gratier, 2004). Based on this, the absence of sufficiently tick evaporite layers would have increased the friction coefficient hence limit the displacement of the sedimentary cover over its basement to the advantage of the development of a steeper and narrower structure. The latter would have absorbed the shortening of the basin, leading to an evident relationship between the displacement of the sedimentary cover, the internal steep geometry of the fold and thrust structure and the thickness of the detachment level. A revised regional distribution and thickness maps of the Triassic series (Sommaruga et al., 2017) highlights important thinning out of the Triassic units West of the Vuache fault. This is confirmed by the seismic interpretation carried out in this work. Local apparent thickening of the Keuper seismic unit at the base of major thrust structures (Fig. 6E and F), result from tectonic thickening associated to the formation of duplexes in the evaporite layers in response to the compressive deformation (Sommaruga et al., 2017). The Gros-Foug Mountain is also further affected by important NW-SE strike-slip faults as well as similarly oriented smaller-scale faults of same type restricted to the crestal allochthonous compartment. This configuration compared to its N-S axis orientation gives the Gros-Foug

Mountain structure a transpressive origin of opposite direction than that of the Jura first Chaîne bordering the Geneva Basin.

If the Montagne des Princes can be morphologically and geographically considered as the northward continuation of the Gros-Foug Mountain, its internal architecture is rather different. The Montagne des Princes is affected by a simpler tectonic deformation, made of a single thrust fault extending eastward (Fig. 6E) and recording a smaller amount of shortening than the Gros-Foug Mountain structure. Seismic data reveals that this fault continues northward below the Molasse cover where its connection with the Vuache fault cannot be univocally established.

The junction between the Gros-Foug Mountain main basal thrust and the Montagne des Princes, respectively developed (at latest deformation stage) in the exact opposite directions, operates along a major strike-slip fault oriented NW-SE, at 45° angle with the anticline axis. Compare to former interpretations (Fig. 3) the orientation of this latter has been reinterpreted here as running from the eastern entrance of the «Val-de-Fier» to the North of the Seyssel village (Fig. 4), in the exact alignment of a well-marked bend of the Rhône river. This overall architecture assembly tends to suggest that initially, both the Gros-Foug and Prince mountains developed as a single structure made of an East-verging thrust that still prevails today below the Prince Mountain. The Gros-Foug Mountain, however, continued to evolve with the development of another West-verging basal thrust that decapitated, straightened up and finally overthrusted the original thrust, accompanied and isolated from the Prince Mountain structure by the development of the above-mentioned strike-slip fault.

The apparent missing amount of shortening of the Montagne des Princes is similar to that observed for the Gros Foug Mountain. This is overtaken by the Âge Mountain thrust further South and by a series of curved backthrust faults that extend the Mont de Musiège structure basinward (Figs. 1, 4 and 6E).

3.6 Smaller-scale structures identified in the Geneva Basin

In the northwestern corner of the Geneva Basin, the connection zone between the Jura Haute Chaîne and the Vuache Mountain corresponds to the convergence between the 2 strike-slip systems described above. Across this area, a series of curved reverse faults is identified on seismic data (Fig. 4). These structures, which for most of them affect the entire Mesozoic series, respond to the intense shortening and rotation that undergoes this hinge zone (Fig. 9). In addition, the presence of kink fold structures in the Urgonian limestones (lower Cretaceous) observed on the northwestern flank of the Vuache Mountain (Charollais et al., 2013), is consistent with the presence of reverse structures oriented almost N-S, on the back of this relief. These latter might also record a horizontal displacement component to accompany laterally the Vuache fault displacement (Fig. 4).

Toward the center of the Geneva Basin, a denser seismic information allows the identification of a series of low-amplitudes thrust faults, limited to the limestone-prone units of the uppermost Mesozoic interval (Upper Malm and Cretaceous) (Fig. 6B and Fig. 7). Individually, these shallow thrusts record very limited apparent displacement and their extension through the overlying Cenozoic-Molasse interval is not clear. At depth, these objects root at the base of the Upper Malm calcareous units, suggesting the existence of a local, secondary detachment level probably occurring in the ductile intervals of the Oxfordian such as the stratigraphic interval formed by the Effingen-Geissberg shale-prone formations (Clerc et al., 2017; Moscariello et al., 2019). Such secondary decollement level splits the Mesozoic cover into two main geomechanical zones:

The uppermost one (Upper Malm and Lower Cretaceous), more competent, responding to the stress field in a brittle manner and the lowermost one (Middle Jurassic down to the regional decollement level in the Keuper interval), made of overall weaker lithologies deforming in a more ductile manner. This kind of large-scale mechanical differentiation is also documented further South, in the subalpine units of the Bornes Massif. There, this differentiation occurs higher in the stratigraphy. The upper and brittle mechanical zone corresponds to Cretaceous and Oligocene sediments hosting the development of several thrust planes. This package is decoupled from a lower mechanical zone of more ductile behavior through a decollement layer located in a shale-rich layer at the base of the Cretaceous sequence (Huggenberger & Wildi, 1991).

At the scale of the Mesozoic sedimentary cover, additional intermediate decollement levels can potentially occurs at various scale and levels of ductile shale- or marl-prone intervals, separating mechanically competent massive limestone units and splitting the series into several mechanical zones. In the lower Mesozoic sequence (Dogger and Lias), similar behavior can be associated with the Alenian, Toarcian and Pliensbachian shales. Within the Cretaceous sequence of the Geneva Basin (Moscariello, 2019) and more specifically across the Vuache fault, such intermediate decollement levels have also been observed from 2D seismic data (Fig. 5). These might correspond to several shaly and marly intervals such as the Goldberg Fm, Vions Fm and Hauterivian Marls.

3.7 Other objects revealed from 2D seismic interpretation

Beside the large tectonic elements described above the detailed interpretation of 2D seismic lines allowed the identification of other objects both structural and stratigraphic, which are considered relevant for a complete characterization of the tectono-stratigraphic framework of the study area.

Smaller-scale but denser structural discon-

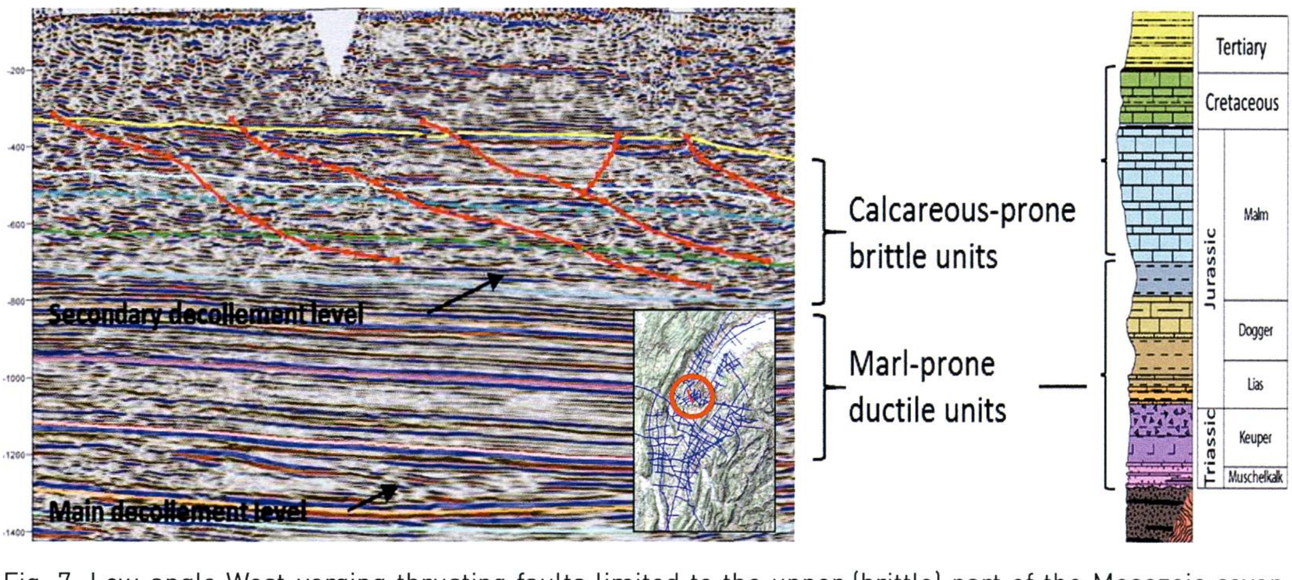

Fig. 7: Low-angle West-verging thrusting faults limited to the upper (brittle) part of the Mesozoic cover, locally suggesting the presence of a secondary detachment level at the base of the Upper Jurassic Malm (Effingen Fm. marls). This fault system is located at the center of the Geneva Basin. A number of thinner shale/marl-prone intervals may also exists within the Lower Cretaceous and Cenozoic sequences, which can complicate further the shortening mechanisms operating in the study area (see text).

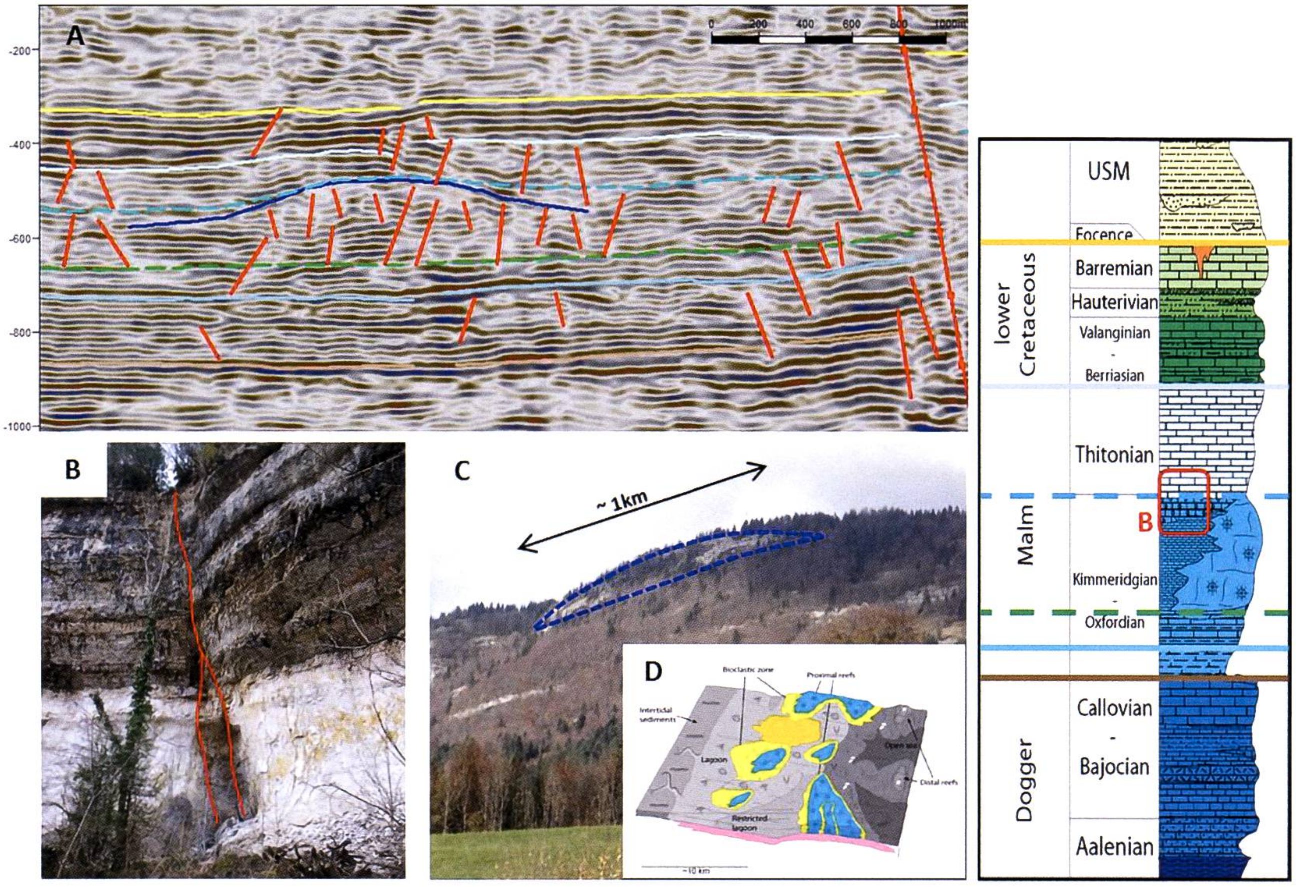

Fig. 8: A) Seismic profile illustrating the small discontinuities observed mainly within the Upper Jurassic and Lower Cretaceous limestone units and a characteristic domed structure potentially interpreted as Kimmeridgian reef buildup; B) example of possible analogue of these discontinuities in outcrop, in the Landaize and Vouglans Tidalites limestone formations (photo: E. Rusillon); C) Kimmeridgian Reef outcropping in the Champfromier region (photo: D. Do Couto); D) Conceptual depositional model of the Kimmeridgian Reef Complex (modified after Meyer, 2000).

tinuities, mainly restricted to the most brittle – limestone-prone units of the Upper Jurassic and Lower Cretaceous (Fig. 8A) have been identified using high-quality seismic profiles across the study area. Due to their limited length compared to the spacing of the 2D seismic data, it is not possible to map these elements in 3-dimensional space and thus determine their real extension and orientation. On outcrop, these elements can be related to plurimetric faults observed in the same formations (Fig. 8b). At small-scale (below seismic resolution) fault system observed in outcrop (Fig. 8b) suggests that these faults can be likely associated with a high density fracture network (Rusillon et al., 2016; Clerc, 2017).

In different locations of the study area, 2D seismic data show dome-shaped, convex-up structures with irregular to chaotic internal reflection pattern and surrounded by onlapping and draping seismic reflectors (Fig. 8A). According to their seismic facies, shape, size and stratigraphic position, these objects are interpreted as the reef buildups («calcaires récifaux» formation) occurring in the Kimmeridgian (Upper Malm) stratigraphic interval and well known in outcrop (Meyer, 2000); (Fig. 8 C and D). These reef buildups are in lateral contact with coeval lagoonal deposits («calcaires plaquetés» formation) which onlap their flanks. These structures are then overlaid by the Tithonian, «Tidalites de Vouglans» Formation which drape the Kimmeridgian reef-complex unit (Rusillon et al., 2016; Clerc, 2017; Moscariello, 2019). These objects can be observed across the study area in different locations. However, their identification and exhaustive mapping from 2D seismic is challenging because of the spacing of 2D seismic lines, which is often larger than these objects and the important heterogeneity of seismic quality and resolution among the different campaigns available that do not allow a definite identification of such fine-scale features across the entire dataset.

4 Discussion

In the study area, the shortening direction of the Meso-Cenozoic sedimentary cover is oriented NW-SE to NNW-SSE. It is largely absorbed by the development of folds and thrusts of the Jura fold and thrust belt, as well as by the Salève and Gros-Foug – Prince Mountains which, despite their physical detachment from the Jura Mountain, belong to the same tectonostratigraphic unit (Meyer, 2000; Homberg et al., 2002; Affolter and Gratier, 2004; Clerc, 2016). This displacement is also accommodated by the strike-slip movement of the Vuache fault, as well as the transpressive structuration of the Vuache Mountain itself (Blondel et al., 1988). Combined effect of smaller-scale strike-slip fault systems within the basin also contributed in the accommodation of the displacement of the allochthonous sedimentary cover.

Analysis of the regional stress trajectories in the Jura reveals that many of these strike-slip lineaments are very likely inherited from tectonic regimes that have pre-dated the Miocene fold and thrust deformational phase («Jura phase», Homberg et al., 2002). A strike-slip tectonic regime associated with a maximum stress direction oriented NNW-SSE to N-S during the Eocene, followed by an extensive regime associated with the opening of the Bresse and Rhine grabens in the Oligocene resulted in the development of strike-slip, than normal faults within the sedimentary cover (Homberg et al., 2002; Affolter and Gratier, 2004). Some of them might probably have developed in favor of existing weakness zones or discontinuities inherited from tectonic activity occurring in older geological times.

The study area can be subdivided in two main sectors characterized by a different orientation of predominant fault lines. The first sector located to the South of the study area including the Rumilly and Bellegarde Basins, the Bornes Plateau and the southern part of the Geneva Basin (Fig. 4) is characterized by faults with an overall NW-SE direction. The regional continuous high-angle deeply-rooted NNW-SSE trending left-lateral strike slip faults, generally thought to be crossing the Geneva Basin seem to be characterized instead by a much higher level of segmentation and lateral discontinuity. Exception to this is the Vuache fault which remains one of the major continuous regional line which most likely operated since Mesozoic time with different kinematics. Detailed work of this latter fault indicate a complex polyphasic behavior with a latest deformation affecting the shallower lithostratigraphic units (Fig. 5) characterized by West-SW-verging shallow thrusts, likely decoupled from the deeper regional detachment layer represented by the Triassic evaporites. The second sector includes the northernmost part of the study area encompassing the northern part of the Geneva Basin and the Jura chain foothill. This sector is dominated by E-W-trending overall right-lateral strike-slip faults whose orientation is consistent with the lineaments and fault system visible at surface in the first chain of the Jura Mountain (Fig. 4). The two sectors described above are separated by a ca 5 km-wide convergence zone (Fig. 9) characterized at the center of the Geneva basin by a number of West-verging low-angle «shallow» thrust planes restricted to the calcareous-prone brittle interval of the upper Mesozoic sequence and mostly rooted in geomechanically ductile lithostratigraphic units of the Oxfordian shales ad marls

(Fig. 7). Toward the hinge zone between the Jura first chain and the Vuache Mountain, this convergence zone is characterized by deep reverse faults radially distributed.

The new fault scheme proposed in this work (Fig. 4) is coherent with rotational movements of the Jura system established in the region on the basis of paleomagnetic data (Gehring et al., 1991; Affolter et Gratier, 2004) and field evidence i.e. fracture and stylolite orientations (Homberg et al, 1999). According to this new interpretation, the left-lateral movement of the NNW-SSE strike-slip system mapped in the study area would be driving the counter-clockwise rotation observed to the West of the Vuache fault, whereas the overall right-lateral movement of the ESE-WNE to E-W strike-slip faults would be able to accommodate the clockwise rotation measured further NE (Fig. 9).

Overall, these considerations would place the Geneva Basin at the convergence of these two opposite rotational movements (Fig. 9) separated by a zone with different deformation style (convergence zone).

These observations have provided new insight on the complexity of the structural framework of the subsurface, which ultimately determine and control the circulation and accumulation of geo-energy fluids such as geothermal water and hydrocarbons. In a geothermal exploration perspective, understanding the structural framework plays an even more important role where primary matrix porosity and permeability of reservoir rocks is low. This is in fact the case of most of the Mesozoic carbonate reservoirs found in

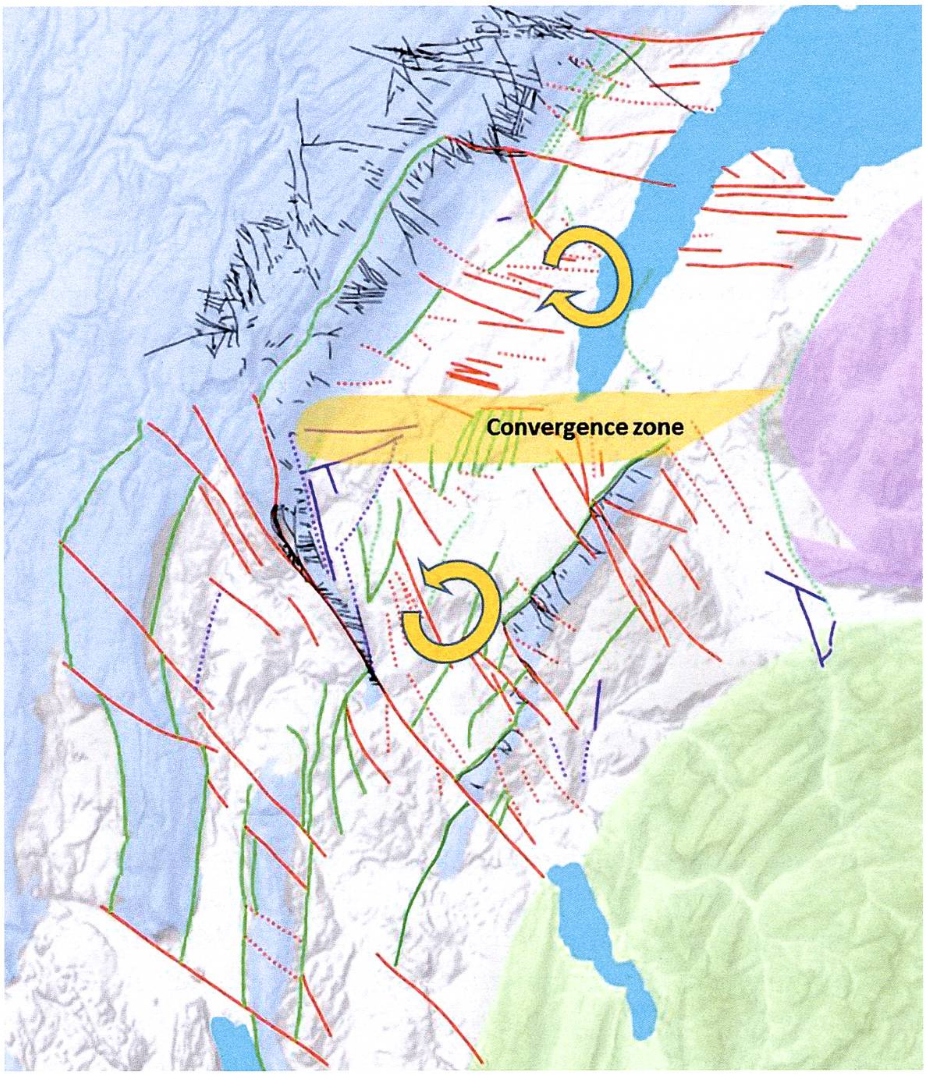

Fig. 9: Proposed kinematic model of the Geneva Basin and surrounding areas based on the current 2D interpretation. The predominant NNW-SSW overall left-lateral strike-slip faults that occupies the southern part of the study area accommodates an anticlockwise rotation of the sedimentary cover, whereas the predominant E-W overall right-lateral strike-slip faults in the North account for its clockwise rotation. The convergence region of these two main systems occurs in the Geneva Basin, where specific deformation styles such as west-verging shallow thrusts or high-angle reverse faults are observed. (see text for more details).

the study area (Rusillon, 2018; Moscariello, 2019; Moscariello et al., 2020). Any insight on the fault and fracture network orientation, vertical and lateral distribution (i.e. geomechanical stratigraphy) and density, is indeed crucial to establish the effective hydraulic conductivity within these stratigraphic units.

The proposed zonation of the study area in three main structurally different sectors will have an impact on the definition of the variety of geothermal play concepts occurring in the study area. These will in fact rely on the understanding of the geometry and extension of the permeability network made of faults and associated fractures in order to predict the path, behavior and properties of geothermal fluids (i.e. recharge mechanisms, fluid movement by advection or/and convection, pressure, temperature, chemical composition, occurrence of hydrocarbons, etc.).

The occurrence of deeply seated faults such as the strike-slip systems characterizing the southern sector may have higher chance to be associated with convective circulation of hot fluids, likely chemically affected by sulfates and hydrocarbons generated by the evaporites and source-rocks located in the deep Mesozoic and Paleozoic sequences. Similarly, the northern sector may have the same characteristics. The shallow thrusts, identified so far in the central sector of the convergence zone, on the other hand, would be potentially less prone to convection processes with a more complex effective communication between the recharge zone and the fault systems.

Despite some very encouraging results from the GEo-01 exploration well drilled in 2018 in the northern sector, the proposed new structural framework should be always updated with new data and information acquired through time. In fact, given the uncertainties associated with the density and variable quality of the current while constantly enriching seismic data set, as well as the complex deformational history experienced by the study area, a more complex structural framework cannot be ruled out at the moment.

5 Conclusion and perspectives

The deformational processes, which affected the Geneva Basin and the neighboring France region, resulted in the development of different structural elements (i.e. fault planes) with a large variability of geometry (i.e. inclination, lateral and vertical extension, displacement and rooting depth). This variability resulted in complex shortening processes mostly associated with low angle thrusts rooted in geomechanically favorable strata occurring throughout the Jurassic and Lower Cretaceous sequence. These latter acted as shallow detachment layers while high angle/vertical strike-slip are often deeply rooted at the base of the Mesozoic sequence at the top of the regional detachment layer represented by the Triassic evaporites.

With the exception of the Vuache Fault, the current interpretation does not reveal the existence of large persistent strike-slip structures throughout the basin as assumed in the past, but rather multiple systems composed of a number of faults of reduced extensions most likely genetically and kinematically connected. Moreover, with the exception of the St-Cergues detachment, most of the detached faults show relatively thin envelopes. This reflects the fact that, as a unit, these objects register little displacement and that this displacement eventually occurs in a combined manner over the whole fault system.

The results of this work represented by a new structural framework and a related large regional 3D-geological model represent a first building stone towards an improved understanding of the subsurface structural framework of the study area and specifically of the Geneva Basin where a specific focus on geothermal exploration occurs at the moment. By its extent to neighboring French regions, this model and associated derived cartographic product could also participate in encouraging these regions to look at such energy development in the future. This model represents also the starting point for both new academic research programs aimed at reconstructing the regional kinematic and the industry and associated consultancy companies who will have to respond more specifically to concrete requirements associated with the exploration and well planning and drilling activities linked to the ongoing GEothermies program.

Further in-depth work on the seismic data, adding the results of the most recent seismic and drilling campaigns is certainly encouraged in order to reduce the uncertainties associated with the present data set affected by largely variable data coverage and quality. This new approach will undoubtedly lead to an evolution of the proposed model offering an update vision of the structural framework that will have to be refined continuously following the results of future geophysical and drilling campaigns as well as ongoing and future interpretation work.

Soon to come 3D seismic data over the Canton of Geneva territory will provide new insights on the identification of smaller-scale objects geometries such as Kimmeridgian reef buildups, but will also allow a more accurate evaluation of the real extension of the strike-slip lineaments, as well as their connections with smaller-scale tectonic features.

References

Affolter, T. & Gratier, J.-P. 2004: Map view retrodeformation of an arcuate fold-and-thrust belt: The Jura case. Journal of Geophysical Research, 109(B3).1–20.

Allenbach, R., Baumberger, R., Kurmann, E., Michael, C. S. & Reynolds L. 2017: GeoMol: Geologisches 3D-Modell des Schweizer Molassebeckens – Schlussbericht. 128 pp., ISBN number: 978-3-302-40109-6.

Arn, R., Conrad, M.A. & Weidmann; M. 2004: Feuille 1261 Nyon. – Atlas géol. Suisse 1:25 000, Carte 117.

Arn, R., Conrad, M.A., Meyer, M. & Weidmann, M. 2005 : Feuille 1261 Nyon. – Atlas géol. Suisse 1 :25'000, Notice expl. 117.

Baize, S., Cushing, M., Lemeille, L., Gelis, C., Texier, D., Nicoud, G. & Schwenninger, J.-L. 2011: Contribution to the seismic hazard assessment of a slow active fault, the Vuache fault in the southern Molasse basin (France) Bull. Soc. géol. France, 2011, t. 182, no 4, pp. 347-365

Blondel, T., Charollais, J., Sambeth, U., & Pavoni, N., 1988 : La faille du Vuache (Jura méridional): un exemple de faille à caractère polyphasé. Bulletin de la Société vaudoise des Sciences naturelles, 79(2):65–91.

Brentini, M. 2018 : 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). PhD thesis, University of Geneva.

Burkhard, M. 1990: Aspects of the large-scale Miocene deformation in the most external part of the Swiss Alps (Subalpine Molasse to Jura fold belt). Eclogae geologicae Helvetiae, 83, 559-583.

Burkhard, M. & Sommaruga, A. 1998: Evolution of the western Swiss Molasse basin: structural relations with the Alps and the Jura belt. Geological Society of London Special Publications, 134, 279-298.

Buxtorf, A. 1916: Prognosen und Befunde beim Hauensteinbasis- und Grenchenberg-tunnel und die Bedeutung der letzteren für die Geologie des Juragebirges. Verhandlungen der Naturforschenden Gesellschaft Basel, 27, 184-205.

Cardello, G. L. 2017: Fault evolution and fluid flow record in the Western Alpine Molasse Basin (France and Switzerland): insights from structural analysis and stable isotopes. Technical report n° GEG2017005, Department of Earth Sciences, University of Geneva.

Cardello, G. L., Carminati, E., Doglioni, C. & Mercuri, M. 2020: Fault and fold control in a karst geothermal system: internal Jura mountains and Geneva Basin (France and Switzerland), Technical report n.1 – 06/04/2020, University la Sapienza, unpublished, 21 pp.

Charollais, J., Clavel, B., Amato, E., Escher, A., Busnardo, R., Steinhauser, N., Macsotay, O. & Donze, P. 1983 : Étude préliminaire de la faille du Vuache (Jura méridional). Bull. Soc. vaud. Sci. nat., Lausanne, 16, n° 3, 217-256.

Charollais, J., Plancherel, R., Monjuvent, G., Debelmas, J., avec la collaboration de Deville Q., Donzeau, M., Gallay, A., Gorin, G., Nicoud, G., Kindler, P., Ruchat, C., Turrel, C., & Wernli, R., 1998 : Notice explicative, Carte géol. France (1/50 000), feuille Annemasse (654). Orléans: BRGM, 130p. Carte géologique par Y. Kerrien et al. (1998).

Charollais, J., Weidmann, M., Berger, J. P., Engesser, B., Hotelier, J. F., Gorin, G., Reichenbacher, B. & Schäfer, P. 2007: La Molasse du bassin franco-genevois et son substratum', Archives des Sciences, 60/2–3, 59–174.

Charollais, J., Wernli, R., Mastrangelo, B., Metzger, J., Busnardo, R., Clavel, B., Conrad, M., Davaud, E., Granier, B., Martin, M. S. & Weidmann, M., 2013 : Présentation d'une nouvelle carte géologique du Vuache et du Mont de Musièges (Haute-Savoie, France). Stratigraphie et tectonique. Archives des Sciences, 66, 1-64.

Clerc, N., Rusillon, E., Moscariello, A., Renard, P., Paolacci, S. & Meyer, M., 2015 : Detailed structural and reservoir rock-typing characterization of the Greater Geneva Basin, Switzerland, for geothermal ressources assessment. Proceedings of the World Geothermal Congress 2015, Melbourne, Australia.

Clerc, N. 2016: GeoMol-CH project: Interpretation and modeling report of the Geneva area. Technical report n°GEG2016001.2, Department of Earth Sciences, University of Geneva.

Clerc, N., Rusillon, E., Cardello, L., Moscariello, A. & Renard P. 2017: Structural characterization of the Greater Geneva Basin (Switzerland and France) for geothermal resource exploration. AAPG SEG International Conference and Exhibition 2017, London, England.

De L'Harpe, A. 1996 : La faille du Vuache et ses conséquences : étude du séisme du 15 juillet 1996. In: Le Globe. Revue genevoise de géographie, tome 136, 1996. Frontières et territoire. pp. 85-94

Donzeau, M., Wernli, R., & Charollais, J. 1998 : Interprétation nouvelle de la géométrie de l'accident du Vuache dans le Jura méridional: le relais de failles transpressif sénestre Léaz-Champfromier (Ain). Géologie de la France, 2: 25–45.

Donzeau, M., Wernli, R., Charollais, J. & Monjuvent, G. 1997 : Carte géol. France (1/50 000), feuille Saint-Julien-en-Genevois (653). Orléans: BRGM. Notice explicative par M. Donzeau, R. Wernli, J. Charollais, G. Monjuvent (1997), 144p.

Donzeau, M., Wernli, R., Charollais, J. & Monjuvent, G., 1997 : Notice explicative, Carte géol. France (1/50 000), feuille Saint-Julien-en-Genevois (653). Orléans: BRGM, 144p. Carte géologique par M. Donzeau, R. Wernli, J. Charollais, G. Monjuvent (1997).

Dupuis, D., 2009 : Etude des sédiments quaternaires, de la Molasse et sa tectonique, dans le Grand Lac (Léman) a partir de données sismiques 2D et 3D.

Favre, S., 2018 : Système d'information pour les données géologiques 2D et 3D: Perspectives et limites pour l'analyse du sous-sol genevois et ses ressources. PhD thesis, University of Geneva

Gehring, A., Keller, P. & Heller F., 1991: Paleomagnetism and tectonics of the Jura arcuate mountain belt in France and Switzerland: Tectonophysics, 186, 269–278.

Gorin, G. 1989 : Interprétation géologique de la campagne sismique GG 87 dans le canton de Genève. Service cantonal de Géologie, Département de l'Intérieur et de l'Agriculture. Unpublished.

Gorin, G. 1992 : Rapport sur l'interprétation de la campagne de sismique réflexion 1990 dans le canton de Genève (périmètre Vernier – Onex – Sezegnin – Avully – Vernier). Services Industriels de Genève, Unpublished.

Gorin, G. E., Signer, C. & Amberger G. 1993: Structural configuration of the western Swiss Molasse Basin as defined by reflection seismic data. Eclogae geol. Helv., 86/3, 693-716.

Guellec, S., Mugnier, J. L., Tardy, M., & Roure, F. 1990 : Neogene evolution of the western Alpine foreland in the light of ECORS data and balanced cross sections, in Roure, F., et al., eds., Deep structure of the Alps: Mémoire de la Société Géologique de France 156, 165–184.

Haq, B. U. 2014: Cretaceous eustasy revisited Global and Planetary Change 113, 44–58

Haq, B. U. 2017: Jurassic sea-level variations: A reappraisal GSA Today, no. 1, doi: 10.1130/GSATG359A.1

Hindle, D. & Burkhard, M., 1999: Strain, displacement and rotation associated with the formation of curvature in fold belts; the example of the Jura arc. Journal of Structural Geology, 21, 1089-1101.

Homberg, C., Hu, J. C., Angelier, J., Bergerat. F., & Lacombe, O. 1997: Characterization of stress perturbations near major fault zones: Insights from 2-D distinct-element numerical modelling and field studies (Jura mountains).- Journal of Structural Geology, 19, 703–718.

Homberg, C., Lacombe, O., Angelier, J. & Bergerat, F. 1999: New constraints for indentation mechanisms in arcuate belts from the Jura Mountains, France. Geology 27/ 9, 827–830.

Homberg, C., Bergerat, F., Philippe, Y., Lacombe, O. & Angelier, J. 2002: Structural inheritance and cenozoic stress fields in the Jura fold-and-thrust belt (France). Tectonophysics, 357(1-4) :137–158.

Huggenberger, P. & Wildi, W. 1991 : La tectonique du massif des Bornes (Chaînes Subalpines, Haute-Savoie, France). Eclogae geol. Helv. 84/1: 125-149

Ibele, T. 2011: Tectonics of the western Swiss Molasse Basin during Cenozoic times, GeoFocus. University of Fribourg.

Kastrup, U., Zoback, M. Lou, Deichmann, N., Evans, K. F., Giardini, D. & Michael, A. J. 2004: Stress field variations in the Swiss Alps and the northern Alpine foreland derived from inversion of fault plane solutions, Journal of Geophysical Research: Solid Earth, 109(B1).

Kerrien, Y., Turrel, C., Monjuvent, G., Charollais, J., Lombard, A., Balmer, F., Olmari, F., Papillon, R., Fontannaz, L., Amberger, G., Ruchat, C., Grebert, Y. & Marthaler, M. 1998 : Carte géol. France (1/50 000), feuille Annemasse (654). Orléans : BRGM. Notice explicative par J. Charollais, R. Plancherel, G. Monjuvent, J. Debelmas et coll. (1998), 130p.

Laubscher, H. 1961: Die Fernschubhypothese der Jurafaltung. Eclogae geol. Helv., 54, 221-282

Laubscher, H. 1985: The eastern Jura: Relation between thin-skinned and basement tectonics, local and regional. Nagra Technischer Bericht 85-53.

Laubscher, H. 1992: 'Jura kinematics and the Molasse Basin', Eclogae geol. Helv., 85(3), 653–675.

Mastrangelo, B., Charollais, J., Wernli, R. & Metzger, J. 2013 : Accidents longitudinaux dans la Molasse rouge auct. et dans son substratum sur le versant oriental du Salève (Haute-Savoie, France). Swiss Journal of Geosciences, 106, p. 253-263.

Meyer, M. 2000 : Le complexe récifal Kimméridgien - Tithonien du Jura méridional interne (France), évolution multifactorielle, stratigraphique et tectonique. PhD thesis, Université de Genève.

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, 475–500.

Moscariello, A. 2016: Reservoir geo-modeling and uncertainty management in the context of geo-energy projects Swiss Bull. angew. Geol. 21/1, 29-43

Moscariello, A. 2019: Exploring for geo-energy resources in the Geneva Basin (Western Switzerland): opportunities and challenges. Swiss Bull. angew. Geol., 24/2, 105-124.

Moscariello, A. 2021: The geomorphological landscapes in the Geneva Basin. In Reynard E. (ed.): Landscapes and Landforms of Switzerland, Springer Mature Switzerland, 83-96.

Moscariello, A., Clerc, M., Eruteya, O. E., Omodeo-Salé, S. & Guglielmetti, L. 2019: Complex shortening tectonic style in the undisturbed Alpine foreland: Example from the Geneva Basin (Switzerland) and implications for subsurface geo-fluid circulation. Proceedings AAPG Europe Regional Conference, Vienna 26-27 March 2019, P-65.

Moscariello, A., Guglielmetti, L., Omodeo-Salé, S., De Haller, A., Eruteya, O.E., Lo H.L., 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. 2020a: 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 2020, Reykjavik, Iceland, April 26 – May 2, 2020, 12 pp.

Moscariello, A., Do Couto, D. & Omodeo Salé, S. 2020b: An analysis of the petroleum system in the SwissMolasse Basin with a focus on Western Switzerland (UNCONGAS). – Rep. Swiss geol. Surv. 13 (in press)

Paolacci, S. 2012: Seismic facies and structural configuration of the Western Alpine Molasse basin and its substratum (France and Switzerland). PhD thesis, Université de Genève, unpublished.

Polasek, D. 2020: Kinematic and hydrogeological role of the Jura Mountains Haute-Chaîne fracture network. Unpublished MSc thesis, University of Geneva.

Rusillon, E., Clerc, N., Brentini, M. & Moscariello, A., 2016 : Rock typing, structural characterization and stratigraphy harmonization in support of geothermal exploration in the Greater Geneva Basin (Switzerland). Proceeding of the European Geothermal Congress (EGC) 2016, Strasbourg, France.

Rusillon, E. 2018: Reservoir Characterisation and Rock Typing of Deep Geothermal Reservoirs in the Greater Geneva Basin (Switzerland and France). PhD thesis, University of Geneva.

Signer, C. 1992 : Interpretation sismique structurale et sismostratigraphique entre Jura et front alpin dans la région genevoise. Diplôme, Univ. de Genève, unpubl.

Signer, C. & Gorin, G. 1995: New geological observation between the Jura and the Alps in the Geneva area, as derived from reflection seismic data. Eclogae geol. Helv., 88/2, 235-265.

Schegg, R. & Leu, W. 1996: Clay mineral diagenesis and thermal history of the Thonex well, western Swiss Molasse basin. Clay Min., 44, 693-705.

Schegg, R., Leu, W., Cornford, C. & Allen, P.A., 1997: New coalification profiles in the Molasse Basin of Western Switzerland: Implications for the thermal and geodynamic evolution of the Alpine Foreland. Eclogae geol. Helv., 90, 79-96.

Sommaruga, A. 1997: Geology of the Central Jura and the Molasse Basin: New insight into an evaporite-based foreland fold and thrust belt. PhD-thesis Université de Neuchâtel. Mémoire de la Société Neuchâteloise des sciences naturelles 12, 176pp.

Sommaruga, A. 1999: Décollement tectonics in the Jura foreland fold- and-thrust belt. Marine and Petroleum Geology, 16, 111- 134.

Sommaruga, A., Mosar, J., Schori, M. & Gruber M. 2017: The role of the Triassic evaporites underneath the North Alpine foreland. In: Soto J. I., Flinch J. and Tari G. (eds.). Permo-Triassic salt provinces of Europe, North Africa and the Atlantic Margins: tectonics and hydrocarbon potential, Elsevier.

Thouvenot, F., Frechet, J., Tapponnier, P., Thomas, J.-C., Le Brun, B., Menard, G., Lacassin, R., Jenatton, L., Jean-Robert, G., Coutant, O., Paull, A. & Hatzfeld, D. 1998 : The ML 5.3 Epagny (French Alps) earthquake of 1996 July 15: a long-awaited event on the Vuache Fault. Geophysical Journal International, 135/3, 876-892.

Wildi, W., Blondel, T., Charollais, J., Jaquet, J.-M., & Wernli R., 1991: Tectonique en rampe latérale à la terminaison occidentale de la Haute-Chaîne du Jura. Eclogae geol. Helv. 84/1, p.265-277.
Wildi, W. & Huggenberger, P. 1993: Reconstitution de la plate-forme européenne anté orogénique de la Bresse aux chaînes subalpines; éléments de cinématique alpine (France et Suisse occidentale). Eclogae geol. Helv. 86/1, p. 47-64.