UNIVERSITÉ DE GENÈVE

a CERN FCC- UNIGE joint project

Swiss Accelerator Research and Technology

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Department of Earth Sciences

Geo-Energy Group
Department of Earth Sciences
University of Geneva

3D GEOLOGICAL MODEL FOR THE FCC PROJECT

Report n.	GEG2022002
Date	1.11.2022
Author (s)	Dr. Aymeric Le Cotonnec
Approved by	Prof. Andrea Moscariello

This page is intentionally left blank

Context

The Future Circular Collider (FCC) is the new particle collider planned by the CERN, it is planned to span over 85 to 100 km in circumference around Geneva. This study aims at providing a geological model of the subsurface along the trace of the FCC (Fig. 1), focusing mainly on the upper geological boundaries as the tunnel is planned to be drilled in the Molasse deposits as much as feasible. The point of this study is thus to provide a geological as accurate as possible, given the current available data, to provide indications about areas where geological risk is the highest, thus where more investigations are needed.

The subsurface of the Geneva basin (Fig. 1) consist of a deep basement, overlain by sedimentary deposits ranging from Permo-Carboniferous to Quaternary consisting of clastic, massive and heterogeneous limestone and evaporites. The top of this sequence is characterized by a large hiatus during which the top of the Cretaceous limestone was intensely karstified. Those karsts were then infilled by sandstone and breccias forming the siderolithic deposits, which are underlying the Molasse sequence. Across the Swiss Plateau the Molasse deposits are generally characterized by four sequences of alternating marine and continental clastic deposits. Those units are highly influenced by the shaping of the foreland basin and thus are not present throughout the area, they generally tend to pinch out towards the Jura mountains, therefore the Molasse sequence tends to vary significantly in thickness from SE to NW. In the FCC area the Molasse consist of a marly and sandy, subordinately associated with gypsum rich intervals. Finally, Quaternary deposits top the sequence, they consist mainly of glacio-lacustrine deposits which are relatively loose and hosts most of the drinking water for the area. Quaternary deposits reach important thicknesses along major river valleys (Rhône and Arve) as well as under the Leman Lake.

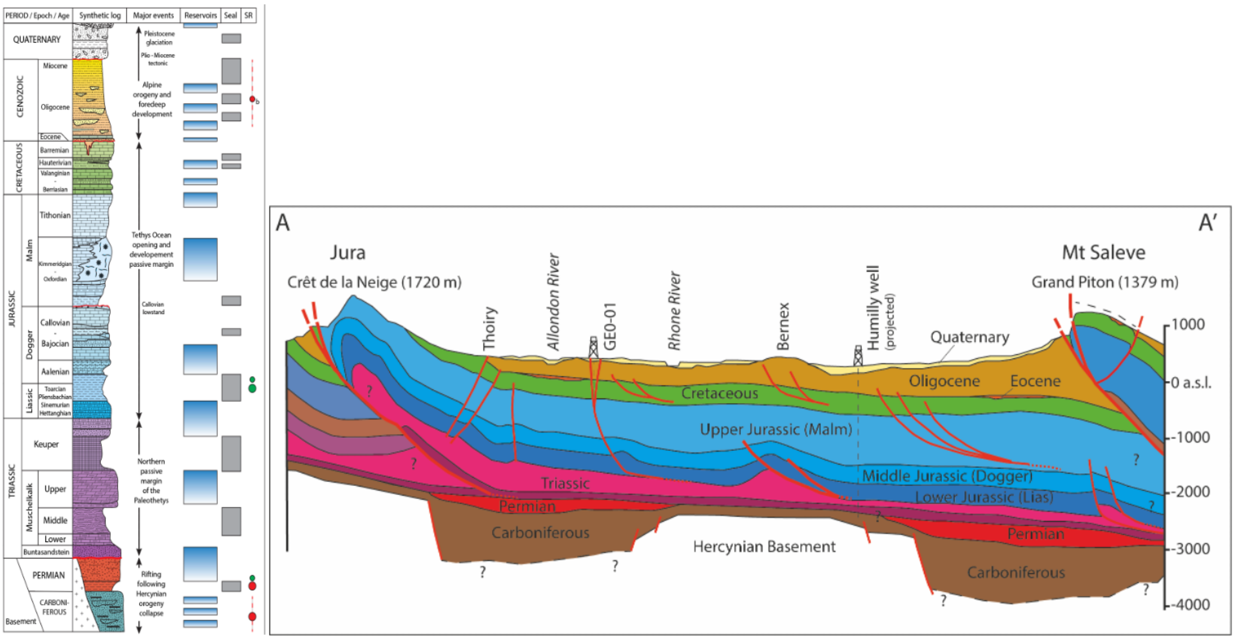

Figure 1. Synthetic stratigraphic log across the Geneva Basin, Moscariello, 2019

Given the projected depth of the FCC project and the geological setting of the Geneva basin, the geological units of interest are the Quaternary, Molasse, and the Cretaceous as well as its upper, complex boundary. Therefore, the main deliverable of this study consists of 3D surfaces indicating the boundary between the Quaternary and Molasse deposits as well as the surface boundary between the Molasse and Cretaceous carbonates. Alongside these surfaces the main faults affecting the project area have also been delivered. Although dedicated studies are ongoing at the University of Geneva focusing on the top Cretaceous karsts and their siderolithic infill, this unit at the moment remains not yet well understood. This is mainly due to its significant discontinuity, heterogeneity and variation in thickness over short distances (as observed during the Geo-02 well drilling performed by the Geneva Industrial Services). Furthermore, the scale of the karsts, generally between 0 and few tens of meters, up to over 100m makes it very challenging to detect and correlate in seismic, even more so in 2D seismic lines. Therefore, this feature of the Geneva Basin, relating to the FCC requires data to be acquired at specific locations. One of the motivation of this study is therefore to support as accurately as possible the decision process regarding the location of future data acquisition campaigns.

To provide information about the subsurface where the FCC is planned to be located, a 3D geological model has been generated using the SLB Petrel platform. This geological modelling software allows the import, analysis, manipulation, and display of geological data. Boundaries between geological units can be generated using various algorithms and these can be generated by interpreting seismic data and converting those interpretations from two-way-time to depth using a velocity model.

Dataset

The data used have been provided by UNIGE PhD student Emna Meftah, who has assembled a database of all well and seismic data available within the study area. In addition, several geological models already existing in the area, those were mostly generated for the geothermal exploration and development campaign currently ongoing by the SIG (Geneva Industrial Services). The dataset consists of 2D seismic lines as well as wells, both deep wells coming from past oil and gas exploration activities, mostly drilled during the 80’s and 90’s as well as the current geothermal exploration campaign, and shallow wells in the form of piezometric wells for water table monitoring. Generally, deep wells include a large panel of petrophysical data taken along the borehole, including caliper, gamma ray, neutron porosity, resistivity, and sonic, some wells include more data, some less. Due to different timing of the various drilling campaigns, the measuring equipment and thus the quality of the data is heterogeneous. Fortunately, a normalized[1] set of logs are available to UNIGE which allows the comparison of logs over a heterogeneous dataset.

In addition to raw and normalized data, well data also contains a stratigraphic interpretation, for the purpose of this study, the difference between Molasse and Cretaceous deposits appears very clearly in the gamma ray log and is usually accurate. Notably, sonic logs are important because they allow the calibration of the seismic. Seismic calibration is a process by which the sonic well logs is used to tie the depth scale of the well to the two-way-time scale of a close by seismic line, which allows the identification of the reflectors for stratigraphic horizons, without which the seismic is not interpretable with confidence. It is important to note, that seismic interpretation is done by starting to pick one seismic reflector at a calibrated well and then it will be propagated on the intersecting seismic lines. Therefore, if clusters of seismic lines are not connected to a calibrated well, interpretations can be significantly less accurate and must be taken with caution. Finally, sonic logs are used to generate a velocity model, which approximates the velocity of acoustic waves through the different deposits. This can vary from one stratigraphic interval to another as well as spatially. Notably, in siliciclastic deposits, such as the Molasse, velocity is highly dependent on compaction.

Shallow borehole data are much more limited as those usually contain a crude description of the deposits encountered and sometimes an interpretation of the associated stratigraphic horizons.

The wells selected for the purpose of this study are the ones that reach down to the top of Molasse. Whereas deep wells are sparse but with a much higher number of information, shallow wells carry very limited data but are very dense.

[1] Normalization is an operation by which well logs are rescaled to a common scale for all identical logs in a dataset.

Top Molasse

The top Molasse horizon is generated using the identified depth of the top Molasse in shallow, piezometric wells coming both from the Geneva geological survey (GESDEC) and the French geological survey (BRGM) databases (Fig.2). After a clean-up operation, which mainly consisted of verifying alignment between shallow wells depth and DEM data as well as any abnormal values (e.g., a point 50m below it’s close by neighbors), the surface can be generated. Given the data density and the limited thickness of Quaternary deposits, the modelling approach taken is to generate first a thickness map (Fig. 3), from which the top Molasse surface is generated from the DEM (Fig. 4).

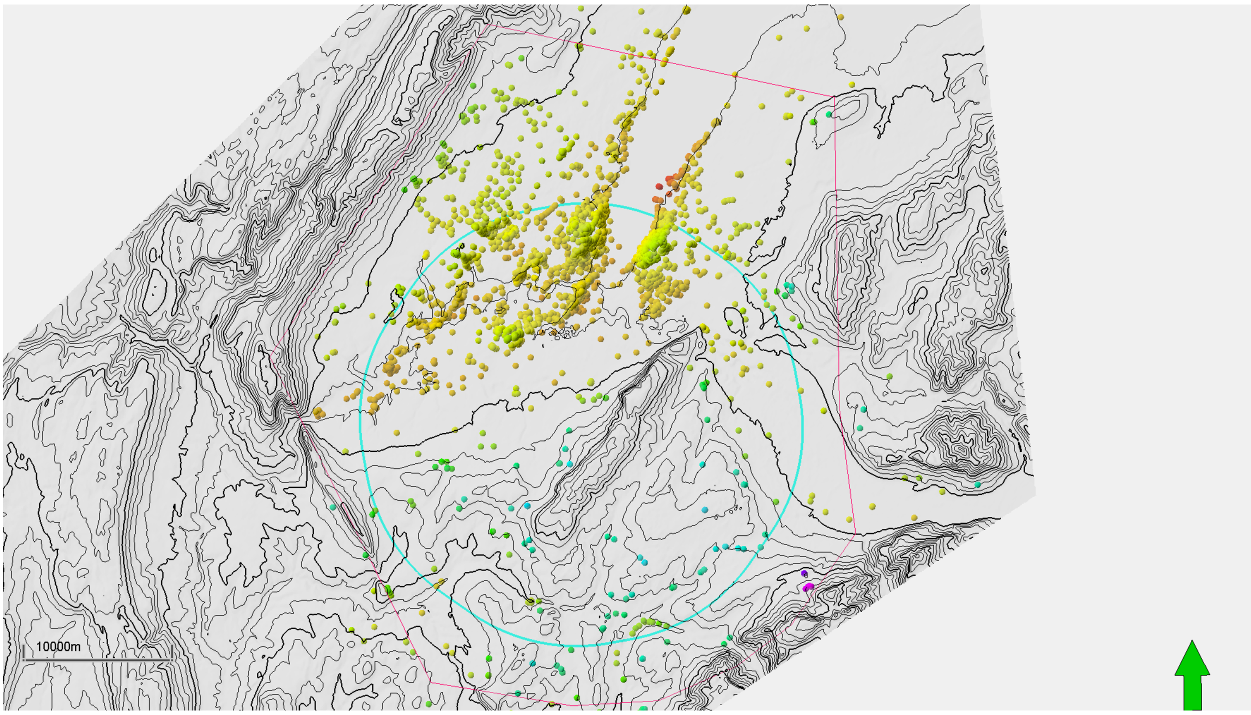

Figure 2. Top Molasse dataset. In light gray, DEM of the area; red polygon, study area extent; light blue circle, PA 3.1.10 FCC alignment; shallow well points colored by depth of the top Molasse.

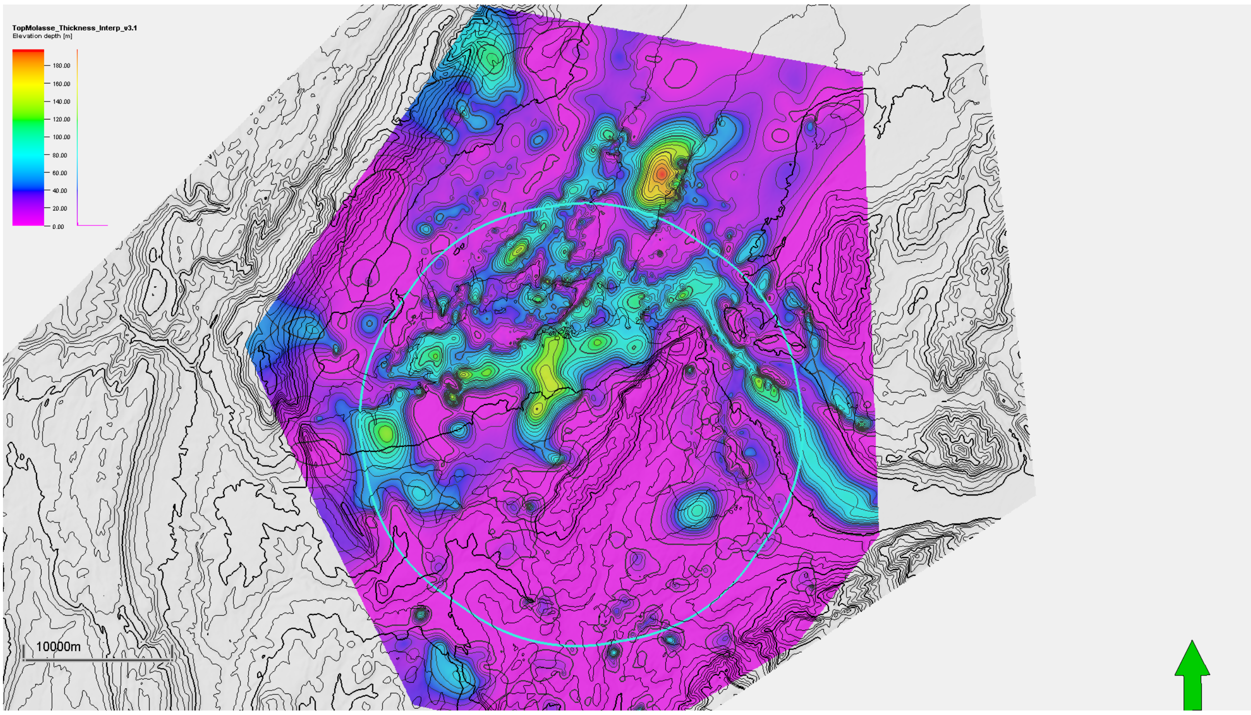

Figure 3. Top Molasse thickness map within the study area.

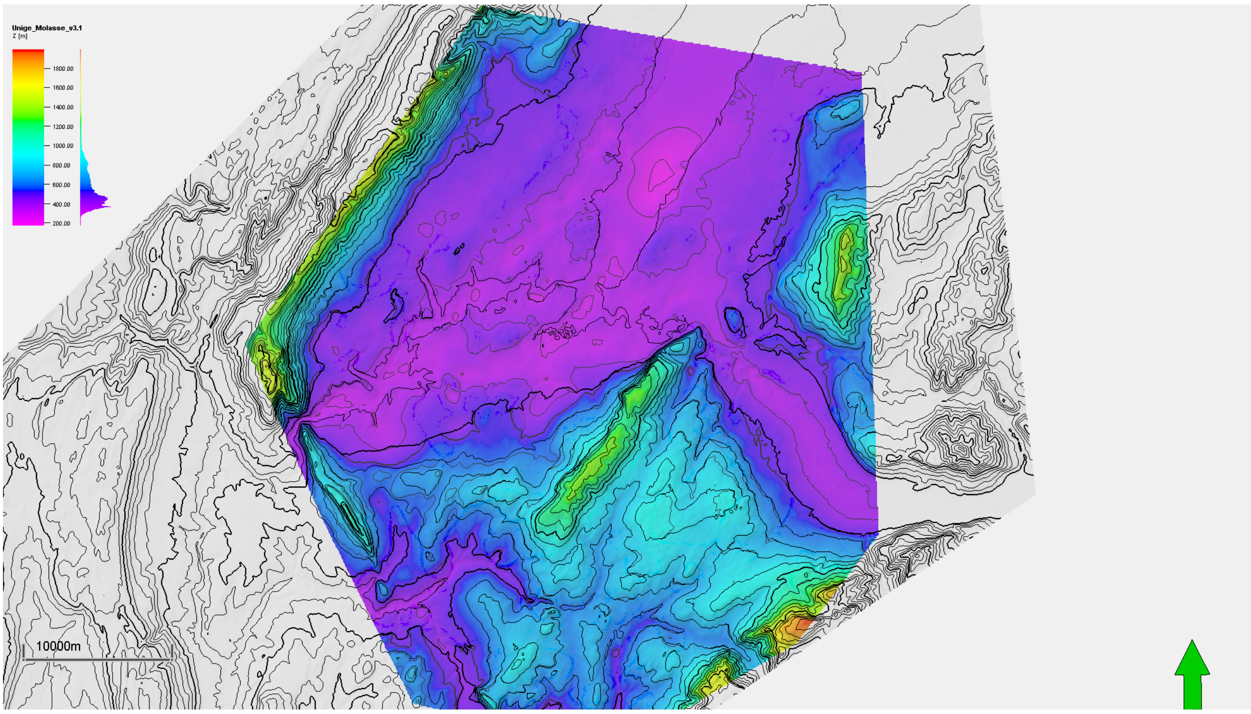

Figure 4. Top Molasse surface in the study area, generated from the subtraction of the thickness map to the DEM.

Surface data integration

Finally, this surface does not respect the information provided by geological maps in the area, meaning that Cretaceous and Molasse deposits are outcropping at the surface in the Jura mountains, the Salève and the Pre-Alpes. The thickness map reflects accurately the absence of Quaternary deposits within these areas, except for some local border effects due to the algorithm (e.g., the Jura foothills around Collonges area). This was corrected by removing the Top Molasse in accordance with geological maps (Fig. 5).

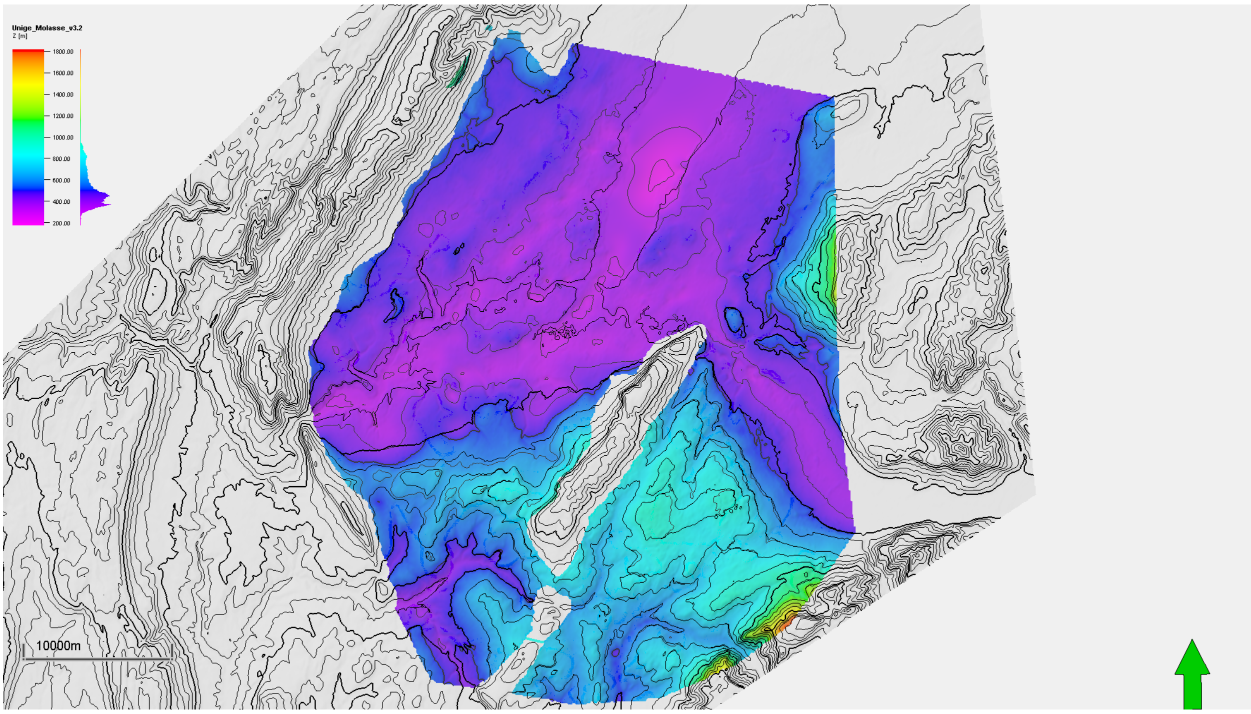

Figure 5. Final top Molasse surface generated from shallow, piezometric wells and surface outcroping data.

It should be noted that while the data density is very high in the Geneva area, it tends to drop rather drastically in the surrounding French area, as well as under the Leman Lake (Fig. 2), which means that the thickness of Quaternary deposits is estimated with acceptable accuracy within the Geneva area, but variations can be expected under the lake, as well as in sensitive areas, such as the Arve and Rhône valleys.

Top Cretaceous

The top Cretaceous surface is more complex that the top Molasse one, which is mostly due to the depth at which it is present and the fact that the wells reaching the Molasse-Cretaceous boundary are limited in numbers (Fig. 6). Therefore, for defining this surface we have relied on the seismic data present in the area. However, seismic data are in two-way-time, which means that seismic interpretations need to be converted back to depth using a velocity model. Therefore, the steps to modelling the top Cretaceous boundary are seismic well tie, generate the velocity model, seismic interpretations, time-depth conversion, structural framework modelling and finally surface generation.

Seismic well tie

Seismic well tie is a process by which the sonic and density well logs are used together with a synthetic wavelet to generate a synthetic seismic response along the well, this seismic response is then compared to a close by seismic trace of seismic line. This response can then be calibrated to match more accurately the seismic trace, thereby adapting the velocity along the well (Fig. 7). This process also allows the conversion of the well tops (stratigraphic boundaries along the well) in depth, which then is used to pick the correct seismic reflector during seismic interpretation. This process has been done for ten wells which have adequate data: Humilly-1, Humilly-2, Gex-1, Gex-3, Gex-4, Thonex-1, Geo-01, Geo-02, La Balme-1, and Mont de Boisy-1 (Fig. 8). It is important to note that none of those wells are located within the area south of les Usses and southeast of the Arve Valley, south of the Salève.

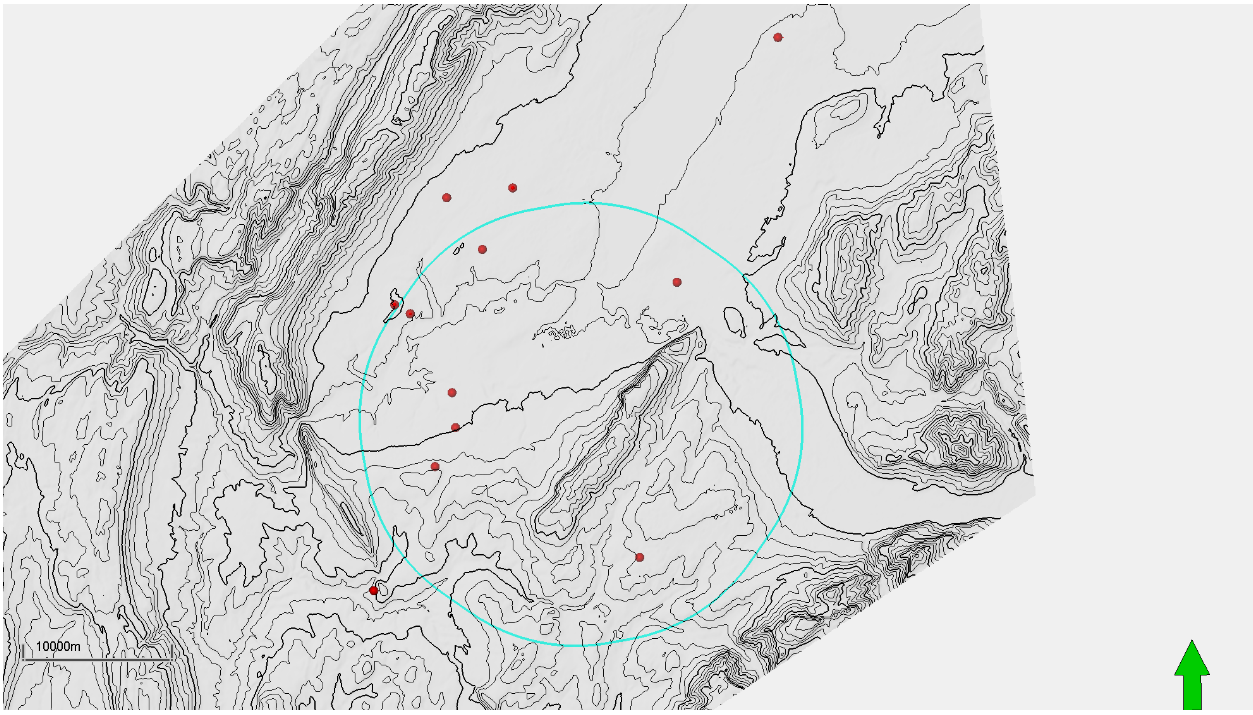

Figure 6. Top Cretaceous points within the deep wells database.

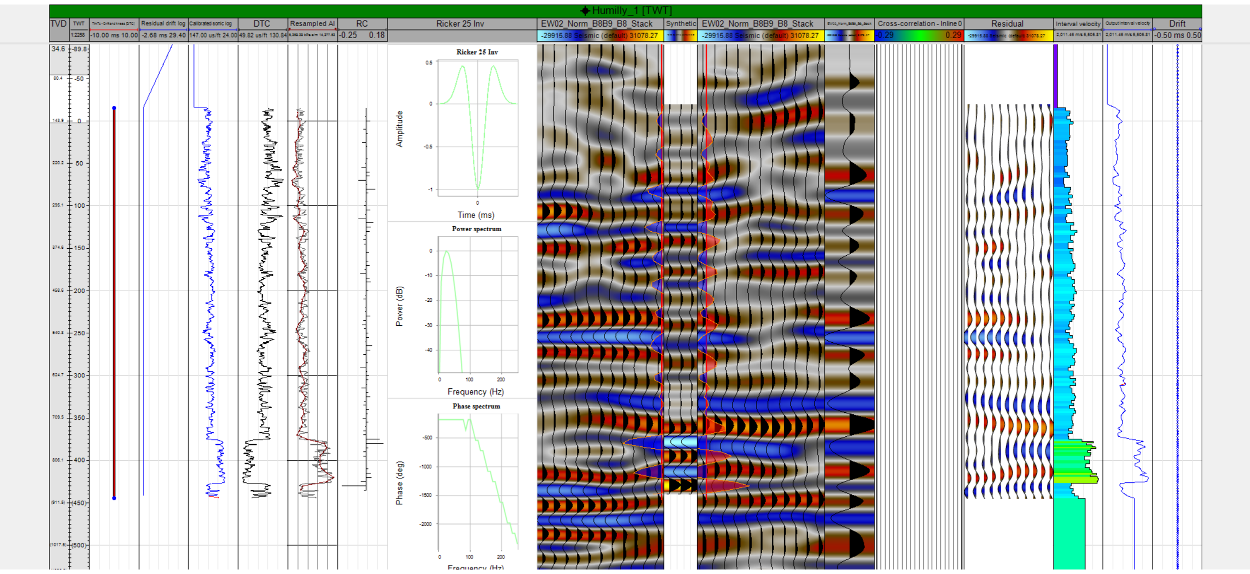

Figure 7. Example of the seismic well tie for Humilly - 1 well and EW02 seismic line using a Ricker 25Hz inverted wavelet.

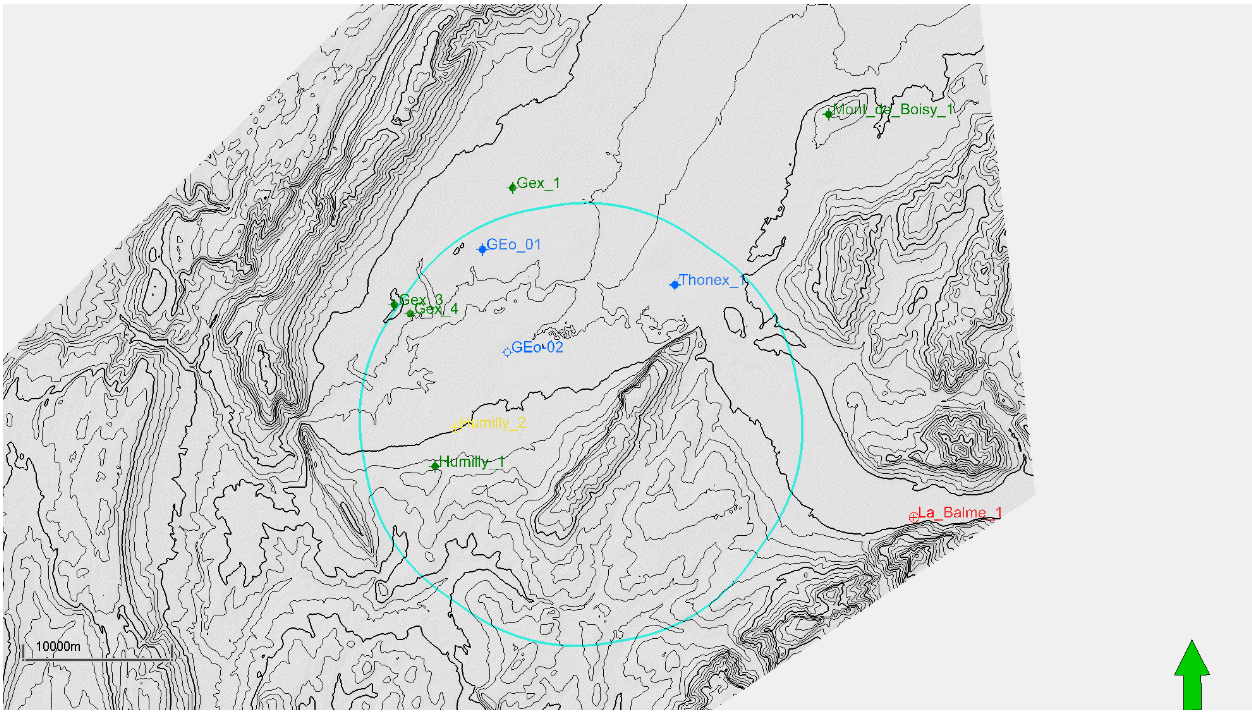

Figure 8. Wells used for the seismic well tie process.

Velocity model

The velocity model is a volume that spans from an arbitrary elevation above the ground down to the top Cretaceous, it assumes a constant velocity for the interval above the ground, which is equal to the replacement velocity, then every stratigraphic interval is considered as a homogeneous layer with an average velocity. This velocity can change spatially but is considered uniform along the vertical axis.
The replacement velocity is established at the creation of the project, it is used to set a seismic reference datum which is necessary when working with seismic data. Practically, it is used to correctly align the surface in depth and in two-way-time. In this study, the seismic reference datum is set at 500 m.a.s.l (meters above sea level) with a replacement velocity of 3000 m/s.

Quaternary deposits are composed of very heterogeneous rocks, including moraines, lacustrine muds, river sands, etc. which can vary significantly over short distances. However, those deposits are generally thin, as shown during the modelling of the top Molasse surface, it does not exceed 198 meters in thickness locally, and averages 24 meters in thickness. Therefore, although the variations in density within Quaternary deposits can greatly impact velocity, the limited thickness of the deposits will limit this effect significantly. From a practical perspective, mapping accurately the velocity within Quaternary deposits can improve the geological model, however, the efforts in data acquisition, interpretation and modelling are far outside the scope of this study. Thus, the approach taken is to average the velocity of Quaternary deposits over the entire study area.
To calculate the velocity within Quaternary deposits, a depth/velocity graph is used (Fig. 9). The graph clearly shows the trend of increasing velocity within Molasse deposits, which is interpreted as the effect of compaction, while limestone deposits are generally cemented and their density is not impacted significantly by compaction, thus they have a more uniform velocity. For the velocity of Quaternary deposits, an average of the velocity at 25 meters (average thickness of Quaternary deposits) is taken, which is roughly equivalent to 2200 m/s.

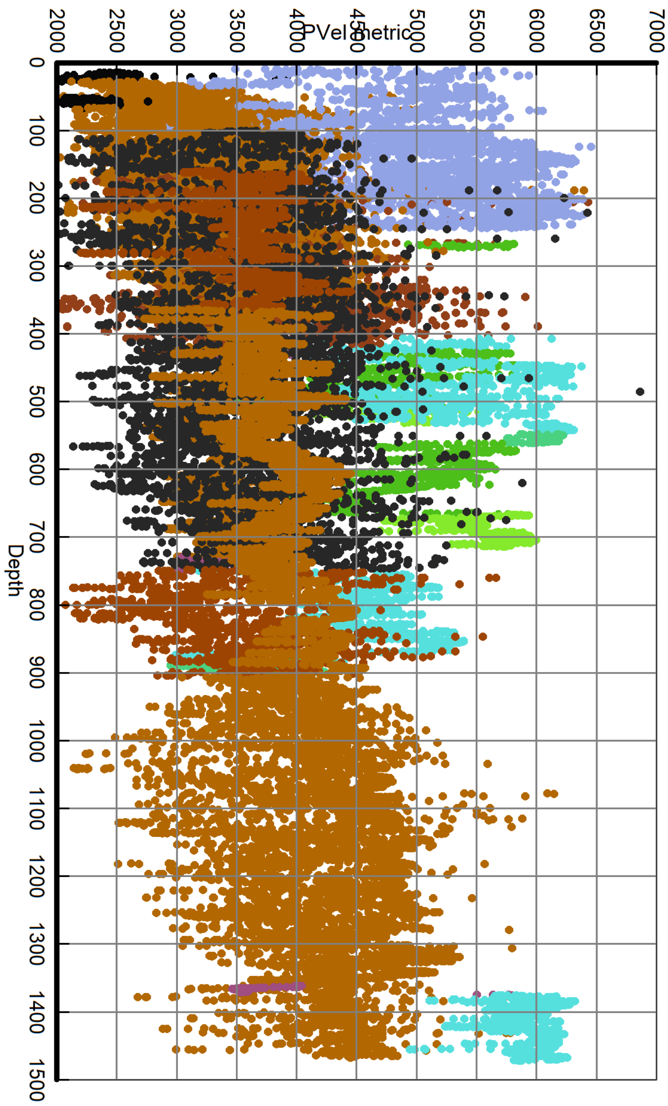

Figure 9. Depth velocity cross plot of wells within the study area, colors represent the different stratigraphic units, Quaternary and Molasse in black to brown, tertiary limestones in green, blue, and purple. It shows clearly that velocity is depth dependent within Molasse deposits, and relatively uniform in limestone units.

The Molasse velocity map is generated using the average velocity along each well within the Molasse interval combined with a simple convergent interpolation algorithm, which is often used with sparse data. The resulting velocity map (Fig. 10) represents the average velocity for Molasse deposits, as expected, it increases gradually towards the south and east of the study area, where the Molasse is the thickest. The low values towards the southwest (Vuache area) are relatively low compared to the one close to the Jura, where the thickness of the Molasse is relatively similar. This is mostly due to the lack of well within this area, however, as we can see on figure 9, the values are within a reasonable range, considering the probable thickness of the Molasse deposits.

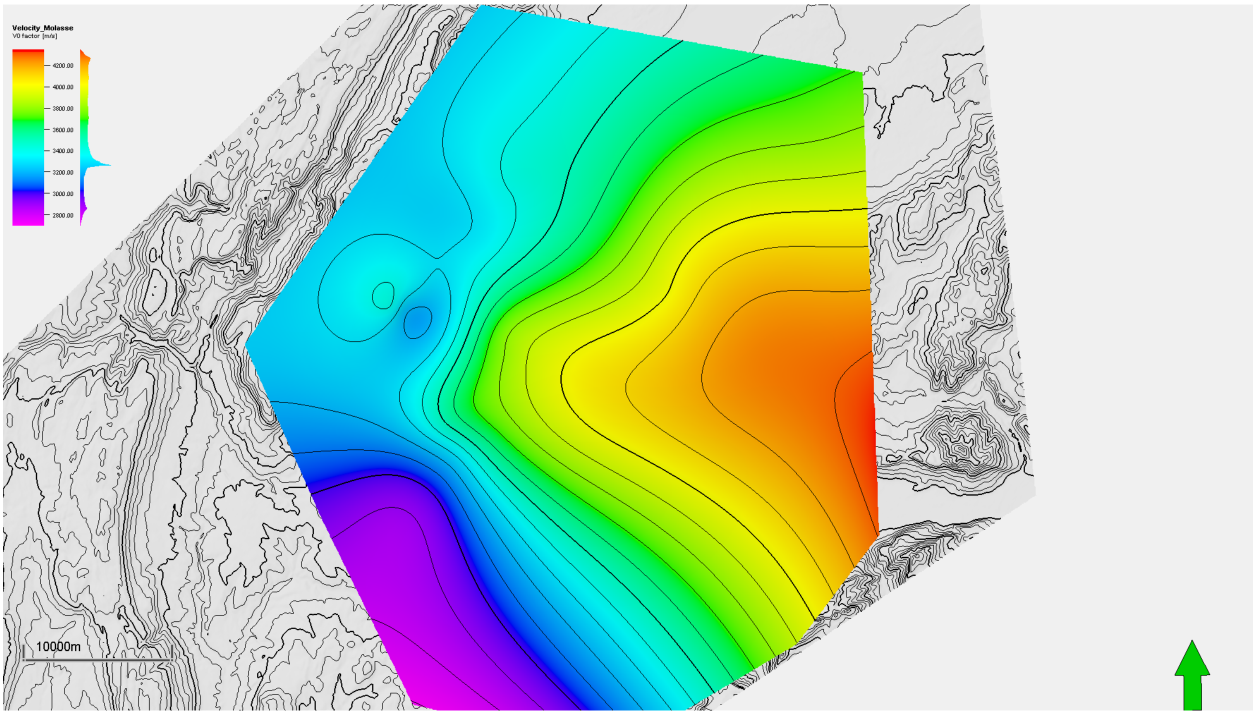

Figure 10. Molasse deposits velocity map

Seismic interpretations

Seismic lines are interpreted in two-way-time, using seismic well ties. First the seismic line on which seismic well tie was executed is interpreted, then this interpretation is propagated through lines intersections. However, as previously addressed, wells are sparse and not evenly distributed along seismic lines (Fig 11). Structural features such as faults impact the continuity of seismic reflectors, understanding the structural context of the modelling area is therefore necessary to propagate horizons accurately. However, faults with limited offset, and especially limited damage zone (which is manifested by a band of chaotic reflectors forming an area around the fault), have small impacts of horizon propagation. Although seismic lines south of the Salève are connected to Humilly-1 and Humilly-2 wells, there is a major thrust front at the base of the Salève and Mandallaz mountains, with a very important offset as well as a major chaotic zones of reflectors. Therefore, interpretations are challenging to propagate through the Salève (Fig. 12), which means that uncertainties rise substantially within the Plateau des Bornes area.

Before starting the interpretation process, seismic lines where selected to better suit the needs of this study, which means that lines that are outside the study area as well as restricted to the center of Geneva where dismissed (Fig. 13). After this step the interpretation was carried out on all seismic lines. Notably, a thorough review of the interpretation of the structural features was carried out by Dr. F. Mondino, a senior structural geologist with extensive knowledge of the Geneva Basin. Faults were interpreted based on seismic interpretation as well as digital model elevation, which is often used to visualize fault expression at the surface as well as their general orientation, which is a useful tool for fault correlations.
It is important to note that while many faults can be interpreted on a single seismic line, to be able to integrate them properly into a 3D geological model (i.e. their extent and orientation is accurate), faults need to be correlated between at least two seismic lines. This poses a greater challenge during the interpretation process especially in areas with widely sparse 2D lines. In addition, the structural interpretation work carried out in this project was only focusing on the general surroundings of potential FCC alignments, with particularly detailed interpretation in the direct vicinity of the tunnel (e.g., faults

interpreted along the alignment on the left-hand side of figure 14). Additionally, interpreted faults were categorized either as low, medium, or high confidence, depending on their seismic expression and correlatability.

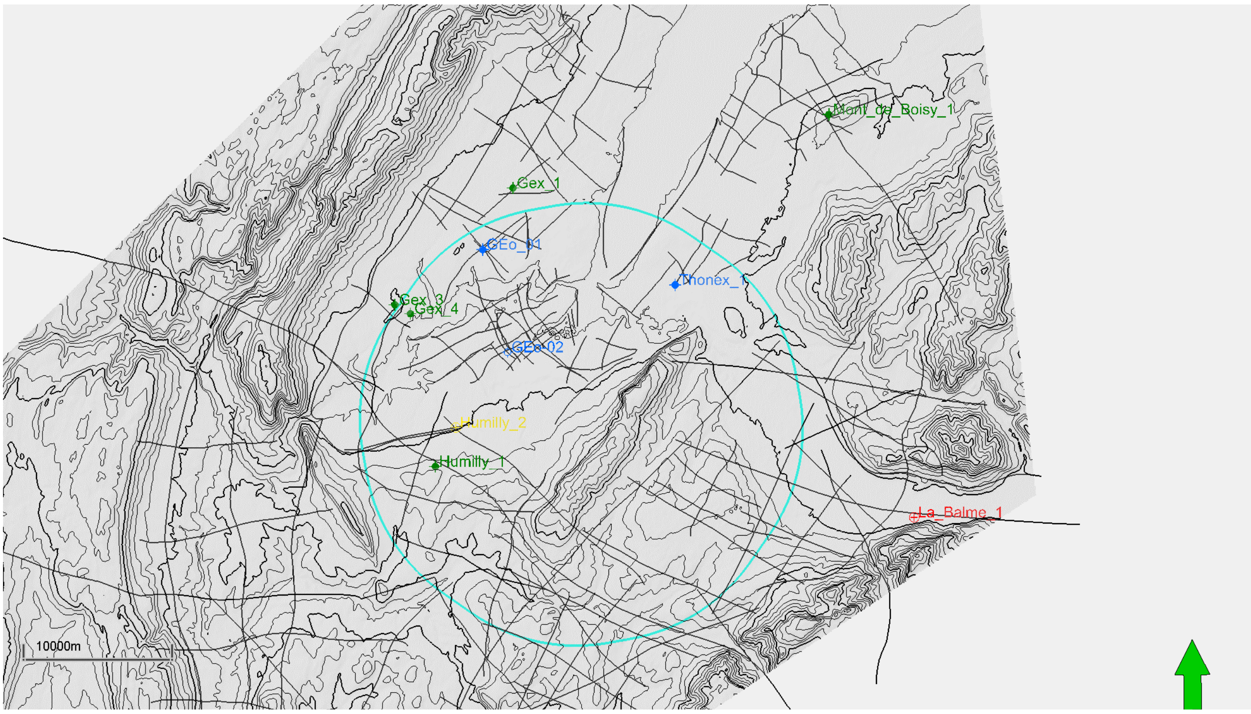

Figure 11. Available seismic lines within the Geneva basin (black lines) with well used for seismic well ties

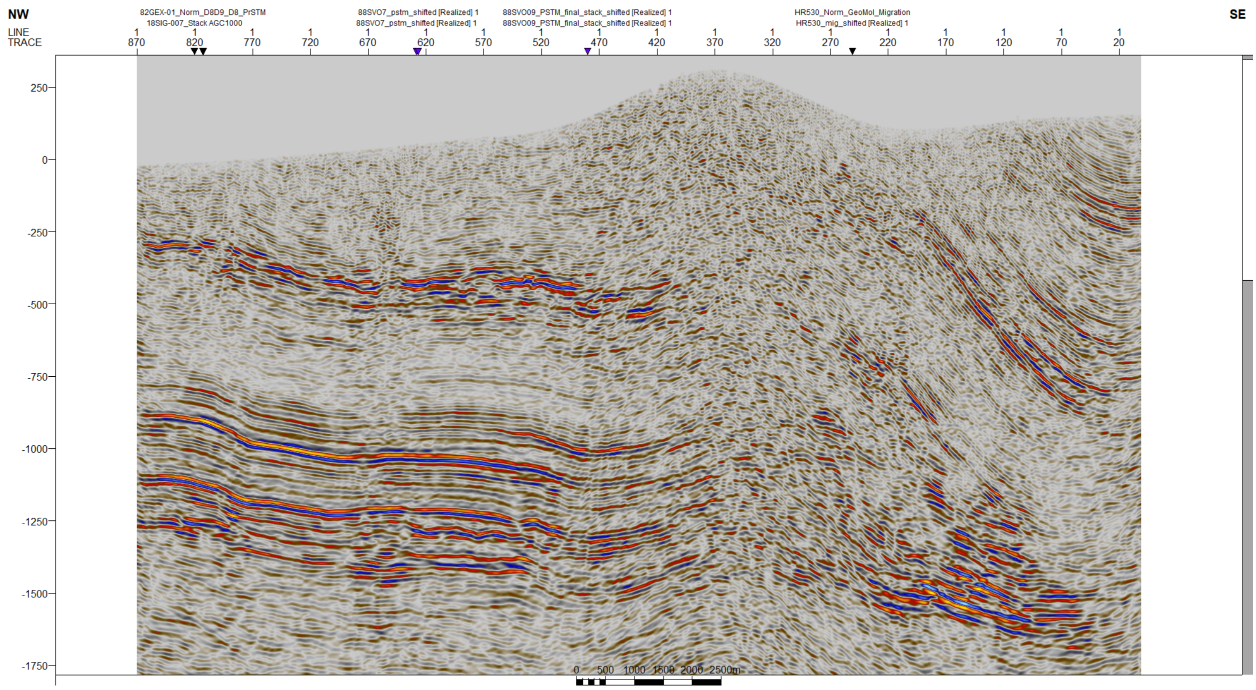

Figure 12. Example of a seismic line crossing the Salève (88SV-07) showing the large chaotic zone created by the Salève structural features

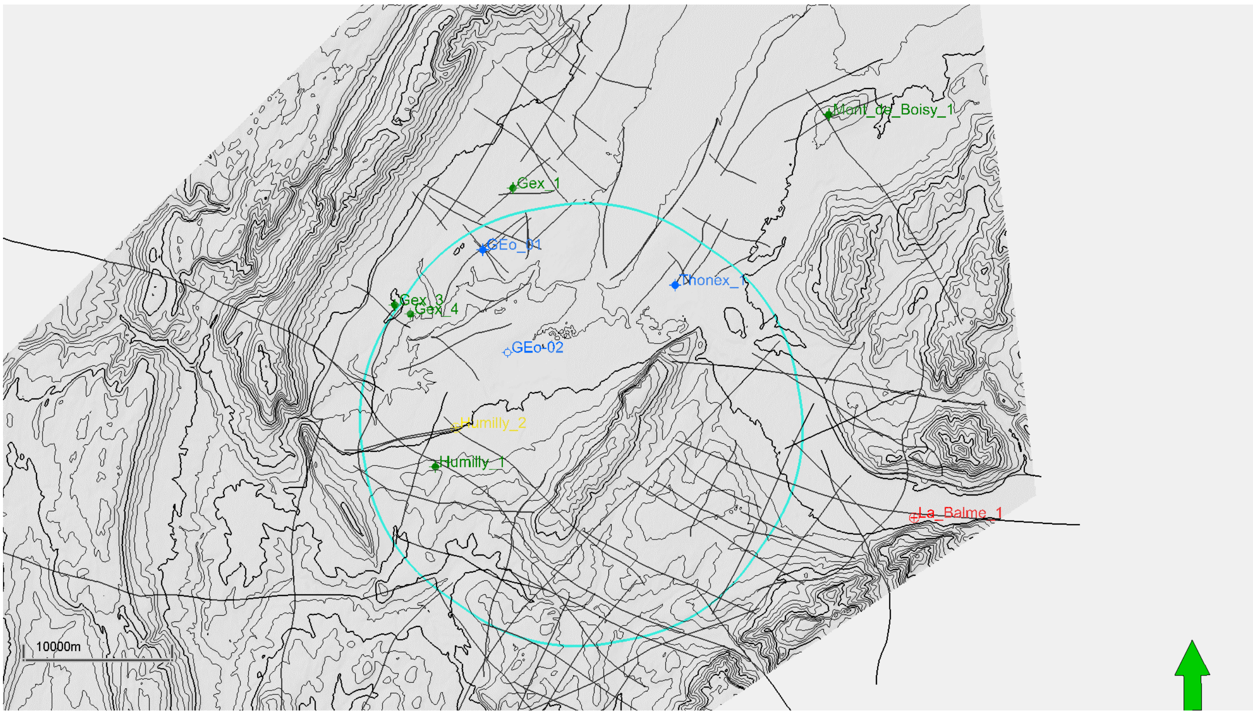

Figure 13. Seismic selected for the purpose of this study

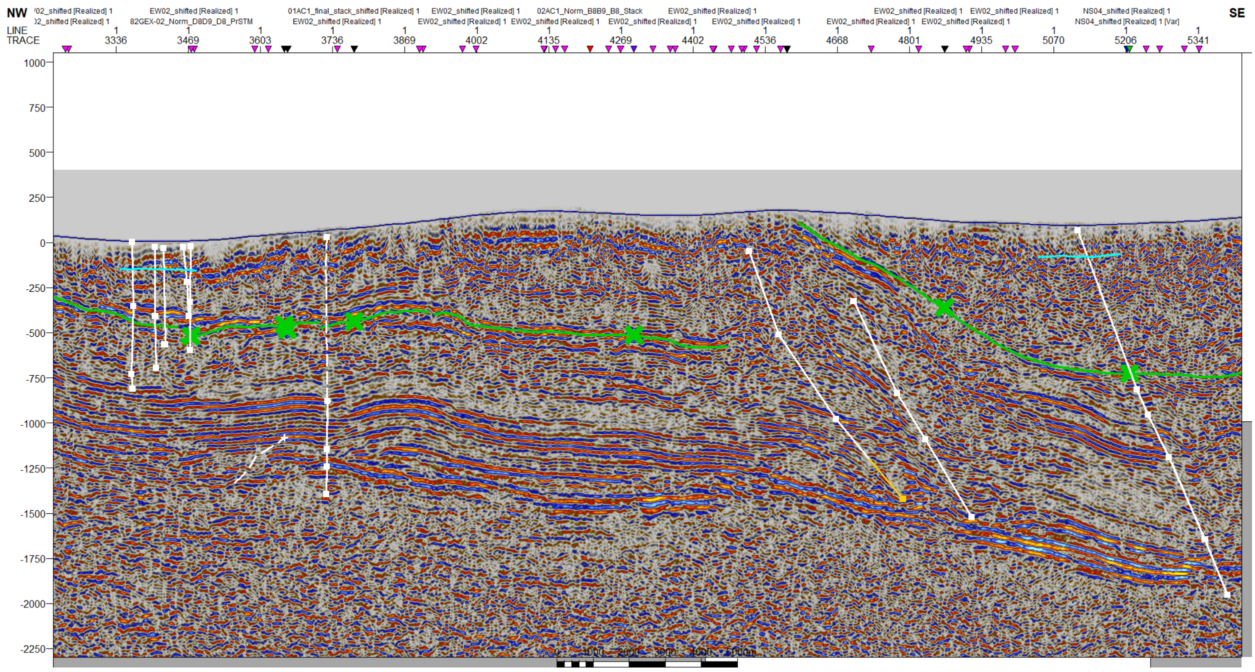

Figure 14. Interpreted seismic line (EW02) between the Salève and Mandallaz mountains, with top Cretaceous horizon (green line), intersecting seismic lines (green crosses), interpreted faults (white lines) and approximate path of the FCC 3.1.10 alignment in two-way-time (light blue)

Time-depth conversion

Commonly, time-depth conversion is performed after surfaces and faults have been modelled, however, in a structurally complex settings such as the one in this study, surface modelling is performed using a volume-based modelling (VBM) approach. The major advantage for using VBM is that it allows the modelling seamlessly overlapping surfaces as well as faults offsets. Using conventional modelling techniques surfaces cannot be complex, meaning that only z value is possible for each xy coordinates, which forces to model separately each sector of the study area where overlap of surfaces is possible. However, the drawback to using VBM is that time-depth conversion cannot be done after the modelling step. Therefore, inputs need to be converted before modelling. However, a velocity model requires a top and bottom surface for each velocity interval which results in a kind of “snake biting its own tail” situation. The most practical and efficient method is thus to first generate a good approximation of the top Cretaceous horizon, but that does not consider overlaps, then seismic interpretations are converted from time to depth and the VBM process can take place.

Since the parameters for the velocity model were generated early during this study, once the first top Cretaceous horizon is generated, input data for the VBM modelling can be converted from time to depth.

Structural framework modelling

Structural framework modelling is the process by which fault planes are generated using the structural interpretation of seismic data. Fault surfaces typically develop in preferential directions according to the stress field, which can change over time and change according to local constraints. Therefore, multiple generations with generally two dominant directions of faults can develop. In addition, the alpine thrust leads to large thrust fronts development (e.g., Salève and Mandallaz mountains). All those structural phenomenon leads to fault cross cutting each other, while faults are a natural zone of weakness and new stress field will often utilize pre-existing faults, new ones can develop and offset pre-existing faults. All this means that faults cross cutting happens in succession and that in the subsurface fault planes cross cutting each other will lead to fault offset. Thus, once fault planes are created, all intersections between those need to be handled to be in accordance with faults hierarchy and their logical, successive development (Fig. 15). The way these faults intersections are handled is by deciding the major-minor relationship (which fault offset the other) as well as if the minor is truncated above or below the major, this needs to be parameterized for each fault pairs.

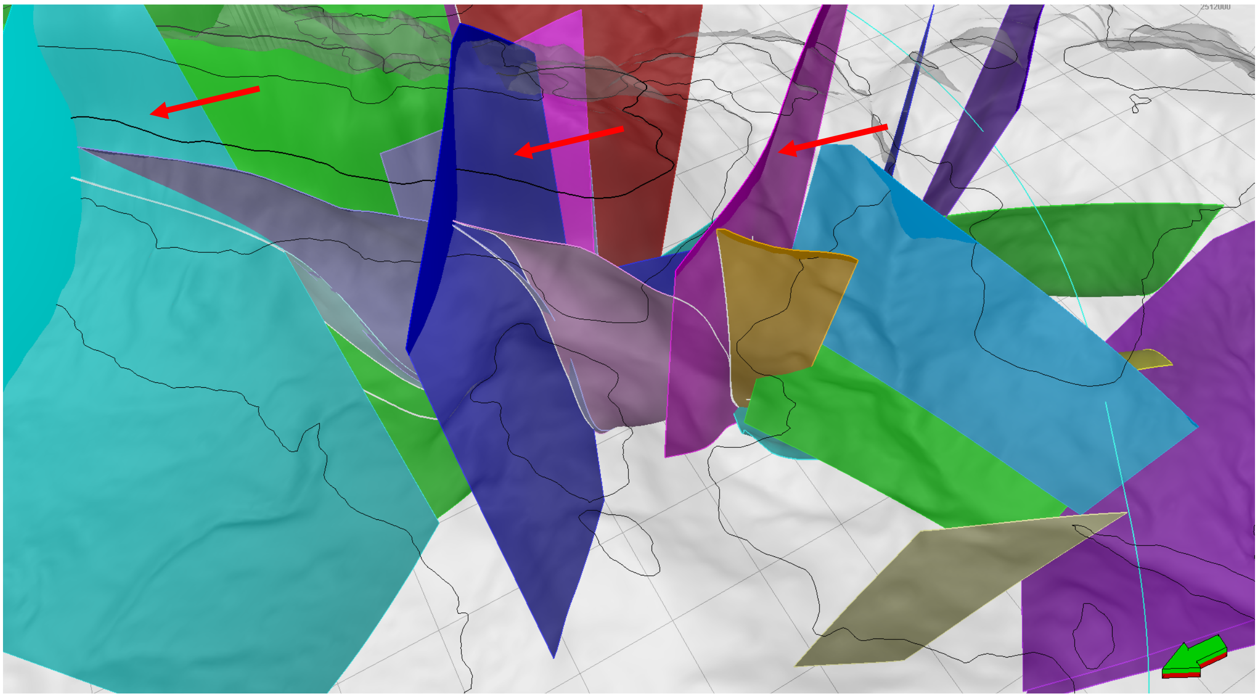

Figure 15. Salève frontal thrust offset by successive, roughly aligned, transpressive faults (pointed by red arrows). The model is under 5x vertical exaggeration. Lower right green arrow indicates North direction.

Top Cretaceous surface modelling

Once all the data is set up and converted to depth, the volume-based modelling process can be done. Importantly, as for the top Molasse surface modelling, surface geological information where added to the inputs It requires multiple steps including creating a tetrahedral mesh and a stratigraphic function. The tetrahedral mesh includes the model boundaries, faults, and unconformities, it functions as the volume for further properties modelling and its resolution can vary spatially depending on data density and architecture complexity. The stratigraphic function is computed from the fault framework and the horizon interpretation. The structural model horizons are extracted as iso-values of the stratigraphic function (meaning that one horizon is considered as deposited at the same point in time over its entire extent), then the stratigraphic function extends evenly between horizons (Fig. 16). The stratigraphic function includes faults geometry and offset by considering the horizon throw along a fault and diminishing to null towards the tips (termination) of the fault and allowing for discontinuities through the fault.

The outcome of the volume-based modelling VBM, for the purpose of this study, is to create a tetrahedral mesh of the top Cretaceous boundary (Fig. 17). However, this type of surfaces is not accepted by conventional GIS software (ArcGIS, QGIS, etc.), thus it was separated into two partially overlapping surfaces in an acceptable format, one south to southeast of the Salève Mountain, the other covering the rest of the study area.

The outcome of this modelling study is a series of transects along FCC alignments displaying the surface, top Molasse and top Cretaceous surfaces as well as modelled faults. This tool can be used to assess with accuracy the zone of geological risks related to proximity with Cretaceous or Quaternary deposits, or faults (Fig. 18).

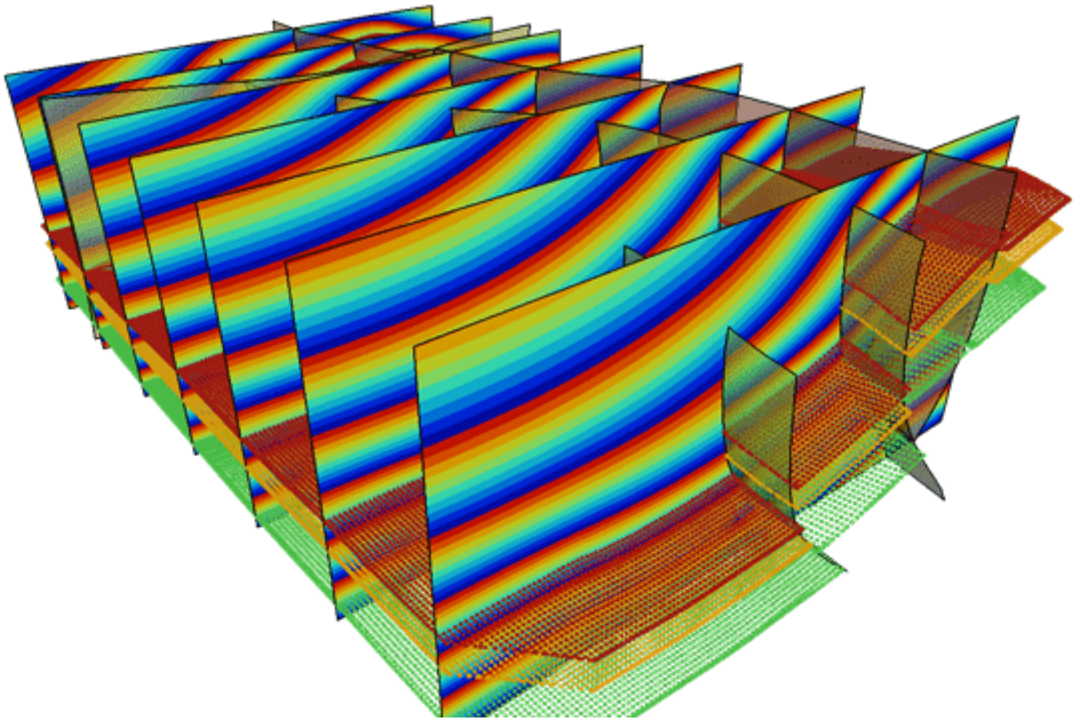

Figure 16. Stratigraphic function example in sliced view with model faults and horizons.

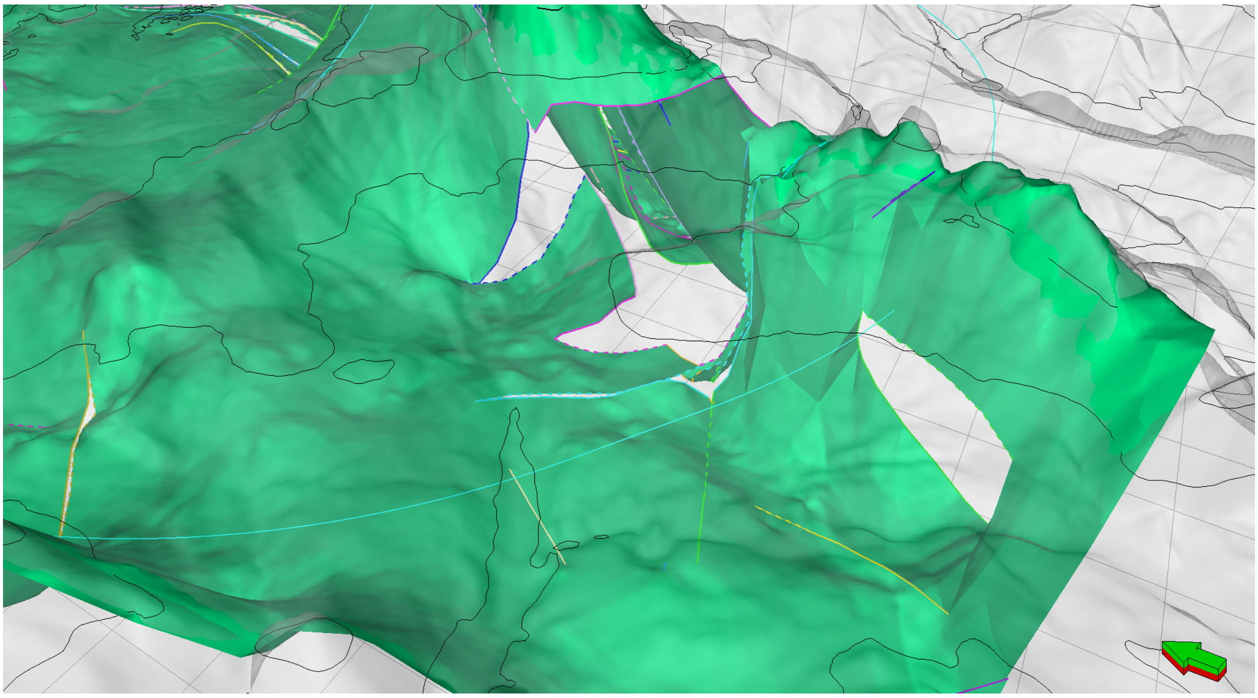

Figure 17. Top Cretaceous tetrahedral mesh generated by volume-based modelling in the Mondallaz mountain area.

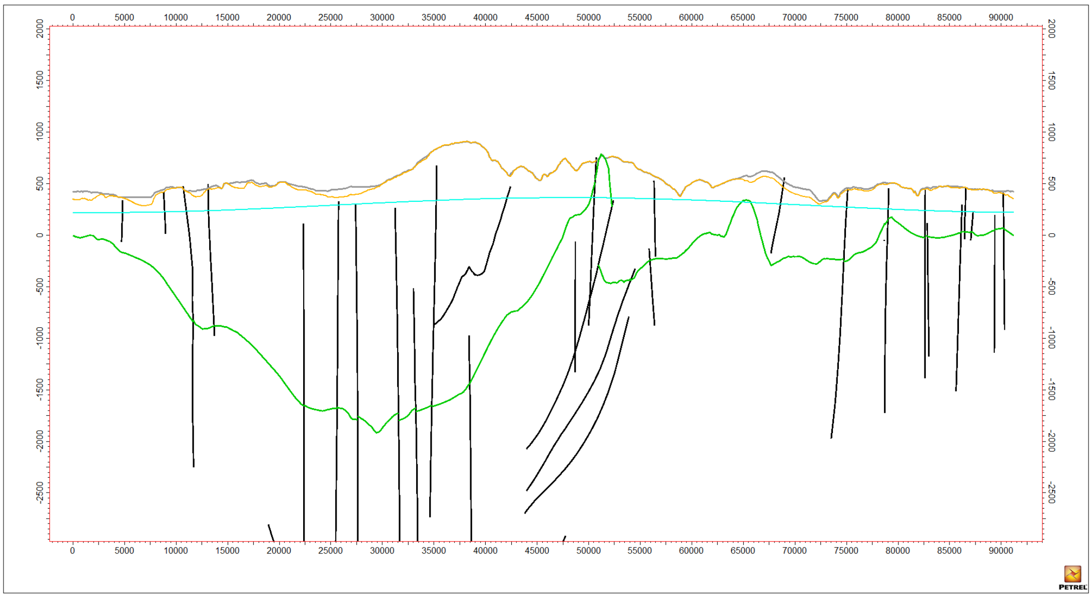

Figure 18. Cross section along FCC 3.1.10 alignment (light blue), DEM (dark grey), top Molasse (orange), top Cretaceous (green) and faults (black lines).

Conclusions

- The 3D geological model to date provides a **solid knowledge framework** based on all available data known to date, highlighting the different lithological and structural heterogeneities crossed by the planned trace of the FCC tunnel.
- The model allows the **visualisation of the subsurface conditions** known to date in the areas of high geological uncertainty identified **enabling to take informed decisions during the forthcoming geotechnical and seismic investigation campaign** which will take place across the French and Swiss territory.
- The model constitute a tool which will be used during the investigation and excavation phase especially to provide guidance to avoid undesired encounters of geological challenging features (karst) and subsurface fluids (i.e. over-pressured water, HC).
- Following each investigation campaign, the geological 3D model will be updated with the new acquired data and will therefore provide more accurate view of the subsurface.
- This 3D model represents therefore a practical working tool which will support the FCC project throughout the different phases of tunnelling design, planning and execution.

References

Clerc, N. and Moscariello, A., 2020. A revised structural framework for the Geneva Basin and the neighboring France region as revealed from 2D seismic data: implications for geothermal exploration. Swiss Bull. Angew. Geol., Vol. 25/1+2, 109-131.

Haas M., Carraro D., Ventra D., Plötze M., De Haller A., Moscariello A. 2022. Integrated geo-engineering characterisation for CERN's Future Circular Collider subsurface infrastructure (Geneva Basin, Switzerland-France) from well-log, field and laboratory data. Swiss J Geosci, in press SJGE-D-21-00030.

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