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Seismic and Well Logging as Key Elements for the Subsurface Evaluation of Geothermal Projects - Examples from the Canton of Geneva

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1 Introduction

As part of its project «GEothermie 2020», the canton of Geneva under the operatorship of SIG has accelerated its evaluation for potential geoenergy opportunities. This requires a detailed mapping of the structural elements in the subsurface, to reflect the dips of the formation, faults and fractures. Previous drilling results from the area have shown that the encountered formations have insufficient matrix permeability for economic geothermal opportunities in the Mesozoic. Sufficient flow rates can only be obtained if an open fracture network is established. There is a high chance that such features can be found near faults or fault zones.

In this context, 86 km of 2D seismic data were acquired in the fourth quarter of 2018. In preparation for this data acquisition, the existing vintage data were evaluated with respect of the acquisition parameters and to achieved satisfying data quality. In that framework, some lines were reprocessed. This approach provided the base for an optimized parametrization of 2018 acquisition campaign, while allowing the development of optimized processing workflows.

The 2D seismic data already brought a great insight of the deep geology in the targeted region. Additionally, a 3D seismic acquisition planned for summer 2020, will significantly reduce the uncertainties regarding seismic interpretation, especially for faults detection and positioning. For this 3D survey, a similar parameter optimization was performed to ensure the data quality for the target zones, but also considering the survey footprint in the environment and the associated costs.

Fractures and faults can be evaluated at a smaller scale using conventional well logging and state of the arts image logs. This has been successfully achieved on the latest well borehole GEo-1 (2018, TD at 744 mMD) in Meyrin-Satigny (Geneva Canton).

The combination of high resolution well information with the seismic images will provide a model of the subsurface over a large area. Within this model a portfolio of geothermal energy opportunities can be established and subsequently matured for implementation.

2 Seismic data acquisition, from 2D to 3D data

Seismic acquisition in the Geneva basin has started with oil exploration (BP-France) in neighboring France in the 1980's (well Humilly-02, and Gex-1 to Gex-6 wells). However, it was for geothermal prospection that the canton of Geneva ordered the GG87 lines in 1987. Following this direction, SIG decided to explore the Geneva underground for gas and

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geothermal energy, by acquiring the 900X lines in 1990 which led to the first deep exploration well in the Canton: Thonex-01. Since the 2010's SIG has re-launched its exploration and acquired many lines in collaboration with local contractors Geo2X and Geoexperts. During these decades, UNIGE has been a great contributor and has helped compiling knowledge derived from these seismic lines. It was crucial to maintain this data; this has been done by Geo2x, HGE, GGE, or BRGM for the French neighboring lines. This data storage and maintenance will be centralized by the «Service de géologie, sols et déchêts de Genève (GESDEC)».

The multiple seismic vintages acquired by different contractors, led to a heterogeneous seismic database in terms of acquisition parameters (Fig. 1). Hence, the seismic resolution can be quite different from a family of lines to another. It is mainly controlled by the source types (Fig. 2). Indeed, weight drop technique or mini-vibro will have a shallower resolution than one or two 20t vibros. For that reason, it was important to adapt the source type to the specific depth targets for the 2018 seismic acquisition. Therefore, it was decided that one weight drop truck will be used for Quaternary lines only and one Vibrator 20t for illumination of Quaternary to Paleozoic units («Mesozoic lines»). Short source-receiver offsets, dense seismic source and appropriate receiver intervals were needed to image the near-surface geology, 0-300 ms. The resulting CMP spacing are 2.5 m and 6 m for the Quaternary and Mesozoic lines, respectively.

3 Seismic data processing and valorization of vintage data

The pre-existing seismic data needs to be valorized, homogenized and normalized. To do so, a reprocessing using the same imaging computation sequence for all the lines (except GG87 lines because no raw seismic tapes could be retrieved) was achieved by DMT with the supervision of GGE. This reprocessing was adapted for three targets, the Mesozoic interval, and when possible for the Quaternary and shallow gas. Indeed, it is not possible to obtain one image that constrains focused information for all three targets (Fig. 3). Hence, three seismic versions were produced. With this approach, we increased the resolution of each target in comparison with the original processing. The improvements in image quality for the Mesozoic originate from the latest processing algorithm namely CRS stacking or shallow layer tomography and statics corrections. PostSTM algorithm has proved to be the most efficient migration tool. PreSTM was also tested but did not show significant improvements. Regarding the processing performed for the Quaternary objectives, PostSTM solution was also chosen, but only after applying an elevation statics correction. As the lines processed specifically for Quaternary are only used to interpret this layer, velocity push-down artefacts in the layers below were not considered. Another important part of the processing was to select the adequate velocities for the low velocity Quaternary layer (800-2200 m/s for the first 0-0.2 s). To this aim, we tested 15 constant velocity models. The processing was performed by DMT, with geological/geophysical supervision of GGE. This approach allowed incorporating additional geophysical and geological expertise in the iterative processing and a quality assurance in line with the required tasks. Some shallow gas anomalies were also noticed on certain lines which match hydrocarbon indications of shallow boreholes. A specific processing workflow has provided enhanced images to predict the shallow gas occurrences. During this reprocessing, and for all the lines, it was also important to apply for a given target the same seismic reference datum and replacement velocities in order to facilitate the time-depth conversion (for the resulting interpretation).

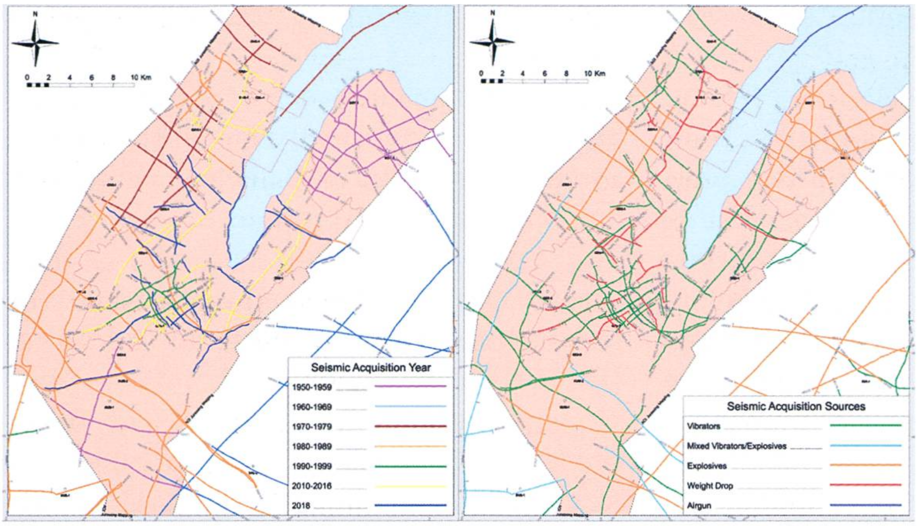


Fig. 1: Map showing the seismic lines. Colorscales show source types (right) and year of acquisition (left).

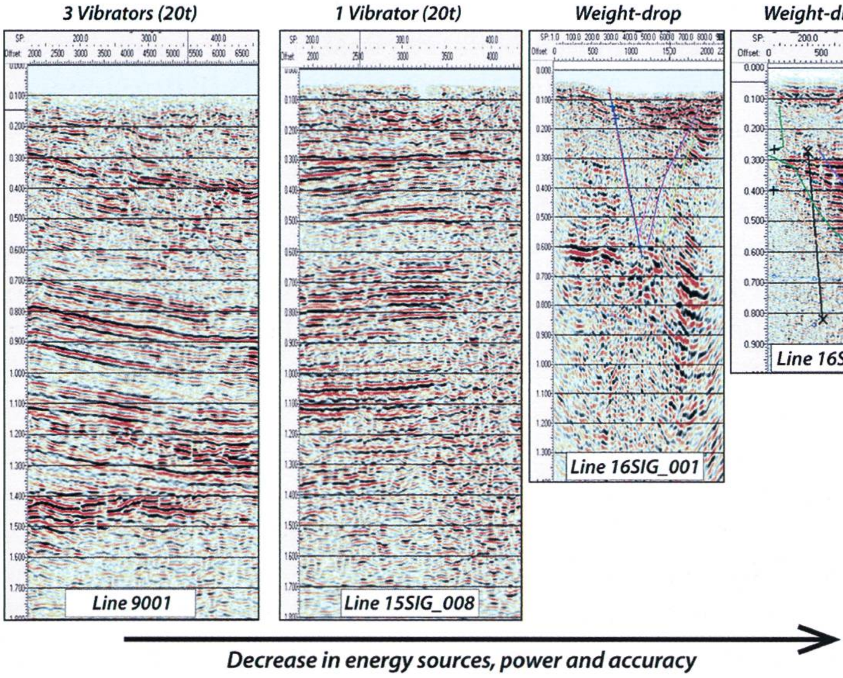


Fig. 2: Energy penetration of different acquisition schemes as a result of selected seismic sources.

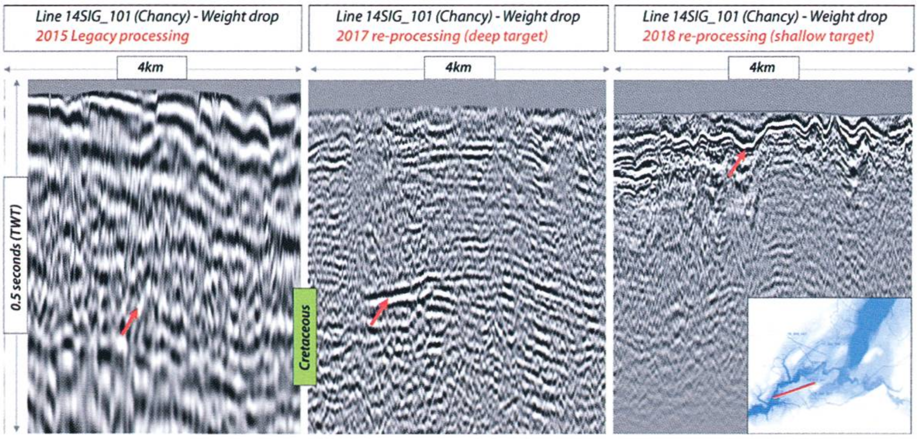


Fig. 3: Same seismic data that require different processing approach for various objective. This line was reprocessed again in 2018 with focus on the shallow (Quaternary) imaging. With the resulting level of details, quaternary infill and top Molasse can be reliably interpreted. Arrows in left and middle pictures show top Cretaceous and the arrow in the right-hand side picture shows top Molasse.

4 Seismic interpretation

The interpretation of the Quaternary seismic profiles has shown promising results. Some of the lines allow the characterization of internal architectural elements and seismic facies (Fig. 4). However, well data and surface data are needed in order to precisely link these seismic facies with Quaternary units. Direct well ties or analogues suggest for example, that the «alluvion ancienne» (characterized as «sandur») was deposited during the retreat of the glacier and correspond to very clear high amplitude reflections and low frequencies. The main benefit of these Quaternary seismic lines is to update the Base Quaternary Grid which, in the past, was only based on well data interpolation. It also brings crucial information on the vertical geometry of the Base Quaternary surface, especially on the flanks. Additionally, it gives a better insight on the different units of the Quaternary and their lateral and vertical extensions using mainly the seismic facies analysis (Fig. 4). The aim of the Quaternary interpretation in Geneva is primarily to get hydrological information on the various nappes (Geneva main source of water) and reliable Quaternary velocity model that will be useful for the future 3D seismic acquisition and processing.

The seismic lines focused on Mesozoic intervals have revealed new tectonic features (Fig. 5) and reduced uncertainties of previously interpreted structures. The development of «shallow» SW-NE thrust-related structures is attributed to several detachments' levels that include marls in the lower part of the Malm (and/in the Cretaceous interval) and the main Triassic (Keuper Group) decollement level of the Western Swiss Molasse Basin. The resolution of many of the seismic lines is high enough to show Permo-Carboniferous grabens indications. The major NW-SE strike-slip faults in the Mesozoic cover linking the Jura Mountains and the frontal Penninic thrust are going to be explored in more details, particularly considering their complex along strike geometries. The kinematics of the basin and the differential subsidence which

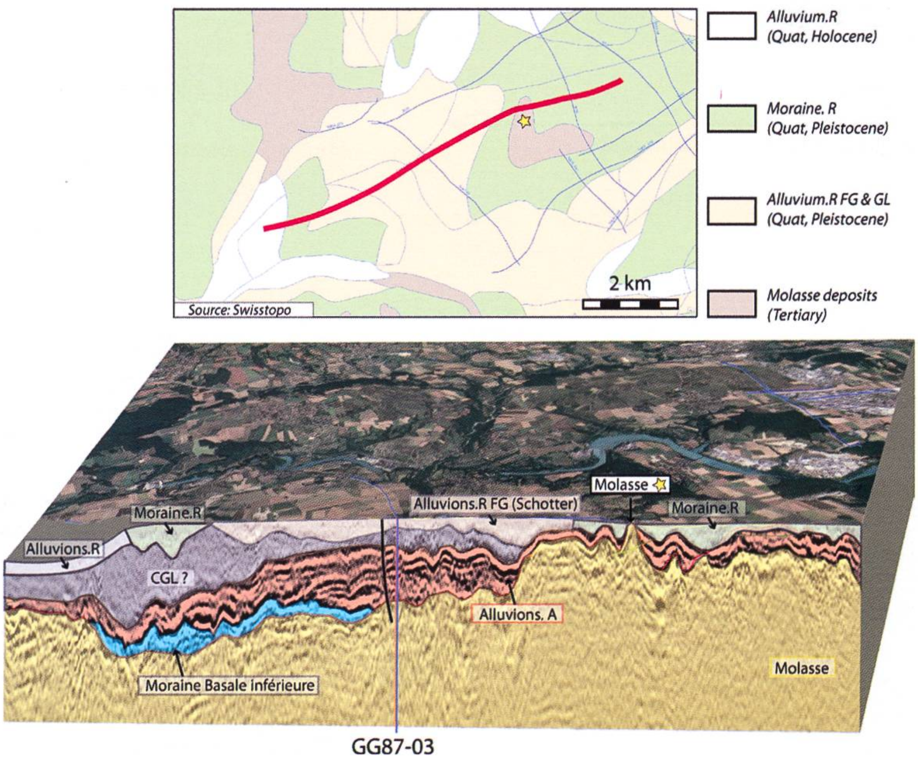


Fig. 4: Example of Quaternary seismic interpretation in relation to the surface geological information.

is potentially linked with faults will also be investigated. It will be achieved mainly using thickness maps of Mesozoic sediments (Triassic and Jurassic) in relation to Paleozoic grabens or basements highs. Balanced cross-sections will subsequently help obtain a better understanding of the tectonic development.

5 Planned 3D survey

SIG has planned a 3D seismic acquisition over the major part of the Geneva Canton for summer 2020. Although the actual density of 2D seismic data is significant, there are uncertainties on the position of the 2D fault interpolation and detailed facies map can't be constrained. This is related to the data quality and in particular to the imprecise lateral positioning of the subsurface within the 2D lines.

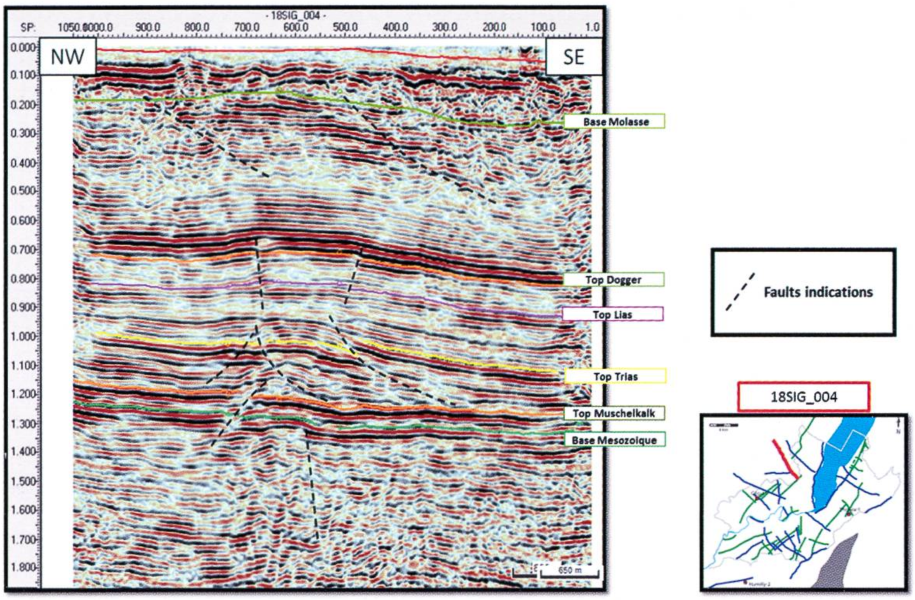


Fig. 5: Example of seismic interpretation of a recently acquired 2018 2D seismic lines with the main Mesozoic horizons and potential faults indications (dashed black lines).

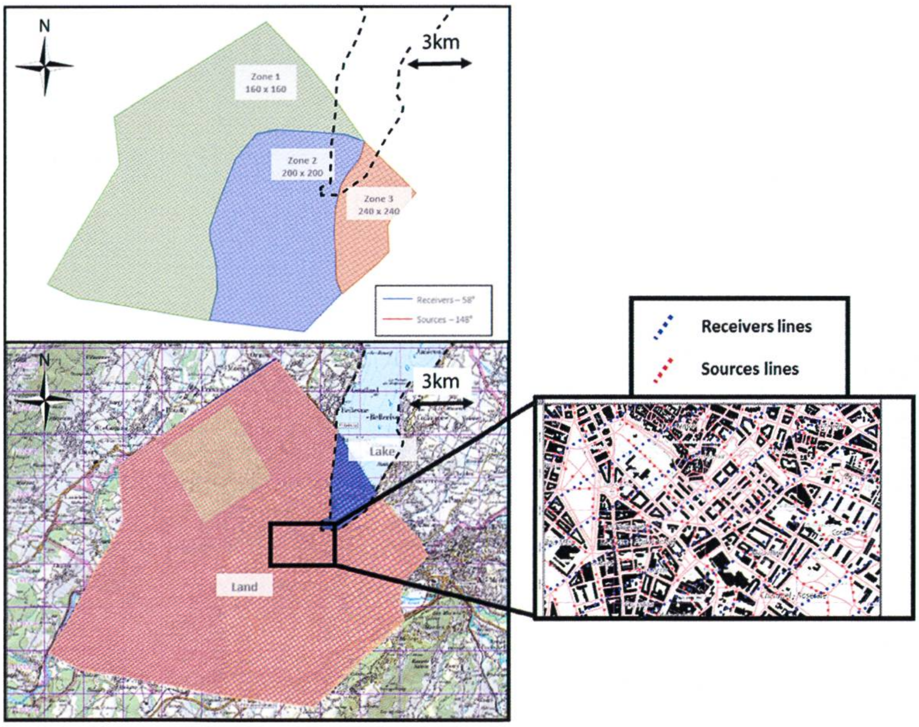


Fig. 6: On the left part, the proposed 3D seismic survey design with notional parameters. On the right part, the very dense acqusition grid that will tackle all the subsequent surface issues for seismic sources.

Hence, 3D data is the only method that would allow picking up all the small lateral heterogeneities and considerably reduce the uncertainties related to faults positioning. Seismic facies maps will help understand the lateral developments of the stratigraphic units over the basin by identifying potential reef extensions in the Jurassic (a potential reservoir interval for hot water with high matrix permeability). The density of the acquisition grid scheme needs to be adapted to the depth of the target levels (Fig. 6). The shallow depth of the top Mesozoic in the NW requires a dense (160x160 m) source and receiver line distance scheme. In the SW, this scheme can be extended to 240x240 m while maintaining the same stacking fold to ensure good image quality at top Mesozoic. Moreover, the acquisition in the city center will be challenging as the grid has to be deployed in a dense urban area.

6 Log data

The seismic images have good spatial coverage but low vertical resolution and cannot give any information about petrophysical properties such as porosity or permeability. On the contrary, cores have very high resolution but usually have a very limited coverage along the borehole. This is where the log data

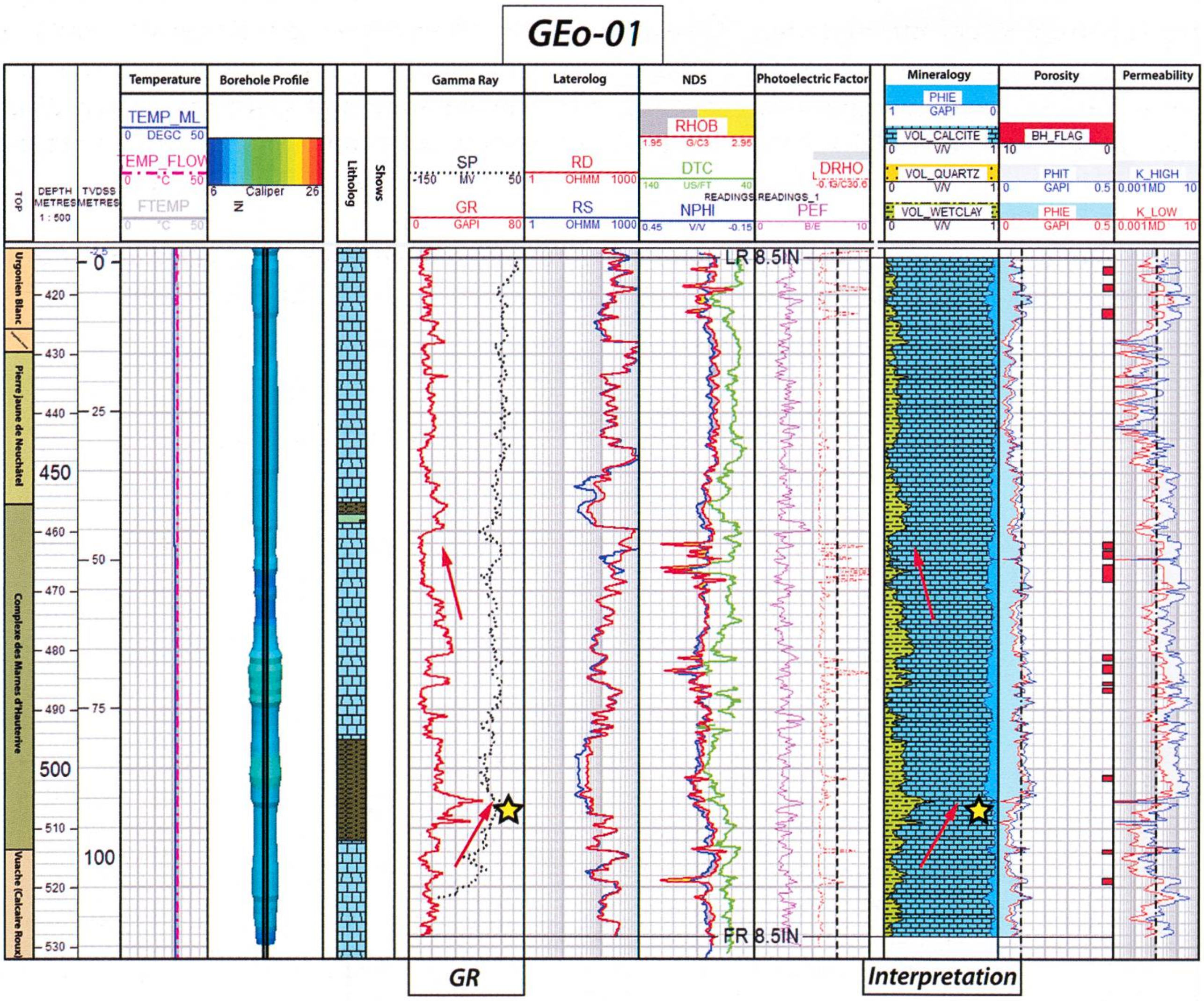


Fig. 7: Log data measurement on a certain interval GEo-01 (2018). Yellow stars correspond to increase in gamma ray values interpreted as increase in clay content. Reduction of effective matrix porosity is also interpreted over the same interval.

is advantageous, lying between seismic data, cuttings and core data. In the Geneva area, logging acquisitions strongly vary depending on wells and sections. In GEo-1, the static conventional logs were recorded (Fig. 7):

- Caliper Geometric properties of the borehole (diameter, deviation, and azimuth)
- Natural radioactivity of the rock (uranium, thorium and potassium content).
- Formation conductivity.
- Spontaneous potential.
- Slowness of acoustic waves in the formation.
- Bulk density & photoelectrical factor.
- Neutron hydrogen index.
- Acoustic and optical image logs.

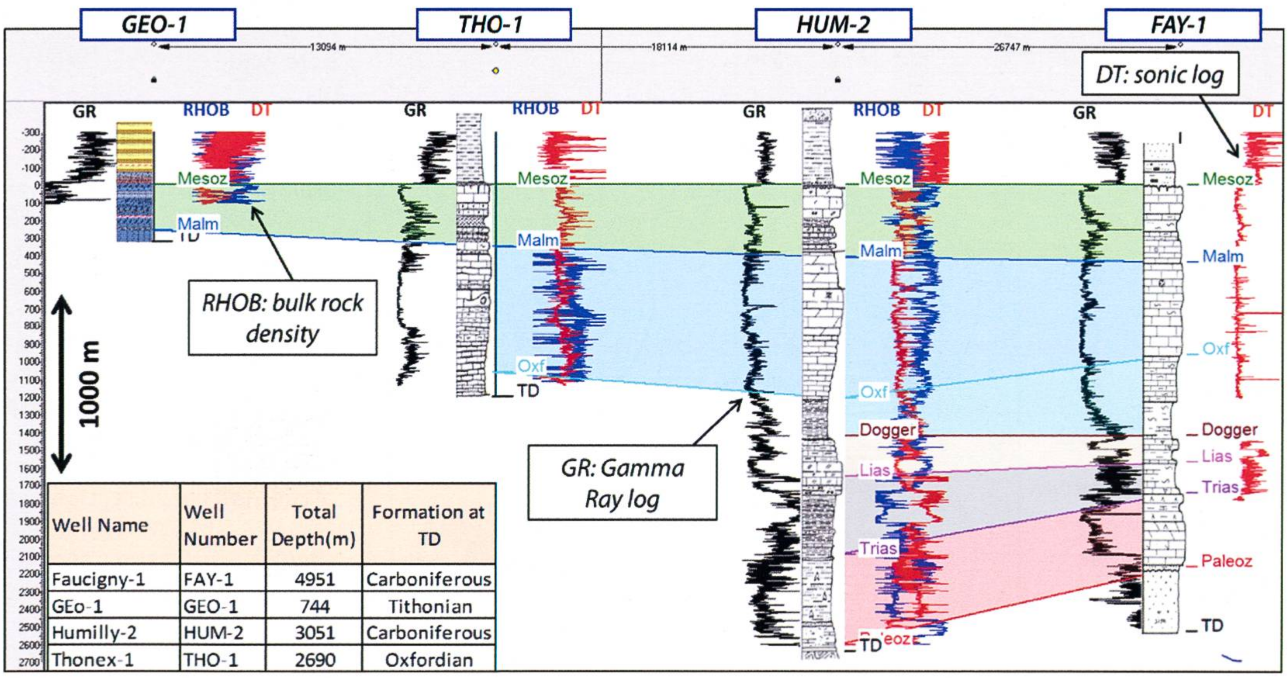
As previously mentioned, some wells have incomplete log suites preventing from detailed petrophysical interpretation. However, regional knowledge and geological concepts were used to generate composite logs, and thus provide the material for well log correlation and sequence stratigraphy analysis (Fig. 8). These are crucial to understand the regional geology and predict the special changes in rock properties which cannot be done with seismic only.

The petrophysical evaluations of GEo-1 (of all surrounding wells in the canton) have established matrix porosity below 10-12% in the evaluated sections of the Mesozoic. This porosity does not provide sufficient flow rate permeability for geothermal opportunities. Therefore, special investigation for an open fracture network is essential for the subsurface evaluation.

7 Image log data

Borehole imagery (BHI) is valuable as it has one of the tightest spatial vertical resolutions (0.2 in or 0.51 cm for FMI (resistive images tool manufactured by Schlumberger)) among all wireline logs. Resistivity, optical and acoustic images allow detailed structural interpretation and gives key information on nature, orientation and scale of fracture sets but also possible compartments.

In GEo1, acoustic (ABI) and optical borehole images (OBI) were acquired (Fig. 9). ABI pro-



Well Name	Well Number	Total Depth(m)	Formation at TD
Faucigny-1	FAY-1	4951	Carboniferous
GEo-1	GEO-1	744	Tithonian
Humilly-2	HUM-2	3051	Carboniferous
Thonex-1	THO-1	2690	Oxfordian

Fig. 8: Well log correlation example of the main deep wells around the Geneva area. GGE has generated composite logs for all wells with Mesozoic penetrations to help current and future work.

vides 360° coverage of the wellbore and is designed for acquisition in all type of liquids except air or foam (loss of signal is also possible in heavy mud environment). This tool is composed of transducer (that also acts as the receiver) mounted on a rotating sub at the bottom scanning the borehole wall at high frequency (from 200 to 700 kHz). Its scanner follows a spiral path and the spacing of the spiral depends on the logging speed. The acoustic receiver measures the interval transit time between the transducer to the borehole wall and back alongside the reflected amplitude of the emitted signal (Luthi, 2001). Optical borehole imager also provides an image with a 360° coverage. It is composed of a camera recording the borehole surface continuously through a prism mechanism. The main technical advantage of this tool is the ability to be used in air or clear water filled well (Zemanek and al., 1970) additionally it requires limited processing.

In GEo-1 study, the wide general workflow established and used by GGE for the evaluation, processing and interpretation of borehole image was reduced to the following steps:

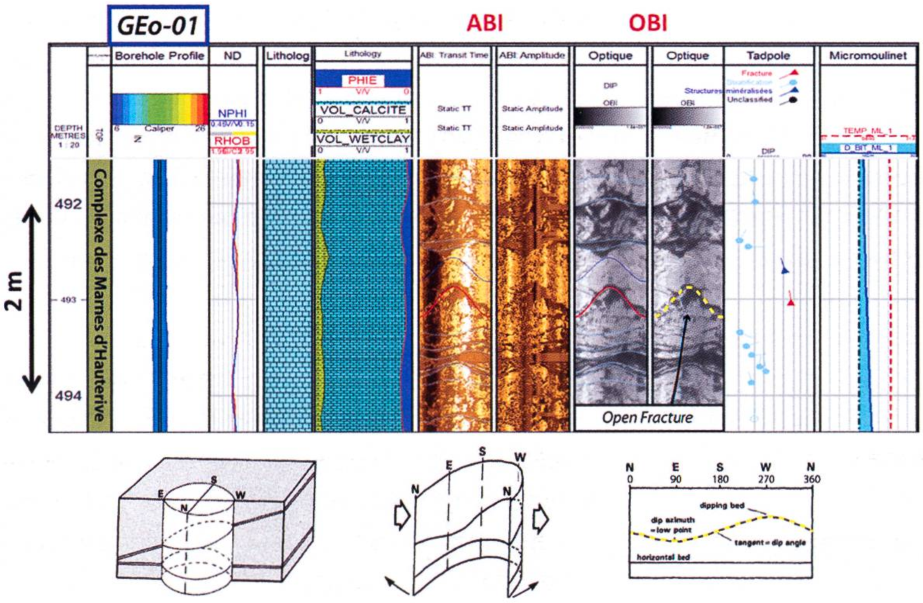


Fig. 9: Example of image logs along GEo-01 well showing fracture and bedding indications. Display of BHI are unrolled (360°) and oriented image of the borehole wall.

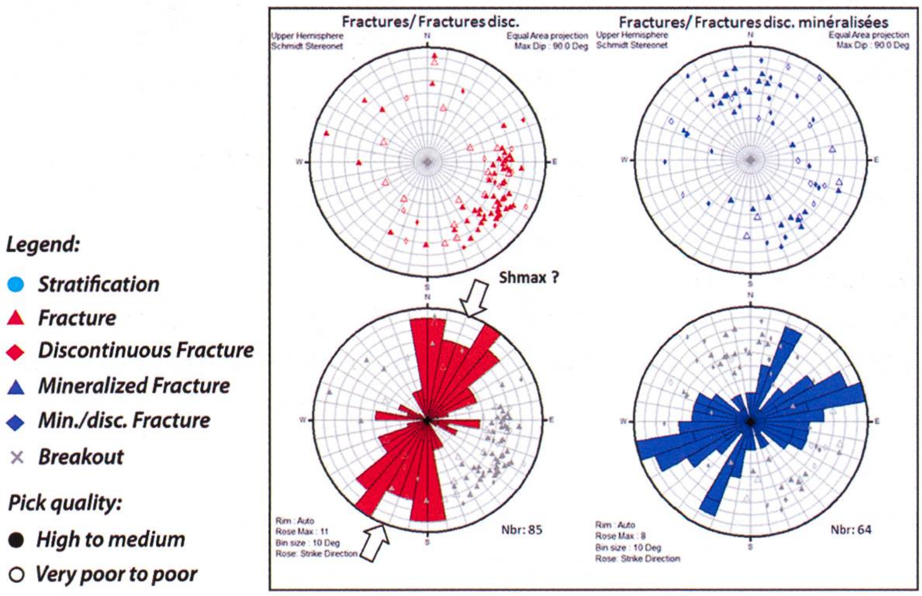


Fig. 10: Fractures analysis along GEo-01 well. Upper hemisphere of a Schmidt stereonet shows the orientations and dips of the fracture planes interpreted in GEo-1. The rose diagrams represent the strike orientation of the fracture planes. The dominant orientation of the fracture plane (strike direction) is N-S to NE-SW. Two main orientations of the mineralized fracture planes (strike direction): NE-SW, parallel to the non-mineralized fracture zone, ENE-WSW probably related to a second set of fractures.

- Image quality control consisting in visual image quality check, image orientation validation and image processing and/or re-processing.
- Structural interpretation allows to identify: a) Bedding and regional structure like shale intervals and determine dominant regional dip; b) Faults and unconformities identification (generation of cumulative dip and azimuth vector plots); c) Identify fractures and fractures typing (open, closed, healed, etc.).
- Stress indication: Drilling induced fractures, image borehole break and calipers borehole breakouts are used to determine maximum horizontal stress orientation.

The resulting beddings and fractures interpreted with this methodology can then be plotted and classified considering their morphology (continuity, filling, displacement, dissolution, and so on) (Fig. 10). The orientations and depths of the visible fractures can be combined with the seismic interpretation to obtain a full integrated study at different scales.

8 Discussion and conclusion

a) The subsurface part of geoenergy projects need intensive investment, especially with energy source at medium or substantial depth. Therefore, the energy industry applies a high diligence to select potential drilling locations. The key method is the seismic approach which accounts for >95% of the surface geophysics budget of the oil industry. It remains relatively expensive and unfortunately over the last 60 years cheaper alternatives have not been found. There is no alternative providing sufficient vertical, and more importantly, lateral solutions.

   Seismic is an established technology and most of the innovation funds were and are still used to improve it and to reduce its cost.

   A key aspect for a successful implementation of the method is to adapt the parameters to the geological objectives. Poor parameter selection and imperfect execution can lead to more uncertainty. Unfortunately, the client might also be inclined to support inadequate results to avoid conceding wrong initial choices of parameters or contractor. In some cases, technology may be not available to fit specific tasks of the project with a reasonable budget. A good balance between risk and reward should be adopted to ensure the success of the venture.

   For future geothermal projects in Switzerland choosing an optimum location for the deep wells will be the essential. Only 3D seismic has the lateral resolution for localization of such features (using 3D migration in time and depth). It provides a dense coverage of the subsurface data despite challenging surface conditions.

b) Log Well data are a unique source of knowledge for subsurface energy resource evaluation. From core data to seismic scale and from exploration to final investment, they represent the closest view of an aquifer / reservoir in situ conditions. The main advantages are that it brings real quantification of reservoir properties (continuous, discrete, quantitative) and is adapted to almost all types of subsurface characteristics. It is significantly cheaper than coring and provides data acquisition under real reservoir conditions which significantly help reducing uncertainties for geoenergy exploration.

   For a successful acquisition, proven equipment with adapted procedures and an experienced team are needed. The final seismic image also requires refined calibration, processing/correction/editing, well history, fluid chemistry and hole size before performing any petrophysical evaluation or well log correlation.

The drilling program of any exploration or development wells shall be adapted to obtain a suitable borehole quality for well evaluation logging. State of the art drilling execution and mud management are essential to obtain satisfying borehole shape.

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