

4 SEISMIC SYNTHESIS OF THE SWISS MOLASSE BASIN; REPORT FOR 2006

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ABSTRACT

During this year, we completed the geological interpretation of the seismic profiles in western and central Switzerland. Nine seismic horizons were interpreted and digitized. Time miss-ties between sections were corrected using a program that minimizes offsets while taking all sections into account. All digitized data were introduced into our ArcGIS data base. We used this software to compute time and depth contour maps for the different horizons as well as isopach maps. Time to depth conversion was carried out using velocities from approximately 20 wells. Normal, reverse and strike-slip faults affecting the interpreted horizons were mapped and digitized. In western Switzerland, three major fault systems are observed: a sinistral strike-slip zone with a NNW orientation, and two dextral strike-slip zones with a NW, respectively WNW orientation.

The mapped seismic horizons emphasize the presence of Permo-Carboniferous basins, the thicker ones being located in Canton Vaud and Canton Geneva. Their main trends are ENE and NW. Mesozoic series are mainly composed of alternating limestones and marls that coincide with strong reflectors. Triassic layers show thickness variations of evaporites under anticlines, while Jurassic series may vary at basin scale. Dogger limestones are seismically expressed as well defined reflectors. Thickness maps underscore the prism of Tertiary sediments.

RESUME

Au cours de cette année nous avons terminé l'interprétation géologique des profils sismiques de Suisse occidentale et centrale. Neuf horizons sismiques ont été interprétés et numérisés. Les décalages en temps des sections ont été corrigés selon un algorithme qui minimise les délais en prenant en compte l'ensemble des sections. Toutes les données numérisées ont été introduites dans notre base de données ArcGIS. Ce logiciel a été utilisé pour calculer des cartes de contours en temps double et en profondeur pour les différents horizons ainsi que des cartes d'isopaques. La conversion temps-profondeur a été réalisée à partir des vitesses extraites des données d'une vingtaine de forages. Les failles normales, inverses et en décrochement affectant les horizons interprétés ont été cartographiées et numérisées. En Suisse occidentale, trois systèmes de failles principaux sont observés : un décrochement sénestre d'orientation NNW et deux décrochement dextres d'orientation NW et WNW, respectivement.

La cartographie des horizons sismiques fait ressortir la présence de bassins Permo-Carbonifères dont les plus épais sont localisés dans les cantons de Vaud et de Genève. Leurs directions principales sont ENE et NW. Les séries mésozoïques sont principalement représentées par des alternances de calcaires et de marnes qui correspondent à de forts réflecteurs. Les couches du Trias présentent des variations

d'épaisseur dans les évaporites sous les anticlinaux, tandis que les séries du Jurassique varient à l'échelle du bassin. Les calcaires du Dogger s'expriment en sismique par des réflecteurs bien marqués. Les cartes d'épaisseurs mettent en évidence le prisme des sédiments tertiaires.

4.1 INTRODUCTION

The project to interpret seismic and borehole data mainly from the petroleum industry in the entire Swiss Plateau is now in its third year of activity. The aim of the project is to provide a synthesis to address fundamental geological issues related to the Molasse Basin, to the Mesozoic fill and to the occurrence of Permo-Carboniferous basins. Also, this work will help address large scale scientific problems such as the evolution of the alpine foreland basin and the development of the Jura mountain fold belt. Besides its scientific interest, this project will provide regional information that may help address other issues such as the search for commercial hydrocarbon, storage of nuclear waste, better understanding of large scale groundwater circulation, heat-flow distribution and safety of main urban and industrial sites.

One of the final products of the project will contain a series of major transects across the Molasse Basin, a summary of well data, as well as subcrop and isopach maps of major structures that involve Cenozoic (Tertiary), Mesozoic (Secondary) and Pre-Mesozoic strata. The output will be available in digital form through a GIS data bank that will not only allow on screen visualization of the various products, but it will also provide access to the results with all data handling possibilities offered by a GIS based system.

During 2006, the work consisted in interpreting the data in western Switzerland, extending our GIS based system that can be used both for data interpretation and for data visualization, and reaching out to other scientists through individual discussions, scientific meetings.

4.2 THE DATA SET

Data collection, one of the major tasks in 2004 and first part of 2005, is now completed. The data consist in paper copies of seismic lines and approximately 20 borehole logs. The complete seismic grid from Switzerland is shown in Figure 1 and colors indicate the origin of the seismic profiles. The meaning of the legend is as follows.

- Blue, published lines available in the literature;
- Green, public lines in Canton Vaud and lines in Canton Fribourg obtained from the Department of environment and construction and from the FREAG (see the 2005 report).
- Purple, public lines available at the archives of the Swiss Federal Office for Water and Geology (previously with the former BWG and now SwissTopo).
- Red, lines received from SEAG for this project (see contract in the 2005 report).
- Black, lines not selected for the project.

In summary, all lines that are not in black in Fig. 1 are presently available for the project.

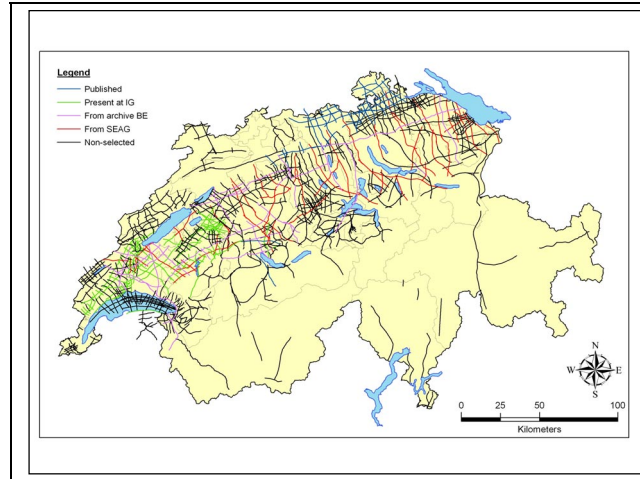


Figure 1: Seismic data in Switzerland. For explanations of the color legend see text.

The seismic data were calibrated to deep wells (fig. 2) using, for instance, seismic synthetic sections and T/Z curves.

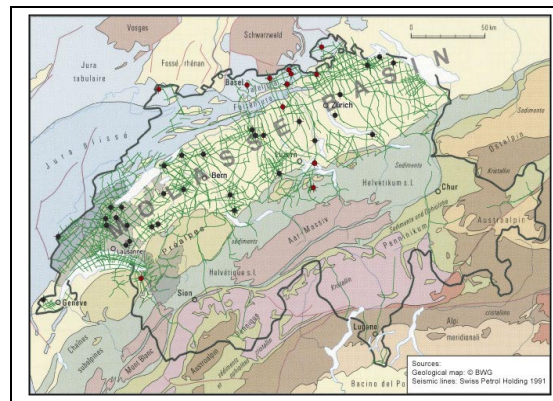


Figure 2: Well data and seismic 2D data in the Swiss Molasse Basin. Unfortunately, not all the displayed wells contain useful data for this project. Wells acquired for hydrocarbon exploration are shown in black, wells in red were acquired for waste disposal studies

4.3 DATA INTERPRETATION

Work techniques to interpret seismic lines were presented in the 2006 report. The following horizons were mapped: Near Base Tertiary (BTer), Near Top late Malm (TIMa), Near Top early Malm (TeMa), Near Top Dogger (TDo), Near Top Liassic (TLi), Near Top Triassic (TTr), Intra Triassic (TMuka), Near Base Mesozoic (BMes), Intra Permo-Carboniferous 1 and 2 (PC1, PC2). Faults affecting one or more of these horizons were also mapped.

Because not all the seismic sections were immediately available, we subdivided the data set in three areas A, B and C (Fig. 3):

Area A: The data interpretation in Canton Vaud and Canton Fribourg is finished. In 2005 and during the first part of 2006, the work focussed on the western most part of the Swiss Molasse basin. It involved nearly 1700 km of 2D seismic from 121 lines. Seismic profile acquisition between 1971 and 1986 resulted in a rather dense seismic grid with about 316 profile crossings. Together with the

seismic sections we used 10 deep wells with geological stratigraphy and velocity data, and about 15 geological surface maps at 1:25'000 scale. The interpreted seismic horizons as well as faults were digitized and later loaded in our ARCGIS data base. TWT contours and isopach maps were constructed as well as depth maps.

Area B: Most of the data interpretation in Canton Geneva and Canton Bern is done. Seismic lines in Canton Bern and their connections with those of Canton Luzern are partially interpreted. To groundtruth the seismic lines we used the wells of Hermrigen, Tschugg, Ruppoldsried, Thun, Linden and Pfaffnau.

Access to data in Canton Geneva was obtained near the end of the year (December 2006). Interpretation started at the end of December and results will be included in the 2007 report. Data from Canton Geneva will be included in the contour maps of western Switzerland during the early part of 2007.

Area C: Data interpretation in eastern part Switzerland is the main remaining task for 2007 (see perspectives for 2007). In this area, the seismic grid is less dense than in western Switzerland and there are about half the number of seismic line crossings. Checking line crossings is one of the main time consuming time tasks before geologic interpretation may actually start. In the northern part of Switzerland, data interpretation will benefit from the already existing interpretation carried out by NAGRA.

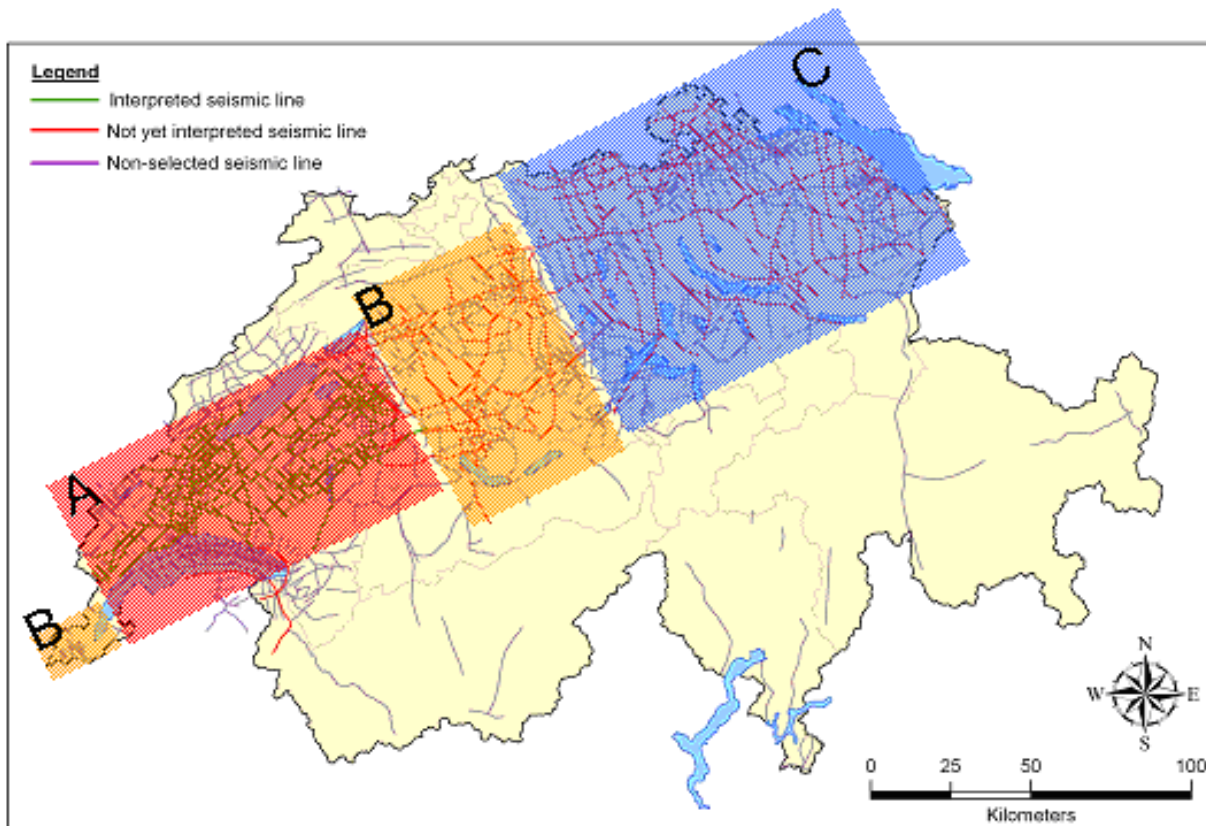


Figure 3: Location of seismic lines and their subdivisions in three areas A, B and C following the progress of the geological interpretation with time (see text for explanation).

4.4 ELABORATION OF CONTOUR MAPS

The eight seismic horizons (see chapter 3) were digitized from the interpreted seismic sections. The data were later corrected for two-way travel time miss-ties, gridded and finally contoured. Combination with velocity information enabled us to convert the data to depth.

Miss-tie corrections

The seismic reference levels (SRL) of 300 m, 400 m, 500 m and 700 m of the various data vintage were reduced to 500 m above sea level. Data from vertical seismic profiles (VSPs) and up-hole surveys were used to determine seismic replacement velocities for this calculation where there was no direct line link between areas of different SRL. Where lines of different SRL cross each other, the TWT adjustment can be read directly from the vertical time scale. A two-step miss-tie correction was carried out.

1) At line intersections, we decided by visual inspection of the sections if and by how many milliseconds one line had to be shifted in order to obtain a best fit for all the interpreted horizons. This best fit miss-tie value was then noted as difference between the zero time lines between the two sections (Fig. 4).

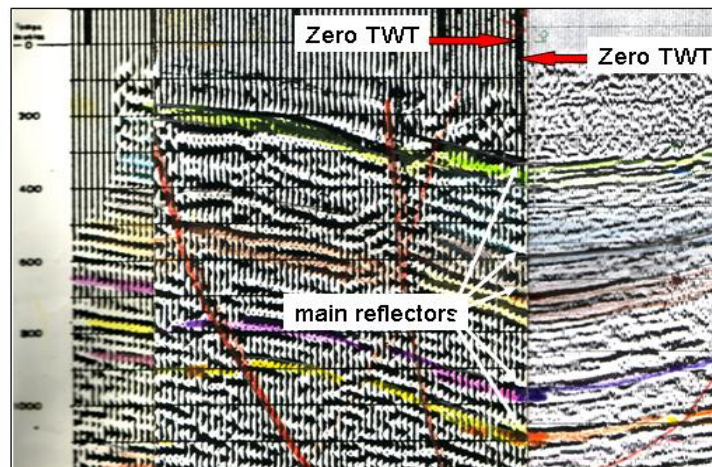


Figure 4: Miss-tie at an intersection of two seismic lines. Both lines are treated for a seismic reference level of 500 m a.s.l. Note the difference at the level of the zero time line and the acceptable correlation of the main reflectors.

2) In a second step, the miss-ties at all intersections of all interpreted sections were listed in a two-entry table. This allows for a quick analysis of the “worst” intersections (Fig. 5).

Figure 5: Excel table of miss-tie values for each seismic line intersection. Green and red rectangles indicate low and high miss-tie levels, respectively.

Using this table, an average time shift was calculated by least square fit to reduce the total value of miss-ties at all intersections. This correction needs several iterations of the program. We defined a few interconnected reference seismic lines that should not be shifted or only by a minimal amount. Other lines were then shifted such as to minimize their time miss-tie relative to these reference lines.

Sometimes, it appeared that a solution would have been to reduce miss-ties by slightly rotating entire lines or by shifting a single horizon rather than the whole set of horizons within one line. However, because such operations would falsify the data acquisition, they were not allowed.

4.4.1 Velocities

To convert TWT (in seconds) contour maps (see section 4.2) to depth maps (in meters) it is necessary to have velocity information.

The velocity data were acquired from the few available deep wells of the basin. These data can be simple sonic logs, well shooting or more sophisticated vertical seismic profiles with synthetic seismic calculations. The geologist's well stratigraphy provides the depth of formation boundaries. These depths were reduced to the SRL of the velocity surveys in the wells, and velocities were defined from the TWT difference recorded over the stratigraphic interval. An additional correction was made to reduce the SRL to our project base level of 500 m above seal level (Fig. 6).

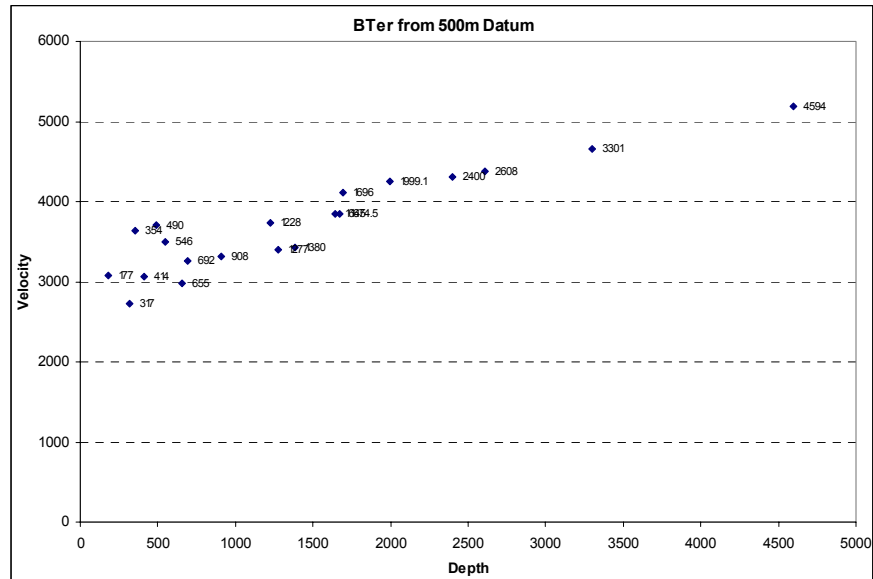


Figure. 6 : Interval velocities for the Tertiary sequence at different depths for available wells in the Molassic Basin.

The values in each well were then inter- and extrapolated in order to complete a velocity grid over the entire basin. The first depth horizon was calculated by multiplying the first TWT horizon by twice the first interval velocity. All other depth horizons then were added subsequently using the multiplication of TWT difference times twice the interval velocity to the next horizon. So far, all velocity data were taken directly from the well information. Final corrections need to be added to the depth maps, if one wants to present the correct depth situation for each horizon at all well locations.

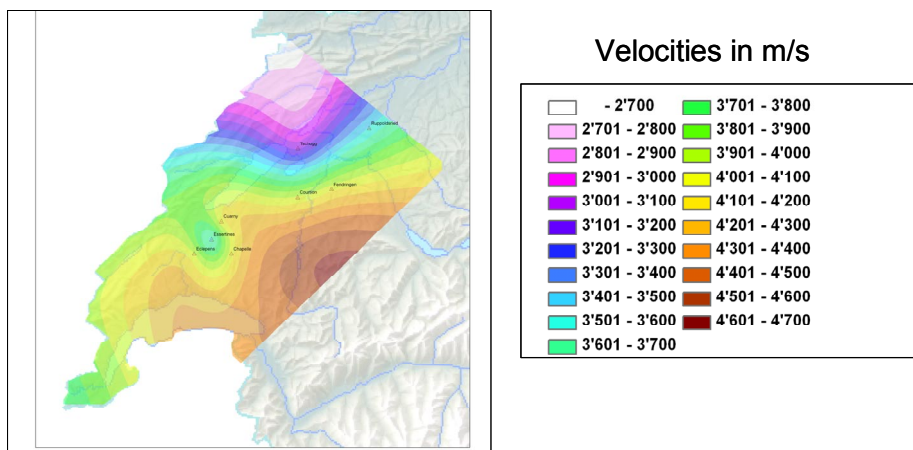


Figure 7: Example of a velocity map in the VD and FR area showing the interval velocity of the Tertiary sequence.

Some artificial wells had to be added to minimize edge effects. The estimation of the velocities in such artificial wells was based on trend curves derived from the data (Fig 6)

The velocity values then were extra- and interpolated using a kriging operator with strong smoothing filter, in order to produce simple interval velocity maps (Fig. 7).

4.4.2 Contour maps

Contour maps represent the surfaces obtained through the inter- and extrapolation of interpreted horizons on seismic 2D lines. Interpolation of the TWT values extracted from interpreted seismic lines was performed using the “GeoStatistical Analyst” kriging algorithm of ArcGIS software. Default parameters of the kriging method were kept to carry-out the interpolation and the output grid cell size was set to 100m. We also tested several algorithms like “gradient projection”, “inverse distance” and “cubic spline”, all with grid cells of 100 m and 500 m using “The Kingdom Suite” (TKS) interpretation software. For display at scales of 1:100'000 to 1:500'000, the “cubic spline” with 500 m cell size, medium smoothing and high “affichage” setting is most appropriate in TKS.

We calculated contour maps in time and depth for the following horizons: Near Base Tertiary (BTer), Near Top late Malm (TIMa), Near Top early Malm (TeMa), Near Top Dogger (TDo), Near Top Liassic (TLi), Near Top Triassic (TTr), Intra Triassic (TMuka), Near Base Mesozoic (BMes), Intra Permo-Carboniferous. Isopach maps have also been calculated and contoured.

Time and depth interval maps are easily calculated from the above data.

Examples of contour maps are shown in figures 8 and 9 that represent the Base Tertiary in time and in depth respectively for western Switzerland. The maps highlight an extended monocline with a general dip to the SE. In the southern part of Canton Vaud, we can observe a rising up of the horizons that define a syncline with an axis parallel to the alpine front. At local scale, changes of direction are observed e.g. To the south of Lake Neuchâtel. These changes are related to a major fault system oriented N-S or NW-SE as shown in figure 8. No major differences are observed between the time and depth contour maps. The Base Tertiary surface dips from 700 m to approximately -3000 m.

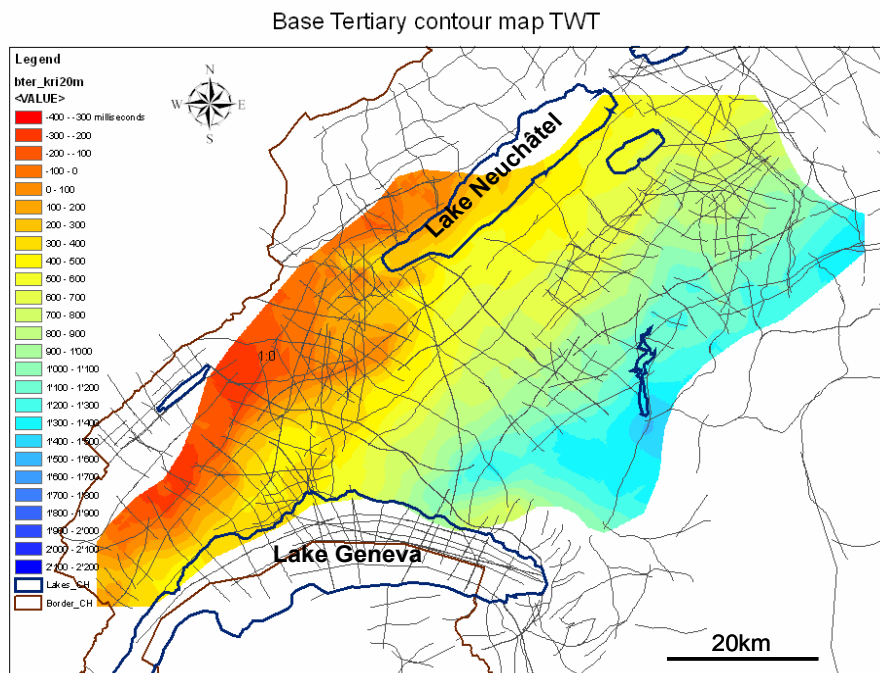


Figure 8: Contour map of the Base Tertiary sequence in western Switzerland. TWT contours (colours) are separated by 100 milliseconds. This map was calculated with ArcGIS 9 using a grid size of 100m. The Swiss seismic grid is superimposed. . Negative or positive values are referred to datum plane we selected (0ms = 500m elevation).

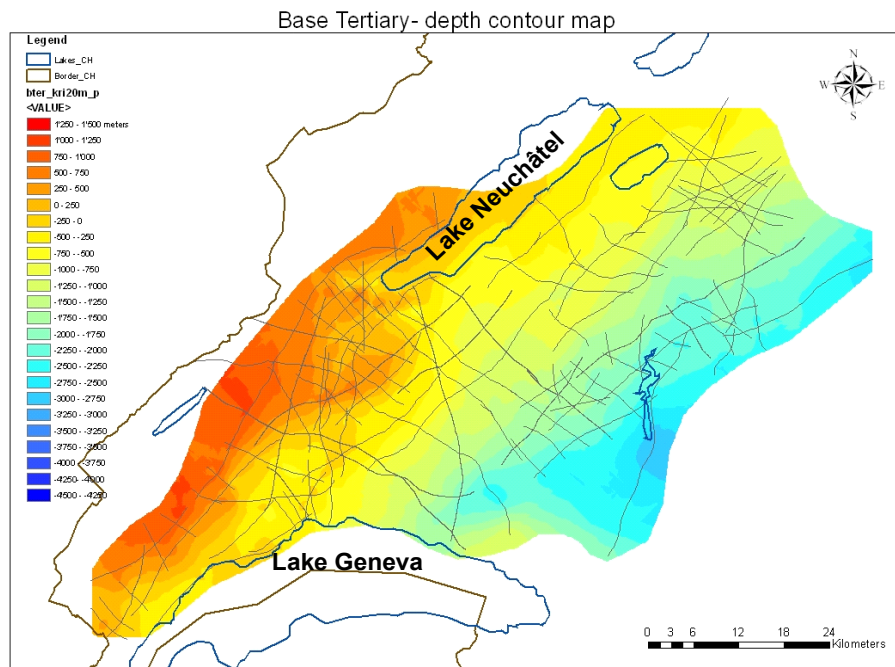


Figure 9: Depth-converted contour map of the Base Tertiary sequence in western Switzerland. Contours are in meters. This map was calculated with ArcGIS 9 using a grid size of 100m. Seismic sections used in the interpretation are shown in grey. Values refer to elevation.

4.4.3 Faults

On seismic 2D sections, faults appear as diffuse zones of discontinuous horizon reflectors. Abrupt vertical displacement of several reflectors along a distinct line (faults plane) is the best indicator for the presence of faults. In some rare cases, fault planes do occur in seismic as clear reflectors. For example, the thrusts within the evaporate series of middle Triassic are observed on some lines of Canton Vaud. Also, we are aware that many of the faults we observed have a 3D configuration that may not be truthfully represented in our 2D data set.

We distinguished three types of faults in our data:

- 1) Normal faults with dip angles of about 60° to 70° in the main extensional direction.
- 2) Thrust faults which can be inclined or flat lying planes in compressive setting. Often, thrust-faults double the series.
- 3) Strike-slip faults that tend to cut the subsurface with very steep angle (80°-90°).

While digitizing seismic horizons from paper sections, the horizon continuity was given priority and the tips of the horizon to either side of the fault plane were linked by a horizon segment lying within the fault plane.

Faults were digitized as independent elements, crosscutting continuous horizons. Crossings were computed using "The Kingdom Suite" software. We then established four horizon maps on which fault patterns were compiled for a) the surface (from various data existing sets), b) Base Tertiary, c) Top Dogger and d) Base Mesozoic.

The length and orientation of the individual fault segments are hypothetical, they are based on model results from the literature and experience in other foreland basins. Figure 10 shows an example for the Top Dogger sequence.



Figure 10: Sketch map of faults in the Top Dogger sequence from seismic data between Lake Neuchâtel and Lake Geneva. Three major strike-slip fault systems are highlighted.

For 2D fault correlation, the dip orientation and the nature of the displacement along the fault are important criteria. In Fault zones, the all over displacement defines the style of relay or “en echelon” geometry. Often faults are active several times (reactivated) and change their sense of displacement. In such cases, the more obvious and regionally more important fault expression is taken into our interpretation.

Because of the low line density of our 2D data set, fault correlations are not self evident. We followed some basic rules: 2D fault interpretation tends to overestimate the individual fault length and to underestimate the number of faults present. Correlation is pushed far across from one seismic line to the next as the geologist tries to make sense of scarce observations.

The detailed fault observation on each line does not allow for very large faults that would over several kilometres. The variation of the displacement vector in the fault plane is a good indicator for fault termination and relay. Unfortunately the seismic line spacing is too large for determination of fault displacement variations and fault extension.

4.5 FUNCTIONALITY OF GIS

A geographical information system (GIS) was used in this project to position seismic lines and wells, to elaborate horizon contour maps, to build velocity models and to calculate depth-converted maps. Geo-referenced maps, e.g. geological, geophysical or geographical maps, can be added to our data base in order to enlarge the functionality.

4.5.1 3D visualisation of results

Seismic horizons can be visualized in 3D with the ArcScene software. This functionality makes it possible to better visualize the geometry, the angular relationships and the thickness of various units.

As example, figure 11 shows all the digitized horizons from the Base Tertiary sequence in light green to the Base Permo-Carboniferous sequence in dark grey. Faults appear as red “spaghettis” in figure 11 (see also Fig. 14). They show the fault intersection with the seismic profile plane.

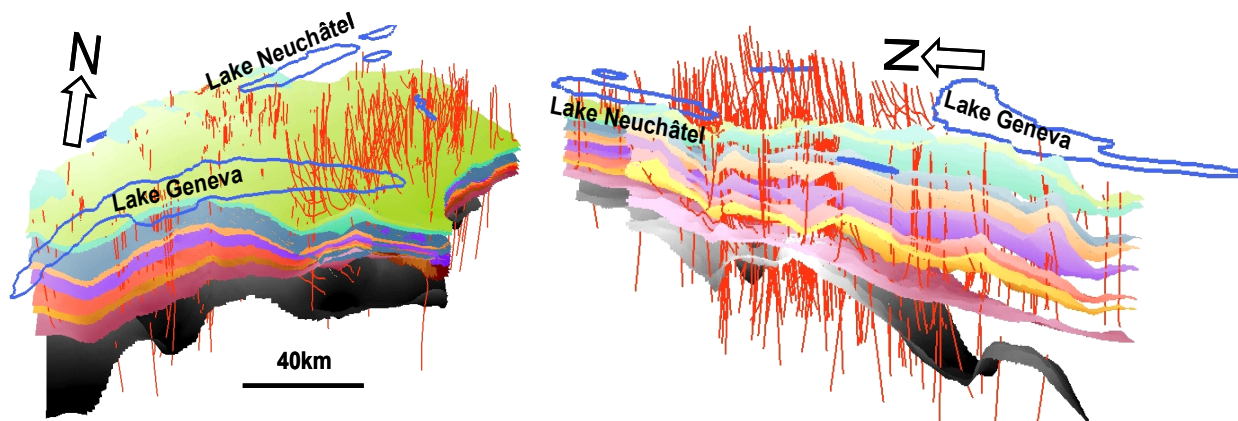


Figure 11: 3D visualisation of seismic horizons in TWT: from the Base Tertiary sequence (top) to the Base Permo-Carboniferous sequence (bottom). On the left side, North is pointing to the top, on the right side, North is pointing to the left. Lake Neuchâtel and Geneva are used as geographical reference. Vertical exaggeration is 10 times.

4.5.2 Data sets

In this project, we also use our GIS data base to combine different data sets. In the 2005 report we presented the combination of seismic shot point map with geological data. Here, we present a seismic contour map from western Switzerland (Base Tertiary), and we display it on the same figure with a map of the same horizon elaborated by Nagra (Fig. 11). The map shows a striking continuity of the horizons from South-West to North-East.

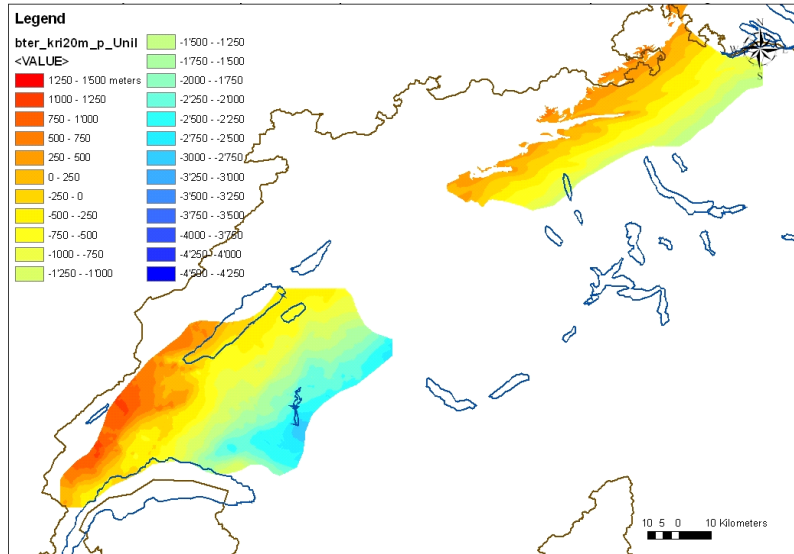


Figure 12: Depth contour map of the Base Tertiary sequence: results from south-western part were elaborated in this project. The north-eastern part is from unpublished results from Nagra and unpublished data from SEAG (Schweizerische Gesellschaft für Erdöl AG).

Another example of combination of data set is the Tertiary sequence isopach map from our project and the Bouguer Anomaly map (Olivier et al. in press). The anomaly was calculated with a reduction density of 2.67.

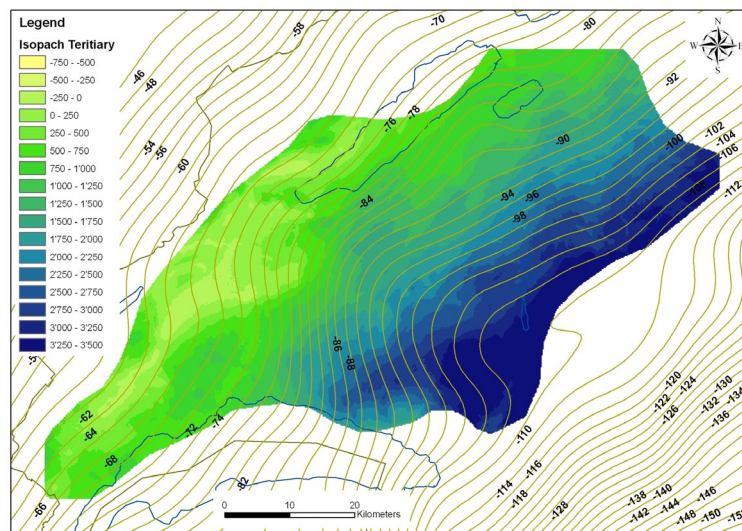


Figure 13: Tertiary sequence isopach map with superimposed contours of the Bouguer anomaly in mgal. (Olivier et al., in press).

4.6 GEOLOGICAL OBSERVATIONS

Here we report some of the most significant geological observations based on our interpretation of the seismic lines.

4.6.1 Stratigraphy

The result of this study is presented as a stack of 9 horizons in the subsurface between the Jura mountains and the Swiss Alps. Based on well data, we chose main stratigraphic boundaries and identified strong reflectors near by. These reflectors were interpreted along the available seismic lines (Fig 1). The real geologic architecture of the basin however is more complex than it appears from the horizon stack. It could be worked out on basis of the same data by adding more horizons and applying a sequence stratigraphy approach. Changes in reflector quality and in seismic facies identification are not reported in this study.

Permo-Carboniferous

The presence of Permo-Carboniferous sediments is well known from alpine outcrops and NAGRA drillings (e.g. Weiach well). On many seismic lines, there are reflective packages underneath the base of the Mesozoic sequence. Unfortunately, there are only three wells in the Swiss Molasse Basin (south of the Jura mountains) that reached the Palaeozoic basement. Heterogeneities in the crystalline basement can cause reflectors and Permian clastics can appear almost transparent on 2D seismic.

The region of Canton Geneva and canton Vaud, however, show strong Palaeozoic reflectors in presumably Carboniferous grabens with steep limits. The most reflective packages are probably shaly or coaly layers. From those grabens (late?) Permian sediments spread out in more shallow sag basin geometry.

Most of the area of Canton Geneva and Canton Vaud and half of Canton Fribourg are covered with pre-Mesozoic clastics. Two main directions of graben structure limits are observed, WSW-ENE and NW-SE.

Mesozoic

The Mesozoic sediments show strong reflectors where shaly series alternate with thick limestone or dolomite beds. This is the case in the Triassic and early and middle Jurassic. Also the Cretaceous strata show a few strong reflectors.

Less reflective sediments are e.g. the shaly evaporites of Triassic age, the shales of the Dogger and the shaly limestone of the Oxfordian. The homogeneous limestone of the late Malm also doesn't show strong reflectivity.

The Triassic beds show strong thickness variations. At their base, clastic sediments include calcareous sandstones that contrast with the less sorted late Permian sediments or the altered crystalline basement surface. Locally, an angular unconformity is visible. The middle Triassic evaporite series contains salt that forms gentle pillows in the core of anticline structures. Dolomite and shale packages floating in the evaporites are at the origin of a rather high amplitude chaotic seismic expression. The late Triassic clastic-carbonate mixed layers vary less but seem to reflect early salt movements due to differential loading or subsidence movements.

The Jurassic series is rather well organized with several sedimentary cycles, the top of which produce some of the strongest reflector within the Swiss Molasse Basin. The Liassic mixed series show varying reflector strength. In general a rather well marked top-reflector can be identified. Thickness changes reflect also early salt movements. The Dogger limestone beds create a series of strong reflectors. In Canton Vaud, they occur in a shingled down-lap configuration with slopes pointing towards ESE. The Oxfordian shale and limestone seem to accumulate in north Canton Vaud and thin towards the basin axes and to the east, whereas the more homogeneous Kimmerigian seems to thicken towards the basin. Some reef geometries can be distinguished up flank and in the main basin. In general there are more low amplitude parallel reflectors to be found in the deeper part of the present day basin.

The Cretaceous layers are present in two parts of the basin: In the West, the thickest section is preserved in the Geneva area where up to 320 m of Cretaceous limestone and marls form three to four high amplitude markers. These shallow water sediments were deposited to the south on a W-E oriented

shore line located to the North of the city of Biel. Pre-Tertiary erosion reduced the Cretaceous sediment thickness and resulted in a limit of occurrence to the south-west of a line running through Besançon – Biel – Thun. In most of the VD-FR area, two seismic reflectors can be distinguished. Their absence to the North is explained by the close shore line and non depositional area; the absence to the East of the Aar River seems to be caused by pre-Tertiary uplift and erosion. The internal structure shows discontinuous packages. It is not clear if those are separated by faults and thrusting or by sedimentary architecture and facies distribution of limestone.

Tertiary

The prism of the Tertiary sediments reaches maximum thickness underneath the Prealps and within the dislocated Molasse in front of the Alps and rises in front of the external massifs. The complex and the interesting internal architecture of the Molasse has not been worked out in this study.

Some of the more recently acquired seismic line allow for detailed interpretation of the sedimentary fill, although acquisition parameters were laid out to image Mesozoic strata. The units of the lower marine Molasse (UMM) can not clearly be distinguished within the western part of the basin. The seismic character of the lower fresh water Molasse (USM) shows the low continuity of clastic channel units, coarse grained fan systems and shore line deposits.

The all over geometry of the Tertiary fill is calculated by multiplication of the base Tertiary TWT horizon (BTer) with the interval velocity for the total of the Tertiary sediments as defined in approximately 20 well penetrations.

4.6.2 Faults

The seismic imaging of faults was already discussed above (chapter 4.3, see also Fig. 14).

The spacing of the 2D lines in the Molasse basin is in the order of 2 km to 15 km. This leaves us with large volumes without information and the fault patterns have to be estimated using models and

comparison with better known analogues situations. The largest fault zones in the western part of the basin are N-S oriented sinistral strike-slip faults and W-E oriented dextral strike slip faults.

The most obvious ones have been interpreted on four levels: surface, Base Tertiary, Top Dogger and base Mesozoic level.

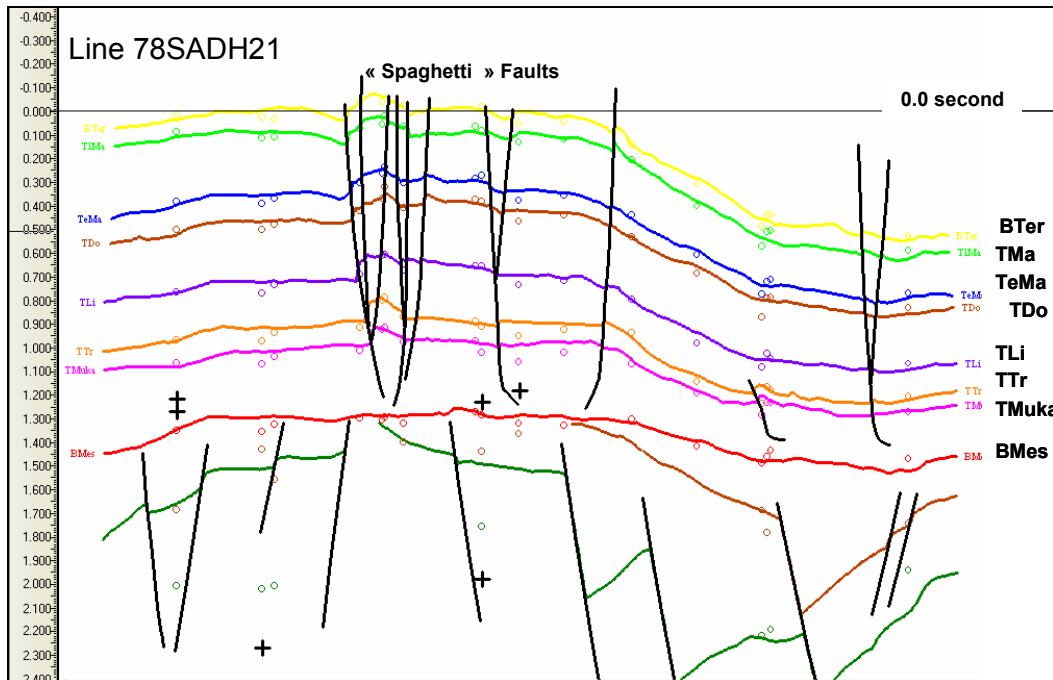


Figure 14: Example of digitized seismic horizons and faults. Dots represent the horizon position on the intersecting line; crosses represent the fault position on the intersecting line

4.7 SCIENTIFIC CONTACTS

4.7.1 Contacts

During 2006 we had scientific contacts with various groups:

- Nagra, Proseis, Geoform: exchange of data, discussions on specific topics as Tertiary unit or ArcGIS data base.
- Geowatt, Zürich: we provided them with some of the results in western Switzerland (grid of seismic horizons).
- Prof. E. Klingelé, Zürich: exchange of data, especially on the Bouguer anomaly and aeromagnetic data.
- Celtic, London: a British private oil company, presentation of our results and exchange of ideas.
- Swiss-topo, Bern: contracts in order to use digital files of geological maps.
- Prof. G. Gorin and S. Paolacci (PhD student), University of Geneva: exchange of data from Canton Geneva, informal discussion and presentation of our results.

4.7.2 Workshop

In November (the 13th), we organized a successful workshop in Lausanne. We presented the project as well as intermediate results and we invited the participants to an informal scientific discussion based on the seismic data. More than 25 persons from oil industry, private companies, universities and federal or

cantonal offices were present. All were interested to see the results and to have the possibility to observe the seismic data and to discuss them.

4.8 ACKNOWLEDGEMENTS

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NAGRA, unpublished results from Nagra.

SEAG (Schweizerische Gesellschaft für Erdöl AG): Unpublished data from wells and various seismic surveys.