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GeoNE: an integrated project for the exploration of low enthalpy deep aquifers in the canton of Neuchatel, western Switzerland

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ABSTRACT

During the mid 2000's, two preliminary studies on the evaluation of shallow and deep geothermal resources of the canton of Neuchatel, Switzerland, have shown that three potential aquifers could provide interesting low enthalpy geothermal resources. From May 2010 to July 2012, the Laboratory for Geothermics of the University of Neuchatel has carried out an integrated project called GeoNE, which was funded by the energy and economy departments of the canton. The main goals of this work were, to develop geothermal projects aimed at heat production from deep regional aquifers and to strengthen the competence of the Center for hydrogeology and Geothermics of the University of Neuchâtel in ensuring transfer of technology for different actors in the private domain through the organization of different training courses and workshops.

In the absence of deep wells and rare existing data providing information on the deep subsurface of the study area, several indirect exploration methods have been used in this study. Based on a synthesis of the available geological data, a series of 3D geological models were elaborated at both regional and local scales. These geological models were then used to compute the distribution of temperatures in the subsurface and predict the temperature ranges expected in the three deep aquifers.

Among the indirect exploration methods deployed in this study, micro gravity surveys were carried out over an area of 145 km^2 to identify the presence of underground faults and fracture zones, which might act as preferential flow paths for hydrothermal fluids.

The analysis of the gaseous compounds in soils, mainly He and CO_2, was also tested as its effectiveness in detecting permeable fault zone is proven for different geothermal systems. This method had however never been used in such karstic environment.

As part of this project, two complementary studies were conducted for the two most urbanized areas of the canton to evaluate the utilization and distribution of the geothermal heat. They highlighted the interest of several scenarios involving the geothermal resource within the existing district heating systems.

Under the technology transfer aspect of this project, a new geothermal training course in deep geothermal systems (CAS DEEGEOSYS) was conceived and organized at the University of Neuchatel. The first edition took place in 2011-2012 with 26 participants and 11 international experts teaching a total of 160 hours of courses, exercises and field trips. The main topics covered were Geology and Geophysics, Geochemistry and Hydrochemistry, Drilling and Logging, Reservoir Evaluation and Production.

1. INTRODUCTION

The GeoNE project started in 2010 with the goals of characterizing the subsurface of the canton of Neuchatel to locate possible targets for the development of low enthalpy geothermal systems, strengthening the competences at the University of Neuchatel and promoting competences and technology transfer among academic institutions and private companies (CREGE - Laboratoire de Géothermie, 2012).

The canton of Neuchatel does not show widespread evidences of geothermal anomalies. In addition, no data about the targeted deep aquifers, sitting at more than 400 m in depth, had ever been collected before. However thermal waters have always been exploited for spas at the foothills of the Jura range. Only a few studies to estimate the geothermal potential of the canton of Neuchatel and the feasibility of geothermal energy production have been carried out before (Matthey, 1986; Borreguero, 1996; Tecnoservice Engineering, 2004; Groupes de Travail PGN, 2008 & PDGN, 2010). These studies, along with the little deep geological data available, provided the background of knowledge, which was enriched with new data acquisition during the GeoNE project.

Between May 2010 and July 2012 several exploration methods were applied on the following areas, selected as the most promising (Figure 1):

- Neuchatel - St Blaise
- Le Locle - La Chaux-de-Fonds.

The targets were located below 400 m in depth, within the Mesozoic sedimentary formations, where deep carbonate aquifers represent possible candidates for geothermal exploitation. In this region the top of the crystalline basement is inferred at depths between 2000 and 2500 m. At this stage of the study, it was not investigated although the presence of permeable fracture zones in its upper part resulting from intense weathering cannot be excluded. The selected deep aquifer targets are located within the following formations:

- Malm (Upper Jurassic) between 250-360 m deep
- Dogger (Middle Jurassic) between 850 and 1200 m deep
- Muschelkalk (Triassic) between 1450 and 2150 m deep.

Because of the lack of geological, hydrogeological and thermal data deeper than 400 m, the GeoNE project developed an exploration program including the following phases:

- 3D geological modelling
- 3D thermal modelling
- Gravity surveys
- Production estimations.

The production estimation results were transferred to third party private companies in order to dimension the future surface installations (geothermal plants and district heating networks). With a fluid temperature expected to be below 100°C, only direct use of the heat is forecasted. The geothermal exploitation of these deep aquifers is planned with doublets systems, composed of a production well and a reinjection well. A similar configuration (the first one in Switzerland) was installed in the site of Riehen near Basel, where geothermal waters are exploited for district heating since 1994.

2. METHODS

In the framework of the GeoNe project 3D geological models were created according to the available geological data (Schardt, 1900; Favre, 1911; Suter, 1920; Schaer, 1955; Kiraly, 1966; Suter & Lüthi, 1969) and seismic data (Sommaruga, 1997). A microgravity campaign covered the selected areas of interest and allowed validating and calibrating the 3D geological models and highlighting areas where low densities can be associated to fault zones representing possible upflow channels for deep waters. Moreover a gas sampling campaign was carried out to constrain the composition of gaseous elements discharging from the soil, in particular across fault zones. Finally the 3D thermal models computed allowed constraining the temperature distribution in the subsurface.

2.1 3D geological modelling

The 3D geological models have been computed using the software 3D Geomodeller (BRGM, Intrepid Geophysics). The modelling approach is built on implicit geological modelling, which is based on 3D potential-field interpolation of potential field function (Lajaunie et al., 1997; Calcagno et al., 2008). The 3D geological models at different scales were computed according to geologic maps and cross-sections. 3D Geomodeller also allows computing 3D thermal models giving the proper thermal properties to the modeled formations.

2.2 Temperature modelling

Temperature models were computed with both 3D Geomodeller and the code FRACTure (Kohl & Hopkirk, 1995). To simulate the temperature distribution in the subsurface, assuming conductive heat transport only, the following parameters were defined:

- Surface temperature, $T_0(z)$ – defined according to the elevation (Signorelli & Kohl, 2004)
- Thermal conductivity λ and heat production rate A for each modeled formation - defined according to the study of Schärli & Kohl (2002) and to the Western Switzerland Geothermal Atlas (Baujard et al. 2007)
- Basal heat flux q – defined according to the Swiss Atlas (ETH and SwissTopo, 2004) and the Western Switzerland Geothermal Atlas (Baujard et al. 2007)

2.3 Gravity survey

The goal of the gravity survey was to highlight areas of lower density, affected by fault zones, constrain their extension and geometry and determine the existence of geological structures such as synclines and old sedimentary basins at depth, which might act as potential geothermal reservoir.

Data were collected using a Scintrex SG-5 gravimeter that assures a reading resolution of 1 μGal. The instrument was calibrated and stabilized following standard procedures during the week before each survey. Gravity measuring adopted a looping procedure, which involves the measuring at the base stations of the survey and of each profile at recorded time intervals, usually at the beginning and at the end of each survey and cycle. Raw data were processed taking into account the standard gravimetric corrections using the GraviFor3D code developed at the CREGE. One of the main advantages of this code is the high accuracy of the plateau and topographic corrections, which are computed simultaneously using a Digital Terrain Model (DTM).

The gravity effect is computed using an exact formula for a rectangular prism (Blackely, 1995; Parasnis, 1996). Topography is therefore discretised into prisms and the effect of each prism on the gravity stations is then computed. The high resolution DEM (LIDAR-0.5m per pixel, SITN 2011) and the 25m DEM (MNT, 25-Swisstopo 2011) modelling of the region were a courtesy of Système d'information du territoire neuchâtelois (SITN). Moreover the GraviFor3D code allows computing the gravity effect of a discretized 3D geological model. This tool was useful to remove gravity influence of the Neuchatel Lake and, as many observations were collected in urbanized areas, also the effect of cellars and basement was removed. The residual gravity data set has an uncertainty of 70 µGal. Such resolution allows us to characterize gravity anomalies bigger than 150 µGal

2.4 Soil gas sampling

In the framework of the GeoNe projects CO_2 and He were sampled along three gravimetric profiles running perpendicular to selected fault zones. This approach allowed comparing the local gravity signal to the variation of the concentration of these two gases. Samples were collected from small holes (0.8-1 m deep and 1cm in diameter) according to the method of Michel-le-pierres (2010) using a pump integrated to a portable gas analyses. Measurements of carbon dioxide, methane and oxygen were made directly in the field using a portable gas analyser (model LFG20, ADC Gas Analysis Ltd.). CO_2 and CH_4 are analysed by means of an infrared detector and oxygen electrochemically. Measures of the three gases were calibrated using ambient air, where the respective concentrations were 0.03%, 0.00% and 20.9% for CO_2, CH_4 and O_2.

The soil gas samples were collected in Tedlar® bags and analysed within four hours from sampling to avoid drift induced by storage of samples. The Helium analysis was performed by mass spectrometry using a leak detector type Adixen ASM 102 S (Pfeiffer Vacuum GmbH). Analyses were calibrated using a He standard 50.1 ppm and air samples collected in the field (5.24 ppm). The response of the instrument is given as linear in the range 0-100 ppm.

3. GEOLOGICAL SETTING

The canton of Neuchatel is located in the central part of the internal Jura mountains, a fold and thrust belt at the north-western limit of the Swiss Molasse Basin (e.g Sommaruga, 1997).

3.1 Stratigraphy of the Jura in the canton of Neuchatel

The sedimentary cover of the Jura is 2500 m thick and consists of rocks whose age ranges from Triassic to Miocene. In the canton of Neuchâtel, the outcropping formations are mainly Late Jurassic to Early Cretaceous limestones and marls, overlain by molassic deposits of Tertiary age and Quaternary sediments (Figure 1). The Triassic geological formations are not exposed in this area and the data presented correspond to an extrapolation of the eastern Jura. The three main aquifers present in the Neuchâtel Jura mountain area, highlighted in Figure 2, are located in the upper Malm limestones (Aquifer 1), the Dogger (Aquifer 2) and the Upper Muschelkalk (Aquifer 3).

3.2 Structural setting of the canton of Neuchatel

The internal Jura consists in a succession of folds developed on NW verging thrusts during the Cenozoic. At regional scale, the general orientation of the fold axes oscillates around the NE-SW direction (Figure 1). These folds are cut by a series of sinistral strike-slip fault systems oriented NNE-SSW, showing variable size and amplitude. Based on the rare and low-quality reflection seismic data available in this area, these faults affect the entire Meso-Cenozoic sedimentary cover (Sommaruga, 1997).

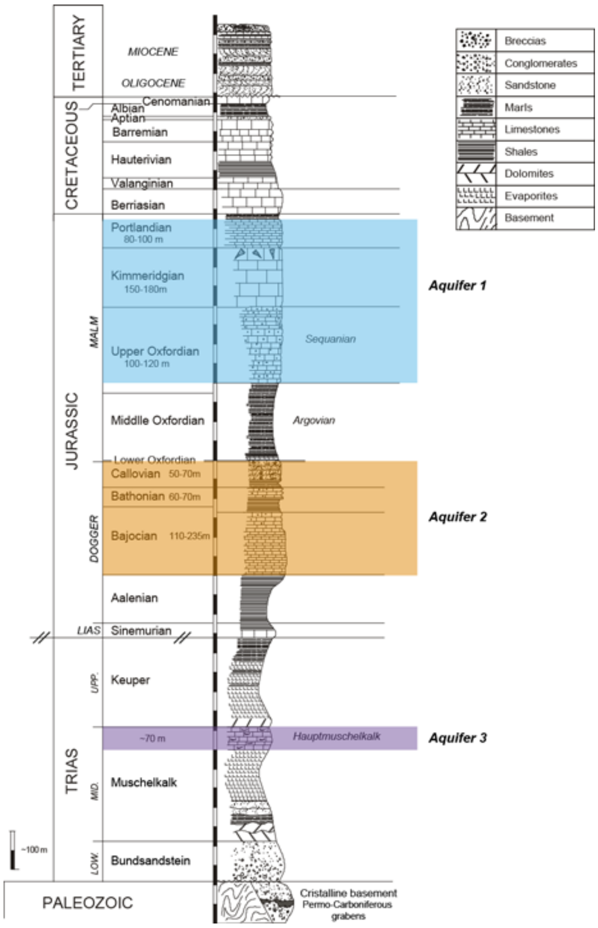

FIGURE 2: Stratigraphic pile of the Jura in the canton of Neuchatel (mod. after Sommaruga, 1997 and Valley, 2002). The stratigraphy of Triassic is extrapolated from Jordan (1994).

The structures of the study area, between Neuchâtel and La Chaux-de-Fonds consist in a series of six major ramp folds (Figure 3). These folds are cut by strike-slip fault systems oriented NNE-SSW, such as the La Ferrière, St. Blaise and Fontaine-André faults (Figure 3). The folds have a NE-SW direction, which can be locally modified by sinistral movement along important discontinuities (Figure 1).

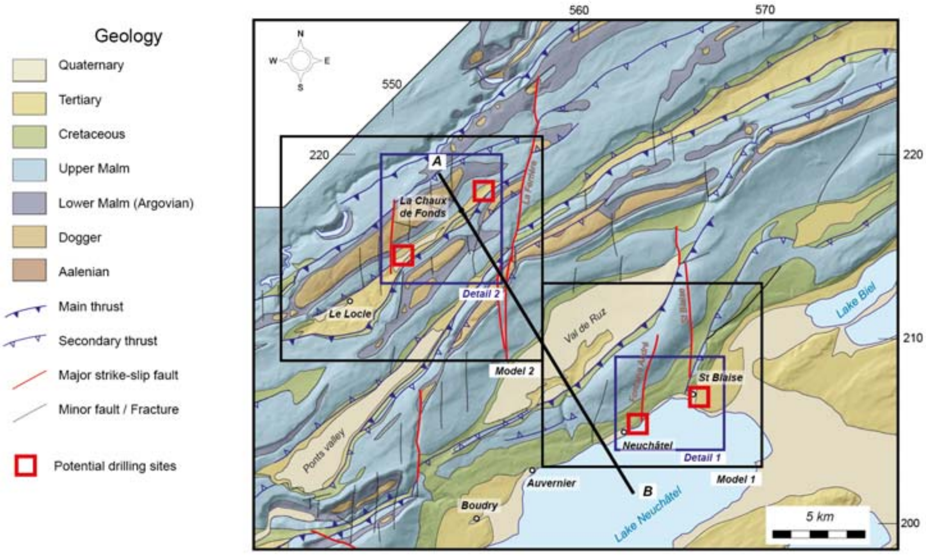

FIGURE 1: Geological map of the canton of Neuchatel showing the areas covered by the 3D geological models

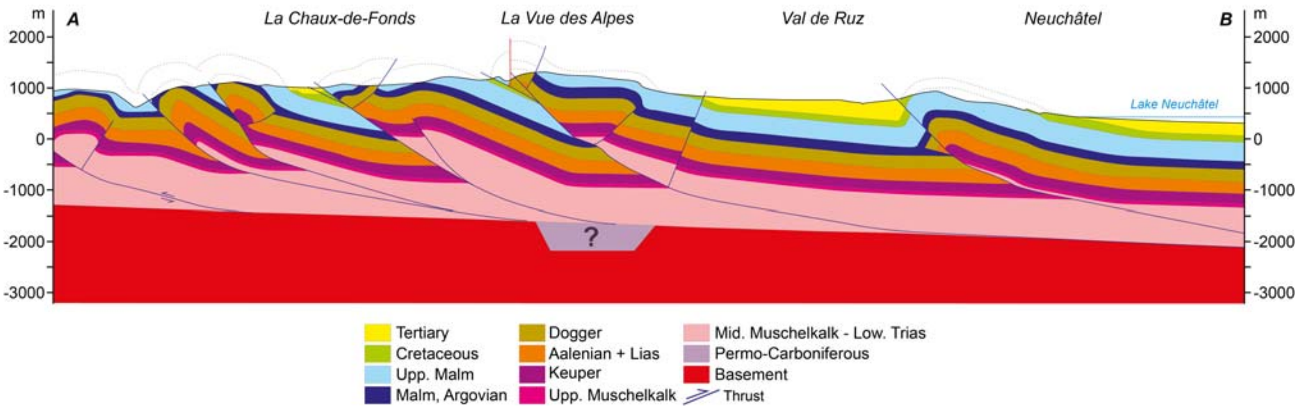

FIGURE 3: Geological cross-section along the Jura in the canton of Neuchatel (mod. after PGN, 2008). Location in Figure 1.

4. 3D GEOLOGICAL MODELLING OF THE DEEP AQUIFERS

Several 3D geological models were created in order to better constrain the geometry of deep aquifers. The employed software was 3D GeoModeller (BRGM, Intrepid Geophysics). The models were constructed using the 1/25.000 geological maps from the area (Neuchâtel, Bieler See, Val de Ruz, Le Locle-la Chaux de Fonds, Biaufond-Les Bois-La Ferrière-St Imier), and a 25m resolution DEM. The regional structure has been constrained using maps and cross-sections from: Schardt (1900), Schaer (1955) and Kiraly (1966) for Model 1; Favre (1911), Suter (1920), Suter & Lüthi (1969) and Dessor & Gressly (1859) for Model 2; as well as unpublished cross-sections from Burkhard (2002) and Meia (2004). Interpretations of seismic lines from Sommaruga (1997) have been used to constrain deep structure of the two models.

Model 1 covers an area of 12x10 km and extends to a depth of 3 km (Figure 4a). The detail Model 1 covers an area of 6x5 km and extends from the surface to a depth of 2.5 km (Figure 4b). It takes into account all the geological formations of the different aquifers (Figure 2) and secondary tectonic structures. Finally, two synthetic drilling logs (1x1 km) have been computed on potential drilling sites of Neuchâtel - Monruz and St. Blaise - Marin (Figure 4c). This strategy allowed estimating depth of target aquifers from regional to local scale.

Model 2 covers an area 14x12 km around Le Locle and La Chaux de Fonds, and was limited to a depth of 3 km (Figure 5a). The detail Model 2 covers an area of 7x7 km around La Chaux-de-Fonds and reaches a depth of 2.5 km (Figure 5b). Stratigraphy has been taken into account in more detail compared to Model 2, as well as the secondary tectonic zone of La Chaux-de-Fonds. Finally, two synthetic drilling logs (1x1 km) have been computed on potential drilling sites of Crêt du Locle and La Chaux-de-Fonds (Figure 5c).

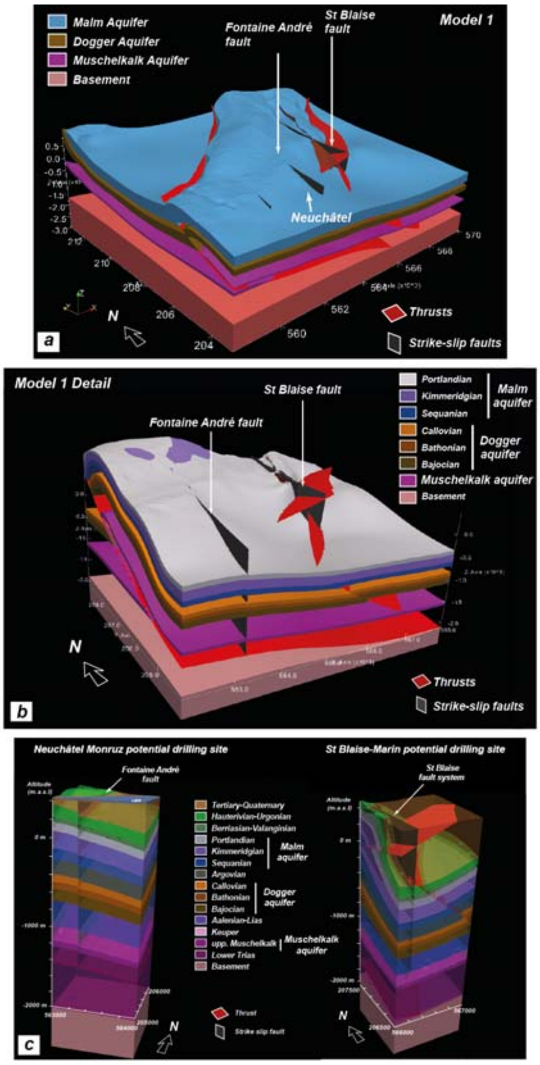

FIGURE 4: 3D geological models of the Neuchatel-St. Blaise area. Location in Figure 1.

5. THERMAL MODELLING

The goal of the thermal modelling was to get a preliminary estimation of the temperature distribution in the three target aquifers at depth. The thermal models were computed by Geowatt AG (2011) (Figures 6a and 7a). Thermal modelling for the detailed models and potential drilling sites was computed using the forward thermal modelling tool of 3D Geomodeller (Figures 6b,c and 7b,c). The thermal properties for the detailed models are reported in Table 1.

The surface temperature was defined as the mean annual temperature (10°C for Model 1 and 8°C for Model 2). The basal heat flux was set to 75 mW/m^2 and 68 mW/m^2 for Model 1 and Model 2 respectively, based on the surface heat flux data from Medici & Rybach (1995).

The temperature distribution at the top of the Dogger and Muschelkalk aquifers in the Neuchâtel-St Blaise region is presented on Figure 6b and 6c respectively. Higher temperatures are observed SE of St Blaise and reach ~50°C for the Dogger and ~65°C for the Muschelkalk.

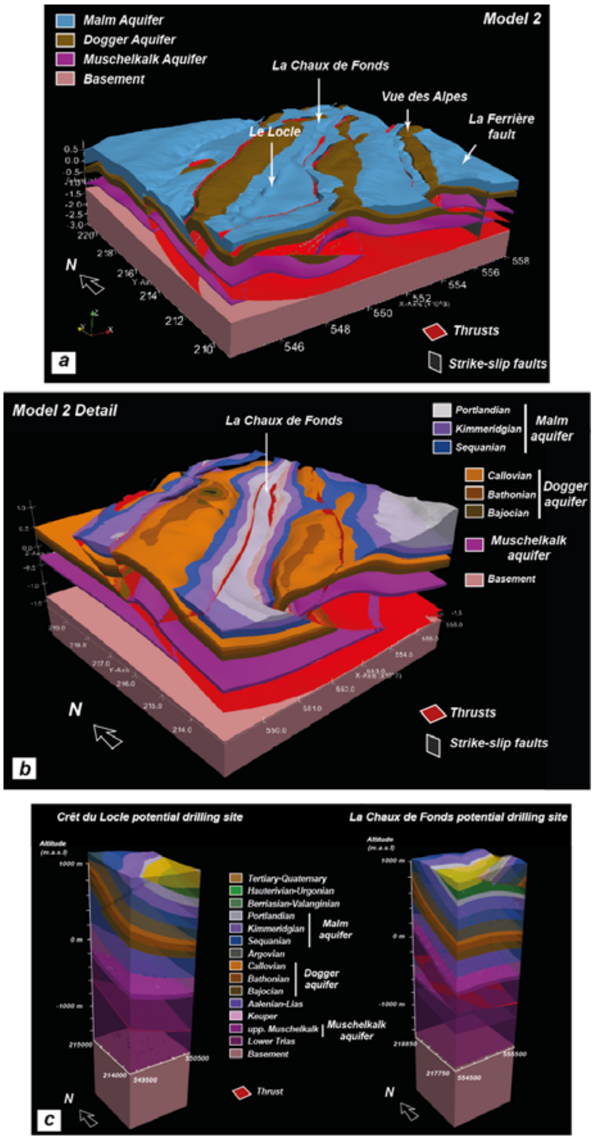

FIGURE 5: 3D geological models of the Le Locle-La-Chaux-de-Fonds area. Location in Figure 1

Table 1: Rocks thermal properties for the detailed models. Data form Schärli and Kohl (2002), Andenmatten and Kohl (2003) and this study.

		Thermal conductivity (λ) W/m.K	Heat production (A) µW/m3
	Tertiary	2.2	0.5
Cretaceous	Hauterivian-Urgonian	2.9	0.25
	Berriasian-Valanginian	3	0.25
Upper Malm	Portlandian	2.8	0.5
	Kimmeridgian	2.9	0.5
	Sequanian	2.6	0.5
Lower Malm	Argovian	2	1
Dogger	Callovian	2.5	0.25
	Bathonian	2.6	0.25
	Bajocian	2.6	0.25
Aalenian	Aalenian-Lias	2	0.7
Trias	Keuper	3	0.8
	Upper Muschelkalk	3.1	0.4
	Lower Trias	2.7	0.9
	Basement	3.1	2.8

The temperature distribution at the top of the Dogger and Muschelkalk aquifers in the La Chaux-de-Fonds - Crêt du Locle region is presented on Figure 7b and 7c respectively. Higher temperatures are observed SE of la Chaux-de-Fonds where the Dogger reaches ~35°C and the Muschelkalk ~55°.

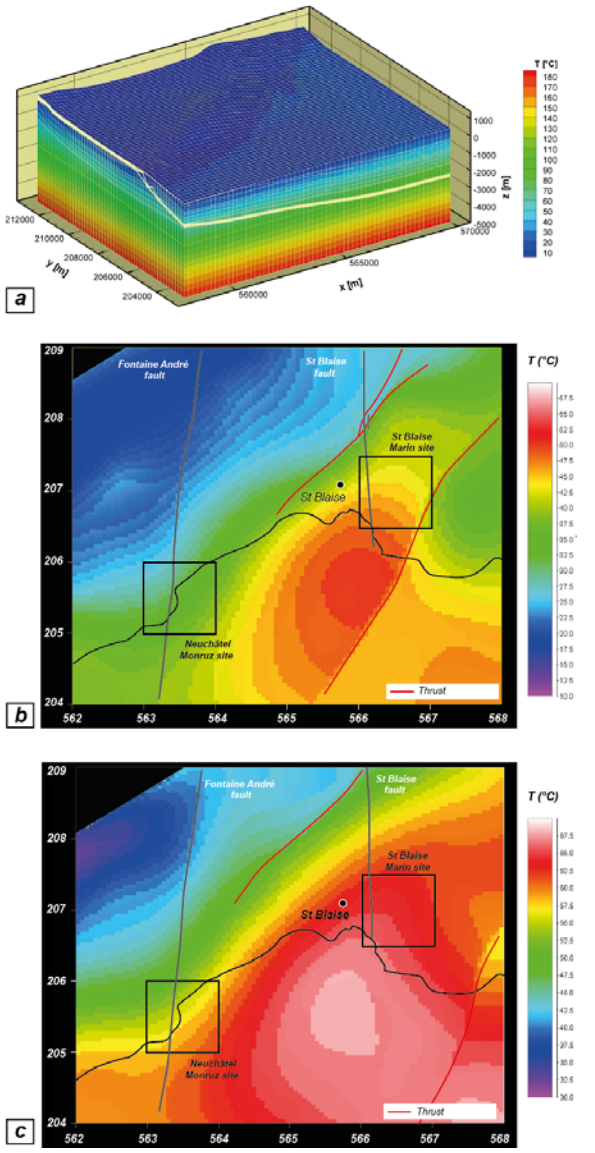

FIGURE 6: 3D temperature distribution of the Neuchatel-St.Blaise regional Model 1 (a) and temperature at the top of the Dogger (b) and Muschelkalk aquifers (c) for the detailed Model 1.

6. GRAVITY SURVEY

A gravity survey was carried out and 2100 gravity stations were collected over an area of 145 km^2, which were merged to the gravity stations available from the Gravity Atlas of Switzerland (Klingele & Olivier, 1980).

Figure 8 shows the residual Bouguer Anomaly of the Neuchatel-St.Blaise areas after processing the raw data to remove the earth tide, instrumental drift, latitude, altitude, Neuchatel lake and cellars effects and to apply the Bouguer correction and the removal of regional trends. For each GeoNE gravity station, the overall uncertainty is calculated to be below 0.070 mGal. Such uncertainty allows characterizing gravity anomalies with amplitudes 0.150 mGal or larger.

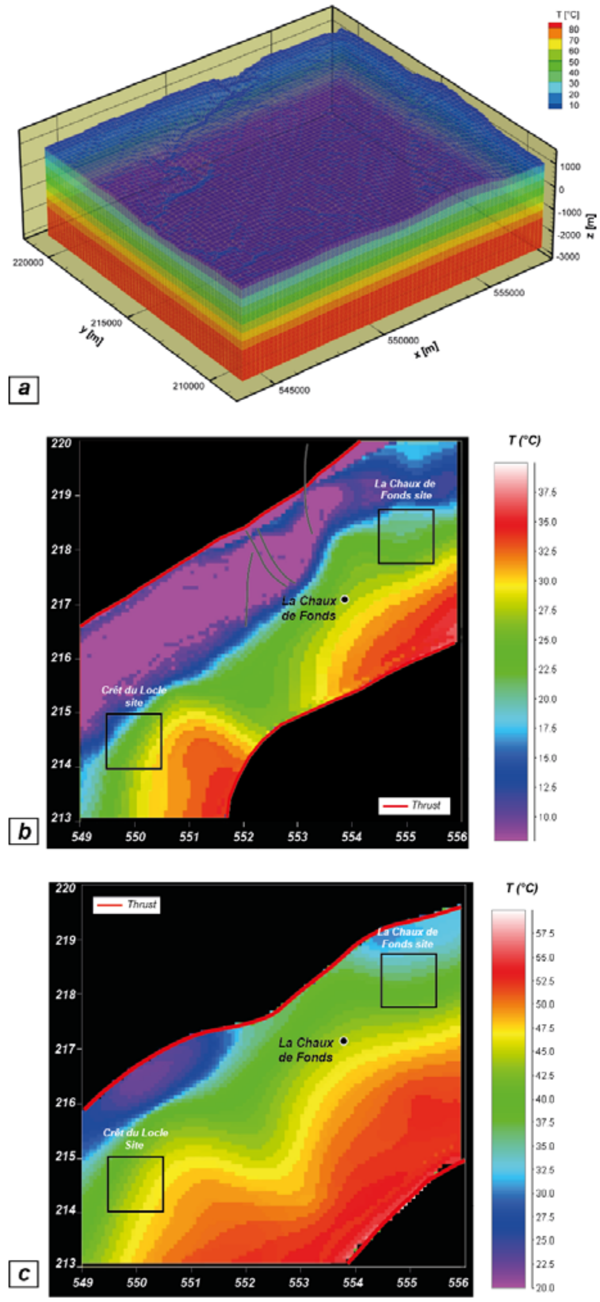

FIGURE 7: 3D temperature distribution of the Le Locle-La-Chaux-de-Fonds regional Model 2 (a) and temperature at the top of the Dogger (b) and Muschelkalk aquifers (c) for the detailed Model 2.

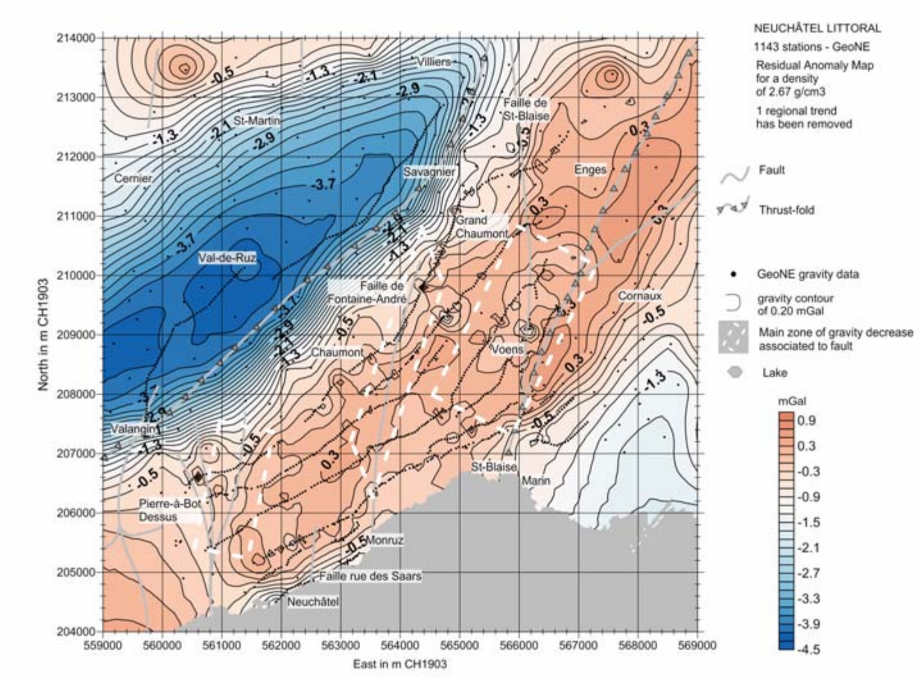

FIGURE 8: Residual gravity anomaly of the Neuchatel-St.Blaise area

This map highlights the existence of gravity anomalies related to:

- Post-Mesozoic sedimentary deposits, which are located in the Val-de-Ruz and in the area east of Marin City. These gravity anomalies, covering several km^2, are greater than 1 mGal.
- Sudden gravity contrasts due to the presence of thrust fronts. The most important being the anticline of Chaumont. Their associated gravity anomalies are several kilometres long and are restricted to the edge where they overlap.
- Local gravimetric variations with low amplitude (less than 0.8 mGal) are due to the presence of faults. These faults have a major strike-slip, creating lateral lithological contrasts. In addition, they can be locally responsible for mechanical alteration of the rock creating local variations in rock density around fault zones, which result in small variations in gravity. In the region of Neuchâtel - St Blaise, this is particularly visible on the St. Blaise, Pierre-à-Bot and Fontaine-André faults.
- Very low amplitude (less than 0.3 mGal) gravimetric variations, extended over several kilometres, which are due to lateral variations in lithology and low density variations within the same lithology

The S.Blaise fault represents a nice example of how 3D geological modelling and gravity can be jointly interpreted to highlight the density variations related to a fault zone. The formation of this fault system is contemporaneous to the Chaumont thrust and strike-slip tendency allowed accommodating of the deformation and consequently rotation of the axis of the Chaumont anticline. Most of the faults associated with this fault system are very small (less than one kilometre) and have very little throw. Therefore, only the most important faults have been reconstructed into the geological model. Some gravimetric profiles were collected across the area of St. Blaise and the gravity signature of the residual map shows some variations in correspondence to the St. Blaise fault (Figure 9).

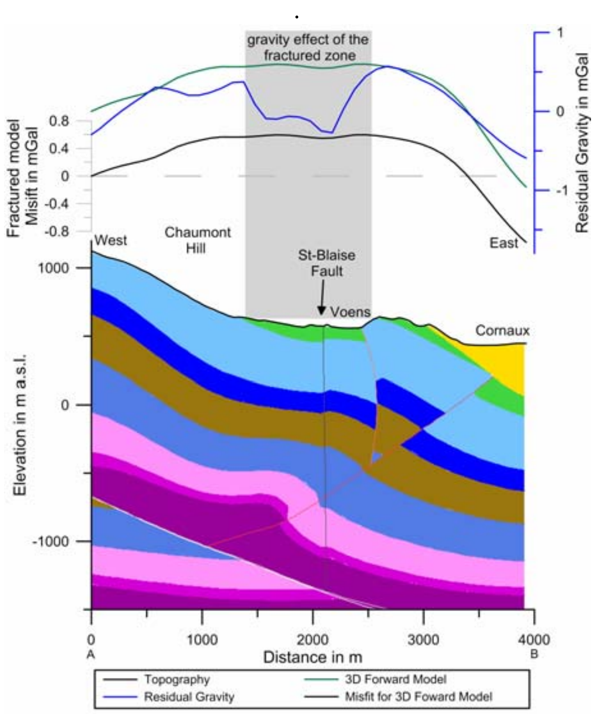

FIGURE 9: Comparison between the 3D geological model, its gravity effect (green line) and the field observations (blue line). The brown line represents the topography and the black line is the misfit between gravity observations and effect of the model.

The effect of the St. Blaise fault is the result of two sources of gravity changes. The first source is the small vertical offset of geological layers along the fault plane. The gravity response of the geological model (green curve) shows the effect of the fault marked by amplitude of about 0.3 mGal. The second source of gravimetric anomaly is likely due to a decrease in the density of the rocks in the fractured zone associated with the fault of St. Blaise. The gravitational effect of the total fault of St. Blaise of about 0.3 mGal is clearly marked on the residual gravity profiles (blue curve). The gravitational decrease of the geological layers offset is estimated at about 0.1 mGal (green curve). Therefore, the gravitational effect due to the decrease of rock density, caused by the fracturing near the fault is less important than the total measured residual anomaly. At this stage of knowledge, it is not possible to accurately quantify the loss of rock mass in the fractured zone.

In the La Chaux-de-Fonds region (Figure 10) the thrust front of La Petite Crosette, which marks the southern edge of the city, creates a strong gravimetric contrast with the sediments filling the valley.

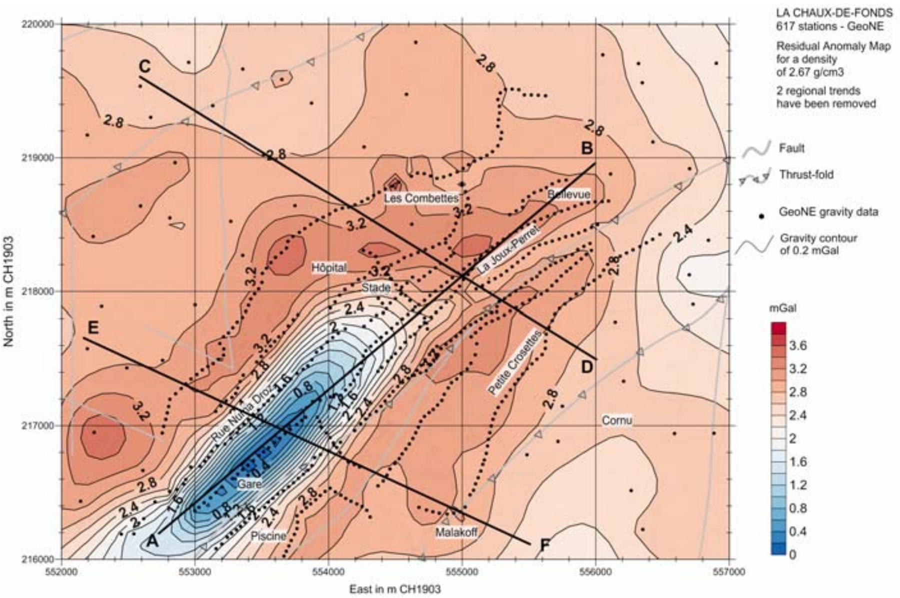

FIGURE 10: Residual gravity anomaly of the La Chaux-de-Fonds area

This is due to the density contrast between the rocks involved in thrusting (limestone and marl) and the post-Mesozoic sediments, which fill the valley.

Other thrust fronts (in the northwest and southeast corners) do not show a specific gravimetric signature. This is likely due to the fact that the types and densities of these rocks (limestone and marl) are similar on both sides of the thrust fronts.

In the area of La Chaux-de-Fonds, the main fault is located northwest of the city and is composed by a system of several small NS oriented strike-slip faults (Suter & Lüthi, 1969), which locally accommodated the deformation. This fault system has no gravity signature, unlike the faults of the region of Neuchâtel. This is probably due to the fact that the faults of the region of La Chaux-de-Fonds have little or no offset and the fractured zone is thin.

7. SOIL GAS SAMPLING

Soil gas samples were collected along three profiles intersecting known faults or fault zones in the Neuchatel-St. Blaise area (Figure 11).

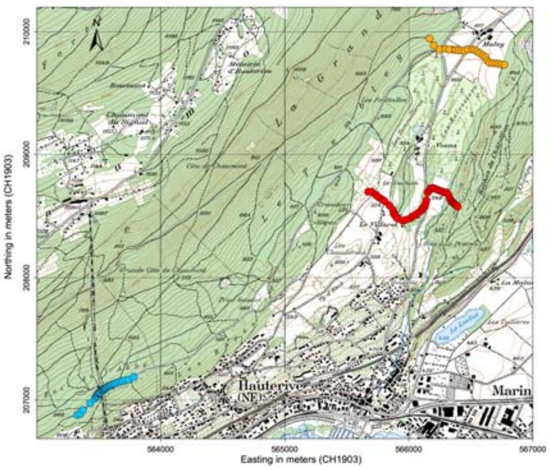

FIGURE 11: Map showing the location of the three profiles for gas sampling. (blue: profile 1, red: profile 2; orange: profile 3)

The first profile runs perpendicular to the fault of Fontaine-André. The results of the first profile are not discussed as their quality is insufficient. Several factors are responsible for these results. The surface layer consists of a humus layer overlying the bedrock. The outcrops are numerous and the thickness of the humus rarely reaches the desired depth for the sampling campaign, 90 cm. In the thin soil, rock fragments and many roots make the drilling difficult and sealing between the copper probe and soil questionable.

Figure 12 shows the results of analyses of He, CO_2 oxygen O_2 of profile 2. This section shows negative anomalies of Helium (red dots in Figure 12) to -0.2 ppm relative to the concentration of helium in air. Values of CO_2 (green dots) and O_2 (blue dots) are inversely correlated, high CO_2 values corresponding to the values of the lowest oxygen.

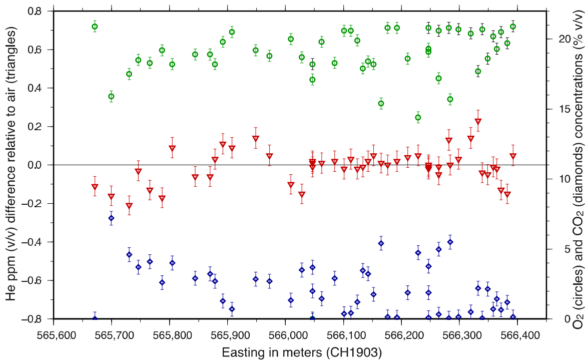

FIGURE 12: Plot of the measured concentrations along profile 2 (blue: O_2, red: He; green: CO_2)

Measurements up to two stations east of the coordinate 566'000 have been performed in a wide variety of soils resulting in a high variability of the data for all gases. An inverse correlation between the carbon dioxide and oxygen is also observed at these stations. Nevertheless, three stations located around the bend in the road, show helium measure values above 0.09 ppm over the value of the air. This positive anomaly, although very small, may be related to the presence of the fault observed in outcrop rocks located just below. The rest of the profile shows no anomaly for helium, carbon dioxide and oxygen vary probably because the biological activity in the soil.

Profile 3 (Figure 13) was collected in one day, which greatly limits the influence of weather changes that may affect the gas compositions of soils in other profiles. Helium shows two anomalies, one large scale in the western part of the profile and a second affecting two stations in the eastern part of the profile. The western anomaly is not characterized by extreme levels, the higher value measured reached just 5.44 ppm. All stations forming this anomaly were sampled and analysed in a single session and the quality of the analyses was excellent. Besides helium, the values of CO_2 and O_2 of these stations are the highest and the lowest respectively measured in this campaign, but these two gases show a very high variability of concentration. An inverse correlation between the two gases is also observed, but the positive correlation between helium and carbon dioxide is less obvious, because of the high variability of concentration of the latter.

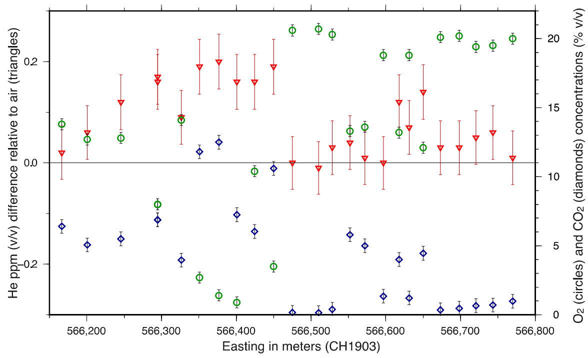

FIGURE 13: Plot of the measured concentrations along profile 3 (blue: O_2, red: He; green: CO_2)

8. POSSIBLE USE OF THE GEOTHERMAL HEAT

Within the frame of GeoNE project, the investigation on the possibilities for the use of the extracted heat was carried out for the Neuchâtel - St Blaise region by the consultants Bernard Matthey Ingénieurs-Conseils SA. The aim of the study was to analyse the different scenarios that could be used to develop the economic use of extracted heat. For Le Locle – La Chaux-de-Fonds region, a similar study was carried out by the Laboratory of industrial energy at EPF-Lausanne.

8.1 Neuchâtel - St Blaise region

For both sectors (Neuchâtel and St. Blaise Marin), the most likely scenarios according to temperature and flow rate of the resource have been proposed according also to engineering and economic parameters (B. Matthey Ingénieurs-Conseils SA, 2011):

- At Neuchâtel: the integration of geothermal low temperature fluid (15-60°C) to the existing district heating network.
- At St-Blaise-Marin: pre-sizing of distribution networks and high-temperature heat from a central heat production with a share of geothermal energy from 54 to 58% by considering a centralized heat production.
- At St-Blaise-Marin: pre-sizing of distribution networks in low enthalpy ~20-30°C with a heat output according to a decentralized heat production.

For Neuchatel, to measure the competitiveness of the delivered geothermal heat, we considered the selling price of ~14 ct/kWh practiced by the current operating network. The exploitation of Malm at 20°C (10 to 15 l/s) is unfavourable (respectively 25.6 and 20.3 ct/kWh), except in case of resale of drinking water. The production from the Dogger is competitive from 15 l/s (15.6 to 11.6 ct/kWh). The exploitation of the Muschelkalk is usually very competitive (12 to 9.8 ct/kWh). The extra cost of drilling is partly absorbed by improving the performance (energy costs) with the operating geothermal installation running with T>50°C. In terms of quality of the geothermal resource, the objectives are a flow of 15 l/s and a temperature of 40°C. Below these values the resource is exploitable, but in less favourable conditions.

At St. Blaise, due to the absence of heat distribution network, the following plans were evaluated:

- Completion of boreholes coupled to a centralized network of distribution at high temperature, from the exploitation of Dogger and Muschelkalk.
- Completion of boreholes producing from both the Dogger and the Malm to run a distribution network and low enthalpy heat production facilities.

Operating conditions in St-Blaise Marin are generally favourable, particularly for distribution at high temperature. Probable scenarios, without considering the resale of water consumption, are slightly above the threshold of 14 ct/kWh.

8.2 Le Locle - La Chaux-de-Fonds region

Three types of scenarios were considered for the valorisation of a geothermal resource in La Chaux-de-Fonds (Gerber & Maréchal, 2011):

- Integration of produced geothermal heat to existing heating network using heat pumps;
- Cogeneration of heat and power using available other resources (wood or waste heat) coupled to geothermal;

All the scenarios provide improvements over the current situation in terms of annual profits generated. This is mainly due to the substitution of natural gas. Although this study can be continued and improved on many points, some trends emerge from the analysis and optimization of these different scenarios.

It first appears that the limited availability of wood prevents an efficient exploitation of the resource either by hybrid or ORC plant exploiting the waste heat from an incineration plant.

Integration into the existing heating system via heat pump seems the more promising and allows a significant reduction in annual operating costs. A comparison of three configurations indicates that deeper resources in the Muschelkalk, appear to be slightly more profitable than the shallower resources in the Dogger, even if the investment is higher.

A final important point to mention is the effect of the temperature level of the heating network distance, which is relatively high and penalizes the coefficient of performance of the heat pump system. It would therefore be interesting to study the possibility of reducing the temperature of the heating system, even building a second network, independent from the first, and operating at low temperature as part of the extension of the existing network. If this option is considered, it might be possible to use direct heat from the Muschelkalk without using heat pumps, which would significantly reduce investment and operating costs related to the integration of geothermal in the heating system of La Chaux-de-Fonds.

9. CONCLUSIONS

9.1 Neuchâtel - St Blaise region

For the region of Neuchâtel-St Blaise, two areas were separately investigated, Neuchâtel and of St. Blaise. For each area, this study has demonstrated the existence of faults associated with the existence of fracturing highlighted by a relative decrease of gravity interpreted as being related some loss in the density of rocks. This relative density reduction might indicate enhanced permeability conditions. Detailed 3D geological models show that the number of faults is more important in the area of St-Blaise, than in Neuchâtel. This interpretation is confirmed by gravimetry, which shows anomalies around the most important faults of St. Blaise and of Fontaine-André.

The study of the thermal potential of deep aquifers showed that thermal distribution in the subsurface is controlled by the geometry of geological formations. This study highlights that the temperatures of the deep aquifers increases towards the area of St. Blaise. In this study, the analysis of the quality of the 3D geological model by gravimetry showed that the geological model of the region of Neuchâtel - St. Blaise is validated for:

- Geometry of large structures, such as large anticlines;
- Distribution and limitations of different thrusts;
- Relative geometry of the deep layers.

However, inconsistencies remain on:

- Exact depth of the different formations, which can not be confirmed for the deep aquifers;

These differences between observed gravity and gravity response of the model are due to the lack of geological information on the orientations and thicknesses of geological structures. Information on flow of the aquifers remains to be determined by exploration drilling.

The 3D geological model is an essential step in the study of geothermal potential. However, there are variations between the model and reality, in particular those for the exact depth of each aquifer, which should be constrained by the realization of two 2D seismic profiles in the region Neuchâtel-St Blaise. These profiles will provide additional information on this study, which are necessary before the exploration drilling. From the point of view of heat production, the two areas show favourable conditions for geothermal heat production from the Dogger and Muschelkalk aquifers. However, the installation costs for the area of St. Blaise will be slightly higher than for Neuchâtel, because of the absence of an existing district heating network. However, the existence of large potential consumer makes the site of St. Blaise also attractive.

9.2 Le Locle - La Chaux-de-Fonds region

For the region Le Locle - La Chaux-de-Fonds, two areas were studied, La Chaux-de-Fonds and the Crêt-du-Locle. For each zone, this study has highlighted the following aspect: in both areas gravity anomalies show no fracture zone where the rock density would be lowered;

In this study, the analysis of the quality of the 3D geological model detail by gravimetry showed that the geological model of the area Le Locle - La Chaux-de-Fonds is validated for:

- Geometry of large structures, such as large anticlines;
- Distribution and limitations of different thrusts;
- Relative geometry of the deep layers.

However, inconsistencies remain on:

- Exact depth of the various formations can not be confirmed, however, for deep aquifers;
- Precise orientation of the structures along the planes of retro-duplication and overlap, when the slopes of these plans are very low.

As for the Neuchatel areas these differences in the 3D geological model are due to the lack of geological information on the orientations and thicknesses of geological structures and the realization of two 2D seismic profiles in the region will provide the necessary additional information before drilling. The temperature modelling highlights that the temperatures of the deep aquifers are increasing in the area of La Chaux-de-Fonds, being around 46°C at the top of Muschelkak located at 1650 m in depth.

From the point of view of heat production, several scenarios were tested for La Chaux-de-Fonds taking into account the possibility of integrating geothermal in existing urban heating systems. Integration into the existing heating system via a heat pump system seems the most promising and allows a significant reduction in annual operating costs. A comparison of three possible configurations indicates that resources in the Muschelkalk appear to be slightly more profitable than the resources in the other aquifers. Despite the greater investment for the Muschelkalk, the higher temperature offers a superior heat production.

A final important point to mention is the effect of the temperature level of the heating network, which is relatively high and penalizes the coefficient of performance of the heat pump system. It would therefore be interesting to study the possibility of reducing the temperature of the heating system remotely, or even build a second network independent of the first, operating at low temperature in the framework of the extension of the existing network.

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