Geothermal Exploration in a foreland basin: Study case of a Swiss City

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Abstract. Switzerland policy has changed after a national referendum last year, Swiss people have decided to use renewable energies for their energy production and consumption. This green turn, is important, however the country already used hydropower as a main source of energy. Thus wind, solar and geothermal power are also going to be developed for the good of the country. The intention is to increase the use of geothermal energy, particularly for large-scale district heating. This complete study follows five steps of exploration, from the seismic interpretation where geological structures have to be defined, and the building of a 3D geological model, then dynamic flow model, to have a better understanding of the reservoir.

1. Switzerland Sustainable Energy Policy
Switzerland utilizes different type of energies for its national production and consumption. Most of the consumption comes from liquid fossil fuel (almost 35%) and then electricity is the second source, about 25%, the rest of the consumption is divided into three sources: liquid fossil combustibles, natural gas, and other.
For electricity, the majority of generation (around 56%) is from sustainable hydropower, followed by nuclear (39%) and finally 5% is thermal plant energy production [4].
Switzerland is limited in terms of energy supply; it is a small country of about 41.285 km2 and 8 million 287 inhabitants. Hydroelectricity is the main stay of country’s own energy source, whereas photovoltaic and geothermal are perceived to not be resource constrained.
In 2007 the Swiss government decided that the nation will take a green turn and proposed the Energy Strategy 2050 described in the Energy Act. Because the country works by direct democracy, Swiss people have to vote for every law and proposition; and the national referendum on the Energy Strategy 2050 was held on May 21st, 2017, the result was clear; 58.2% of the Swiss people voted for the Energy Act [5].
The Energy act gives some guarantees to the development of geothermal energy. Under this scheme up to 50%, of the actual subsurface development cost may be reimbursed to project developers in case of a failure to find a geothermal resource.

1.1. Conceptual model and geothermal play
After all the previous parts, regarding the geology of the area it is possible to get a general overview of the conceptual model.
A conceptual model brings together our understandings of the geothermal reservoir, and the main characteristics, from the heat source, the recharge, the reservoir depth, and hydraulic characteristics. As was defined in the geology and reservoir sections, or geothermal targets are in sedimentary layers.
The geology here is far different from Iceland or others important geothermal countries of the world, like Indonesia, Mexico, Italy, where a volcanic (Magmatic) system provides the heat source. The geothermal system here is quite similar to those in Germany (Munich) or in Paris basin, the distribution of temperature is controlled by thermal equilibration through conduction, the geothermal play is a typical Sedimentary basin in intracratonic settings (figures 1& 2).

The heat source is the natural heat that is conducted from deeper in the earth, and from radioactive decay in the crystalline basement.

Permeability is in the faults, fractures and matrix of permeable layers, the recharge is the meteoritic water infiltration through the basin, the geothermal fluid is thermal waters stored in two permeable layers.

2. **Seismic Interpretation and geological modelling**

This chapter describes the interpretation of seismic data which is used to add detail to the conceptual model and allow us to build a geological model of the Lausanne basin which is of interest to the city of Lausanne for geothermal utilization. The interpretation has been made by implementing the lines of a global oil and gas projects in the canton, taking in account data from previous oil and gas prospection wells reports and seismic interpretation. Four seismic lines were processed in the city (Table 1).
2.1. Seismic Interpretation
The IHS Kingdom suite software version 2016.1 has been used to perform the seismic interpretation. It can be used for 2D or 3D interpretation, well integration with logs, production of synthetic traces, misties corrections, depth conversion, gridding and mapping, loading of various format data.

2.1.1. Reflector identification. For all the wells used in this project, the depth of these horizons was introduced as markers (formation tops), which could be projected on a nearby depth converted seismic section. When a time/depth chart is available, the markers depth was converted in TWT and could also be projected on the seismic section in the time domain. If the wells which had velocities logs available, a synthetic seismogram was calculated. If no density log was available for the well, the density was extrapolated from the velocity log. For this project the reflector identification has been made by interpolation with the closest lines, indeed any deep well is located in the area.

2.1.2. Horizon Picking. The aim is to pick the best reflector to make it fit with top formation or geological unit, the horizon could be a positive or negative seismic attribute (maximum or minimum amplitude). The picking is made by using editing tools, like an automated filling of the horizon. Due to some seismic quality problems the horizon can be refined with a manual picking or during the interpolation.

2.1.3. Depth-Time conversion. Once the interpretations on times seismic line are done, the next step is to convert them into depth in order to get an estimation of the depth of the main formations and structures; the conversion by following the three steps (final line on figure 3):

- Depth conversion of the horizons
- Depth conversion of the faults and others structures
- Depth conversion of the seismic lines

Three types of faults have been defined for the interpretation:

- Linkable faults: Faults which can be linked from a section to another one, with the same features on each, same direction, slip.
- Non-linkable faults: No link between fault on the other section, neither the same direction nor slip.
- Hypothetical fault: Structures observed on one section but cannot be identify on the other sections, structures mainly visible on pseudo-relief section.

| Profil | Method       | Length (km) |
|--------|--------------|-------------|
| LS-01  | Vibroseismic | 12,550      |
| LS-02  | Vibroseismic | 9,400       |
| LS-03  | Vibroseismic | 11,675      |
| LS-04  | Vibroseismic | 10,600      |

Table 1: Profiles of the acquired seismic lines
All these steps have to be done in this order to get the final interpretation, the main aspect of it, is that we have to use velocity data of the geological formation or issued from the geophysics and available with the giving data. For this project two Velocity maps from the previous oil and gas project, data from the national Swiss administration have been imported. The goal of the depth conversion is to visualize the structures and evaluate the depth of the top formations. With this conversion, reservoirs like Cretaceous and Malm, and the main tectonic structures at the vicinity can be identified.

Figure 3: Depth converted seismic line

A first assessment is possible after this major step on the exploration phase, first a stratigraphic study of the lines, as it is possible to see the layers are relatively plan, no overlap or major seismic event is visible. The system is not a fault dominated one, and most of the faults identified are non-correlated, it means that they are local faults affecting only few meters of the geological formations. The main correlated faults that affect a larger zone and more lines can be interpreted to be the result of regional structures.

Figure 4: Top formation dataset importation
2.1.4. Seismic interpretation results. The horizon picking is normally based on the wells data, but here no wells enough deep are located close to the lines, only three wells are located in Lausanne but are shallow. The top formation horizon picking was made with others data available on previous projects, the top formations on previous lines, were virtually expand to the new lines to make the limit the most geological feasible as possible, and follow the previous tops drawn. The second step after drawing the top of the formations is to compare the horizons at the line crossing and make them fit, to get the best geological interpretation as possible.

Finally, with the seismic interpretation, the identification of the potential reservoir and main structures is now possible. It allows a better understanding of the reservoir; we can use this depth conversion to estimate the thickness of the reservoir and build a geological model. Then, a Monte Carlo simulation provides a first estimation of the heat production, given an estimate of the general parameters such as porosity, specific heat of the rock, temperature of the reservoir, ambient temperature, and specific heat of the fluid.

2.2. Geological model
The 3D geological modeling was done with Leapfrog Geothermal from Seequent. Leapfrog Geothermal is a software capable of handling complex geological geometries and provides a unique interface that allows the integration of geothermal information such as temperature and geophysical datasets.
The software implements a special technique the radial basis function to give a dynamic solution to solve geological modelling questions. The geological data for this project comes from the previous seismic interpretation and well data. After some work on these data with csv files, the data has been imported as points in Leapfrog and the converted to meshes and structural data. The meshes determine the stratigraphic contacts in order to make geological volumes and build the geological model. The stratigraphic surfaces are shown in Figure 4 below, and they the result of the previous seismic interpretation, it will help to build the model.

Moreover, the lithology defined in the model and in the interpretation, part is based on previous geological studies, as it was detailed by official reports [3].

The main conclusion of this seismic interpretation process, apparently the western part of the Lausanne area seems to have the best features for a geothermal development, good depth for a low to medium temperature system (between 1200 – 2000m), faults are mainly localized in this part, and they affect the targeted formations. The thickness of Malm or Dogger is of interest, considering a Geothermal district heating project.

The faulting area is considered to be good for a geothermal exploration purpose, because of the permeability of the area, and a good porosity. It is also a good indicator of the possible reservoir fluid recharge zone, and fluid circulation. On this assessment it is quite clear that the next exploration step should be in this area and conducted by an exploration drilling.

The main point to notice, is the temperature, as this area is not really deep, the estimation sounds to be between 30°C and 60°C, it is perfect for the low temperature district heating project.

The resulting 3D model in Figure 30 shows the detailed geology of beneath the Lausanne area. In this model main faults of the area are imported as well as points and defined as fault in the model after being defined as structural data. Visualization of the faults is important to see them in the context of the reservoir for the next dynamic flow model step.

![Cross-section of the model](image)

**Figure 6:** Cross-section of the model
This section detailed the study done in order to get an overview of the geology of the Lausanne Basin by interpreting seismic lines, the by modeling in 3D the basin to see the main geological structures. The final analysis successfully addressed a 3D geological model of the Lausanne basin. It appears to have limitations with respect to the seismic interpretation, the result will contribute to the next section to get the hydraulic modeling.

2.3. Hydraulic modeling

From the previous seismic interpretation and geological model, the aim of this is chapter is to describe the hydraulic modeling simulation. Feflow is used to run the simulation, and it consists of a computational mesh, boundary conditions to simulate the reservoir exploitation (figure 7). As the major local fault represents the main permeable area of the basin, no more information is available about permeabilities in the Malm, the faulted zone gave us a limit to the model, it explains why the model is fault-bounded.

![3D Feflow Model for the Lausanne Basin aquifer, showing initial temperature distribution.](image)

**Figure 7**: 3D Feflow Model for the Lausanne Basin aquifer, showing initial temperature distribution.

2.3.1. Dynamic flow model. Feflow is a software made for type of modeling, particularly applied in the hydrological, hydrogeological fields. Feflow has the capability to model heat and mass flow in porous media. It is possible to simulate various combinations of hydraulic parameters and different boundary conditions. As for the previous fields, feflow is also utilized in Geothermal to evaluate the heat transfer, flooding of the reservoir.
In order to run, the software uses grids, made of meshes, nodes and elements to build a model, each of those elements have an importance on the dynamic simulation then. The resulting mesh for the Lausanne Basin model is shown in figure 7.

2.3.2. Model parameters. The parameters used to run the model are: Conductivity, porosity, temperatures, boundaries conditions, hydraulic head. The hydraulic conductivities are defined in X, Y, and Z axes in order to define this parameter on the 3D model for each layer. Each stratigraphical unit has different conductivities, those values were defined by literature or well data. Conductivities are higher in the faulted zone than the surrounding area (Figure 8 & table 2), although wells have a different conductivity, the highest on the model. We define a factor 5 between the faulted zone and the surrounding area [1]. The lithology below was defined as impermeable layer which is not going to impact the temperature transfer below.

![Figure 8: Hydraulic Conductivities](image)

**Table 2:** Conductivities used for the flow model

| Elements       | Conductivity |
|----------------|--------------|
| Molasse        | $10^{-10}$   |
| Cretaceous     | $10^{-6}$    |
| Upper Malm     | $10^{-6}$    |
| Lower Malm     | $10^{-7}$    |
| Argovian       | $10^{-8}$    |
| Faulted Zone   | $5.10^{-5}$  |
| Well Casing    | 0.01         |
Porosity plays an important role for the reservoir parameters, in a transient simulation, because it is the parameter that defines the storage capacity of the reservoir (Table 12).

Table 3: Porosities of the flow model

| Elements   | Porosity |
|------------|----------|
| Well       | 1        |
| Carbonates | 0.004    |
| Molasse    | 0.1      |

Temperatures are defined with temperature data, loaded at the top and the bottom of the 3D model, and then are interpolated by the model. It gives a good overview of the temperature distribution as shown in figure 35. The local temperature at the two wells were also defined with fixed boundaries conditions. Reinjection temperature is fixed at 35°C, whereas for the pumping well, there is no limit in order to see the general evolution of the reservoir. A fixed temperature delta of 25°C between pumping and reinjecting.

Four flow models have been made, two of them with different rates (20 and 40 m3/L) during 40 years, in these first models the rates are not changed during the years, the aim is to see the general affect on the flooding rate and get a better understanding of the reservoir, moreover this is a good indicator of the temperature evolution within the reservoir over the years, and conclude to a future feasible exploitation and how the reservoir works on a long-time scale.

2.3.3. Simulation results. This model takes in account a full exploitation during 40 years with a rate of 20 L/s, according to the simulation results, the exploitation is viable, we fixed the temperature delta to 25°C, by planning to reinject water around 30-35°C. The impacted zone or faulted zone is defined to 80 m, a first simulation run with a faulted zone of 160m but it was inappropriate in regards of the impacted area in the Malm layers. The simulation ran during 40 years (14600 days). The results are quite decent and the temperature changes are clear on both reinjection and pumping wells. It is important to evaluate the effects of the various rate of the reservoir flooding. As we have seen
previously, for models were run, this part will detail the results and conclude about the reservoir behaviour. Full reservoir exploitation during 40 years with a flow rate of 20 L/s. This model takes in account a full exploitation during 40 years with a rate of 20 L/s (Figure 40), according to the simulation results, the exploitation is viable, we fixed the temperature delta to 25°C, by planning to reinject water around 30-35°C. The impacted zone or faulted zone is defined to 80 m, a first simulation run with a faulted zone of 160m but it was inappropriate in regards of the impacted area in the Malm layers. The simulation ran during 40 years (14600 days). The results show that the temperature changes are clear on both reinjection and pumping wells.

Feflow has in the results the Hydraulic Head estimation, which is the drawdown in the reservoir when we exploit it. The variation of the Hydraulic head for 20 L/s is roughly 35 meters (figure 11), and we can estimate the drawdown to 17.5m (half of the hydraulic head).

![Hydraulic head graph]

**Figure 11**: Hydraulic Head result of the simulation

**Table 4**: Drawdown for different flow rates

|                | 20 L/s | 40 L/s | 100 L/s |
|----------------|--------|--------|---------|
| **Hydraulic Head (m)** | 35     | 70     | 120     |
| **Drawdown (m)**       | 17.5   | 35     | 60      |

The simulation results show that, drawdown and hydraulic head grow in proportion to the flow rate. For the 20 L/s scenario (the most probable), the drawdown is insignificant, a good result for our project as it means that the reservoir is not going to be depleted rapidly.
According to the simulation results with 20 l/s a cold zone is visible at the pumping well and its vicinity. This cooling quickly appears on the simulation, few seconds after the beginning of the reservoir utilization. This cooling area is symbolised by a plume in the reservoir, that is moving North-South, East and West. The plume development is mainly going through the fault, on the pumping well direction. It seems that the fault is the path for the cold plume, it is important to notice that the plume after 40 years of simulation does not impact the pumping well. This flow rate was based on the Monte Carlo simulation, in regard of the simulation, the reservoir exploitation is feasible on 40 years. Now the second step was to take another flow rate and still by looking at the Monte Carlo simulation, 40 l/s which is really optimistic flow rate was also defined as a possibility in order to see the reservoir behaviour with this amount.

Results are clear, with this flow, the plume is going further than the one for 20 l/s approximately at the middle of both wells (Figures 12 & 13).

![Figure 12: 40 L/s plume after 40 years](image1)

![Figure 13: 40 L/s plume after 40 years](image2)

To conclude, on the simulation part, we can say even with the best case of a 40 l/s flow rate, the reservoir exploitation is still viable, as the expected flow rate shall be 20 L/s or less, and by taking in account the introduction of a seasonal variations (4 month of 20% pumping and 8 month with 100% of the flow rate), the project is feasible on a long time scale of more than 40 years.

2.4. Conclusion

This study has used previously reported geothermal and geological studies, and extensive analysis of seismic data, to build a geological model of the Lausanne Basin that is of interest to the local utility as a source of geothermal energy. The Malm and Cretaceous geological units were identified as the most important geothermal aquifers in the sequence. A decision to focus on the Malm was made due to the aquifer thickness and the Monte Carlo simulation made with the defined parameters, shows the best flow rate evaluation was about 20 L/s.
The geological model is used to build a fault-bounded flow model using feflow software, from the geological interpretation a faulted zone has been defined. This whole fractured zone is the main objective and target of the project, because of its fractures the local permeability appears to be the decisive parameter of the geothermal target. Moreover, the fault seems to be only present from the Dogger to the Cretaceous, without any link with the basement and the surface.

This concludes that the geothermal potential exists and Lausanne can have a geothermal plant and uses earth energy as a source for district heating. In light of the geological study, it appears that the faulted area in the west Lausanne has the main features for a geothermal utilization, because of the fault permeability, although more detailed studies have to be done to see if other structures exist for instance reef structures which are targeted in other sedimentary basins in Germany.

Thus, this study shows that there is geothermal potential in the Lausanne Basin. Simulation results, show that the reservoir exploitation is viable on a long-time scale, more than 40 years, with a low flow rate. The whole study, seems to underline that the Malm can be used as a geothermal reservoir, but it is important to notice that it may appears that Cretaceous has better flow rate or is more fractured than the Jurassic and has a better permeability. But the thickness is by far lower than the Jurassic, and the temperature is going to be cooler. Hence the reservoir life will be shorter than the Malm.

References

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