3D Temperature numerical computation based on geological model to quantify geothermal energy in a reservoir:

The Limagne case-study (French Massif Central)

Final Conference Vilnius, Lithania 12-15 Feb. 2008

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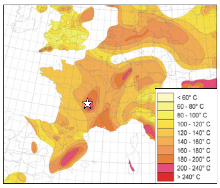
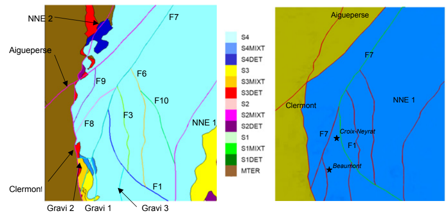
The Clermont-Ferrand basin, a part of the Limagne graben system is characterized by a geothermal anomaly with clastic reservoirs showing 100°C at 1.5 km depth. 3DGeoModeller (developed by BRGM) was used in the in order to build a 3D consistent geological model of the area. These studies were described earlier (see Calcagno et al., 2006).

The geothermal significance of the area is investigated. A full 3D unstructured Finite Element mesh is built using meshing capabilities from GEOWATT AG. This mesh is essentially based on the geological model provided by BRGM. A thermal temperature model is applied and temperatures of the aquifers are extracted from the model. Combining temperature and thickness of the aquifers, the geothermal potential of the region is estimated.



>Location of the investigated area.

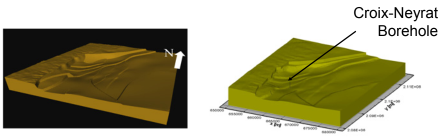
Construction of a Finite Element mesh

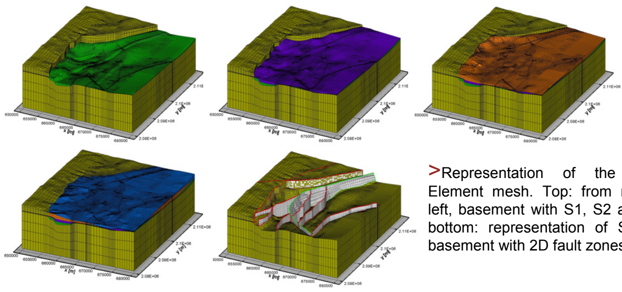


>Adaptation of the geological model to a Finite Element Mesh. Left: simplified geological map from the geological model of Dagallier (2004); right: faults taken into account into the numerical model and simplified geological map.

The geological layers were discretized using **hexahedra and prisms** (3D elements). Faults were discretized using **squares and triangles** (2D elements). The Finite Element mesh was built using the *Winfra* mesh generator and the *Orion* extension. Both tools were internally developed in GEOWATT AG. The resulting mesh is an unstructured mesh composed of more than **100'000 elements**. The crystalline basement (defined by top MTER), and a suite of 4 sedimentary units (defined by top of S1, top of S2, top of S3 and topography) were taken in account into the mesh. The faults are modelled as 2D elements, implying the use of a thickness parameter. Most of the faults are taken in account in the mesh. Most of them were assumed as vertical, except the faults F7 (northern part) and F1. These 2 faults were manually meshed in 3D in order to respect at best their deeping.

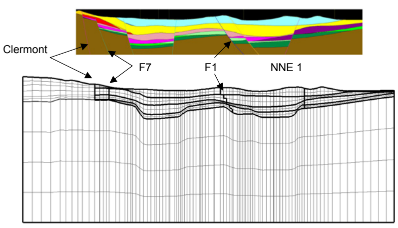
>Adaptation of the geological model to a Finite Element mesh. Left: top of the basement in the geological model of Dagallier (2004); right: top of the basement in the Finite Element mesh.

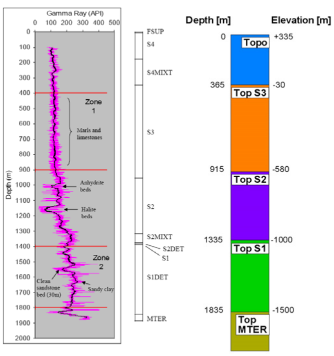




>Representation of the Finite Element mesh. Top: from right to left, basement with S1, S2 and S3; bottom: representation of S4 and basement with 2D fault zones.

>Right: Comparison at the Croix-Neyrat Borehole between a Gamma-ray Log and modelled log;
>Bottom: Comparison of a E-W crossection in the geological model and in the mesh.

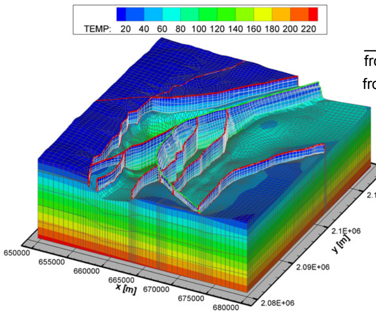


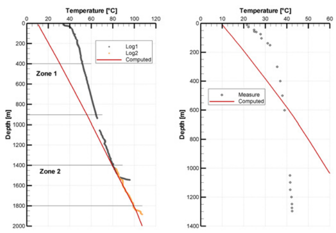


Thermal diffusive model

The diffusive thermal numerical model is realised using two boundary conditions: a **Dirichlet boundary condition** (T imposed , 10 °C) is set at the surface of the model (topography), and a **Neumann boundary condition** (imposed flux, 105 mW m^{-2}) is set at the bottom of the model. The next table gives the thermal parameters of the calibrated model.

Layer	Thermal Conductivity [W m^{-1} K^{-1}]	Heat Production [W m^{-1} K^{-1}]
from –5000 to top MTER	3.00	$3.0 \cdot 10^{-6}$
from top MTER to top S1	2.25	$0.5 \cdot 10^{-6}$
from top S1 to top S2	2.40	$0.5 \cdot 10^{-6}$
from top S2 to top S3	2.30	$0.5 \cdot 10^{-6}$
from top S3 to topo	2.20	$0.5 \cdot 10^{-6}$
Faults	3.00	$0.5 \cdot 10^{-6}$

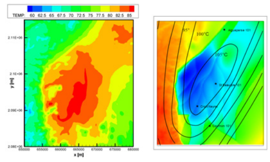




>Top: computed temperature distribution in the model (only basement and faults are shown). Computations were performed with computer code FRACTure;
>Right: comparison between available temperature data and computed temperature profiles in boreholes.

The gradient in the lower part of the Croix-Neyrat borehole (1400 - 1800 m depth) is very well reproduced in the model. Above that level, as for the Beaumont well, recorded temperatures seem to be disturbed by local water circulations, and the measured temperature could not be accurately reproduced by the model.

>Comparison between computed temperature at 1500 m depth and predicted temperature by estimation from borehole data.

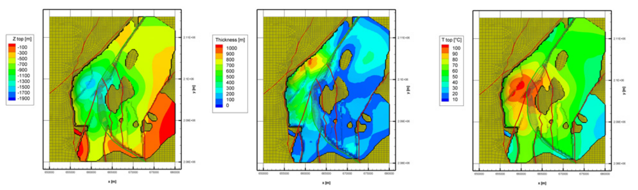


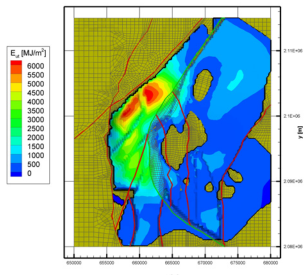
Geothermal potential of the area

The potential targets for a geothermal exploitation of the area are the aquifers of the detritic sediment layers, S1DET, S2DET, S3DET and S4DET. The geothermal potential of the aquifers S1DET to S3DET has been evaluated, S4DET being to close from the surface to constitute an interesting target.
Therefore, Heat in Place (corresponding to the total energy available in each aquifer) in each aquifer is computed, as a function of temperature distribution in the model and of the thickness of each aquifer. A recovery factor (R=E_{ut}/E_{HIP}) of 5 % is then assumed to compute the amount of energy that can be technically recovered.

$$E_{HIP} = \rho c_P \cdot V \cdot (T_{prod} - T_{reinj})$$

Example of aquifer S1DET





>Top: elevation of the top of the S1DET aquifer, thickness and temperature at the top of the aquifer S1DET;
>Left: map of the utilisable energy, in MJ m^{-2} in the S1DET aquifer, computed from the thickness and temperature of the aquifer;
>Bottom: geothermal energy computed on the domain, for each aquifer.

Aquifer	E_{HIP} [PJ]	E_{ut} [PJ]
S1DET	11'300	560
S2DET	4'700	235
S3DET	600	30

A finite element model was used in order to reproduce temperature distribution in the Limagne area. Depth and thickness of the different aquifers S1DET, S2DET and S3DET were extrapolated over the area. The calculated temperature at the top and at the bottom of these formations was extracted from the model. The total amount of energy (Heat in Place) was computed in each aquifer, and maps of the productivity (utilisable energy per surface unit) are shown.

These computations show that aquifer S1DET seems to be the best potential target for a geothermal exploitation, due to high temperatures and to a thickness up to 1000 m. This conclusion could be questioned by the fact that the hydraulic conductivity of this aquifer seems quite low (0.02 mD=$2 \cdot 10^{-9}$ m/s at 80 °C) (Dagallier, 2004). This parameter was only indirectly taken in account in the computation of the utilisable energy. On the other side, it is possible that the potential of aquifers S2DET and S3det could be higher than predicted, thanks to a good hydraulic conductivity (this is clearly the case for S3DET). The temperature model could be enhanced by better temperature data and a detailed analysis of hydrogeological behavior of the system in order to take in account advection processes in the numerical model.

> **References**

- Calcagno P., et al., 2006. How 3DGeoModeller helps to define and assess a geothermal reservoir: the Limagne case-study (French Massif Central). From Bruhn D. & Manzella A. (eds.) 2006, Proceedings of the Engine Workshop 1 "Defining, exploring, imaging and assessing reservoirs for potential heat exchange", 6-8 November 2006, Potsdam, Germany. ISBN 978-2-7159-2986-9. Orleans, BRGM Editions. Collection Actes/Proceedings. ISSN 1773-6161.
- Dagallier, A., 2004. Assessment of Geothermal Energy Potential of the Tertiary Limagne Basin (France), Technical University of Denmark.