Zwischenbericht Juni 2003

Geothermische Ressourcen

Erarbeitung und Bewertung des geothermischen Potentials der Schweiz

ausgearbeitet durch
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in Zusammenarbeit mit der
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1 PROJEKTZIELE

Ziel dieser Arbeit ist eine Erhebung des geothermischen Potentials der Schweiz. Mit Hilfe der gemeinsamen finanziellen Unterstützung von BfE und SGPK (Schweizerische Geophysikalische Kommission) wird in diesem Projekt eine detaillierte geologisch/geothermische Erfassung und Bewertung der Untergrundstruktur des Schweizerischen Mittellandes vorgenommen. So sollen Art, Mächtigkeit und Verbreitung und Grundwasserführung der Gesteine betrachtet sowie langfristig für eine Prospektion geeignete Zonen (erhöhter Durchlässigkeit oder Wärmeleitfähigkeit) kartiert werden. Für ausgewählte Standorte sollen dann die interpretierten petrophysikalischen Parameter für geothermische Nutzungsszenarien optimiert werden. Aufgrund der umfangreichen Untersuchungen ist ein Mehrjahreszeitraum für die Projektarbeit vorgesehen.

2 BEWERTUNG UND AUSBLICK BIS ENDE 2003

In der ersten Projektphase werden die notwendigen Werkzeuge weiterentwickelt, um exemplarisch diese Berechnung in einem Gebiet der Nordschweiz durchzuführen zu können. Dabei musste zunächst das vorhandene Interface-Programm zwischen den Programmen GOCAD (geologischen Modellierung) und FRACTure (physikalischen Modellierung) für beliebige Gitterstrukturen erweitert werden. Es ist mittlerweile möglich geworden, ausgehend von Bohrlochdaten und geologischen Sektionen, dreidimensionale Untergrundstrukturen zu visualisieren, zu diskretisieren und zu berechnen. Mit diesem mächtigen Werkzeug wurden danach erste Berechnungen von einem Gebiet im Zürcher Weinland gemacht. Diese Entwicklung hat international bereits grossen Eindruck hinterlassen. So sollen mit unseren Berechnungen künftig für GOCAD geworben werden. In diesem ersten Halbjahr sind zwei Publikationen erschienen:

Kohl, T. and Andenmatten, N., 2003. Geothermal data analysis from low enthalpy resource mapping, Proceedings European Geothermal Conference - 25-30 May, 2003, Szeged, Hungary

Andenmatten, N. and Kohl, T., 2003. Numerical simulations of 3-D thermal fields from GOCAD geological models. In: J.-L. Mallet (Editor), 23rd Gocad User Meeting, Nancy, pp. 1-8

Die Arbeiten gehen planmässig voran. Im zweiten Halbjahr werden für mögliche HDR Nutzung und oberflächennaher Nutzung mehrere Ziele weiterverfolgt:

- Umfassende geothermische Auswertung der tieferen Untergrundstruktur im Bereich der Kantone Aargau/nördl. Zürich
- Erste Anwendungen von GIS Systemen in diesem Gebiet, um eine Verbindung von Oberflächen-Nutzung (Industrie, Wald, ...) zu den Untergrundsystemen zu schaffen
- Erste Kartierung von oberflächennahen petrophysikalischen Eigenschaften basierend auf geologischen Strukturen und vorhandenen Datensätzen

Diese Arbeiten werden Ende 2003 in einem Bericht dokumentiert.

3 ZUSAMMENFASSUNG BISHERIGER RESULTATE

In dem Anfang 2003 begonnen Projekt sollte das geothermische Potential der Schweiz erarbeitet und bewertet werden. Im Gegensatz zu vorherigen Arbeiten wird hier der gesamte 3D geologische und topographische Kontext betrachtet, sowie deren thermischen Auswirkungen quantifiziert. Beide Ziele werden durch die Kombination der geologischen Modellierungssoftware GOCAD mit dem numerischen Finite Element Packet FRACTure erreicht. Durch das neu geschaffene Interface können sechsseitige SGrid wie auch TSOLID Tetraeder-Strukturen von GOCAD in ein numerisches Schema umgewandelt werden. Tetraeder-Modelle erlauben die Diskretizierung von komplexen geologischen Diskontinuitäten.

Erste Ergebnisse wurden von einem gut dokumentierten Gebiet der Nordschweiz erhalten. So wurde ein Struktur-Modell der Nordschweiz aus einer Vielzahl von Bohrlochdaten und interpretierten seismischen Profilen entwickelt, das ein Gebiet von über 2000 km^2 umfasst. Das geologische Model berücksichtigt bekannte Diskontinuitäten wie Störungszonen oder Trog-Strukturen wie auch die Sedimentdecken und das kristalline Basement. Das numerische Model erlaubt die Simulation des diffusiv-advektiven thermischen Feldes und quantifiziert so die Bedeutung von dichte-angetriebener konvektiver Strömung im Untergrund. Die erarbeiteten Tetraeder-Modelle wurden in mehreren Patch-Tests erfolgreich getestet. Unterschiedliche Modelle mit verschiedenen Grössen und Verfeinerungsgrad wurden entwickelt.

Mit Hilfe von FRACTure liessen sich erste diffusive-advective Simulationen aus regionalen und lokalen Modellen der Nordschweiz berechnen. Die Anwendung von GOCAD und FRACTure ist mittlerweile ein mächtiges Instrument, mit dem geothermische Ressourcen in einem Gebiet identifiziert werden können.

Kohl, T. and Andenmatten, N., 2003. Geothermal data analysis from low enthalpy resource mapping, Proceedings European Geothermal Conference - 25-30 May, 2003, Szeged, Hungary

GEOTHERMAL DATA ANALYSIS FROM LOW ENTHALPY RESOURCE MAPPING

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ABSTRACT

With increasing interest in geothermal energy, also geothermal data analysis is becoming an important issue. The portion of geothermal among all renewable energy sources in Switzerland and its undiminished growth highlight the need for regional resource evaluations. Rather 1-D models have interpreted the temperature data, systematically collected since many years, however, only now the computing power allows for joint interpretations, including for large-scale 3-D effects from geological, topographical and hydrogeological features. By our study an integrated assessment and evaluation of the geothermal potential is intended, accounting for individual utilization scenarios and their specific requirements. The state-of-the-art compilation is based on comprehensive 3D geological and thermal regional models of 20-40 km extent. Thereby, zones of significant convective flow or preferential sites for borehole heat exchanger systems (BHE) should be identified. In contrast to results obtained from earlier geothermal resource assessments, now, existing geological, hydrogeological information and petrophysical data are comprised within a full 3D numerical evaluation. First results are now obtained from a well-documented subsurface area in Northern Switzerland and from a Alpine topographies in central Switzerland. Among various studies that have been performed on these sites, we could demonstrate that geological mapping procedure provides accurate results when compared to small-scale high-resolution 3D seismic profiles. The necessity for these considerations is demonstrated by temperature data analyses.

Analyses of thermal data

A major goal of thermal potential mapping is not only the quantification of heat in place (i.e. temperature) but also the evaluation of hydro-thermal zones which allow to use the heat. Very often, these hydro-thermal zones can be identified as thermal anomaly [*Kohl et al.*, 2000] already at shallower depths. It is therefore a preferential task in our approach that a sophisticated data analysis will be carried out, that should allow to account for possible structural effects and should identify high-permeability zones in subsurface.

In the past, many global geothermal data have been interpreted on the basis of the 1-D Fourier law, relating the measured values of thermal conductivity, λ, heat production, A, and temperature gradient, ∇T, to the vertical heat flow [*Chapman and Rybach*, 1985]. Further model attempts have than accounted for fluid flow on the basis of 1-D Péclet analysis or 2-D effects [*Forster and*

Smith, 1989]. The thermal perturbations of topography [*Birch*, 1950] and transient, climatically induced ground surface temperature variations [*Cermak and Bodri*, 1995] have also been evaluated, however, on the basis of reducing these effects from thermal data, rather than accounting for simultaneously. Under typical situations of Europe with pronounced morphology, simple 1-D interpretations are often not sufficient and the temperature field needs to be evaluated solving the following thermal energy equation:

$$\langle r c_p \rangle \frac{¶T}{¶t} = \quad \nabla \cdot \left(\langle l \rangle \cdot \nabla T \right) \quad - \left[r c_p \right]_f \cdot \mathbf{v} \cdot \nabla T \quad - A$$

TRANSIENT DIFFUSION FLUID ADVECTION SOURCE

In Alpine environment, an additional uplift term would add, to account for the mixed effect of uplift and erosion. In the following sections, this equation is solved by the finite element package FRACTure in 3-D [*Kohl and Hopkirk*, 1995] [*Rybach et al.*, 1980]using a well elaborated data processing with a geological visualisation tool. The basis of our considerations are thermal data archived by the Swiss Geophysical Commission [*Schärli and Kohl*, 2002] . An extensive example will be illustrated on an area in Northern Switzerland.

Geological and numerical model

The subsurface in Northern Switzerland is well explored from nuclear waste disposal studies. Many seismological sections and boreholes have been drilled through the sedimentary cover into the crystalline basement. Fig. 1 illustrates the location of borehole data together with the structures of the Muschelkalk and Malm units and topography. The South dipping geological layers are clearly identified.

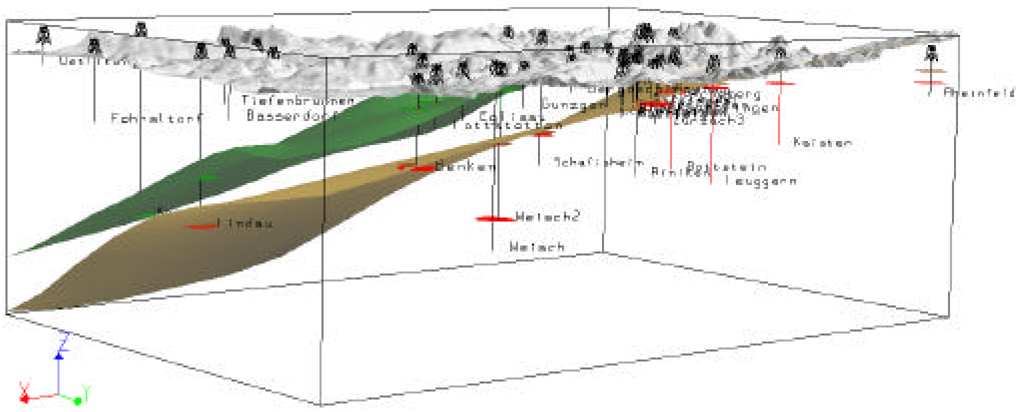

Fig. 1: Inclination of top Malm and Muschelkalk in Northern Switzerland. Available borehole data and topography are additionally shown.

The finally elaborated geological model comprised depth domains between 100 m and ~5 km and included major lithological units and local fault zones. In further steps, these results are transferred into FE schemes to highlight the possible interaction of geology and thermal transport processes.

As example of such model development a smaller subset around the Benken borehole is illustrated. Various sedimentary layers characterize the well-explored location, foreseen as preferential site for nuclear waste disposal. Top basement is at around 1000 m. Further features of interest are the large Neuhauser - Fault zone and the E-W trending permocarboniferous trough identified by several boreholes. The excellent data situation allowed to quantify the error associated by the interpolation function of geological modelling tools and also to establish a geological model which is based on numerous data sets. In detailed studies our model was compared to high-resolution seismic data: only maximum deviations of 20-40 m for the 200 and 800 m deep Malm and Muschelkalk layers were forecasted by the geological modelling tool Gocad, a fact that provides high confidence. Next, this model could be transferred into a numerical Finite Element scheme (Fig. 2) by tetrahedrisation. A first discretized model consisted of >100'000 nodes and >300'000 elements. For the thermal parameters of the 21 selected material sets the mean of measured values including anisotropy have been taken. The hydraulic conductivity was stepwise increased to evaluate their impact on a pure diffusive temperature field.

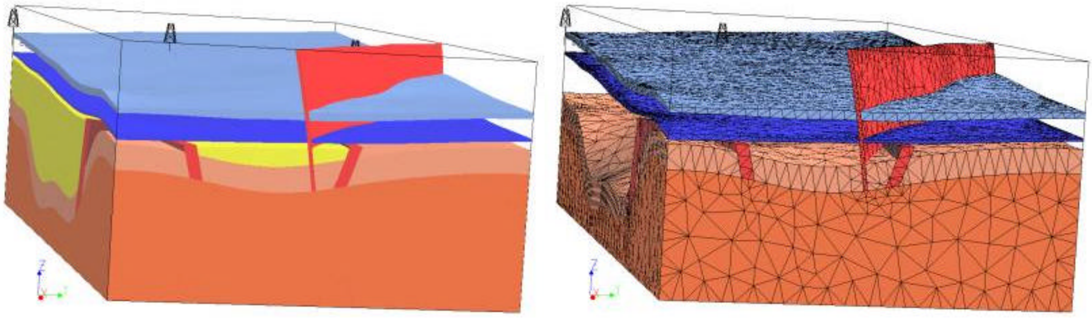

Fig. 2: Geological model (left) and numerical realisation (right) of a 20x10 km subset. The models show topography, Muschelkalk and crystalline basement. Furthermore, the E-W trending Permocarboniferous trough and the Neuhauser Fault system are also accounted for.

Model Results and Outlook

First results are obtained assuming pure diffusive thermal transport. The hydraulic conductivity was taken as $<10^{-15} m^2$, values far too low to imply significant advective drive transport. A nearly sufficient model match is obtained (Fig. 3, left) without strongly adapting individual parameters, such as basal heat flow or thermal conductivity at the location of Benken. Due to the basically pure diffusive assumption, the 3D temperature field (Fig. 3, right) is not strongly influenced by individual geological layers and a nearly horizontal stratification results.

Only by future cross-comparisons with calculations from adjacent boreholes, the validity of the present model results can be shown. The non-uniqueness of simulation results can be strongly reduced if more data are accounted for. Our experienced has shown that it is well possible to constrain 3D data by assuming identical boundary conditions. Our approach will therewith quantify deep regional boundary conditions and deeper energy transfer. Thereby, possible deep-rooted fluid circulation would be characterized by a regional analysis.

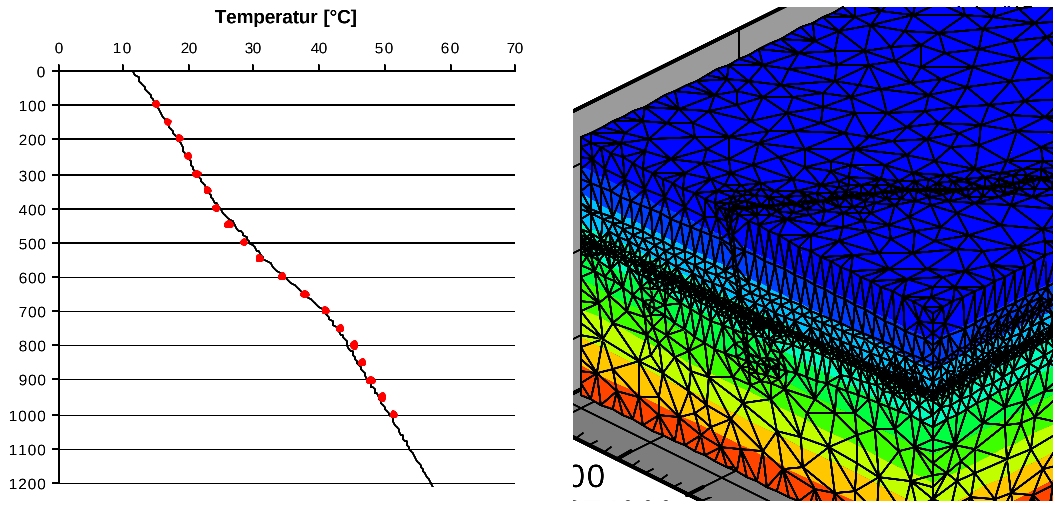

Fig. 3: Temperature data of Benken (left, red dots) and model fit (straight line). A detail of the 3D thermal model is also shown (right).

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NUMERICAL SIMULATION OF 3-D THERMAL FIELDS FROM GOCAD GEOLOGICAL MODELS

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Abstract

In a recently started project the geothermal potential in Switzerland should be assessed and evaluated. In contrast to earlier evaluations, now the full 3D geological and topographical context should be accounted for and its thermal impact should be quantified. Both topics are targeted by combining the geological modeling software GOCAD with the numerical Finite Element package FRACTure. By a new developed interface GOCAD's SGrid (hexahedral blocks) and TSOLID (tetrahedrons) were transferred into the numerical scheme. Tetrahedral models allow discretizating more complex and discontinuous geological structures.

First results were obtained from a well-documented area in Northern Switzerland. A structural model was build with GOCAD on data from numerous boreholes and interpreted seismic profiles covering an area of more than 2000 km^2. The geological model accounted for discontinuities such as fault and trough structures as well as multi-sedimentary covers and crystalline basement. The numerical model allows simulating the diffusive-advective thermal field and to quantify the significance of natural-driven fluid flow. The derived tetrahedral model has proven to be mesh consistent. Several models have been built with different sizes and refinement.
Using FRACTure first diffusive-advective simulations could be achieved in regional and local models from Northern Switzerland. The application of GOCAD and FRACTure provide a powerful tool to determine and manage geothermal resources for an area.

Introduction

Generally, geothermal resources are defined from the complex interplay of various petrophysical and geophysical processes. The current worldwide experience shows that the geothermal high enthalpy resources are often related to fractured zones. Indeed, the encouraging experience from the Soulz Hot-Dry-Rock project demonstrated that convective thermal signatures indicate well exploitable permeable fault zones. To develop a geothermal study and identify zones with significant fluid flow, it is necessary to take 3D geological structures into account.

Therefore this project aims to compile, visualize and quantify geological, hydrogeological and petrophysical data. In contrast to earlier evaluations, all those parameters will be integrated in a full 3D geological and topographical model. By combining this information with mathematical 3D models regional thermal models and individual utilization scenarios could be calculate.

On the basis of boreholes, seismic data and their interpretation, the geological modeling software GOCAD was used to interpolate geological surfaces and derived structural models. Using the mesh generator TGridlab (F.Lepage, 2002, and personal communication 2003), unstructured meshes are elaborated from the triangulated surfaces. By a new developed numerical interface (GO2FE) TSOLIDS (tetrahedral mesh) and SGRID (hexahedral mesh) were transferred into the numerical finite element program FRACTure (Kohl & Hopkirk, 1995).

Procedure

Geological analysis

The project is carried out on a well-documented area in Northern Switzerland; the subsurface is mostly explored from nuclear waste disposal studies by the NAGRA. Many seismological sections and boreholes have been drilled through the sedimentary cover into the crystalline basement.

The major data sources used for the construction of the geological model are borehole and seismic data. Interpreted profiles of 28 seismic lines representing a total of more than 420 km and data from 85 boreholes were compiled in GOCAD environment and constitute the basic material for the geological elements interpolation. Fig. 4shows the location of the data and the geological context of the region.

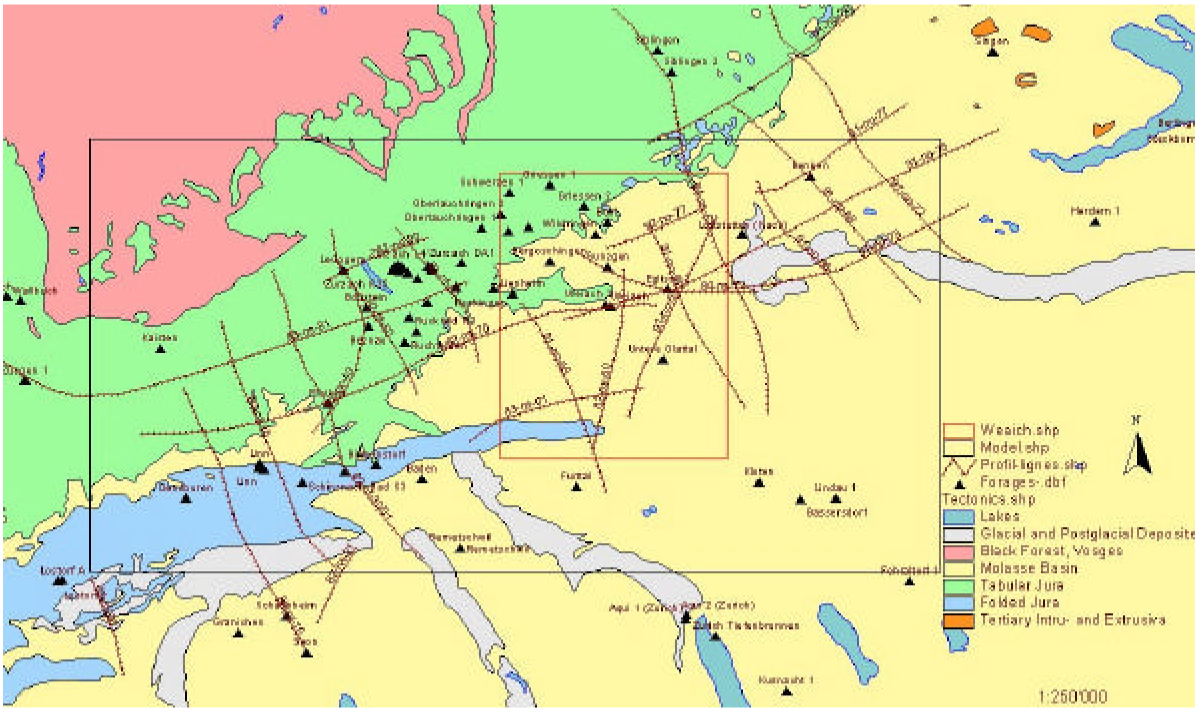

Fig. 4: Geological context of Northern Switzerland and location of the boreholes, seismic lines and the models perimeter.

On the basis of borehole data, seismic profiles, geological interpretations and literature (see NAGRA reports, Diebold P., 1991, and Naef, 1985 and 1995) the stratigraphic layers and the major structures in the area have been determined. A topological model is defined and a first regional structural model of Northern Switzerland with an extension of about 2400 km^2 (40x60 km) is build.

The discontinuities inside the area, such as faults and trough structures, constitute a complex geometry and are therefore difficult to model, in this case unstructured mesh are indispensable. Taking into account the geological data, constraints are defined on each surface contact. New triangulated surfaces are generated and the model is meshed in tetrahedral elements respecting the constraints, as illustrated on Fig. 5 and Fig. 6.

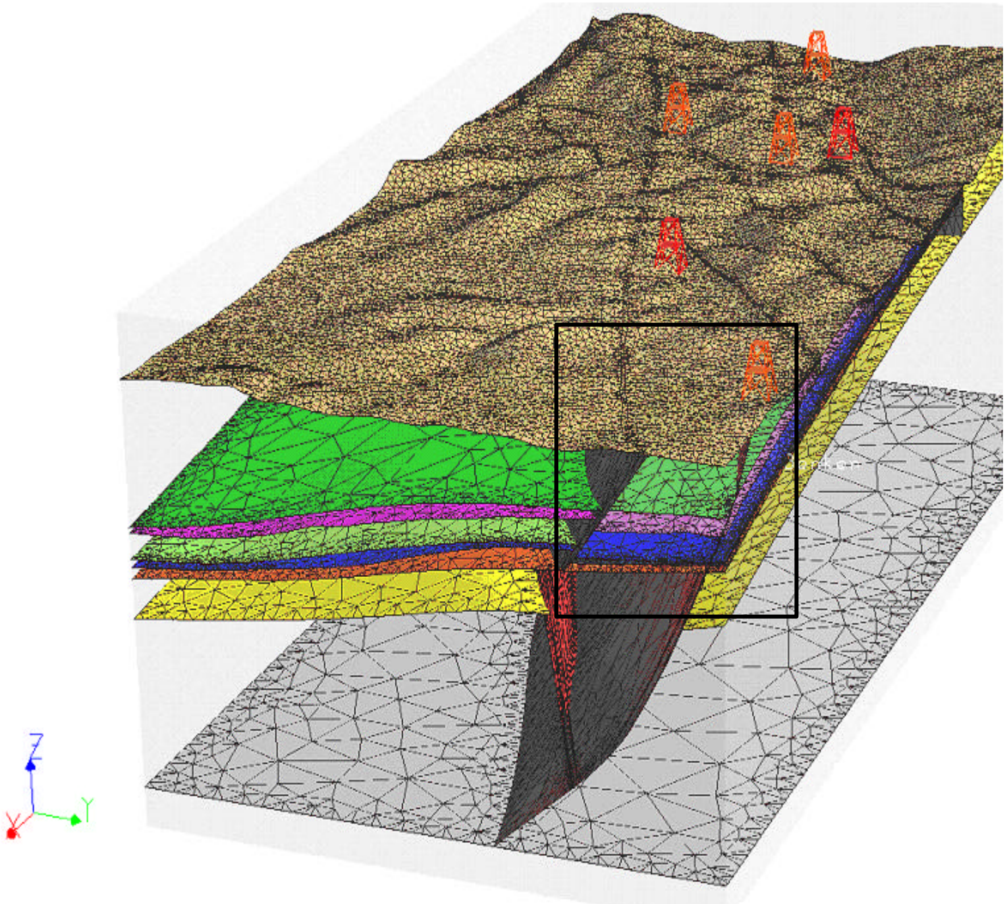

Fig. 5: Structural model of Northern Switzerland with the new generated triangulated surfaces, taking into account the Permo-Carboniferous Through and the Jura structures. In red, location of the major NAGRA boreholes is shown. Vertical exaggeration 3x

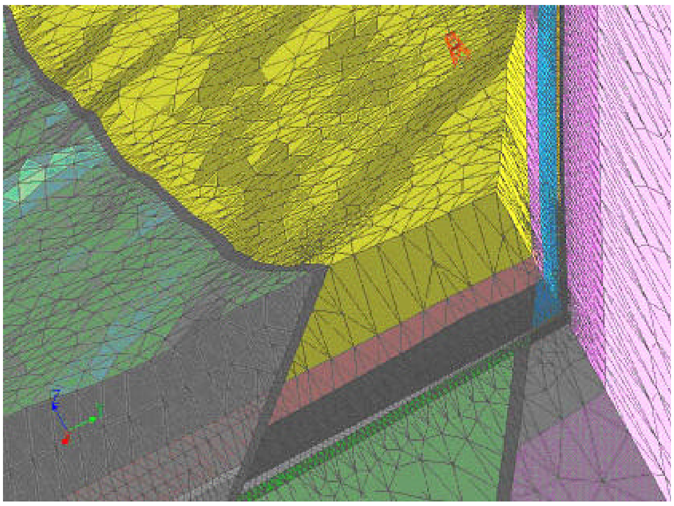

Fig. 6: Enlargement of Fig. 5 showing the tetrahedral mesh of the TSolid generated from the triangulated surfaces and the perfect fit between tetrahedral elements. Vertical exaggeration 2x.

In contrast to SGRID hexahedral meshes, the flexibility of tetrahedral meshes allows dealing with discontinuities, such as inclined faults. Fault zones are treated herein as a volume. The tetrahedrization guaranties the mesh connectivity necessary for a numerical simulation.

Based on the regional model of Northern Switzerland, local models with integrated geophysical data have been constructed. In this paper we present the local model of Weiach located in the center of Fig. 4.

Numerical Interface

The transfer from a structural / geological model to the tetrahedron model has been accomplished by the new internal Gocad plug-in TGridlab. Since we continued this approach towards a numerical quantification, a specific interface was written to combine Gocad with the numerical tool, FRACTure, a well-experienced finite element code (Kohl & Hopkirk, 1995). Clearly, these two applications are not always congruent and additional conditions need to be formulated and individual processes may require additional local mesh refinement. The newly programmed interface Go2FE has to fulfill several tasks.

Firstly, depending on the physical process, individual boundary conditions have been defined. Considering thermo-hydraulic interaction, as in our case, they should define at least the distribution of basal heat flow and surface temperature and hydraulic head or infiltration rate at surface. In our case, a uniform basal heat flow and an altitude dependent surface temperature condition is defined. For simplicity, water table was taken at surface.
Secondly, the distribution of material sets, defined already by the structural model has to be updated. The intersection of structures by fault zones or thrusting creates new region in Gocad, to witch a material property as to be assigned. Clearly, these properties have to be properly treated by the Go2FE interface since thy can become numerous in a complex model.

Finally, the created tetrahedron model needs to be checked, if all tetrahedral elements are well placed and shaped. The performed box discretization with surface topography constructed as internal structure, requires eliminating surplus tetrahedron from overburden "air" elements and from "base" elements placed underneath. Additionally, our developed routine allows establishing a correct finite element mesh by eliminating further redundancies of not well-elaborated tetrahedron (see also "Patch Test" below).

Further features of this interface are the preparation of a numerical input file that includes possible transient effects, such as thermal signatures of Ice-Age glaciation, and of heat generation in crustal units.

Numerical Scheme

The thermal and hydraulic data analysis is performed with the finite element (FE) code FRACTure (Kohl & Hopkirk 1995). This code is suited for three-dimensional coupled simulations for hydraulic, thermal and elastic processes. Besides the full hydrothermal coupling, further mechanisms such as non-linear stress dependent joint aperture laws, linear and non-linear effects of temperature or pore pressure perturbations can be treated. In addition to the newly implemented numerical interface Go2FE, a graphical mesh generator exists that allows generating semi-automatically irregular 2D or 3D FE meshes from geological or hydrogeological structures. FRACTure has already often demonstrated its capabilities for general-purpose simulations in geothermal related fields. A special feature of this code is the combination of lower and higher dimensional elements. Thus, a 1-D element can be used for calculation of transport in fault-like structures that are surrounded by 2-D or 3-D matrix elements. Furthermore, the impact on the thermal transport of topography or hydraulic groundwater flow (forced or density driven convection) can be calculated in selected regions of the model domain. FRACTure assumes complex thermal transport mechanisms, which may be written in a simplified way as follows (Kohl 1992):

$$\overline{rc_p} \times \frac{\P T}{\P t} = \nabla \times \left(\overline{l} \times \nabla T\right) - \left[rc_p\right]_f \times \mathbf{v} \times \nabla T + h \times A/V \times \Delta T$$

with T temperature, t time, $\overline{rc_p}$, heat capacity of rock, $\overline{l}$ thermal conductivity of rock, v Darcy velocity, $[?c_P]_f$ heat capacity of fluid, h heat transfer coefficient, A cross-section of heat transfer, V volume. In our model, the Darcy velocity field is calculated from the Darcy-Equation.

By defining individual load-time functions the transient evolution of selected system parameters or boundary conditions, such as surface temperature distribution, can be controlled. By discretizing an assumed climatic pattern, the temperature signals can be transferred exactly into the numerical calculation scheme.

Modeling

General

A first application to our procedure is a local model presented here. The model has an extension of 300 km^2 (20x15 km) and a depth of more than 5 km. It is situated in the perimeter of the Weiach borehole. This 2482 m deep NAGRA borehole is very well-documented and provides good quality temperature, petrophysical, hydrogeological and lithological data for the modeling.

The model is composed of 12 different material units delimited by surfaces as illustrated on the structural model in Fig. *7*:

- -sedimentary covers (Molasse, Malm, Dogger, Keuper-Lias, upper and lower Muschelkalk units)
- -Permo-Carboniferous Trough (Permian and Carbon units)
- -Crystalline basement (altered and unaltered crystalline)
- -structures (border faults of the trough and Jura overthrust).

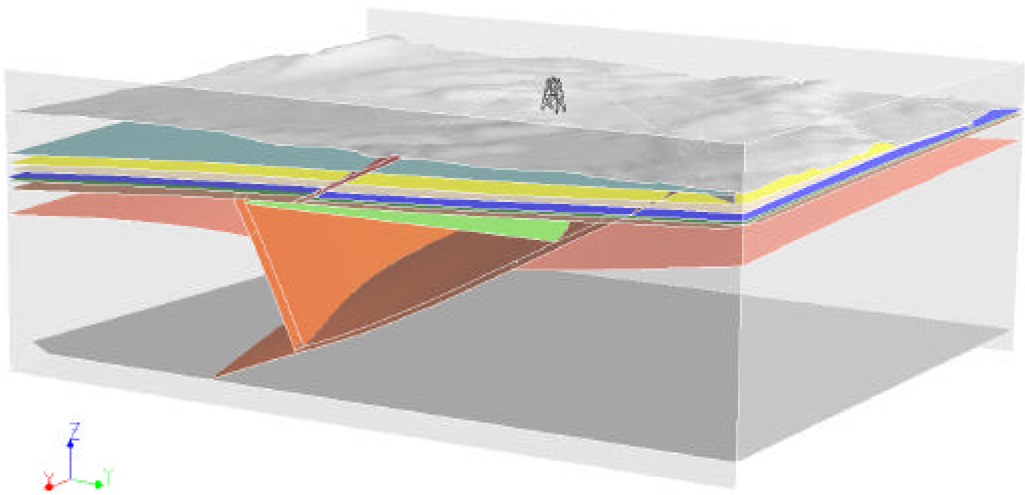

Fig. 7: Structural Model of Weiach area showing the surfaces delimiting geological units.

On the basis of the constrained structural model, a frame model has been established. Almost all the constraints could be respected. A restriction occurred when surfaces pinching out, like erosional contact between geological surfaces and topography. In this case, the problem was solved by adding vertical contact surfaces. The final tetrahedral model obtained consists of ~116’000 points and ~335’000 tetrahedral elements. A section of the model near the borehole location is illustrated on Fig. 8.

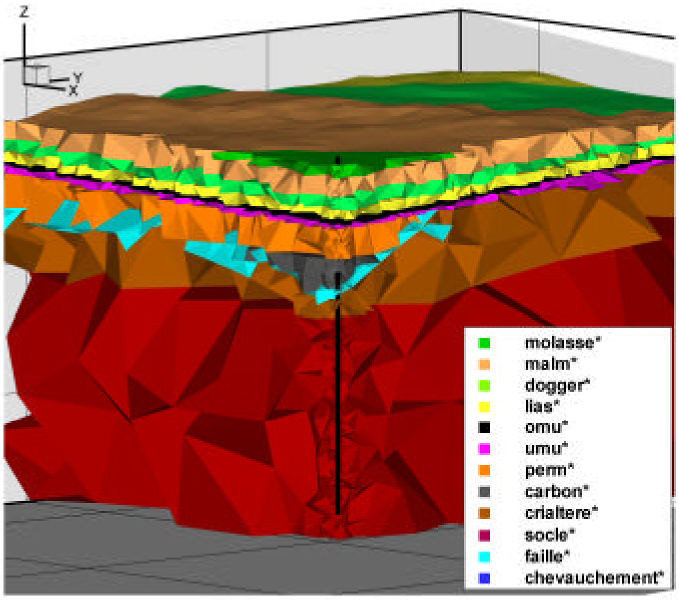

Fig. 8: Section of Weiach model near the borehole location with geological units. Individual shading can identify the tetrahedral mesh of the subsurface.

For each geological unit a set of different parameters were integrated in the model. Especially we accounted for following petrophysical parameters: thermal conductivity (perpendicular and parallel), density and heat production. The data have been measured in the Weiach borehole and are archived by the NAGRA (Nagra, 1989) and the SGPK (Schärli, 2002). We assume for each of the 12 considered geological units one material set, calculated as mean from the data.

Patch Test

In order not to apply the generated mesh as "black box" but to check its reliability, several sensitivity tests have been conducted. According to our experience, mesh accuracy is best checked by a "patch test" which investigates the accuracy of numerical parameters derived from primary variables. The results will be illustrated on behalf of the heat flow pattern that is calculated from the temperature field. However, also the fluid flow pattern (derived from pressure field) would be an appropriate parameter. For this patch test, a homogeneous subsurface was taken without any volumetric heat sources. It is only assumed that heat flows from bottom to surface. Topography represents the only "perturbation" in the model, since heat flows preferentially to the lowermost part of surface (valleys) and thus creates a near-surface heat flow variation. This variation however reduces exponentially with depth and the main model should reflect the heat flow value from the lower boundary condition.

Due to the high sensitivity of this procedure, it may be expected that even partly overlaying elements would create an additional positive anomaly in the model domain. Missing elements create a negative anomaly. Fig. 9 illustrates the result of such a patch test: as expected, only the near-surface anomalies are visible (note that topography is cut along the uppermost slice) and all interior elements represent the basal inflow value. This procedure confirms that well-elaborated meshes are obtained by the tetrahedrization..

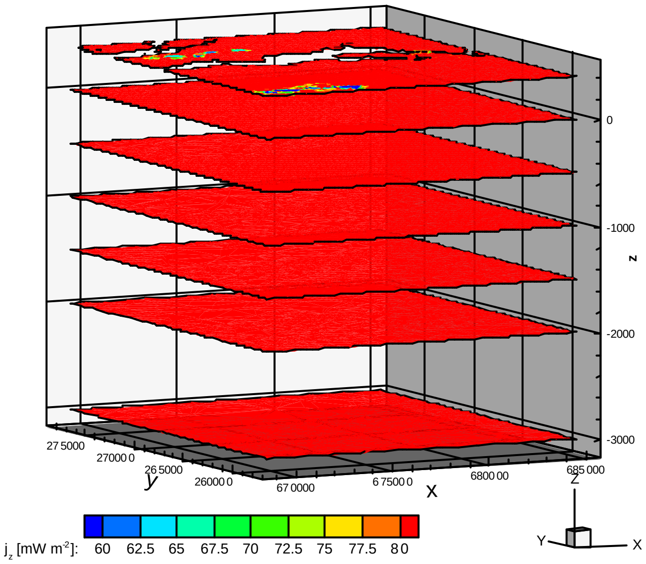

Fig. 9: Horizontal slices of the Weiach model. Surface is cut along the 400 m altitude. Furthermore, the slices at z=0, z=-500, z=-1000, z=-1500, z=-2000 and z=-3000 m (absolute altitude) are shown.

Simulation results

Fig. 10 (left) shows the calculated 3-D thermal field around the Weiach area. The thermal stratification is well visible and independent of mesh structures. At surface an altitude dependent temperature distribution was assumed (Signorelli & Kohl, 2003) that can be recognized by the 1°C temperature scale at surface temperature range. To illustrate the influence of near-surface advection, the impact of the hydraulic field to the diffusive driven thermal process was also calculated. The derived temperature and temperature gradient for the Weiach borehole is presented on Fig. 10 (right). Temperature reaches ~130°C in 2500 m.

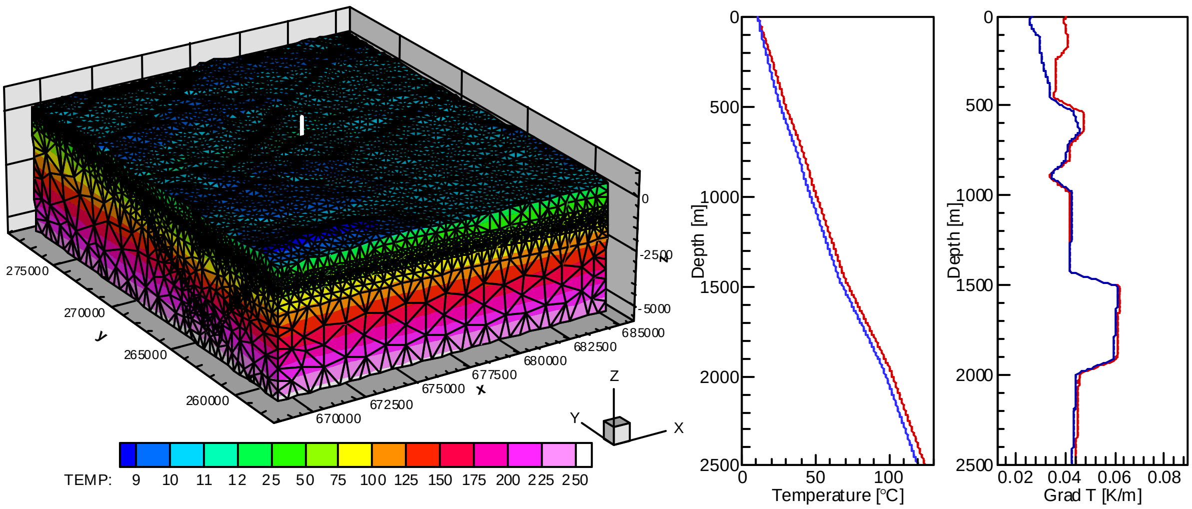

Fig. 10: 3-D temperature field with mesh discretization (left) from a pure diffusive calculation and temperature profile at the Weiach borehole (right). The location of the borehole is shown as white line in the 3-D model. The temperature curves illustrate pure diffusive (red) and diffusive-advective (blue) model runs.

The effect of fluid flow calculated in a diffusive-advective simulation is best seen on the temperature gradient curve with much lower values near surface due to the infiltration of cold fluids from higher (and therewith colder) altitudes. Borehole data from this area are generally fitted by pure diffusive modeling.

Conclusion

The successful application of Gocad and FRACTure has demonstrated that a link can be established between a 3-D geololgical modeling tool and a numerical finite element scheme. Therewith multiple and complex data can be assembled into a consistent model of subsurface. Such a procedure constitute an important step towards the targeted integrated geothermal resources evaluation

The present tetrahedralization has proven to perform good results, however further checking needs to be performed. The use of unstructured tetrahedral meshes allows modeling complex geometries and therefore evaluating the impact of geological structures. It is now possible to model 3D potential fields and not only for geothermal, but also for hydrogeological, gravimetric or electric methodologies.

Actually, these calculations are performed for local borehole models. In future, we will integrate these results in a large scale model of Northern Switzerland..

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