Abstract Volume
9th Swiss Geoscience Meeting

Zurich, 11th – 13th November 2011

20. Deep Geothermal Energy

sc | nat
Geosciences
Platform of the Swiss Academy of Sciences

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

20. Deep Geothermal Energy

Keith Evans, Nicolas Deichmann, Christoph Heinrich

Swiss Geological Society,
Swiss Geophysical Commission,
Swiss Geotechnical Commission,
Swiss Society of Mineralogy and Petrology

TALKS:

20.1 *Rybach L.: Introduction:* Status and prospects of deep geothermal energy, globally and in Switzerland

20.2 *Siddiqi G.:* Bringing Switzerland's geothermal resources to market – technological, economic and institutional challenges

20.3 *Schill E., Fisch, H., Uhde, J.:* Deep geothermal systems – advantages and limitations of using natural permeability

20.4 *Evans, K.F.:* Enhanced/Engineered Geothermal Systems (EGS) – experience to date and lessons learned

20.5 *Jung, R.:* Enhanced Geothermal Systems (EGS) - the way forward

20.6 *Deichmann N., Wiemer S.:* EGS and induced seismicity -- the good and the bad

20.7 *Driesner T., Jenny P.: Process simulation:* understanding and judging geothermal reservoir processes

20.8 *Gerber L., Maréchal F.:* Efficient conversion of geothermal resources for multiple energy uses

20.9 *Meier P., Burri P.:* Key success factors for Enhanced Geothermal Systems

POSTERS:

P 20.1 *Evans, K.F., Zappone, A., Kraft. T., Deichmann, N., Moia, F.:* A survey of the induced seismic responses to fluid injection in geothermal and CO_2 reservoirs in Europe

P 20.2 *Goertz-Allmann B. P., Bachmann C., Wiemer S.:* What can induced earthquake source properties tell us about reservoir geomechanics?

P 20.3 *Kraft T., Husen S., Wiemer S.:* GEOBEST - A contribution to the long term development of deep geothermal energy in Switzerland

P 20.4 *Schoenball M., Baujard C., Kohl T., Dorbath L.:* Changes of Coulomb Failure Stress due to dislocations during stimulation of well GPK2 in Soultz-sous-Forêts

P 20.5 *Sikaneta S.G., Evans K.F.:* Natural fractures and stress heterogeneity in the host granite of the Basel Deep Heat Mining project

P 20.6 *Zerlauth M., Ortner H., Pomella H., Schulz M., Fügenschuh B.:* Geothermal energy potential of Vorarlberg (Austria)

20.1
Prospects of Deep Geothermal Energy in Switzerland

Ladislaus Rybach[1,2]

[1]*Geowatt AG Zürich, Dohlenweg 28, CH-8050 Zürich (rybach@geowatt.ch)*
[2]*Institut für Geophysik ETHZ, Sonneggstrasse 5, CH-8092 Zürich (rybach@ig.erdw.ethz.ch)*

Deep geothermal energy resources and utilization come in two main categories: hydrothermal and petrothermal. While the first is restricted to specific subsurface conditions and does not exist everywhere, the second is ubiquitous (in principle). The utilization is mainly for direct uses like district heating, for power generation or for both ("co-generation"). The –rather arbitrary– delimitation between shallow and deep is at 400 m depth.

Hydrothermal
The goal here is to find and develop ample thermal water in deep aquifers for space heating and/or co-generation. The problem of finding is that so far no method exists to determine the water content and/or the permeability of the subsurface from surface measurements. Only production tests in deep wells can prove the suitability of a given location. This constitutes a substantial finding risk. To mitigate this a system of risk coverage for deep geothermal drillings in Switzerland was applied in the years 1988–1998 for 13 wells 655–2690 m deep, with rather limited success: 5 successes, 1 partial success, 7 failures. Expenditure was 8.7 million CHF for risk coverage and 3.6 million CHF for development support (details in Rybach 2005). Currently a Federal risk guarantee fund (150 million CHF) has been established for geothermal power generation facilities. Hydrothermal targets are deep aquifers like karstified and/or fractured limestone formations (e.g. Malm or Oberer Muschelkalk). Whereas real, regionally extended deep aquifers exist elsewhere (Paris basin: Dogger limestones, Hungarian lowlands: Pannon sandstones, which can be tapped by drilling without much exploration) the Swiss deep aquifers are rarely regionally productive: the practically dry geothermal wells Thoney/GE, Reinach/BL, Triemli/ZH or Yverdon/VD testify this. Deep water-bearing fracture zones could be more frequent but their exploration (preferably with 3D seismics) is costly. Besides, such structures are often steeply dipping (i.e. with little area-wide coverage) and of limited extent only.

Petrothermal
Due to the above-mentioned facts a widespread development of deep hydrothermal resources is hardly possible in Switzerland. Significant utilization can arguably be envisaged only with petrothermal systems (in particular: EGS). However, many questions still remain. Nowadays there is general agreement about the requirements for a technically feasible and economically viable EGS heat exchanger at depth: fluid production rate 50-100 kg/s, fluid temperature at wellhead 150-200 °C, total effective heat exchange surface area $>2x10^6$ m^2, total rock volume $>2x10^8$ m^3, flow impedance <0.1 MPa/(kg/s), water loss <10%. Although the minimum requirements for an operable EGS reservoir are herewith set, their realization in a custom-made manner to comply with differing site conditions is not yet demonstrated. Local subsurface conditions (rock temperature, lithologies, stress field properties, kind and degree of natural fracturing) can be highly variable. The key issue is to have a technology for producing electricity and/or heat from a basically ubiquitous resource, in a manner independent of local subsurface conditions, i.e. to create EGS downhole heat exchangers, wherever wanted, with the properties quantified above. In addition it will be decisive to see whether and how the EGS power plant size could be upscaled, at least to several tens of MWe. A decisive parameter in this context is the recovery factor (the fraction "extractable heat/heat in place"). The recovery factor can change with time: permeability enhancement (e.g. new fractures generated by cooling cracks or dissolution of mineral species) could increase the recovery factor, while permeability reduction (e.g. due to mineral deposition) or short-circuiting could reduce heat production. Without having field-scale experience with long-term EGS production the economic estimates about production and maintenance costs remain unsubstantiated. It is obvious from all this that EGS is presently still at the "proof of concept" stage. More details about global EGS status and problems are given in Rybach (2010).

Legal and coordination needs
Contrary to other countries it is impossible in Switzerland to obtain a concession for exploration and development of deep geothermal resources. A general planning regulation of deep subsurface usage is also lacking. A federal working group has been set up to look into this; hopefully a suitable legislation will be soon formulated (and approved by Parliament) that facilitates the development of deep geothermal resources in Switzerland.
Another need is increasingly evident: enhanced coordination. Even in small Switzerland various geothermal groups are active, with often widely diverging interests. It is evident that the manifold problems can only be solved by a concerted and concentrated acting-together of the key players (Wyss & Rybach 2010), which underscores the need for coordination. Federal and Cantonal governments, City service companies like the ones of Zurich and St.Gallen, utilities and companies like Axpo AG or Geo-Energie Suisse AG as well as other actors should join forces. The various endeavours should be merged into a generalized concept and harmonized course of action (like the one described in FEGES 2007 (Mégel et al. 2007), in order to advance the development of deep geothermal resources in Switzerland.

REFERENCES
Mégel, T., Wilhelm, J. & Wyss, R. 2007: Forschungs- und Entwicklungs-programm zur geothermischen Stromerzeugung in der Schweiz (FEGES) - Strategiepapier der Dachorganisation GEOTHERMIE.CH, 23 p.
Rybach, L. 2005: Die Schweizer Risikodeckung für Geothermiebohrungen 1987-1997 – Ausgestaltung und Erfahrungen im Rückblick. In: Tagungsband, GtV Jahrestagung 2005, S. 18-23, ISBN 3-932570-53-7
Rybach, L. 2010: The "Future of Geothermal Energy" and its challenge. In: Proceedings World Geothermal Congress 2010, Bali, Indonesia, 25-30 April 2010. Available at: www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/3109.pdf
Wyss, R. & Rybach, L. 2010: Developing deep geothermal resources in Switzerland. In: In: Proceedings World Geothermal Congress 2010, Bali, Indonesia, 25-30 April 2010. Available at: www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/3169.pdf

20.2

Bringing Switzerland's geothermal resources to market – technological, economic and institutional challenges

Siddiqi Gunter[1]

[1]*Swiss Federal Office of Energy, CH-3003 Bern (gunter.siddiqi@bfe.admin.ch)*

Switzerland's energy sources have each their own large potential and highly variable paths to deliver what the Swiss population wants in terms of power, heat/cold and transport fuels. The Fukushima nuclear accident, consumer choices and technological progress fuel vigorous debates. Politically the Federal Council - in the framework of the Energy Strategy 2050 – has projected a scenario where power from nuclear sources is no more required. Many new energy sources need to come into play – in particular for power. Geothermal energy owing to its exceptional characteristics can and should play a significant role. Initially hydrothermal resources will feature strongly, where high temperature, geothermal brine from formations or geological structures with high productivity. But as experience grows, Engineered Geothermal Systems EGS are expected to come to the fore – substantially reducing, if not eliminating, costly exploration risk.

Bringing geothermal reserves to market in a commercially viable manner requires the lowering technological, economic and institutional barriers while reducing the risks related to geothermal development to a level as low as reasonably practicable. With technological progress and experience, unit technical cost of geothermal power can be substantially reduced from today's Rp. 40-50 per kWh for geothermal resources. Hydrothermal resource development and operation are generally managed to low risk exposure and do not face insurmountable hurdles. Considering the response of the population of the Basel region, EGS induced seismicity - while very much a desired feature that testifies to reservoir development – is a major hurdle. But 5 years on, we are beginning to develop a more thorough understanding on how to reliably and predictably minimize the likelihood of causing an earthquake that harms people and the environment remains a major research topic.

Switzerland's federal administration aims to support research and development, piloting and demonstration and project development through a number of programs, for example by sponsoring various research efforts into thermal spallation drilling, a technically challenging yet highly promising method to substantially reduce unit technical well cost.

20.3
Deep geothermal systems – advantages and limitations of using natural permeability

Eva Schill[1], Hansruedi Fisch[2] & Jörg Uhde[2]

[1] *University of Neuchâtel, Emile-Argand 11, CH-2000 Neuchâtel, Switzerland (eva.schill@unine.ch)*
[2]*Axpo AG Neue Energien, Flughofstrasse 54, CH-8152 Glattbrugg, Switzerland*

The concept of hydrothermal systems in the sense of non-volcanic ressources is based on the conceptual model of deep regional aquifers. In contrast, an Enhanced Geothermal System (EGS) is defined by improvement of the natural resource (ENGINE, 2009) usually either by hydraulic or chemical stimulation. In Switzerland, major regional aquifers have been distinguished in the Molasse basin in earlier studies: the Upper Malm, the Upper Muschelkalk and the upper crystalline basement. The Upper Marine Molasse and the Dogger are considered regional aquifers in northern and western Switzerland, respectively (e.g. Müller et al., 2001, Pasquier et al., 1999), but are usually too shallow for significant power production. One of the most productive examples world-wide for heat and electric power is the Upper Malm aquifer in the German Molasse basin. The permeable reef facies in the area of Munich, however, reveals also variable productivity depending on its degree of fracturation. The productivity can be naturally enhanced, when exploiting fracture zones within the aquifer, as most recently targeted in the Taufkirchen project, and it can be limited in undeformed areas or re-filled fractures. Thus, an expected hydrothermal project can turn into an EGS project such as the case of Mauerstetten. Analyzing recent hydrothermal projects and older wells in Switzerland, we come to the conclusion that the degree of fracturation is crucial for both hydrothermal and EGS projects and that our concept of regional aquifers lacks of confirmation by productive wells.

One of the few geothermal projects with long-term experience in central Europe is the heat exploitation of Riehen (BS). The geothermal system in Riehen is in operation since 1994 and produces 65 °C thermal water from the Upper Muschelkalk at a depth of 1547 m with a production rate of 18 l s^{-1}. It is used to feed the district heating system of Riehen (Switzerland) and Stetten (Germany) and supplies 26'000 MWh_{th} per year to 202 consumers. With the project "Riehen Plus" it is planned to increase the production rate to 23 l s^{-1}. Riehen is located at the Eastern boundary of the Upper Rhine valley with SSW-NNE-striking boundary faults. The development of the Upper Rhine graben in the Oligocene caused the formation of many small tectonic units. It is assumed that the sediments of the geothermally relevant Upper Muschelkalk in this area are highly fractured. Geochemical investigation proposes that a significant contribution of geothermal fluid is coming from the Permo-Carboniferous sediments which are related to deep trough structures in the crystalline basement. This indicates that the thermal anomaly observed at 1.5 km depth is caused by a regional circulation system along deep faults.

Current hydrothermal projects in Switzerland are planned along major fault zones. Examples are the projects of GP la Côte and St. Gallen in western and NE Switzerland, respectively. In both cases known existing fault zones have been further investigated by 2D or 3D seismic. Seismic investigations reveal the outline of fault zones in the sedimentary pile and the top basement. In general, the depth of the fault in the basement is difficult to access with any geophysical method. Tests of exploration methods at the Soultz site (Geiermann and Schill, 2010; Schill et al, 2010) have shown that gravity in combination with 3D geology or seismic investigation have potential to trace deep seated structures of anomalous porosity such as the Soultz reservoir area (Baillieux et al., this volume). Recently, the CHYN has applied similar methods in the deep target zone of St. Gallen, where on the basis of a 3D seismic survey we are able to distinguish different structural elements in the gravity data, which are relevant for the determination of the drilling path. First and preliminary estimates of porosity in the target fault zone have been made. This method is again applied for the EGS prospection of the deep underground of parts of Switzerland.

REFERENCES

Baillieux, P., Schill, E., Dezayes, C., this volume. 3D structural regional model of the EGS site Soultz (Norhtern Upper Rhine graben, France): insights and perspectives

ENGINE, 2009. Best Practice Handbook for the Development of Unconventional Geothermal Resources with a Focus on Enhanced Geothermal System. ENGINE Coordination Action (ENhanced Geothermal Innovative Network for Europe), www.engine.brgm.fr.

Geiermann J., Schill E., 2010. 2-D Magnetotellurics at the geothermal site at Soultz-sous-Forêts: Resistivity distribution to about 3000m depth. C. R. Geosciences, 342: 587-599.

Müller, W.H., Naef, H., Graf, H.R., 2001. Geologische Entwicklung der Nordschweiz, Neotektonik und Langzeitszenarien Züricher Weinland. Nagra Technischer Bericht, NTB 99-08, Wettingen.

Pasquier, F., Bouzelboudjen, M., Zwahlen, F., 1999. Carte Hydrogéologique de la Suisse, Sarine, feuille 6. Commission Géotechnique Suisse et Service Hydrologique et Géologique National.

Schill E., Geiermann J., Kümmeritz J., 2010. 2-D Magnetotellurics and gravity at the geothermal site at Soultz-sous-Forêts. World Geothermal Congress 2010, Bali, Indonesia, 25-29 April 2010.

20.4

Enhanced Geothermal Systems (EGS) – experience to date and lessons learned

Evans Keith F.

Engineering Geology, ETH Zürich, Sonneggstrasse 5, 8092 Zürich, Switzerland. (keith.evans@erdw.ethz.ch)

The first Enhanced or Engineered Geothermal System (EGS - previously known as Hot Dry Rock) to be constructed was at Fenton Hill, near Los Alamos, New Mexico in 1972. There, two 2-well systems at depths of 2.8 km and 4.2 km and temperatures up to 320°C were created in gneissic rocks. Extended circulation tests were performed to evaluate reservoir performance. Since then, a further three large-scale multi-well systems have been built and tested. These include: a 3-well system in granite at Rosemanowes in Cornwall, UK (depth 2.2 km and temperature 85°C); a four-well, multi-level system in granodiorite at Hijiori, Japan (depths 1.8 km and 2.2 km and temperatures of 250 and 270°C respectively); and a 2-well and 3-well system at 3.5 km and 5 km with temperatures of 160°C and 200°C respectively in granite at Soultz-sous-Forêts in France. All reservoirs were subject to extensive circulation testing. A long-held requirement of commercial reservoirs is that the circulation impedance (the pressure difference between wells required to produce unit production flow rate) should be less than 0.1 MPa/l/s. Whilst this is not the only requirement, it is particularly important because it largely dictates the maximum flow rate that can be produced from the reservoir. This is because there are limits to the maximum operational pressure difference that can be applied between the wells that are placed by geomechanical constraints (e.g. the injection pressure cannot exceed the minimum principal stress). Of the reservoirs built and tested to date, only the Soultz 3.5 km system has met the target for impedance. For the other reservoirs, the impedance could not be reduced to the level required to yield commercial production flow rates at sustainable pressures. Lower impedance can be promoted by placing the injection and production wells closer together, but this shortens the operation lifetime of the system set by the thermal breakthrough time (i.e. the time when the cooling front from the injection well reaches the production well). So there tends to be a trade-off between impedance and thermal breakthrough time. In this presentation I will show how close we have come to meeting the circulation performance target at the four large tests sites and indicate the principal factors that limited system performance at each site.

20.5
Enhanced Geothermal Systems (EGS) – the way forward

Jung Reinhard[1]

[1]JUNG-GEOTHERM, Gottfried-Buhr-Weg 19, D-30916 Isernhagen (jung.geotherm@googlemail.com)

The heat content of the crystalline basement is in almost every country and so in Switzerland by far the biggest energy resource of the earth crust. First attempts of the Los Alamos National Laboratory in New Mexico to access this resource date back to the early 1970´th and more than a dozen research projects have been performed since than in various countries. But still the technique, known as HDR (Hot-Dry-Rock) or EGS (Enhanced Geothermal Systems) is not mature and the thermal power achieved so far from HDR- or EGS-Systems does not meet economical standards. In addition further development of this technique is now hindered by the risk of induced seismicity.

The main reason for both problems is the present exploitation concept being applied in all major projects since the early 1980´th. Until that time the crystalline basement had been regarded as an almost un-fractured rock mass and the leading concept was to connect two inclined boreholes by a number of parallel vertical fractures created one after the other by hydraulic fracturing in short insulated borehole sections. After realizing that the crystalline basement already contains open natural fractures even at great depth it was assumed that it is not necessary or even impossible to create artificial fractures by fluid injection since the formation of artificial fractures will always be preceded by shearing of the natural discontinuities. Accordingly the term hydraulic fracturing was replaced by "hydraulic stimulation" and the corresponding mechanism interpreted as a pressure diffusion process in an existing fracture network accompanied by shearing and widening of favorably oriented fractures. As a result the overall permeability of a large rock volume is irreversibly enhanced. Size, shape, and orientation of the stimulated rock volume are determined by the spatial distribution of seismic events induced during the stimulation process. The remaining task to complete the circulation system is simply to drill a second or third borehole through this seismically defined volume.

The rapid adoption of this concept in the HDR-community was to a big part due to its technical simplicity. The original concept requires deviated boreholes and packers or other devices for insulating the borehole sections selected for the hydraulic fracturing tests and the pioneering HDR-project at Los Alamos was facing insurmountable technical problems with these devices at temperatures above 200 °C. The new concept in turn can be applied in vertical boreholes and is working without borehole packers since it is desirable to stimulate very long borehole sections containing a large number of natural fractures at once. The change in the leading concept had severe consequences:

- Much larger quantities of water were required for single tests.
- The development of high temperature directional drilling techniques and packers was no longer important.
- Heat exchanging area as a measure for the service life of a HDR-system was replaced by accessible rock volume.
- Fracture mechanics was no longer relevant.

By following this easy path HDR-research has maneuvered itself into a dead end street. It is evident today that industrial EGS-Systems after the present concept will need much higher flow rates and fluid volumes as being applied so far, e.g. in the European Soultz-project or in the Basel-project. This however increases the seismic risk and it is unlikely that this risk will be accepted by the public in densely populated and industrialized countries like Switzerland.

A more promising way is to go back to the original multi-fracture concept. Directional drilling and packer technology improved significantly during the last three decades and multi-fracture concepts are applied with great success in unconventional gas reservoirs. In the shale gas projects these multi-fracture-systems are approaching the dimensions of future industrial HDR-Systems. There are differences of course: The mass flow rate of HDR-systems, their depth and temperature will generally be higher, the rock type is different and in contrary to the shale gas application the fracture systems have to be intersected by a second or even a third borehole. But considering the experiences from both applications it seems almost certain that industrial HDR-Systems can be realized in this way in the near future.

20.6

EGS and induced seismicity – the good and the bad

Deichmann Nicholas[1] & Wiemer Stefan[1]

[1]*Schweizerischer Erdbebendienst, ETH Zürich, Sonneggstrasse 5, CH-8092 Zürich (deichmann@sed.ethz.ch)*

In contrast to hydrothermal systems, which attempt to exploit hot aquifers often found in pre-existing fault zones in sedimentary formations, Enhanced Geothermal Systems (EGS) rely on the possibility to create an artificial heat exchanger in the naturally more or less impermeable rock volume of the crystalline basement. In order to increase the permeability sufficiently to allow water to circulate between two or more production boreholes, large quantities of water are injected at high pressure through a first stimulation well into the potential heat reservoir. This procedure is invariably accompanied by high levels of microseismic activity and has, in a few cases, produced ground shaking strong enough to cause public concern or even some property damage.

Fluid-induced earthquakes are a common phenomenon and in many instances society has learned to live with the associated risk. They are known to occur not only in the context of the exploitation of deep geothermal energy but also as a consequence of reservoir impoundment, fluid-waste disposal in the deep underground, hydrocarbon exploitation and underground gas storage. In all cases, increased fluid pressure counteracts the normal stress on a given fault, thus decreasing its strength. In the common situation of a tectonically pre-stressed environment with numerous pre-existing faults at all scales, this can enable the differential stress acting on a fault to cause sudden slip, thereby producing an earthquake. Even massive rainfalls are known to have triggered earthquake swarms, and fluids probably play a significant role in most other naturally occurring earthquakes as well. Due to the inherent roughness of faults, earthquake related slip generally results in an increase in permeability along the fault. It is exactly this feature that is exploited for the stimulation of a deep heat reservoir. In addition, detailed monitoring of this microseismic activity and the precise location of the corresponding hypocenters delivers the decisive input for assessing the degree of permeability increase, that is being achieved by the stimulation, and thus for designing the final EGS. In other words, induced microseismicity is not only an inevitable but also a necessary attribute of EGS development.

The big challenge is to prevent this «good» microseismicity to reach magnitudes of those «bad» earthquakes that constitute a risk to society. Although the basic principles are well understood, it is still very difficult, particularly in the forefront of a proposed project, to quantify the relative role of each of the parameters that influence the probability of unwanted earthquakes, e.g. ambient tectonic stress, rock strength, density and orientation of pre-existing faults, injection pressure, rate at which fluid is injected and total volume of injected fluids. Case studies of the few projects already underway, laboratory experiments, numerical modeling and the development of statistical tools are being pursued in an attempt to quantify and minimize the seismic risk associated with EGS projects. However, just as with every other method of energy production, it is unlikely that it will ever be possible to reduce this risk to zero. Thus, for deep geothermal energy to offer a substantial contribution to the total energy mix of our society, the equally large challenge will be to actively engage the public in a dialogue about what risks it is willing to accept in view of the possible benefits of an abundant and environmentally friendly energy source.

20.7

Process simulation: understanding and judging geothermal reservoir processes

Driesner Thomas[1], Jenny Patrick[2]

[1]*Institute of Geochemistry and Petrology, ETH Zurich, Clausiusstrasse 25, CH-8092 Zürich (thomas.driesner@erdw.ethz.ch)*
[2]*Institute of Fluid Dynamics, ETH Zurich, Sonneggstrasse 3, CH-8092 Zürich (jenny@ifd.mavt.ethz.ch)*

Permeability creation during stimulation, heat extraction, scaling in installations, early cold water breakthrough during production, and other reservoir processes are crucial for the economic viability of enhanced geothermal systems. Yet, the systematics of their behavior are still rather poorly understood, mainly because only few test sites have so far been operated and knowledge of the actual geological structure of the respective reservoirs is limited.

Numerical simulation is an attractive test bed to obtain fundamental insights into how geological parameters affect these physical and chemical processes. Depending on the problem, meaningful simulations reach from simple generic evaluations to studying coupled processes operating on complex geometries.

The latter can be addressed with a new generation of simulation tools that allow increasing realism in the model representation of geological structures, the accuracy with which the governing equations can be solved, and the size of models that can be handled within reasonable computing time. These developments center on simulating the mechanical behavior of complex fracture networks, the long-term permeability changes and scaling due to fluid-rock interaction, and the efficiency of heat extraction from reservoirs with heterogeneously distributed fracture permeability.

Such simulators allow building a knowledge base on optimal reservoir characteristics that may become a valuable tool for geothermal exploration models. Simulating "what if" scenarios may ultimately aid in decision making during reservoir engineering and operation.

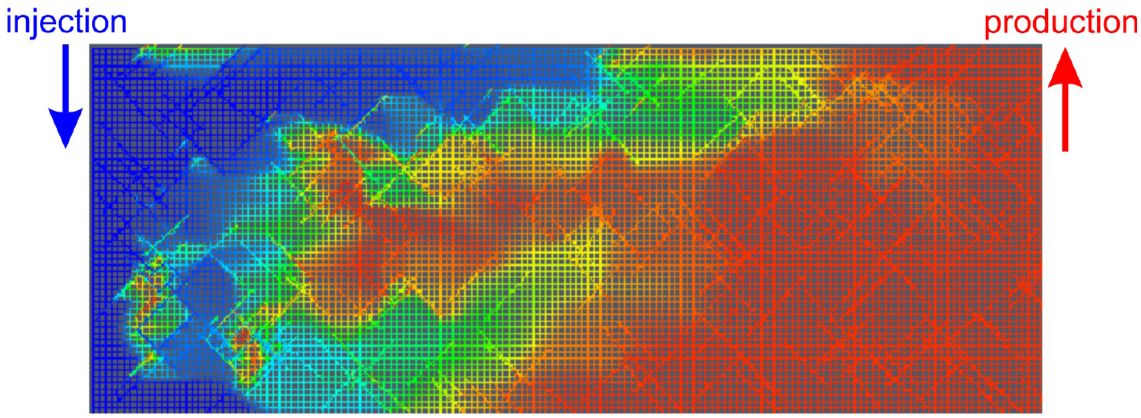

Fig.1: Non-uniform progression of cold water front (blue) from injection well (left) towards production well (right) in a highly schematic geothermal reservoir model with heterogenous matrix and fracture permeability. Simulation by D. Karvounis, Institute of Fluid Dynamics, ETH Zurich.

20.8
Efficient conversion of geothermal resources for multiple energy uses

Gerber Léda[1] & Maréchal François[1]

[1]*Industrial Energy Systems Laboratory, Ecole Polytechnique Fédéral de Lausanne, LENI-IGM-STI, Station 9, CH-1015 Lausanne (leda.gerber@epfl.ch)*

Everything is not about obtaining hot water from the ground: it has as well to be decided how to realize the best use of the available resources, and which ones of them have to be targeted in priority. Important objectives that have to be accounted for in the design of the conversion system are the maximization of its economical profitability and of its efficiency.

High temperature geothermal energy from Enhanced Geothermal Systems (EGS) can be used for the polygeneration of multiple energy services: electricity, district heating and domestic hot water. Several conversion technologies can be used for this, such as flash systems and binary cycles.

In order to choose the best conversion technology and its operating conditions, the temperature levels of the geothermal resource and of the demand in district heating have both to be accounted for. Another important parameter is the seasonal variation of the demand in energy services.

By combining models of the different technologies with models of geothermal resources and of the seasonal demand in district heating, the overall conversion system can be simulated and designed. With a simulation of all the potential combinations of technologies and resources at different depths, it is possible to identify the technological orientations that have to be favored in the future development of cogeneration from EGS.

Results for a given case study, displayed at Figure 1, show that even at low electricity and district heating prices, cogeneration of electricity and district heating from EGS is profitable. The optimal depth of the exploited resource as well as the conversion technology to be used varies depending on these prices. Except at high electricity prices, where double-flash with an EGS at a depth of 8000m is the best combination, the optimal technology is an organic Rankine cycle with an EGS at 7000m.

Figure 1. Best technology and depth of EGS in function of electricity and district heating selling prices

REFERENCES

Hoban, M., Gerber, L. & Maréchal F. 2010: Integrated Thermo-economic Modeling of Geothermal Resources for Optimal Exploitation Scheme Identification, Proceedings of the 23rd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, 14-17 June 2010, Lausanne, pp. 2239-2246

Gerber, L. & Maréchal F. 2011: Defining optimal configurations of geothermal systems using process design and process integration techniques, Chemical Engineering Transactions, 25, pp. 881-886

20.9
Key success factors for Enhanced Geothermal Systems

Meier Peter & Burri Peter

Geo-Energie Suisse AG, Steinentorberg 26, CH-4051 Basel (p.meier@geo-energie.ch)

Geo-Energie Suisse AG is the Centre of Competence for the development of deep geothermal energy created by seven Swiss utility companies. These shareholders want to join their forces and share the risks associated with the development of deep geothermal power generation in Switzerland. Most of them have already been partners of the Deep Heat Mining Project Basel. Therefore one of the most important assets of the newly founded company are the experience and the data from the project in Basel, which has been suspended in 2006 as a consequence of significant induced seismicity.

For Geo-Energie Suisse AG the focus lies on the development of Enhanced Geothermal Systems (EGS), since, given the geological setting of Switzerland, only EGS can lead to an important production of electrical power from geothermal energy (Rybach, 2011). The overall objective of the company lies a) in developing the EGS-concepts and technology further and b) in proving their technical feasibility by executing several pilot projects within the next three to five years.

The key success factors include reservoir creation, risk mitigation and predictability of induced seismicity, drilling technology especially in crystalline rocks, repeatability and long term economic feasibility and public acceptance.

Many international researchers are working since 2006 with the data from the project in Basel. Their work has resulted in a much better understanding of the processes involved with the creation of a large geothermal reservoir in crystalline rock in Switzerland and the risk of induced seismicity. A first task of Geo-Energie Suisse was therefore to compile the results from research and to identify the remaining open questions from a practical point of view. In cooperation with many specialists from industry and research the knowledge gaps are being filled by applying established techniques and tools from other geothermal research projects and also from nuclear waste disposal programs in crystalline rock.

The main objective is to identify and work on the key success factors for a new improved EGS-concept in comparison to the concept of the Basel project. Demonstrating considerable improvement since Basel-1 in understanding the mechanisms of creating artificial reservoirs and in predicting the impact of the methods, is essential to get the support of investors for a new project and gain the acceptance of authorities, politics and the population.

We will discuss the main conceptual ideas for the creation of an economically viable and safe EGS-System and show preliminary results for a horizontal multifrac-system, for which induced seismicity will be reduced and heat exchange area increased with respect to earlier used EGS-concepts. We will also discuss the main challenges for the further development and address some prioritary requirements in the interaction with government, politics, public opinion and universities.

REFERENCES

Rybach, L. 2011: Prospects of deep geothermal energy in Switzerland, 9th Swiss Geoscience Meeting, Zürich 2011

P 20.1

A survey of the induced seismic responses to fluid injection in geothermal and CO_2 reservoirs in Europe

Keith F. Evans[1] Alba Zappone[2], Toni Kraft[2], Nicolas Deichmann[2], Fabio Moia[3]

[1] *Engineering Geology, Swiss Federal Institute of Technology (ETH), Sonneggstrasse 5, 8092 Zürich, Switzerland.*
[2] *Swiss Seismological Service, Sonneggstrasse 5, 8092 Zürich, Switzerland.*
[3] *RSE-Ricerca Sistema Energetico S.p.A., Milan, Italy.*

We document 41 European case histories that describe the seismogenic response of crystalline and sedimentary rocks to fluid injection. The work is part of an on-going study to identify factors that have a bearing on the seismic hazard associated with fluid injection. The data generally support the view that injection in sedimentary rocks tends to be less seismogenic than in crystalline rocks, although the presence of faults near the wells that allow pressures to penetrate significant distances vertically and laterally can be expected to increase the risk of producing felt events. All cases of injection into crystalline rocks produce seismic events, albeit usually of non-damaging magnitudes, and all crystalline rock masses were found to be critically stressed, regardless of the strength of their seismogenic responses to injection. Thus, these data suggest that criticality of stress, whilst a necessary condition for producing earthquakes that would disturb (or be felt by) the local population, is not a sufficient condition. The present data are not fully consistent with the concept that injection in to deeper crystalline formations tends to produce larger magnitude events. Injection at sites with low natural seismicity, defined by the expectation that the local peak ground acceleration has less than a 10% chance of exceeding 0.07g in 50 years, has not produced felt events. Although the database is limited, this suggests that low natural seismicity, corresponding to hazard levels at or below 0.07g, may be a useful indicator of a low propensity for fluid injection to produce felt or damaging events. However, higher values do not necessarily imply a high propensity.

P 20.2

What can induced earthquake source properties tell us about reservoir geomechanics?

Goertz-Allmann Bettina[1], Corinne Bachmann[1], and Stefan Wiemer[1]

[*] ETH Zurich, Institute of Geophysics / Schweizerischer Erdbebendienst,
Sonneggstrasse 5, CH-8092 Zurich (bettina.allmann@sed.ethz.ch)

Hydraulic fracturing is an increasingly utilized technology to enhance the extraction of hot water or gas from a subsurface reservoir. Fluids are pressed into the reservoir formation from a treatment well at high pressures to open fractures and hence increase the permeability of the reservoir. Monitoring the seismic emission associated with the fluid injection allows to estimate the stimulated reservoir volume, and hence the effectiveness of the treatment. However, oftentimes little is known about the mechanical properties of the reservoir rocks, making it difficult to predict the response of the medium to the fluid injection. On the one hand, one would like to ensure that the fluid injection operation alters the medium sufficiently to make the reservoir economic, and on the other hand it needs to be insured that the magnitude of induced seismic events does not exceed values where shaking can affect surface infrastructure. A proper estimation of the in-situ mechanical properties of the reservoir is therefore necessary for an assessment of both the economics of reservoir treatment as well as the associated seismic hazard at the surface.

In this presentation, we show that the analysis of source properties of induced seismicity allows an estimation of the in-situ stress regime, and thus of the mechanical properites of the reservoir. For this purpose, we analyse seismicity induced by fluid injection in the Basel geothermal project in 2006. More than 10,500 events were induced since the beginning of stimulation, most of them during the actual 6-day stimulation period. The induced seismic activity culminated in several larger magnitude (up to M_L=3.4) earthquakes shortly after well shut-in, which were felt at the surface. The Basel case is an example for the potential seismic risk associated with hydraulic fracturing. The events were recorded by a six station seismic array installed in five monitoring boreholes within 5 km of the injection at depths between 317 m and 2740 m.

We estimate stress drops of the induced events from the best-fitting corner frequency of the P-wave source spectra. We also analyse spatial variations in the frequency-magnitude distribution of the seismicity. We observe significantly lower stress drops and higher b-values near the injection point. Stress drop increases by about a factor of five with radial distance from 10 m to 300 m. Comparison with forward-modeled pore pressure perturbation using a linear diffusion model reveals a correlation of both source properties with the pore pressure distribution in the reservoir. Stress drop is inversely proportional to the forward-calculated pore pressure perturbation within about 300 m of the injection point.

We can describe the observations by forward-modeling the pressure-induced stress changes and seismicity triggering based on Coulomb friction. We assume a stochastic heterogeneous stress distribution in the medium based on literature values of the minimum and maximum horizontal stresses, and the coefficient of friction. In an injection experiment, the stress field is mainly modified by the injection pressure. Increasing the pore pressure in the medium causes a reduction of the normal stress to an effective stress. If the stress is near the critical state (Mohr circle close to the Coulomb envelope) the reduction of the normal stress may cause the shear stress to exceed the Coulomb failure envelope and hence trigger an event. We model the spatio-temporal evolution of the effective stress based on a linear diffusion model and the actual wellhead pressure, and record an event once the Mohr circle has crossed the failure envelope. Stress drop and b-values are linked to differential stress in the modeling. The result is a forward-modeled seismicity cloud with origin time, stress drop, and magnitude assigned to each event location in the medium.

Our model is able to explain in principle the observation of reduced stress drop and increased b-values near the injeciton point where pore pressure perturbations are highest. The higher the pore pressure perturbation, the less critical stress states still trigger an event, and hence the lower the differential stress is before triggering an event. Less critical stress states (lower differential stresses) result in lower stress drops and higher b-values, if both are linked to differential stress.

We are therefore able to establish a link between the seismological observables and the geomechanical properties of the source region and thus a reservoir. Understanding the geomechanical properties is essential for estimating the probability of exceeding a certain magnitude value in the induced seismicity and hence the associated seismic hazard of the operation.

P 20.3

GEOBEST - A contribution to the long term development of deep geothermal energy in Switzerland

Toni Kraft[1], Stephan Husen[1] and Stefan Wiemer[1]

[1]*Swiss Seimological Service @ ETH-Zurich, Sonnegstrasse 5, 8092 Zurich, Switzerland, (kraft@sed.ethz.ch)*

Summary
The Swiss Seismological Service (SED) is implementing the GeoBest project on behalf of the Swiss Federal Office for Energy (SFOE) to provide cantonal and federal authorities with guidelines on how to handle seismic hazard in the framework of the environmental risk assessment. Within GEOBEST, selected pilot projects in Switzerland will be supported in the necessary seismic monitoring of natural and induced seismicity. GeoBest supports the pilot project in the first two years, that are most critical with respect to the financial risk, by providing seismological instrumentation from the GeoBest instrument pool and partial financial support for the installation and operation of the seismic monitoring network. In return the pilot projects grant SED access to project data needed for seismic hazard assessment and the development of best practice guidelines.

Background
With the global challenge to satisfy an increasing demand for energy while at the same time stabilizing or reducing carbon dioxide (CO_2) concentrations in the atmosphere, deep geothermal resources are being increasingly recognized by society as an attractive alternative energy source. Deep hydrothermal resources, such as aquifers at depths larger than 2km with sufficiently high productivity, have been successfully exploited for many years, but their distribution and potential for supplying electricity is limited. However, artificially created Enhanced or Engineered Geothermal Systems (EGSs) do not suffer this restriction.

In general, deep geothermal resources are exploited by circulating fluids through a geothermal reservoir using a number of deep injection and production wells, thereby extracting heat from the permeable or fractured rock mass. This operation invariably alters the stress and pore pressure in the subsurface. The changes tend to be most pronounced during the EGS reservoir creation (i.e. stimulation) phase, but they also occur in the operational phase of EGS and deep hydrothermal systems (Giardini, 2009).

It has been realized over the last 20 years, that the Earth's crust generally supports high shear stress levels and is often close to failure. Thus, even small changes of the stress and pore pressure in the subsurface due to Earth engineering endeavors or even anomalously heavy rainfall can be sufficient to induce seismicity in natural systems (e.g., Hainzl et al. 2006, Husen et al. 2007). Historically, the most damaging events, are associated with the impoundment of reservoirs (Gupta, 1992). However, earthquakes of sufficient size to cause damage to localities have also been associated with mining activity (Gibowicz, 1990), long-term fluid withdrawal wells (Segall, 1989), and long-term fluid injection wells (Nicholson and Wesson, 1990; Evans et al. 2011).

Even though, massive stimulation injections have routinely been performed at EGS sites since the early 70s, the issue of the seismic hazard associated with these operations has only recently come to the fore. This is because the pioneering EGS developments at Fenton Hill (USA), Rosemanowes (UK), Hijiori (JP) and Soultz (F, 3.5 km reservoir) did not produce events large enough to disturb the local population. Recent attempts to develop EGS at 4.5-5.0 km at Soultz (F), Cooper Basin (AUS) and Basel (CH), and deep (~3km) hydrothermal systems in Landau (D) and Unterhaching (D) produced events approaching or exceeding magnitude ML=3. A recent review of induced seismicity associated with deep fluid injections in Europe, including recapitulatory case histories, is given by Evans et al. (2011).

The processes and conditions underpinning induced seismicity associated with deep geothermal operations are still not sufficiently well understood to make useful predictions as to the likely seismic response to reservoir development and exploitation. The empirical data include only a handful of well-monitored EGS experiments; models are consequently poorly constrained. Unfortunately, datasets of well-monitored deep hydrothermal experiments are missing and empirical constraints of induced seismicity models for these cases do not exist. Given that the majority of the projects underway or planned in Europe are of the hydrothermal type, there is hope that this deficit can be remedied in the near future through a close cooperation of geothermal industry, science and public authorities.

This is where the GeoBest project comes to play. By supporting selected pilot project for a limited time, SED facilitates the dialog with geothermal industry. Besides of the unique opportunity to collect high quality seismic data and being able to access relevant project data, gaining first hand practical experience in this field is of paramour importance for the development of significant best practice guidlines.

Project Description

A detailed description of the goals of the GeoBest projects can be found in the document (www.seismo.ethz.ch -> Groups -> Special Seismic Networks -> GEOBEST).

REFERENCES:

Evans, K.F., A. Zappone, T. Kraft, N. Deichmann and F. Moia (2011). A Survey o induced seismic response to fluid injection in geothermal and CO2 reservoirs in Europe, accepted for publication in Geothermics.

Giardini, D. (2009), Geothermal quake risks must be faced, Nature, 461, pp. 848-849.

Gibowicz, S.J. (1990). Seismicity induced by mining. Advances in Geophysics, 32, pp. 1-74.

Gupta, H.K. (1992). Reservoir-induced Earthquakes. Elsevier, Amsterdam, 364 pp.

Hainzl, S., T. Kraft, J. Wassermann, and H. Igel (2006). Evidence for rain-triggered earthquake activity, Geophys. Res. Lett., 33, L19303, .http://dx.doi.org/10.1029/2006GL027642.

Husen, S., C. Bachmann, and D. Giardini (2007). Locally triggered seismicity in the central Swiss Alps following the large rainfall event of August 2005. Geophys. J. Int., 171, pp.1126-1134.

Kraft,T., K.F. Evans, D. Giardini, N. Deichmann, and S. Wiemer (2010). Induced seismicity associated with the exploitation of deep geothermal resources, European Geologist, 29, pp.19-20.

Nicholson, C. and R.L. Wesson, 1990. Earthquake hazard associated with deep well injection. US Geological Survey Bulletin 1951, 74 pp.

Segall, P. (1989). Earthquakes triggered by fluid extraction. Geology, 17/10. pp. 942-946.

P 20.4

Changes of Coulomb Failure Stress due to dislocations during stimulation of well GPK2 in Soultz-sous-Forêts

Schoenball Martin[1,2], Baujard Clément[1], Kohl Thomas[1,2] & Dorbath Louis[3]

[1]*GEOWATT AG, Dohlenweg 28, CH-8050 Zürich (schoenball@geowatt.ch)*
[2]*Karlsruher Institut für Technologie, Institut für Angewandte Geowissenschaften, Kaiserstr. 12, D-76131 Karlsruhe*
[3] *EOST, University Louis Pasteur, 5, rue René Descartes, F-67084 Strasbourg*

The European deep geothermal research project at Soultz-sous-Forêts (Alsace, France) has been developed since 1987. The geothermal reservoir is situated in a horst structure within the granite basement of the Upper Rhine Graben. During the project for developing an Enhanced Geothermal System (EGS) several well stimulations have been conducted and induced several tens of thousands of microseismic events. During the stimulation of well GPK2 the maximum event recorded during stimulation reached magnitude 2.5.

In the field of seismology of tectonic earthquakes, aftershock sequences produced by a large magnitude main shock have been successfully described by changes of Coulomb failure stress due to the dislocation (in the following denoted as ΔCFS) by the main shock (e.g. King et al. 1994 and Toda et al. 2003).

We present 3D computations of ΔCFS by different geometries of the fault plane to find a computationally efficient way to approximate circular sources taking into account an appropriate slip distribution. We then compute transient ΔCFS in the Soultz reservoir during the stimulation of GPK2. For this analysis we use an extensive database of over 700 derived focal mechanisms (Dorbath et al. 2009). This allows us to conclude that the stress perturbation of all microseismic events during stimulation cannot be depicted by one single fault. Furthermore analysis of this dataset allows us to estimate the influence of ΔCFS by dislocation over the total change of Coulomb failure stress by other processes like the increase of pore fluid pressure, thermal stresses, hydraulic response of the reservoir and coupling of these.

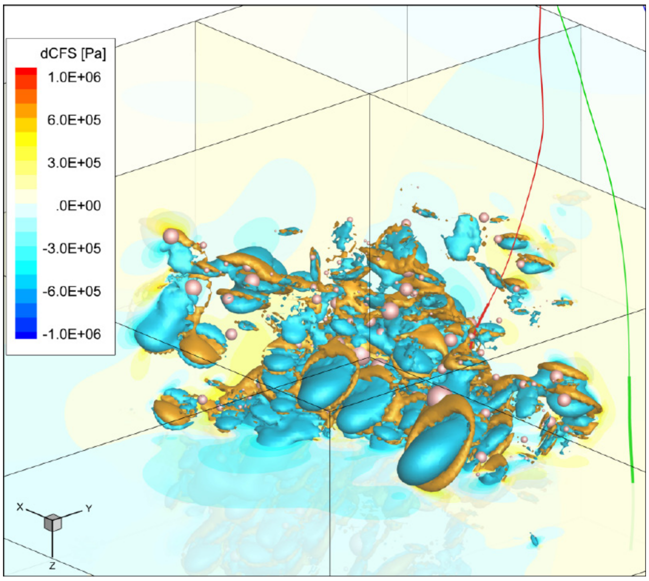

Figure 1. 3D views of ΔCFS in the Soultz reservoir with isosurfaces at ±0.5 MPa. The wells GPK2 (red), and GPK3 (green) are displayed with bold open hole section. The microseismic events used for the computation are represented by sphere symbols that scale with the event magnitude.

REFERENCES

Dorbath, L., Cuenot, N., Genter, A. & Frogneux, M. 2009:. Seismic response of the fractured and faulted granite of Soultz-sous-Forets (France) to 5 km deep massive water injections. Geophysical Journal International, 177(2), 653–75.

King, G. C. P., Stein, R. S. & Lin, J. 1994: Static stress changes and the triggering of earthquakes. Bulletin of the Seismological Society of America, 84(3), 935–953.

Toda, S. & Stein, R. 2003: Toggling of seismicity by the 1997 Kagoshima earthquake couplet: A demonstration of time-dependent stress transfer. J. Geophys. Res., 108(B12), 2567.

P 20.5

Natural fractures and stress heterogeneity in the host granite of the Basel Deep Heat Mining project

Sikaneta Sakalima & Evans Keith

Engineering Geology, ETH Zürich, Sonneggstrasse 5, CH-8092 Zürich (sakalima.sikaneta@erdw.ethz.ch) (keith.evans@erdw.ethz.ch)

To understand of the processes underpinning permeability enhancement and attendant seismicity in the hydraulic stimulation of Enhanced/Engineered Geothermal Systems (EGSs) requires a geological model of the reservoir that includes discontinuity families and also knowledge of the state of stress. The ultrasonic borehole image (UBI) log provides high-resolution information on both these reservoir characteristics. A UBI log was acquired in the 2.6 km granite section of the Basel BS-1 well prior to the stimulation. We present evidence from borehole breakouts and drilling induced fractures visible on the UBI log that the stress profile within the BS1 well has a significant level of complexity. The stress orientation and stress magnitude fluctuate over the metre to hundreds of metre scales, with fluctuations demonstrably correlated to the occurrence of natural fractures visible on the UBI log. The complexity of the stress field in BS1 contrasts with the commonly held assumption that the state of stress in the subsurface has a constant orientation and magnitudes that vary in a simple, linear manner with respect to depth. The findings of this study emphasise the importance of including stress heterogeneity in geomechanical models of the reservoir seismic and hydraulic response to fluid injection.
hence the associated seismic hazard of the operation.

P 20.6

Geothermal energy potential of Vorarlberg (Austria)

Zerlauth Michael[1], Ortner Hugo[2], Pomella Hannah[1], Schulz Marcel[1], Fügenschuh Bernhard [2]

[1]*alps GmbH, Grabenweg 68, A-6020 Innsbruck (zerlauth@alps-gmbh.com)*
[2]*Institute of Geology and Palaeontology, Innrain 52, A-6020 Innsbruck*

Several tectonic units in Vorarlberg are potential targets for geothermal exploration, regarding the geological requirements for a hydrothermal system – a water bearing layer with an adequate permeability in an appropriate depth. From the top to the base of the Alpine nappe pile the Mesozoic cover (Bavarian Lechtal nappe) of the Silvretta nappe (Upper Austroalpine basement nappe), the Helvetic nappes as well as autochthonous units of the Northern Alpine foreland are comprised. Out of these units only the last two are probably present in a promising depth of more than 2500 m. The number of suitable locations for a deep hyrothermal system is additionally reduced by the required proximity to industrial customers. According to these limitations the focus in this study is on the Northern Alpine foreland and the Helvetic nappes in the area of the Rhine valley.

The most promising structure is a normal fault system offsetting the autochthonous sedimentary cover of the down-going European plate. This set of south to south-southeast dipping faults, located below Bregenz, was recognised by numerous seismic campaings during the last 40 years, carried out in the course of the oil and gas exploration in the Molasse basin. Interestingly the currently realized St. Gallen deep geothermal project deals with a quite similar tectonic and stratigraphic setting and is therefore of substantial interest for our Vorarlberg study.

Concerning the southerly located site of interest in the Helvetic nappe stack, the situation is much more complex. Available seismic data reveal the lower and upper boundary of the whole Helvetic nappe stack without internal resolution and the reflectors are mostly afflicted with some uncertainties. Additionally to the seismic data, several deep drillings (V-Au 1, Maderhalm 1, Kierwang 1, Hindelang 1) have been carried out in the years 1961 to 1986. Based on the drill logs, seismic sections, and surface data, various cross sections have been constructed. Thereupon a model for the tectonic evolution of the Helvetic unit was created, in accordance with the situation in Eastern Switzerland and Lichtenstein and partly based on findings of previous authors (e.g. Wyssling 1985 & 1986, Zacher 1973). The facies development of the Helvetic shelf was reconstructed based on literature data and implemented in the model. Special attention was drawn to the Jurassic Quinten-Fm. and the Cretaceous Schrattenkalk-Fm. Both are prominent shelf limestones with a high hydrothermal potential, especially when fractured due to folding or faulting.

Based on all the so far available constraints, two blocks of some square kilometres around Bregenz and Feldkirch were defined for the construction of a 3D model, using the software package Move. These two 3D blocks will provide the basis for further planning of a 3D seismic campaign.

REFERENCES

Wyssling, G. 1985: Palinspastische Abwicklung der helvetischen Decken von Vorarlberg und Allgäu. Jb. Geol. B.-A., 127, Heft 4, 701-706.

Wyssling, G. 1986: Der frühkretazische helvetische Schelf in Vorarlberg und im Allgäu - Stratigraphie, Sedimentologie und Paläogeographie. Jb. Geol. B.-A., 129, Heft 1, 161-265.

Zacher, W., 1973: Das Helvetikum zwischen Rhein und Iller (Allgäu - Vorarlberg). Tektonische, paläogeographische und sedimentologische Untersuchungen. Geotekt. Forsch., 44,I-II, 1-74.