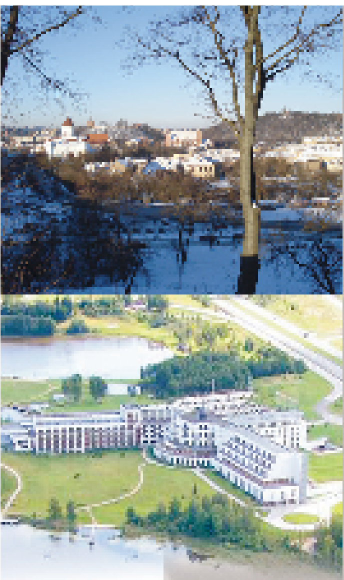

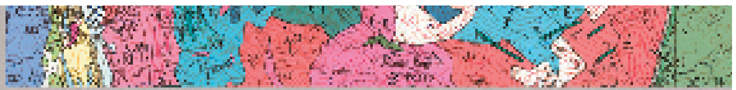

ENGINE

ENhanced Geothermal Innovative Network for Europe

The ENGINE Final Conference

12 - 15 February 2008

VILNIUS - LITHUANIA

Conference Abstracts

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EDITED BY: PHILIPPE CALCAGNO (BRGM) & SAULIUS SLIAUPA (IGGL)

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Cover pictures
Thumbnail upper top: Vilnius, Lithuania
Thumbnail lower top: Le Meridien Villon, Vilnius, Lithuania
Background: Klaipeda Geothermal Station, Lithuania

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ABSTRACT SUMMARY

OPENING SESSION

Session 1: Information and dissemination system

Session 2: Investigation of Unconventional Geothermal Resources and EGS

Session 3: Drilling, stimulation and reservoir assessment

Session 4: Exploitation, economic, environmental and social impacts

Session 5: Risk evaluation for the development of geothermal energy

Session 6: International perspective for the development of geothermal energy and Enhanced Geothermal Systems

Session 7: Project generation and discussion

Opening session

The final conference of the ENGINE Coordination Action: a milestone towards EGS demonstration projects

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The heat engine of the Earth represents an infinite and renewable source of energy that could potentially satisfy a significant part of our needs. While conventional geothermal resources already cover a wide range of uses for power and heat production in profitable conditions, the development of engineered geothermal systems still requires significant R&D investment. A large scientific and industrial community has been involved for more than 20 years in promoting Enhanced Geothermal Systems (EGS) and has been recently assembled in ENGINE, a Coordination Action of the 6th Framework Program, aimed at coordinating on-going actions concerning Unconventional Geothermal Resources. The achievement of this project will be a handbook defining best practices and proposing a road map for future demonstration projects. The main results will be presented during the final conference that will be held in Vilnius, Lithuania (12-15 February 2008).

The project, that joins 35 partners (4 of them from Third Countries) and 19 countries, started on 1st November 2005 and up to now, 2 conferences (launching and mid-term) and 7 workshops have been organized. All material elaborated during the project are available through the web site at http://engine.brgm.fr. Proceedings, reports, abstracts and slides can be downloaded, presenting an updated framework of activities concerning (i) investigation, (ii) drilling, stimulation and reservoir assessment, (iii) exploitation, economic, environmental and social impacts.

The enhancement challenge requires the development of innovative methods for exploring, developing and exploiting geothermal resources that are not economically viable by conventional methods. This definition embraces different tracks for enlarging access to heat at depth in order to provide continuous base load-power and to contribute to reach the target of the European Strategic Energy Technology Plan, i.e. 20% renewable market penetration in 2020. Lessons learned from the Soultz EGS experiment, the sustainable development of the Larderello field in Italy, and the Icelandic geothermal power network, among other case histories, highlight the importance for coordinated research for technology improvement and for a continued reduction in cost through R&D developments. Based on the Soultz experience, and thanks to significant progress in binary power plant technology, a new EGS power plant was done in the Upper Rhine graben on the German side and others projects are planned for the coming years, showing a learning curve effect.

There is a sound knowledge shared by the European scientific community to promote geothermal projects and active links with the International Energy Agency and other EGS programs in US, Australia and Japan. In that scope, ENGINE Coordination Action provides that conditions are gathered to promote new EGS demonstration projects through a common approach between R&D teams and stakeholders, providing an added value for European energy resources and industry development. What could be the next move in this direction? Standardization of the elaborated technology and quantification of geologic and technical risks are among the main issues that come out from the contact with the stakeholders and that were debated during the Leiden workshop (Netherlands). Each stage of development of EGS includes several phases and involves pluridisciplinary approaches that can be run in parallel or successively. Decisions are taken at critical moments of the development of the project, marked by go/no go milestones. Review of best practices and lessons learned from the different projects and partners enable the definition of a workflow on which well proven methods and risk assessment can be identified. Concerning each main topic, proven methodologies have been reviewed. Their objectives and main outcomes were presented during the different conferences, workshops and meetings and will be synthesized in the European Reference Manual. Concerning each topic, gaps and barriers must now be identified and evaluated in terms of risk-related and probability of success. R&D themes and investments required to overpass these gaps and barriers could then be defined and constitute a road map for the R&D task force mobilized during the ENGINE co-ordination action for the next years.

In conclusion, it is important on one hand to evaluate the investment and the expected savings on cost operation at the 2020 horizon for each R&D initiative and industrial project. On the other hand, it must be demonstrated that geothermal energy can contribute to achieve the goals defined in the European Strategic Energy Technology Plan. These are our priorities for the next months, until the closure of ENGINE, and for the next years, through EGS demonstration projects. The ENGINE task force is now operational and motivated to develop EGS at the European scale

Ongoing cooperative EGS activities within the IEA GIA framework

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The Geothermal Implementing Agreement (GIA) of the International Energy Agency (IEA) provides the umbrella for a world-wide cooperative programme on geothermal research and technology. The IEA GIA aims to promote the sustainable utilization of geothermal energy by improving existing technologies, by developing new technologies to render usable the vast and widespread global geothermal resources, by facilitating the transfer of know-how, by providing high quality information and by widely communicating geothermal energy's strategic, economic and environmental benefits. The IEA GIA started its third 5-year term of operation in 2007.

The GIA project activities are defined and organized in Annexes, the specific R activities as Tasks. With respect to EGS there are specific R activities, termed in the Annexes as Tasks:

Annex I - Environmental Impacts of Geothermal Energy Development

Task D: Seismic Risk of Fluid Injection into EGS (Task Leaders: R. Baria and D. Wyborn)

Annex III - Enhanced Geothermal Systems (EGS) – Annex Leader: R. Baria

Task A: Economic modelling (completed)

Task B: Application of Conventional Geothermal Technology to EGS (Task Leader: J. Renner)

Task C: Data Acquisition and Processing (Task Leader.: T. Mégel)

Task D: Reservoir Evaluation (Task Leader: D. Wyborn)

Task E: Field Studies of EGS Reservoir Performance (Task Leaders: P. Rose, A. Genter)

Activities relevant for EGS and ENGINE are also conducted in Annex VII: Advanced Geothermal Drilling. The IEA GIA activities are governed by an Executive Committee (ExCo). At two ExCo meetings annually the GIA Participants (presently 11 countries, the EC, and 3 industrial sponsors) regularly report about their activities, so e.g. the EC about the Soultz project. For EGS the focus is on the flourishing scene in Australia, where 6 companies are listed in the Australian Stock Exchange (ASX), 25 companies hold exploration rights over 170 licences, ranging in size from 120 to 12'000 km2. Efficient ties between ENGINE and the IEA GIA have been established in 2006: Patrick Ledru is Member of the ExCo. Results and products of IEA GIA are accessible through its website www.iea-gia.org. Here the especially the White Book and the Protocol about EGS-induced seismicity, the Seismic Risk Study of the Cooper Basin, and the EGS handbook "Project Management Decision Assistant (PMDA)" can be mentioned.

Session 1:

Information and dissemination system

The ENGINE information system: a reference base of knowledge for EGS in Europe

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The Information and dissemination of ENGINE helps to organise, share and promote the work of the coordination action. The major vector of the information system is the Web site at http://engine.brgm.fr.

The coordination action relies on 3 concentric categories of population. Various information and dissemination practises and tools have been set up to answer the needs of each of them:

- Organisation tools for the ENGINE core (workpackage leaders and partners): material for ENGINE progress, meetings organisation management
- Participation tools for the ENGINE contributors (partners and related): meetings information, abstracts submission; registration, minutes of the committees
- Information tools for the ENGINE recipients (related, decision makers, public): proceedings of the meetings, newsletters, education and training analysis, geothermal lighthouse projects compilation

By the achievement of ENGINE, organisation and participation activities won't be useful anymore. They mainly helped to concretise 3 conferences, 7 workshops, various special meetings and other deliverables. However, it is important to make an audience as large as possible able to access the results of the coordination action such as proceedings, compilations, recommendations and the forthcoming "Best practise handbook" and "European reference manual".

The dynamic that grew during ENGINE shows the need of such coordination action to strengthen the link between EGS actors in Europe and beyond and to accompany on-going projects. Consequently, it is proposed to capitalise the results of our coordination action by making them a piece of the basement of EGS development in Europe. For instance, the analysis conducted within the ENGINE information system about education and training allows the development of a project setting up a route for training specialists at the European scale.

The ultimate goal of the ENGINE information system is to keep offering the framework material elaborated during the project for helping future EGS demonstration projects and to make it the seed for forthcoming actions aiming at EGS coordination and support.

Future Project Proposal on Geothermal Education and Training

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The presentation is intended to start the discussions on building a team to prepare a new project proposal for a series of short courses on different aspects of geothermal energy exploitation and utilization including, but not limited to, EGS. The proposal should be submitted to the EC under the FP7 Human Potential action. A significant number of geothermal research projects have already been financially supported by the EC, some of them finalized, many other being now in the final stages, with most of the research activities completed. The topics of the proposed courses should include the results of as many as possible of these EC funded projects.

ENGINE Geothermal lighthouse projects in Europe

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CALCAGNO Philippe, BRGM, France

One of the goals within the ENGINE project was, as part of the WorkPackage2 (WP2), to locate and classify main Geothermal Lighthouse projects, related to ENGINE topics and significant on a European scale. At first, only projects using geothermal for power/energy production are included; excluding projects using heat pumps.

The intention is to give an overall broad presentation of the most important Lighthouse Projects mainly based on a questionnaire guided by a simplified structure and relevant keywords and on additional information derived from the Internet and the World Geothermal Proceedings (WGC2000 and WGC2005).

The hope was that the questionnaires could lead to a condense description of each project suitable for the public and for displaying on the ENGINE Web-site, - even though some questions could be difficult to answer (project could be in it's early phase; rules of confidentiality etc..).

Based on a list of the known most important projects possible contact persons, either in charge or persons that could have knowledge of the project, received a questionnaire that was divided into two parts:

1) Comparable facts/statements that, for each project, could pop-up when e.g. the mouse pans over the site-location map on the Web-site; e.g. Web-site link, no. of wells, avg. flow rate, capacity etc.
2) Information to follow the pop-up facts, i.e. a short additional text displayed as information boxes divided into 4 categories; exploitation history, reservoir characteristics, exploitation, and future plans. If possible, a few relevant figures were appreciated.

Out of 17 questionnaires 11 were returned and have resulted in an updated list of contact persons and information on projects covering 4 main types; 1) EGS or related EGS projects, 2) Hydrothermal projects, 3) Technological projects and 4) Other Projects.

Furthermore, the returned questionnaires also served as a good basis for compiling a Web-site suitable for the public displaying. Examples of this will we shown.

Other geothermal projects e.g. in Poland, Denmark, Slovakia and Greece are mainly dedicated for heating purposed and was at first not relevant for the ENGINE project. In the future, it could be informative to incorporate theses projects. Furthermore, projects that have no production or drill sites, but where tools, software or methodologies are implemented for improving the use of geothermal energy could also be appreciated.

Geothermal Education and Training Recommendations

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The previous two papers on geothermal training and education prepared for the ENGINE Conferences present an overview on some currently existing programs available in Europe and other continents. The poster to be displayed at the ENGINE Final Conference presents a brief concise information on the geothermal education and training opportunities in Europe, proposes some advice on integrated routes for students seeking specialization in geothermal related fields of study, and makes some recommendations on topics to be included in regular courses currently taught in universities offering study programs related to the exploitation and utilization of geothermal energy.

Geothermal Web site for Lithuania and Baltic Region

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A considerable amount of the geothermal information was collected during the four decades of the deep geological mapping and oil exploration in Lithuania. The scientific geothermal activities in Lithuania began in late eighties. It started with the regional-scale estimation of the geothermal potential of the country. As a result, the first demonstration Klaipėda geothermal station was installed in west Lithuania. Still, the access to the geothermal data and their application were quite restricted due to dilution of the data in many industrial reports that are kept in the archives.

The digital data base and associating geothermal atlas were compiled at the Geological Survey of Lithuania to make an access and the management of the geothermal information more easy and efficient in order to assist in further geothermal industrial activities (Sliaupa, 2002).

Still, there is a little public knowledge of the existing geothermal data and geothermal energy potential in Lithuania. In order to promote the dissemination of the geothermal information the Geothermal website for Lithuania was created within the frames of the ENGINE project. It contains the information on the ongoing geothermal research activities in Lithuania, describes the geothermal field of Lithuania and adjacent territories, provides information on the available geothermal data and major sources for obtaining this information. The HDR/EGS opportunities in Lithuania are presented based on the available geological, geophysical, geothermal information. Also, the list (and some links) of the publications concerning geothermal field of Latvia, Estonia, Belarus is provided. The greenhouse geothermal projects in Lithuania are presented. The temporary web site addressee http:\\ 193.219.43.40\engine\.

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Geoinformation technologies in geothermal power of Daghestan

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Geothermal power is developing branch of a science, directly linked to exploration, investigation and assessment of geothermal deposits (reservoirs). Realization of such estimation is essentially facilitated by modern geoinformation technologies and systems. We have some developments now, such as "The electronic 3D-atlas of Daghestan", the thematic module "Geothermal objects" implemented in the framework of the atlas and the technology for construction a thematic map by diverse data. The developments are in progress. The last one (from listed) is planed to integrate into the atlas to provide possibility of its quick up-dating.

In the end of 2008 it is planed to release the first version of "The electronic 3D-atlas" soft, focused to the geothermal power investigation. The atlas data will contain: 1) digital elevation model, 2) thematic texture "Vegetation", 3) thematic texture "By altitude", 4) thematic texture "Administrative division" 5) theme "Water-basins", 6) theme "Rivers, Channels", 7) theme "Highways", 8) theme "Railways", 9) theme "Cities", 10) theme "Settlements", 11) theme "Cities names", 12) thematic module "Geothermal objects", 13) thematic module "Temperature field".

Geothermal Welcome Centres in Iceland. A poster showing points of interest

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Geothermal energy is closely associated with the image of Iceland. It has been harnessed for space heating, power generation and a multitude of other uses. Now practically all houses are connected to geothermal district heating systems (90%) and there has been a rapid increase in electricity generation. Public acceptance has been excellent as and the economic benefits are substantial as half of the country's primary energy supply is of geothermal origin. The importance of dissemination of geothermal knowledge has been recognized by the geothermal industry and educational institutions. The large utilities have run visitor centres, and public access to geothermal areas is good, some of these becoming magnets for tourists. One of the objectives of ENGINE is to increase the public awareness of geothermal power and the role it can play. As Iceland is a good place to learn about geothermal activity and see the many ways geothermal energy is put to use, it was decided that ÍSOR would produce a poster "Geothermal Welcome Centres" to highlight good places for tourists to visit. These are information centres at power plants as well as geothermal areas people can explore on their own. The points of interest are shown on a map together with the 130 public outdoor swimming pools. The posters, with the ENGINE logo, have been on display for the past two years in the thirty official tourist information offices around the country.

Exploration Tools Database

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The exploration tools database is an attempt at collecting all the information about the exploration tools used by ENGINE partners for geothermal investigation and exploration. The database is organized on the base of the methodology used for exploration of deep EGS reservoirs, and lists the equipment, hardware and modelling software that ENGINE partners use. The database will be hosted on the IGG-CNR server and it will be linked in the ENGINE project website: this way it will be easily available to ENGINE partners and to the geothermal community.

By mean of this tool it is also possible to take a look to the international geothermal exploration Projects that gave important occasion to ENGINE partner to work in the field of geothermal exploration.

The database allows search by using keywords and institution names. With the help of the partners, the database will be regularly updated and enriched, and will be an on-line tool to define what services can be offered by ENGINE partners.

Dissemination of geothermal knowledge by Iceland GeoSurvey

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Geothermal energy utilization is widespread in Iceland. Almost 90% of houses are geothermally heated, about 17% of the electricity generated and half of the countries primary energy supply is from geothermal sources. Iceland GeoSurvey (ÍSOR) and its predecessors have played a major role in this development by providing scientific service to the geothermal industry and advice to the government of Iceland. ÍSOR has been active in promoting geothermal development by enhancing public and political awareness and understanding.

The poster presents the contribution of ÍSOR in training scientists throughout the world in geothermal science and development by providing lectures and supervisors.

In Iceland, ÍSOR has established cooperation contacts with academic institutions, and holds visiting professorships. ÍSOR and its predecessor have since 1989 collected data spanning over 50 years and managed the repository together with Orkustofnun (National Energy Authority) into a relational database. This database contains a comprehensive set of data on research and exploration of geothermal areas in Iceland as well as on their exploitation, well drilling, monitoring and geothermal reservoir management. A part of this basic data has been inserted into an interactive map interface, "Gagnavefsja," which is accessible over the internet. The database is meant to serve different user groups, the public as well as power companies and contractors, and is presented in both Icelandic and English (password protected access to proprietary data and publications). Each year ÍSOR prepares research reports on various projects and a list of all of them can be accessed at the national library database "Gegnir".

The most comprehensive dissemination activity is ÍSOR´S contribution to the United Nations University Geothermal Training Programme (UNU-GTP). The UNU-GTP has been operated in Iceland since 1979. It is financed mainly by the Icelandic Ministry of Foreign Affairs, but is administered by Orkustofnun. About 60% of all its training is provided by ÍSOR. The trainees work along with our professionals, and acquire knowledge in various aspects of ÍSOR specialized fields of research, exploration, and development. Annually, over 20 fellows from the developing countries participate in a 6 month intensive geothermal course in Iceland and 6-9 complete a 2 year MSc studies in geothermal sciences at the University of Iceland. The UNU-GTP has been very successful in world-wide capacity building in the field of geothermal energy.

The government of Iceland is funding annual short courses in geothermal development in Africa, Central America and Asia as a contribution towards the Millenium Development Goals of the UN. They are organized by the UNU-GTP. ÍSOR´s experts play a significant role as lectures and advisers at these courses.

ÍSOR has also organized courses and workshops in connection with projects for the Icelandic International Development Agency, such as in Nicaragua which is a target country for Iceland´s development aid.

Session 2:

Investigation of Unconventional Geothermal Resources and EGS

From identification towards exploitation of geothermal reservoir: concepts and experience

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The presentation comprises the results of first chapter of the Best Practice Handbook of ENGINE. It gives an overview of the investigation, exploration, and exploitation of unconventional geothermal reservoirs and Enhanced Geothermal Systems (EGS) to different groups of interest such as engineers, politicians, decision makers from industry. In contrast to the conventional high-temperature steam reservoirs in volcanic environments, unconventional and EGS resources and reservoirs are more difficult to localise and to assess. While volcanic resources are clearly indicated by obvious effects at the surface (e.g. geysers, fumaroles, etc.), unconventional and EGS resources leave mainly indirect traces (e.g. increased surface heat flow). Usually, they are water-dominated systems and characterised by a wide range of production temperatures. The lower temperature limit in unconventional reservoirs is defined by the current technical limitations in conversion of heat into electric energy. An EGS is defined by artificial improvement of the hydraulic conductivity of the reservoir.

This chapter covers the initial phase of an unconventional project. It provides an investigation scheme for possible EGS resources and reservoirs and includes a validation of appropriate exploration techniques in different geo-environments. The Site Investigation is subdivided in Site Screening and Site Characterization. The first one applies a scale-dependent workflow and describes a step-by-step procedure, how to locate a reservoir using different, geoscientific techniques. It introduces different tools and approaches to investigate resources on continental scale. While downscaling to regional and local scales, tools and approaches are adopted to the respective scale and the information of interest on the specific scale. The second topic (Site Characterisation) supports the understanding of physical and chemical processes in the reservoir and proposes techniques to investigate the key properties influencing the productivity of the reservoir. This chapter provides an overview of the necessary evaluation and relevant geoscientific tools to characterise the thermal, hydraulic and chemical conditions of an unconventional or EGS reservoir. A validation of the applied techniques is given in the description of the analogue sites.

In general, geothermal energy can be analysed on different scales and for various purpose. Accounting for these different scales or levels of interest (e.g. planning of European-wide energy mix or local energy provision), in the BPH the different groups of interest are guided by different entry points.

Lithosphere tectonics and geothermal exploration and production

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EGS are planned in areas with high temperatures at depths of 3-6 km. Until now areas have been selected largely on the basis of observations of high temperature gradients near surface (e.g. volcanic areas such as Iceland) and/or relative high temperatures assessed in deep boreholes drilled mainly for Hydrocarbon exploration and production (e.g. Gross Schönebeck).

For assessing the exploration potential of continental regions for geothermal energy we need to look beyond depths of temperatures known from shallow wells and need capability to predict temperatures at depth in areas where no well control is available. For this reason knowledge the thermo-mechanical signature of the lithosphere and crust is important to obtain critical constraints for the crustal stress field and basement temperatures.

Thermal characteristics of lithosphere beyond well control

Predicting the temperature of the earth at depths beyond existing well control and in areas where no well data is available has been a prime topic in earth science for centuries. Tectonic models integrating geological and geophysical databases in a process-oriented approach provides a continent-wide approach in first order temperature prediction of the lithosphere. In these models the lithosphere constitutes a mechanically strong topmost layer of the earth, which is c.a. 100-200 km thick and which is floating on the astenosphere, which behaves –on geological times- as fluid. The base of the lithosphere is marked by a relatively constant temperature of around 1330 °C (Figure 1).

The actual temperatures extrapolated at depth are sensitive to surface heat flow, and thermal parameters of the rocks (thermal conductivity and heat production essentially). Knowledge of rock conductivity is based on measurements in boreholes and values extrapolated from laboratory experiments, taking into account mineralogical, temperature and porosity effects.

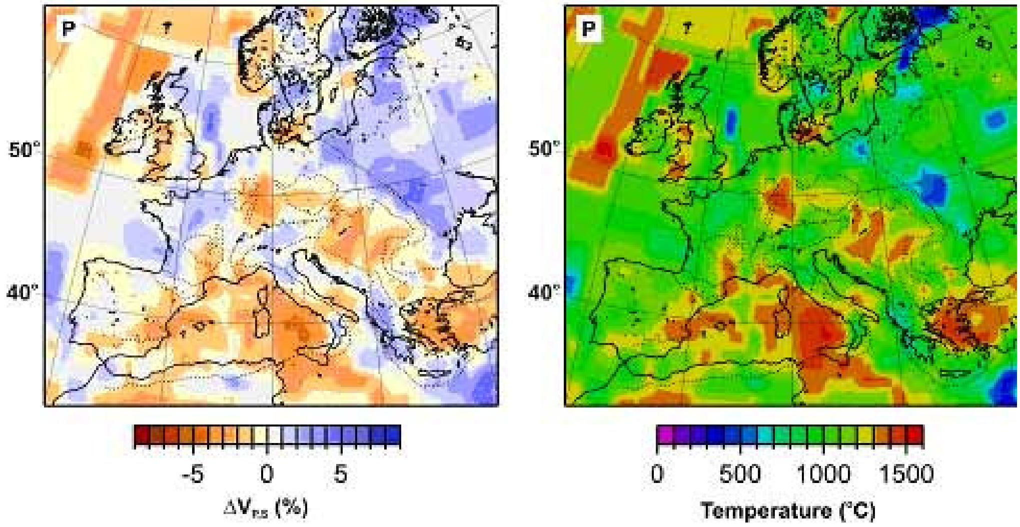

Figure 1: Seismic velocity anomalies from tomography (left) and conversion of velocities to temperature (blue=500 °C; red=1300 °C). The high temperature zones at 100 km depth derived from P waves correspond to areas with mantle plumes (e.g. Eifel area and Massif Central) and lithosphere extension in postorogenic collapse and/or backarc extension (e.g. Western Mediterranean, Aegean, Panonian Basin, after Goes et al., 2000).

Continental scale transient effects

Due to plate tectonics in the earth, the continents deform. This deformation is most pronounced at the boundaries of plates, e.g. spreading ridges or subduction zones. However plate boundaries forces are transmitted deeply into to the continental interior resulting in intraplate deformation. This deformation is reflected by extension or compression of the interiors of the lithosphere (Ziegler et al., 1998),which can have a significant effect on predicted heat flow and temperature.

The McKenzie passive stretching model has been the first tectonic model delivering a quantitative assessment of kinematic extension of the lithosphere in relation to the sedimentary infilling history of basins. Tectonic models show that extension can be accompanied or preceded by a period of deep lithospheric thermal upwelling, related to mantle plumes. This upwelling, and associated magmatic activity results in a significant increase of heat flow. Examples in Europe include portions of the Rhine Graben, the Eifel area and the Massif Central. In addition back-arc extensional settings can be marked by a mantle upwelling effect as witnessed in the Panonian Basin.

Lithosphere compression typically results in crustal thickening and mountain building. The lithospheric thickening results in relatively low heat flows. However elevated mountains can be actively eroded in fault bounded zones, resulting in elevated heat flows close to the surface. Exhumation with elevated heat flows can also occur in lithosphere extension in particular on rift flanks of extensional basins.

The earth is marked by a multistage deformation history in which extension can occur over areas that have been previously marked by a compressional orogeny with significant mountain building. Extension over such areas can result in thinning and thermal attenuation of the crust in absence of significant sediment infill and loss of heat production in the crust. Consequently the heat flow can be strongly elevated. Areas in Europe include the Western Mediterranean (western Italy, Larderello) and the Aegean (e.g. Milos Island). In these areas, active deep mantle processes may partly enhance heat flows.

Thermo-mechanical aspects

The temperatures in crust and mantle lithosphere can be used to calculate the rheology of the lithosphere. Doing so, the development of innovative combinations of numerical and analogue modeling techniques is key to thoroughly understand the spatial and temporal variations in crustal stress and temperature. From these models we derive that the strength of continental lithosphere is controlled by its depth-dependent rheological structure in which the thickness and composition of the crust, the thickness of the mantle–lithosphere, the potential temperature of the asthenosphere, the presence or absence of fluids and strain rates play a dominant role.The strength of the European lithosphere typically shows a stratification into a brittle upper crustal, ductile lower crust and strong ductile upper mantle (Fig. 2).

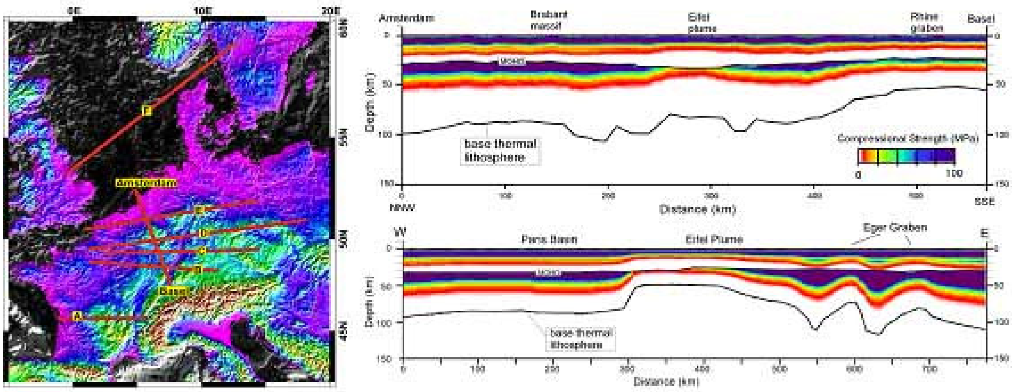

Figure 2: Section Amsterdam-Basel and Section D of strength reconstruction of the European foreland of the Alps, showing a clearly stratified rheology strongly controlled by crustal structure and deep lithosphere thermal structure (after Cloetingh et al., 2005)

The layered rheology is clearly reflected in the way stress is transmitted from the plate boundaries into the European continent resulting in upper crustal extensional and strike faulting and complex stress and strain interactions in the Mediterranean domain.

Field studies of kinematic indicators and numerical modeling of present-day and paleo-stress fields in selected areas have yielded new constraints on the causes and the expression of intraplate stress fields in the lithosphere, driving basin (de)formation. The actual basin response to intraplate stress is strongly affected by the rheological structure of the underlying lithosphere, the basin geometry, fault dynamics and interplay with surface processes.

Integrated basin studies show that rheological layering and strength of the lithosphere plays an important role in the spatial and temporal distribution of stress-induced vertical motions, varying from subtle faulting to basin reactivation and large wavelength patterns of lithospheric folding, demonstrating that sedimentary basins are sensitive recorders to the intraplate stress field. The long lasting memory of the lithosphere, in terms of lithospheric scale weak zones, appears to play a far more important role in basin formation and reactivation than hitherto assumed. A better understanding of the 3-D linkage between basin formation and basin reactivation is, therefore, an essential step in research that aims at linking lithospheric forcing and upper mantle dynamics to crustal vertical motions and stress, and their effect on sedimentary systems and heat flow. Vertical motions in basins can become strongly enhanced, through coupled processes of surface erosion/sedimentation and lower crustal flow. Furthermore patterns of active thermal attenuation by mantle plumes can cause a significant spatial and modal redistribution of intraplate deformation and stress, as a result of changing patterns in lithospheric strength and rheological layering. Novel insights from numerical and analogue modeling aid in quantitative assessment of basin and basement histories and shed new light on tectonic interpretation, providing helpful constraints for geothermal exploration and production, including understanding and predicting crustal stress and basin and basement heat flow.

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Geophysical exploration of geothermal resources

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The general characteristics of the geophysical methods used for exploration of geothermal resources are given. Their application in the regional, intermediate (concessional) and local scales is considered and effectiveness of their usage depending on geological conditions is demonstrated.

Regional geophysical surveys are aimed at studying geological structures (inter-arc basins, subduction, spreading and rift zones, faults) that could host the geothermal reservoirs and contain appropriate ways of the heat transfer to the surface. The main methods used for regional studies are magnetotelluric (MT) and seismic surveys, while gravity and aeromagnetic ones are often applied for increasing the reliability of conclusions drawn basing on the former two methods. Seismic tomography of the earth's crust (being quite expensive) reveals the geometrical boundaries of the lithological units and is especially good in detection of the regional stratigraphy. Magnetotelluric sounding (relatively cheap method) results in the resistivity model of the studied area that may be interpreted in lithological terms and guide the most favorable areas for future geothermal exploration.

None of the geophysical methods used without geological or other geophysical information can produce reliable results that can be used for decision making on the existence of the geothermal reservoir and its boundaries in the concessional scale. So, seismic and EM methods are often supplemented by gravity and/or aeromagnetic surveys of different scale that depends on the required resolution. Magnetic anomalies correlate quite well with horizontal zonation of the structures, while the gravity maps are used to locate deep faults and to delineate fracture zones characterized by low density.

The tasks of the geothermal studies at local scale are spatial delineating of the geothermal reservoir, indirect evaluation of the temperature and permeability of the geothermal zone and finding the best locations for drilling. Electromagnetic and, in particular, magnetotelluric sounding is a direct method for in situ studies of 3D structure and fluid circulation in the geothermal area. Due to theoretical relations between the electrical resistivity, on the one hand, and temperature, porosity and permeability formed by the presence of alteration minerals, on the other hand, it is often applied for the indirect estimation of these parameters.

Thus, geophysical sounding of the geothermal zones could be used

- to reveal stratigraphical layering;
- to produce a static image of the reservoir and surrounding structure;
- to locate fractures and faulted zones and determine the strike orientation;
- to detect the boundary between the cap formed by clay minerals and high temperature reservoirs;
- to estimate the permeability and porosity values;

- to monitor the phase change of pore fluid in fractured rocks and resident fluids resulting in resistivity changes in the host rocks;

- to improve the accuracy of reservoir temperature estimates;

- finally, to reduce exploration costs.

An integrated approach to geophysical exploration: Progress in the I-GET project

BRUHN David and the I-GET consortium

The project I-GET is aimed at developing an innovative geothermal exploration approach based on advanced geophysical methods. The Project Acronym stands for *Integrated Geophysical Exploration Technologies for deep fractured geothermal systems.* The objective of the project is to improve the detection, prior to drilling, of fluid bearing zones in naturally and/or artificially fractured geothermal reservoirs. This new approach has been tested in four European geothermal systems with different geological and thermodynamic reservoir characteristics: two high enthalpy (metamorphic in Travale, Italy and volcanic rocks at Hengill, Iceland), and two middle enthalpy geothermal system (deep sedimentary rocks in Gross-Schoenebeck, Germany and Skierniewice, Poland).

For Travale, a recently acquired 3-D seismic dataset was reprocessed and the seismic amplitudes with azimuth as well as the amplitude versus offset (AVO) of signals reflected from the subsurface targets were analysed. For the analysis of *amplitude with azimuth* in the data gathers with sufficient coverage the sinusoids matched to the observed amplitudes all show one specific orientation. The available geological information and borehole data are currently studied to see if the observed preferred orientation corresponds to a preferential fracture orientation.

In the AVO analysis, the top of the geothermal reservoir corresponds (at least in this area) with high acoustic impedance contrasts. Consistently high values of the *intercept* attribute correspond with target reflections. In addition, the *amplitude gradient* of the reflections from the target shows an increase of the amplitudes with increasing offset. Well information is currently analysed and synthetic seismograms based on borehole logs are developed to see if these observations can be matched with the presence of fractures and fluids.

In addition to seismic data, magnetotelluric (MT) measurements at low and high frequencies were carried out at 22 and 35 sites respectively in the Travale area, in addition to the already acquired 60 sites. The observed resistivities were analysed with respect to the known lithologies and alteration affecting the reservoir rocks, with particular regard to conductive and phyllosilicate minerals, the physico-chemical characteristics of the fluids, and their distribution and evolution with time. 1D inversion of MT soundings and 2D inversion along parallel profiles was performed and a 3D resistivity structure compiled from the individual models. Moreover, 3D forward models have defined the minimum size of the resistivity anomaly characterizing the Travale subsurface. By means of 3D forward models and 2D inversions, resolution of MT to different permeability features was analyzed..

At Hengill, an extensive MT survey was carried out. A total of 70 MT soundings were made within the framework of the I-GET project. 117 pre-existing soundings and additional 30 soundings funded by Reykjavik Energy are available to the project. The I-GET project therefore includes a total of 217 MT soundings in the Hengill area. Almost all the MT soundings were made at locations previously visited by TEM soundings which is now used for static shift corrections of the MT data. Joint 1D inversion of all MT and TEM soundings in the Hengill area was performed and a 3D reisistivity structure was compiled from the individual 1D models.

In addition to electromagnetic measurements, a broad-band passive seismic survey was carried out. Seven broad-band seismic stations were installed in and around the most seismically active part of the area and recorded continuously for four months. The data base includes 662 earthquakes recorded by at least 4 of the stations. 424 of the recorded events were micro-earthquakes with clear P and S waves. Finally, 19 low frequency earthquakes were recognised with sharp onset and resonance having a large peak at about 1.5 Hz. The analysis of location and magnitude of all the earthquakes is still in process, because of the large number of earthquakes recorded. The analysis of the relation between seismicity rate and steam production is ongoing (data supplied by the geothermal power company). Efforts will also concentrate on the location of earthquakes and magnitude for which P and S waves have been picked (about 50 % of them) and on trying waveform inversion on lower frequencies of the long period earthquakes. This data set is unique and complete analysis may need longer time than initially expected.

At Gross Schoenebeck, seismic experiments included two parts: First a 40 km long profile to derive a regional 2-D seismic model of the potential reservoir layers and overlying sediments. The profile is centered at the geothermal drill sites GrSk 3/90 and GrSk4/05 and is oriented parallel to the estimated strike of the regional stress field. Second, a star-like arrangement consisting of 4 profiles each of 6 km length was deployed and a low-fold (low budget) 3-D seismic experiment was conducted to identify fractures around the geothermal well location.

The signals of the first arriving P-waves from the long profile are used for the inversion of travel times to determine P wave velocities and vertical gradients, and represent the input data for the attenuation tomography. Both the P wave velocity tomography and, in particular, the derived vertical gradient of the velocity reveal new aspects how sedimentary sections can be imaged.

Besides the analysis of the first arrival travel time and spectral wave form information, new techniques were developed to benefit from the secondary wave field, which was also measured. In particular, the detection (filtering) of reflections and diffractions from steep dipping features would be an important input information for the geological and geo-hydraulic modeling of the geothermal system.

MT measurements were carried out along a 40 km long profile coinciding with the seismic profile, with 58 MT stations; 20 new MT sites were recorded along a 20-km profile located 5 km to the east of the long profile. In addition, 159 new sites were recorded on a 3 km x 28 km grid around the Groß Schönebeck borehole, with a site spacing of 500m x 500m. Data analysis indicates a mainly two-dimensional conductivity structure. Ongoing interpretation of the results yields generally a good agreement with the known geology of the area. Several zones of high conductivity coincide with structural lows, probably due to sedimentation of more porous material or fluid accumulation. Two distinct conductors located at depths of 4-5 km coincide with the Lower Permian reservoir rocks

Data acquisition in Skierniewice was just finished. Data processing is ongoing.

Integration of different geophysical approaches is the key concept of the project. To this end, seismic and magnetotelluric data have been acquired in the test sites, and new acquisition and processing techniques are developed to solve problems related to the particular target such as high temperatures, anisotropy, phase condition, etc.. The static and dynamic three-dimensional model of geothermal reservoirs is reconstructed by means of all the data acquired. The input of the results of new geophysical prospecting into reservoir modelling is a crucial test of the quality of the new exploration method.

Parallel to in-situ data acquisition, petrophysical and geomechanical properties of the investigated rocks have been defined by laboratory measurements. With respect to the high enthalpy sites, elastic and electric rock properties are determined at the steam/liquid transition of the pore fillings. The validity of the laboratory and simulation results will be verified by the new field experiments.

The ultimate goal is the development of an efficient, low-cost exploration method, by taking advantage of the strengths of different disciplines and combining them to an integrated approach.

Triassic geothermal Clastic reservoirs in the Upper Rhine Graben

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In France, the main exploited low enthalpy geothermal reservoir is embedded within the Jurassic fractured limestone formation of Dogger located in the central part of Paris Basin, where 34 doublets are currently heating 600 000 people since 30 years ago. The development of renewable energy combined with the energy demand implies to search other geothermal reservoirs either below the Paris area or either in other promising areas in the country.

In this framework, a co-funded Ademe-BRGM project, namely CLASTIQ (CLAyed SandSTones In Question), was launched in order to study the deep geothermal potential of the Rhine Graben for the heat, or even electricity production if temperature conditions are high enough. This resource is located in argillaceaous and clastic formation of the Buntsandstein of the Lower Triassic.

The goal of the presented study is to make a first assessment of this reservoir at a regional scale in order to delineate the most favourable areas for exploration and exploitation of the geothermal resources.

In this framework, we have compiled the maps based on modelled geological layers. These maps were built from former data based on a geothermal compilation (Munck et al. 1979). Main characteristics of the Buntsandstein aquifer, such as depth, thickness, and temperature, have been mapped by interpolation method. Based on these maps, the heat in place has been computed for the whole Upper Rhine Graben from Basel to Karlsruhe.

It appears that the northern part of the Rhine graben constitutes a more favourable area than the southern part. The top of the Buntsandstein reservoir is located at around 2000-3000m depth with a temperature of about 150°C and the sandstone thickness of 500-600m. The exploitable geothermal potential is between 15 and 30GJ/m2.

This study confirms that the Buntsandstein formation of the Upper Rhine Graben has a good geothermal potential for the heat and/or electricity production based on a binary geothermal power plant scheme. Some prospective areas have been identified and the need of the new geophysical acquisition such as 2D or 3D seismics should be very helpful for providing relevant information about the reservoir structure.

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Comparative analysis of structural controls on geothermal activity in western Turkey and the Western Great Basin, USA: Preliminary results

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Similar to the western Great Basin in North America, western Turkey contains complex systems of active, kinematically related strike-slip and normal fault zones and abundant geothermal activity. In both regions, geothermal activity is focused in a transtensional setting and is largely amagmatic. In western Turkey, the right-lateral North Anatolian fault splits into several branches, and the tectonic regime changes from translation to transtension toward the southwest. Heat flow is higher in the transtensional region south of the Marmara Sea. In the western USA, geothermal activity is greatest in the transtensional setting of the western Great Basin. Here, a system of right-lateral strike-slip faults known as the Walker Lane accommodates ~20% of the Pacific / North American plate motion. As the Walker Lane terminates northward, dextral shear is transferred into extension in the northwestern Great Basin. This strain transfer enhances extension in the western Great Basin, thereby favoring dilation, deep circulation of fluids, and ultimately geothermal activity along fault zones.

Faults are known to be the primary control on geothermal activity in amagmatic transtensional regions, but questions remain concerning the favorable types and parts of faults for geothermal activity. Better characterization of the structural controls in such regions is needed to develop and enhance exploration strategies, particularly the selection of drilling sites in fields without surficial expressions (i.e., blind or hidden fields). Developing better methods of discovering blind geothermal fields is critical for future development, because these systems can represent the bulk of the resource in arid regions and their development minimizes impact on thermal springs in culturally sensitive areas (e.g. Turkey).

Due to the need to develop alternative sources of clean energy worldwide, we have recently initiated a comparative analysis of geothermal activity in western Turkey and the western Great Basin, USA, through integrated geologic and geophysical investigations. The major goal of this study is to better characterize structural controls on geothermal systems in transtensional amagmatic regions. This project involves 1) detailed geologic mapping and reconnaissance of ~6 geothermal fields in western Turkey; 2) structural analysis of related fault zones in these fields; 3) GIS compilation of geologic, geochemical and geophysical data; and 4) comparative analysis of fields in western Turkey and the Great Basin (USA). Our recent studies have defined several structural settings common to geothermal fields in the western Great Basin, including 1) discrete steps in normal fault zones, 2) belts of intersecting, overlapping, and/or terminating normal faults, and 3) small pull-aparts at the intersection of strike-slip and normal faults. Our initial assessment suggests that similar settings characterize geothermal fields in western Turkey. If certain structural features are common to geothermal systems in both western Turkey and the Great Basin, our findings may serve as a guide to exploration, including targeting of drill sites, in amagmatic transtensional settings throughout the world.

The in-situ stress field of a geothermal reservoir in the Rotliegend of the NE German Basin: Implications from 3D structural modelling

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The combination of fault throw analysis from a 3D structural model and the empirical approach based on the frictional equilibrium provides a limitation of the in-situ stress regime in the Lower Permian of the Groß Schönebeck geothermal aquifer system. This limitation is explained by the throw of faults in the Rotliegend where no reverse faulting can be observed indicating a stress regime between normal to transition to strike slip faulting regime. The minimum horizontal stress evidenced by hydraulic fracturing tests is Shmin~53 MPa (Legarth et al. 2005), the vertical stress Sv~105 MPa is estimated from overburden rock density and thickness. The coinciding values of Shmin from the calculation from the frictional equilibrium and from hydraulic fracturing shows that the reservoir rock in Groß Schönebeck is in frictional equilibrium. The allowable stress values for SHmax range between 74 MPa (in a normal faulting regime) and 105 MPa (in a transitional stress regime between normal and strike slip faulting). Compared with the results from a geomechanical analysis of borehole breakouts these stress regimes and their magnitudes seem reasonable. The geomechanical study incorporated core tests and numerical modelling, indicating similar stress values of the maximum horizontal stress Shmax~95-100 MPa.

Furthermore it is demonstrated how pre-existing data can be re-used in order to develop a 3D structural model with modern 3D vizualisation software. The 3D model describes both the morphology of the geological formations and the fault pattern that is decoupled by the Upper Permian Zechstein salt in a subsalt and suprasalt faultsystem, respectively. The Lower Permian Rotliegend fault system is dominated by major NW-SE and minor NE-SW trending faults. The NE-SW oriented faults bear the highest shear stresses related to the current stress field, and as critically stressed faults they are supposed to act as hydraulically conductive structures. The suprasalt fault pattern is characterized by various normal fault directions that are related to hinges of salt antiforms. The dominating structure of the suprasalt is given by the Zechstein morphology of NE-SW trending saltridges and the location of salt synforms. The Tertiary layers equalize the salt movement induced morphology of the suprasalt successions. Despite its uncertainties the 3D model remains the most detailed geological model of the Groß Schönebeck area until more or newly generated seismic data are incorporated to a new model. Since additional 2D seismic data from former gas exploration are available for the area of northern Brandenburg, future work will focus on the integration of more seismic data to extend and refine the existing geological 3D model.

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First results of the Geothermal Resource Analysis in Rhineland- Palatine

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In the past, the analysis of the surface heat flow and the measured temperatures in the subsurface has revealed clear geothermal anomalies in the Rhine graben of Rhineland-Palatine (e.g. Hurter and Schellschmidt, 2003). Partly, these geothermal anomalies have now been selected for geothermal energy production. They are in various stages of project development from initial exploration to failed, "dry" boreholes.

The aim of the new geothermal resource atlas of Rhineland-Palatine is to characterise the geothermal resources in terms of their potential evaluation and quantification for geothermal energy production. The large-scale evaluation is related a similar approach conducted for the Swiss geothermal atlas (Signorelli and Kohl, 2006). Similar findings are expected to the region of Rhineland-Palatine. The analysis is based on an approach integrating geological, thermal, hydrogeologic and surface utilization data. The geological model represents the basis of the interpretation. Temperature is evaluated by elaborating a 3D numerical thermal calibration model using the finite element program FRACTure (Kohl and Hopkirk, 1995). It represents the result of a fit from borehole temperature data accounting for effects caused by large-scale geological, topographical and partly even hydrogeological structures. The final results are reported for the known aquifer types (Muschelkalk, Buntsandstein, Crystalline basement). It accounts for the local hydrothermal situation. The findings are displayed in terms of geothermal productivity and energy.

Geological models

The currently investigated area (2'000 sq.km) is located in the southern Pfalz and for practical reasons subdivided in three smaller areas of 25x28 km.

Topography is obtained from Shuttle Radar Topography Mission (SRTM, US Geological Survey). Geological models have been calculated using a potential field approach (Lajaunie et al., 1997), which incorporates geological layers as equipotential surfaces and the geological dip as gradient of the geological potential. In addition to own field observation, the following data were used to calculate the 3D geological model of the Landau area: geological maps (e.g. Griessemer, 1987, Steingötter, 2005), borehole information (Doebl, 1970; Doebl and Bader, 1971) and interpreted seismic sections (Doebl and Teichmueller, 1979). The geological model of the Landau area considers 11 different geological units and the major 28 faults (including approximately 80 relative age relation).

Temperature, heat and hydraulic conductivity data

The topographic and geological 3D model is used as an input model for a calibrated 3D numerical model of the temperature field in the investigated area. For calibration of the temperature model, temperature data in a 250x250x250 m grid covering a depth of 250-2500 m provided by the GGA Institute are used. The calibration of the temperature field aims (1) to identify thermal signatures (= potential aquifers) and (2) to extrapolate the temperature field to greater depth (where no measured data are available) based on a physical model.

Heat conductivity data are taken from the European geothermal project at Soultz and literature. Although the uncertainties in heat conductivity have a direct influence on the heat flux distribution they are less relevant to the calibrated temperature field.

Measured hydraulic transmissivity data are generally rare but further investigation is under way. In this regional resource analysis, we review the available data from literature and assume measured data to be representative for the complete geological unit. It should be noted, that for detailed local exploration this assumption is not appropriate.

Calculation of the temperature field

The calculation of the temperature field is carried out using Finite Element models derived from the geological models by triangulation of the surface and tethraedrisation of the geological units. The boundary conditions of the model are an altitude dependent ground surface temperature and a basal heat flux that is adapted in the calibration model. The geological units are characterised by different petrophysical parameters such as heat conductivity and heat production etc. The calculation of the temperature field is based on a diffusive heat transport. Heat transport by advection is considered only if evident from the measured temperature data.

Determination of the geothermal potential

The thermal productivity pth of the subsurface is coupled with the type of utilisation. For a doublette system Gringarten (1978) introduced an analytical solution:

$$pth = (rhocp)f \times Q \times (Tprod - Tinjec) \quad [W]$$

where (rhocp)f is the specific heat capacity of the fluid [J m^3 K^{-1}], Q is the production rate [m^3 s^{-1}] and Tprod – Tinjec is the temperature difference between production and injection [°C]. The production rate includes the geometry of the borehole and the geological unit, and the hydraulic transmissivity of the geological unit. It is assumed that the hydraulic transmissivity can be enhanced through stimulation. Factor of improvement of '10' for crystalline and '2.5' for sediments are taken that reflect recent achievements. The presented scheme accounts for the difference between total energy ("heat in place") and producible energy. By integrating the geothermal productivity with operation time the producible potential is calculated. Generally, recovery factors between 1% and 4% are obtained for the selected well-known aquifers.

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MAPS

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Exploration and assessment of geothermal resources in Poland

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Because of geological conditions on area of Poland, which have more or less in common with those of other new EU member states in Central and Eastern Europe, low-enthalpy geothermal resources are available for commercial utilisation and are a quite abundant there. Relatively low geothermal gradient means heat and electricity generation with the use of geothermal resources would be possible in Poland provided reservoir media are available at depths greater than 3 km, where often either no data are available or no suitable reservoir properties occur. By now working geothermal plants of Poland are located in Podhale (the biggest) and in number sites on Polish Lowlands. Mesozoic aquifers of Polish Lowlands have a huge geothermal potential, and several sites have been assessed and their feasibility evaluated in some cases. Geothermal resources of metamorphic, fractured rocks and Carpathian flysch are of secondary importance. Though a general picture of geothermal basins and perspective geological formations is known in Poland, characterisation of geothermal sites needs a comprehensive evaluation of geological setting in order to provide sufficient information for further studies, including the reservoir modelling. Our company provides services on recognition of geological formations and structures perspective for the occurrence of geothermal resources. Such studies, where we use especially geoelectric and electromagnetic geophysical methods, constitute an important step of the geothermal site characterisation and assessment.

The GeneSys-Project: Single-Well-Concepts for Deep Geothermal Energy from the Northern German Basin

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Within the GeneSys-Project, the BGR (Federal Institute for Geoscience and Resources) and GGA-Institute (Leibnitz Institute for Applied Geoscience) aim at the extraction of deep geothermal energy (3500-4000m) from the tight sediments of the Northern German Basin. Therefore three new concepts for geothermal heat extraction using a single-well-concept have been developed, since drilling costs are a crucial point to the efficiency of geothermal plants.

All concepts have been developed for the use in low-permeable sediments, which are supposed to provide heat energy for small to medium-sized consumers in the order of 2MWth.

- Deep circulation concept: Via a hydraulic fracture a highly permeable geologic fault is connected to the well. Hot water can be withdrawn from the formation.
- “Huff-Puff”-concept: A hydraulic fracture is created, which acts as a storage reservoir for injected cold water. The cold water heats-up and can be produced as necessary. The cycles of injection and production can be adapted to the needs of the consumer – e.g. injection during weekend and production during working days or injection in summer and production in winter.
- Two-strata concept: A hydraulic fracture connects two strata of sandstones. Both strata are connected to the well. A tubing passing a packer gives access to the lower stratum while the upper stratum is linked via the annulus of the same well. Water is injected into the lower sandstone, heats-up while migrating through the fracture and is produced from the upper sandstone layer. A persisting circulation is established.

Key technology to all concepts is the water-frac-technique, which is used to create large fractures in the sedimentary rocks. The Huff-Puff and the Two-Strata concept have been successfully applied at the geothermal research well Horstberg Z1 in the Mittlere Buntsandstein formation. By the end of 2007 a 3800 m deep well will be drilled in the town of Hannover to supply office and laboratory buildings of the GEOZENRUM with geothermal heat by using single-well concepts.

Subsurface thermal inference from simultaneous inversion of thermal information from many wells: Improving the geothermal field predictions

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One of the major risks in geothermal energy exploration is related to defining the areas of high heat flow. Due to the frequently poor quality of borehole thermal information this may be the case even in areas with a relatively high density of wells.
The use of exploration wells in geothermal studies is often made difficult by the poor quality of borehole temperature observations, which cannot be corrected for the influence of the drilling process, and the absence of proper thermal conductivity measurements. However, in many areas the density of wells is high enough that useful information can still be extracted. Here we present a flexible inverse formalism that allows analysing thermal parameters such as surface heat flux and basement heat production rate from exploration wells and to assess the uncertainty of subsurface thermal inference for use, for example, in terrestrial heat flow studies and geothermal energy planning.

Our quantitative model is based on three-dimensional heat conduction in a horizontally stratified subsurface. The solution is obtained using a two-dimensional Fourier cosine representation. The borehole data are modelled using the Markov Chain Monte Carlo method. This method is very flexible and provides histograms of the parameters of interest, including, for example, the surface heat flow or the temperature at the depth of planned geothermal reservoir.

The West Lithuanian thermal anomaly displays a surface heat flow greater than 100 mW/m^2 in a background East European Platform (EEP) heat flow of 50-60 mW/m^2. This makes it one of the most profound heat flow anomalies of the EEP. It is located in an area of mainly early Palaeozoic platform sediments of thickness ~2 km overlying crystalline basement of Palaeoproterozoic age in western Lithuania and the Baltic Sea. The data available comprise borehole temperatures, basement heat production rates and estimates of thermal conductivity. The results show that the thermal anomaly can be explained by the thermal blanketing effect by sediments overlying a basement with an excessive heat production rate.

Origin of the cratonic granitoids – source rocks of West Lithuanian Geothermal anomaly

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The west Lithuania is prospective for the development of the HDR/EGS geothermal systems. For the planning of the exploration activities it is important to understand the origin of the anomalous heat flow. The recent studies revealed that one of main components of West Lithuanian Geothermal anomaly is the heat generated by granitic plutons intruded as one of last pulses of granitic magmatism at 1.46 Ga in the crust of western margin of East European Craton. Plutons of this generation are known in SW Sweden, on Danish island Bornholm and West Lithuania.

This magmatic pulse is explained by hypothetical Danopolonian orogeny and related crustal deformations. However geochemical composition of plutons suggests their formation rather by melting of cratonic crust, influenced by mantle plume.

Largest of these plutons is Žemaičių Naumiestis (ZN) in West Lithuania, composed by monzo and sienogranites and minor phase of monzodiorite. Geochemical features of these rocks essentialy differ from coeval Swedish plutons and cratonic intrusions in Southern Lithuania. They are mainly ferroan, alkali-calcic and shoshonitic, thus fitting to A-type granites. Same age rocks are dominantly peraluminous and have other features of S-type granites. They are comparatively enriched in K, Th, U, Rb, REE.

These specific features might be explained by source rocks of magma, which presumably derived from metamorphosed pelitic and semipelitic rocks strongly migmatised during the orogenic period and originally enriched in Al, K, REE and other incompatible elements. Such a composition results in a higher heat generation capacity of cratonic granitic rocks.

The potential of the low-enthalpy geothermal aquifers of Latvia

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The prospects for the practical use of geothermal water in Latvia are related to the Cambrian and Lower-Middle Devonian aquifers composed of sandstones and siltstones with subordinate shales. Based on the thermal studies of the wells, the two areas of the increased temperatures were defined.
(1) The Southwestern Geothermal Area is defined in SW Latvia, where prospective aquifers were drilled by 29 wells. The temperature of the Cambrian water attains 38ºC – 62ºC at the depths from 1192 to 1714 m. The thickness of the Cambrian aquifer varies from 63 m to 86 m. The temperature of the Lower-Middle Devonian aquifer in the Southwestern Area reaches 20 – 30ºC at the depth of 600 – 775 m. The effective thickness is of the order of 70 – 120 m.

(1) The Eleja Geothermal Area is located in central Latvia. Over 35 wells, which penetrated the prospective aquifers, were drilled in the area. In the southern part of the geothermal area the temperature of the Cambrian reservoir has is 33ºC – 55ºC at the depths from 1100 to 1436 m. The thickness of the Cambrian aquifer varies from 27 to 60 m. The temperature of the Lower-Middle Devonian aquifer in the Eleja Area is 20 – 30ºC at the depths of 400 – 584 m. The thickness of the complex is in the range of 140 – 225 m.

The Latvian Environment, Geology and Meteorology Agency carried out the geothermal project aimed at the data collection and creation of the database of the thermal and geophysical information of the deep wells. The blocks characterising aquifers were prepared.

This kind of the database and associating maps are essential for better access of the potential users (essentially industry) to the geothermal information.

The possibility of exploitation of the geothermal waters in Latvia is at the stage of a preliminary evaluation. The investigations aimed at more precise assessment of the geothermal energy resources and evaluation of technological and economic aspects of the use of the geothermal waters is the next stage.

Temperature-Dependent Fluid Substitution Modeling of Geothermal Rocks

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An analysis of two rock samples, hyaloclastites and basalts, at in-situ reservoir conditions has been done to identify the role of temperature on the seismic velocity and attenuation. The goal is to present the result of using Gassmann equation within the framework of Biot's poroelasticity for a fluid substitution analysis of geothermal rocks. The analysis of temperature-dependent wave attenuation is shown for hyaloclastites. The results show that P wave velocities decrease with the temperature rise in a systematic way. The general decreasing trend of seismic velocity towards temperature may be related to the fluid characteristics with the temperature. Using Gassmann equation it has been shown that the presence of steam bubbles can reduce the effective elastic property of rocks. The Q factor, inverse of attenuation, behaves surprisingly almost in the same way as the seismic velocity with temperature, except in the lower temperature range. The Q factor increases with the temperature is supposed to be a quick viscosity decrease. The later decrease of Q factor may indicate the presence of steam bubbles due to the further temperature increase. This finding demonstrates that the application of Gassmann fluid substitution modelling may be used for the characterization of geothermal reservoir systems.

Geothermal Energy in the Netherlands

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In the Netherlands geothermal energy would seem a promising renewable source for heating homes and offices at a municipal level and for heating industrial greenhouses. Aquifers that are of potential interest for heating purposes occur at depths of less than 1000 m to more than 3000 m in Permian, Lower Triassic and Lower Cretaceous/Upper Jurassic sandstones and in two Tertiary sand units. In total, ca. 90000 PJ (more or less equivalent to the energy content of the huge Groningen gas field) of heat in place (HIP) may be present in these deep Dutch aquifers. The fraction of this energy that may eventually be produced successfully, however, depends strongly on location-specific reservoir properties.

Whereas The Netherlands are already fairly advanced in shallow geothermal energy with roughly 600 Seasonal Heat & Cold Storage installations, in the 1980s to 1990s several deep geothermal evaluation projects were carried out, but these did not lead to any application of deep geothermal energy. Since 2000, there has been a resurgence of interest in the use of deep geothermal heat in the Netherlands in the last years. The inspiration for this has been broad based. In addition to the Kyoto agreement, which encourages governmental institutions to explore the use of renewables, the sharp rise in gas and oil prices is forcing private enterprises to consider the use of alternative energy sources. Recent studies show that geothermal energy is now highly competitive with other forms of energy. Under the new Dutch Mining Law in 2003 large quantities of geological information on the subsurface became available and this is enabling a proper assessment of the subsurface conditions for geothermal applications. Moreover, this law regulates the production of geothermal energy, giving it a firm base in the Dutch legal system. Earlier, in 2002, Senter-Novem initiated the founding of a Dutch Geothermal Platform in which several actors such as governmental bodies, energy companies, R&D institutes and consultancies are participating to promote the use of geothermal energy and to lobby for a subsidiary programme for green heat.

Today the first two deep geothermal projects are being developed/constructed in the West Netherlands Basin, both in Lower Cretaceous sandstones: in Bleiswijk a horticultural enterprise is currently producing geothermal energy from 1750 meter depth and in The Hague an urban housing project is in development, which will use geothermal energy produced from 2100 meter depth. Currently some 10 additional project initiatives for direct use are also on track. This renewed interest for the earths' interior heat in the Netherlands also initiates the proper R&D climate for the exploration of EGS opportunities in depth ranges below 3000 m.

Geological and geophysical criteria for selecting the potential HDR/EGS sites in Lithuania

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West Lithuania is situated in the central part of the cratonic Baltic sedimentary basin of about 2 km thick, overlying the Paleoporoterozoic crystalline basement. It is characterized by a high heat flow ranging from 60 to almost 100 mW/m^2. Therefore it is considered as a potential area for the development of the HDR/EGS geothermal systems. The highest heat flow is related to the cratonic Middle Proterozoic "hot" granitoid intrusions, the largest Žemaiciu Naumiestis massif discovered in the south of west Lithuania (geothermal gradient 42-45^{o}C/1km) (Sliaupa et al., 2007). However, this area is devoid of detailed geophysical information and therefore is considered as an area of a high risk, despite that the available drilling information indicates the presence of the rather thick fractured zones that can be utilized for the development of a stimulated reservoir. Some areas of the slightly lower geothermal gradients were mapped in other parts of west Lithuania. The best geothermal parameters were identified in the Vilkyčiai oil field area, where the geothermal gradient attains 40-42^{o}C/1km. The area is covered by 3D industrial seismics that was shown to be an effective tool for the mapping the fractured zones in the basement (Sliaupa et al., 2007). Besides, a number of wells were drilled into the basement with drill core sampling.

The distribution of the geotherms was modeled in the Vilkyčiai area based on the heat production, thermal conductivity and heat flow data. The heat production of the basement rocks (metapelitic granulites migmatised at different extent) in the Vilkyčiai area has apparently too low values (1.5 µW/m^3) to explain the high heat flow. Therefore, it was assumed that hot granites of the Žemaiciu Naumiestis intrusion extends under the Vilkyčiai area bellow the granulites. 23/4 modeling of the gravity and magnetic fields was carried out to identify the depths of hot granites. The obtained gravimagnetic model was used to correct the geothermal model.

The transformations of the gravity and magnetic fields revealed the prevailing NW-SE structural trend in the basement. This trend is visible in the 3-D seismic data as a set of parallel lineaments (faults). They are also traced in the overlying sediments that suggest the fault reactivation (and a high probability of the open fractures). Several major W-E and N-S (NNE-SSW) trending high-angle reverse faults are identified in the sediments that control the oil-bearing uplifted blocks. 3-D seismic data show that they extend into the basement. The NNE-SSW family of faults is considered as a most prospective target for drilling, taking into consideration the recent stress field. West Lithuania is subject to the uniaxial WNW-ESE extension, therefore the fractured zones of NNE-SSW direction can be most efficiently stimulated for fluid circulation in the basement (the permeability of fractures also strongly depends on the stress field).

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Geophysical exploration methods at European sites

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Geophysical methods in geothermal exploration can be divided in four main groups, depending on the physical parameters measured:

- potential methods, based on density and magnetic properties of rocks and two of the Earth potential fields : magnetic and gravity;
- electrical and electromagnetic (EM) methods, based on the electromagnetic properties of rocks (conductivity, permittivity) and the Maxwell equations;
- seismic methods, based on the elastic properties of rocks and the equations of wave propagation in continuous media;
- radiometric methods, based on radioactive emission of rocks and atomic physics equations. These methods are most commonly used in well-logging.

Each method has a specific application, depending on the physical properties of the target and how precisely these properties can be detected by the technology available.

Gravimetric methods are comparatively easy to use and fairly economical, they provide a good estimate of the extent of bodies with certain density. The resolution and quality of data, however, decrease considerably with depth. Gravimetric studies therefore provide a useful tool to be used for shallow reservoirs *in combination* with other geophysical methods.

Similarly, *magnetic* methods have been very popular during the last 30 years for the rapidity with which the measurements can be made and the low cost of operation. Restrictions are the resolution with depth, the complexity of the interpretation which makes it most reliable only for structures with simple geometric shapes, and the insensitivity to the actual presence of water.

Methods to measure the *electrical* resistivity of the subsurface can basically be divided into two general groups:

- Those that measure the difference in electrical potential
- Those that measure an electromagnetic field, natural or artificially created

Electrical potential has been used mainly for shallow depths, for example for ground water aquifers or very shallow geothermal reservoirs.

He most commonly used methods today are electromagnetic. They are either induced actively, as in the *TEM (Transient Electro Magnetic*) method, which is now routinely applied to depths of down to 2000m. For greater depths, the *magnetotelluric (MT)* method, which measures the earth's impedance to naturally occurring electromagnetic waves, has become the standard choice in most geothermal areas.

Seismic methods use the propagation of elastic waves, which are either generated artificially by an explosive source or occur naturally due to earthquake activity. Active seismic methods are the standard tool for hydrocarbon prospecting, as they can be used to supply a detailed image of the subsurface structure in the sedimentary environment of most oil and gas reservoirs. Passive seismology, if recorded appropriately, can be used to help understand the structural context or to give an outline of the actual fluid/geothermal reservoir.

Last not least, electrical and sesimic methods are also used for downhole tools. Some specific tools are specially developed for well-logging, for example for radiometric measurements of the rock units accessed by the well (neutron and gamma-ray measurements).

Examples of how these methods have been applied at some European in metamorphic, volcanic and sedimentary environments were gathered in a specific workpackage of the EU-project IGET.

<u>Metamorphic rocks</u> in Larderelle/Travale, Italy

The geophysical case history of the Larderello-Travale geothermal site is well representative of the development of the geophysical methods applied to geothermal exploration and of the different stages of a conventional geophysical exploration. The gigantic reservoir formed above a young granitic pluton, which intruded sedimentary and metamorphic units and caused local contact metamorphism. Up to the early 1980s, geophysical exploration was limited to electrical sounding and with temperature measurements in some shallow boreholes. Structural information was derived from gravity surveys. For the last 25 years, reflection seismic, initially used for geological-structural goals, has been more and more used to image the deeper reservoir and provide information directly related to geothermal production, since the method seemed to be the only methodology able to provide resolution useful for targets deeper than 3 km.

MT, which struggled initially with technical insufficiencies, has now developed into a tool that is also used regularly for surveys, most recently to complement seismic surveys for joint interpretation within the IGET project. In addition, well-logging to measure gamma- and neutron rays, sonic and resistivity logs are routinely used.

<u>Volcanic rocks</u> in Hengill/Iceland, Milos Island/Greece and Bouillante/Guadeloupe, French Carribean

All three field have in common their recent volcanic activity, associated with hot water springs from shallow reservoirs, implying high geothermal gradients, and the association of the geothermal reservoirs with intense fracturing and local fault systems. At *Hengill*, extensive geological, geophysical and geochemical surveys started as early as 1947. Aeromagnetic, gravity and DC-resistivity surveys were carried out between 1975 and 1986. These delineated a 110 km2 low-resistivity area at 200 m b.s.l. and showed a negative and transverse magnetic anomaly coherent with the most thermally active areas. EM soundings were used to construct resistivity maps of the uppermost kilometre. These maps were revised by TEM measurements conducted from 1986 onwards, with a much better depth resolution. Most recently, the seismic activity in the region was used to collect broadband seismic signals within the IGET project and use them for a combined interpretation with recent MT and TEM data.

At *Milos*, volcanic units overlay a sedimentary unit and metamorphic basement, which is highly fractured and serves as reservoir for high temperature fluids. Geophysical studies conducted mainly in the 1980s include a multidisciplinary approach by international teams. Gravity measurements were applied to get an image of the thickness of the geological units, EM and MT soundings were carried out and show clear low resistivity areas. Passive seismicity was recorded to construct seismic tomography fro the island. In addition, many shallow and five deep holes were drilled for detailed temperature mapping, exploration and exploitation. Nonetheless, surface geophysical methods did not supply the detailed resolution with depth which would be possible today.

Exploration at *Bouillante* was started in 1973 when four wells were drilled, based on hydrothermal surface manifestations, geology, temperature gradient in shallow wells, geochemistry and geophysics (mainly electrics and electromagnetics). Geophysical investigations carried out at in 2003 and 2004 consisted of i) offshore, in a low penetration, high resolution seismic survey and a magnetic survey and ii) onshore, in a 2-D electrical resistivity tomography and a magnetic survey. The seismic survey did not reveal any information about the reservoir, while magnetic and electric surveys provided detailed information about the characteristics of the reservoir. However, the investigation depth of the electrical method clearly appears insufficient for correctly delineating the base of the main conductive anomalies and the productive zones.

<u>Sedimentary Rocks</u> at Gross Schoenebeck/Germany.

Exploration of the area in the Southern Permian Basin started with 2-D seismic surveys in the 1970s and ‘80s, with the East German gas exploration programme. The gas exploration well at Gross Schoenebeck was dry but showed the existence of a deep hat water reservoir. That’s why the well was reopened in 2000, deepened and used as an in-situ geothermal laboratory. To intensify geothermal activities, there, the old seismic lines were reprocessed to construct a geological model of the area around the reservoir, with very good results. A new seismic survey with a parallel MT profile was performed within the IGET and provides new insight about the resisitivity distribution around the reservoir.

Geothermal Energy Potential of Czech Republic

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Deep Borehole distribution on the Czech territory is very irregular. More than 2000 boreholes deeper as 1000m were drilled for various purposes to the end of year 1989. The deepest borehole exists nearby the town Jablůnka (6306 m). For geothermal interpretation it was able to use about 3300 boreholes with utilizable temperature data and only about 550 boreholes have a complete temperature logging.

Whole borehole database was detailed treated using new special formula for deep temperatures approximation: T(℃) = a*h2 + b*h + c. This equation was used on about 3300 boreholes for the estimation of temperature values for the depth 4 and 5 km as the correlation with measured temperature, witch was used for calculation of geothermal potential.

Theoretical Geothermal Potential of whole area of Czech Republic for the upper part of the Earth crust can be estimated on EGT = 118 000 000 PJ (One year total need of primary sources Czech Republic is only 1 800 P). More than sixty localities were identified to be able to produce 3400 MW electrical energy (about 24 TWh/year) at present drilling technologies. Whole area of Czech Republic can produce 1500MW energy for the heating using heat pumps at the same time.

Session 3:

Drilling, stimulation and reservoir assessment

Drilling Stimulation and Reservoir Assessment - State of the art and challenges ahead

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During the course of the last two years, the ENGINE group has explored and compiled the state of the art and best practices in Drilling, Stimulation and Reservoir Assessment for various classes of Geothermal Systems in typical and representative geological settings.

The main question we have to answer is are we capable of exploiting and operating geothermal reservoirs in a safely plannable and cost effective manner, and which gaps are still left for us to be filled, in order to achieve this target?

The presentation summarises the second chapter of the Best Practice Handbook of ENGINE Drilling, Stimulation and Reservoir Assessment.

Drilling issues are illustrated by a detailed description of the experience gained in Gross Schönebeck (sediments), Iceland (volcanics), Soultz (granites), Larderello & Philippines (metamorphics).

Various stimulation techniques are evaluated. The hydrofracturing experiments in the Gross Schönebeck (sediments), in Soultz (granites) and in Larderello & Philippines (metamorphics) are analysed. Also the thermal stimulation technique as applied in Iceland (volcanis) is considered.

The chemical stimulations are important parts of the reservoir improvement as well. Hydraulic and tracer testing are presented.

The reservoir assessment, management, monitoring, the corrosion and scaling problems are discussed.

Needs and gaps, are identified within the aforementioned technical fields, which hamper a more dynamic development and more widespread utilization of deep geothermal energy as a contribution to achieve the EU objectives for the supply of renewable energy

Detection & Simulation of Mineral Precipitation in Geothermal Installations

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In this work, a dynamic optimization of the fouling process in the Soult-sous-Forźts geothermal plant is being considered using the gPROMS distributed process modelling capabilities. The development of the reaction scheme is based on lab-scale experiments. gPROMS (general PROcess Modelling System) is a simulation tool widely used for creating and executing models of any level of complexity, particularly in areas characterized by complex physical and chemical phenomena as those encountered in geothermal environments. Once an accurate predictive model is available it can be used for many different activities in analyzing and optimizing a wide range of aspects of design and operation. The result is improved design solutions, such as equipment dimensions, control tuning values and set point trajectories, with capital and operational savings that will be realized over the lifetime of the plant. The work considers also some of the issues associated with the generation and reliability of the laboratory data used in the construction of the model. The new laboratory scale data have been acquired from a series of tube blocking experiments using nuclear techniques.

Progress report on the use of tracer tests in characterizing deep (enhanced) geothermal systems in Germany

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Tracer tests (artificial spikings) are indispensable in characterizing fluid-based geothermal reservoirs, in that they provide the only means for determining fluid residence times and fluid-rock contact-surface (i.e., heat exchange) areas; hydraulic and geophysical methods are largely insensitive w.r. to these parameters.

Two single spikings and three complex spiking sequences (comprising single-well intra-layer push-pull, dual-scale push-pull, single-well inter-layer and inter-well flow-path tracings) were conducted in 4 km deep crystalline or sedimentary formations (candidate or actual geothermal systems) in Germany over the last five years (2003-2007). Main results were:

- at pilot KTB hole (intersecting permeable fault system in Mid-German crystalline basement): estimation of near-field and far-field fracture densities and of their increase/decrease during depletion/stimulation
- at Urach-3 (HDR system in SW-German crystalline): superposition of tracer push-pull signals from at least two fractures with ambiguously-determined transport properties; interpretation remains unclear as yet
- at Landau (hydrothermal system in mainly Buntsandstone layers, Upper Rhine Graben): improved estimation of least reservoir size (and thus of earliest thermal breakthrough) from lowered detection limits in tracer analytics
- at Horstberg (water-induced frac in tight clay/sandstone layers in N-German sedimentary basin): estimation of inter-layer flow capture angle based on extrapolated tracer recovery; computing the flow-storage distribution of the induced hydrofrac based on a statistical time-moment analysis of the measured tracer breakthrough
- from the ongoing tests at GroßSchönebeck (induced water- and gel-proppant fracs in volcanic and sandstone layers in N-German sedimentary basin): provisional estimation of frac volume and of fluid exchange with adjacent regions

In particular, an explanation is proposed for the relatively high tracer BTC tailing seen in the Horstberg flow-path tracing (from which signal background contributions could be excluded with certainty), which appeared as irritating at first from the point of view of local geothermal modeling.

Time-rate design options of continued fluid sampling and of new spiking operations are proposed and analysed for the KTB, Horstberg/Hannover, GroßSchönebeck, Landau and Bruchsal sites.

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Analysis of microseismic events induced by stimulation treatments at Geothermal Research Well GtGrSk4/05 in Groß Schönebeck, Germany

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Spectral analysis was performed on a group of microseismic events ($-1.9<M_L<-1.1$) that occurred during a stimulation experiment at the Geothermal Resesearch Well GtGrSk4/05 in Germany. These events were recorded by a downhole 3-component sensor (natural frequency 15Hz, sampling rate 1000Hz) located in the accompanying borehole E GrSk 3/90 at 3800m depth, close (~500m) to the injection point. The seismicity level was very low and only 70 events were detected and located during an injection period of 6 days. They exhibited strong spatial and temporal clustering and mainly occurred towards the end of stimulation phases. Calculated source parameters provide the evidence for the dependence between the static stress drop and seismic moment as well as for scaling of apparent stress with seismic moment.

InnovaRig - an innovative drill rig for science and industry

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InnovaRig Basics: inside poster.

The HDR/EGS Project Soultz: Stimulation of the Soultz wells by hydraulic fracturing

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The main objective of the HDR/EGS project at Soultz is the installation of a geothermal pilot plant for power production in 2008. The system consists of a triplet with two production wells (GPK2 and GPK4) and a central injection well (GPK3), all drilled down to 5000 m into a crystalline formation with temperature of 200℃.

The after-drilling hydraulic tests, performed to determine the natural performance of the wells, showed a very low productivity of the production wells. Each well was therefore stimulated by massive water injection with volumes up to 30000 m^3 and typical flow rates of 30 - 50 l/s. The productivity of the wells could be enhanced by a factor of up to 20 after hydraulic stimulation operations. The results of stimulation operations were evaluated using short-term hydraulic tests, conventional pressure transient analysis, interference pressure data, microseismic monitoring, as well as temperature and flow logs. This combination of evaluation techniques helped in getting insight into the origin of the productivity enhancement.

The poster presents a general overview of the Soultz project and illustrates, on the example of the stimulation of GPK2, the reservoir development with the hydraulic and microseismic observations. The current reservoir, after completing all hydraulic stimulations, covers a volume of 2.5 km in N-S-direction, 1.5 km in E-W-direction and roughly 1 km height. With the current performance of the wells, the geothermal fluid can be produced at a flow rate of 30 – 35 l/s from one of the two production wells, with a production temperature of 175℃. This configuration allows, in a first step, the construction of a 1.5 MWel power production unit in 2008. Later on, the power plant can be upgraded by including GPK4, the second production well, into the geothermal circuit and by installing a second power unit.

A multi approach geothermal reservoir characterization: the Soultz-sous-Forêts EGS experience

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At the Soultz-sous-Forêts EGS (Enhanced Geothermal Systems) site and in general in other crystalline reservoirs, the fluid flow paths between the injection and the production boreholes are mainly controlled by a set of permeable and non-permeable structures occurring from the hectometric to micrometric scales. The objective of our work is thus to define the architecture of these paths within the heat exchanger, which was currently poorly constrained and difficult due to the great depth of the hot granite.

Thus we will expose an up to date global synthesis of our ongoing works, already detailed in some other past ENGINE workshops:

Direct investigation

The direct investigation of the reservoir consists in some in situ geophysical data acquisitions and the following interpretations. Both logging and seismic methods are used for the multi-scale delineation of the structures intersected by the well, or the faults affecting the sedimentary cover of the reservoir basement. A special attention is paid to VSP (Vertical Seismic Profiling) data after an adapted isotropic processing which reveals the location of some permeable faults affecting the reservoir, even several hundreds of meter away from the acquisition well. Other structures are identified as well, like diffracting faults intersections or strongly attenuating zones. In addition, at well location these VSP results are in full agreement with the local results of structural logging data (UBI, ARI, FMI,...).

Field analogue analysis

As the Soultz-sous-Forêts granitic basement is covered by thick sediments (1500 m thick), an indirect characterization is led on an analogue outcropping batholith located north of Barcelona (Catalunya – Spain). This granitic massif indeed presents strong analogies with the geothermal reservoir in Soultz-sous-Forêts: these two hercynian granites exhibiting very close petrologic compositions have recorded similar tectonic histories (Pyrenean or Alpine compression, Oligocene rifting). These two granites currently present alike thermal anomaly, seismic and geothermal (hot springs) activities, and evidences of hydrothermal alteration. Based on field measurements and observations, the preliminary results of a 3D structural recognition and detailed fracturation analysis will be presented at different scales (from hectometre to centimetre). A special attention is paid to fault zones, studied by consideration of their inner architecture (fault core, damaged zone, protolith) and their petrophysical properties resulting in different behaviour regarding fluid flows (porosity, dissolution, precipitation, permeability, thermal conductivity). In addition, these intragranitic faults will be investigated by seismic and radar methods in order to make a link between the geological structures and their geophysical responses, in order to help the interpretation of the Soultz-sous-Forêts VSPs.

Conclusions

Thus, from these two approaches, a comparison is proposed so as to complete the Soultz-sous-Forêts EGS multi-scale characterization. As the structural data acquired by logging are collected only locally in the wells, the macro-structural pattern of the reservoir deduced by seismic methods can be completed by the analogue field 3D fracturing data. In addition, petrophysical properties of fault zones measured on Soultz-sous-Forêts cores and on the analogue samples are compared. An analogue allows having a conceptual idea of a hidden reservoir with a better fidelity.

In the future, thanks to these approaches, the drilling strategy of an EGS should absolutely take in account a preliminary targeting of permeable structures before and during the drilling phase, as not rigorously done in the past at Soultz-sous-Forêts EGS due to the lack of knowledge of the deepest granite rocks. Thus, by this way, a better global productivity could be reach by a lower number of producing deviated boreholes (improvement of the ratio (fluid flows)/(drilled length)). In addition, an accurate reservoir knowledge could help with benefit the management of the heat resource in the exploitation phase.

Geothermal energy resources in Belarus

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Republic of Belarus is located within the western part of the Precambrian East European Platform. In geologic respect it represents a junction of crustal blocks of different age and origin. The crystalline basement within the whole territory of the country is covered by sediments of variable thickness. In result of recent investigations a contrast pattern of the terrestrial temperature field was revealed within the sedimentary cover of the counntry. Heat flow density distribution in the whole region varies in the wide range from 20 to 70-80 mW/m^2 and it increases up to 100-120 mW/m^2 within salt domes, widely developed within the Pripyat Trough (PT).

The platform cover within the trough and the Podlaska-Brest Depression (PBD) is the most warmed up. Temperature reaches up to 100-115˚ C within the PT at the depth of 4-4.5 km and up to 40-42˚ C within the PBD. The Orsha Depression is the third deep sedimentary basin within the considered area. Temperature at the crystalline basement here doesn't exceed 30-35 C at the depth of 1.5-1.7 km. The Belarussian anteclise (BA) is a vast positive structure with a thickness of sediments up to 500 m with observed lower temperature values (10-20 C).

Estimates of geothermal resources available in the platform cover of Belarus were based on the approach used in the the Atlas of Geothermal Resources in Europe. Results show that resources of geothermal energy existing within sediments are varying in a wide range from first dozens of kg.o.e./m2 within the Belarussian anteclise to 300 – 350 kg.o.e./m^2 within the PBD. The highest values for the Orsha Depression reach approximately 100 kg.o.e./m^2.

The so-called Intersalt sediments, the thickness of the Upper Salt, Devonian deposits, overluing the Upper Salt, and the Jurassic accumulations, comprising the geologic crossection within the PT, were considered as geothermal horizons. Calculations show that the density of geothermal resources within the Intersalt Complex range from 0.1 to 1.75 t.o.e./m^2. Maximal values correspond to the north-eastern part of the PT. In the southern part of the unit they are lower (0.25-0.65 t.o.e./m^2). Within the Jurassic and the Devonian deposits, overlying the Upper Salt, the density of geothermal resources usually corresponds to a few dozens of kg.o.e./m2. Within the impermeable Upper Salt Complex they are much higher and reach in some blocks of the PT up to 2-4 t.o.e./m^2. Their utilization is possible by means of borehole heat exchangers. There are already 8 small geothermal installations under exploitation in the country. They use heat pumps with the total installed heat capacity of them around 1.5 MWt. Works were undertaken to construct the first in Belarus geothermal station for the greenhouse complex "Berestye" in the Brest town. Here the Republican Unitary Enterprise "Belgeologiya" recently finished to drill and test a borehole to recover warm water. Its bottomhole is at the depth of 1.5 km. Dozens of deep holes, drilled in the process of oil prospecting works outside oil fields, are available within the PT. It is possible to use them as a basis to create geothermal installations for heating of dwelling, as well as to satisfy demands of agricultural and industrial users. Terrestrial heat is a perspective renewable and ecologically clean resource of energy in Belarus. Its utilization represents an important national goal for the economics of the country.

Experience to use geothermal energy in Belarus

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During the last years a rapid growth of prices was observed for traditional sources of energy, such as the natural gas, oil and petroleum derivatives both in the world and in Belarus. In this relation, the actual problem of power engineering became to use local sources of fuels and renewable sources of energy, accessible in the country.

The geothermal energy, available within entrails of Belarus, belongs to one of such sources. The first eight low capacity geothermal installations, based on the heat pumps technology, were already put into operation in the country. They use groundwater with low temperature, typically below 10 ºC. Five installations are under exploitation mainly associating with the water supply works in Minsk and the Minsk district. They use groundwater from shallow boreholes as a primary heat source for heat pumps. The total heat capacity of such installations is around 0.6 MWt. All existing heat pump systems are used for heating of buildings.

One installation is under exploitation in the north-eastern part of the country, near the Polotsk Town, it uses the water from the Zapadnaya Dvina River as a primary source for a heat pump and one more installation was constructed in the southern part of Belarus, in the vicinity of the Mozyr town. During 2006 a heat pump installation was put into operation in “Novaya Ruta” at the Belarus - Ukraine border.

The peak capacity of all geothermal installations, operating in Belarus, is around 1.5 MWt. At present the activities are undertaken to construct the pilot geothermal station in the western part of the country in the urban area of Brest town for heating of the greenhouse complex “Berestye”. A borehole was drilled here to receive warm water. Tests showed that it is possible to pump out a fresh water with the content of dissolved chemicals around 0.6 gram per litre from the depth up to 1000 m with the temperature at the hole mouth around 25 ºC. It is planned to project and construct here a geothermal station with the installed capacity around 1.5 MWt.

3D Temperature numerical computation based on geological model to quantify geothermal energy in a reservoir: The Limagne case-study (French Massif Central)

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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).

In a second phase, 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. Geological layers are discretized using hexahedra and prisms (3D elements). Faults are discretized using squares and triangles (2D elements). A diffusive temperature model is applied, and temperature field is computed using the Finite Element code FRACTure (Kohl and Hopkirk, 1995). Different thermal properties are assigned to the various geological units. Thermal boundary conditions are derived from available data. Results of the model are compared with available temperature logs and the value of parameters is discussed and adjusted. Sections of the logging data from the two available boreholes Croix-Neyrat and Beaumont are well fitted, indicating local fluid movements along the other parts. This is in agreement with the hydrogeological description of the area.

As a final result, the total amount of geothermal energy available for each aquifer is computed, and the geothermal potential (recoverable energy) of each aquifer is mapped over the entire model. The most interesting geothermal target is identified (S3-DET); the total amount of recoverable energy in this aquifer is estimated to more than 500 PJ in the modeled area. 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.

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Session 4:

Exploitation, economic, environmental and social impacts

ENGINE – **EN**hanced **G**eothermal **I**nnovative **N**etwork for **E**urope
The ENGINE Final Conference
Vilnius, 12-15 February 2008, Lithuania

Design of geothermal power plants – holistic approach considering auxiliary power

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Power plants generally serve for net-power production. In geothermal power plants the provided net-power results from the produced gross power output, from which auxiliary power needs to be deducted due to power consuming components in (i) the binary conversion cycle such as pumps and valves, (ii) the cooling cycle such as pumps and fans, and (iii) the thermal water cycle such as down-hole pumps. The resulting net-power output therefore depends not only on plant-specific parameters but also on geological reservoir characteristics and - concerning the cold end - on site-specific ambient conditions.

The poster addresses the different auxiliary power characteristics of geothermal power plants and derives recommendations for a holistic approach to power plant design. As in conventional power plant design, plant-specific parameters such as component efficiencies and temperature differences in heat exchangers, which allow a general statement on the quality of particular components, need to be considered. In addition, reservoir-productivity and the choice of thermal water flow rate, injection temperature and condensation temperature have a decisive impact on the net-power output. An example of a reference plant in the North-German Basin shows that the maximum net-power output cannot be achieved by striving for the maximum gross-power.

For the reasons outlined above, a detailed analysis of the particular site-specific characteristics of the net-power output needs to be carried out for each site in order to optimise project development. Beyond the approach presented here as example, further constraints (such as seasonal cycle of ambient temperature and humidity, availability of cooling water, cooling water treatment) need to be considered. Depending on the plant site, non-technical aspects (such as noise emission, land use) can be further limiting factors for power plant design. A successive development of geothermal power generation is hence related to the development and implementation of appropriate planning instruments.

Technological and social aspects of EGS development

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Best practices in EGS exploitation include different configurations of production wells, two phase pipelines, separators, steam and brine pipelines, power generation plant or heat exchanger, and reinjection wells. Power plants may be either condensing or binary or hybrid. Power generation costs vary from 0.04-0.07 €/kWh(e) in hydrothermal systems to 0.17-0.35 €/kWh(e) in enhanced geothermal systems. The corresponding costs for heat supply vary from 0.004-0.007 €/kWh (th) in hydrothermal systems to 0.017-0.035 €/kWh(th) in enhanced geothermal systems. Other important practices include field management, environmental protection, monitoring and control, as well as establishing partnership with local community from the very beginning of an EGS project. Innovation needs should aim towards improving EGS economics by increasing useful energy output per EGS plant or reducing capital and maintenance costs

Preservation of Thermal Water Resources and Sustainable Exploitation for Therapeutic Tourism content

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The objective of the project is to preserve the thermal water resources of the area of Gure in the Aegean region of Turkey, and exploit fully their therapeutic qualities. There is already a sizeable tourism activity that is based on the archaeological site of Hierapolis and the attraction of the unique thermal spring travertines but the therapeuting potential of the thermal waters is not exploited. Developing therapeuting tourism will broaden the tourist attraction base of the area, strengthen significantly its economy, provide new jobs, and establish conditions for sustainable development. The project will develop fully documented plans for regulating the usage of thermal waters to ensure the sustainability of thermal water resources and for introducing thermal health facilities and developing therapeutic tourism, and will initiate their implementation.

Actions and means involved

• Assess and monitor current usage of thermal water; locate al thermal water users, measure usage characteristics, install metering equipment in selected user establishments to monitor usage.

• Determine level of maximum usage that will secure sustainability of the thermal water resources; conduct geological survey.

• Determine therapeutic qualities of thermal waters; conduct chemical analyses and draw on specialist opinion.

• Determine demand of thermal water; conduct market demand survey and take into account projected tourist accommodation as set by Development Plan, including projected usage for therapeutic tourism

• Prepare plan for therapeutic tourism development; conduct feasibility study for Therapeutic Health Centre facility, prepare business plan and implementation plan.

• Design operations and management system for regulating the use of thermal waters; conduct feasibility study, prepare business plan and action implementation plan.

• Establish Thermal Waters Management agency with responsibility for implementation plans and thermal water regulation and control; conduct feasibility and organisational design study.

• Coordinate and manage project; establish Steering Committee that will include, apart from the beneficiary and partner, representation of the Special Environmental Protection Council and of thermal water users in a consultative role, including Gure Hotel Association and pension owners who will be invited to organise their representation in the Committee.

• Inform and involve users of thermal water throughout the project duration; disseminate information on project objectives and progress through newsletters, establish user panels to consult on options available before decisions are taken.

Expected results

• Assessment of present-day situation of thermal water resources, the risk of depletion and determination of the level of thermal water usage that will secure their sustainability.

• Business plan and implementation plan for an operations and management system for the regulation and control of the thermal water that will secure the sustainability of thermal water resources.

• Plan for maximizing the health potential of the thermal water resources by developing therapeutic tourism, including business plan and action implementation plan for a Therapeutic Health Centre.

• Initiation of implementation through the setting-up of Thermal Water Management Agency and developing and piloting prototype state-of-art metering and control equipment for the thermal water regulation and control management system. Consensus with thermal water users regarding the thermal water regulation and control system to be introduced, and active involvement in the process of developing therapeutic tourism

Perspectives towards future activities for EGS project management tools

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The exploitation of high enthalpy geothermal systems through the use of EGS technologies is one of the most promising options for providing sustainable and environmentally acceptable electricity generation and direct use applications.

For over 35 years, scientific, technical and organizational knowledge has been obtained from a succession of long-lived EGS research projects in different countries. It is extremely important - but also a big challenge – that new project teams have access to all the relevant knowledge and experience acquired to date to ensure as successful and smooth a project start as possible.

Recognition of this prospect led the GIA to create Annex III in 1997 to investigate various aspects of EGS. One very important component of the Annex III studies is the acquisition and processing of data, which is currently being addressed in Subtask C. Under this Subtask the so-called Project Management Decision Assistant (PMDA) tool was developed.

The PMDA assembles an overview of data, data analyses and experiences (as lists of reports and publications, including many abstracts) obtained from the major EGS projects worldwide since the early 1970s, and provides an example index of suppliers of services and equipment that can be developed in detail for the local part of the world of interest.

The presentation provides an outlook and perspectives towards future activities for EGS project management tools.

The combined use of geothermal and biomass for power generation– drawbacks and opportunities

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To introduce a greater variety of geothermal systems on the market, the potential of using geothermal energy in combination with other renewable sources has to be analyzed.

The presentation addresses the possibility to increase the power generation of one system by the combined use of geothermal heat and biomass. A recent study shows that a synergetic effect can be achieved by combining a biomass driven cogeneration unit with a geothermal power plant by using the waste heat on a higher temperature level. Within the study a technical and an economical analysis of combined systems were carried out. The results show, that

- the use of waste heat from a biomass driven engine could have a positive effect on the overall efficiency
- the advantages depend on the geothermal properties as well as on the temperature level of the waste heat source
- the additional costs of the combined systems are negligible in comparison to the overall costs of the geothermal system (e.g. drilling costs)
- a combination may be useful if,

- the generated power can be increased by implementing waste heat on a similar temperature level

- the medium temperature of the supplied heat can be increased and therefore the overall efficiency

Session 5:

Risk evaluation for the development of geothermal energy

Using Decision support models to analyse the performance of deep geothermal projects

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In this study we present a techno-economic models for deep geothermal projects using best practices for asset evaluation from the Oil&Gas industry, taking into account natural uncertainties and decision trees to evaluate sensitivities and different scenarios (cf. Floris and Peersmann, 2002). In this approach Fast model calculations for the techno-economic evaluation are used to calculate the performance of the geothermal systems, investigating sensitivities of the performance due to both natural uncertainties beyond control (e.g. flow characteristics, subsurface temperatures), engineering options (bore layout and surface facilities options) and economic uncertainties (e.g. electricity price, tax regimes).

We developed the methodology first for the re-use of deep boreholes drilled by oil and gas industry for a Deep Borehole Heat Exchanger (DBHE). A DBHE is based on the principle of a fluid migrating through a coaxial pipe in the subsurface, heated gradually by migrating downwards in the outer pipe, whereas the inner pipe acts as the return path for the heated fluid. The energy performance of the DBHE is proportional to the temperature difference between injected and produced water multiplied by the injection rate (m3/h). Kohl et al, 2002 have presented a full numerical performance analysis of such systems. In our decision support approach we use fast models for the temperature evolution of the water in the well based on fast analytical solutions of Kujawa and Nowak (2000a, 2000b). This allows to calculate in a matter of seconds the performance and its sensitivity to uncertainties and the effect of various engineering options.

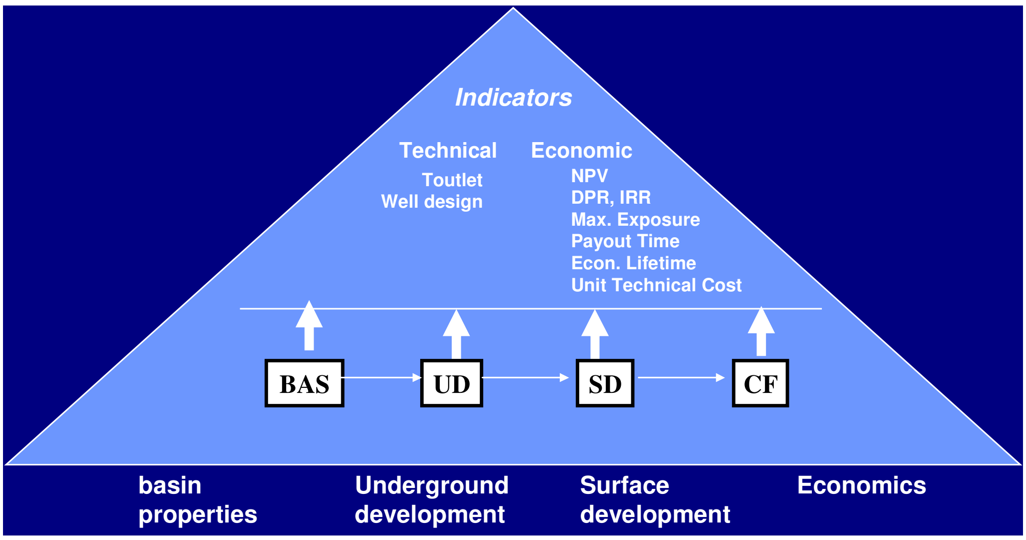

Figure 1: Fast model components for deep Geothermal systems.

For doublet systems in deep (enhanced) geothermal systems we use analytical methodologies developed for the Soultz project (Heindiger *et al*., 2006). Preliminary results indicate that the performance of the system is primary sensitive to subsurface temperature, flow rates which can be sustained in the fractured rock, and the fracture area involved in the fluid flow.

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Quantification of Exploration Risks for Hydrogeothermal Wells content

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Exploration risk concerning hydrogeothermal wells is defined as the risk of not achieving a geothermal reservoir by one (or more) well(s) in sufficient quantity or quality.

The term quality in the definition can in general be interpreted as fluid composition (fluid chemistry). Component parts (gas, salinity, oil, etc.) can appear in the fluid, which, if they exceed certain limiting values, hinder or complicate the thermal utilization. The term quantity is defined by the (thermal) power which can be achieved by one well (or more wells). Therefore, the essential parameters regarding the quantity for the exploration risk are flow rate Q and aquifer temperature T. Both parameters are decoupled und independently measurable. The flow rate Q will be determined by production tests, the temperature T can be measured by wireline measurements.

A geothermal well is successful, if minimum level of thermal water production (minimum flow rate) Q at maximum drawdown s and if minimum level of reservoir temperature T are achieved; for that the depth of the aquifer is determined as exactly as possible from seismic reflection surveys.

Information about the hydraulic parameters of the aquifer can mostly be determined in a regional scale only. Information from boreholes nearby or other boreholes having similar conditions can be weighted in a suitable manner. For the temperature prognosis, local conditions must be considered besides regional trends. An area of 1000 km² was normally chosen in the previous assessments. Because of the small data base, the simplest way to calculate the POS of a project is to multiply the single POS of flow rate and temperature.

The composition of all fluids explored in deep aquifers in Central Europe has not stopped geothermal utilization. But sometimes the technical effort can be great and induce additional costs. Nevertheless, there is no approach to assess the possibility of success for the quality.

Assessment of geothermal exploitations risks. A case study

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As many mining venture, geothermal energy shares both exploration and exploitation risks. In the present case study, which addresses a large geothermal district heating (GDH) scheme, the drilling success ration approached 100% (one recorded failure out of ca.100 wells) whereas exploitation of the low temperature deposits showed, in the early stages, severe technical and non technical shortcomings leading to frequent, prolonged, well shutdowns and, ultimately, to their abandonment.

As a result, the ad-hoc mutual benefit insurance fund, setup to mitigate such damages, was asked by the subscribing GDH operators to assess, site wise, the exploitation risks, the remedial procedures and, last but not least re/evaluate the relevant repair/preventing costs and related sinking fund requirements.

Given a five to ten year well monitoring record a deterministic scenario approach was adopted. It consisted of classifying and ranking risk impacts, for each GDH site, according to weight and severity degree for selected technical and non technical criteria, namely:

1. Technical (weighted 1)

a. last casing status assessed from residual thickness provided by periodical logging/inspection (three classes);

b. corrosion rates, prior to implementing chemical inhibition protocols, inferred from material balances after well cleaning/logging (three classes);

c. efficiency of corrosion inhibition practice based on thermochemical monitoring and direct metering of corrosion kinetics and log quantifying (two classes);

d. well completion status with respect to damage repair opportunities via casing (re)lining, either total, partial, impossible (three classes);

e. the likely dates estimated for drilling/completing new well/doublet (three classes related to early to late deadlines);

2. Nontechnical (weighted 3). Those were globalised as either favourable or non favourable conditions respective to future sustainable exploitation issues. They address, among other issues, heating grid extension, natural gas competition, operator's managerial, financial and motivation capacities.

The survey enabled to appraise three classes of risks on a representative sample of 18 doublets, further extended to the whole GDH set (i.e. 36 doublets), distributed as follows:

- low risk 12; - fair risk 14; - high risk 10.

The ultimate stage led to a cost schedule, estimated from an itemised list of repair works and three scenarios regarding completion dates, projected for each risk level over a 15 year life. It formed the core of the sinking fund and subsequent subscription fees. Twelve year after its initiation, the exercise proved rewarding since 80% of predicted figures were validated.

Session 6:

International perspective for the development of geothermal energy and Enhanced Geothermal Systems

Global perspective of Engineered Geothermal Systems and how it can be brought to the marketplace in Europe.

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The idea and the development of Hot Dry Rock (subsequently called Engineered Geothermal System) started at around 1974 in Los Alamos with the view that it gets hotter as one gets deeper in to the earths crust and that it may be possible to extract this energy and convert it in to electricity. It was also recognised that although hydrothermal systems are economically attractive and relatively easy to develop, they are unlikely to become a global player, as it requires very specific conditions only available on the margins of tectonic plates. The idea of developing EGS has spread to many industrialised countries in the last 30 years recognising it's potential for being able to deliver both heat and power on a much wider spread of the land mass.

The most successful project to demonstrate the technology was the European EGS site at Soultz (1990-2005). The project demonstrated that economic target parameters such as the cost of deep well, impedance to flow and a large heat exchange rock volume (to sustain the extraction of the reservoir) could be engineered and successfully demonstrated. This was done in conjunction with international cooperation of scientific and engineers.

The rising cost of hydrocarbons and the continuing degradation of the climate have made it imperative to find other environmentally friendly energy sources which can deliver power and heat. EGS fits very well in to this scenario but as the ENGINE programme has shown that <u>further research (in an international environment) and groundwork is necessary to bring it to the market place in Europe</u>. The resource, technology and economic aspects covered in the recent study on EGS by MIT (USA) illuminated benefits of the application of EGS and encouraged the industry to take a lead. A number of commercially funded projects have already started in Australia and the USA but Europe seems to be lagging behind except for a few privately funded projects in Germany. <u>A study complimenting the MIT study is necessary for the European scene to highlight prospects for EGS</u> and inform the European Industry of the benefits of investment in this technology.

Role of Geothermal Energy in the XXI century

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Electricity has been generated commercially since 1913, and geothermal energy has been used on the scale of hundreds of MW for five decades both for electricity generation and direct use. The utilisation has increased rapidly during the last three decades. Geothermal resources have been identified in some 90 countries and there are quantified records of geothermal utilisation in 72 countries. The present installed capacity of 9 GW will increase up to 11 GW in 2010. It has medium investment costs, depending on the quality of the resource (temperature, fluid chemistry and thermodynamics phase, well productivity,..), ranging approximately from 2 to 4,5 euro/MW, and with very attractive generation costs, from 40 to 100 euro/MWh. It is a resource suitable for base load power.

It can be considered as broadly cost-competitive, despite its relatively high capital costs for the development of the geothermal field (resource evaluation, mining risk, drilling and piping) for its very high availability and the stability of the energy production. For the next generation it is expected to see the implementation of the Enhanced Geothermal System production and an intensive increasing of the low-to-medium temperature applications through binary cycle and cascade utilizations.

Geothermal Project in Hungary

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The presentation concerns the Geothermal Potential in Hungary, a company that converted its activity from a plastic manufacturer status into a geothermal energy provider, the projects, the business model, the Life and energy in Hungary.

Session 7:

Project generation and discussion

Strategy for a reassessment of the geothermal potential of Europe

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Enhanced Geothermal Systems (EGS) and Unconventional Geothermal Resources (UGR) correspond mainly to blind geothermal resources which are much more difficult to estimate and to explore from surface due to the lack of hydrothermal manifestations like in conventional high enthalpy fields. At the scale of Europe, the strategy for finding EGS and UGR is therefore significantly related to the deep seated litho-tectonic conditions. During the ENGINE project, it was stated that heat, stress and fluid pathways as well as the structural inventory of the subsurface are the key elements that could be considered as priority for research needs as well as for defining new geothermal targets.

Then, different EGS or UGR systems can be defined: stimulation of low permeable reservoirs in hot environment, enlarging the extent of productive geothermal fields by enhancing permeability in the vicinity of naturally permeable rocks, supercritical fields, electricity production from medium-enthalpy geothermal resources by binary plants, combined heat and power generation and cascade use of heat resource…

In the future, the possible contribution of Enhanced geothermal energy to the European Strategic Energy Technology Plan at the horizon 2040 requires an evaluation of the stored geothermal energy, i.e. the thermal potential available of the first tenth kilometres of the European continental crust. From very sparse in-situ measurements of temperature in wells at depth, how can we extrapolate the distribution of heat at a continental scale and calculate temperature at depth maps based on an appropriate geological model? For instance, the contributions of geothermal resources embedded in sedimentary basins and/or in basement rocks have to be evaluated. Moreover, coupling thermal conductivity with other physical and chemical parameters (gravimetry, resistivity, seismology…) represents an ultimate achievement for imaging solid earth by providing a thermal tomography.

GIS approaches combining most suitable geodynamical conditions (heat, stress, fractures) and socio-economic criteria (inhabitants, road, river, energy needs…) have to provide EGS potential maps for selecting the most promising areas for geothermal prospecting.

Towards a European Geothermal Deep Drilling program

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Ambitious energy and environmental policy goals are creating new challenges for energy suppliers: The energy mix of the future will have to be ecologically friendly, secure in resources, competitive, and most especially sustainable. The goal of the European Union to at least double the proportion of renewable energy sources in the overall energy consumed in the EU by the year 2010 makes it clear just how high the expectations vis á vis the energy producers are. Geothermal energy is becoming more and more interesting in the course of this process. Energy in the form of technically usable heat or electric power can be produced from geothermal sources as needed. A European Geothermal Deep Drilling program is necessary to trigger a significant contribution to the goal of the EU.

The Earth contains a high potential for supplying heat to the energy economy. The occurrence of geothermal heat sources is therefore not limited to regions with noticeable volcanism. In principle, there is geothermal heat everywhere, including under Central Europe. To be sure, there one must drill down to depths of four to five kilometres in order to tap a level of temperatures which is high enough to effectively generate electric power using steam turbines. This potential can be utilised only after the costs and risks of its development have been effectively reduced. The challenge lies in the establishment of technologies which improve the yield of geothermal repositories and reduce the risks associated with their exploration and exploitation.

The development of suitable technologies for the exploitation of underground heat has been one of the central research goals of the EU in the past years, e.g. at Soultz-sous-Forêts (Alsace) for application to HDR processes. The research and development projects within a forthcoming European Geothermal Deep Drilling program require the combination of inter-disciplinary basic research for the characterisation of potential geothermal repositories with economic and technological planning concerning the operation of geothermal installations. We need expertise to the investigation of the geological, geochemical, geophysical, and geomechanical aspects of geothermal site development. In addition, the analysis and evaluation of the overall systems has to be carried out. The overall goals of the program are the improvement of the reliability of geothermal drilling, the standardization of geothermal drilling and stimulation operations, system studies with focus on operational issues, the development of drilling instruments and tools and completion components based on innovative 3D seismic geothermal exploration technology.

For each geological context, best practices are available: size of drilling, directional drilling, completion, cementing, and application of an extended set of instrumentations developed for drilling into hydrocarbon reservoirs. Learning curves exist for drilling in traditional geothermal areas (Philippines, Iceland, Italy). In these areas standardised procedures are established whereas reliability of drilling and careful reservoir access remains as major tasks in future. For the rest of Europe the standardisation of geothermal drilling with all aspects of drilling large diameters, directional drilling, and drilling mud technologies has to be established. Exploration for geothermal resources require drilling solutions and machineries that address the lowest possible pay-zone formation damage, maximum characterization of the target geology, high deviation and large drill holes directional drilling as well as intelligent well completion designs. A general task for all geothermal sites is the development of reliable drilling technologies into the reservoir with almost mitigation of formation damage, and providing other techniques to monitor in situ downhole the drilling, the testing, the stimulation, and the operation of a thermal water loop.

The drilling into geothermal reservoirs requires most of the specific costs of geothermal energy provision. Beyond the experiences of geothermal reservoir development in traditional geothermal areas and application of methods of drilling into hydrocarbon reservoir the development of reliable drilling technologies into geothermal reservoirs with almost mitigation of formation damage, and providing other techniques to monitor in situ downhole the drilling, the testing, the stimulation, and the operation of a thermal water loop is required. A group of drilling projects in areas representing European sites should be accompanied each applying at least one innovative approach addressing improvement in drilling, mitigation of formation damage, or installation of new monitoring techniques downhole. The research program should be focused as follows:

• The preferred way to drill a geothermal payzone would be with low pump volume at under-balanced conditions. Aerated mud systems operated in counter-flush mode do provide such minimized impact on the formation, even with large bit sizes at penetration rates equivalent to oilfield rotary drilling. Research will have to be done, how to advance this drilling method for depths beyond 3000 m and hole deviation angles up to 90^{o} and long horizontal as well as multi-lateral well sections.

• The optimal formation evaluation and geologic characterization of the geothermal reservoir would be to drill it with core drilling techniques. Wireline coring systems can provide an efficient and safe way to recover hundreds of meters of large diameter (94 mm) cores at close to 100% recovery. Its low mud circulation characteristics, combined with an under-balanced aerated hole opening thereafter, will assure maximum information recovery from the payzone under least reservoir damage and maintenance of best borehole stability conditions for later complementary logging runs. Research efforts will be needed of how to advance such core drilling system for high angle and horizontal drilling performance.

• The provision of the largest possible last production casing string has a significant impact on geothermal well economics. Research will be needed into the area of new high grade tubular materials combined with slim premium connections, and alternatively with new technology field welding techniques in order to avoid diameter constraints in geothermal wells from conventional oilfield casing string geometry. Expandable tubulars, casing while drilling techniques and other novel procedures will have to be evaluated for geothermal applications.

• High angle and horizontal well profiles do provide large exposures to a producing reservoir and can therefore maximize water productivity and hence improve financial performance of a project. Such wells will however require in addition selective and intelligent well completions, in order to maintain a uniform productivity over its entire length in a heterogeneous reservoir over time. Research will be needed into downhole controlled flow-control valves, multi-lateral spider well layouts and/or distributed submersible pump configurations in order to insure a uniform and uninterrupted water production over the entire life cycle of a geothermal production well.

Post ENGINE tasks – What remains to be done

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The EU project ENGINE was a major step forward in moving EGS ahead. It assembled a large, knowledgeable group of wide specialization; the results will represent a milestone in EGS R&D. Yet it must be realized that only as an intermediate position has been established on a still long way to reach the ultimate EGS goal: development of a technology to produce electricity and/or heat from a basically ubiquitous resource, in a manner relatively independent of site conditions. There are still major knowledge gaps, unanswered questions, and unavailable solutions to work on. Here only a selection is listed.

Although the minimum requirements for an economically viable EGS reservoir are set since quite some time (size, heat exchange surface, flow impedance, thermal and stress-field properties), their realization in a tailor-made manner to comply with differing site conditions is not yet demonstrated. The creation, characterization and operation of an EGS reservoir at depth needs techniques of remote sensing and remote control; here we are still far from having “best practices”.

Many questions of rock mechanics like the degree of anisotropy, stress propagation -again under different site conditions- are unanswered; connectivity throughout a planned reservoir cannot yet be engineered.

How to control induced seismicity? Most economic and long-term production models assume uniform reservoir permeability and heat exchange surfaces, consisting of numerous, well-distributed fractures. If stimulation results in larger seismic events the created, correspondingly extended single fractures could easily form short-circuiting pathways.

There is no experience about possible changes of an EGS heat exchanger with time. Permeability enhancement (e.g. new fractures generated by cooling cracks) could increase the recovery factor while permeability reduction (e.g. by mineral reactions) or short-circuiting could reduce recovery.

So far the envisaged electric power capacity of EGS systems is limited at a few MWe. But in order to play a significant role in electricity supply a system capacity of at least several tens of MWe would be essential. One of the main future R&D goals will be to see whether and how the EGS power plant size could be upscaled.

For prospective investors a well-designed cost-risk analysis and corresponding measures still remain to be developed.

The competence and working spirit of the ENGINE team should by all means remain focussed and united. Already existing, important but not yet realized R&D action plans like GEISER should be rapidly implemented. And most importantly: as many kilowatt-hours of electricity as possible needs to be produced from EGS sources, as soon as possible.

Economic perspectives for developing EGS

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The presentation shall be focussed on EGS development on an industrial and economical point of view. Based on recent experiments in the Rhine Graben area (Soultz-sous-Forêts, Landau), basic investment costs for a 2 wells system at 3000 m depth shall be estimated. Power and/or heat generation shall be considered and the tariff issue shall be discussed taking into account the specific problem of auxiliaries' consumption in the case of EGS. As a conclusion, a rapid comparison with other subsidised renewable energies (wind, solar) shall be presented and pros and cons of EGS shall be highlighted.

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