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Shear-wave Splitting, New Results, Old Problems

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Imaging the subsurface structure of geothermal fields with passive seismic experiments is becoming a useful tool of exploration that can give important clues as to the geometry of the fracture system, the movement of fluids and even the size of the main cracks in the reservoir. I will describe results obtained by my geothermal research group in California's Coso and The Geysers, and in Iceland's Krafla and Hengill geothermal fields using observations of shear-wave splitting recorded on temporary arrays of seismic sensors deployed around the reservoirs. Though using shear wave splitting to image subsurface cracks is a straightforward process it is also labor intensive when done even semi-automatically. I shall present a strategy we have successful developed to automatically and in real time detect and eventually invert the shear wave splitting parameters into useful subsurface crack structure information. I will also briefly mention results, some old, some new, which we will hopefully develop further, including the use of full-wave seismogram inversion and the determination of crack size.

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Detailed structure of the Hengill geothermal volcanic complex, Iceland, inferred from 3-D tomography of high-dynamic broadband seismological data

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Structural features of geothermal systems allow us to infer location of productive areas before drilling. We use broad-band seismological records from high-dynamic instrument to perform a detailed tomography at Hengill volcanic triple-junction complex and geothermal system. This well developed geothermal system is exploited to extract hot vapour which is used for electrical power and heat production. In order to improve our understanding of the relationships between seismic activity and vapour production, a seismological network including 5 broadband instruments (120 s - 50 Hz) and 2 broadband instruments (60 s - 50 Hz) was setup from June 26th, 2006 till October 17th, 2006, at the Hengill geothermal system, in the framework of the I-GET project (European Commission FP6 program). In addition, we included continuous seismic data from 3 permanent stations of the SIL network. Data analysis allowed us to detect automatically and classify semi-automatically more than 600 earthquakes, amongst which long-period (LP) earthquakes were observed for the first time in this area. We used about 250 local volcano-tectonic earthquakes with clear P- and S- arrival times to perform a simultaneous inversion for the 3-D velocity structure and hypocenters location determination. Results give us more insights than previously obtained in this area, especially on the existence of a high velocity anomaly, that matches with a low resistivity anomaly, in the area of Olkelduhals (south-east of Hengill volcano), from about 2 to 4 km depth. We also detect a low vP/vS ratio anomaly beneath the northern part of Mt. Hengill below 4-5 km. We discuss possible interpretations and implications of those observations.

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Beyond Seismic: Combining Seismic and Electromagnetic Exploration

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Geophysical exploration in geothermal fields routinely includes both electromagnetic and seismic surveys, the interpretations of which are usually done separately and then combined in some ad hoc way. Instead, because these data share geological constraints, combining them in some systematic, quantitative way is far preferable. Aside from the shared geological background, a “joint” analysis can also dampen large errors and noise in one data set by less sensitive responses in the other. A simple classic example is the marked improvement in earthquake location when P-wave data are supplemented by S-wave data.

In the two exploration oriented examples presented here, we describe some method for combining seismic and electromagnetic survey data to 1) detect average fracture orientations using seismic shear wave splitting and magnetotelluric (MT) polarization directions and 2) derive porosity from seismic velocity and resistivity.

Shear wave splitting is routinely used to detect fracture orientation since in aligned sets S-wave motions propagate faster parallel to their long dimension. Thus S-waves split into fast and slow components. However shear wave splitting can also be caused by other geological phenomena such as 2-D layering. MT polarization can also be the result of preferred fracture orientation, as well as 3-D structural effects. But the latter effects are notably different from those effecting S-waves. As a result, detecting similar orientation in both shear wave splitting and MT polarization makes it clear that the cause is the same, namely aligned fractures.

Porosity plays a different role in determining the relationships between seismic velocities and electrical conductivities. Seismic velocities are more sensitive to rocks with different lithologies and densities while electrical conductivities are more sensitive to rocks with different porosity and associated permeability. In this case, the combination of sensitivities helps constrain strong local fluctuations in all these properties as well as background noise.

We show how such seemingly different data can be combined through joint quantitative analysis using, for example, simple linear and more advanced inversion schemes. In some cases the examples have been validated through drilling and other methods, with noted improvement in the combined images.

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POSTER

Passive-seismic research in New Zealand's geothermal fields: present-day work and future plans

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Current geothermal passive-seismic research at GNS Science, New Zealand, has several objectives, including further development of waveform-based location techniques to delineate fracture networks, as well as studies on the combined qualitative use of passive seismic and MT data for reservoir delineation. In this poster we illustrate some of the developments using recorded seismicity from a 10-station recording array above the 34MW Rotokawa geothermal field. Separate 3-D modelling of magnetotelluric data from a closely spaced survey above the same field (by Heise et al, 2008) allows comparison of earthquake locations and the resistivity structure, suggesting that induced seismicity is occurring in the high temperature (300-350C) core of the geothermal system, the improved locations helping to identify deeper fault structure. We also outline the geophysical component of a new research programme planned for 2009-2012, hopefully to be funded by the New Zealand Foundation of Research Science and Technology, (FRST). This new programme, termed "Hotter and Deeper", aims to develop tools and background data to encourage successful deep exploration and production in New Zealand, possibly but not necessarily by extension of the existing high temperature geothermal fields. In part the planned work will aim at improving knowledge of physical properties (seismic velocity, attenuation, resistivity) at depths between 3-6 km, for a 25 x 35 spatial area of New Zealand's Taupo Volcanic Zone (TVZ); the planned work also incorporates numerical modelling and geochemical studies, working towards greater understanding of the nature of the deep fluids, and their flow pathways.

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POSTER

Towards fully automated fracture characterisation in microseismic datasets using shear-wave splitting

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Identifying the location and geometry of fractured rock is of interest for a wide array of applications. In mining, the stability of excavations is reduced, thus increasing production cost. In hydro-carbon reservoirs (meso-scale) fractures and (grain-scale) cracks connect the pores of the reservoir rock, improving the flow to the wells and thus reduce production cost. Finally, in geothermal projects fractures increase not only permeability but also the effective contact surface, which eases the heat transport from rock to the transfer fluid, thus increasing effectiveness. It is yherefore desirable to have a detailed knowledge of fracture geometry, which in turn allows identifying and predicting optimum well locations.
The method of shear-wave slitting provides arguably the most complete insight to study in fracture characteristics *in situ*. It is based on the fact that a medium with a preferential orientation of fractures and cracks renders seismically anisotropic on a large scale. A shear-wave passing through an anisotropic medium is split into two wave orientated along the anisotropic symmetry axes and separated by a delay time proportional to the strength of anisotropy. When illuminating a fractured rock from various angles, characteristic changes in fast orientation and delay time indicate fracture orientation and fracture densities.
We present results of a shear wave splitting study in a mine using ~40.000 seismograms. This large dataset required the development of an automated analysis. We achieved that by assigning a quality to each measurement base on characteristic differences between the results of two independent splitting techniques. Manual inspection of a subset of the dataset proved that this automatic quality control value is reliable. We then use a series of synthetic models based on rock physics to invert the results for fracture orientation and density. We use synthetic data to verify the approach, and show a strong dependency on the ray coverage. Finally, by applying a 14-day sliding window on our results we are able to identify fracture evolution during the production cycle in the mine. The fracture density increases during production, with horizontal fracture density being stronger than the vertical fracture density. This can be explained by the removal of the supporting rock below during the excavation. In short intervals of reduced production, the horizontal fracture density decreases, while vertical fracture density increases. Future work will analyse the frequency dependence of splitting.

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POSTER

Upper Rhine Graben: Seismic Methods as Basic Tool for Geothermal Exploration In Structurally Complex Tectonic Environments

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The objective of geothermal exploration activities in Upper Rhine Graben region is the analysis of prominent geological structures, fault zones and karst structures in the deeper underground. Thereby the interest is - different from oil field practice - set on fault zones that should be open and active under recent stress conditions: as the actual rift propagation follows a NW-SE direction through the Hercynian folded block of the Rhenish Massif this direction will also be the direction of open fractures in the graben itself. In conclusion geothermal exploration in the given area is focussed on open and high permeable fracture zones.

As first step of the exploration activities all available geologic data in the area of interest was collected and analysed. The primary target formations were identified. In the graben section of our scheduled activities these were Mesozoic rocks (Muschelkalk and Buntsandstein) and the Hercynian basement (gneiss and granite). Thereafter older 2D lines from the industry were acquired, reprocessed and interpreted as possible. At this point problems arose as the seismic measurements for hydrocarbon exploration had different target depths and also different aims in resolution using for these purposes different recording techniques: besides information about structural high and traps it is necessary to get data about source rocks, fairways, reservoir rocks and sealing horizons. Geothermal exploration is primarily interested in the size, shape and age of fault patterns and their accompanying fractures, the activities at the faults and their flow through permeability. This was achieved by new 2D and 3D seismic surveys recorded for GeoEnergy GmbH.

Data from most recent 2D and 3D seismic surveys in the Rhine graben area is presented. The seismic information is of high quality and allows the detailed delineation of the structural pattern that controls the geothermal reservoirs. Characteristic seismic lines are presented as well as results from the analysis of seismic attributes and hydraulic models that predict the flow of hot fluids in a hydrothermal system.

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POSTER

Structural Styles and Geothermal Exploration
Results from 2D- and 3D-Seismic Surveys in a Continental Rift System

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Modern seismic measurements in the Upper Rhine Graben area of southwest Germany supply large data sets about the internal structure and sedimentary fill of one of the most important geothermal provinces in Central Europe. These data has been recorded for the single purpose to explore the geothermal systems below the Tertiary filling of the Upper Rhine Graben which shows considerably higher geothermal gradient than observed in the surrounding areas.

The Rhine Graben forms the most prominent segment of the Cenozoic European rift system which traverses the Earth´s crust of Central and Western Europe with different parallel branches in a general NNE-SSW trend ("Rhenish" direction) for a distance of about 1000 km. It follows a distinct pre-existing weakness zone in the Hercynian basement due to Carboniferous deformation of Central Europe. The Upper Rhine Graben segment in Germany and France is more than 330 km long and about 30 km wide. Its formation started in Mid Eocene times and still continues. The maximum throw between the uplifted graben shoulders and the graben bloc is 5.500 m, the maximum thickness of the Tertiary fill is near 3.200 m. Some of the major faults can be traced down to a depth of at least 15 km.

The Tertiary fill of the graben and also the rocks below the graben floor are extensively fractured. The objectives of the geothermal exploration are to delineate zones of extensional and translational tectonic style and exploit their hydrothermal content for heating and power generation. Due to the recent stress conditions, which are very different to those at the beginning of the graben formation, there are not only extensional fractures to be observed in the exploration, but also compressional features and horizontal movements of the crustal blocs, which reactivate and open older tectonic systems, have to be analyzed. These systems give way to the uprise of hot fluids.

In this presentation three different structural trends within the Upper Rhine Graben will be presented:

- Divergent wrench faulting bound to deep seated fault systems in the basement as response to stress field causing horizontal movements,
- Basement involved fault tectonics with bloc faulting

and

- Pull apart structures and accommodation areas between terminations of major fault zones with related rapid vertical movements.

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As a result of the available high quality of the seismic information it is possible to demonstrate the character of the faults as growth faulting and recent vertical movements up to the surface. Active fault systems intersect inactive ones and confirm the structural pattern as deducted by the intensive use of seismic attributes. In some cases the direct detection of zones percolated by hot fluids may be possible.

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POSTER

3D Numerical modelling for the Travale Geothermal Field (Italy)

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In the framework of the WP5 (integrated interpretation), the natural-state and historical production of an area belonging to the Travale geothermal field has been simulated by using the 3D numerical simulator "Tough2".
The modeled area extends for about 200 km^2 and the Radicondoli_7bis well, drilled during the first I-GET project year to explore a 3D seismic target, is located right at its center. This choice was made to evaluate the evolution of thermodynamic parameters around Radicondoli_7bis during the production history of the whole Travale geothermal system.
In addition to the "local scale" modeling that is in charge to GEOWATT, the structural parameters obtained by the interpretation of the available geological and geophysical data have been used as input data for this "regional scale".
Starting from these structural parameters, the permeability and porosity of the rocks were tuned to match the initial pressures and temperatures that can be referred to the values measured in the first wells drilled in the area.
To fulfill the work aims, no constant pressure boundaries (i.e. mass sources) were introduced.
The depth of the domain was set to 6000 m according to a seismic reflection horizon which is believed to represent the reservoir bottom. Due to the temperature range predictable at this depth, the reservoir bottom can be considered impermeable, but allows the natural heat flow to take place.
The top of the reservoir is constituted by an impermeable layer of rock, which acts as cover of the geothermal system.
The only interactions between the geothermal reservoir and the external environment are the natural manifestations and a well known superficial aquifer where the cover is absent.
The history of the industrial exploitation was then introduced and the relevant pressure distribution was compared with the actually recorded data.
Satisfactory results were achieved, and field production resulted to be sustainable for at least the next 50 years.

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POSTER

Integrated seismic and MT exploration methodology of low-medium enthalpy geothermal systems - Skierniewice site example, Poland

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Overview
The Skierniewice site (central Poland) is one of four I-GET's test sites and represents shallow and low-medium enthalpy geothermal system. The preliminary investigations of the archive geophysical and borehole data allowed selecting three sedimentary aquifers as perspective for the geothermal purposes – the Cretaceous, Jurassic and Triassic. Based on 3D seismic and MT geophysical methods and their integrated interpretation we elaborated and tested the methodology of exploration those systems. These two methods were applied to create a detailed geostructural model surrounding the Kompina-2 well, located in the site centre, and interesting due to the recorded free outflow of 107 °C brine from the Triassic horizon occurring at 4km depth. In specific conditions this temperature of water may be satisfactory for heat and electricity production.

Outflow temperature prediction
The wellhead temperature was estimated taking into account the size of well casing and other heat exchange parameters. A simulation of the expected wellhead temperature for the Kompina-2 well showed that 50 m^3/h flowrate will make it possible to use the geothermal water for standard heating installations excluding heat pumps. The electricity production using binary power stations requires the flowrate being higher than 50 m^3/h.

Seismic
Survey was performed in grid scheme as 3D image with 2,5 km² of homogeneous fold area in the image centre, by using of vibroseis along 6 source lines of a length of 29 km in total, and recording on 8 receivers lines of a length about 54 km in total. This allowed obtaining data sets with very good quality in the centre of the seismic image where the homogeneous fold exists. Processing of seismic data was performed by standard procedures similar to those being used in the hydrocarbon exploration with additional extension for geothermal purpose. Despite of non-uniform offset distribution and fold area inside bins, final migration has very good quality and is comparable with results of standard 3D seismic processing. The investigated site belongs to areas with the complicated geological structure, where many vertical movements and soil tectonics features occur. There were interpreted one big dislocation (with major throw) and 4 minor ones and a vast syncline west of the

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Kompina-2 well spreading out in NW-SE direction. The perspective Triassic formation was correlated to a depth of 40 m above of Tp2 horizon (Middle Buntsandstein).

Magnetotelluric

MT survey was carried out along seismic lines, as the continuous profiling and MT/AMT/CSAMT soundings. CSAMT measurement was made to control and supplement MT/AMT data as the survey area appeared to be highly noisy. Two options of robust data processing were applied to improve the quality of calculated parameters - coherence between time series of magnetic field components and remote sites. Resistivity maps were made based on results of 1D Occam inversion for two different array orientations and on results of 2D NLCG inversion made along six sounding lines. Strictly lateral resistivity changes appear at a depth range related to Jurassic and Triassic complexes. A wide, low-resistivity zone is visible in the central part of the section that is probably related to the fractured area related with a fault zone. That area is a possible way of ascensive filtration of hot mineralized water from Triassic or Zechstein complexes up to Jurassic fractured and permeable hydraulic horizon.

Seismic and MT integrated interpretation

Integrated interpretation was performed mainly by common analysis of the structural maps obtained from seismic and resistivity distribution taken from magnetotelluric data. This assumption allowed indicating zones of relatively lower resistivities which are probably connected with strong fracturing or high porosity forming ways for filtration of the geothermal water. Comparison of the structural maps with the distribution of geoelectric anisotropy allowed indicating the maximum “anisotropy” zones, which represent probably areas with strong fracturing or/and porosity filtrated by hot mineral water. One of such zones is located close to the Kompina-2 well and the other in the southeastern part of the study area.

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POSTER

Temperature-Dependent Seismic Properties of Geothermal Core Samples at In-situ Reservoir Conditions

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In geothermal reservoirs, fluid-steam phase transition, fluid pressure and temperature are some crucial factors that potentially produce and/or contribute to seismic anomalies. When interpreting such anomalies, realistic assumptions based on validated rock physics models are important. Many geothermal reservoirs, as the case of Icelandic reservoir being investigated, are characterized by temperature range up to 200-300 C and pore pressure around 10 MPa with the pore water being in the liquid phase. A controlled petrophysical laboratory experiment simulating those conditions becomes important for the evaluation of such a geothermal resource.

An analysis of core scale properties of rock sample at in-situ reservoir conditions is useful to identify the role of temperature on the seismic velocity and attenuation. The goal of this work is to present the result of using the Gassmann equation within the framework of Biot’s poroelasticity for a fluid substitution analysis of temperature-dependent geothermal rocks. For that, the measurement of ultrasonic transmission wave has been performed on two samples of volcanic geothermal rocks with different alterations. The Gassmann equation is then used to relate the effect of temperature on the fluid and on the effective elastic property of saturated rock. In addition, the temperature-dependent wave attenuation is shown for the hyaloclastite sample. A possible explanation of such attenuation behaviour is related to the thermophysical characteristics of fluid.

The results show that the general decreasing trend of seismic velocity towards temperature may be related to the thermophysical characteristics of fluid. Using the Gassmann equation it has been shown that the presence of steam bubbles can reduce the effective elastic property of rocks which indirectly demonstrates the role of temperature to the seismic velocity. The Q factor, i.e., 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 increase 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 temperature-dependent

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fluid substitution modelling using the Gassmann equation can be applied for the characterization of geothermal reservoir systems.

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Seismic Studies for Fault and Fracture Detection in Geothermal and Gas Reservoirs

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Geothermal reservoirs have been notoriously bad targets for surface seismic investigations. The reasons include a combination of high attenuating near-surface layers and a resource at depth that is often characterized by a high degree of fracturing and/or faulting. In recent years, efforts have been undertaken to integrate state-of-the-art seismic imaging techniques to understand their limitations and applicability to geothermal exploration. In this paper, we present the results of field and modeling studies to determine the location and properties of fault and fracture zones in geothermal and gas reservoirs. The first study included 3-D surface seismic and 3-D VSP data supported by 2-D finite-difference modeling to determine how to best investigate the existence and the location of subsurface faults at the Rye Patch geothermal reservoir, Nevada. A suite of fault models were investigated including blind faults, faults with surface expressions and fracture zones at depth. The seismic data suggest that blind faults can be detected by a sudden attenuation of seismic wave amplitudes, as long as the fault is located below the receiver array. Additionally, a conversion from P- to S-waves indicates the reflection and refraction of the P-waves while propagating across the fault. Both observations can be used to estimate the location of the fault at depth. The seismic study at a fractured gas reservoir in the San Juan Basin, New Mexico, included 3-D surface seismic and 3-D VSP field data supported by 3-D numerical modeling. It was observed that areas with strong S-wave anisotropy reveal an anti-correlated with productivity from gas wells throughout the basin, which suggests that fluid flow is better supported by fractures with a higher degree of random orientations. Furthermore, it was observed that fracture zones at depths of 1000 m are practically invisible in surface reflection data but can be detected in VSP data collected contemporaneously in nearby boreholes. The study at the Yucca Mountain nuclear waste repository, Nevada, was conducted to determine the fracture density in the future repository horizon. A large-scale (> 5 km^2) tomographic experiment was conducted and the resulting P-wave velocity distribution converted to a fracture density distribution using composite medium theory. The resulting fracture density in the horizon matched the observed fracture density along the walls of the access tunnels to a high degree. The result indicates that the southern region of the repository may be subject to higher levels of surface water seepage during future operations. Finally, in our last study of seismic wave propagation in fluid-filled fractures, it was found that Stoneley guided waves show larger amplitudes than any other wave propagating along the fracture walls. Their dispersive character can be used to estimate the viscosity of the fracture-fluid, while their range of propagation can be used to determine fracture conductivity in reservoirs.

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3D Seismic contribution for the exploration of deep targets in the Travale test site (Italy)

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Since the beginning of the 90's, geothermal exploration in Tuscany has been addressed to deep reservoirs, and in 2003-2004, for improving the detection of deep drilling targets, Enel acquired 3D seismic surveys in a few areas of the Larderello-Travale geothermal system.
In the framework of the I-GET project, Enel carried out several studies based on the 3D seismic, sharing both the data and its own experience in seismic prospecting for the exploration of deep fractured geothermal system. Advanced analyses have been applied to 3D seismic data of the Travale test site, where a deep superheated steam reservoir is hosted in metamorphic/intrusive formations at depth higher than 3000m. Reservoir productivity is linked to fractured and permeable levels that are rather confined and not uniformly distributed, and that often give rise to high amplitude seismic reflections. Thus, seismic data processing was aimed at the proper treatment of signal amplitudes and at the detection of peculiar seismic signatures, including AVO and anisotropy features, as well as at the reconstruction of seismic images.
All the available surface and well data of the Travale site have been utilized for an integrated interpretation that was initially oriented to update the geological and structural model. A complete new set of geophysical well logs was specifically acquired in the framework of the IGET project. All the available logs of the area were a very useful tool for the calibration of the 3D seismic survey. In particular, the availability of sonic and density logs allowed the application of wavelet processing that was focused on the deep reflectors. This technique improved the vertical resolution and the lateral continuity of the potential seismic targets.
The detection and location of seismic signatures linkable to deep potential drilling targets was a fundamental interpretative step. To this end, prestack (AVO) and poststack signal amplitude analyses were focused on the identification of areas characterized by anomalous amplitude values. It turned out that many anomalous reflections occur in correspondence of the "H" horizon, an important seismic marker in the study area that, from a geological point of view, is the expression of a contact metamorphic aureole characterized by a higher density of fractures.
As confirmed by a significant number of wells, in the Travale area steam production from fractures occurring within the "H" horizon corresponds to more than 70% of the total.

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Seismic studies at the Travale test site

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The seismic studies carried out on the 3D seismic data acquired by ENEL at the Travale test site have been focused to the extraction of the seismic signatures possibly related to geothermal reservoirs, and to improve the matching of seismic data with borehole information.

The signatures we were interested in are related to the effects produced on the seismic signal by the occurence of fractures and vapor accumulation. Based on previous studies and on experimental evidences, it results that seismic amplitudes and in particular amplitude anomalies in the post-stack images, amplitude variations with offset (AVO), and azimuthal variations of the amplitudes (AVAZ) may be of some diagnostic value.

First of all, the very troublesome acquisition conditions (rough topography, rapid lateral velocity variations, outcrops of lithologies causing strong attenuation) and the complex structural setting of the subsurface made it necessary to reprocess portions of the 3D data. To increase the S/N and to preserve the true amplitude relations of the seismic signal we adopted a surface consistent approach both for the statics computation and for the amplitude treatment and we performed several attempts at reducing noise.

The results were satisfactory, with clearer seismic images and with reflectors pertaining to the potential targets showing better continuity. Overall, the exploration targets could be more easily identified and traced in the 3D volume. Borehole logs allowed a further improvement through the application of wavelet processing on the specific reflectors.

Also the AVO analysis gave interesting results, although, given the pre-stack nature of this indicator, more influenced by the noise still abundant in the data. In general, we observe a strong increase of the Intercept and a moderate increase of the Gradient in correspondence of the reservoirs.

Fractures in the reservoir and in particular their organized orientation can produce detectable variations of the reflected amplitudes with varying source to receiver azimuth. The extraction of reliable AVAZ signatures was quite difficult because the swath acquisition with the cross-spread geometry produced very heterogeneous distributions of offsets and azimuths. Thus it was not possible to perform AVAZ analysis on the whole dataset. Instead, we had to search for the bin gathers with a wider offset-azimuth distribution and to create super-bins to reach a barely sufficient coverage. In the few locations we were able to perform AVAZ, assuming a HTI medium for the reservoir, we found indications on fracture strike oriented at around 60^0-70^0 anticlockwise North. However, a much larger amplitude with azimuth dataset would be necessary to reach a higher degree of confidence.

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As a final remark we may say that, while it is proved that seismic data bring a wealth of useful information for the detection of targets and for prospect generation, there are still some aspects that need further clarification. For instance, similar seismic signatures can be associated to geothermal reservoirs with quite different production capability.

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Integrating seismic velocity and attenuation tomography with reflection seismic data and temperature modelling: results from Gross Schoenebeck (NE German basin)

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I-GET is a European Union funded project to develop integrated exploration methods for fractured and/or porous fluid bearing geothermal systems. The techniques are tested at typical sites in volcanic, metamorphic and sedimentary environments. We present results from the geothermal site at Gross Schoenebeck located in the NE German basin, North of Berlin. The target horizons for a middle enthalpy geothermal system consist of Rotliegend sandstones and volcanic rocks at depths between 3.9 and 4.4 km. These rocks were deposited during the initial stages of the developing Southern Permian basin.

Seismic experiments (2D and 3D) were conducted to study the regional lithological and tectonic environment, and to provide attributes useful for the geotechnical characterization of the potential geothermal reservoir. Tomographic methods were applied to a refraction / wide-angle reflection seismic data set. The first arrival travel times were determined and a damped least-squares inversion was applied to derive a 2D velocity model along a 40 km transect centered at the geothermal research well. Next, the first arrival signals were aligned and spectral analysis was performed using Fourier and wavelet transform methods for comparison. The spectral data were parameterized (e.g., spectral decay) and a damped least-squares algorithm was applied to estimate the attenuation distribution. Furthermore, wide angle reflections were modelled and imaged by using the velocity model along the 40 km transect. The velocity and attenuation tomography approaches were also applied to the low-fold 3D seismic data providing information for the upper 1000 m in a 2.5 by 2.5 km area around GSB 3/90.

The resulting models of P velocity and attenuation reflect the major stratigraphic units. This is supported by the comparison with interpretations of pre-existing industry seismic data and borehole information. New insights are revealed considering the internal structure of the salt and surrounding successions. Combined interpretation of the models together with results from magnetotelluric studies using neural network techniques supports the robustness of these features.These findings provide important constraints for the modelling of the temperature field and the geomechanical conditions. Ongoing work includes analysis of amplitude variations with offset and azimuth (AVO and AVA) for the relevant target reflectors in regional 2D and 3D seismic data sets. This kind of analysis provides information on seismic anisotropy related with predominant orientations of fracture systems to be used for the geothermal energy production.

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Subseismic deformation prediction: A workflow acting between 1-D well data and 3-D reflection seismics

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The evolution of a sedimentary basin is mostly affected by deformation. Large-scale, subsurface deformation is typically identified by seismic data, small-scale fractures by well data. However, faulting at the medium sub-seismic scale plays an important role, e.g. in hydrocarbon or geothermal reservoirs: large individual reservoirs can be disrupted by faults enhancing fluid flow, or producing compartmentalized deposits due to cementation of fractures. Thus, between both scales, seismic and well data, we lack a deeper understanding of how deformation scales in the sub-seismic region. To start tackling this problem, a 3-D reflection seismic data set in the North German Basin was analysed with respect to structure and faults in great detail, calibrated by well data. This led to the determination of magnitude and distribution of deformation and its accumulation in space and time on the seismic scale. The structural interpretation unravels the kinematics in the North German Basin with extensional events during basin initiation and later inversion. For further quantitative deformation and fracture prediction on the sub-seismic scale, two different approaches are introduced. Increased resolution of subtle tectonic lineaments is achieved by coherency processing yielding together with geostatistic tools the distribution of low- and high-strain zones in the region. Independently, the distribution and quantification of the strain magnitude is predicted from 3-D retro-deformation of the identified structures. For the fault structure analysed, it shows major-strain magnitudes between 5-15% up to 1.5 km away from a fault trace, and variable deviations orientation of associated extensional fractures. The small scale is represented by FMI data from borehole measurements, showing main fault directions and densities. These well data allow the validation of our sub-seismic deformation analyses. In summary, the good correlation of results across the different scales makes the prediction of small-scale faults/fractures possible. The temporal component of faulting will be gained by analogue models.
The suggested geomechanical workflow requires principally the 3D coverage of a region. It yields in great detail both the tectonic history of a region as well as predictions for the genesis of structures below the resolution of reflection seismics.

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Magnetotelluric investigation for geothermal resources

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Electrical resistivity is a key physical property to understand the structure of geothermal reservoirs, particularly for high-temperature geothermal resources. Due to the high-temperature condition, electrical resistivity of subsurface rocks in a geothermal area is usually lower than that of geological formation outside the high-temperature area. When pores and fractures in rocks are saturated with water, which often contains considerable amounts of solvates, they have lower resistivity than non-saturated rocks. However, within a geothermal area, the resistivity distribution is not so simple. The geothermal reservoir, which contains plenty of high-temperature geothermal fluids, has a lower resistivity than the surrounding non-geothermal zone, but it usually does not have very low-resistivity values. On the other hand, the cap layer, which covers the top of a geothermal reservoir, often shows the lowest resistivity in the geothermal systems, although the temperature of the cap layer is much lower than that of the geothermal reservoir. This is because the cap layer contains abundant low-resistivity alteration clay minerals, such as smectite, which make the layer hydrologically less permeable.

The magnetotelluric (MT) method is a major geophysical exploration tool for investigating the electrical resistivity structure of geothermal areas. Other electrical and electromagnetic methods, which utilize artificial current or magnetic sources, can also give detailed underground resistivity structure. However, geothermal engineers now prefer to use MT, mostly because it has a deeper investigation depth; field operation and logistics in mountains and forests are easier than other methods; and recent advances in MT data acquisition systems can provide better quality data than before. Current MT instruments have capabilities of low-noise amplifier, high-resolution digitization, GPS synchronization and automatic data acquisition control. These specifications allow us to easily conduct effective remote reference processing, which is an essential tool to improve the data quality.

Recent software developments for MT data interpretation have also accelerated the MT application in geothermal exploration. Several two-dimensional (2D) inversion programs have been public domain in academia and industry since early 1990s. Methodologies for static correction and galvanic distortion decomposition have also become popular. Three-dimensional (3D) inversion techniques are now provided on a commercial basis from a few service companies, although the 3D inversion codes themselves are not yet public domain in the geothermal industry. Only one prototype code is public domain in academia.

With the application of 2D interpretation to MT data in the 1990s, EM geophysicists successfully constructed 2D models from deep crustal studies and long transect-type

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earthquake surveys. However, geological structure is not 2D but mostly 3D in geothermal areas. In such cases, only TM-mode data inversion is practically feasible, and data fitting is often impossible for TE-mode data. Because the TM data is less sensitive to deep resistivity anomalies than TE data, the 2D models are reliable only for shallow parts. Although EM geophysicists began to recognize the limitation of the 2D interpretation, these TM-mode models have been very useful to understand geological structure of geothermal reservoirs to a depth of 1 – 2 km in a 3D environment.

3D MT interpretation has been applied in geothermal exploration since the early 2000s. 3D models show more realistic resistivity structures of geothermal reservoirs, with a lower number of spurious anomalies. However, the number of 3D applications is still very limited at this moment. Also, because of an intrinsic characteristic of the low-frequency electromagnetic field, which is a diffusion field, the resolution of deep models has a limit. Sophisticated 3D inversion algorithms may tackle this problem to some extent and improve the model reliability of deep resistivity structure in the future.

In this paper, several case studies on 3D MT interpretation of geothermal resources in Japan and Asian countries, both good and insufficient results, are presented.

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Electrical resistivity at the Travale geothermal field (Italy)

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Electromagnetic methods have been tested in the Travale geothermal field (Italy), a high-enthalpy field where the geothermal reservoir is located at a depth of 2-4 km in metamorphic and magmatic rocks, characterized by a high degree of heterogeneity and anisotropy and by the presence of superheated steam.
In order to determine whether magnetotelluric method is capable to define different reservoir features, and in particular a steam-dominated system, magnetotelluric data were collected during different surveys. After detailed robust analysis of these very noisy data, we have carried out 1D, 2D and 3D forward and inverse modeling in order to establish the resistivity data distribution at depth, its robustness and the sensitivity of MT data to different features. Resistivity log data, zones of high temperatures and productive fractures from drillholes measurements, a bright-spot type horizon identified in seismic profiles and estimated resistivity values of the lower crust and mantle were considered. The results have shown at the depth of the exploited geothermal reservoir a significant reduction in electrical resistivity whose large volume embrace but cannot be restricted to productive fractures from drillholes measurements and the bright-spot type horizon.
Since the observed reduction in resistivity may be interpreted taking into account the lithology and heterogeneities of reservoir rocks, their alteration and/or to the presence of brines within a fracture net sufficiently interconnected to produce electrolytic conduction, a study on cores and cuttings were carried out in order to identify the types and abundance of primary and alteration minerals and to compare these data with resistivity values. An inverse correlation between resistivity of the encountered formation and phyllosilicates amounts has been observed. However, the quantity of phyllosilicates and their effect on resistivity may account only for the small variation observed in the resistivity logs, but not for the main resistivity anomaly defined by magnetotelluric data in the area. Since lithology and alteration appears to be not the main cause of resistivity reduction, a change the natural state of fluids in the geothermal reservoir remains should be considered.

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A target-oriented magnetotelluric inversion approach for characterizing the low enthalpy Groß Schönebeck geothermal reservoir

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Electrical conductivity is a key parameter for the exploration and characterization of geothermal reservoirs as (hot) mineralized formation water of (active) geothermal areas usually exhibits significantly higher conductivity than the surrounding host rock. Here we present results of a magnetotelluric (MT) exploration experiment carried out in the vicinity of the Groß Schönebeck geothermal test site in Northern Germany. At this location, a doublet system of two 4.3-km deep boreholes was drilled to establish an *in situ* laboratory to investigate the potential for geothermal energy production. The MT data were recorded along a 40-km long main profile, centred on the doublet, and a 20-km long parallel profile, located 5 km to the east. Classical two-dimensional smooth inversion of the MT data reveals a shallow conductive layer which delineates an antiform-like shape above the Zechstein salt, in good agreement with information from regional geology and seismic images. However, at the northernmost part of the profiles, the conductivity models reveal deep reaching conductive structures which appear uncorrelated with existing (geophysical or geological) data. Incorporating information from seismics as independent constraints for the MT inversions allows us to examine the model space rigorously but target-oriented. Employing so-called *tear zone* inversions we can effectively derive an alternative class of models, which are consistent with the MT observations but also with the other data sets. We speculate that the zones of high conductivity imaged at reservoir depth in the Rotliegend are related to salt lows of the overlaying evaporite layer (Zechstein). The enhanced conductivity can be explained by a higher porosity (fracture density) in anhydritc layers and/or generally lower resistivity of the pore fluid.

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Joint 1D inversion of TEM and MT data and 3D inversion of MT data in the Hengill area, SW Iceland

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The Hengill area in SW Iceland is one of the four test sites of the I-GET collaboration project, representing geothermal systems in volcanic environments. An extensive study of its resistivity structure has been carried out by the combined use of TEM and MT soundings. Joint inversion of TEM and MT data can be used to correct for the static shifts in the MT data, which can be severe and systematic due to big near surface resistivity contrast. Joint 1D inversion of 148 TEM/MT sounding pairs and a full 3D inversion of 60 MT soundings has been performed. The 3D inversion was done for the full static shift corrected MT tensors. Both inversion approaches give qualitatively similar results, but the 1D inversion gives a somewhat smeared model as compared to the 3D inversion. Both approaches reveal a shallow resistivity layer reflecting conductive alteration minerals at temperatures of 100-240°C. They also delineate a deep conductor at 3-10 km depth. The reason for this deep seated high conductivity is not fully understood. The distribution of the deep conductors correlates with a positive residual Bouguer gravity anomaly, and transform tectonics, inferred from seismicity, as well as anomalously high P-wave velocity. The deep conductors are believed to reflect hot solidified but ductile, magmatic intrusions that are heat sources for geothermal systems.

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Context, uncertainty and geoscience integration in geothermal applications of 3D MT and seismic methods

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The transition of a geothermal exploration technology from a research topic to an industrial application is often hampered by issues related to context, uncertainty and integration. The I-GET program includes research projects that support such transitions. For example, although an anticipated benefit of research on 3D MT inversion is more reliable imaging of resistivity within reservoirs, few resource decisions in high temperature geothermal fields are currently based on such results. The main conceptual objective for most MT resistivity interpretations over high temperature geothermal fields is still imaging impermeable clay alteration over reservoirs, despite the routine use of 3D MT inversion for over 5 years at more than 20 geothermal prospects. MT imaging of the Glass Mountain prospect in California illustrates the general experience that, in the context of a conventional interpretation of a geothermal clay cap, the value of 3D MT inversion is limited because 1D and 2D inversions are usually adequate, except at complex edges and deep zones. The potential for adding value by imaging resistivity within geothermal reservoirs using 3D MT inversion has been limited by inadequate characterization of resistivity resolution and uncertainty and by insufficient rock physics data to reliably infer parameters relevant to geothermal reservoir performance based on MT resistivity. Similar issues apply to constraining reservoir parameters like steam–water ratio using seismic velocity tomography. The I-GET core analyses are a significant addition to the background rock physics needed to support interpretations within geothermal reservoirs.

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POSTER

Electromagnetic Temperature Estimation in the Hengill Geothermal Area, Iceland

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A new indirect electromagnetic (EM) geothermometer developed recently in (Spichak et al., 2007; Spichak and Zakharova, 2008a,b, 2009) is applied to the temperature estimation in the Hengill geothermal zone (Iceland). The approach used is based on the artificial neural network analysis of the implicit conductivity-temperature relations rather than on the prior assumptions of the electrical conductivity mechanisms.

The samples for indirect EM geothermometer testing consisted from the well temperature records and electrical conductivity profiles determined from the magnetotelluric data measured in the vicinities of 8 boreholes located in the Hengill geothermal area. The testing of the indirect temperature estimates was carried out using the temperature records not involved in the calibration of the EM geothermometer. The results indicate, in particular, that the EM temperature extrapolation to a depth twice as large as the well depth results in the relative error 5-6%, and in case of its threefold excess the error is around 20%.

Practical application of this method enables one, first, to refine the temperature estimates in cases when the amount of temperature logs available is insufficient; second, to provide indirect 4D temperature monitoring during production; third, to carry out contactless remote temperature estimation in wells with extreme conditions unsuitable for traditional geothermometers; and, finally, to perform precise temperature prediction in extrapolation mode.

The latter possibility makes it possible to increase significantly the deepness of the temperature estimations in the geothermal areas without additional drilling. The method developed could be especially useful when exploring supercritical geothermal resources located at depths 4-5 km or deeper, where the temperature estimates could be made using the EM geothermometer calibrated by the shallow parts of the available temperature logs.

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POSTER

2-D Magnetotellurics at the geothermal site at Soultz-sous-Forêts: Resistivity distribution to about 3000m depth

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With the aim of investigating the possibilities if magnetotelluric methods for exploration of potential EGS sites in the Upper Rhine valley, a 2-D magnetotelluric survey has been carried out on a 13 km long profile across the thermal anomaly in the area of the geothermal power plant of Soultz-sous-Forêts in the winter 2007/08. Despite strong artificial noise, processing using remote referencing and Sutarno phase consistent smoothing revealed significant results from 10 out of 16 sites. Indication for 1-D structures were found in the shortest periods, 2-D effects in the periods <40s, and 3-D effects in the long period range. Since 3-D effects were found in the longer periods, 2-D inversion was carried to periods <40s. The results of the inversion are consistent with the geology of the geothermal site and distinguish well the sediments from the granitic basement including the structures given by the faults. A conductive anomaly with a resistivity of about 3Ω m has been found at a depth down to 2000 m in the area of the Soultz- and Kutzenhausen faults, which is attributed to circulation of geothermal brine.

First 1D magnetotelluric studies performed in the vicinity of GPK1 at the Soultz geothermal site (Marquis and Gilbert, 2002) have indicated the possibility of detection of geothermal brine at Soultz. Two positive conductivity anomalies were interpreted as the “Couche rouge” layer at a depth of approximately 500m and a brine bearing fault at approximately 1500m depth, which is in agreement with the results from 2-D seismic interpretation.

After processing, three period ranges can be distinguished. In the first, from $1.25 \cdot 10^{-4}$ to 0.05s, apparent resistivity varies between about 30Ωm at short periods and 1Ωm at 0.05s. A minimum of 0.01-1Ωm is reached at periods of 10^{-4} to 10^{-3}s. The phase angle decreases from 90 to 60 in this range. The second period range reveals smooth and consistent values in apparent resistivity and phase. The apparent resistivity decreases linearly from 10 to 1Ωm and the phase angle varies between 60 and 45. Above 0.15s apparent resistivity varies between 0.01 and 100Ωm with strong bias in particular between 1 and 10s. The phase is less affected, but the angle decreases to almost 0. Above 100s the apparent resistivities and phases of the XY– and YX-components reveals an XY component that is by the order of 1 to 2 magnitudes higher compared to YX. The curves are seriously biased and scattered over a wide range of periods and Hilbert transformation was not successful. In particular, at frequencies from 1 to 1000s corresponding to the target depth transfer functions in terms of dimensionality could not be analyzed.

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2-D inversion was carried out using 10 sites projected on a profile at N142E. The 2-D inversion was applied using Sutarno phase consistent smoothed data after rotation by 52. A regional a priori model accounting for the geometry of the Rhine graben has been used. In the inversion procedure regularization was switched to smoothest variation away from starting model. TE and TM mode as well as phase and apparent resistivity have been inverted simultaneously with 100 iterations. The over-all rms error is 2.28 and the individual site-rms is always below 3. Generally, the Rheingraben model is well accepted. During all inversion steps the boundary between the conducting half layers with resistivities < 10Ωm at depth down to about 750m and the resistive underlying space with resistivities of >1350Ωm was preserved. A conductive zone extends vertically to more than 2000 m between the Soultz- and Kutzenhausen faults. The conductive feature below about 200m can be attributed to the clay-rich Couche Rouge.

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POSTER

A multidisciplinary approach to resistivity modeling at the Travale Geothermal field (Italy)

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Electric and electromagnetic induction methods are widely exploited in the study and characterization of geothermal systems. The Travale geothermal field (Italy) represents an interesting test site: this high-enthalpy field is characterized by a deep-seated geothermal reservoir mainly located in metamorphic and magmatic rocks, by a high degree of heterogeneity and anisotropy and by the presence of superheated steam.

The results of previous studies pertaining this area have outlined a significant reduction in electrical resistivity at the depth of the geothermal reservoirs. However, the origin of such reduction has not been fully identified: resistivity variations depends on lithology and on fluid distribution and state that are in turn controlled by temperature, pressure and tectonic processes. Hence, a multidisciplinary, integrated approach - using seismic, gravimetric and magnetotelluric data, as well as petrophysical analyses - is necessary to understand resistivity variation and to relate them to the lithological properties of the reservoir rock, to the kind and distribution of alterations and to the nature of the geothermal fluid.

Within the framework of this multidisciplinary project, we have developed an electrical resistivity modeling of Travale high-enthalpy geothermal field. Starting from magnetotelluric data collected during different surveys, we have estimated magnetotelluric transfer functions over a wide range of frequencies using a robust algorithm designed to extract magnetotelluric signals from electric and magnetic time series highly contaminated by a wide range of noise sources. We have then carried out one-dimensional, two-dimensional inverse and three-dimensional forward modeling in order to establish the resistivity data distribution at depth, its robustness and the sensitivity of magnetotelluric data to different features. Resistivity log data, zones of high temperatures and productive fractures from drill-holes measurements, a bright-spot type horizon identified in seismic profiles and estimated resistivity values of the lower crust and mantle have been used . The results have shown that at the depth of the exploited geothermal reservoir there is a significant reduction in electrical resistivity whose large volume comprises but is not restricted to productive fractures from drillholes measurements and the bright-spot type horizon.

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Since the observed reduction in resistivity may be interpreted taking into account the lithology and heterogeneities of reservoir rocks, the alteration affecting them (presence/abundance of conductive minerals) and/or the presence of brines within a fracture network sufficiently interconnected to produce electrolytic conduction, detailed mineralogical analyses on cores and cuttings have been carried out. An inverse correlation between the resistivity values of the various formations crossed by drill-holes and the amounts of phyllosilicates has been observed. However, the quantity of phyllosilicates and their effect on resistivity may account only for the small variation observed in the resistivity logs, but not for the main resistivity anomaly defined by magnetotelluric data in the area. Since lithology and alteration doesn't appears to be the main cause of resistivity reduction, the presence of a liquid phase within the pore network of rocks or absorbed water should be considered.

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POSTER

Joint inversion of thermo-hydraulic and resistivity data for geothermal reservoir modelling

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Distributed parameter reservoir modelling has been used extensively to understand and manage development of geothermal systems. In the eighties this was done by forward modelling of thermo-hydraulic data from wells (temperature, pressure, flow rate) by adjusting hydro-geological properties of the rocks (porosity, permeability, density, and heat capacity) and heat and mass sources. There are mainly two codes, TOUGHT2 and STAR which can model two phase conditions (water/steam) that have been used for such modelling. In the late nineties an inversion (automatic parameter estimation) was built on the TOUGH2 forward code in a code called iTOUGH2. When data from a limited number of wells is available, which is often the case in exploration and early development phase, the modelling problem is heavily ill-posed with much more unknowns than data values. The wells are a sort of point measurements and often in only a part of the geothermal system. Well data normally don't give information on the geometry and size of the reservoir until after log production history. The resistivity structure of high-temperature geothermal systems in basaltic rocks is mainly controlled by alteration mineralogy. Cold and un-altered rocks have high resistivity. In the temperature range from about 100°C to 240°C the rocks are normally highly altered by conductive minerals (smectite and zeolites). At temperatures higher than 240°C the conductive minerals are replaced by resistive alteration minerals (chlorite and epidote) and the rocks become resistive. If the temperature distribution is in equilibrium with alteration mineralogy, the resistivity is a footprint of the temperature distribution. A post processor has been included in the TOUGH2 forward modelling code that calculates the resistivity, as a function of temperature, porosity, resistivity of the pre fluid and saturation (steam fraction), in each of the elements of the model grid. The inversion code has been changed such that the resistivity in the grid blocks, deduced from interpretation of resistivity surveys on the surface, can be taken as input data for the inversion and deep resistivity anomalies can be used to locate heat sources in the models. Inversion of synthetic data shows that this stabilizes the inversion greatly and makes it much more robust. Inversion of real data has not been performed as of yet, but will soon be done. If a geothermal system (or parts of it) cools down, the alteration and resitivity distribution prevails. Where drilling has shown this to be the case, the resistivity data should of course not be used in the inversion.

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POSTER

Joint interpetation of magnetotelluric and seismic models for exploration of the Groß Schönebeck geothermal site

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Due to the non-uniqueness of the inverse problem, the interpretation of geophysical models in terms of geological units is not always straightforward. It is common to use a combination of different geophysical methods to obtain the distribution of independent physical properties over the area of interest in order to discriminate between the different lithologies or geologic units. This kind of studies is usually limited to qualitative comparisons of the different models, which may – or may not – support a relation between the parameters in certain areas. Quantitative approaches are in general based on empirical relations between physical parameters, which often are not of universal applicability.

The magnetotelluric (MT) and seismic methods resolve the physical parameters electric resistivity (r) and (seismic) velocity (Vp, Vs) respectively with similar spatial resolution and are often used in combination to derive earth models. By looking at both resistivity and velocity simultaneously, we can keep the strengths of both methods while avoiding their weaknesses. The problem with a joint interpretation is that there is no unique universal law linking electrical and acoustic properties. While electrical resistivity in deep sedimentary basins is mostly sensitive to the pore geometry and contents, seismic velocity is mostly imaging rock matrix properties. However, with a statistical analysis of the distributions of both resistivity and velocity, we can find certain areas of the model space where a particular relation between the physical parameters holds locally, thus allowing us to characterize this region as a particular lithology. In the present work, we use a statistical analysis in order to correlate two independently obtained models of the Groß Schönebeck geothermal test site in the Northeast German Basin.

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POSTER

3D temperature inversion derived from deep borehole Data in the NorthEastern German Basin

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In the framework of the "I-GET" EU-project (Integrated Geophysical Exploration Technologies for deep fractured geothermal systems) Groß Schönebeck has been selected as one of the test sites located north of Berlin, in the North Eastern German Basin. The goal of I-GET is to develop new and reliable geothermal exploration techniques to increase the success rate of drilling for geothermal energy production. Thanks to previous oil exploration, a significant number of geophysical data are available in this area such as deep borehole logs and seismic profiles. After a reinterpretation of these data a 3D geological model has been built.
The elaborated geological model is discretized into a 3-D Finite Element mesh of regional extent. The resulting mesh accounted for 13 geological units of variable thickness. The geological borehole profiles are well respected in the discretized numerical model. It represents the basis of a forward calculation of the temperature field using measured and assumed physical parameters relevant for diffusive thermal transport.
The computations are performed using the numerical code FRACTure and were extended into an inverse scheme using UCODE (Poeter and Hill, 1998) for improved parameter estimation. In addition to the inversion via a modified Gauss-Newton algorithm, UCODE provides comprehensive statistic information, which has been used upfront and for quality estimation of the results. The procedure aims at the calibration of the thermal model and of sensitivity analyses based on the high quality temperature measurements available from deep boreholes of the Groß Schönebeck area.
Besides a parameter estimation, the inversion gives some evidence for spatial inhomogeneities of the thermal conductivity in the different geologic layers. The basal heat flux in the area has been determined as approx. 60 mW m^{-2}. An improved fit of the data is achieved by inversion of single borehole data yielding towards heterogeneities in several significant layers.

Keywords: Groß Schönebeck, geothermal, EGS, numerical model, geological model, temperature, heat flux

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POSTER

Mechanisms controlling the recent thermal field – results from 3D modeling in the Northeast German Basin (NEGB)

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We evaluate processes that influence the present regional geothermal field for a study area in Brandenburg, Northeast German Basin. This part of the area is morphologically differentiated due to the presence of mobilized Zechstein salt that formed salt-diapirs, pillows and other salt structures. The Zechstein salt decouples both tectonical structures and the fluid regime in the basin.
Recent development of geothermal technologies requires a better knowledge of local temperature anomalies as well as of hydraulic conditions. Therefore, we develop a detailed 3D structural model of Brandenburg to use it as base for modeling the recent thermal field.
Our first model integrates the regional distribution of Permian to Quarternary sediment thicknesses as three dimensional units. The stratigraphical units of the model are assigned physical properties such as: thickness and depth of the layer, lithology, porosity, density, permeability, heat capacity, heat conductivity, pressure gradients. We evaluate the sensitivity of modeling results with respect to these parameters. Furthermore, we evaluate the difference of boundary conditions. Results are compared to observed temperatures and hydraulic measurements.

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POSTER

Application of process modelling and spatial analysis approaches to geothermal systems: what lessons can be learned from hydrothermal mineral systems?

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Exploration for mineral resources and geothermal energy are among the most challenging applications of geosciences. In both these areas, targeting and resource assessment require some level of understanding of heat transfer and reactive fluid flow in a highly variable, dynamic 4D geological architecture. During the operation of any hydrothermal system – mineralised or geothermal – the interactions between physical processes and the geological architecture are complex. Spatial heterogeneity of chemical composition, and of permeability at various scales is of major importance, and significant feedback can occur between the involved physical and chemical processes. Examples of the latter include the modification of permeability as a result of rock deformation and chemical reactions, the change in effective stress as a result of increasing pore pressure, or the change of physical properties of rocks and fluids as a result of hydrothermal alteration.
Here, we discuss advances in the use of quantitative methods, and their role in integrated studies on hydrothermal mineral systems. We present km-scale numerical simulations used to test geological hypotheses related to hydrothermal mineralisation of the Mesoproterozoic Mount Isa copper deposit in Australia. The numerical models helped to assess which strain geometries generated permeability in the key structural elements, what the driving process for hydrothermal fluid flow were, and under what hydraulic conditions transport and reaction of fluids most likely generated the observed spatial pattern of mineralisation. On a larger scale we have used conductive heat flow models to investigate the relation between radiogenic heat production, crustal scale tectonic deformation, and the spatial distribution of hydrothermal mineral deposits.
The value of using numerical simulation and spatial analysis lies in the capability to make predictions in areas of insufficient data, and to test scenarios and hypotheses related to palaeo-hydrothermal systems, or earlier stages of existing geothermal systems. One of the requirements, however, is that the models show an adequate level of complexity, e.g. sufficient data to generate a 3D mesh, and the flexibility to vary the 3D geological model in areas of uncertainty. As an example for how this can

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be achieved effectively we present a workflow that provides a short cut from raw geological data to a full 3D simulation mesh by combining GeoModeller to construct the geological model, with SHEMAT for the coupled simulation of heat transfer and fluid flow.

Despite the fact that mineral exploration focuses more on genetic aspects of paleo-hydrothermal systems, while geothermal exploration is concerned with detection and analysis of the present state of the subsurface, geothermal fields and mineralised terrains share key genetic factors such as the flow driving processes and many aspects of the geological setting. Mature mineral provinces are rich in 2D data on the large scale, and rich in 3D data on the mine scale, and therefore provide a valuable resource to unravel the spatial controls on thermally driven fluid flow in the Earth's crust that may be equally relevant to geothermal systems.

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POSTER

Geophysical methods for the identification of high-enthalpy geothermal reservoirs in Hungary using the example of the Fábiánsebestyén-Nagyszénás area

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There is shown the actual situation of identifying and exploring high-enthalpy geothermal reservoirs in Hungary. First results were obtained from the MOL pilot project and the geophysical investigations by TULINIUS et al. (2008). In our paper the combination of geophysical information with well data is highlighted as a suitable method for getting an integrated geological model of a potential high-enthalpy reservoir. For that, investigations done within the framework of the EU supported research project I-GET are used.

1) It is recommended to include seismic data for the identification of geothermal reservoirs as far as sufficiently deep wells provide local stratigraphical information in order to exploit the best suitable depth of the aquifer and to identify appropriate structures, preferentially an antiform deriving from an uplifted block where water paths are given by large-scale faults.

2) For the interpretation of seismic surveys, information on the local stratigraphic conditions of neighbouring wells is indispensable in order to convert the run-times into depth correctly.

3) MT survey is very useful to determine fractured water-bearing areas and should be evaluated in combination with seismic results.

4) Gravity results derived from the rock properties can be used for the detection of local anomalies.

5) The investigation of core data is essential for the identification of an adequate formation of Triassic carbonates. Only by this, an appropriate aquifer can be proven: Sufficiently thick fractured Triassic carbonates are essential for good water yields.

6) Considering the above aspects, additional well data (tests, well logs, water analyses, observations while drilling) can be applied for developing an integrated geological model of the potential reservoir.

Keywords: high enthalpy reservoir, Hungary, geophysical exploration data, Fábiánsebestyén-Nagyszénás

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POSTER

ITB Capabilities in Geophysical Exploration of Geothermal Reservoirs

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This paper deals with some geophysical investigations that have been done by some ITB faculty members in determining subsurface condition and reservoir monitoring in some geothermal fields in Indonesia. Institut Teknologi Bandung (ITB) is the oldest technical university in Indonesia and was officially opened in 1959. Previously ITB was built in 1920 as a technical school, as part of the Indonesian University (UI). The earth sciences department was opened for the first time in 1950. Since that time, geosciences academic and research activities have been carried out in this higher education institution.

Not similar with oil and gas explorations in Indonesia, the number of geophysical investigations in geothermal fields is limited. This makes the number of research and practical activities done by faculty staffs of ITB in geothermal are less than in oil and gas fields. Though, some researches and projects that are related with geothermal in ITB could be identified.

This paper includes four examples of geophysical methods applied in geothermal explorations: The first part deals with hypocenter and velocity determinations of Gunung Guntur Volcano and surrounding area in the West Java Province by using microsesimic method. The second part deals with some Magnetotelluric investigations that have been done in some geothermal field and Volcanoes in Indonesia. The third and fourth parts deal with some results that have been obtained from the Control Source Audio Magnetotellutic (CSAMT) and 4D Microgravity investigations.

Those three above mentioned examples show that higher education institution in Indonesia, e.g. ITB, is now emerging in sustainable energy resources of geothermal exploration, not only for increasing the quality and quantity of research in geothermal field, but also in order to back the industrial needs.

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POSTER

Milos Site (Greece): Integration and evaluation of exploration data

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Geothermal exploration on Milos island started by the Institute of Geological and Mineral Exploration (IGME) of Greece (1971-1976) with detailed mapping of geology, thermal manifestations, temperature gradients, Schlumberger resistivity and drilling the first two deep wells which proved the existence of a high enthalpy geothermal reservoir of 250-300C. It was continued by the Public Power Corporation of Greece (1977-1984), which with the support of the European Commission carried out a geochemical survey, collected additional geological and geophysical information (e.g. gravity) and drilled three production wells. In 1985-1987 the European Commission supported a series of geophysical exploration surveys including monitoring of micro-seismic activity and state of the art Magnetotelluric (MT).

This poster illustrates the results of the above geothermal exploration activities in 10 figures which are maps of geology, thermal manifestations, top of basement depth as derived from gravity data, location-stratigraphy-temperature profiles of the five deep wells, temperature gradients, micro-earthquakes recorded during a 4 months period, DC-apparent resistivity for AB/2 = 1000m, MT- apparent resistivity at 1Hz, distribution of main water types, and chalcedony geothermometer temperatures of shallow waters.
Shallow water table temperatures are higher in Vounalia (50-100C), where the most recent volcanic activity took place. Neogene sediments of high permeability if encountered at sufficient depth and have sufficient thickness (150-200m) they form a geothermal reservoir of expected temperature 100-250C. Most promising areas are in and around the inner Milos bay, including Adamas and Vounalia areas. Overlaying altered tuffs (argillic alteration) form a cap rock to this reservoir. The metamorphic basement comprises green schists of extremely low permeability, which is greatly enhanced in the vicinity of active faults by micro-seismic activity, where below 1 km depth water of 310+C and 45.000 ppm chloride is present. Deep wells intersecting these faults yield 20-45 kg/s fluids of high enthalpy sufficient to produce 2,5-10 MWe per well. Geochemical data, DC and MT resistivity surveys indicate the presence of an active hydrothermal system beneath the east part of the island. MT data indicate promising areas also near the coast southwest of Milos bay.

Future geophysical surveys should cover the entire island & Milos bay with the objective to determine the thickness of neogene sediments and the location of main fault zones down to 3 km, which are the target reservoirs for new production wells. Proposed methods are AAMT with 3-D inversion and reflection seismics.

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POSTER

Geothermal Exploration in East Java Province, Indonesia: Opportunities and Challenges

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East Java Geothermal Resources: Opportunities

Three potential hydrothermal reservoirs have been identified in Eastern Java. In this presentation, our focus will be on two of them, Welirang and Ijen, which are located near Mt. Arjuno and Mt. Merapi, respectively. First surface geological surveys by Pertamina Geothermal in 1993-1995 showed no indication of hydrothermal activity for further development. Only after the next more detailed geological survey of 1999, the potential of those three prospect areas was estimated as shown in the table below.

Table: Identified prospect areas in East Java province with its proven, possible and resource

Prospect areas	Proven (MWe)	Possible (MWe)	Resources (MWe)	Total (MWe)
Mt. Welirang - Arjuno	-	110	120	230
Mt. Wilis – Argopuro	-	60	70	130
Mt. Blawan – Ijen	-	104	50	154

East Java resource potential: Challenges

The first challenge: Inspite of massive geological exploration from oil industry, little attention has been paid to geothermal resources in the East Java province (ESP). A methodological exploration framework that addresses geoscientific and engineering challenges, such as reservoir-dynamics prediction, regional geology and geophysical parameter characteristics, was not available for research and public purpose. The second challenge: The public acceptance for geoscientific activity has declined since in June 2006 a hot mud flow near a gas drilling location 23 km south of Surabaya occurred and could not be stopped until now. It is therefore an urgent task to work with a social image perception analysis in order be able to figure out the core problem and develop methods for a public communication. This task should be handled as a first priority before geothermal exploration activity will commence.

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Thermohaline modelling of hot geothermal fluid systems in coastal environment: the Seferihisar- Balçova Area example (Turkey)

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The worldwide concern about the consequences of global warming is increasing interest in developing geothermal resources, both for power generation and direct use. This is providing new field data for geochemical and numerical investigations of extensional geothermal systems. The numerical models should explore the role of faults and fractures on the different forces driving hot fluid flows as well as the impact of anthropogenic activities and seawater intrusions on thermal fluid circulation. To date, however, there has been limited effort made to systematically determine the basic relationships between system configuration (e.g., hydraulic permeability, inherited geological structures) and the resulting thermally induced flow behaviour of geothermal systems.
An exceptional example to investigate the mentioned issues is the hot Seferihisar-Balçova Geothermal system (SBG) which is part of the Cesme Peninsula, Western Anatolia, Turkey. In the SBG, geothermal processes are extremely vigorous and hot waters close to boiling temperature can be observed at the surface. The driving mechanisms of fluid flow and their interrelationships with faults are poorly understood. Furthermore, the fluid transport processes are characterized by complex temperature and hydrochemical anomalies. Their causes remain still unclear. Not at least, the geothermal energy extraction in the coastal aquifers of this area induces seawater intrusion which pollutes freshwater resources.
In the last years, the SBG, has been thoroughly investigated for its geothermal resources. As a result, an extensive database has been gathered. Owing to a pre-established collaboration between the FU Berlin and the Dokuz Eylül University, Izmir, the database is now available for scientific research. Thus, it will be possible to apply numerical modelling, water chemistry, hydrogeology approaches to study the dynamics of geothermal fluid migration. The final objective is to understand the basic processes driving the thermal waters within the SBG, the role of different driving forces as well as their interactions in controlling geothermal processes. The results will shed new light on the links between the migration of subsurface energy, active transport processes and tectonic structures.

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POSTER

From prospecting to drilling: New exploration strategies for Enhanced Geothermal Systems

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Exploration for Enhanced Geothermal Systems (EGS) requires a combination of imaging methods to characterize the subsurface and to develop a geoscientifically integrated understanding of the reservoir. With an integrated geophysical-geological-geomechanical understanding at a variety of scales it is possible (I) to quantify and characterize the reservoir, (II) to define the location of a drill site, and (III) to support the drilling process in terms of geological risk mitigation. Here, we describe an exploration case study from the geothermal test site Groß Schönebeck, approximately 40 km North of Berlin/Germany, located in the Northeast German Basin. The target for exploration is a hydrothermal system in 4,200 m deep sandstones and volcanic rocks undergoing development for an EGS. The initial investigation of the subsurface was based on pre-existing 2D seismic and well data from former gas exploration. From the existing data we developed a 3D geological model to describe the general structure and main fault systems from surface to a depth of 5,000 m. New geophysical field experiments, using innovative magnetotelluric and wide angle seismic techniques, provided new data and deeper insights into the characteristics of the site.

In 2006 a new geothermal production well GTGrSk4/05 was drilled as part of a well doublet at the Groß Schönebeck site. For the drilling operation it was necessary to develop methods to avoid formation damage by mud solid infiltration and borehole breakouts. Previously, experiments on drill cores were designed to simulate the mechanical behavior of some geological formations and to test for the development of fractures and borehole breakouts under varying in situ conditions. With these data we could define specific mud density windows ensuring a safe drilling process. Hydraulic stimulation of a well is usually used to increase the productivity of a reservoir, i.e. enhancing a geothermal system. A successful application of EGS technologies requires detailed knowledge of the stress field and reactivation potential of existing faults in the reservoir. We therefore applied the so called slip tendency method to estimate the likelihood of fault reactivation in both sandstone and volcanic rock successions which suggested an orientation of NNE-SSW faults with high slip-tendency. These results were confirmed later by microseismicity records during the hydraulic stimulation. This integrated geothermal exploration strategy covers all

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aspects from geosystem analysis, reservoir characterization, and reservoir geomechanics. Such an integrated approach might be essential for an economic and sustainable exploitation not only of EGS but of all geothermal systems.

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Structural Controls of Geothermal Reservoirs in Extensional Tectonic Settings: Developing Successful Exploration Strategies

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Although conventional geothermal systems have been successfully exploited for electrical production and district heating in many parts of the world, exploration and development of new systems is commonly hampered by the risk of unsuccessful drilling. Problems include drilling of hot, relatively dry wells with low flow rates, decreasing temperatures with depth as wells penetrate relatively thin and shallow geothermal aquifers (overturn), and wells with reasonable flow rates but relatively low temperatures. A major problem in selecting drilling sites is that existing geothermal systems are generally poorly characterized in terms of favourable settings and structural-stratigraphic controls. Better characterization of known geothermal systems in different tectonic settings is therefore critical in both exploration for new systems and expansion of existing systems. Locating zones of upwelling (as opposed to thin zones of outflow) is particularly important in developing a sustainable geothermal resource.
In order to characterize the structural controls on geothermal systems in active extensional settings, we have analyzed numerous fields in the western Basin and Range province (USA) and western Turkey through integrated geologic and geophysical investigations. Methods include detailed geologic mapping, structural analysis of faults, detailed gravity surveys, studies of surficial geothermal features (e.g., travertine, sinter, springs, and fumaroles), shallow temperature surveys, and geochemical analyses. Our findings suggest that many fields occupy a) discrete steps in normal fault zones (e.g., Desert Peak, Brady's, Nevada, USA; and Simav, Turkey); b) intersections between normal faults and transversely oriented oblique-slip faults (Astor Pass, Nevada, and Salihli, Turkey); c) overlapping oppositely dipping normal fault zones (e.g., Salt Wells, Nevada, USA), d) terminations of major normal faults (e.g., Gerlach, Nevada, USA; Germancek and Kizildere, Turkey), or e) transtensional pull-apart zones (e.g., Lee-Allen, Nevada, and Canby, California, USA; Pamukkale, Turkey). All of these settings are typically associated with steeply dipping faults, most commonly involving subvertical conduits of highly fractured rock along or near Quaternary fault zones oriented approximately perpendicular to the least principal stress. General topographic features indicative of these settings include: 1) major steps in range-fronts, 2) interbasinal highs, 3) mountain ranges consisting of relatively low, discontinuous ridges, and 4) lateral terminations of mountain ranges. Surficial features, such as tufa towers, travertine spring mounds, and sinter deposits, are also associated with many systems. These structural, topographic, and surficial

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features may indicate hidden or blind geothermal fields, which have no surface thermal waters or steam (i.e., hot springs, fumaroles, or geysers).

As studies characterizing the controls on geothermal systems progress, it is important to assess their impact on ongoing exploration, particularly whether such studies can successfully predict either the location of a previously unknown field (regional scale) or a potentially productive well (local scale). We have successfully applied our findings to exploration of several new geothermal fields in the Basin and Range province of western Nevada (USA). For example, we assisted in selecting drilling sites at the Salt Wells geothermal field. The Salt Wells field lies within a belt of overlapping, oppositely dipping normal faults near the south end of an historical rupture on one of the faults. Our selected drilling site within this structurally complex zone targeted a subvertical conduit of highly fractured rock in a zone of silicified and altered rock, including some sinter. The well reached economical temperatures (>140°C) at <1,000 m and should serve as an effective production well for a newly constructed 10 MWe power plant.

In a separate study, we assisted the Pyramid Lake Indian Reservation in identifying potential sites for geothermal development. Known hot springs within the reservation could not be developed due to their cultural significance. Thus, we selected promising sites for blind geothermal resources through integration of geologic and geophysical studies. In the Astor Pass area we concluded that a belt of tufa towers at the intersection of two dextral-normal faults marked a probable blind geothermal reservoir. The tufa towers were produced by hot springs issuing into glacial Lake Lahonton during a wetter Pleistocene climate. However, no hot springs are present at the site today. On the basis of apparent fault geometries and kinematics, we recommended drilling in the southwest quadrant of the fault intersection, as that quadrant was likely the most dilational. Drilling to 500 m has tapped thermal waters with temperatures of up to 94°C, and fluid geothermometry suggests a geothermal reservoir temperature of 130+°C.

In the Hot Springs Mountains, both the Desert Peak and Brady's geothermal fields (temperatures 180-218°C) reside in small steps in NNE-striking normal fault zones. Power plants operate at both fields and produce >40MWe of energy. The Desert Peak field is notable, because it is a blind geothermal system discovered through extensive drilling in the early 1980's. Approximately 6 km east of Desert Peak, along the eastern margin of the Hot Springs Mountains, a major east-dipping normal fault zone terminates southward in the Desert Queen Mine area. Although no hot springs are found there, linear trends of tufa towers occur nearby. As this east-dipping fault terminates, it probably breaks into multiple splays or horsetails, generating a wide zone of highly fractured rock conducive to the deep circulation of fluids and geothermal activity. Very limited drilling suggests a possible geothermal system in the area. We conducted a shallow temperature survey using 2-m-long probes, the results of which greatly improved the resolution of the near surface thermal anomaly, with temperatures up to ~44°C, and pointed to two potential zones of upwelling geothermal fluids that remain untested by drilling. A similar shallow temperature survey in the Teels Marsh area of west-central Nevada has shown temperatures up to 35°C two meters below the surface in a valley with no known thermal springs or wells. This shallow temperature anomaly is focused along a 3.5 km long segment of

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an apparent rotational and pull-apart fault zone within the Walker Lane transtensional fault system.

These findings provide convincing evidence of the importance of detailed geologic and geophysical work in identifying geothermal systems. Because the favourable settings for geothermal systems are still relatively poorly characterized, such work has strong potential for facilitating geothermal exploration. Improving the conceptual models for geothermal systems through integrated geologic and geophysical studies is an efficient and cost-effective means for developing and enhancing exploration strategies.

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High resolution temperature models for geothermal exploration: methods and application to The Netherlands

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Key factors to geothermal exploration success are sufficiently high temperatures and sufficiently high sustainable production rates. This paper focuses on high resolution temperature models for temperature prediction in mature oil and gas basins. Besides well and log data, numerical thermal basin modelling is required to predict subsurface temperature. In existing thermal basin models for oil and gas exploration, the focus is on predicting past temperature history and oil and gas maturation and expulsion. For detailed 3D models (i.e. involving millions of temperature nodes) these models take long to run and are hard to calibrate to temperature data in wells. Moreover, spatial variations in basal heat flow in between wells is subject to major uncertainty. Tectonic models, capable of modelling thermal consequences of basin formation and reactivation, allow to access spatial heat flow variability based on lithosphere deformation. In order to improve modeling capability, taking these aspects into account, we have developed a novel 3D thermal basin model. In the model transient temperatures are calculated over the last 20 Million years for a 3D heat equation on a regular 3D finite difference grid, allowing for spatial variation in thermal properties, temporal variation in surface temperature and spatial and temporal variations in basal heat flow. Furthermore the model takes into account heat advection, including effects of sedimentation, and lithosphere deformation. The model is iteratively calibrated to temperature data at the well locations, typically taking less than 5 runs. In addition well locations basal heat flow conditions are interpolated based on tectonic constraints.

For The Netherlands the model constructed is composed of over 3 million nodes, having a horizontal and vertical resolution of 1000 to 200 m. For the deeper parts of the lithosphere (>8000m) the vertical resolution is 3000m.

Thermal properties of the 3D model have been based on detailed mapping of the subsurface at a horizontal resolution of 250m, including over 30 different lithostratigraphic formations ranging in age from Carboniferous to Quaternary. For each formation thermal properties, such as heat conductivity and radiogenic heat production, have been determined using generalized relationships of properties based on rock type, temperature and depth dependent porosity. Alternatively thermal properties have been derived directly from well log information. Our model has been calibrated to high quality temperature measurements in wells based on Drill String Tests (DST), and, if not available, on corrected Bottom Hole Temperatures (BHT). The well data are marked by a considerable variation in temperature gradient, which can be related, among others, to spatial variations in thermal properties and basal heat flow.

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Petrophysical measurements at in-situ conditions

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Electrical conductivity of seven rock samples from Icelandic high temperature geothermal zones was measured at in-situ conditions in the rock physics laboratory at GFZ Potsdam. The results are intended to help in the interpretation of resistivity soundings in geothermal exploration in volcanic environments. The rock samples were taken from 187-1003 m depth in boreholes and originate from both the smectite and the chlorite alteration zones. The measurements were performed at 25-250C temperature with pore and confining pressure set to the in-situ hydrostatic and lithostatic pressure, respectively. The conductivity is linear with temperature in the range 30-170C, but when exceeding 170C the conductivity increase with temperature is clearly reduced. A hysteresis appears in the conductivity-temperature relation above ca. 100C, which is explained by ion exchange between the pore fluid and clay minerals covering the pores. The temperature coefficient, α, ranged from 0.027-0.160/C for reference temperature of 25C, but the corresponding value for fluid conductivity is 0.023/C. There was no definite difference in the temperature coefficient between the chlorite and smectite alterations zones. We conclude that interface conductivity is the primary conduction mechanism in both zones and, hence, that lower cation exchange capacity of chlorite is the most likely reason for the abrupt decrease in conductivity that so often is observed at the crossing from smectite to chlorite in resistivity soundings in high temperature geothermal fields.

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Effect of the water-steam phase transition on the electrical conductivity of Icelandic geothermal reservoir rocks

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The effect of the water-steam phase transition on electrical conductivity was experimentally investigated for four specimens of volcanic rocks from Icelandic geothermal reservoirs and one Fontainebleau sandstone sample taken as a reference. The measurements were performed at simulated in-situ conditions: The pore fluid chemistry was chosen to be similar in composition and electrical conductivity to the reservoir fluid; confining pressure, pore pressure, and temperature were controlled. At a temperature of 150C and constant confining pressure pore fluid was gradually released from the sample by steadily increasing the volume of the pore fluid system. At the vapor pressure this allowed a controlled transformation of liquid water into steam.
In all five experiments the pore fluid vaporized at pressures equal to or below that of the boiling point of free water at the respective temperature. The electrical conductivity of the samples decreased continuously until reaching a distinct minimum at approximately 5 % of its starting value.
The qualitative application of a conductivity model proposed by Roberts et al. (2001) enabled us to interpret the observed concurrent evolution of both electrical conductivity and pore (vapor) pressure with respect to the pore size distribution. An estimate based on the concept of capillarity indicates that virtually all pore size classes became affected by vaporization as conductivity decreased. However, a comparison of the pore volume to the total amount of fluid drained from the sample at the conductivity minimum implies that typically less than 1 % of the liquid mass contained within the (connected) pore space was transformed into vapor until this stage.
Knowing where the liquid-steam transition is located at depth is of relevance for both economic and security reasons. Besides being a fundamental petrophysical investigation, this study was therefore also directed to the question if the water-steam phase transition in geothermal reservoirs could be detected by surface monitoring techniques. Our results present evidence, that depending on the amount of steam in the pore space, electrical monitoring systems should particularly be suitable.

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