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Workshop 9

Geosciences for Geothermal Exploration: An Integrated Approach

Monday 9 June, 09:00 – 16:00 hrs

Convenors

Adele Manzella **CNR-IGG**

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70th EAGE CONFERENCE & EXHIBITION

INCORPORATING SPE EUROPEC 2008

9-12 JUNE 2008 | NUOVA FIERA DI ROMA

W9 Programme and Abstracts

Exploration of natural and engineered reservoirs for geothermal resource
June 9, 9:00 – 12:00

Assessment and stimulation of reservoirs for geothermal energy
June 9, 13:00 – 16:00

Posters

Exploration of natural and engineered reservoirs for geothermal resource

June 9, 9:00 – 12:00

Characterizing controls of geothermal systems through integrated geologic and geophysical studies: Developing recipes for successful exploration of conventional and unconventional geothermal systems

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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 stymied 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. Due to the high cost of drilling, such problems can effectively preclude geothermal exploration. Proposals to generate enhanced geothermal systems (EGS) by artificially stimulating hot dry wells, commonly through mechanical hydro-fracturing of rocks, have therefore gained in popularity.

Although EGS research is critical for expanding geothermal resources, it is important to note that existing geothermal systems are generally poorly characterized in terms of favourable settings and structural-stratigraphic controls. In contrast to the petroleum and minerals industries, effective models for guiding exploration and selecting drilling targets are not well developed for geothermal resources. A concerted effort to better characterize the controls on known geothermal systems in different tectonic settings (e.g., volcanic vs. amagmatic; transtensional vs. extensional, etc.) may therefore reap rewards in exploring for new systems at far less the cost than EGS technology. 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 transtensional and extensional tectonic settings, we have been analyzing 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 fault zones (e.g., Desert Peak, Brady's, and Blue Mountain, USA; and Simav, Turkey); b) fault intersections (Astor Pass and Canby, USA; and Salihli, Turkey); c) overlapping fault zones (e.g., Salt Wells, USA), and d) terminations of major normal faults (e.g., Gerlach, USA; Germancek and Kizildere, Turkey). These settings are typically associated with steeply dipping faults and, in many cases, with Quaternary faults, most commonly involving subvertical conduits of highly fractured rock along 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 features may indicate hidden or blind geothermal fields, which have no surface thermal waters or steam (i.e., hot springs, fumaroles, or geysers). Blind geothermal fields can represent the bulk of the geothermal resource in arid regions.

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 geothermal 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 planned 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 had to select promising sites for blind geothermal resources through integration of geologic and geophysical studies. In the Astor Pass area directly northwest of Pyramid Lake, 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 probably 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 the 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 10 km to the northeast 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 here, 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 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 conventional geothermal systems. Considering that the favourable settings for geothermal systems are still relatively poorly characterized, such work clearly has strong potential for facilitating geothermal exploration. Better characterization of the controls on known geothermal systems can also aid in the selection of favourable sites for applying EGS technology. Conversely, EGS applications could expand an already robust fracture system within a favourable setting, thus accentuating the productivity of that system. The geothermal industry can certainly benefit from research activity on both fronts. However, similar to other resources (e.g., petroleum, precious metals, etc.), we contend that it is initially most critical to characterize and catalogue the variety of settings that favour geothermal activity. Improving the conceptual models for geothermal systems through integrated geologic and geophysical studies may be the most efficient and cost-effective means for developing new geothermal systems in the near future.

Lithosphere tectonics and thermo-mechanical properties: an integrated modeling approach for EGS exploration in Europe

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with the contribution of Cloetingh, S., Lenkey, L., van Wees J. D. , Tesauro, M., Förster, A., Kaban, M., Hardebol, N., Ter Voorde, M., Willingshofer, E., Cornu, T., D. Bonté

Abstract

For geothermal exploration and production of enhanced geothermal systems (EGS) knowledge of the thermo-mechanical signature of the lithosphere and crust is important to obtain critical constraints for the crustal stress field and basement temperatures. The stress and temperature field in Europe is subject to strong spatial variations which can be linked to Polyphase extensional and compressional reactivation of the lithosphere, in different modes of deformation. The development of innovative combinations of numerical and analogue modeling techniques is key to thoroughly understand the spatial and temporal variations in crustal stress and temperature. In this paper we present an overview of our advancement developing and applying analogue and numerical thermo-mechanical models to quantitatively asses the interplay of lithosphere dynamics and basin (de)formation. Field studies of kinematic indicators and numerical modeling of present-day and paleo-stress fields in selected areas have yielded new constraints on the causes and the expression of intraplate stress fields in the lithosphere, driving basin (de)formation. The actual basin response to intraplate stress is strongly affected by the rheological structure of the underlying lithosphere, the basin geometry, fault dynamics and interplay with surface processes. Integrated basin studies show that rheological layering and strength of the lithosphere plays an important role in the spatial and temporal distribution of stress-induced vertical motions, varying from subtle faulting to basin reactivation and large wavelength patterns of lithospheric folding, demonstrating that sedimentary basins are sensitive recorders to the intraplate stress field. The long lasting memory of the lithosphere, in terms of lithospheric scale weak zones, appears to play a far more important role in basin formation and reactivation than hitherto assumed. A better understanding of the 3-D linkage between basin formation and basin reactivation is, therefore, an essential step in research that aims at linking lithospheric forcing and upper mantle dynamics to crustal vertical motions and stress, and their effect on sedimentary systems and heat flow. Vertical motions in basins can become strongly enhanced, through coupled processes of surface erosion/sedimentation and lower crustal flow. Furthermore patterns of active thermal attenuation by mantle plumes can cause a significant spatial and modal redistribution of intraplate deformation and stress, as a result of changing patterns in lithospheric strength and rheological layering. Novel insights from numerical and analogue modeling aid in quantitative assessment of basin and basement histories and shed new light on tectonic interpretation, providing helpful constraints for geothermal exploration and production, including understanding and predicting crustal stress and basin and basement heat flow.

Overview

At intermediate depths (<10 km) the Earth presents a huge amount of heat, which allows the extraction of geothermal energy through producing hot water from the subsurface used for heating and electricity production most likely providing about 5-10% of electricity demand in 2050 (e.g. Tester et al., 2007). Enhanced geothermal systems (EGS) is targeted at electricity production from circulating water through high temperatures rocks at depths of approximately 3-6 km EGS involves the fracturing of rock through high injection pressure, improving permeability of the rock for fluid circulations as proved successful in Soultz research project in France (e.g. geothermics Special volume Soultz, 2006). Favourable conditions of tectonic stress are required to allow fracturing the rock with limited injection pressure.

Temperature conditions are critical for the potential of electricity production, as they both influence the thermal power and the efficiency of electricity generation (e.g. DiPippo, 2007). Currently at temperatures of ca 120C, relatively high flow rates of ca 200 L/s are capable to deliver a power of about 3 MWe (Unterhanchung) . On the other hand at much higher temperatures of 150-200C flowrates of 50-100 l/s are sufficient to deliver the same amount of power. are required for electricity production using Given the fact that higher reservoir temperatures both increase efficiency and thermal power it is important to identify prospects with relatively high temperatures, and/or flowrate capable of sustaining power production over the lifetime of the geothermal project.

Up till now exploration and production areas have been selected largely on the basis of observations of high near surface temperature gradients (e.g. volcanic areas such as Iceland and Tuscany in Italy, fig 1) and or relative high temperatures assessed in deep boreholes drilled mainly for Hydrocarbon exploration and production (e.g. Soultz).

For improved assessment of the exploration potential of continental regions for geothermal energy we need to look beyond depths of temperatures known from shallow wells and need capability to predict temperatures at depth in areas where no well control is available. For enhanced flow rates for fluid circulation generated through fracturing, we need to be capable to predict critically stressed conditions, and predict the stress field orientation for optimizing well planning during exploitation.

We review key thermo-mechanical processes which influence the thermal state and the stress conditions in Europe. In doing so we will first introduce basic concepts on the compositional structure of the lithosphere and its relationship with thermal structure of the earth up to ca 100 km depth. We will show how first order thermal constraints from surface heat flow and deep subsurface geophysical datasets can be jointly used to build and constrain thermal models of the lithosphere beyond well control. Although first order patterns in predicted thermal structure and near surface thermal gradients fit well with observations, they can be well explained by both compositional controls and active tectonic processes. Strong local deviations are possible, related to local deviations in compositional properties such as caused by granites and tectonic activity. Next we explain how the thermal and compositional structure of the lithosphere controls the mechanical or so-called rheological properties. Rheological models for Europe are validated relating spatial distributions of low strength with zones of active deformation, as the drivers for earth deformation are far field stresses originating from plate tectonics. We will demonstrate that thermal and rheological model predictions fit very well with earthquake distribution, partitioning of deformation in Europe derived from geodetic measurements. The combined interpretation of the thermal and rheological state of the lithosphere is in close agreement with independent other geophysical data such as the gravity field.

In more detail validation of rheological models through analogue and numerical modeling of deformation processes over geological timescales, demonstrates that first order rheological models fail to take into account lithosphere and crustal scale weak zones which are inherited from previous deformation. These weak zones/faults play an important role in distributing stress and strain in the upper crust representing the top 10 km in the earth. Detailed geomechanical models linking far field stress state and sub-basin fault fabrics allow to validate stress distributions in basins. This type of modeling aids in predicting critically stressed faults. Active faults most likely represent active hydrothermal zones enhancing probability of EGS favourable conditions.

The thermo-mechanical state which is observed for Europe relates to a complex evolution through geological times, involving pervasive extensional and compressional deformation. For selected tectonic settings, marked by a specific deformation style, we discuss the relationship between key-factors in tectonic evolution and geothermal prospect. This relationship allows to approach in a rational fashion continent-scale exploration for geothermal resources and building hypothesis for thermal and mechanical characterization at depth.

Geophysical exploration methods at European sites

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Most geophysical exploration methods have been developed for the oil and gas industry, and ever more sophisticated tools and refinements in the different approaches are designed to solve specific problems associated with the detection and characterisation of hydrocarbon reservoirs. The exploration of geothermal resources has profited greatly from these developments, however, the methods cannot always by directly transferred from oil and gas to hot water and/or steam. First of all, physical properties of H_2O differ from those of hydrocarbons, resulting in differing responses of physical measurement methods. Secondly, geothermal reservoirs can be found in highly varying geological environments, mostly associated with volcanism, where hydrocarbons are usually not present. Thirdly, the economically most interesting geothermal reservoirs are much hotter than any oil or gas reservoir. At the moderate temperatures comparable to those of hydrocarbons many of the advanced exploration methods are simply cost-prohibitive, as the economic potential of a medium-enthalpy geothermal reservoir is much lower than for an oil or gas well. For these reasons, some of the existing geophysical methods have to be adapted to meet the needs of geothermal exploration or different methods have to be developed and applied.

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

potential methods, based on density and magnetic properties of rocks and two of the Earth potential fields: magnetic and gravity;

electrical and electromagnetic (EM) methods, based on the electromagnetic properties of rocks (conductivity, permittivity) and the Maxwell equations;

seismic methods, based on the elastic properties of rocks and the equations of wave propagation in continuous media;

radiometric methods, based on radioactive emission of rocks and atomic physics equations. These methods are most commonly used in well-logging.

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

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

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

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

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

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

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

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

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

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

Metamorphic rocks in Larderello/Travale, Italy

The geophysical case history of the Larderello-Travale geothermal site is well representative of the development of the geophysical methods applied to geothermal exploration and of the different stages of a conventional geophysical exploration. The gigantic reservoir formed above a young granitic pluton, which intruded sedimentary and metamorphic units and caused local contact metamorphism. Up to the early 1980s, geophysical exploration was limited to electrical sounding and to temperature measurements in some shallow boreholes. Structural information was derived from gravity surveys. For the last 25 years, reflection seismic surveys, initially used for geological-structural goals, have been more and more used to image the deeper reservoir and provide information directly related to geothermal production, since the method seemed to be the only methodology able to provide resolution useful for targets deeper than 3 km. The latest 3-D survey and reprocessing of older data led to the definition of two distinct reflectors. Well investigations have shown that the shallower one, named H marker, represents steam filled fractured zones near to the top of Plio-Pleistocene intrusive bodies. The H reflection is remarkable as seismic expression of steam reservoirs potentially of high economic interest and is now regarded as a target for the deep geothermal exploration of the Travale field.

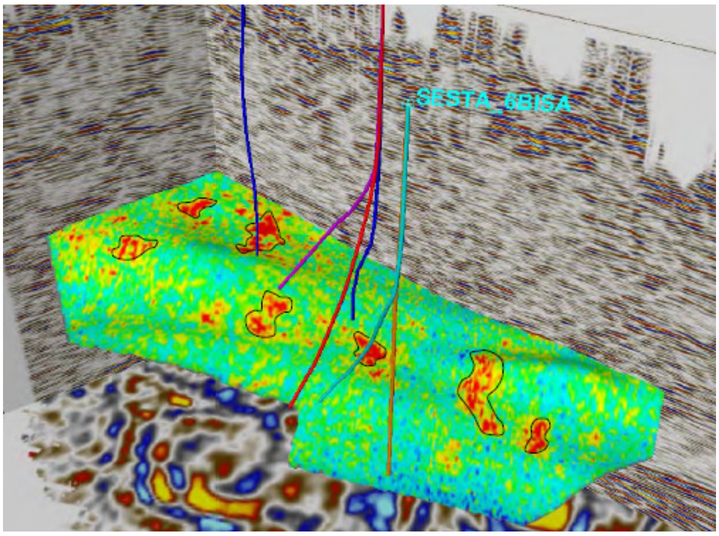

***Figure 1** – 3D-seismic interpretation of the H-marker and selection of potential drilling targets at areas with highest RMS amplitude (Cappetti et al. 2005).*

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

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

All three fields have in common their recent volcanic activity, associated with hot water springs from shallow reservoirs, implying high geothermal gradients, and the association of the geothermal reservoirs with intense fracturing and local fault systems. At *Hengill*, extensive geological, geophysical and geochemical surveys started as early as 1947. Aeromagnetic, gravity and DC-resistivity surveys were carried out between 1975 and 1986. These delineated a 110 km^2 low-resistivity area at 200 m b.s.l. and showed a negative and transverse magnetic anomaly coherent with the thermally most active areas. EM soundings were used to construct resistivity maps of the uppermost kilometre. These maps were revised by TEM measurements conducted from 1986 onwards, with a much better depth resolution. Most recently, the seismic activity in the region was used to collect broadband seismic signals within the IGET project and use them for a combined interpretation with recent MT and TEM data. The broadband seismometers register a much wider frequency range of the seismic spectrum than standard seismometers. At Hengill, microseismicity with more than 600 events was recorded within 4 months, allowing the detailed analysis of the local tectonic situation and of the subsurface structures. (shear wave splitting?)

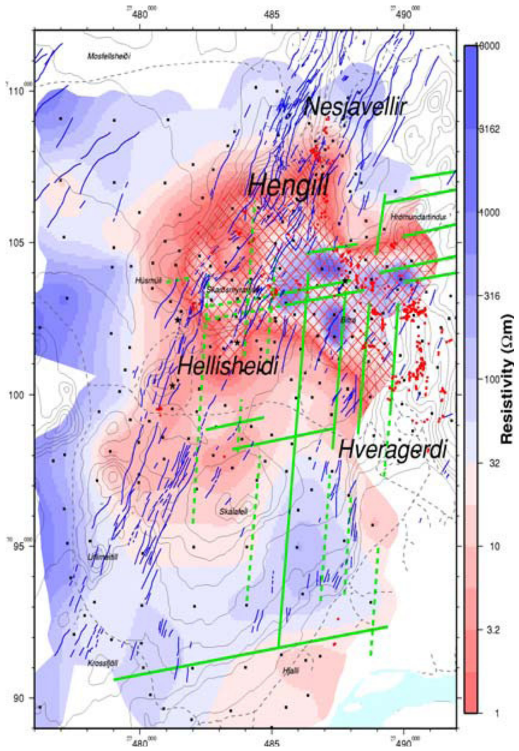

Figure 2 *– Hengill. Resistivity at 100 m b.s.l. according to a recent TEM survey. In blue are visible fault lines; green: faults as defined by earthquake locations (from Arnason and Magnusson, 2001).*

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

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

Sedimentary Rocks at Gross Schönebeck/Germany.

Exploration of the area in the Southern Permian Basin started with 2-D seismic surveys in the 1970s and '80s, with the East German gas exploration programme. The gas exploration well at Gross Schönebeck was dry but showed the existence of a deep hot water reservoir. That's why the well was reopened in 2000, deepened and used as an in-situ geothermal laboratory. To intensify geothermal activities there, the old seismic lines were reprocessed to construct a geological model of the area around the reservoir, with very good results. A new seismic survey with a parallel MT profile was performed within the IGET project and provides new insight about the resistivity distribution around the reservoir. These measurements are combined for an integrated interpretation of the geophysical data. (see presentation Muñoz). Well logging provides additional information about the petrology, porosity and orientation of cracks. With the information from the logs combined with leak-off tests from hydraulic stimulation and analysis of borehole breakouts the orientation of the in-situ stress field was determined. With the knowledge of the local stress, a favorable orientation of a second well to be drilled for installation of a well doublet was possible (Moeck et al., 2007).

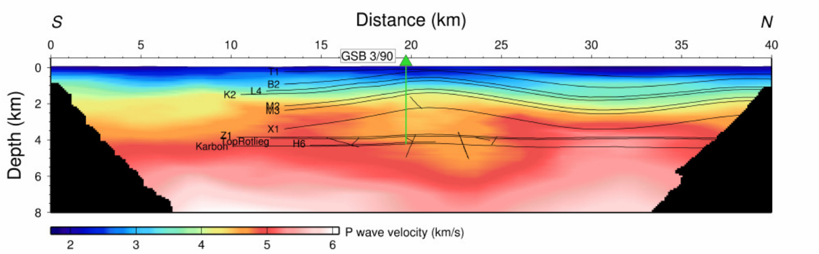

Figure 3 *– P wave velocities derived from damped least squares inversion of manually picked travel time data. Black regions are not resolved by tomography. Superimposed are the geological boundaries from the pre-existing 3-D model extracted along the profile.*

Problems with geophysics arise because of the regional geology, typical of the Southern Permian Basin, which is strongly affected by salt tectonics. The wells at Gross Schönebeck reached the reservoir rocks at a depth of 4200 m in Lower Permian sandstones and volcanic rocks beneath a more than 1 km thick salt pillow (Upper Permian/Zechstein). This salt layer not only dampens all seismic signals but also constitutes a highly conductive body, which represents a challenge for magnetotelluric, which is aimed at finding the conductive reservoir below the salt.

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The geothermal potential of the carbonatic platform buried beneath the Veneto and Friuli coastal areas: preliminary results from the Grado-1 borehole (NE Italy)

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The carbonatic platform buried beneath the Veneto-Friuli plain (NE Italy) represents a distinctive character of the Adriatic foreland, which experienced deformation and flexure by the propagating orogenic loads of the Dinaric mountain range, from the east-north-east, and of the Southern Alps, from the north. Diachronous compression phases characterized both mountain belts during Late Cretaceous and Cenozoic times, favouring the development of thick sedimentary wedges at the north-eastern and northern borders of the Adriatic foreland, respectively. The dinaric foredeep, grown to the east of the plain, was mainly filled during Paleogene times, whereas the south-Alpine foredeep received major input sediments in the upper Oligocene and Miocene times, with further input during Plio-Quaternary times.

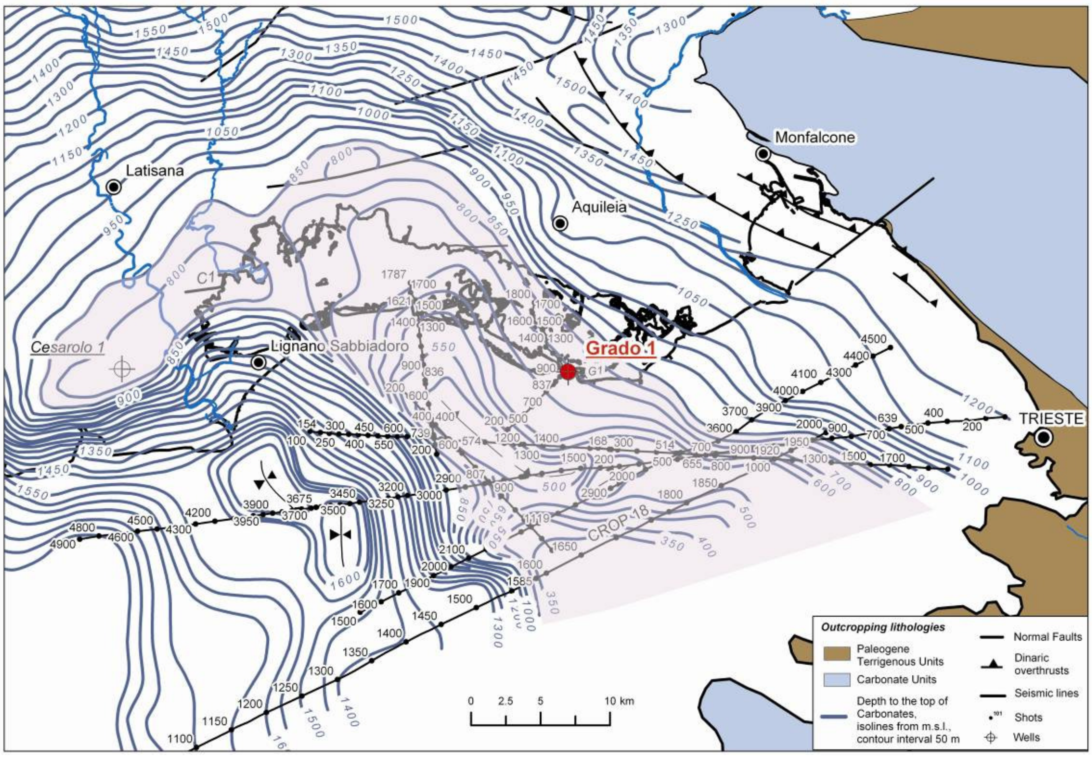

Figure 1 *– Morphology of the top of the carbonatic platform in the Trieste Gulf and in the Veneto-Friuli coastal areas. Depth in m below sea level. Location of the Grado-1 exploratory borehole is also indicated. The coloured area represents the platform highs.*

The structural highs of the carbonatic platforms in the lower Veneto-Friuli Plain and in the adjacent north Adriatic Sea were recently reconstructed (Figure 1) on the base of an integrated study of the available geological and geophysical data, complemented by new high resolution seismic reflection profiles acquired in the mainland (Lignano and Aquileia), Grado island and offshore areas (Trieste Gulf). The composed research program was funded by the Regione Friuli Venezia Giulia. A predominant contribution to this study was provided by the ENI-AGIP seismic reflection profiles and deep boreholes, carried out in the past decades for hydrocarbon exploration (e.g. Fantoni et al., 2003; Nicolich et al., 2004). The morphology of the platform shows two clear ridges beneath the Veneto-Friuli coastal area: the “Cesarolo high”, at a depth of about 700-800 m, and the “Grado high” offshore the Grado Island, at a depth of about 500 m. These culminations are relevant at regional scale and form a right corner approximately oriented sub-parallel to the main far away orogenic loads (Figure 1).

They are delimited by normal and trans-tensional faults deeply rooted into the basement and episodically interested by a weak seismicity. The “Grado high” is NW-SE oriented and is clearly in continuation with the Jurassic-Cretaceous anticline crossing the western part of Istria peninsula.

Despite the low geothermal gradient (< 20 °C/km) of the Adriatic foreland, the Cenozoic terrigenous and molassic cover on top of the platform culminations beneath the Veneto-Friuli coastal area exhibits a positive geothermal heat flow anomaly with temperature gradients > 50 °C/km and temperatures up to 50 °C within the fresh Quaternary aquifers. The stratigraphic records from water wells, together with their temperature and water geochemistry data and with the Cesarolo-1 borehole (deeper than 4 km) data, allowed us to calibrate a simplified 2-D thermal model that requires convection of fossil waters in the upper 2-2.5 km of fractured Paleogene-Mesozoic rocks (representing the reservoir), and a prevailing heat conduction in the overburden molassic deposits.

In order to assess the geothermal potential of the deep aquifer in the carbonatic platform and its suitability for space heating of public buildings in Grado city (by means of a geothermal doublet), the RFVG, supported by European funding, contracted the drilling of an exploratory well entering at least 200 m into the reservoir rocks. The Department of Civil and Environmental Engineering of the Trieste University carried out the site survey and the preliminary thermal modelling, together with a substantial support to borehole projecting, drilling direction and well logging interpretation.

The Grado-1 borehole, initiated in December 2007 and completed in March 2008, was located at the westernmost end of the Grado Island, on the eastern flank of the platform high. It reached the top of Paleogene calcarenites at 616,5 m below ground level, the top of the Mesozoic limestone at about 1000 m and ended at 1108 m total depth, crossing two relevant fractured portions of the reservoir rocks, at 736-740 m and from 1040 to the well bottom (Figure 2).

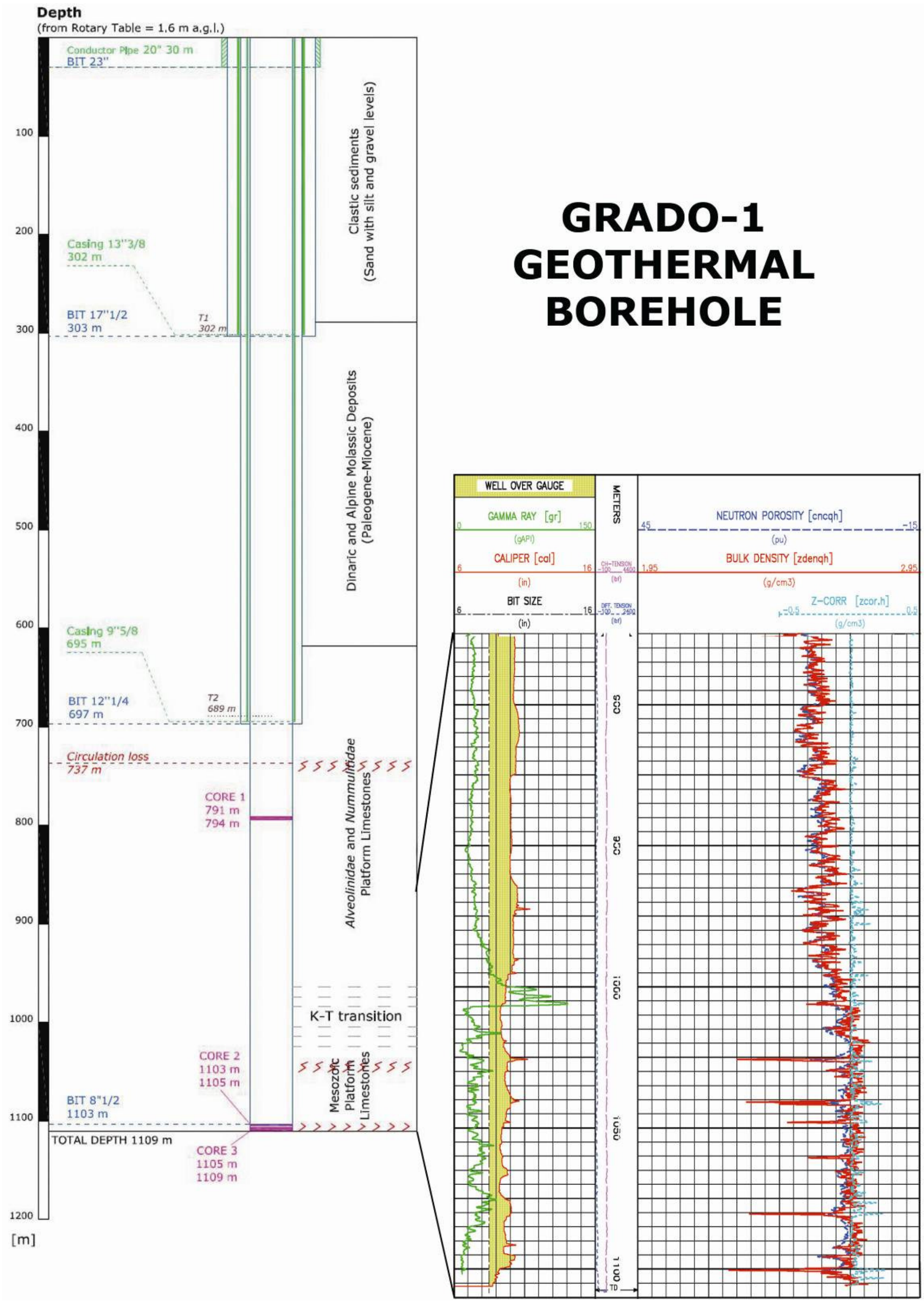

__Figure 2__ – Simplified stratigraphy of Grado-1 borehole (left). Depth in m below rotary table (+ 1.6 m above ground level). Neutron porosity, bulk density, gamma ray and caliper logs of a selected interval are also shown.

We present herewith the preliminary results of the sampling and coring programs, well logging from 700 m to total depth (Figure 2) and of pumping tests, together with a preliminary interpretation of the drilling results within the NE Adriatic foreland.

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Technological challenges of geothermal exploration

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Abstract

The most pressing technological challenges in exploration and investigation of Enhanced Geothermal Systems (EGS) and Unconventional Geothermal Resources (UGR) are considered to be those associated with the identification of the nature of geothermal heat concentrations and prospective reservoirs without drilling, the improvement of methods predicting reservoir performance/lifetime, the optimization of resource exploitation producing the lowest possible effect to the environment.

A list of important research themes is provided, allowing a spatial and temporal reconstruction of the subsurface geothermal condition that might not only cut the time from discovery to production and improve efficiency, but also reduce environmental impacts forecasting possible problems and finding solutions beforehand.

Introduction

The search for geothermal and tools of search have changed. In the '80s the main search focused on large reserve, high enthalpy systems with T >> 150 °C and EGS concept was at its early stage. Now that lower temperature can be exploited and EGS technology is becoming more mature there is still a hunt for high enthalpy fields - especially near known fields - to enrich the portfolio and add growth for the long term, but exploration expands to new conditions and new areas at the expense of a higher risk and failure rate. What was considered unexploited or not economic in the past is becoming possible nowadays, if bottleneck for exploitation are overcome. Moreover, advances in technology make what is uneconomic today economic tomorrow.

In the framework of the ENGINE Coordination Action a main issue has been the definition of innovative concepts for the development of UGR or EGS. Important technical obstacles to attaining near-term and long-term EGS and UGR goals and objectives exist in the areas of resource characterization; reservoir design and development; and reservoir operation and management. In all these fields investigation and exploration provide a fundamental base. *Resource characterization* regards research in geothermal gradients and heat flow; geological structure, including lithology; tectonics; induced seismicity potentials. *Reservoir design and development* includes research in fracture mapping and in-situ stress determination; prediction of optimal stimulation zones. *Reservoir operation and maintenance* includes research in reservoir performance monitoring, hydraulic management, short circuit mitigation, fluid loss control, reservoir properties determination, and fluid chemistry and permeability control. Moreover, in a new era of geothermal development, the sustainability and mitigation of environmental effects should be defined and optimized prior to major financial commitment.

Two main goals should be addressed by exploration and investigation: reduce the mining risk and guarantee the sustainability of the resource and the lowest possible environmental impact.

Toward a reduction of mining risks

One of the main challenge is to find a technology reducing the exploration cost through reduced exploration risk. New development in geophysical methods is sought, while integration of technology and multidisciplinary evaluation of data, such as the one speeding up in the last 10-15 years for hydrocarbon exploration, must become a core competency also in the geothermal world.

The research areas I consider important to develop are here listed.

• Calibration of stratigraphy, reservoir, fluid circulation and thermal history in underexplored areas. Measures to be taken need to involve a critical screening of thermal data, developing baseline temperature models, and investigating the modification through the time of reservoir exploitation, providing the essential thermal rock properties, and combining the temperature field properties with reservoir properties. Analogue sites should be studied and results incorporated in the workflow in order to help the interpreters to take advantages from known similar conditions.

• Calibration of thermal conductivity from a set of well-log parameters. With good control of thermal conductivity versus depth, the variation of heat flow versus depth can be delineated and interpreted in terms of heat-transfer processes, which is essential for the assessment of an EGS.

• Calibration of temperature distribution and extrapolation at depth using neural network analysis of electromagnetic (EM) data and temperature logs.

• Advances in geophysical data acquisition, processing and workflows need continuous attention in order to provide better images in complex areas.

• Petrophysical studies should be extended in order to define the main relations between physical parameters, mineralogical composition, fluid chemistry and water-rock interaction effects.

• Improved Lithology and Fluid Prediction using full wave fields. Reflection seismic through a detailed seismic attribute analysis, gravity, electromagnetic data allow to define density contrasts, porosity and permeability, nature of fluid. All these information, monitored in time, are used to make inferences about reservoir dynamic and helps in optimization of drainage. Depth migrated seismic should pay special attention on the velocity model construction. New inversion modelling tools should be defined, joining different geophysical information.

• Acoustic (compressional and shear wave) signatures of deforming rocks should be investigated with the aim to provide a database on rock physics and rock deformational properties so that high resolution 3D or 4D seismic surveys can be used to image reservoir enhanced permeability zones or to identify rock units where enhanced permeability could potentially occur.

• Development of an integrated tool to handle fault and fracture analyses, drilling engineering, logging, and seismic data.

• Definition of in-situ stress, which is crucial both for understanding the dynamic of the fluid circulation and to help during exploitation, foreseeing the drilling requirements to avoid collapses, stacking and guarantee wellbore stability, as well as controlling stimulation effects including induced seismicity.

• Integrated geomechanics software and workflows are needed as part of an integrated reservoir modelling workflow.

• Data integration (e.g., static and dynamic) is a reoccurring theme throughout most Exploration and Reservoir Characterization elements and must be considered a key area to improve tools. There is no single software tool capable of providing a fully integrated Reservoir Model all the way from geophysics and geochemistry, through Geo Model to Flow Model due to problems with moving data, changing scales (up scaling) and common standards/workflows.

• Development of geostatistical tools to integrate geophysics and well data.

• Uncertainty analysis providing probabilistic results should be incorporated in the workflow to take account of a range of possible outcomes.

• Broad thermo-hydrodynamic conditions should be incorporated in all the main reservoir simulators in order to model all parts of geothermal systems and their evolution with time.

• Geothermal community standards for additional data types should be developed to improve the maintenance of high quality databases and data handling and to facilitate the input of these data into simulators.

Toward a sustainable and zero impact geothermal exploitation

The necessity to guarantee the sustainability of the resource and zero environmental impact add focus on high availability of water including produced water injection solutions, no or reduced fluid discharge, no or reduced induced seismicity. Mapping of environmental condition before entering new areas and monitoring during operational phases is needed. This includes methods to assess impacts from discharges to shallow waters and emissions to air, the effects of compliance to a zero discharge versus a zero harmful discharge framework. A baseline should be established mapping the conditions before operation, predicting the effects of activity (risk and impact based evaluations) and monitoring actual condition during stimulation and production. To this aim a main technological challenge is the development of improved logging tools for imaging physical conditions at depth but also capable to resist at very aggressive condition (high temperature, high pressure, highly corrosive fluids) maintaining the costs as low as possible and guaranteeing a quick and reliable data transfer and storage.

Geothermal exploration and investigation would greatly benefit from tools able to improve imaging between existing wells and performing real time measurements. Some of these tools might be borrowed from oil and gas exploration but adapted to meet unique geothermal conditions, such as high temperature and pressure and possibly aggressive chemical composition. Here I give a list of tools and real time measurements that would improve subsurface imaging and monitoring conditions during stimulation and production.

• Logging through casing should be improved. Cased-hole logging technology is a research field in oil and gas but the different casing problems of geothermal wells requires ad hoc solutions to be defined.

• A main effort should be made to design and demonstrate high temperature (> 200°C) measurement-while-drilling (MWD) tools using a unique high temperature battery system. Research projects made in the hydrocarbon exploration are focused on devices incorporating silicon-on-insulator (SOI) fabrication technology into the manufacturing process for the microchips required. The goal is to improve the reliability of high-temperature electronic components found in MWD tools needed to improve drilling efficiency and success rate at depths up to 8 km and temperatures greater than 200°C. This research should be joined and adapted to geothermal condition, especially in view of the different chemical condition often met in geothermal systems.

• The use of borehole seismic imaging supplemented with electromagnetic methods would help to map fluid content at distance of hundreds of meters from the bore hole with resolution comparable to existing logging methods. Since seismic methods provide information on the structural and mechanical properties of the medium and the conductivity provide independent information on the fluid state, these jointed measurements will provide a more complete map of the fluid distribution and matrix properties. This kind of measurements performed after the first exploratory well is drilled during an EGS project would provide precious information both for designing the subsequent wells and for defining sustainability of the system.

• Computational improvements should be made in order to obtain 3D electrical tomographs, providing the equivalent of electric logs deployed every few meters between existing wells. These high-resolution tomographs have been used with success for oil and gas formation characterization and monitoring subsurface fluid movement (i.e. tank leaks, steam floods), but should be adapted to geothermal condition where also temperature changes must be taken into account. This technique would also address the problem of tracking the fluid during stimulation or production. The ERT tomographs can be interpreted to show where the fluid saturations are changing in the field, providing insight into production and stimulation performance.

• The development of a combined microseismic receiver-tiltmeter system would provide an advanced hydraulic fracture mapping tool to measure created fracture geometry. Such system would eliminate the need for two observation wells and reduce overall costs.

Conclusions

The new demand for better understanding of the reservoir is setting new challenges, which are technical as well as organisational. A reservoir study project requires the availability of all the relevant prospect information, which on turn should be available to all the applications involved in the management and analysis of such a project. The improvement of the conceptual model to decrease the drilling risk of the exploitation wells needs more integration between different methods, advanced 3D modelling coupled with thermo-hydrodynamic modelling and rock physics measurements.

Integrated workflow include geophysical imaging, interpretation and earth modelling, and provides all information necessary for reservoir characterization and well design and simulation. An effective planning should incorporate all data at different scales, making the link between geology and other disciplines. The next generation of exploration tools should include an increased geological realism and representation of uncertainties, improved physics and chemistry, and should be designed for new and future computing environments.

The technical challenge is to create the systems and technologies that will streamline and optimise this sophisticated and complex workflow. The logistical and organisational challenge is to create the units and the processes within the geothermal community.

The new tools would permit the asset teams to work differently, taking advantage of a higher level of professional interaction among the various geosciences and engineering disciplines.
With the advances in geosciences knowledge we can integrate the exploration workflow, advanced volume based visualisation technology and the well design parameters, to optimise the drilling engineering process using the available information from field measurement. Establishing predicted fluid circulation and temperature distribution for optimised well design, interactively locating the optimal well path and using real-time monitoring while drilling would allow to achieve modelling-while-drilling, as well as the interactive redesign and re-engineering of the well path. All of this would save both significant time and expense in the very costly drilling process, and would allow the minimum impact to the environment while providing the sustainability of the accessed resource.

Assessment and stimulation of reservoirs for geothermal energy

June 9, 13:00 – 16:00

Available approaches for increasing the producibility of geothermal wells in natural fracture systems by optimizing their placement, design, and stimulation

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Note: Although it reflects the author's opinion, the present contribution quotes, often verbatim, numerous articles published in the Oilfield Review over the past years and the author is indebted to his Schlumberger colleagues who wrote those various papers.

Introduction

Maybe the greatest value of technology in geothermal energy issues can be assessed in terms of its ability to reduce risk. The present contribution only addresses subsurface matters and, even more specifically, how naturally fractured geothermal reservoirs could be more efficiently tapped and developed in the framework of EGS operations. Lastly, among the two aspects which have to be investigated in EGS projects, i.e. temperatures and flow rates, only the latter is considered here, assuming that the isotherm geometry can, for instance, be constrained by MT (magneto-telluric) surveys looking for electrically conductive altered rocks (clay alteration zones) or other techniques.

The ability to characterize NFSs (natural fracture systems) in the early field development stage of an EGS project reduces economic risk because it enables the development team to determine optimal well placement and trajectories. Characterizing, tapping and developing a geothermal NFS, as well as predicting the heat and fluid flows in response to hot water extraction and cooled water re-injection, is a challenging task that span multiple disciplines and multiple scales.

Context

Let's consider the situation where a series of geologic episodes, including an extensional (rifting) phase, has led to a graben zone where tectonic faults not only cut through the crystalline basement formations but also affect the superincumbent pre-rift and syn-rift sediments. In the, say granitic, hot basement rocks, both porosity and permeability are initially provided by natural fractures: in the fractured zones surrounding faults where hydrothermal fluids have dissolved feldspars in the rocks, a solution-enhanced fracture system provides primary flow conduits, possibly locally complemented by a complex network of smaller fractures contributing to the majority of the storage capacity and somewhat behaving like a porous system.

Issues and approaches

Many factors affect fluid flow within such a NFS and will therefore condition the technical success of an EGS project. Those factors include fault and natural-fracture locations and directions, whether those fractures are mineral-filled or open (since in some instances, descending waters may have progressively sealed some fractures downward), and present-day stress orientation.

Tectonic faults typically occur over a broad range of scales. Surface seismic surveys prior to drilling any boreholes generally allow the detection of the larger faults while subsequent borehole data are required to identify and characterize smaller faults. Even if often seismic methods do not detect individual small faults or fractures but rather exploit, using azimuthal anisotropy analysis, the average response across a large volume of rock, borehole seismic surveys or sonic images acquired in vertical or deviated wells help accurately delineate fault zones and aid in the planning and placement of sidetrack holes.

Last but not least, the knowledge of regional stresses is critical for several reasons. Besides borehole stability issues that may affect the choice of borehole trajectories, the present stress state dictates whether fractures are open and can thereby conduct fluids. Direction of maximum horizontal stress can be indicated by wellbore breakouts and drilling-induced tensile fractures identified in borehole electrical or ultrasonic images recorded by logging tools.

In addition, the magnitude and direction of horizontal stresses play a critical role in hydraulic fracture design, the primary stimulation method for NFSs since high permeability channels (past and present), frequently associated with hydrothermal breccias or parallel fracture corridors, may typically be re-activated, or connected to through hydraulic fractures, and serve as fluid conduits. Passive seismic techniques allow monitoring the efficiency of such hydraulic fracturing operations.

Surface seismic

The recent improvements in land seismic 3D operations and processing can be instrumental in helping delineate EGS target zones. For instance, vibrators with maximum sweep displacement now allow going down to 3 Hz, thereby enabling to map the low-contrast transition in the altered zone at basement top. Multi-component seismic surveys yield important data for the determination of seismic azimuthal anisotropy in the basement or the overlying sediments, which is essential to characterize the orientation of NFSs and to place wells effectively, improving the chance that a well will intersect fractures.

When 3D seismic data are acquired, advantage can also be taken of the relationship between permeability and fault proximity which is generally associated with higher fracture density. Seismic attributes, known as edge-enhancing attributes, can be computed (at least in the sedimentary formations overlying the basement) and the so-called ant-tracking algorithm applied to highlight the discontinuities and to map faults. A distance-to-fault attribute is then generated; it helps identify zones that are highly fractured. In addition, seismic acoustic impedance is mapped to further discriminate between sealing and draining fault zones, low acoustic impedance suggesting a higher proportion of open fluid-filled fractures, and to better select subsurface targets.

Borehole seismic

Once a first (vertical or deviated) well has been drilled, borehole seismic surveys can bring additional value to geothermal exploration and production. In a borehole seismic acquisition, an array of receivers, clamped in the borehole, record multiple components of the seismic energy and the source is located at surface, near the rig in a zero-offset vertical seismic profile (VSP), at multiple offset locations in a walkaway VSP, or in a grid or spiral above the target when acquiring a 3D VSP.

Borehole seismic surveys have several interesting features. Their broader bandwidth and higher signal-to-noise ratio improve the vertical resolution compared with surface seismic results, thus revealing faults not discernable in the surface seismic image. Seismic well tie takes the time-domain surface seismic sections into the depth domain. Seismic surveys in the borehole can help drillers identify targets in a region ahead of the current bottomhole depth and around the current well trajectory. Called look-ahead VSPs, those surveys are acquired during interruptions of the drilling operations, and processed quickly enough to influence drilling decisions. Lastly, borehole seismic imaging helps accurately delineate faults and aid in the planning and placement of sidetrack holes, when needed.

The interest of borehole seismic for EGS projects will also benefit from a series of recent technical developments. Multi-component tools, such as the Schlumberger Versatile Seismic Imager (VSI) tool, and their accompanying acquisition technology, now provide the ability to record frequencies below the 10 Hz lower limit (low frequencies may matter for detecting low-contrast transitional contacts, e.g. at top of granites) and the 100 Hz upper limit of traditional borehole geophones.

Borehole seismic will help detect faults and fractures in several ways. If a 4-component VSP (i.e. with 3-component geophones and a hydrophone) is recorded, it can help detect the presence of large-size open fractures, since they could be causing P-to-Tube wave conversions. More often, the multi-component, multi-offset seismic surveys acquired in a borehole will allow quantifying directional wave-propagation effects caused by velocity anisotropy, by which seismic velocity measured parallel to fractures is different from velocity measured perpendicular. Advanced understanding of such anisotropic wave propagation and the ability to model three-dimensional response will therefore be instrumental.

Sonic and companion logging techniques

Modern sonic logging tools, such as the Schlumberger Sonic Scanner tool, give access to further helpful information from boreholes. Since an open fracture intersecting a borehole causes Stoneley waves to reflect and attenuate, Stoneley waves can now be reliably used, due to the broad range of Stoneley mode frequencies acquired by such new tools (a feature that was not available in the past), to characterize permeability associated with such fractures. The orientation of these fractures is concurrently derived from the interpretation of electrical or ultrasonic images of the borehole wall acquired by well logging tools.

Analysis of flexural wave dispersion curves provided by the Sonic Scanner tool also helps to identify zones where the magnitude and orientation of an elastic anisotropy can be quantified. This information can be compared and combined with borehole seismic data. For instance, the co-occurrence of an isotropic behaviour found by the sonic tool and an anisotropic one highlighted by a borehole seismic survey in the same well may suggest the presence of a faulted or fractured zone in the vicinity of the borehole. Sonic imaging techniques can furthermore sometimes be applied to the detection of large fractures located near but not intersecting the borehole, which could constitute a target for a sidetrack hole.

Hydraulic frac concerns

Once drilled, EGS wells will often have to be stimulated in order to increase their connectivity with pre-existing NFSs. Understanding how hydraulically-created fractures interact with an open and/or partly mineral-filled NFS will actually often be critical for EGS projects, because it is known that it is the combined effects of natural and hydraulic fractures that are largely responsible for improved productivity or injectivity in deviated or horizontal wells, compared to vertical wells.

In the last 15 years, the oil and gas industry has learnt that, although modeling with hydraulic fracture simulators is a necessary tool in fracture engineering, hydraulic fracture growth can be difficult to model in formations that are naturally fractured. Hydraulic fractures tend to propagate according to the present-day stress directions, but also to pre-existing planes of weakness such as natural fractures that reflect ancient and possibly localized stress regimes.

Natural fractures, that are the primary mechanism for fluid flow in low permeability formations, thus compromise the ability to predict the geometry of hydraulic fractures and the effect of stimulation on production and drainage. Notably, there is little reason to believe that a hydraulically induced fracture would maintain symmetry as it propagates outwards from the borehole. In an effort to better characterize hydraulic fracture behaviour and geometry away from the wellbore, two frac monitoring techniques have proved successful though. These far-field hydraulic fracture-mapping methods are surface and downhole tiltmeters and, especially, micro seismic monitoring.

Micro seismic methods

Small seismic events are emitted by fractures and faults, mostly due to shear readjustments in response to changes in effective stress following well production or injection, and especially during hydraulic fracture stimulation operations. Seismic sensors, positioned in nearby wellbores used as monitoring wells, can detect these acoustic emissions and a special processing can estimate the event locations, producing a continuous record of induced micro seismic activity, in space and time.

Although a few events may also occur away from the fracture tip where stress changes cause shear slippage in natural fractures, it is thus possible to construct a map of the created fracture by plotting the locations of acoustic emissions over time, while fracturing. The processing is quite complex and VSP data are used to provide the needed detailed velocity information around the monitoring well. The VSI tool used to acquire the VSP data also records the micro seismic events, ensuring consistency in data acquisition, processing and interpretation, and significantly reducing the uncertainty in defining hydraulic fracture geometry and orientation.

Passive seismic methods can also be used to detect the response to longer injection or production test periods and to help identify fracture and fault directions away from the well location, which in turn will help decide upon the preferred azimuth in which subsequent deviated or horizontal wells should be drilled. In most areas where the rock is not under very severe tectonic stresses, the seismic energy released during those events induced by fluid extraction or injection is low (typically of magnitude 0 to 3) and not felt at the earth's surface. It is e.g. very rare for hydrocarbon reservoir developments to lead to earthquakes strong enough for people to feel. It is nevertheless important to understand the conditions under which seismicity may be induced, so that these operations can be performed safely.

Conclusion

The question that one has now to have in mind is the following: will the time (and money) spent designing, acquiring and processing a surface or borehole seismic survey, acquiring borehole imaging logs, or monitoring micro seismic events while hydraulically fracturing, be paid back by sufficiently reducing the technical and economical risks encountered in one's search for safely and efficiently harnessing geothermal energy sources? The purpose of the present contribution was to bring food for thought, regarding this question one will now hopefully answer positively.

Induced seismicity: Setting the problem in perspective for EGS development

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Induced seismicity is a recognised hazard in practically all engineering endeavours where stress or pore pressure are altered. This can be taken as a reflection of the realisation that has dawned in the past 20 years that the Earth's crust generally supports high shear stress levels and is often close to failure. Historically, the most damaging events, which have sometimes caused many fatalities, are associated with the impoundment of reservoirs. However, earthquakes of sufficient size to cause damage to localities have also been associated with mining activity, long-term fluid withdrawal wells, and long-term fluid injection wells. Given that massive stimulation injections into crystalline rocks have routinely been performed at EGS sites since the early 70s, it is perhaps surprising that the issue of the seismic hazard associated with these operations has only recently come to the fore. Massive injections of fluid have been conducted at Fenton Hill, Rosemanowes, Hijiori and Soultz (3.5 km reservoir) without producing events large enough to disturb the local population. More recently, events approaching or exceeding 3.0 have occurred during or shortly following injections at Soultz , Cooper Basin (Australia) and Basel, all of which were conducted at 4.5-5.0 km. These events, particularly the event at Basel because of it proximity to a major population centre and reports of damage, has galvanised attention on the seismic hazard posed by EGS development.

This talk will present a review of approaches that might be taken to assess and mitigate the hazard. Specifically, it is argued that it is currently not possible to deterministically-predict the likely seismic response to injection at a prospective site on the basis of surface-based geophysical exploration alone. For even in situations where proximity of major faults can be determined with reasonable confidence, the key variables that govern whether large earthquakes will be triggered by injection - the variation of strength and stress on proximate faults - cannot be deduced from surface measurements, nor from point-measurements of stress conducted in a borehole. Injection into an exploration borehole and an analysis of attributes of the microseismicity that is produced, such as moment-frequency relations, greatly enriches the information that is available for seismic hazard assessment and may be a fruitful approach, but this information comes at the cost of drilling the well. A complementary approach is to examine incidences of induced seismicity and attempt to extract semi-quantitative guidelines for assessing the dependence of hazard on such variables as the distance to faults, seismically active and inactive, and the depth of the reservoir.

Finally, it is noted that seismic risk has not halted reservoir impoundment, mining, oil or gas extraction, or liquid waste injection. As with these other economic activities, the complete elimination of risk for EGS development and operation is not possible. This fact should be accepted. Nevertheless, it is incumbent upon us to find ways of assessing the risk, and develop practices that minimise it.

Understanding the stress field and potential fault activity – a key issue to drilling and stimulation in man-made geothermal reservoirs

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Summary

It has been recognized that in-situ stresses have significant impact, either positive or negative, on the short and long term behaviour of fractured reservoirs. The knowledge of the stress conditions are therefore important for planning and utilization of man-made geothermal reservoirs. The geothermal field Groß Schönebeck belongs to the key sites in the north eastern German Basin in Germany. We present a combined approach of stress field determination and application of the new knowledge for drilling and stimulation design at this key site, where 4100 m deep sandstones and volcanic rocks of Lower Permian are ongoing to be explored. In our comprehensive study we use detailed 3D fault mapping, based on available well and 2D seismic data, stress regime determination based on empirical and analytical methods, and slip-tendency analysis to estimate reactivation and leakage potential of any fault population within the stress field under initial and changing pore pressure conditions. We discuss the importance of various fault sets related to the stress field in terms of their potential for conducting geothermal fluids based on the tendency of the faults to dilate and slip. In particular, we demonstrate how the well path trajectory and mud weights can be defined on the basis of principle stress orientation and magnitude to minimize formation damage under mechanically stable borehole conditions and to optimise stimulation designs of multiple fracs in multilayered rocks. Finally, the results of slip-tendency can be used to control seismicity induced by massive stimulation campaigns at geothermal sites. Our approach can be adopted to any other geothermal site investigation.

Methods for in situ stress field estimation

Empirical by using frictional constraints

Where no information on stress magnitudes is available stress models can be developed assuming that in situ stress magnitudes in the crust will not exceed the condition of frictional sliding on well-oriented faults.

Commonly, geometrical constraints (fault throw and fault intersections) in mapped 3D fault pattern (from seismic surveys) indicate a limited variation of stress regimes, ranging from normal faulting ($S_V>S_{Hmax}>S_{hmin}$) to transtensional ($S_V=S_{Hmax}>S_{hmin}$) to strike slip ($S_{Hmax}>S_V>S_{hmin}$) or reverse faulting ($S_{Hmax}> S_{hmin} > S_V$).

Limiting stress values for any given stress regime can be predicted using eq. (1) and assuming Andersons faulting theory and the Mohr- Coulomb criterion.

Applying the known stresses S_V (vertical stress) and S_{hmin} (minimum horizontal stress) and eq. (1), in the reservoir the value for S_{Hmax} (maximum horizontal stress) is limited.

The frictional equilibrium applicable for a geothermal reservoir is (after Jaeger and Cook, 1979):

$$\sigma_{1eff}/\sigma_{3eff} = (\sigma_1 - Pp)/(\sigma_3 - Pp) = [(\mu^2 + 1)^{1/2} + \mu]^2 \qquad \text{eq. (1)}$$

applying a friction coefficient μ = 0.6-1.0, a pore pressure Pp and a vertical stress S_V, σ_1 and σ_3 are the maximum and the minimum principal stresses, respectively (see also Peška and Zoback, 1995).

In Figure 1 the stress ratios are defined by frictional constraints as described above, assuming a frictional coefficient of m=0.85 and a pore pressure of 43 MPa. The circumference of the polygons indicate certain stress ratios where faulting is possible.

The stress field data combined with analysis of former hydraulic fracture direction allowed the detailed planning and operation of a further geothermal well at the Groß Schönebeck site (Fig. 2, well Gt GrSk 4/05) to increase the permeability of the reservoir and hence the productivity of the well.

Analytical by borehole breakout analysis and fracture mechanical modelling

An alternative approach in analyzing and predicting borehole breakouts and wellbore stability is rock fracture mechanics. Fracture mechanics describes the distinct fracture propagation process and therefore mirrors the physical process. The fracture path is governed by the stress field acting at the fracture tips within the existing stress field.

A case study of a fracture mechanics based borehole stability simulation is presented for a deep geothermal well recently drilled at the Groß Schönebeck field, 30 km north of Berlin/Germany. The results from the analysis yielded optimized mud pressures for drilling. One goal of the drilling operation was to apply a near-balanced mud pressure in the Rotliegend preventing formation damage. Low mud pressures, however, might cause instabilities.

A horizon in Lower Permian silicicalstic rock (Upper Rotliegend, Hannover Formation) is highlighted in which during drilling operation borehole instabilities occurred presumably due to the mud pressures. For the fracture simulation a 2D boundary element code was used based on a fracture mechanical failure criterion. All relevant geomechanical input parameter were determined in laboratory and have a physical meaning. The applied simulator FRACOD2D can handle Mode I (tensile) and Mode II (shear) fracturing. Time-dependent (subcritical) fracture growth can be processed in multiple regions with multiple initial fractures. The variation of the maximum horizontal stress S_{Hmax} at different mud pressures yields a breakout geometry using FRACOD2D.

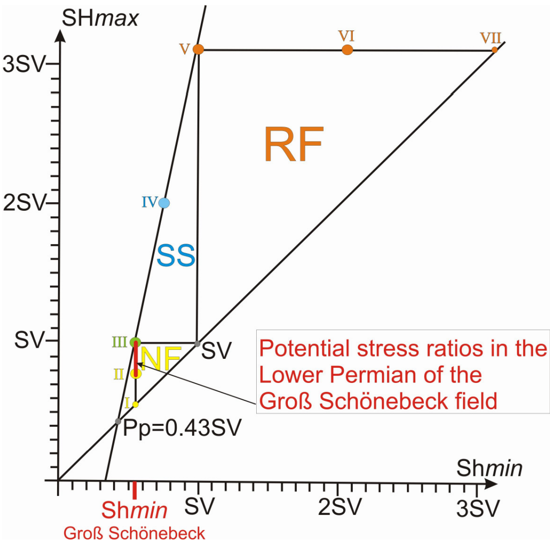

Figure 1 - *Stress polygons that define the possible stress regimes under normal faulting (NF), strike slip faulting (SS) and reverse faulting (RF) conditions, and stress ratios of the maximum horizontal stress SHmax and the minimum horizontal stress Shmin at the certain depth of 4100 m in the Lower Permian of the Northeast German Basin (geothermal field Groß Schönebeck).*

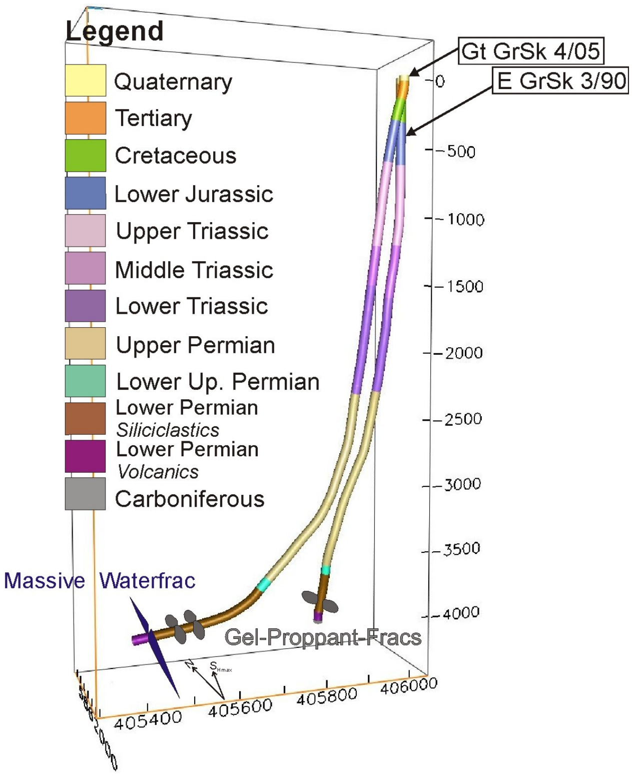

Figure 2 - *Illustration of the hydraulic fractures in the well doublet at the geothermal site Groß Schönebeck in the Northeast German Basin. The well GtGrSk 4/05 completed in 2007 is drilled deviated in the direction of minimum horizontal stress within the Lower Permian reservoir rock allowing the set of hydraulic fracture zones to increase the productivity in terms of enhanced geothermal systems (EGS).*

Estimation of fault behaviour within the in situ stress field: The Slip-tendency method

The slip-tendency methods a technique that permit the rapid assessment of stress states and related potential fault activity of mapped or suspected faults in a known or inferred stress field. The likelihood of slip along a fault plane is a function of the frictional resistance on the sliding surface, which is governed by rock properties and the ratio of shear to normal stress on the surface.The values of slip and dilatation tendency can be compiled together with the maximum slip tendency of each fault and in the three possible stress regimes, which are provided by the stress field calculation above. In the case study of figure 3 the faults with the highest slip and dilatation tendencies in the normal faulting and transitional stress regimes, are the NE-SW striking faults (fault number 2 and 3 in fig. 3).

Faults with a high slip tendency are critically stressed faults with a high amount of shear stress. The have a high reactivation potential. Faults with a high dilatational tendency bear low shear stresses and low normal stresses.

Depending on the rock type, either critically stressed (Barton et al. 1995) or dilatational faults (Gudmundsson et al. 2002) act as hydraulically conductive pathways in fractured reservoirs.

The understanding of the state of stress helps to describe the reservoir condition in terms of fluid flow.

Conclusions

The combination of fault throw analysis from a 3D structural model and the empirical approach based on the frictional equilibrium provides a limitation of the possible in situ stress regime in the Lower Permian of the Groß Schönebeck geothermal aquifer system. Compared with the results from a geomechanical analysis of borehole breakouts the stress regimes and their magnitudes seam reasonable.

A lot of other studies say there is a strong relationship between stress state along faults within the current stress field and their hydraulic conductivity (either as shear or as dilatational fault).

Therefore, the fault orientation related to the current stress field may influence their hydraulic conductivity.

Stress field determination is not only important for considerations of borehole stability and fault reactivation due to reservoir treatments but also for understanding reservoir flow behaviour.

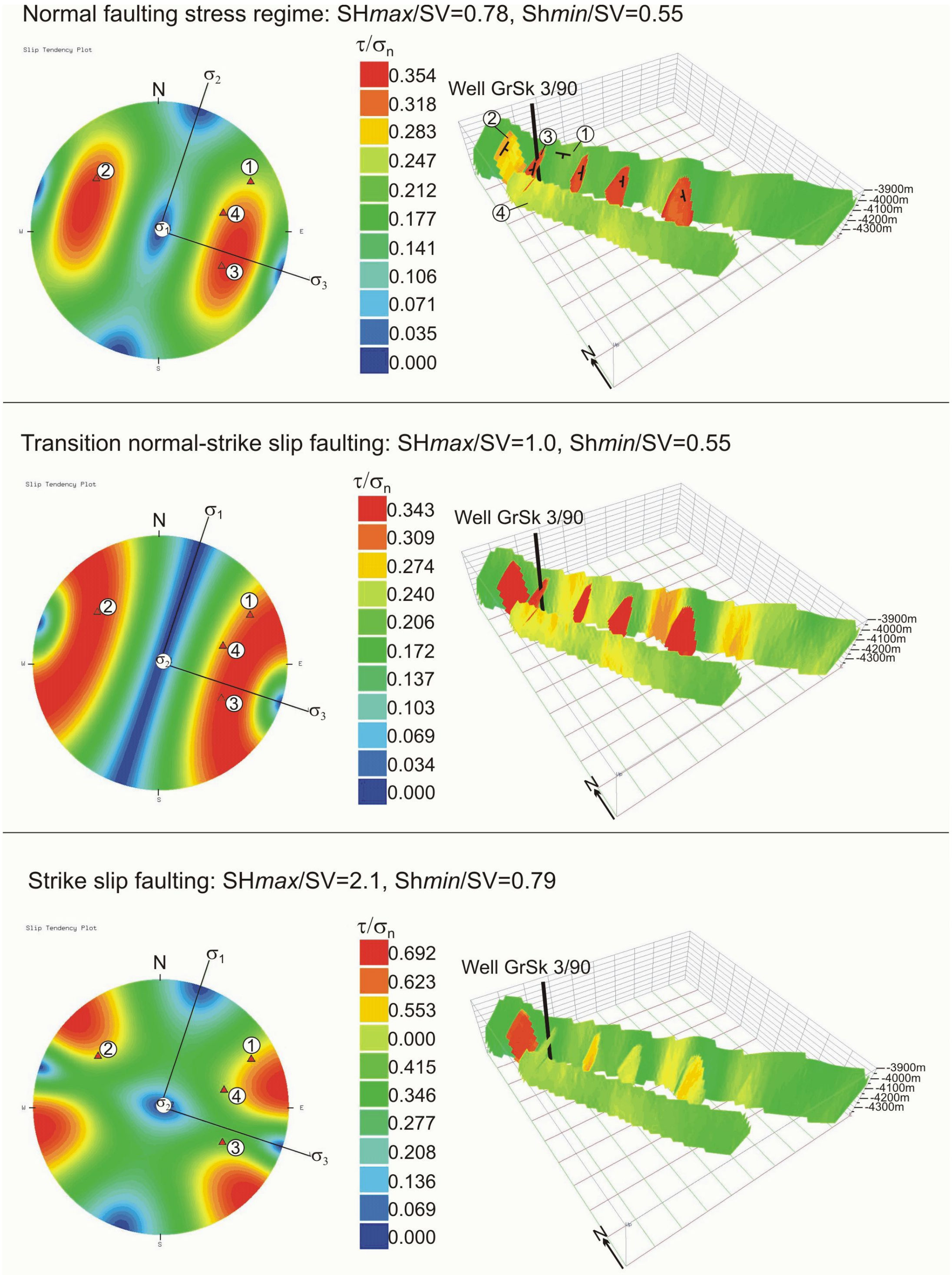

Figure 3 - *Stress state plot for the four fault planes near the geothermal well GrSk 3/90. Faults are displayed as poles in the lower hemisphere projection and visualized in the 3D fault model. The slip tendency for a given fault pole is indicated on the colour scale. Red indicates a high slip tendency, blue indicates a low slip tendency (Moeck et al. submitted).*

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Supercritical fluids and their properties for heat transmission and geochemical reactivity: example of the supercritical CO_2

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The thermodynamic and thermophysical properties of supercritical carbon dioxide (CO_2(sc)) are known and theoretical approaches are introduced in many numerical modeling codes. Various studies have identified the key mechanisms of transport and the physical – chemical behaviour of the field near the CO_2(sc) injection wells in saline aquifers (André et al., 2007, and therein references). The contrast of thermophysical properties between water and carbon dioxide is sufficiently large to envisage the use of CO_2(sc) as a heat transmission fluid in the context of enhanced geothermal systems - EGS (Brown, 2000; Pruess, 2006; Pruess and Azaroual, 2006; Pruess 2008). The carbon dioxide is a poor conductor of heat, low density and low viscosity fluid but it still offers some properties flow quite attractive especially because of its low viscosity and high buoyancy. It is also a bad solvent of solids and water. Analysis of these thermodynamic functions reveals the complexity of the thermal perturbation induced by the injection of CO_2(sc) in the geothermal heat exchangers in which initial conditions of temperature and pressure correspond to the field of supercritical CO_2(sc).

In this study, we analysed these performances, with emphasis on the reactivity of supercritical CO_2 towards minerals, water and the water-rock interaction with carbonate and argillaceous sandstone rocks within the temperature ($35 < T < 120$ ° C) and pressure ($100 < P < 300$ bars) ranges relevant for low enthalpy geothermal exchangers. The numerical analysis of different scenarios of CO_2(sc) injection (coupling thermal, hydraulic and geochemical processes) highlighted important tendencies including i) physical chemical characteristics of the initial porous aqueous solutions has a strong impact on the petrophysical properties of the near field of the CO_2(sc) injection wells. Although the initial aqueous solution is a little salty water (Na-Cl-SO_4 type), precipitation of carbonate, sulphate and halite minerals seem to be an ubiquitous phenomena (André et al., 2007). ii) Because of the contrasted characteristics of prograde (ie, aluminosilicates) or backward (ie, carbonates and sulfates) minerals against the temperature the effect of temperature and heat-transfer processes play a crucial role in the behaviour of the near wells and the development of a permeability and porosity.

The results of various simulations carried out at this stage of the study have made progress in understanding mechanisms of certain physical and physicochemical induced by the injection of supercritical CO_2 in argillaceous sandstone or carbonate aquifers whose salinity varies between 5 and 70 g/l. The impacted near wellbore radius and the spatial extension of these disturbances are defined by the flow rate and time of injection and petrophysical properties of the host geothermal exchanger. The dual process of dissolution / precipitation in the fields near the injection wells seems to be confirmed by some bibliographic data and experimental works (Lombard et al., 2007). The CO_2(sc) injection, at a temperature necessarily lower tan that of the exchanger has an important effect of cooling the area around the injection wells. The extension of this "cold bubble" depends mainly on the injection rate and properties of the transport of mass and heat of the porous/fractured geological structure. The impact of the temperature at which the supercritical CO_2 is injected on the magnitude of the geochemical reaction has shown that precipitated masse of some salts (such as anhydrite) is largest at high temperature. Indeed, the numerical simulation showed that the amounts of precipitated anhydrite are doubled when the temperature injection increases from 50 to 75℃. Of course, this increase in deposits results in a reduction of even greater porosity and there is a more pronounced impact on the hydrodynamic properties and thermal exchange properties.

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Green field evaluation approach for geothermal energy

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"Geothermal resource assessment for green fields" is the evaluation of the expected potential of supplied geothermal electricity that might become available for exploitation of a given reservoir.

The standard technique described ("stored heat method") takes into account only the heat reserves of the inferred geothermal field, without any consideration of the number of wells and economical feasibility: the permeability of the system is simply not used.

This approach could be considered as "step zero", for obtaining a first, rough approximation of what it is possible to install on a given field, when the available information are very poor and speculative. We will discuss the physical and mathematical basis of the method, and we will present some application at two real cases. We are restricting our analysis only for water dominated systems, both high enthalpy (flash plant) and medium enthalpy (binary plant). Some examples have been chosen as a benchmark of the technique.

With the introduction of an high (realistic) value of the abandon temperature, the correction for the cooling effect specific consumption degradation and the effective flash technology a value significantly lower than the standard approach is obtained. We believe this result as a better estimation of the effective industrial capacity that can be supported by a realistic approach in a geothermal project. More detailed benchmarks will be conducted in the future, with a comparison from the effective geothermal field performances and the estimated capacity.

As a operative conclusion, we can draw the following guideline:

- identify at the best the geometrical and physical parameters
- try the first simulation without the cooling correction
- evaluate the degradation with the continuous cooling
- choose a value in between, taking into account also the maximum number of wells that physically can be drilled in the field and their average productivity

evaluate the possibility of an over-exploitation, increasing the production up to its maximum for half of the expected life, and accept a degradation for the second half.

Posters

Advances in magnetotelluric sounding of geothermal zones

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Advanced 3-D interpretation tools based on imaging, Bayesian inversion and artificial neural network (ANN) recognition developed by the author (Spichak et al., 1999; Spichak, 2007) form a basement of a new paradigm in the electromagnetic data interpretation that takes into account the geological information known, noise level in the data, prior estimates of the unknown parameters, hypotheses formulated in probabilistic terms, data available from other methods and formalized expert estimates. Application of these methods to magnetotelluric sounding data enables constructing 3-D electrical resistivity models of the geothermal areas, mapping the geothermal reservoirs and monitoring macro-parameters of the fluid bearing faults.

In particular, Spichak (2002) used Bayesian inversion of MT data in order to construct 3-D resistivity model of the Minamikayabe geothermal area (Hokkaido, Japan). Spichak (2001) has found the most suitable data transforms for adequate interpretation of MT measurements carried out with the purpose of monitoring variations in the geothermal reservoir resistivity with temperature. Finally, using ANN Expert System enabled to estimate the Minou fault (Kyushu, Japan) macro-parameters (Spichak et al., 2002).

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The Green tuff units of Mt. Epomeo, Ischia Island (Italy): evidence of an exhumed fossil geothermal system

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The hydrothermally altered Green Tuff units that outcrop on the Western and North-Western flanks of Mt Epomeo on Ischia island offer the rare opportunity to see a section of a hydrothermal system exposed on the surface. The Ischia island fossil hydrothermal system shows numerous common features with the typical active geothermal systems developed on volcanic islands.

The mineralogy, the chemistry and the space distribution of the hydrothermal assemblages observed in the Green Tuff units and in hydrothermally altered xenoliths agree with most of geothermal environments (Browne, 1978). Based on (1) the occurrence of temperature-sensitive minerals such as mixed layers I/S (<150°C), illite-phengite-chlorite (>220-240°C) and biotite (>320°C), and (2) chlorite and illite geothermometry, the secondary minerals of Ischia island fossil hydrothermal system indicate ambient paleo-temperatures ranging from 120-140°C to about 340°C.

Stable isotope investigation was useful to give constraints on the origin of hydrothermal fluids circulated in the Ischia island fossil hydrothermal system. This revealed two different origins: seawater in the deeper and hotter (reservoir?) zone and meteoric water in the shallower cover zones. All these features lead to propose a conceptual model of Ischia island fossil hydrothermal system that is broadly similar to the model of seawater-entrained geothermal systems (such as the Aegean arc type) associated with emergent volcanoes (Naden et al., 2005). The main features of our model may be summarized as follow: 1) the heat source of the system was represented by the Ischia island magma chamber. Hydrothermal circulation penetrated its most external portions giving rise to high-T alteration hydrothermal paragenesis observed in some xenoliths; 2) we envisage a well developed deep hydrothermal reservoir dominated by seawater recharge, in which fluids maintained quite constant temperature (220-230°C) over some hundreds meters of drop, suggesting a convective heat transfer (geothermal reservoir?); 3) a distinct aquifer(s), characterized by low temperatures (120-140°C) and by meteoric water recharge occurred at shallow levels.

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The Ischia Island hydrothermal system: hydrogeochemical conceptual model

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Ischia island is located in the north-western part of the Gulf of Naples and is part of the Phlegrean Fields Volcanic District. Ischia is marked to be an example of resurgent caldera and is characterized by a high heat flux comprised between 200 and 400 mWm-2. Hydrothermal activity is well know on the island since Roman Age and more than 200 hotels and SPA resources, located all over the island, use thermal waters (T ranges from 30°C to 99°C) for balneo-therapeutic medical cures. The deep wells, drilled by SAFEN in 1950's and subsequent investigations (De Gennaro et al., 1984; Panichi et al., 1992; Inguaggiato et al., 2000), also revealed the occurrence of high temperature fluids (up to ~220°C) in the subsoil of the island, hosted within a possible geothermal reservoir. The aim of this work is to characterize the main geochemical processes that explain the water geochemistry of the thermal fluids of Ischia Island, to classify the water composition data into genetic groups and to delineate a conceptual model to explain the composition of the discharges.

The main features may be summarized as follow: seawater plays a major role as constituent of the thermal water of Ischia island. Shallow recharge is supposed to be effective as seawater intrusion, which becomes strongly modified by water/rock interaction processes that lead to various degree of enrichment or depletion in chemical elements. Solute and thermodynamic geothermometry suggests the existence of two different deep reservoirs in the subsoil of Ischia Island, in which fluids attain equilibrium with host rock at about 160-180°C and 200-220°C. Chemical composition of hydrothermal fluids present in wells near the coast is in agreement with a thermal modification of seawater by water/rock interaction, boiling and admixtures in different proportions with surficial fluids. CO2 – H2S bearing fluids, from the deep reservoir, interact with shallow groundwaters originating a sodium-bicarbonate–sulphate waters, mainly in the northern sector of the island. Along the coast a major zone exists where mixing between the components described above takes places, thus leading to the formation of mixed waters with various chemical characteristic, depending on the prevailing component. As suggested by SAFEN I3 deep well, located in the Western sector of the island close to Mt. Epomeo resurgent area, deep recharge of geothermal fluid seems to be related with meteoric waters, although seawater influence cannot be ruled out at depth more than 1051m. Cooling of the deep fluid is mainly due to mixing and conductive temperature loss in the shallow aquifers. We infer that the geological structures strongly condition the circulation of hydrothermal fluids in the subsoil of the island determining the complex hydrogeochemical features in a multilayer fractured hydrothermal system. Main direct master faults, bordering Mt. Epomeo horst, drive the location of thermal springs and the upflow of geothermal fluids in the shallow hyper-thermal aquifers.

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Migration of fluids in the Boccheggiano-Montieri (southern Tuscany, Italy) fossil geothermal system: insights for the Larderello high-enthalpy active geothermal field

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Understanding the migration of hydrothermal fluids represents a continuous task for successful exploration of geothermal resources. Contributions to better constrain the hydrogeological models in geothermal areas can derive from field and laboratory studies on fossil geothermal systems, evidenced by the concentration of ore deposits in wide areas. This work presents an integrated study based on fluid inclusion and structural analyses on a Pliocene-Pleistocene fossil hydrothermal system, located to the south of the present active Larderello geothermal field. Mineralization, mainly made up of quartz and pyrite, is widespread distributed in the damage zone of the Pliocene Boccheggiano normal fault and, far from it, in the older cataclastic levels, deriving from previous deformational events.

Fluid inclusion investigation indicates that fluid salinity and temperatures decrease moving from the Boccheggiano fault toward the farer and older cataclastic levels. The fieldwork and the structural study carried out in the study area highlights that: a) the Boccheggiano normal fault intersected at depth a ~3 Ma old granodiorite, where already existing data indicate the highest temperatures of homogenization and salinity values; b) the older cataclastic levels are hydraulically connected through the dissecting Pliocene Boccheggiano fault; c) the permeability of the damage zone of the Boccheggiano fault is high and fluid flow initially through diffusion, mainly, and then through advection via fractures.

The proposed model indicates that a single fluid flow path occurred through the damage zones of the Pliocene normal faults and within the older cataclasites. The damage zones of the Pliocene-Present normal faults acted either as an infiltration path-way of the meteoric fluids down to the granite, and as the up-flow conduit for the fluid heated by the intrusion.

In the Larderello geothermal field extensional north-east–dipping crustal shear zones have been recognised as possible conduits controlling the present hydrothermal circulation. If it is the case, the Boccheggiano-Montieri geothermal system would represent a similar but fossil geothermal system.

Shallow versus deep thermal circulations at Bagni di S. Filippo (M.te Amiata, Tuscany, Italy)

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The M.te Amiata sector constitutes a volcano-geothermal area of the southern Tuscany,. This area has been affected by extensional tectonics from the Early-Middle Miocene onwards (Carmignani et al., 1994), that led, in Pliocene, to the emplacement of a deep seated intrusive body and to the eruption of dacitic-rhyodacitic lavas through a NW-SE-trending fissure (Ferrari et al., 1996). Currently, this area is characterized by a high heat flow (up to 600 mW/m^2; Baldi et al., 1995) that feeds important geothermal fields. Main geothermal reservoirs are located at depths of several hundreds of meters within Triassic evaporitic horizons, constituting the base of the Tuscan Unit.

Besides, hydrothermal activity occurs also at shallow levels, as testified by the occurrence of thermal springs and gas discharge at Bagni di S. Filippo, on the NW flank of the M.te Amiata volcano. Thermal waters discharge at temperatures up to 50 °C and rates of 40 kg/s, delivering a thermal power of about 6 MW. The upflow of the of thermal waters is associated with the widespread deposition of travertines and occurs through Triassic evaporites, cropping out in this sector together with the sedimentary sequences composing the Tuscan Unit. Owing to these conditions, a question arise as whether a hydraulic connection exists between the shallow and the deep thermal fluids circulating within the evaporites. Possible linking between deep and shallow hydrothermal circulations has been suggested for this area (Donnini et al., 2007), but the mechanisms accounting for this mixing are yet to be clarified.

This study aims at proposing a model of hydrothermal circulation by coupling the results of structural field surveys, hydrochemical and isotopic analyses and numerical thermo-hydraulic simulations. As an example, structural field works revealed that topographically-driven shallow circulations are likely to migrate along systems of N- and NW- and NE-trending high-angle faults, providing the conditions for long-distance connections between permeable reservoirs.

Chemical composition of thermal waters coming from Bagni di San Filippo springs reflects circulation in a carbonatic-evaporitic reservoir (i.e. Tuscan carbonatic succession), as depicted by correlation diagram between HCO_3, SO_4, Ca and Mg. Mixing between cold freshwater and deep thermal water is also evidenced. Highest equilibrium temperature obtained with silica geothermometer is about 95°C, while maximum temperature measured on the field was 50°C at Bollore spring location. TDS is around 4000 mg/l and is mainly due to HCO_3, SO_4, Ca and Mg; Sr concentration is relatively high (13 to 16 mg/l), and Ca and F show a positive correlation, linked with the presence of fluorite.

The combination of on field geological studies, water geochemistry and numerical simulation provides a useful approach to investigate the possible connections between shallow and deep hydrothermal circulation systems and, in perspective, for planning geothermal exploration programs.

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Resistivity reduction in the vapour-dominated field of Travale (Italy)

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The aim of this multidisciplinary work is to find out what can account the significant reduction in resistivity (from 10^3 to 10^0 Ωm) observed at the depth of the geothermal reservoirs in the Travale area (SE of Larderello, Italy). Since the exploited fluid is supersaturated steam and thus resistive, its presence and localisation can not explain the observed resistivity reductions. The observed reduction in resistivity could be related: 1) to the lithology and heterogeneities of reservoir rocks and the alteration affecting them (i.e. presence-abundance of conductive minerals), and/or 2) to the presence of brines within a fracture net sufficiently interconnected to produce electrolytic conduction.

For this purpose two different studies have been carried out: 1) a study on cores and cuttings in order to identify the types and abundance of primary and alteration minerals and to compare these data with resistivity values measured in the wells by Enel and in MT campaigns, and 2) the analyses of fluid inclusions and of exploited fluids from deep geothermal wells which permitted to reconstruct the physico-chemical nature of fluids that have interacted and still interact with the reservoir rocks.

Heterogeneities of the reservoir rocks, alteration and different amounts of conductive minerals (phyllosilicates) have been pointed out with the study of well-core samples and XRD and XRF analyses performed on cuttings. An inverse correlation between resistivity of the encountered formation and phyllosilicates amounts has been observed.

In vapour-dominated system both interstitial and adsorbed water can be contained in geothermal reservoirs, where local conditions in microfractures and small pores might be very different from the average conditions observed at large scale. These geothermal waters can be characterised even by high concentration of dissolved salts (electrolytes) enhancing current passage in the reservoir rocks. Therefore, the increasing in salinity and temperature of these geothermal fluid cause a sharp decrease in resistivity (Ussher et al., 2000). Experimental data on Monteverdi samples evidence that the presence of 2 mg/g of adsorbed liquid water inside the pore network of the rocks is possible (Bertani et al., 1999). The study of fluid inclusions have also shown that high-salinity fluids (up to 50 wt. % eq. NaCl) circulated in the reservoir. The occurrence of brines was also suggested by Truesdell et alii (1989) taking into account the chemical characteristics and temperature of the exploited fluid.

Thus, our studies evidenced that both heterogeneities/alteration of reservoir rocks and the presence of a liquid saline phase are possible causes of resistivity reduction in the Travale geothermal area.

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