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Workshop 2

Exploring high temperature reservoirs: new challenges for geothermal energy

1-4 April 2007

SIAF - VOLTERRA - ITALY

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EDITED BY: ADELE MANZELLA & CATALINA MAYORGA (CNR-IGG)

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Thumbnail upper top: Volterra historical centre, Tuscany, Italy, by courtesy of SIAF (International High Formation School)
Thumbnail lower top: SIAF (International High Formation School), Volterra, Tuscany, Italy.
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Session 1

Signatures of high temperature condition

Deep-Seated unconventional geothermal resources in Tuscany

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The Larderello and Mt Amiata geothermal fields in Tuscany are large active geothermal systems which overlie young plutonic rocks. The features of the two geothermal systems are similar. The geothermal fields of Larderello and Mt. Amiata are located in the inner part of the Northern Apennines, characterized asthenosphere uplift and delamination of the crustal lithosphere or underplating. The heat source both at Larderello and Mt. Amiata can be ascribed to the presence of shallow igneous intrusions, and there is evidence of an early contact metamorphism related with the intrusion of the granites. The heat flow data for the area surrounding both the Larderello and Mt. Amiata geothermal fields show a comparable areal extension and similar values (up to 200-300 mW/m^2). Cap rocks and reservoirs are also similar: both fields have shallow vapor-dominated sedimentary, and deep metamorphic reservoirs. At Larderello super-heated steam is present in both reservoirs, to depth of more than 3.5 km, whereas the deep reservoir of the Mt. Amiata geothermal fields is likely water-dominated. In both fields the upper reservoir is present below the flysch units forming the cap rocks. Permeability is due to rock fracturing, even at depths of about 4 km and temperatures as high as 350 °C. Pressure greater than hydrostatic and a supercritical fluid can occur in the deepest part of the geothermal fields. The water stable isotope values of the steam discharged by the geothermal wells at Larderello indicate a meteoric origin of the recharge. A geochemical regional study on the thermal waters and gases of the Mt. Amiata area indicates that the geothermal reservoirs originated from a meteoric fluid, mainly stored in a regional Mesozoic dolomite-anhydrite unit, and evolved in a Na-Cl, CO_2 gas-reach reservoir by interaction with calcite-bearing metamorphic rocks. The high temperatures existing in correspondence of a deep seismic reflector suggest the occurrence of a deep-seated unconventional geothermal resource (UGR), which can be possibly exploited. The heat could be mined from silica-rich rocks close to a plastic state, but where fracturing can be induced by fluid overpressure and abrupt high strain rates. This geothermal resource is very important, requires a re-assessment of the geothermal resources in Italy, considering the possibility of the exploitation of the new reservoirs.

Thermal and rheologic signatures of high-enthalpy resources

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Surface heat flow measurements over high-enthalpy systems indicate strongly positive thermal anomalies. Whereas in "normal" geothermal settings the surface heat flow is usually below 100-120 mW m^{-2}, in active geothermal areas heat flow values as high as several W m^{-2} can be found. Systematic interpretation of heat flow patterns sheds light on heat transfer mechanisms at depth on different lateral, depth and time scales. Borehole temperature profiles in active geothermal areas show various signs of subsurface fluid movement, depending on position in the active system. The heat transfer regime is dominated by heat advection (mainly free convection). The onset of free convection depends on various factors, such as permeability, temperature gradient, and fluid properties. The features of heat transfer are different for single or two phase flow.

Two main factors affect the rheology of the lithosphere in active geothermal areas: steep temperature gradients and high pore fluid pressures. Combined with lithology and structure, these factors result in a rheological zonation with important consequences both for geodynamic processes and for harnessing geothermal energy. As a consequence of high temperature, the mechanical lithosphere is thin and its total strength can be reduced by almost one order of magnitude with respect to the average strength of continental lithosphere of comparable age and thickness. The brittle/ductile transition is located within the upper crust at depths less than 5-10 km, acts as the root zone of listric normal faults in extensional environments, and at least in some cases is visible on seismic reflection lines.

Characteristic heat flow and heat transfer signatures as well as structural and rheological features in high-enthalpy systems will be demonstrated by examples from Iceland, Italy, New Zealand and the USA.

More in:
Ranalli, G., Rybach, L.: Heat flow, heat transfer and lithospheric rheology in geothermal areas: Features and examples. J. Volc. Geotherm. Res. 148 (2005), 3-19

Present-day and paleo-geothermal fields related to granites: origin and composition of related fluids

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Paleo-hydrothermal systems related to granite intrusions and deep migmatisation which characterize the late stage of collision belt, the exhumation and the evolution of metamorphic core complex involve a series of fluid types including in particular pseudo-metamorphic fluids deeply equilibrated with metamorphic rocks, and meteoric waters, sometimes having preserved pristine isotopic features, indicating short time penetration and insignificant interaction with rocks. The latter experienced quick heating and convection in the shallow crust, and are responsible subsequently for the enhanced cooling of the crust especially along discontinuities. These features display striking similarities with active geothermal systems such as the Larderello system where most fluid types, already identified in paleo-hydrothermal systems and their surroundings, are found and considered to have been migrated and partially mix within a short period of time and a few kilometres of the shallow crust.

The initiation of the active metamorphism around the inferred deep seated intrusion (Larderello): lessons from paleofluids

Several zones can be distinguished in the Larderello geothermal field (southern Tuscany, Italy) based on the nature of the fluid, mineralogical assemblages and the fluid flow as a function of depth. The deepest levels of field are characterized by mineralogical assemblages produced by currently active thermal metamorphism that is thought to have started a few million years ago, e.g. during or later than the main intrusions that are dated from 1.6 to 3.8 Ma. At depths between 2 and 4 km below ground level (b.g.l.), the rocks are characterized by the assemblage quartz-biotite-tourmaline.
A detailed study of fluid inclusions has been carried out in order to investigate the P-T conditions and the nature of the fluids circulating in this deep zone. A series of representative deep samples from 8 wells (Bruciano, Lumiera, Badia, Canneto, Sperimentale, Padule 2, Monteverdi 3 and 5) that contain the quartz-biotite assemblage have been selected from the available cores, and compared with the results from previous studies (Monteverdi 7, San Pompeo 2, Sasso 22, Serrazzano VC 11). The fluid inclusions were studied to enable a reconstruction of the fluid composition, determination of the $CO_2/CH_4/H_2O$ ratios and fO_2 (Boiron et al. 2007).
The dominant fluids belong to the C-H-O-N system and occur as CO_2-CH_4-N_2-H_2O vapors with CO_2 as the dominant gas. The CO_2/CH_4 ratio and the water content, which are not affected by immiscibility or mixing processes, are compatible with values expected from calculations of water-graphite equilibrium. A thermal metamorphic origin is suggested for the genesis of the aqueous-carbonic fluid, especially the volatiles (CO_2-CH_4). Such fluids may be considered as the dominant type, compared to other fluid types in the deeper levels, especially within the K-horizon. The water component of the aqueous-carbonic vapours has a rather low salinity (< 5 wt.% eq. NaCl) and may correspond either to water produced by dehydration reactions or to waters that have extensively equilibrated with the metamorphic host-rocks. Two other fluid sources may also contribute to the variety of fluids found in the biotite zone: i) the deep Li-rich brines considered as having a magmatic origin (Cathelineau

et al., 1994), ii) the brines resulting from water-halite interactions within the evaporites, which penetrated downwards.
The carbonic vapours were generated and trapped under lithostatic conditions of 100 to 120 MPa and high temperatures between 600 and 420°C, depending on the depth and the distance to the granitic intrusives. These fluids may be considered as representative of the dominant fluid at depth within the pressurised zones that have been inferred by geophysical investigations. After cooling, and in many cases decompression, aqueous fluid inclusions were trapped at pressures fluctuating between lithostatic and hydrostatic. The estimated pressure corresponds to depths between 2 and 4 km, which is in agreement with the transition from lithostatic to hydrostatic conditions. The end of the proposed fluid path corresponds to an evolution towards the present-day temperature and hydrostatic pressure conditions (Valori et al., 1992, Ruggieri et al.,1999).

Metamorphic core complex and exhumation of collision belts: initiation of convection cells, granite intrusions, and hydrothermal systems at the end of the Hercynian orogeny
In the Limousin area of the French Massif central (FMC), several hydrothermal systems were active during the late Carboniferous and were responsible for rare metal (Sn, W, Ta) and precious metal (Au) deposition in various settings. The space and time relationships between granitic magmatism, thermal and tectonic events and fluid circulation at the crustal scale have been studied in detail, and show many similarities with present day active systems such as that of the Larderello area. A detailed geochemical study of fluids from representative quartz-sealed faults, especially hosting late Hercynian gold concentrations, shows that fluids percolating the mineralised faults had two main distinct reservoirs: one was a quite shallow and the other rather deep-seated. Both fluids have lost a great part of their original geochemical signature through interactions with host metamorphic formations. Early fluids, present during the primary sealing of the faults by quartz, are considered to have effectively equilibrated with the metamorphic pile and then predominantly flowed upwards along the faults. They are characterised by $CH_4/CO_2/H_2O$ ratios rather typical of fluids equilibrated with graphite, and moderate to medium chlorinities with a high Br/Cl ratio (Boiron et al., 2003). The quartz-wolframite or quartz-cassiterite mineralized systems display similar metamorphic fluids. Gold appears however late (later micro-fractures and associated with Pb-Bi-Sb sulfosalts and sulphides) and related to fluids experiencing mixing (salinities decreasing to very low values indicating their progressive dilution by waters of more surficial origin in the fault system). Low salinity fluids are then extensively found in the granites, as shown by the systematic study of fluid inclusion planes in several zones of the St Sylvestre granite (El Jarray et al., 1993, Andre et al., 2000). Circulating at lower pressures, but still rather high temperatures, the episyenite fluids (responsible for the total dissolution of the granite quartz grains), and the Sn-W depositing fluids at Vaulry in the Li-rich Blond leucogranite (Vallance et al. 2001) are considered as linked to the last generation of granite intrusions (305-310 Ma) or to concealed intrusions. Renewal of hydrothermal activity resulted in the percolation of heated meteoric water (very low salinity fluids), at a depth of 3.5 km, the waters having the features of high relief (more than 6000 m altitude) fluids, on the basis of isotopic studies. This late evolution depicts the deep penetration of meteoric waters in the shallow crust and their convection around hot spots linked probably to concealed deep-seated intrusions (still not necessarily identified or dated at that period), a striking similarity with the Larderello geothermal system.

Acknowledgements: This synthetic overview was possible thanks to long lived collaboration with CNR-Pisa (G. Ruggieri, G. Gianelli) for the Tuscan geothermal area, and collaborators

from G2R (A-S Andre, O. Vanderhaeghe, J. Vallance), CRPG (C. Marignac) in Nancy, Geosciences Rennes (S. Fourcade) and University of Leeds (D. A. Banks).

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Corrosion study in HDR geothermal wells. Experience from Soultz

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A scope of this study is to evaluate corrosion aspects of the casings and equipment that handles the production and injection fluids in hot dry rock geothermal wells. In this presentation we report preliminary findings from the Soultz project.

Towards the evaluation of the geothermal potential of Italy

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The methods proposed in the past to evaluate the geothermal potential of a given area can be grouped in the following four classes: (a) the heat-flow method; (b) the volume method; (c) the planar-fracture method and (d) the magmatic-heat-balance method (Muffler, 1973; Bodvarsson, 1974; Nathenson and Muffler, 1975; Renner et al., 1975; Smith and Shaw, 1975; Muffler and Cataldi, 1978; Cataldi et al., 1978; Cataldi and Squarci, 1978; Cataldi and Celati, 1983; Wohletz and Heiken, 1992).

They were critically re-examined by Marini et al. (1993) who: (1) modified the volume method by taking into account the geochemical data available for shallow groudwaters and gas emissions from soils; (2) calibrated this method based on the production data available for the geothermal fields either under exploitation or explored through deep drilling (Larderello, Travale, Bagnore, Piancastagnaio, Torre Alfina, Latera, Cesano and Mofete); (3) applied the modified volume method to several areas of Italy for which geochemical data are available.

In the original volume method, the heat stored underneath the considered area, until a given depth (which depends on economical and technological parameters), is computed for each of the recognisable geological-hydrogeological units, by means of simple heat balances (e.g., Cataldi et al., 1978). This exercise requires knowledge of the following parameters: volume, porosity and temperature of each unit, density and heat capacity of the rocks, density and heat capacity of the fluids and reference temperature (usually 25 °C). A recovery factor is then used to compute the extractable geothermal energy.

In the modified volume method, the areas of high CO_2 flux (recognisable at the surface based on the presence of high-PCO_2 waters and/or CO_2-rich gas emissions from soils) are used to bound the extension of geothermal reservoirs. This approach is based on the fact that a continuous flux of deep CO_2 occurs through all known geothermal systems of medium-high enthalpy in the same manner as the heat flux (e.g., Mahon et al., 1980; Marini and Chiodini, 1994; Gambardella et al., 2004).

Here we present an example of application of the modified volume method in Central Italy, through the superposition of the maps depicting the geographical distribution of the following parameters:

(a) depth of the potential geothermal reservoir (from Buonasorte et al., 1995);
(b) temperature at the top of the potential geothermal reservoir (from Buonasorte et al., 1995);
(c) PCO_2 in shallow groundwaters (from Gambardella et al., 2004).

Suitable assumptions (Marini et al., 1993) are adopted to quantify the total volume of the geothermal reservoir and its productivity. This exercise leads to the identification of:

(1) a total extractable thermal power of 440-550 MW from conventional geothermal reservoirs with temperature higher than 200 °C;
(2) a total extractable thermal power of 1070-1540 MW from conventional geothermal reservoirs with temperatures of 45-90 °C.

In order to apply this approach to areas where low-enthalpy geothermal resources are present (e.g., the sedimentary basin of the Po Valley in Northern Italy), research must be focussed towards the identification and use of permeability-indicator(s) other than carbon dioxide.

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High-temperature geothermal deposits of Daghestan and prospects of their development

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When exploring and developing the oil and gas deposits on the territory of the Republic of Daghestan, a number of high-temperature geothermal fields are found: Tarumovskoye, Ozjornoye, Kumukhskoye, Jubileinoye, Talowskoye, Dimitrovskoye and Tarkinskoye ones. They are coincided with sedimentations of the Upper Cretaceous, the Middle Jurassic and the Lower Triassic periods and deposited at depth 3400-5500 m. The reservoirs of the Upper Cretaceous and the Lower Triassic are represented with fractured and cavernous limestone and dolomites, and the Middle Jurassic – with sandstones. The temperatures of the beds vary from 156 °C (Tarkinskoye and Dimitrovskoye) to 190 °C (Tarumovskoye). Reservoir drive it is sedimentogeneous active water drive. The stratal pressures 20-50 % exceed the hydrostatic pressure. Salinity of the stratal waters of chlorine and calcium type ranges from 30 to 220 g/l. They content such rare-earth components as lithium, strontium, cesium, and so iodine, bromine, boron in industrial quantities. The barriers for development of above deposits they are: tendency of waters to salt sedimentation and corrosiveness and insufficient previous study of ecological consequences. The combination of high temperatures with availability of valuable chemical components is promising for profitable geothermal power production together with extraction of rare deficit components.

The terrestrial heat-flow density database in the framework of geothermal potential studies

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The terrestrial heat-flow density is not only an important constraint for geophysical studies, but it is also a fundamental parameter for the assessment of geothermal resources. In principle, the determination of heat-flow density is straightforward, but possible perturbations to the subsurface thermal field, arising from geological evolution, thermal conductivity structure, climatic history, and groundwater movement, need to be carefully evaluated, if possible, for each heat-flow density site. The form of the so far used databases generally mixes text and tabular data in irregular fields and requires users to write specific computer programs to extract information in a useful format. This reduces the flexibility of the databases and impedes accessing to most of the scientific community. An appropriate data model has to be established in order to store all the information contained in the terrestrial heat-flow density determination and to simplify the access to databases. The data format should satisfy the analysis problems that might arise. An applicative example is presented for the Tyrrhenian-Northern Apennines region (Italy). Heat-flow density data have been divided into subsets, based on the measurement techniques: determinations in boreholes, mine shafts and tunnels, in petroleum exploration wells, in sea sediments. The main corrections for drilling disturbance, topographic relief, sedimentation and erosion, climate and nearby bodies of water were included. Based on the main geological features, the dataset was sorted into various groups, each belonging to a different tectonic province. We compiled the current data into a relational database and developed subsets of retrievable data and derivative maps. The data subsets are accessible in a variety of forms, e.g., tables, colour contour maps, location maps, borehole sections, etc., and include text descriptions that enable non-specialists to understand the strengths and limitations of the resource.

Application of oil exploration 3D seismic data for imaging HDR systems in west Lithuania

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The crystalline basement of Lithuania is composed of the high-grade metamorphic and igneous rocks of the Early Proterozoic age in some places intruded by Middle Proterosoic cratonic granitoids and associating mafic rocks. Two major lithotectonic domains are identified in Lithuania, i.e. the East Lithuanian Domain and West Lithuanian Granulite Domain. The latter is characterized by increased heat flow, in some places attaining 80-90 mW/m^2. The concept of HDR can be a prospective alternative (to geothermal aquifers) option for exploitation of the geothermal energy in west Lithuania. The exploration of the HDR systems is rather difficult, as the basement is overlain by about 2 km thick sediments of the Baltic sedimentary basin. The base of the basin is composed of the Cambrian petroleum play, represented by the Lower Cambrian shaly source rocks and Middle Cambrian siliciclastic reservoir. It directly overlies the crystalline basement. A few hundred exploration wells were drilled in west Lithuania, most of them penetrating the basement rocks. Still, the drill cores are not sufficient to image the structural grain of the basement. A number of 3D oil exploration seismic experiments were performed in west Lithuania seeking to better understand the architecture of the oil fields hosted by the Middle Cambrian reservoir. The 3D seismic data of the Girkaliai oil field were provided by AB “Geonafta” for investigation of the possibility of application of seismic data for imaging the basement structures. These data are supplemented by drill cores from the four oil exploitation wells drilled into the basement for 10-350 m deep. Furthermore, the 3D seismic area also covers the Vydmantai geothermal area, where two deep wells were drilled to the basement more than dozen years ago for utilization of the Cambrian and basement geothermal resources. Due to economic perturbations the wells were conserved. One of them was drilled to the depth of 2560 m (450 m into the basement). Two large-scale shear zones were identified in the basement by drilling and seismics. Also, a number of the smaller scale tectonic features were recognized in the basement that well correlate with the borehole data. The quality of the seismic data enables consistent identification of the structural features down to the depths of 6-7 km where the temperatures reach 200-250 °C. The experiment shows that this complex can be applicable in the other areas of west Lithuania, where 3D seismic data are available.

CO_2 budget of the Reykjanes and the Krafla geothermal systems in Iceland

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Recent work on the CO_2 budget of geothermal systems in Iceland offer new insights into the relative importance of different geochemical sinks for CO_2 in geothermal systems. Diffuse CO_2 soil emissions have been determined by soil gas flux surveys at the Reykjanes geothermal system, SW Iceland, and at the Krafla geothermal systems, NE Iceland. The amount of CO_2 fixed in the bedrock in these systems has also been determined by analyses of drill cuttings from several geothermal production wells in these systems. The observed natural atmospheric CO_2 emissions of geothermal origin from Reykjanes (2 km^2) amount to about 5,000 t/yr and the corresponding value for the eastern part of the Krafla caldera (20 km^2) is 84,000 t/yr. The amount of CO_2 fixed in the bedrock in these two systems is 56 Mt and 1400 Mt for Reykjanes and Krafla, respectively. The best available estimates of the age of the geothermal activity in these systems are 10 to 100 kyr for Reykjanes and 110 to 290 kyr for Krafla. Assuming that both the atmospheric emission rate and the CO_2 fixation rate in bedrock have remained constant throughout the history of geothermal activity of these systems we find that the ratio of atmospheric emissions to bedrock fixation is between 10:1 and 1:1 in Reykjanes and 17:1 and 6.5:1 in Krafla.

High-temperature tracer testing: a necessary tool for significantly enhancing reservoir useful life

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Experience gathered worldwide during the last two decades demonstrated the tremendous economic importance of artificially recharging high-temperature geothermal reservoirs. The importance of recharging stems from the fact that it can significantly extend the useful life of the reservoir. However, artificial recharge may also result in unwanted thermal interference with producing wells. Due to the unavoidable uncertainties in the distributions of reservoir pressure and permeability, even in so-called “homogeneous” reservoirs, the only sure way to prevent thermal interference is to actually probe where, how fast and in what amount the injected fluids flow. This is achieved by adding appropriate tracers to the injectate and monitoring their concentrations in the production wells. These tracer tests reveal: (i) which production wells, if any, are hydraulically connected with the injection well(s); (ii) the fraction of injected fluid arriving in each production well under injection conditions; and (iii) the velocity distribution of the tracer in the reservoir. With this information it is possible to estimate the thermal effects of the artificial recharge on the production wells.

In this work we first discuss the special challenges presented by high temperature geothermal reservoirs for tracer testing, and current solutions to them. The first challenge is the thermal stability of the tracers: at 250 °C and above, most traditional tracers have inadequately short thermal half-lives.
Another important challenge is that often the injected fluid undergoes boiling in the reservoir, frequently causing the resulting vapor- and liquid-phase to flow by different “channels” to the producing wells.

Then we illustrate solutions to these challenges by means of results recently obtained in two tracer tests run at the Los Azufres, Mexico, geothermal field, where we injected a liquid-phase and a gas-phase tracer. We present several detailed field examples illustrating the power and resolution of high temperature tracer testing concerning points (i) – (iii) above. These results also reveal the complex behavior of injected fluids in this high-temperature, fractured reservoir. In particular we found that the maximum speed of the gas-phase tracer in the reservoir is significantly higher than the maximum speed of the liquid-phase tracer, except when the gas-phase tracer travels in solution. We also found that, in general, liquid recharge was orders of magnitude more efficient than vapor recharge in the monitored producing wells. However, in one case where the injector-producer distance is short (195 m), we found that 42.8% of the gas tracer injected was recovered in only ten days, raising the possibility of serious thermal interference in this well.

This work illustrates the power and resolution of modern tracer testing and highlights its extraordinary value for enhancing the useful life of high temperature geothermal reservoirs.

Continuous Measurement of Gases for Effective Geothermal Reservoir Management

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Efficient and sustainable production of geothermal energy requires constant monitoring of changes occurring in the reservoir. These changes, which may result from mass extraction for production, waste fluid injection for disposal and pressure support, and from natural geologic processes, are usually manifested in the chemistry and physical characteristics of the wells. Experience has also shown that these changes are related to the structure of the reservoir—the faults that transect the field as well as smaller fractures contained in the reservoir rocks. Identification and evaluation of chemical changes, and their correlation with the structural features, require among others the constant analysis of hot brine and gases discharged by the wells.

Changes in water and gas chemistry, for example, can indicate: 1) lowering in the water level of the reservoir, 2) invasion of cold and degassed re-injection fluids, 3) entry of shallow acidic steam condensates and deep corrosive volcanic related fluids, 4) precursor of an earthquake, etc. Any of these changes can significantly alter the short- and long-term viability of the geothermal operation. Hence, it is critical that up-to-date collection and analysis of water and gases be undertaken. However, since almost all of the production wells are connected to the power plant, it is rarely possible to disconnect the wells in order to collect samples for analysis because such disconnection will result to shortfall in power generation. In addition, the process is time-consuming and significant lapse is achieved from sample collection to the availability of the information. There is therefore a pressing need for a continuous and on-line system of measuring chemical parameters in the field.

A progress in this field is presented in this paper with the development of a new versatile measuring system called MEDAS (MEDAS – Modular Environmental Data Acquisition System) based on experiences and recent results from different research groups. MEDAS is an innovative multi-parameter station, which can continuously record as a function of time up to more than 100 geochemical and physical parameters suitable to earthquake research and other applications. A microcomputer system inside the MEDAS handles data exchange, data management and control and it is connected to a modular sensor system. The number of sensors and modules can be selected according to the needs at the measuring sites.

A MEDAS has been installed in four production wells in the Mahanagdong production sector of the Leyte Geothermal Production Field located in the island of Leyte, central Philippines. This field is chosen because: 1) it is the largest geothermal field in the Philippines with five separate power plants with total installed capacity of about 700 MW, and 2) the area is bisected by the Philippine Fault, a major left-lateral transcurrent fault similar to the San Andreas fault.

The preliminary results of the three years measurement on radon and CO_2 concentrations; gas flow, temperature and humidity; water temperature and pH; Cl-concentration the Redox potential and conductivity will be presented. These parameters will be correlated with the historical and current data from the PNOC EDC established monitoring set-up for seismicity, micro-gravity and precise levelling surveys, wellhead pressure trends and wellbore chemistry changes from monthly production sampling.

Petrophysical Signatures of the Liquid-Steam Phase Transition in Geothermal Resevoir Rocks

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The petrophysical properties of geothermal reservoir rocks have been investigated at in-situ conditions in the laboratory. For this purpose, cylindrical samples from a reservoir in volcanic rocks (Iceland) and samples of Fontainebleau sandstone, a typical porous reservoir rock, were subjected to elevated temperatures, pressures, and pore-pressures, using a pore-fluid with well-defined salinity. Electrical resistivity and seismic velocities were measured, with increasing temperature (Tmax: 250 °C) at constant pressure and pore-pressure, similar to reservoir conditions.
After several temperature cycles, pore-pressure was slowly reduced at a constant temperature of 150 °C by pumping pore-fluid out of the sample, until the liquid–steam phase transition was reached.

When the phase transition was reached, no further change in pore-pressure was observable, despite the continuous release of pore-fluid from the sample. The loss in fluid volume was compensated by steam, until the phase transition was completed for the entire porespace. Only when pore-fluid was pumped out beyond this point the pore-pressure continued to drop.

During this process, electrical resistivity showed a gradual increase with increasing steam content in the pore-fluid, while the seismic signals (p-waves only) showed a slight decrease in velocity. Increasing pore-pressure again and that way approaching the phase transition from the steam field did not result in the initial resistivities of the fully-saturated rock.

These preliminary results suggest that the liquid-steam transition in geothermal reservoirs should be detectable by geophysical methods.

Lithium isotopic signature of high temperature geothermal fluids in volcanic arc islands (Guadeloupe and Martinique, French West Indies): an efficient tool to determine the rock nature of the reservoirs and their location

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Numerous geochemical tools, which are based upon the acquisition of chemical and isotopic data obtained from thermal waters, fumaroles or escapes of gases collected in surface conditions, or in fluids sampled from deep wells, are commonly used to study and better understand the high temperature geothermal reservoirs. If it is possible to characterize the fluids of the geothermal reservoirs and their deep circulation, estimate their residence time and the reservoir temperature (using chemical, isotopic or gas geothermometers, for example), no present geochemical tool is available to determine the rock nature of these reservoirs and their location without no sampling and analysis of reservoir rocks nor direct access by drilling. This study shows that the lithium isotope measurements performed in hot waters collected from thermal springs (Diamant area, Martinique) and deep production wells (Bouillante area) can be very useful to determine these parameters when the temperatures of the geothermal reservoirs are known. In the Diamant area, the reservoir temperature was estimated to be close to 180-200 °C using most of the chemical and isotopic geothermometers. In the Bouillante area, it was measured at the bottom of the wells (250-260 °C) and confirmed by the chemical and gas geothermometers. For each area, the lithium isotopic signature of the reservoir rocks was estimated using the lithium isotope signature of the hot waters and the temperature dependant isotopic fractionation equation experimentally determined for basalt-seawater interactions. This value close to δ^7Li= -2.5‰ ± 0.5 suggests that the geothermal reservoirs in the Diamant and Bouillante areas are located in the transition zone, a zone which marks the contact between volcanic flows and the basaltic oceanic crust and is the centre of intense fluid mixing and circulation.

Clay mineral occurrences in volcanic and granitic geothermal contexts: signatures of high temperature fluid circulations in natural permeable fractures

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Based on well and surface data, hydrothermal alteration and namely clay minerals have been investigated in the volcanic area of Bouillante (Guadeloupe) and in the European EGS wells penetrating the Soultz granite (France).

In the volcanic area of Bouillante, a surface sampling zone of about 40 km^2 surrounding the geothermal field of Bouillante, which produced 15 MWe, was investigated. Several mineral associations were outlined: (1) dioctahedral smectites with calcite ± quartz ± kaolinite; (2) ordered I/S clay with adularia, silica ± calcite and (3) kaolinite smectite ± halloysite ± kaolinite ± smectite ± silica. The argillaceous signature of the present-day surface geothermal activity (i.e. dioctahedral smectites) can be distinguished from argillization due to weathering, which is dominated by kaolinite smectite mixed-layers and halloysite. Clay minerals thus provide a reliable tool to distinguish mineral associations derived from weathering processes or hydrothermal fluids.

Moreover, the drilling of 3 geothermal deviated wells in 2001 offered the opportunity to investigate the clay content related to the hydrothermal activity within the reservoir between 0 and 1,5 km depth. Special attention has been paid to the clay signature of the fractured zones which channel the present geothermal fluids. Three successive zones, dominated, respectively by dioctahedral smectite, illite and chlorite were identified at increasing depths. Alteration petrography indicates that these mineralogical clay zones result from the spatial superimposition of at least two successive hydrothermal alteration stages. The first one, assimilated to a propylitic alteration stage, consisted of crystallization of chlorite or corrensite, zeolite and epidote. The later stage of alteration is related to the circulation of the present geothermal fluids (T=250 °C) and is assimilated to argillic or phyllic alteration. It consists of a more or less intense argillization which results from the crystallization of aluminous dioctahedral clay phases (smectite, illite ± I/S mixed layers, and accessory kaolinite) associated with quartz, calcite, hematite or pyrite. At Bouillante, the permeable zones which channel most of the present geothermal fluids are fracture controlled and do not contain specific clay paragenesis. However the illite ± I/S mixed layers minerals differ from those of the surroundings by specific properties including both crystal structure and texture. Being mainly a product of the earlier propylitic alteration stage, chlorites are much less informative on the fracture controlled permeable levels.

From the EGS Soultz site located in the Upper Rhine graben (France), clay minerals have been investigated from cuttings collected within the granitic sections of the Soultz wells between 1,5 km and 5 km depth. Two main hydrothermal assemblages have been distinguished: (1) an illite ± quartz ± calcite ± hematite assemblage which characterise vein alteration related to fluid flow circulation in fractures. Locally, the association of tosudite (a regular dioctahedral mixed layered chlorite/smectite bearing lithium) with the illite assemblage characterises permeable fracture zones. (2) A chlorite ± corrensite ± calcite ± epidote assemblage which evidences earlier hydrothermal event defined as propylitic alteration. This assemblage which corresponds to poorly fractured massive granite occurs at the scale of the granite body. It is interpreted as an early hydrothermal event related to small scale fractures and characterises low permeability. On the opposite, the illite-secondary quartz assemblage characterises later hydrothermal events related to the tectonic activity of the Rhine graben. It occurs within some localized rather permeable fluid pathways corresponding to large-scale normal faults that support natural fluid flow (brines, 100g/l).

Clay minerals appear to be rather good indicators of geothermal fluid circulations in natural permeable fractures in volcanic and granitic reservoir environments.

High temperatures and Variscan structure of Western Poland

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Polish geothermal resources are classified as low enthalpy. However, higher temperatures are expected in the younger Paleozoic Platform characterized by 60-90 mW/m^2 Heat Flow (HF). It is decreasing in North Eastern Poland reaching 40-50 mW/m^2 at the old Precambrian craton.

The Paleozoic Platform (28-34 km thick) and up to 10 km thick sedimentary cover (Guterch i Grad, 1996) is accompanied by increased HF, elevated mantle HF, and thin thermal lithosphere of less than 100 km (Majorowicz, 2005). High HF anomaly axis agrees with the Dolsk Fault course and the Variscides extent. The Variscan Front lines up with increased surface gradient of HF. Rapid HF decline correlates with Trans European Suture Zone and it is explicitly seen at temperature cross sections below 1.5 – 2 km. The temperatures of the upper part (less than 1.5-2 km) may be influenced by long surface temperature changes (Gorbachev, 1995; Szewczyk and Giętka, 2003; Wróblewska and Majorowicz, 2006). The temperature pattern at 1 and 2 km depth does not reflect tectonic structure but a general division between the platforms (Precambrian-cold vs. Paleozoic-warm). Deeper temperature patterns from -4 km (max. T 150 °C) and -5 km (max. T 175 °C) are in good correlation with the course of the Variscides Front Zone occurence.

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Electrical resistivity 3-D modelling of the crust structure at Travale high enthalpy geothermal field

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The present study is aimed at attaining an approach of the crust structure at Travale area (Tuscany, Italy) by 3D electrical resistivity modelling and forward computing, and understanding the differences between the forward computed results and measured magnetotelluric resistivity data. Pointing to these targets, different 3D models were built including the resistivity of geological units from a resistivity log, zones of high temperatures and productive fractures from drillholes measurements, bright-spot type horizons identified in seismic profiles and estimated resistivity values of the lower crust and mantle. Responses from forward modelling were calculated and compared with magnetotelluric data obtained in the field. The outcomes of the study point out that low resistive bodies are present at the depth of the exploited geothermal reservoirs, that cannot be explained only by means of the geological units.

A secondary scope of this study was to establish if MT method is capable to distinguish between different porosity structures in geothermal reservoirs, as fluids situated within rock pores or within spaced or dense fracture systems. 2D-3D modelling and forward computing of models containing different porosity-type reservoirs were developed to achieve this aim.

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Seismo-Acoustic Signatures Analysis of Temperature and Pressure Dependence of Porous Rocks

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Seismo-Acoustic signatures of temperature and pressure dependence of geothermal reservoir rocks, two samples of volcanic rocks (Iceland), have been observed using laboratory experiment measured at in-situ conditions. The analysis of the seismo-acoustic signatures has been employed using the acoustic waveform recorded during laboratory experiment in terms of their P-wave velocities, instantaneous frequency, and spectral energy. The acoustic wave propagation was measured at a constant confining and pore pressure, but different temperature (Tmax 250 °C). After several temperature cycles, pore pressure was slowly reduced at a constant temperature of 150 °C by pumping pore-fluid out of the sample, until the liquid–steam phase transition was reached. Only when pore-fluid was pumped out beyond this point the pore pressure continued to drop. During the experiment the P and converted wave velocities decrease with the temperature rise. For two couples of temperature cycles it seems most likely that no hysteresis phenomenon of P wave velocities was observed. During the liquid–steam phase transition experiment stage, almost no P wave velocity change was observed. In addition to the velocity measurement the instantaneous frequency and its spectral energy have been computed. In accordance to the decrease of velocities the instantaneous frequency and spectral energy of the seismic waveform have shown systematic change with the temperature change. In this analysis, it can be shown that, not only the (confining and pore) pressure, the temperature change has substantial and systematic signatures on the seismic properties of the rocks.

Water- and gas-based geochemical prospecting of geothermal reservoirs in the Tarapacà and Antofagasta regions of northern Chile

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The Andean Central Volcanic Zone, which runs parallel the Central Andean Cordillera crossing from North to South the Tarapacà and Antofagasta regions of northern Chile, consists of several volcanoes that have shown historical and present activity (e.g. Tacora, Guallatiri, Isluga, Ollague, Putana, Lascar, Lastarria). Such an intense volcanism is produced by the subduction process thrusting the oceanic Nazca Plate beneath the South America Plate. The anomalous geothermal gradient related to the geodynamic assessment of this extended area gives also rise to intense geothermal activity not necessarily associated with the volcanic structures. Preliminary investigations on fluids discharging from some of these hydrothermal systems (e.g. El Tatio, Puchuldiza and Apacheta) have already been performed (Cusicanqui et al., 1975; Giggenbach, 1978; Urzua et al., 2002; Tassi et al., 2005), in response to the increasing Chilean energy demand from alternative sources. Nevertheless, the geochemical features of the majority of the thermal fluid discharges widespread all over this area are still almost unknown and, at the present, a correct evaluation of the geothermal potential of northern Chile remains a challenge. In this work the chemical and isotopic compositions of gas and water discharges collected, from November 2002 to October 2006, at several different thermal emission sites (e.g. El Tatio, Apacheta, Surire, Puchuldiza-Tuya, Puritama, Salar de Tara, Hecar) are presented and discussed in order to propose conceptual models aimed to describe the main mechanisms regulating the underground fluid circulation for geothermal purposes.

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Reservoir equilibrium temperatures at the Ahuachapan and Berlin geothermal fields (El Salvador) constrained by the organic gas species composition

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Geothermal exploration in El Salvador, which started in 1954, has identified ten geothermal areas characterized by medium-to-high temperature (180-300 °C) fluids. The geothermal energy of this country is currently provided by two distinct areas: i) Ahuachapan-Chipilapa, located approximately 80 km West of San Salvador, and ii) Berlin, 100 km East of the capital city and related to the Pleistocene Tecapa-Berlin volcanic complex. These two geothermal fields produce about 161 MW (95 MW from Ahuachapan-Chipilapa and 66 MW from Berlin), accounting for the 24 % of the total electricity output of El Salvador. The evolution of physical-chemical conditions of Ahuachapan-Chipilapa and Berlin geothermal reservoirs during exploitation has been extensively described on the basis of the compositional features of gas and water phases discharged by exploration and production wells (e.g. D'Amore and Mejia, 1999; Jacobo, 2003).
The present study is aimed to test in these well-known liquid-dominated systems different geothermometric techniques by using compositional data of naturally discharged fluids. Our results have shown that the chemistry of the fumarolic gas vents is significantly affected by both dissolution-driven fractionation, due to the interaction of geothermal fluids with shallow aquifers, and complex secondary gas-water-rock chemical reactions. As a consequence, a correct application of the classical inorganic gas geothermometers was not possible. On the contrary, the relative abundances of the structurally homogeneous C2-C9 hydrocarbons during geothermal fluid rising through natural fumarolic pathways appear to be only regulated by the diffusion velocity of gases within the shallow aquifers, a parameter that is function of the molecular volume of each gas species. Therefore, the chemical equilibrium of reactions among the C3-C3 and the C4-C4 alkane-alkene pairs, which are characterized by similar molecular dimensions and structure, seems to be not depending on secondary interactions thus, representing a useful tool for reliable estimations of geothermal reservoir temperatures and dominating redox conditions, especially during the first stage of exploration in promising areas for geothermal resources, before drilling any exploration wells.

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Fluid circulation in the geothermal field of Tianjin (north-eastern China)

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The low-enthalpy geothermal system of Tianjin (average thermal gradient of 3 °C/100 m) is located in-and around the City of Tianjin (China), in the NE part of the Hua-Bei plain, a tectonic depression affected by subsidence since the Neogene. In the framework of a cooperation project between the Italian Ministry for Environment and Territory (IMET) and the Ministry of Science and Technologies of the People's Republic of China (MOST), major, trace and isotopic composition of 35 thermal water and dissolved gases from both productive and reinjection wells in the Tinajin area (North China) have been investigated to reconstruct the fluid circulation at depth. The fluid exploited derives from two main aquifers. The shallower one (Tertiary and Quaternary formations) is characterized by T < 80 °C, prevalent Na-HCO_3 composition, salinity <1,000 mg/L and high Na/K ratio (up to 300). The deeper one (pre-Tertiary formations) has a temperature up to water boiling conditions, prevalent Na-Cl composition, salinity >1,000 mg/L (up to 4,000 mg/L) and low Na/K ratio (<20). The two aquifers are quite localized in their respective geological horizons, not showing any really evident chemical mixing trend. The pH of both aquifers is neutral-to-slightly basic, suggesting scarce contribution of acidic gas compounds (such as H_2S and CO_2). Although several wells have CO_2 as the main dissolved gas species in solution, its concentration seems to be consistent with that expected, according to the Henry's law, by considering the increasing hydrostatic pressures. In spite of the fact that the Tianjin geothermal field is located close to the ocean, the thermal fluids do not show any significant contribution from seawater. This fact suggests that the Na concentrations, relatively high with respect to the K contents, as well as the prevalent Na-HCO_3 composition of fluids hosted in the Tertiary, are likely due, at least partly, the dissolution of continental evaporites that are typically rich in Na-carbonate material. This interpretation is also indirectly supported by the relatively low PCO_2 values of the water phase, suggesting that the typical Na-Ca exchange, commonly observed in sedimentary environments affected by a high CO_2 flux, can be excluded. On the basis of the $^{18}O/^{16}O$ and D/H isotopic ratios the recharge waters of the two exploited aquifers seem to have a similar origin, prevalently deriving from precipitations at elevations ranging roughly, 1200-1600. According to the depth-temperature profiles, only few wells have a thermal gradient up to 6 °C/100 m, whereas are either that of the average Earth crustal gradient (3.3 °C/100 m) or even lower. Therefore, the Tianjin geothermal field must be considered as an excellent example of exploitation of a natural energy resource in an ordinary thermal environment. However, excessive over-exploitation of the thermal aquifers with possible depletion of the water resource, reinjection-induced scaling, plugging phenomena and seawater intrusion have to be regarded as impending problems.

The geothermal potential of continental Yemen: new geochemical and isotopic insights from thermal water and gas discharges

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Most thermal springs of continental Yemen, fumaroles and boiling water pools have been sampled and analyzed for chemical and isotopic compositions in liquid and associated free-gas phases. Whatever the emergence, all the water discharges have an isotopic signature of meteoric origin. Springs discharging in the central volcanic plateau show a prevalent Na-HCO_3-composition, clearly affected by an anomalous flux of CO_2 likely related to active hydrothermal systems located in the Jurassic Amran Group limestone sequence that underlies the 2000-3000 m thick volcanic suite and/or the Cretaceous Tawilah Group sandstone. Although organic CO_2 contribution from meteoric recharge waters, at least at limited extent, cannot be ruled out, all the CO_2-rich gas samples have a $\delta^{13}C$-CO_2 signature that falls in the range of mantle CO_2 ($-3<\delta^{13}C<-7$ ‰ V-PDB). The relatively high $^{3}He/^{4}He$ ($1<R/Ra<3.2$) ratios measured in all the CO_2-rich springs and also some mixed N_2-CO_2 gas vents in the far east Hadramaut region suggest significant contribution from mantle to hydrothermal systems residing at the crust level in several areas of Yemen. Presently, thermal springs of Yemen are only used as spa, bathing and irrigation. Nevertheless, liquid- and gas-geothermometry and geological considerations suggest that there are at least three areas (Al Lisi, Al Makhaya and Damt) inside the Yemen volcanic plateau (around Dhamar) that may have promising perspectives for the future development of geothermal energy in Yemen. Alternatively, they could be used as a source of energy for small-to-medium scale agriculture and/or industrial purposes.

The deep reservoir of the Travale geothermal area: mineralogical, geochemical and resistivity data

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The aim of the present multidisciplinary study is to explain the changes in resistivity observed in the deep reservoir of the Travale area taking into account the lithology and alteration affecting the reservoir rocks, with particular regard to conductive and clay minerals, the physico-chemical characteristics of the fluids, and their distribution and evolution with time. The study is also directed at calibrating petrophysical experiments in order to reproduce realistic physical conditions on a small scale. The deep reservoir consists of metamorphic Paleozoic units and younger granite. The metamorphic units include: i) the Phyllitic–Quartzitic Complex (metagreywacke with minor metabasite levels and locally carbonate–siliciclastic metasediments); ii) the Micaschist Complex (almandine-bearing albite micaschist with minor amphibolite); and iii) the Gneiss Complex (gneisses with minor amphibolite layers and rare calc-silicate rocks). Deep drillings have encountered Pliocene-Quaternary granites at depths between ~2 and 4 km below ground level (b.g.l.). All the crystalline units are affected by contact and hydrothermal metamorphism originated by the granite intrusions.
X-ray diffraction was carried out on one well in the Travale area (63 cutting samples in 2400 m of drilled depth) to identify the types of minerals present, their relative abundance and to compare the mineral characterisation with resistivity values. The Phyllitic–Quartzitic Complex is characterised by clay minerals (chlorite and mica types), quartz, plagioclase, calcite, anhydrite and rare dolomite: the relative abundance of these minerals is not homogeneous throughout the complex. A clear correlation between the abundance of clay minerals and a change in resistivity was not observed.
The study of fluid inclusions provided information on the fluids that interacted with the reservoir rocks, their composition, physico-chemical nature, origin and evolution. A multi-stage fluid circulation was observed, consisting of an early magmatic stage characterised by high-salinity fluids (around 50 wt. % eq. NaCl) of magmatic origin, and vapours and liquids resulting from heating of the Paleozoic rocks during contact metamorphism. The hydrothermal stage that follows is characterised by low- to high-salinity aqueous fluids with vapours produced by boiling processes. The high salinities can be explained by the interaction of these fluids with evaporites and/or connate waters.
The present-day geothermal fluid is superheated steam with similar gas/steam ratios. The components of the geothermal fluids are H_2O, CO_2, CH_4, H_2S, N_2 and H_2, with part per million (ppm) amounts of He, Ar, O_2 and CO.
Since the state of the geothermal fluid produced cannot explain the observed reduction in resistivity, the latter could be related to the abundance and type of i) heterogeneities in the reservoir rocks, ii) the abundance and type of alteration minerals, and iii) the presence of brines similar to those evidenced by the fluid inclusion study, whose interconnection would be sufficient to produce electrolytic conduction.

Preliminary results from fracturation analysis on an analogue granitic batholith and "direct broadcast" of the VSP acquisition at Soultz-sous-Forêts geothermal site

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At Soultz-sous-Forêts geothermal site, the fluid flow paths between the injection and the production boreholes are mainly composed by a set of permeable structures, occurring from the hectometric to micrometric scales. The objective of our work is to define the architecture of these paths within the heat exchanger, which is difficult due to the great depth of the hot granite.

Thus we will expose the present day development of our work organised in two different domains:

First, an outcropping batholith located in Catalunya presenting strong analogies with the geothermal reservoir in Soultz-sous-Forêts is studied. The preliminary results of a detailed fracturation analysis will be presented. A special attention is paid to fault zones, studied at different scales (from decimetre to centimetre), thus enhancing different fracturation domains (fault core, damaged zone, protolith) resulting in different behaviour regarding fluid flow for geothermal exploitation.

Second, the large VSP survey carried out at Soultz-sous-Forêts in March-April will be presented "in live". The objectives of this acquisition will be detailed (in particular, the sensitivity of the downhole tools to temperature and hard other conditions could be emphasised), and the latest news from the field work will be given.

2-D inversion of a magnetotelluric profile in Travale geothermal field using invariant responses

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We utilize a magnetotelluric profile in the Travale geothermal field, in Tuscany, Italy, to obtain a resistivity model using 2-D inversion of the series and parallel (S-P) invariant impedances. The idea is to experiment the performance of the S-P responses as compared with 2-D inversion of conventional TE and TM impedances. Resembling TE and TM responses, S-P are complementary, as series impedance is more sensible to galvanic effects while parallel is to inductive effects. Moreover, as both responses are rotation invariants, they overcome the trouble of selecting a rotation angle or using a tensor decomposition technique. For S-P inversion we used a Gauss-Newton algorithm designed to minimize the data misfit at the same time as the model is kept as smooth as possible. The trade-off between data misfit and model roughness is balanced by a regularization factor. We change this factor in a search for the model with the best tradeoff between data misfit and model roughness. TE and TM impedances were inverted using the algorithm of Rodi and Mackie, after rotation of data toward the main strike direction of the area. The resulting TE-TM and S-P model shows many similarities in defining resistivity anomalies at both shallow (500 m) and deep (1-5 km) depth. The 2D models show resistivity anomalies that correlate with zones of high permeability and fluid content representing exploited geothermal reservoirs. The shallow resistivity anomalies show a good correlation with the shallow geothermal reservoir, located in carbonate units. The anomalies are particularly visible in correspondence of the faults, suggesting an increase of permeability, a pathway for fluids and possible related alteration minerals. The most conspicuous feature of the 2D models is the presence of low resistivity anomalies inside the resistive basement at a depth of 1-4 km b.g.l. This deep resistivity anomaly corresponds to the deep fractured and highly productive geothermal reservoir located in the metamorphic rocks. This deep reservoir is made of sparse fractures and hosts superheated steam.

Geothermal Potential and Chemistry of Geothermal Fluids of Volcanic and Non-Volcanic Zones in Costa Rica

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Costa Rica is characterized by a magmatic arc associated with high enthalpy geothermal systems. The mean geothermal potential to produce electricity in Costa Rica is on the order of 1000 MWe, but only 170 MWe are produced at present with the installed capacity. The estimated potential is based on temperature measurements in deep boreholes drilled in oil exploration, on surface gravimetric studies, and on estimated hydrogeological features of aquifers. The main geothermal potential of the country, characterized by geothermal manifestations, is estimated to be provided mainly by the Guanacaste area (Miravalles and Rincón de la Vieja areas) and Central volcanic ranges. It is expected that non-volcanic zones with surface manifestations have a medium potential to produce electricity, but the geothermal potential of these regions is not well known. At present, all exploitation activity is concentrated on the Miravalles geothermal field, mostly due to limits set by the existence of environmental parks and habitat of wild life and due to the limited current economic potential to finance exploitation at larger scale. Normally, boreholes are used for the identification of the geological structure and for testing the aquifer performance in terms of fluid production. Seismic and magnetotelluric investigations were made to delineate the main areas of fluid containment. These data were incorporated in hydrogeological modelling performed with sophisticated software (e.g. FFFLOW, TOUGH) to simulate different geological scenarios in specific zones and their impact on fluid and electricity production.

Temperatures at Miravalles geothermal field and in the non-exploited area of Las Pailas (northwestern slope of Rincón de la Vieja volcano) range between 230 °C and 250 °C. In the areas of Arenal and Poás volcanoes, some springs identified along the slopes have temperatures of about 60 °C or lower. Hydro-geochemical data from Rincón de la Vieja, Miravalles, Arenal and Poás volcanic zones and from the southeastern part of the central valley (a non-volcanic zone), already published in scientific articles or available at Instituto Costarricense de Electricidad (ICE) allow a basic characterization of geothermal fluids. The majority of water samples from the Miravalles and Rincón de la Vieja volcanic areas is neutral in pH and of bicarbonate- sodium/potassium or mixed type. In the Arenal and Poás areas, the waters are neutral in pH and of Bicarbonate/sulfate-calcium character. The samples in the southeastern part of the central valley are of chloride/sulfate-sodium type. Several hot springs in the volcanic and non-volcanic zones have a northwestern orientation, associated with the main geological structures on the pacific slope of the volcanic chain.

Further research is needed to explore the Costa Rica resources in more detail. Open questions pertaining to reservoir temperatures at depth in the Guanacaste and Central volcanic range and the southeastern part of the central valley of Costa Rica could be tackled by the use of hydrochemical data from hot springs, wells and small streams. The data allow to make use of the Na-K-$(Mg)^{1/2}$ and SiO_2 chemical geothermometer.

Fluid – flow in the Boccheggiano-Montieri palaeogeothermal system: insights for the Larderello-Travale 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 hydrological 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. In this presentation we show data from fluid inclusions and structural studies dealing with the path of the hydrothermal fluid-flow in the mineralised Boccheggiano-Montieri area. Here a deep seated granite (3Ma) was recently reached by boreholes at about 3km depth. In this area, the widespread mineralization is located within tectonic breccias belonging to the Miocene and Pliocene normal faults and to the Oligocene thrusts. Independently from the structural level, fluid inclusions investigation indicate that a fluid flow, mainly consisting of meteoric water, occurred through the damage zones of the Pliocene normal faults and within the cataclasites of the older detachment surfaces. Then, since temperatures indicated by fluid inclusions are higher in the Pliocene faults, it is suggested that such faults might act 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 possible analogue of the Larderello geothermal system.

Geothermal Power Potential of "Jermakhpyur" Geothermal Site of Syunik Marz, Republic of Armenia

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Regional investigations conducted in the Soviet times have revealed anomalous geothermal sites on the territory of Armenia. One of them, related to the development area of quaternary volcanism with a lot of warm and hot springs is located at the south-east area of Syunik highland in Armenia. The site is located at watershed of Syunik volcanic highland with the absolute altitude of 2800-3000m and a gentle-undulating relief.

The purpose of seismic, gravimagnetic, electric, geothermal and geological investigations was to prove the presence of a geothermal anomaly identified earlier, to determine the properties and elements of its bedding, as well as to reveal the proven prerequisites for the presence of mobile heat carriers. The successful solutions of the issues mentioned helped identify the location for the first exploratory well, provide a justification for its depth up to 2500 m and, by that, to minimize the risk of drilling works.

Session 2

Modelling and reservoir simulation of high temperature systems

Modeling the Fluid Dynamics of Multicomponent Compressible Magma in Sub-Surface Volcanic Environment

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Magmas are multiphase multicomponent fluids which undergo chemical evolution and phase changes during their sub-surface history, implying large variations in fluid flow properties and a richness and variety of fluid dynamic behaviours. The formation of gas bubbles upon exsolution from the liquid of magmatic volatiles, mainly water and carbon dioxide, represents the major factors inducing density differences and convection in magmatic bodies. This results in complex patterns of fluid flow which occasionally generate conditions for rock fracturing, magma ascent, and eruption. In order to simulate the fluid dynamics of magma in magma chambers and conduit/fissures, we have developed a C++ numerical code which solves the transient, 2D mass, momentum and energy transport equations for a homogeneous multiphase multicomponent magma with liquid-gas non-ideal equilibrium and locally defined P-T-composition-dependent physical/chemical properties. The numerical algorithm is based on a finite element formulation and space-time discretization with Galerkin least-squares and discontinuity capturing terms, which allow high numerical stability and robust and accurate solutions over a wide range of flow regimes from compressible to incompressible. The multicomponent formulation makes the code particularly suitable for the investigation of several relevant aspects of magma dynamics involving density changes, mixing, multiple volatile saturation and phase transitions.
Applications of the code have been done to simulate the dynamics of free and forced convection in magmatic systems originating from gravitational instabilities, magma chamber replenishment, and conduit flow and magma ascent towards the Earth surface. The results highlight several aspects of the complex sub-surface magma dynamics, among which, the major role of carbon dioxide in inducing efficient magma convection and mixing dynamics, the possible occurrence of magma re-circulation from shallow reservoirs into deeper feeding conduits, the effect of convection of compressible magma in causing overpressure and enhancing stress on the confining rocks, and the generation of pressure fluctuations over a large range of frequencies encompassing those typical of quasi-static and dynamic rock deformation commonly registered in volcanic areas. The future research needs to improve the modelling and simulation of deep magmatic properties, specifically by coupling the dynamics of the fluid magma and the rock structure, are briefly outlined.

Japanese EGS experience and modeling efforts – a review of Hijiori HDR project

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Hijiori was one of the hottest Hot Dry Rock reservoir in the world whose fracture system was reasonably restricted by natural fractures and faults associated with the formation of the caldera structure. Japanese HDR project in Hijiori was started in 1984 by NEDO and five companies (GERD, Mitsui Mining, JAPEX and CRIEPI) with a funding of Japanese government. The project finished its long life (18years) research activity in 2002 with the 550-day successful circulation test showing the feasibility to generate electricity by using the binary system. The project established the basis for essential technologies and cleared up issues for future development of EGS system. Fracture characterization was achieved by integrating core analysis, logging, microseismic monitoring, tracer test and geochemical monitoring. Successive or periodic applications of these measurements enabled an evaluation of the reservoir dynamics. Fracture network modeling based on the knowledge of the fracture system was sufficient to develop a circulation strategy. We believe the outcomes of the Hijiori HDR project will be utilized by successive EGS projects and will become valuable data to initiate a new project.

Feasibility of using supercritical CO_2 as heat transmission fluid in the EGS integrating the carbon storage constraints

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A novel renewable energy concept based on using supercritical CO_2 as heat transmission fluid was proposed by Brown (2000). Pruess (2006) evaluated thermophysical properties and performed comparative numerical simulations to studying fluid dynamics, heat and mass transfer potentials of water and CO_2 as heat transfer fluids in an engineered geothermal reservoir. He highlighted some advantages of using CO_2 with respect to well bore hydraulics. Pruess and Azaroual (2006) extended previous analysis to include physicochemical interactions induced by CO_2 between fluids and reservoir minerals. They concluded a potential of porosity increase and reservoir volume expansion. Simulation of multiphase reactive transport (CO_2 in a porous carbonated rock initially saturated with water) illustrates existence of different zones featuring distinct reactive behaviour around the injection well (Andre et al., 2007). Supercritical CO_2 reacts differently to CO_2-saturated solution in each zone. First, it dissolves into the aqueous phase and increases both water acidity and mineral dissolution potential, favoring higher porosity. Next, hydraulic processes induced by supercritical CO_2 injection are accompanied by a desiccation phenomenon of the porous medium. Irreducible water, entrapped in pores, sustains the increase in CO_2 pressure. When the pressure is sufficiently high under a continuous dry (without water vapour) CO_2 flux, an evaporation process starts leading to the precipitation of salts and other secondary minerals from capillary metastable water (Lassin et al., 2005).
This new concept based on specific advantages thermophysical and physicochemical properties of CO_2 as a heat transmission fluid integrating geochemical interactions and carbon geological storage constraints will be presented.

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Modeling of short term stimulation and long term operation of EGS reservoirs

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With the beginning of the new century, the European EGS project got into its decisive state by reaching the final reservoir depth of 5 km. The three boreholes, GPK2, GPK3 and GPK4 have been successfully targeted at their predefined reservoir positions. Improvement of the reservoir conditions by stimulation with a minimized seismic risk represents now a primary challenge to enable economic operation and future extension. In this context, the new HEX-S code has been developed to simulate the transient hydro-mechanical response of the rock matrix to massive hydraulic injections. The present paper describes the successful forecast of the pressure response and shearing locations for the GPK4 stimulation in September 2004. As basis for this predictive modelling the reservoir model was derived from data analysis of the stimulation of GPK3 in May 2003. Stimulation flow rates up to 45 l/s at GPK4 and of >60 l/s at GPK3 have been applied, triggering several ten thousand of microseismic events. The transient numerical simulations with the HEX-S code match the main characteristics of both, the microseismic and the hydraulic behaviour. Different model calculations demonstrate the capabilities of our new approach. It is noteworthy that the modelling became possible only due to the excellent data quality at the Soultz project. The results demonstrate that simulations based on solid physical ground can reveal the complex reservoir behaviour during hydraulic stimulation. The use of HEX-S also provides perspectives for future developments such as design calculations that enable optimizing cost-intensive hydraulic stimulations before hand.
Long term operation data are however rare at the current stage of EGS development. The access of long term effects can however be estimated through modeling approaches. Therefore, the same finite element kernel is used for a combined hydro-thermo-mechanical simulation of long operation periods. Different examples will be shown from 2D and 3D models. The models highlight especially the thermo-elastic impact that can cause tensile fracturing perpendicular to the fracture surface. At long term, the reservoir will thus behave fully dynamically and the risk of short circuiting will be reduced.

Hydro-thermal coupling in a rough fracture

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Heat exchange during laminar flow is studied at the fracture scale on the basis of the Stokes equation. We used a synthetic aperture model (a self-affine model) that has been shown to be a realistic geometrical description of the fracture morphology. We developed a numerical modelling using a finite difference scheme of the hydrodynamic flow and its coupling with an advection/conduction description of the fluid heat. As a first step, temperature within the surrounding rock is supposed to be hot and constant. Influence of the fracture roughness on the heat flux through the wall when a cold fluid is injected, is estimated and a thermalization length is shown to emerge. Our model shows that fracture roughness is responsible for channelling effects. Fluid flow is dominant in a significant subpart of the fracture where heat advection is important. Accordingly, temperature distribution is strongly affected by small fluctuations of the fracture aperture.

Coupled thermal-hydraulic-chemical modelling in a fractured geothermal reservoir

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The TOUGHREACT code (Xu et al., 2004) has been used to numerically model the gas-water-rock interactions occurring in a vapor-dominated geothermal reservoir. The model conceptualizes the behaviour of the production zone of a generic geothermal well in which highly producing, fractured zones are surrounded by tight matrix blocks. Fracture zones are characterised by high values of porosity and permeability and represent preferential flowing pathways for the geothermal fluids in the reservoir, whereas matrix blocks are characterized by large porosities and permeabilities and control the storage capacity of the reservoir. System geometry has been described through simplified 0D and 1D (in both cartesian and radial geometry) domains.
The initial conditions have been constrained on the basis of numerical values reasonably representative of the “average” physical and geochemical conditions encountered at depth within the Mt. Amiata geothermal field . The focus of the study is on the variations of porosity and permeability properties of the reservoir due to precipitation/dissolution processes involving the minerals of the host rocks. A sensitivity-analysis approach has been followed to ascertain the role of mineralogical and T,P-conditions spatial heterogeneities on the final numerical results.

References

Xu, T., Sonnenthal, E., Spycher, N., Pruess, K. (2004) TOUGHREACT User’s Guide: A Simulation Program for Non-isothermal Multiphase Reactive Geochemical Transport in Variably Saturated Geologic Media. Lawrence Berkeley National Laboratory Report 55460, California, September 2004, pp. 192.

Session 3

Supercritical fluids: a new frontier for geothermal

ENGINE – **EN**hanced **G**eothermal **I**nnovative **N**etwork for **E**urope
Workshop 2, **Exploring high temperature reservoirs: new challenges for geothermal energy**
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The Physical And Chemical Nature Of Supercritical Fluids

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Inferences about the likely physical and chemical nature of fluids at temperatures and pressures above the critical point of water (CPW) come from studies of hydrothermal ore deposits related to shallow magmatic intrusions, from studies of metamorphic rocks, and from results of laboratory experiments investigating (1) mechanical properties of rocks, (2) fluid-mineral reactions, and (3) PVT characteristics of brines and gases. Fluid pressures that are likely to be encountered at drillable depths where temperatures are above the CPW are greatly influenced by the transition from brittle to plastic behaviour of rock. This occurs at about 400 °C in silica-rich rocks in tectonically active regions (assumed strain rate 10-14 sec-1). In contrast, in basaltic rocks the transition from brittle to plastic behaviour occurs at about 500° to 600 °C. Thus, seismicity that opens new fractures and reopens old fractures that have become clogged by mineral deposition can occur at much higher temperatures in basaltic rocks than in silicic rocks.

A second important factor is self-sealing of fractures by mineral deposition that appears to occur very rapidly in most rocks at about 400 °C. Aqueous-rich fluids and gases evolved from crystallizing magma and/or by metamorphic reactions, tend to become trapped beneath this self-sealed zone at greater than hydrostatic pressure. In rocks that behave plastically, and where the least principal stress is the lithostatic load, the mechanically most stable configuration for brine and coexisting gas is in flat-lying sheets or discontinuous lenses at or near lithostatic pressure. However, many epithermal ore deposits appear to have formed where there has been episodic rapid movement of substantial quantities of fluids from the high-temperature, high-pressure plastic region across the self-sealed zone into lower temperature brittle rock. In this process brecciation of rock occurs adjacent to channels of flow in the shallower and cooler brittle region.

Saline fluids above the CPW evolve to mixtures of hypersaline brine and coexisting gas. The brine becomes more saline and the coexisting gas less saline either as temperature increases or as pressure decreases. Brecciation occurs in the plastic source region where “boiling” of brine and expansion of gas are induced by a temporary drop in fluid pressure that occurs as the gas, or a froth of brine and gas, moves rapidly through breaches in a self-sealed zone. A continued decrease in pressure results in the system entering a field of gas plus solid salt. In this region significant concentrations of HCl tend to be generated by hydrolysis of the precipitated salts. However, the HCl is a highly associated species which is non-reactive. It becomes dissociated and reactive only where the gas moves into a cooler environment and liquid water condenses.

Above the CPW non-condensable gases, such as CO_2, H_2S, and SO_2 strongly partition into the “steam” phase coexisting with brine. With decreasing pressure the SO_2/H_2S ratio in the vapor phase exsolved from a crystallizing magma increases. Thus, volcanic gases tend to be relatively rich in SO_2. However, underground, as a hydrothermal system cools, SO_2 reacts with water and with the surrounding rock producing H_2S and sulfates.

Development of Deep Unconventional Geothermal Resources (DUGR's) in Iceland and their Potential Application Elsewhere in Europe

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The Iceland Deep Drilling Project (IDDP) represents a new and challenging step forward in the development of geothermal resources worldwide (see http://www.iddp.is). The IDDP is designed to assess the economic potential of producing deep, supercritical, geothermal fluids as a source of steam for power production. A two-year long feasibility study concluded that drilling to reach high-temperature supercritical fluids is possible, and that producing the resultant superheated steam could yield a power output ten times that of a conventional well producing subcritical steam with the same volumetric flow rate. However, in order to reach the required temperatures of 400-600 °C, drilling to depths of 4 to 5 km is necessary, at a cost three to four times that of a conventional 2 to 3 km deep well. The first deep well will be drilled in 2008 at Krafla at the northern end of the central rift zone of Iceland within a volcanic caldera that has had recent volcanic activity. In the coming decade we anticipate that the IDDP will drill a series of deep holes in other geothermal fields in Iceland, including the Reykjanes peninsula in SW Iceland.

A recent comprehensive assessment of the potential for "enhanced" geothermal systems (EGS) within the USA, (by a panel headed by J.W.Tester of MIT)*, indicates that a cumulative capacity of more than 100,000 MWe from EGS can be achieved in the United States within 50 years with modest multiyear government investment. However, given the environmental and economic incentives of producing an order of magnitude more energy from geothermal wells occupying the same area, but at less than an a half order of magnitude increased cost, supercritical volcanic geothermal resources are an especially attractive component of EGS. Such deep unconventional geothermal resources (DUGR's) are not restricted to Iceland, For example, in the USA, the resource base of conventional hydrothermal resources is estimated to be 2,400-9,600 Exajoules (1 EJ = 1018 J), whereas the supercritical volcanic EGS resource base is estimated to be as much as 74,100 EJ (excluding sytems in National Parks). A preliminary review of existing data from Europe suggests that DUGR's are likely to occur in Italy, Turkey, Greece, the Canary Islands, in the Azores and in Russia (Kamchatka). A systematic survey of the potential of DUGR's in Europe is therefore desirable and plans should be developed to investigate these potentially large resources further.

* "The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century". (see http://geothermal.inel.gov)

The Iceland Deep Drilling Project (IDDP) – Status April 2007

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The IDDP (http://www.iddp.is/) is a long-term program to improve the efficiency and economics of geothermal energy by harnessing Deep Unconventional Geothermal Resources (DUGR). The aim is to produce electricity from natural supercritical hydrous fluids from drillable depths. This requires drilling wells in active high-temperature (high-T) geothermal systems to depths of at least 3.5 to 5 km, to reach temperatures of 450-600 °C, and pressures of 230-350 bar.
Modeling indicates that one such well, at sufficient permeability, e.g. capable of producing ~2400 m^3/h of steam, at temperatures above 450 °C, could generate some 40-50 MW electric. This exceeds by an order of magnitude the power typically obtained from conventional geothermal wells, e.g. producing the same amount of steam at 240 °C. The long-term plan is to drill a series of such deep boreholes in Iceland at the Krafla, the Hengill, and the Reykjanes high-T geothermal systems. Beneath these three developed drill fields temperatures should exceed 550 °C, and the occurrence of frequent seismic activity below 5 km, indicates that the rocks are brittle and therefore likely to be permeable.

The poster shows the IDDP drillhole design, drilling schedule and time plan. Drilling a fully cased and cemented well to about 3.5 km is scheduled for 2008. Deepening that well to ~4.5 km could take place the same year, or the year after, and will be followed by a major flow test and detailed chemical study of the deep geothermal fluids. Most likely, a mechanical and chemical engineering pilot test will be needed before power production from supercritical resources is realized. The IDDP feasibility study assumed a heat exchange system would be needed, but to a large extent this will depend on the chemical composition of the supercritical fluid, which most likely will be retrieved at the surface as superheated steam.

The main financial supporters are leading Icelandic energy companies together with the government of Iceland. Negotiations are already underway with international aluminum companies for participation in the innovative IDDP experiment. The International Continental Drilling Program (ICDP) and the US National Science Foundation (NSF), have already allocated funds for scientific studies by supporting considerable core drilling in the deeper parts of the IDDP well. The plan is to seek additional funds to the EC-FP7 for developing the engineering pilot plant test of the supercritical fluid for power production, likely to be needed in 2009-2010. The EC-FP6 support HITI project is intimately linked to the IDDP project.

Probing of high temperature geothermal reservoirs from electrical methods : HiTI EC project and the IDDP

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The general objective of the HiTI EC project is to provide geophysical and geochemical sensors and methods to evaluate deep geothermal reservoirs up to supercritical conditions (T>380°C). Supercritical geothermal wells are still non-conventional but may provide a very efficient way to produce electricity from a clean, renewable source. A deep geothermal well will be drilled in 2008 for this purpose into the NE Icelandic Krafla volcanic zone, as part of the IDDP (“Iceland Deep Drilling Project”).

Aimed to explore supercritical reservoirs, HITI is to develop, build and test in the field new laboratory or downhole tools and methods for deep high-temperature boreholes and a highly corrosive environment. The new set of tools and methods has been chosen to describe, in particular, the supercritical reservoir structure and dynamics. Slickline tools up to 450°C and wireline tools up to 300°C will be developed due to the present limitation in wireline cables (320°C). The more extreme, supercritical conditions will be explored taking advantage of cooling during the drilling phase.

For reservoir characterisation, the measured quantities are temperature and pressure (for in situ fluid, thermodynamic modelling of the reservoir and thermo-mechanical modelling of borehole integrity), natural gamma radiation and electrical resistivity (for basement porosity and alteration), acoustic signal (with borehole wall images for reservoir fracturing and in-situ crustal stresses) and reservoir storativity and equilibrium (from geothermometers and organic tracers). The presentation will focus here on the solving of the electrical problem as part of HiTI and as a means to describe reservoir structure and dynamics. This will include both laboratory and downhole measurements, aiming at describing the different components of the electrical signal, from alteration to porosity (matrix and fractures), and with the objective to identify in situ pore fluids in terms of salinity. This method will be developed first in a high temperature (200°C – 300°C) hole from the Krafla region, then appiled to the IDDP hole. The presentation will be illustrated with IODP core and downhole data from the oceanic crust.

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