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Achievements and Ongoing Progress of the European HiTI Project: High Temperature Instruments for Supercritical Geothermal Reservoir Characterization and Exploitation

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ABSTRACT

The HiTI project (High Temperature Instruments for supercritical geothermal reservoir characterization and exploitation) was funded within the European Sixth Framework Programme (*FP6*), lasting three years and starting in 2007[1]. HiTI brings together geothermal downhole sensor developers and research institutes. The project is providing geophysical and geochemical sensors and methods to evaluate reservoirs and deep geothermal wells up to supercritical conditions (temperature above 374 °C and pressure exceeding 22 MPa for pure water). Supercritical geothermal wells are presently non-conventional but may provide a very efficient way to produce electricity from a clean, renewable source.

The set of new instruments tolerate high temperature & pressure in a highly corrosive environment. A slickline tool (memory tool) tolerating up to 400°C and wireline tools up to 300°C are developed, the latter lower limit due to the present limitation in wireline cables (320°C). Furthermore, geothermometric methods are developed to address temperatures beyond 400 °C. The new downhole tools are demonstrated in Icelandic high-temperature geothermal fields. Temperature, pressure, fluid flow and casing collar location might be measured up to 400°C from a single multisensor tool. Natural gamma radiation spectrum, televiewer signal (acoustic), electrical resistivity and fiber optic cables using distributed temperature sensing method are also being developed for borehole applications up to 300°C.

For a better understanding of supercritical reservoirs, a HPHT (high pressure high temperature) laboratory has also been adapted to study the electrical resistivity of rocks and fluids, as well as rock rheology and chemical processes in supercritical conditions. A Na/Li geothermometer, based on chemical and isotopic analysis of Icelandic fluids, has been developed to determine reservoir temperature and rock nature. Moreover, tests with organic tracers tolerating up to 350°C are performed, to evaluate the reservoir storativity and flow rate in the Krafla geothermal field.

Identification of new concepts of tools and evaluation methods at temperatures beyond 400 °C, conducted within the project, will potentially lead to future development of very high temperature geothermal instruments and methods, increasing our knowledge of supercritical reservoir behaviour and our abilities to exploit such resources.

1. INTRODUCTION

The HiTI project (High Temperature Measurements) aims at developing sensors and methods to study the supercritical environment. This FP6 (Sixth Framework Project) European project brings together the following tool makers and research institutes: Advanced Logic Technology (Luxembourg), BRGM (France), Calidus Engineering (UK), CNRS-Géosciences Montpellier (France), CRES (Greece), GFZ-Potsdam (Germany), ÍSOR (Iceland), and Oxford Applied Technology (UK). More information is available at the HiTI website: http://www.hiti-fp6.eu/.

Utilization of supercritical geothermal fluid for electricity production is not conventional at the moment, but may provide a high gain compared to conventional wells, as has been estimated by Albertsson et al. (2003). However, drilling and monitoring a supercritical well is a challenge in this harsh environment with high temperature (above the critical point of water, 374°C and 220 bar), complex chemical composition and therefore unknown physical behaviour of fluid and formations. Supercritical geothermal fluids have been encountered previously but, in order to exploit such resources, both drilling and logging methods need to be operational at high temperature.

In 2009, a well was drilled in North-Iceland at the Krafla geothermal field to reach the supercritical geothermal environment, as part of the Iceland Deep Drilling Project (IDDP), with the latest developments described in Friðleifsson et al. (2010a) and Friðleifsson et al. (2010b). HiTI tools, methods and data analysis have been tested in hot Icelandic wells including IDDP, in addition to other laboratory studies on supercritical fluids and rock behaviour. All the HiTI wireline logging tools are designed to be used with the same high-temperature tolerant cable-head built by Calidus Engineering and used with a 4-conductor Rochester wireline cable rated to 320°C.

At the time of writing the final version of this paper (September 2009), tools and methods are in the field test phase. Herein we present 1) characteristics of tools and methods; 2) first results obtained; and 3) the work which will be done in 2010, which is the project's final year.

2. WELL FLUID PROPERTIES

Well fluid properties are key parameters to evaluate the energetic potential of the supercritical reservoir. This includes temperature and pressure, but also fluid conductivity evaluated directly from the combined

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electrical resistivity, as high solute concentrations are expected at supercritical conditions. For this purpose, 2 tools are developed in the HiTI project: a multi-sensor, rated to 400°C, and a wireline temperature sensor rated to 300°C.

2.1 Multi-sensor

The Multi-sensor, developed by Calidus Engineering, is an instrument that measures temperature, pressure, fluid flow and casing collar location, at temperatures up to 400°C and 700 bar pressure. The electronics are protected with a heat shield (dewar) and at the highest temperatures the tool can be operated for several hours, recording measurements into memory that are extracted when the tool reaches surface again.

2.2 High temperature wireline sensor

The high temperature wireline sensor measures real-time temperature up to 320°C. The design made by BRGM is based on previous work conducted in the 1980s on instruments for ocean drilling projects, using a platinum resistivity sensor (Lebert, F. (2009)). The surface electronics required consideration to be given to current losses in the cable, using high impedance voltage readouts. This temperature sensor can be operated for an unlimited time, or as long as no failure in the cable communication occurs.

3. RESERVOIR EVALUATION

Detailed knowledge about the structure and dynamics of the geothermal reservoir is needed to assess the sustainability of hot to supercritical fluid production from thermodynamic, petrophysical, thermomechanical and economical points of view. For this purpose, the acoustic imaging device (for fracture mapping and stress), natural gamma ray spectrometer and resistivity sensors rated to 300°C are key logging tools. Within the project, geothermometric methods have been applied and organic tracers have been injected, with lab research conducted on the behaviour of rocks at supercritical fluid conditions. All those tools and methods in combination should provide data to allow understanding of the intricate relationships at in-situ conditions.

3.1 Gamma-Ray sensor and acoustic televiewer in open hole mode

Natural gamma measurements are very useful for rock nature and alteration determination. The natural gamma spectrum analyser SGR85, developed by ALT, is designed to tolerate 300°C and 140 MPa for up to 12 hours. The tool diameter is 85 mm and it is stackable with the acoustic televiewer ABI85-92, which has the same tolerance limits. Combined, the tool is 6.26m long (without centralizers). The acquisition system *ALT logger* has been implemented for those tools.

The acoustic televiewer in open-hole mode provides information on fractures, crustal stress regime and orientation. In addition to amplitude and travel time of the acoustic signal, the tool contains internal and external temperature sensors, orthogonal accelerometers and magnetometers.

The natural gamma sensor was successfully tested in March 2009 at the Krafla geothermal field in Iceland, very close to the IDDP drill site. It reached 300°C while still maintaining high resolution measurements. The internal temperature rise was approx 5.5 °C per hour at 270°C borehole temperature, calling for maximum measurement time of 18 hours in that environment (the electronics tolerance is 125°C and the initial electronic temperature at start of logging was close to 25°C).

An example of data obtained with the stacked tool is displayed in Figure 1, using the software *WellCAD*. A series of structures and two open fractures are drawn, using travel time and amplitude of the acoustic signal. Logging was made at the Krafla geothermal field in North-Iceland, in an open-hole section of a vertical well, K-18.

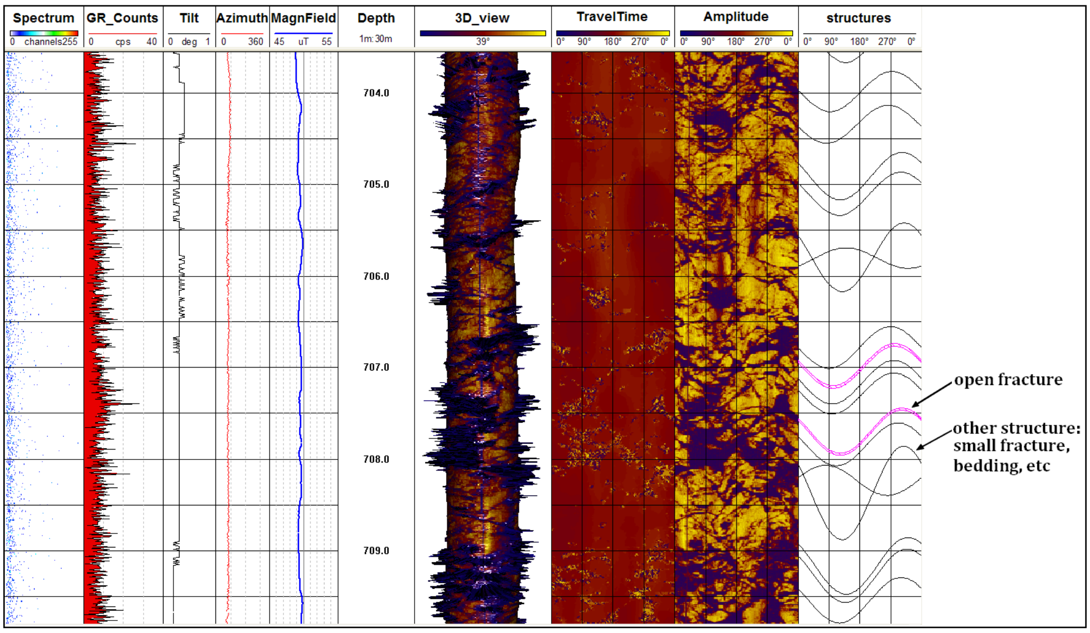

Figure 1: Results of logging using the spectral gamma ray sensor SGR85 and the acoustic televiewer ABI85-92 stacked together, in a vertical well situated at the Krafla geothermal field (Iceland, Well K-18). From left to right: gamma ray spectrum, counts of natural gamma radiations, tilt, azimuth, total magnetic field, depth, 3D-view of the well using the acoustic signal, travel time and amplitude of the acoustic signal, structures drawn using the acoustic logs.

A systematic analysis of structures was showing that the main direction of structures is coherent with surface observations performed by Massiot et al. (2009).

3.2 Resistivity measurement: development of a high temperature DLL

Electrical resistivity can give important information regarding reservoir characterization, such as porosity, pore space geometry, rock mass alteration, and fracturing. The Dual Laterolog (DLL) is a 300°C rated tool with both laterolog shallow (LLs) and laterolog deep (LLd) capabilities; Tool diameter is 73 mm. The DLL is designed and built by Calidus Engineering, while the architecture of the resistivity tool is recommended by CNRS Montpellier using theoretical simulations via numerical modelling. The current tool version also contains a fluid electrical conductivity meter and a temperature gauge.

During the resistivity tool design, correction charts for borehole size and fluid nature (and temperature) were computed from numerical modelling and compared to relevant charts provided by Schlumberger. The existing numerical modelling code “RtEvrest” developed by *Atemis Technologies* (Marseille, France) and based on the work of Touron (1996) was adapted to the need of calibration and resolution of the HiTI DLL. The code computes synthetic electrical resistivity logs of electrode (such as the laterolog) and coil-based (induction) tools. An application of this code can be found in Belghoul et. al (2010).

3.3 Rock properties evaluation using the Paterson press

In order to evaluate the supercritical reservoir properties in the context of IDDP, the physical properties of basaltic rocks have been studied in the HiTI project under geothermal conditions, i.e, high temperature (200-600°C), high confining pressure (50-200 MPa), pore pressure (0-100 MPa), and more specifically under supercritical conditions. In particular, laboratory measurements of electrical resistivity of basaltic rocks as a function of temperature, pressure and fluid nature (phase, chemistry) are essential to analyze the downhole electrical resistivity measurements and large scale magnetotelluric data, as described in Violay et al. (2009a).

These parameters are investigated in an internally heated, gas pressure apparatus called a Paterson machine, at CNRS Montpellier (France). First designed as a dry rock deformation machine, the Paterson apparatus has been modified in order to (i) measure the electrical resistivity of saturated rocks with different kinds of fluids (including gases and very corrosive fluids), (ii) perform these measurements under controlled pore pressure and at high temperature, and (iii) measure the permeability of the rocks.

In addition, an important parameter in evaluating the reservoir properties in terms of geothermal exploration is the maximum temperature that can be reached by hydrothermal fluids. As this temperature is directly related to the maximum depth where hydrothermal fluids may circulate, the maximum temperature corresponds to the temperature where rocks become non-permeable. This temperature is generally related to the brittle to ductile transition temperature. In 2008, a series of about 25 conventional triaxial compression deformation experiments were performed in order to identify the conditions of the brittle to ductile transition in basalts.

First results indicate that, in the context of the Icelandic geothermal system, hydrothermal fluids may circulate, at least briefly, through the oceanic basaltic crust down to 6 to 8 km depth and temperatures up to 700°C, well above the critical point of water, Violay et al.(2009b).

Effects of strain rate, alteration and presence of a reactive pore fluid (such as saline fluid) on the rheology of basalts are being investigated in 2009-2010.

3.4 Na/Li chemical geothermometer and lithium isotopes

The chemical composition of the geothermal waters for most of the major and trace elements is related to the temperature at depth of the reservoir from which the water is derived, the mineral assemblage of the reservoir rock and the gas composition in contact with these waters as well as the degree of water/rock/gas interaction. Unlike traditional geothermometers (silica, Na/K, Na/K/Ca, K/Mg, etc.) applied to geothermal waters, the Na/Li geothermometer associates a major chemical element (sodium) and a trace element (lithium), and gives an additional temperature estimation.

Geothermal waters and surface waters were sampled in Iceland by BRGM (France). A preliminary bibliographical review and chemical and isotopic analyses of those fluids show that two new Na/Li geothermometric relationships can be used for these fluids, one for seawater-derived fluids and one for dilute fluids, in addition to the three other relationships existing in the literature. Uncertainty on the temperature values is about 20°C. For more details, see Millot et al. (2008), Sanjuan and Millot (2009) and Sanjuan et al. (2010). The two Na/Li geothermometric relationships obtained for the HT deep fluids collected in the Krafla and Reykjanes geothermal areas must now be tested on the supercritical fluids which will be sampled in these areas during the current IDDP drilling in Krafla, and in preparation of IDDP-2 which is expected to be drilled later on in Reykjanes.

Particular emphasis was placed on the characterization of the behavior of Li isotopes (δ^7Li, ‰) in geothermal waters at high temperature with or without the presence of seawater during water/rock interaction. These data show that Li isotopes are potentially a good tracer of the water/rock interaction occurring in the deep reservoir since Li isotopes seem to be controlled by the intensity of water/rock interaction and by secondary minerals (dissolution/precipitation). However, further work is required to more accurately constrain the temperature dependence of Li isotope fractionation in geothermal systems taking into account the role of secondary minerals on the control of Li isotopic fractionation in this volcanic environment.

3.5 Tracer tests using organic compounds

Organic tracers selected by BRGM were released in the summer of 2009 into an injection well and into the first IDDP well in the Krafla geothermal field, in order to study the reservoir storativity and the fluid flow rate. The naphthalene disulfonate family of compounds and aromatic acids (sodium benzoate) were determined to be the most suitable for the hot waters, and the alcohols and hydro-fluorocarbons for the steam. At Krafla, the naphthalene disulfonate family was selected and analysis of collected samples is ongoing (Gadalia et al. (2010)).

4. PRODUCTION INTEGRITY MONITORING

Higher temperatures and corrosiveness in geothermal wells may lead to production difficulties. Monitoring of all relevant parameters in an operating geothermal system allows timely actions to be taken to preserve production integrity. Well casings and cement integrity can be investigated using acoustic techniques and continuous temperature monitoring from a fiber optic cable for distributed temperature sensing.

4.1 Acoustic televiewer with casing thickness and cement evaluation mode to 300°C

A monitoring policy of geothermal wells throughout their production lives includes the development of a tool for casing surveys, which can be complicated due to the harsh environment. ALT developed an acoustic televiewer with a casing thickness mode rated to 300°C (same specifications as for the open-hole televiewer, see 3.1). The new tool, ABI85-92 is able to image the inner and outer surfaces of all casing tubing in a deep hot well. These data can be displayed in a 3D view to allow the best assessment of the current status of the infrastructure. These recurrent inspections contribute to a better understanding of the evolution of the cased hole in such an environment, and will allow an efficient management of the maintenance, which is big part of the exploitation costs.

Two types of acoustic head ABI85-92 exist, one enhanced for open-hole mode, and the other with both casing thickness and open hole mode. A first test of the head with both modes was made in 2008, providing a casing thickness study in a deviated well (30°), reaching 220°C (an example of results is displayed in Figure 2).

In March 2009, the open-hole enhanced televiewer acoustic head was tested at the Krafla geothermal site and maintained perfect functionality up to 285°C. New in-line centralizers were also tested in this well, providing good centralization, which is a key parameter for good quality data.

4.2 Fiber optics with Distributed Temperature Sensing method

A fiber optic cable for Distributed Temperature Sensing (DTS) has been developed in cooperation between GFZ Potsdam and nkt cables GmbH (Germany) for deployment in hot geothermal wells. In contrast to the other tools developed in the framework of HiTI, the DTS technology employs an optical glass fiber as sensing element and requires no downhole electronics, which makes it especially suitable for high temperature applications. Several fibers with different coating materials have been tested under laboratory conditions at temperatures up to 400°C, Reinsch et al.(2008); Reinsch & Henninges (2009), and a fiber with a sufficient lifetime at temperatures up to 350°C suitable for inclusion in a sensor cable has been selected. To test the design under in situ conditions within a hot geothermal well, a cable has been installed permanently behind casing within the 300m section of well HE-53 in the Hengill geothermal area (South Iceland). On-line temperature information was acquired during the cementation process which has been used to aid in the evaluation of cement integrity, as described by Henninges & Brandt (2007). After completion of the well, high temperature profiles were acquired during a flow test.

5. STUDIES ON HIGH TEMPERATURE WELL LOGGING

Getting high temperature well logs is a challenge, because of the current limitation of tools which need to be enhanced. Nevertheless, temperature is a key parameter for reservoir evaluation, and can be estimated by numerical models. Also, interest in electro-magnetic techniques is growing, since they give information on the deep parts of the reservoir.

5.1 Prospects to 500°C

Most of the technologies used for geophysical and geochemical measurements and fluid sampling into deep wells are available up to 200°C. Some of them can be adapted to temperatures up to 350-400°C, but very few technologies are available at 500°C. A report is being written on 1) the state of art of the accessible and existent technologies at the highest possible temperatures and 2) prospective strategies and new concepts to develop new reliable tools and instruments measuring temperature, pressure, gamma radiation, acoustic signal and fluid conductivity up to 500°C. Investigations are especially focused on electronics, ultra-high temperature resistant materials, use of cooling processes (chemical solids or gases), use of optical fibers and development of a downhole fluid sampler. Details on the borehole instruments' design is presented by Halladay et al. (2010).

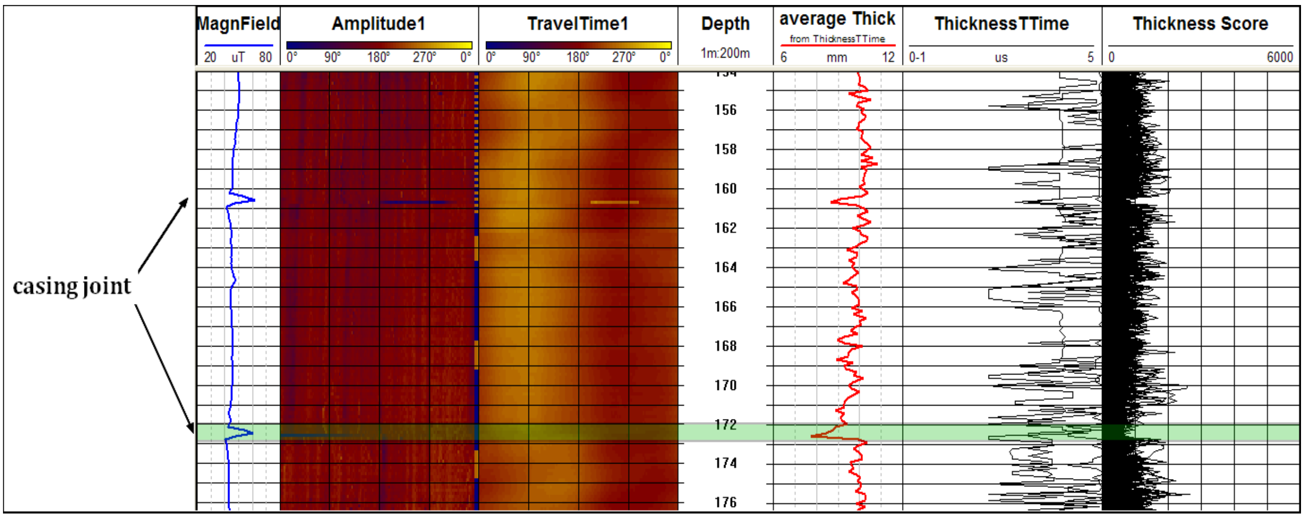

Figure 2: Results of a logging of ABI85-92 in casing thickness mode, in a deviated well at the Krafla geothermal field. Average thickness is calculated by WellCAD from the thickness travel time.

5.2 TEM and MT 3D modelling around an unexpected supercritical well

In October 2008, temperatures measured in geothermal well K-39 that was being drilled at Krafla geothermal site in NE-Iceland reached 385°C at 2530 m true vertical depth within a cooling water filled drill-string situated in the inclined well. Measured pressure was 22.7 MPa, and the pressure was seen to deviate from a steady build-up. This combined temperature and pressure measurement proved the existence of supercritical water conditions (present for pure water if temperature is above 374 °C and pressure above 22 MPa).

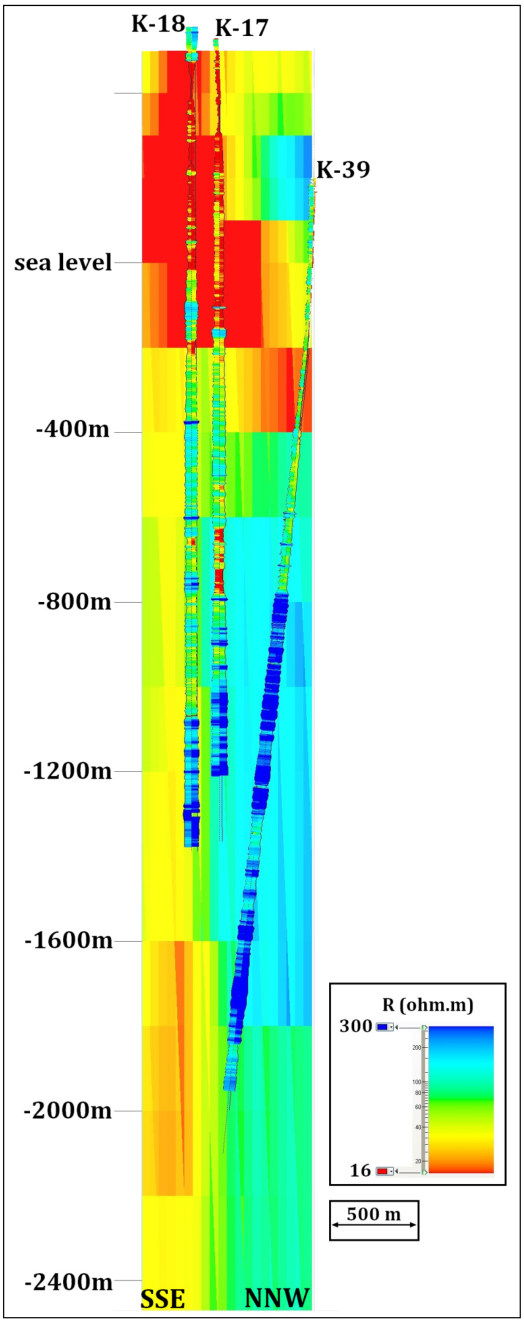

Figure 3: Cross section along well K-39 derived from the 3-D resistivity model of the Krafla geothermal site (N-Iceland). Wireline resistivity measurements are displayed from wells K-18, K-17 and K-39 (64'' electrode spacing on the right and 16'' spacing on the left).

Transient electromagnetic measurements (TEM) combined with magneto-telluric (MT) measurements conducted previously from surface indicate the existence of a low resistive "pocket" near the supercritical encounter, of about 70 million m^3 (see Figure 3). This body may be evidence of a partially molten rock area, with very high temperature, especially since the drill cuttings extracted from this depth contained a large amount of glassy basalt, or dacite, as expected from a recently cooled magma body. Low resistivity could also be related to the higher conductivity of supercritical fluids circulating on and around this pocket, due to higher salinity. Unfortunately, it was not possible to sample fluids at this depth.

The latest volcanic activity in Krafla area took place in 1984, after 9 years of semi-continuous activity, consisting of lava flows covering an area of some 36 km^2. A simple thermal transfer calculation was carried out on a sphere and shell model using the same method Lord Kelvin applied while evaluating the age of the Earth (Carslaw and Jaeger (1959)), indicating that a body of the estimated size in Krafla could indeed still be existing since the last eruptions at the measured temperature.

Correlations between borehole measurement, lithology, alteration minerals and MT/TEM are also investigated.

6. CONCLUSION

In the European project HiTI, a suite of tools and scientific methods to study the supercritical geothermal environment was developed. All the new logging tools are rated to 300°C in wireline mode, which is the limit of the cable, and 400°C in memory mode, opening the door to very high temperature fluid analysis. They are tested in hot Icelandic wells, with some of them scheduled for deployment in the first IDDP well.

New methods of investigation are also tested, such as geothermometers, organic tracers and fiber optic cable using the distributed temperature sensing method, which has the potential of becoming a standard installation in geothermal fields.

To complete the multi-disciplinary approach of the supercritical environment, lab experiments are being performed to study the behaviour of basalts at high temperature, pressure, and with different kinds of fluids. In addition, well logs and magnetotelluric data of known supercritical zones are investigated to determine with precision the physical parameters of fluids and rocks.

Data analysis of tracer testing, downhole measurements and cores from IDDP will be made by HiTI members, in collaboration with the IDDP consortium.

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