Results from the European I-GET Projet on Integrated Geophysical Exploration Methods

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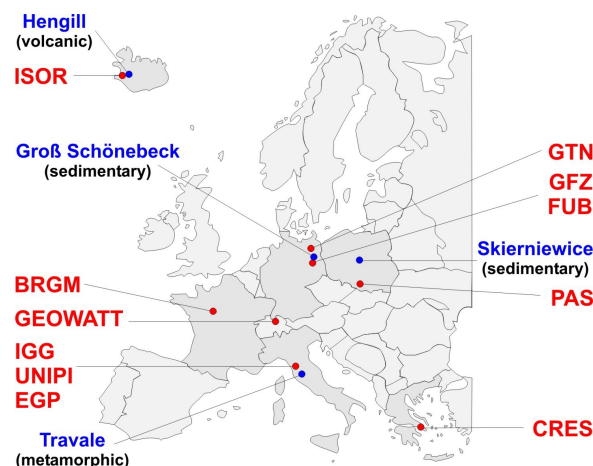
ABSTRACT

The project I-GET was aimed at developing an innovative geothermal exploration approach based on advanced geophysical methods. The objective was to improve the detection, prior to drilling, of fluid bearing zones in naturally and/or artificially fractured geothermal reservoirs. This approach was tested in four European geothermal systems with different geological and thermodynamic reservoir characteristics: two high enthalpy (metamorphic and volcanic rocks), and two low enthalpy geothermal system in sedimentary rocks.

Petrophysical and geomechanical properties of the investigated rocks have been defined by laboratory measurements. With respect to the high enthalpy sites elastic and electric rock properties have been determined at the steam/liquid transition of the pore fillings. Results of these measurements are presented in a separate presentation.

Seismic and magnetotelluric measurements were acquired at the test sites, and new acquisition and processing techniques have been developed to solve problems related to the particular target such as high temperatures, anisotropy, phase condition, etc. The static and dynamic three-dimensional models of geothermal reservoirs have been reconstructed by means of all the data acquired. Results of the field measurements and of the integrated modelling are shown in separate, more detailed presentations.

1. INTRODUCTION

The integration of geophysical exploration methods was tested and further developed within the project I-GET (Integrated Geophysical Exploration Technologies for deep fractured geothermal systems), co-funded by the European Commission within the *6th Framework Programme for Research and Technological Development*. Within the project, 11 partners from 6 European countries (Table 1) joined forces with the objective to develop a methodology to improve the detection, prior to drilling, of fluid bearing zones in naturally and/or artificially fractured geothermal reservoirs. The basic idea was to integrate data and measurements from several existing geophysical methods into one final reservoir model. This approach was tested at four European geothermal systems with different geological and thermodynamic reservoir characteristics: two high enthalpy (metamorphic rocks in Travale, Italy and volcanic rocks at Hengill, Iceland), and two lower enthalpy geothermal systems (deep sedimentary rocks in Gross Schönebeck, Germany and Skierniewice, Poland).

Figure 1: Locations of field sites (blue) and partners.

At the end of the project, a final conference was organised (February 2009) where project results were presented to an international audience from science and industry: In addition, keynote presentations on the state of the art in geophysical exploration methods (active and passive seismic and MT) for geothermal resources as well as case studies from all over the world were presented.

2. GEOPHYSICAL MEASUREMENTS

2.1 Travale

At *Travale*, an existing 3-D seismic dataset (Cappetti et al., 2005), was reprocessed for a joint interpretation with all the available geological, geophysical, and well logging data (Casini et al., 2010). The area covered 60 km², 33 km² with full fold. In total, 1484 shot points were acquired. The seismic data were complemented by well logging information from existing deep wells in the area. Besides an accurate reconstruction of the structural and geological model, the interpretation was aimed at identifying any seismic signal possibly associated to fractured systems inside the deep geothermal reservoir.

The data quality was highly variable due to environmental noise and outcropping of massive limestone that caused high energy absorption and, as a consequence, a decrease of the signal to noise ratio. The heterogeneity in the quality of the acquired data required a number of unconventional processing steps to better interpret the results. To this end, the detection of the post-stack high amplitude signals and pre-stack AVO analysis brought important information for locating drilling targets. In addition, azimuthal analysis of the seismic signal amplitudes reflected from the geothermal targets provided further information about preferred fracture orientation. These measurements visualized a distinct reflector as a potential target horizon which coincides with a productive zone containing dry steam. A detailed presentation about this analysis is given in a separate presentation by Fiordelisi et al (this volume).

Part of the area covered by seismic measurements was also investigated by new and old magnetotelluric (MT) measurements (Manzella et al., 2010). These data were processed and modelled, taking into account geological and seismic information. Modelling results showed evidence for a major conductive anomaly in some areas of Travale at the depth of the geothermal reservoir, but with no clear relation to mineralogy, lithology and seismic parameters, and only partially related to the evidence of more productive areas. The major question addressed by a separate contribution (Manzella et al., this volume) is, why there is such a low resistivity anomaly, as the geothermal fluid exploited at Travale is superheated steam, which should not contribute to a resistivity reduction. Dry steam is much more resistive than water in the liquid state, and does not cause extensive fluid-rock interaction in a fractured zone, and therefore extensive alterations, such as those created by fluids. In addition, the Travale geothermal reservoir has a very low permeability caused by a few main fractures. However, the geothermal fluid may have included a liquid phase during a previous stage, as indicated by hydrothermal alteration minerals observed in Travale as well as in the whole Larderello region and by fluid inclusion studies. An alternative and/or additional reason for the anomaly may be the presence of a fluid phase in addition to the steam produced for energy generation purposes. These questions are part of ongoing research. Detailed results of the MT measurements at Travavel are presented in a separate contribution (Manzella et al., this volume).

2.2 Hengill

The *Hengill* geothermal system is one of the best studied in the world owing to its particular geodynamical context (e.g., Ingolfsson et al., 2008; and references therein). It is therefore ideally suited as a natural laboratory to test new exploration techniques, such as the combination of electromagnetic and passive seismic measurements including broadband seismology, aiming at improving our knowledge of structural and dynamical behavior of geothermal systems. One of the questions that have been object of debates is the possible existence of a partial melt body vs. supercritical fluids at depth, which have been proposed to be responsible for several geophysical observations. At present, geothermal fluids are derived from a depth of about 2 km, but the ongoing Iceland Deep Drilling Project (IDDP) aims at extracting supercritical fluids from a depth of about 4 km.

Within the I-GET project, a total of 70 MT soundings were acquired in addition to 59 pre-existing soundings and 30 soundings funded by Reykjavík Energy. The project therefore includes a total of 159 MT soundings in the Hengill area. All the MT soundings were made at locations previously visited by TEM soundings which were used for static shift corrections of the MT data. Joint 1D inversion of all MT and TEM soundings in the Hengill area was performed and a 3D resistivity structure was compiled from the individual 1D models (Árnason et al., 2010). A full 3D inversion was performed for 60 static shift corrected MT soundings covering the Hengill volcanic complex. The 3D inversion delineated deep conductors that correlate with transform tectonics reveiled by intense seismicity between 1990 and 2000. The deep conductors are thought to be dikes and intrusions which are heat sources of the geothermal system.

In addition to electromagnetic measurements, seismic tomography using local seismicity was used to improve the resolution of structural features within the geothermal field. For this purpose, seven broad-band seismic stations were installed in the summer of 2006 in and around the most seismically active part of the area and recorded continuously for four months. The data base includes 662 earthquakes recorded by at least four of the stations. 424 of the recorded events were micro-earthquakes with clear P and S waves. Finally, 19 low frequency earthquakes were recognised with sharp onset and resonance having a large peak at about 1.5 Hz. 339 micro-earthquakes with clear P- and S- arrival times detected by at least 4 stations were inverted to apply tomography inversion of the compression P-wave and shear S-wave structure of the geothermal reservoir (Jousset et al., 2010).

The velocity structure of the Hengill area, as revealed by the joint 3D tomography inversion, was compared to other geophysical data. The location of high P-wave velocity coincides with areas where a deep conductor is at shallowest depth (about 3 km), according to the results from the 1D inversion of TEM and MT soundings and 3D inversion of MT soundings acquired within the I-GET project. No sign of attenuation of seismic S-waves is observed under the Hengill area, indicating absence of extensive magma chambers at depth. The area where high velocity bodies are found correlates with positive Bouguer anomalies, indicating dense rocks at depth.

Generally, $v_P = v_S$ ratios vary by 6% throughout the area. The most coherent anomaly involves a low $v_P = v_S$ at 0 to 2 km depth, and correlates with areas of hot springs and fumaroles, within the striking fissure swarm in the Hengill area. This low-v_P anomaly extends at depth beneath the northern part of Hengill volcano and to the east.

Local seismic events (predominantly VT events) were found at depths between 1 and 10 km depth beneath the network. Several individual clusters can be identified, however, most of the seismicity was located along an E-W plane slightly dipping to the south at depths ranging from 2 to 4.5 km. The seismicity is found to locate at the boundary at the top of the high velocity body at the SE of Mount Hengill. This area corresponds to the NW-SE oriented low resistivity anomaly at the depth of 3 - 5 km under is the location where the intense seismic activity form 1991 to 2001 revealed a distinct transform tectonics. The anomaly is under an area of wedges where E-W oriented faults meet N-S oriented faults.

2.3 Gross Schönebeck

At Gross Schönebeck, activities were centered around a former gas exploration well (4.3 km deep) Both seismic and MT data were acquired in parallel along a 40 km long profile to derive a regional 2-D seismic model of the potential reservoir layers and overlying sediments. The profile is oriented parallel to the estimated strike of the regional stress field. Second, a star-like arrangement consisting of 4 profiles each of 6 km length was deployed and a low-fold (low budget) 3-D seismic experiment was conducted to identify fractures around the geothermal well location. Detailed results of these measurements are presented in a separate contribution by auer et al. (2010, this volume).

In addition to the surface geophysical measurements, borehole geophysics was used to complement the set of field data. For this purpose, a chain of seismometers was located in the well GrSk 3/90 while stimulation tests were performed in the other well at the same site. The data of this test give a clear image of the fractures created during the stimulation. The results of this experiment are presented in a separated, more detailed contribution by Moeck et al. (2010, this volume).

MT data was collected along a 40-km long main profile (55 stations) and a 20-km long parallel profile located 3 km to the east. Electrical resistivity models obtained from two-dimensional inversion of the data identify two conductive anomalies at the level of the reservoir (Lower Permian/Rotliegend) which seem to be correlated to anhydrite-rich salt lows. High fracturing in the anhydrites could be responsible for higher fluid content, enhanced permeability and corresponding electrical conductivity.

A joint interpretation of the two parameters measured in the field at Gross Schönebeck is limited to a mostly qualitative analysis due to the lack of a fundamental law linking the two. Resisitivity and velocity models were investigated in the joint parameter space using a statistical approach. This approach resulted in the identification of regions with high correlation between the two model parameters (Muñoz et al., 2010). By back-mapping of these regions onto the spatial domain common classes were identified which could then be compared with lithological information. Comparison with local geology yielded interesting results, in particular, a high velocity – low resistivity class which is interpreted as related to salt lows, where highly fractured anhydrite can produce enhanced permeability.

2.4 Skierniewice

At *Skierniewice*, seismic lines and MT profiles were measured in a grid around the well Kompina-2 with a depth of 4,5 km depth (Bujakowski et al., 2010). The target horizon for geothermal exploration is a Triassic sandstone at 4100 m depth, which was found to contain hot brines. Pre-existing 2D seismic lines were reprocessed as well as VSP from 9 surrounding wells to define and identify possible structures that may allow exploitation of the reservoir as an EGS. The seismic survey covered an area of about 36 km² with 2.5 km² of homogeneous fold area in the centre. The total length of source lines was 29 km, while that of the receiver lines was 54 km (42 points in each source line and 170 in each receiver line). Six lines served for sources and eight for receivers. Four lines intersected at the location of the Kompina-2 well. 4 Vibroseis were used with a sweep length of 16sec and with a frequency range of 8-100 Hz for one seismic source. The maximum offset of X = 6188.78 m ensured the recognition of the deepest horizons within the survey area.

The datasets obtained are of high quality in the centre of the seismic image where the homogeneous fold exists. Processing of seismic data was performed by standard procedures similar to those used in the hydrocarbon exploration with additional extension for the geothermal purpose. Despite of non-uniform offset distribution and fold area inside bins, the final migration has very good quality and is comparable with results of standard 3D seismic processing. The new data reveal fault structures that were not known prior to the project. These structures may prove to be of major importance for the development of the EGS at Skierniewice. Additional advanced interpretation of the data set is ongoing as part of an ongoing PhD thesis.

The MT survey was carried as continuous profiling and MT/AMT/CSAMT soundings along one of the seismic profiles crossing the well location. CSAMT measurements were added to control and supplement MT/AMT data as the survey area was highly noisy. Even two remote reference stations could not reduce the noise problem to an acceptable limit. CSAMT helped to fix the top part of the MT profile. These measures helped to greatly improve the subsurface image of the potential reservoir around the well. The integrated seismic and MT interpretation supported by the borehole data resulted in construction of the 3D geological model. Previously unknown fractured zones were identified to select the optimal areas to locate new geothermal boreholes.

2.5 Laboratory Rock Physics

Parallel to in-situ data acquisition, petrophysical and geomechanical properties of the investigated rocks have been defined by laboratory measurements at high pressure and temperature at the high pressure laboratory at GFZ Potsdam (Kristinsdóttir et al., 2010). Conditions in the reservoirs have been simulated, with controlled pressure, temperature and pore pressure as well as pore fluid salinity. Rock samples from Iceland, Italy and from Germany were subjected to conditions comparable to those in the geothermal reservoirs investigated, while electrical conductivity and seismic velocities were determined on the cores. By varying the difference between pore pressure and confining pressure at a given temperature, the transition from liquid to steam in the pore fluid was simulated while changes in physical properties were observed (Milsch et al., 2010). The raw ultrasonic velocity data acquired by these experiments have been further analyzed and interpreted in terms of their elastic properties (Jaya et al., 2010).

CONCLUSIONS

The results of the project showed that a joint interpretation of different methods in one reservoir model reveals potentially interesting geothermal targets more reliably than the individual methods applied and interpreted separately. The integrated models (e.g., Ollinger etal., 2010) give a much improved image of the subsurface to be developed for geothermal use.

The project generated 13 contributions to the WGC 2010. Detailed results are collected and presented in a Special volume of *Geothermics* (40, no.1; 2010).

Table 2: Partners, locations and project facts (Website: www.i-get.it).

Partners	Country
GFZ Potsdam (co-ordinator)	Germany
Enel Produzione	Italy
BRGM	France
CNR-IGG	Italy
ÍSOR	Iceland
Università di Pisa	Italy
CRES	Greece
Freie Universität Berlin	Germany
Geowatt AG	Switzerland
GTN	Germany
Polish Acdemy of Science (PAS)	Poland
Funding period	Nov. 2005 - April 2009
Budget	3.8 Mio. €
EC contribution	2.7 Mio. €

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