Proceedings European Geothermal Congress 2007
Unterhaching, Germany, 30 May-1 June 2007

Developing new concepts for the exploration of high and medium enthalpy geothermal reservoirs, the I-GET project.

David Bruhn[1], Hubert Fabriol[2] and the I-GET consortium

[1] GeoForschungsZentrum Potsdam, Section 5.2 Geothermics, 14473 Potsdam, Germany

dbruhn@gfz-potsdam.de

[2] BRGM, Development Planning and Natural Risks Division, 45060 Orléans, France,

h.fabriol@brgm.fr

Keywords: Geothermal exploration, geophysical sounding, magnetotellurics, EU-project

ABSTRACT

The project I-GET is aimed at developing an innovative geothermal exploration approach based on advanced geophysical methods. The Project Acronym stands for *Integrated Geophysical Exploration Technologies for deep fractured geothermal systems.* The objective of the project is to improve the detection, prior to drilling, of fluid bearing zones in geothermal reservoirs. This new approach has been tested in four European geothermal systems with different geological and thermodynamic reservoir characteristics: in metamorphic (Travale, Italy) and volcanic rocks Hengill, Iceland), and two in deep sedimentary rocks (Groß-Schönebeck, Germany, and Skierniewice, Poland).

Integration of different geophysical approaches is the key concept of the project. To this end, seismic and magnetotelluric data were acquired in the test sites, and new acquisition and processing techniques were developed to solve problems related to the particular target such as high temperatures, anisotropy, phase condition, etc. The static and dynamic three-dimensional model of geothermal reservoirs will be reconstructed by means of all the data acquired. The input of the results of new geophysical prospecting into reservoir modelling is a crucial test of the quality of the new exploration method.

Simultaneously to *in situ* data acquisition, petrophysical and geomechanical properties of the investigated rocks are 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. The validity of the laboratory and simulation results will be verified by the new field experiments.

The ultimate goal is the development of an efficient, low-cost exploration method, by taking advantage of the strengths of different disciplines and combining them to an integrated approach.

1. INTRODUCTION

The exploration of geothermal resources aims at the detection and delineation of thermal anomalies and the macroscopic geological structures such as large-scale permeability or intensely fractured zones that determine the productivity conditions of the geothermal reservoir. Indeed, many geothermal reservoirs are associated with fractures characterised by high permeability, which are quite often heterogeneously distributed. However, one of the ***major problems not yet satisfactorily solved, is the detection of fractures and high permeability zones.*** More than 30% of exploitation wells world-wide have been drilled into promising - i.e., high temperature -, targets, but lacked sufficient permeability to sustain commercial production. This percentage of failures significantly increases for exploration wells. The search for high permeability zones is not limited to geothermal exploration, but is equally important for hydrocarbon exploration and the detection of deep aquifers. However, a unique problem to geothermal exploration is posed by the rock environment of the geothermal reservoirs. The salinity of geothermal fluids is usually high and temperatures are close to the liquid/steam transition. High temperature and fluid salinity potentially change rock transport properties even during production. The behaviour of rocks with increasing pressure and temperature has been studied by many laboratory measurements and seismic and magnetotelluric (MT) field tests. However, these peculiar features of geothermal areas have never been studied in detail until now.

2. THE I-GET PROJECT

2.1 Objectives

The I-GET project is aimed at ***developing an innovative strategy of geophysical exploration.*** This strategy integrates all the available knowledge, from rock physics to seismic and magnetotelluric (MT) data processing and modelling, and exploits the full potential of seismic and electromagnetic exploration methods to detect permeable zones and fluid bearing fractures.

This geothermal exploration approach ***has been applied in European geothermal systems with different geological and thermodynamic reservoir characteristics***: in Italy (high enthalpy reservoir in metamorphic rocks), in Iceland (high enthalpy reservoir in volcanic rocks) and in Germany and Poland (low to middle enthalpy reservoir in sedimentary rocks).

2.2 Project description

For the project, f***our main topics*** are identified:

(1) Construction of a petrophysical and geomechanical database obtained from laboratory experiments on geothermal reservoir rock samples belonging to the various geothermal systems under study. The elastic and electric rock properties at the reservoir condition up to the steam/liquid transition of the pore fillings are determined.

(2) Field acquisition and data processing of seismic and MT field experiments at several test sites.

(3) Geothermal reservoir numerical modelling. Results from (1) and (2) are integrated with the elastic and

anisotropic models and with the well testing data, in order to verify the presence of fluid-bearing zones inferred from seismic and magnetotelluric experiments. Local 3D models will be built on the basis of field data and laboratory measurements to produce the static image of geological structures and to identify the fluid-dynamic behaviour of the fracture system from available well tests.

(4) Validation of the methodology applied.

The newly developed methodology will represent a fully integrated exploration methodology able to detect favourable prospects, highlight the spatial distribution of petrophysical and geomechanical properties and predict the fluid-dynamic behaviour within a potential reservoir. The result can be applied in reservoir exploration of natural and/or enhanced geothermal systems, and in exploration of deep aquifers.

2.3 Case studies

The case studies that have been analysed in this project are:

- The Travale (Italy) geothermal system, where the exploration targets are mainly located in metamorphic and magmatic rocks up to 4000-m depth, characterised by a high degree of heterogeneity and anisotropy and by high temperatures.
- The Hengill (Iceland) geothermal system, where the exploration targets are mainly located in volcanic centres (up to 2000-m depth), within a rift zone characterized by anisotropic permeability. At present, geothermal fluids are mainly mined at the depth of about 2 km, but the ongoing Iceland Deep Drilling Project (IDDP) aims at extracting supercritical fluids from the depth of about 4 km.
- Groß Schönebeck (Germany) deep sedimentary reservoir, representative for large sedimentary basins all over Europe with a well-doublet for future use as power plant.
- Skierniewice (Poland), a prospective geothermal reservoir especially representative for medium enthalpy application in Eastern and Central Europe. Experiments there will commence in the summer of 2007.

For the different case studies, the adaptation of existing techniques and methodologies was required. Advanced petrophysical and geophysical aspects have been applied in the projects, and all data will be integrated. The results will be used as input for static and dynamic numerical models, which will be verified by well data, where available, and compared to existing reservoir models.

The innovative aspect of the project is the realisation of ***an integrated multidisciplinary approach*, *leading to a synergy among different technologies*** (geophysical, geological, and thermodynamical) in order to reduce the interpretation ambiguity and to optimise the geothermal reservoir knowledge assessment.

2.4 Data acquisition

The data for the integrated models come from several different geophysical subdisciplines:

2.4.1 Petrophysics

Laboratory experiments on rock samples have been carried out at temperatures and pressures similar to reservoir conditions. This kind of data have been severely lacking for quantitative interpretation of geophysical characterization. Quantitative relations between relevant petrophysical properties (e.g. permeability or secondary porosity), elastic parameters and electrical conductivity at the steam/liquid transition of the pore fillings have been determined. In addition, elastic properties have been simulated numerically Such a combination of laboratory measurements with numerical tests of rock-physical relationships has never been applied before. Logging data complement the information for all four sites. New logging data were acquired within the project at the well Radicondoli for the Travale site.

2.4.2 Magnetotellurics

Continuous, high density tensorial electric field mapping along selected profiles (i) improved the resolving power of the method, (ii) can provide better control of static shift effects and (iii) are prerequisite for the application of new imaging methods. Full coverage of the target area with laterally extended distribution of sites forms the basis for advanced data processing and 3D interpretation schemes.

The quality of MT responses is often reduced in geothermal areas, due to the presence of strong cultural noise. As a consequence, it may become difficult or impossible to resolve structural details of a geothermal target. For the I-GET project, the data quality was improved significantly by additional recording of MT data at a remote site. In addition, data processing procedures which reduce the influence of coherent noise have been applied and improved. These adjustments make the method much more robust and applicable even in extremely noisy areas.

For the interpretation, natural source MT provides direct information on directionality and dimensionality of the investigated subsurface. Preferred orientation of currents systems (electrical strike directions), current channelling or electrical anisotropy can be calculated directly from the tensor nature of the measurement. Based on this intrinsic feature of MT data the strike orientation of fracture zones has been determined to locate and image regions of electrical anisotropy. The MT experiments have been carried out with as much as possible overlap to the seismic experiments which opens up additional prospects for integrated modelling.

At Hengill and Groß-Schönebeck, field measurements are completed and data analysis has started. At Travale, some field work is ongoing, while field work at Skierniewice will start in the summer of 2007.

2.4.3 Seismic methods

For the seismic field measurements, different data acquisition methods were used for the different sites. At Travale, a full 3D seismic data set provided by project partner ENEL has been available for detailed analysis. Unlike other geothermal exploration approaches, which have essentially been based on post-stack data, the information contained in the pre-stack data has been exploited in the present project. This approach allows us to study reflections properties wit h respect to the incidence angle on the target: therefore, this information is more likely related to the petrophysical properties and in particular to the presence of fluids. Moreover, 3D P-wave surveys with offsets equal to or greater than the target depth in all azimuths allow highlighting the directional variation of seismic attributes in P-wave anisotropy, revealing the presence of fractured zones. First results of the reprocessing by the University of Pisa show a significant increase in quality over the originally processed dataset. Our work continues with the integration of well information, in assessing the presence of azimuthal amplitude variations and of AVO effects.

For the sedimentary sites (Germany and Poland), 2D/3D seismic profiles have been / will be acquired. In Groß Schönebeck, seismic measurements along a 40 km long profile approximately parallel to the orientation of the regional maximum stress were taken. From the seismic lines high resolution P-velocity tomographic models have been derived. These models will be jointly interpreted with the distribution of the electric resistivity determined by MT methods. Besides this, the seismic signals have been interpreted with AVO techniques benefiting from a large ratio of offset range with respect to the target depth (up to 40 km to 4 km). These investigations are of great importance to describe the properties of the subsurface with respect to its porosity and/or fluid content. In addition to the long 2D profile, low-coverage (low-budget) 3-D seismic experiments were conducted in a star like arrangement with a denser shot and geophone spacing than for the long profile to allow imaging of the fault system around the geothermal reservoir. All seismic field experiments were completed successfully, data interpretation is ongoing

In Iceland, active seismic methods are not normally feasible due to the unsuitable geological conditions. However, development of broadband seismometers allows the acquisition of long-period signals (0.1 to 2 s) and very-long-period signals (2 to 100 s), having specific characteristics, described mainly in terms of duration and frequency content. These signals have been observed at many active volcanoes, hydrothermal systems and even oilfields. Detailed analysis of temporal and frequency characteristics of long-period volcanic and hydrothermal earthquakes allows describing and quantifying fundamental geometrical and dynamical parameters within hydrothermal systems. In addition to the location of the source within the hydrothermal system, these parameters include quantification of the size of fractures containing fluids, liquid/gas ratio, and fluid migration processes, hydraulic fracturation mechanisms. Hence, a network of broadband seismometers allows a direct observation of the interaction between fluid and solid, where those fluids migrate by strong pressure gradient, and constitutes a fundamental tool for a better understanding of hydrothermal activity. In addition to that, the classical interpretation of natural and induced seismicity allows mapping of active fractured zones and zones of anomalous propagation of seismic waves. In the Hengill area, a network of 7 broadband seismometers was deployed for 4 months in 2006 and data processing is currently in progress.

2.5 Integrated modelling

Diagnostic tools for detecting fluid-bearing zones in the geothermal systems will be provided by individual numerical tools for specific reservoir types. Characteristic signatures of reservoir transmissivity will be related to the interpretation of geophysical field measurements and laboratory findings. Typical analogies between reservoir porosity –being related to permeability – and seismic velocity and / or electric conductivity will be explored at individual sites. The examination of these signatures will require a careful study of geological setting (fracturation of reservoirs), the proper design of field experiments and the appropriate treatment of temperature / pressure conditions in the reservoir.

Since typical geothermal production sites from different geological settings have been considered, a broad perspective is ensured. The models will account for realistic dimensions, fracture orientation, alteration mineral filling and stress field. Seismic and MT data will provide the basic input into numerical models that may at least partially be calibrated hydraulically against existing pressure/flow data. Different reservoir types will account for individual treatment: Finite difference forward modelling, capable of handling general anisotropic media, will be used to calculate the seismic response of permeable zones in steam reservoirs (Hengill and Travale); finite element modelling will account for single phase reservoirs (Groß-Schönebeck) with a strongly refined control of fracturation. Seismic anisotropy due to foliation and open fractures will be accounted for. In addition, the specific 3D finite difference models will evaluate magnetotelluric response linked to the hydraulic reservoir models. This can define the MT parameters mostly affected by fracture density and porosity. The ultimate goal of the numerical evaluation is to develop an estimation tool for the reservoir productivity from geophysical measurements and data interpretation, under the local temperature, pressure and stress conditions.

Finally an innovative joint interpretation will be performed of both geophysical and thermo-hydraulic data. The key element in the joint interpretation is the use of geothermal reservoir simulators with post-processors. The post-processors calculate the electrical and seismic response of the reservoirs, using the rock physics database and the simulating and modelling software mentioned above. The aim of the joint interpretation is to have the final model to comply with all available data, both geophysical and thermo-hydraulic.

GENERAL PROJECT INFORMATION

The project started in November 2005 and is funded for 3 years. 11 partners from 6 countries participate in the different tasks. These are

1	GeoForschungsZentrum Potsdam (co-ordinator: E. Huenges) Section 2.2 Geophysics: M. Weber, A. Schulze, K. Bauer, K. Becker, O, Ritter, G. Muñoz	Germany
2	ENEL Produzione A. Fiordelisi, S. Ciuffi, M. Casini	Italy
3	BRGM H. Fabriol, P. Jousset, J.-M. Balthasat	France
4	Istituto die Geoscienze e Georisorse A. Manzella	Italy
5	University of Pisa A. Mazzotti, E. Stucchi, A. Grandi	Italy
6	Íslenskar orkurannsóknir (ÍSOR) Ó. Flóvenz, K. Árnason	Iceland
7	Centre for Renewable Energy Sources (CRES) K. Karytsas, D. Mendrinos	Greece
8	Freie Universität Berlin S. Shapiro, M. Jaya	Germany
9	Geowatt AG T. Kohl	Switzerland
10	Geothermie Neubrandenburg (GTN) M. Wolfgramm	Germany
11	Polish Academy of Science W. Bujakowski, M. Pussak	Poland

Project website: www.i-get.it