Geophysical exploration methods at European sites

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

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

- potential methods, based on density and magnetic properties of rocks and two of the Earth potential fields: magnetic and gravity;
- electrical and electromagnetic (EM) methods, based on the electromagnetic properties of rocks (conductivity, permittivity) and the Maxwell equations;
- seismic methods, based on the elastic properties of rocks and the equations of wave propagation in continuous media;
- radiometric methods, based on radioactive emission of rocks and atomic physics equations. These methods are most commonly used in well-logging.

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

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

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

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

- Those that measure the difference in electrical potential

- Those that measure an electromagnetic field, natural or artificially created

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

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

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

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

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

<u>Metamorphic rocks</u> in Larderello/Travale, Italy

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

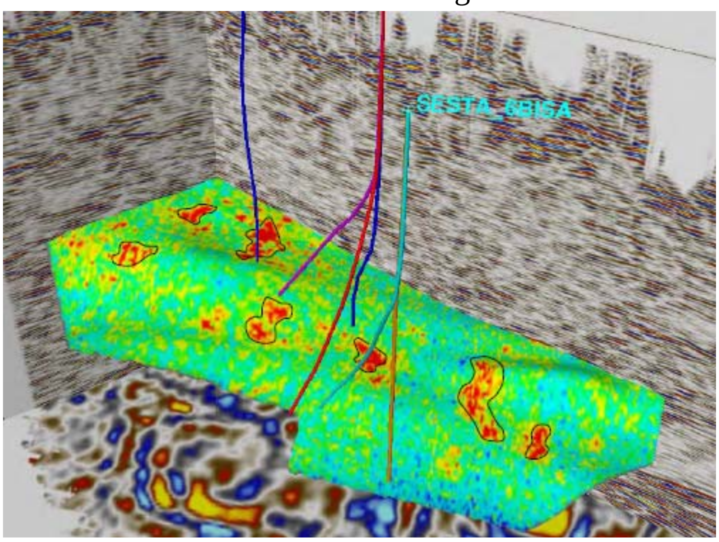

Figure 1 – 3D-seismic interpretation of the H-marker and selection of

potential drilling targets at areas with highest RMS amplitude (Cappetti et al. 2005).

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

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

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

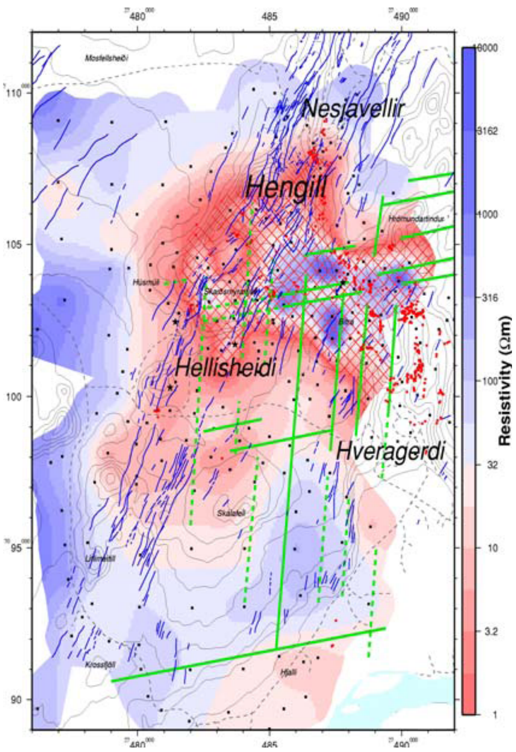

Figure 2 – Hengill. Resistivity at 100 m b.s.l. according to a recent TEM survey. In blue are visible fault lines; green: faults as defined by earthquake locations (from Arnason and Magnusson, 2001).

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

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

Sedimentary Rocks at Gross Schönebeck/Germany.

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

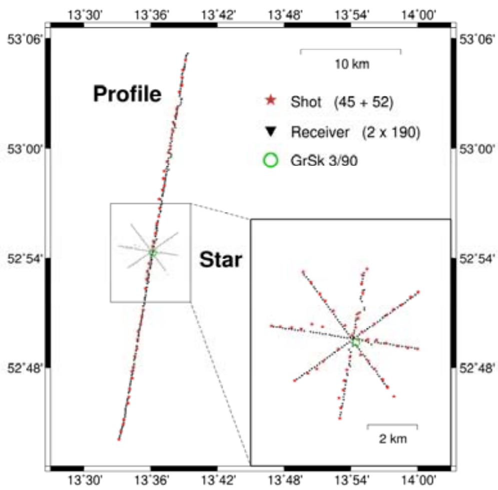

Figure 3: *Experimental setup of the seismic campaign I-GET 2006 around the well Gross Schönebeck (GrSk 3/90). The star profile was designed to get an image of the seismic anisotropy of the subsurface. The long profile was duplicated by MT measurements and complemented by a dense grid of MT stations around the well.*

Problems with geophyiscs arise because of the regional geology, typical of the Southern Permian Basin, which is strongly affected by salt tectonics. The wells at Gross Schönebeck reached the reservoir rocks at a depth of 4100 m in Lower Permian sandstones and volcanic rocks beneath a more than 1 km thick salt pillow (Upper Permian/Zechstein). This salt layer not only dampens all seismic signals but also constitutes a highly conductive body, which represents a challenge for magnetotellurics, which is aimed at finding the conductive reservoir below the salt.

Moeck I, Schandelmeier H and Holl HG (in press). The stress regime in the Rotliegend of the NE German Basin: Implications from 3D structural modelling. Int J Earth Sciences.

Cappetti G., Fiordelisi A., Casini M., Ciuffi S., Mazotti A. (2005) – A new deep exploration program and preliminary results of a 3D seismic survey in the Larederello-Travale geothermal field (Italy), Proc. World Geothermal Congress 2005.

Arnason K. and I.Þ. Magnusson: Geothermal activity in the Hengill area. Results from resistivity mapping. Orkustofnun report, in Icelandic with English abstract, OS-2001/091, 250 p., (2001).