GEOPHYSICAL EXPLORATION OF GEOTHERMAL RESOURCES

V. Spichak[1], A. Manzella[2]

[1]Geoelectromagnetic Research Centre IPE RAS, Troitsk, Russia, e-mail v.spichak@ru.net

[2] Institute of Geosciences and Earth Resources, CNR, Pisa, Italy, e-mail manzella@igg.cnr.it

REGIONAL SCALE

Main tasks: Regional geophysical surveys are aimed at studying geological structures (inter-arc basins, subduction, spreading and rift zones, faults) that could host the geothermal reservoirs and contain appropriate ways of the heat transfer to the surface.

Main methods used: magnetotelluric (MT) and seismic surveys, while gravity and aeromagnetic ones are often applied for increasing the reliability of conclusions drawn basing on the former two methods.

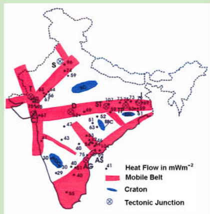
Seismic tomography of the earth's crust (being quite expensive) reveals the geometrical boundaries of the lithological units and is especially good in detection of the regional stratigraphy.

Magnetotelluric sounding (relatively cheap method) results in the resistivity model of the studied area that may be interpreted in lithological terms and guide the most favorable areas for future geothermal exploration.

Aeromagnetics provides the large-scale horizontal zonation and estimation of the Curie temperature depth.

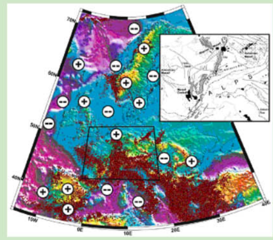
Gravity data provides large-scale density distribution, which is related to lithospheric structure.

CORRESPONDENCE OF THE TECTONICALLY ACTIVE REGIONS AND HIGH HEAT FLOW



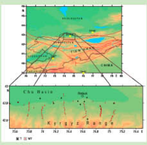
Tectonically active regions and heat flow data in India (Veeraswamy and Harinarayana, 2006). The presence of high conductive anomalies in the upper crust of the Himalayan belt region revealed by magnetotelluric sounding is attributed to the presence of partial melt generated from the subducted Indian crust. More detailed geophysical studies provided in this area afterward revealed two perspective geothermal zones.

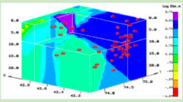
SEISMICITY AND TECTONIC FEATURES



Topographic map of Europe with superimposed distribution of seismicity (red dots), illustrating present-day active intraplate deformation (Cloetingh et al, 2005).

TECTONIC STRUCTURE REVEALED FROM REGIONAL MAGNETOTELLURIC SOUNDING





Upper panel: MT sites location map in the northern Tien Shan crustal area.

Lower panel: Volume resistivity model (Spichak et al., 2006). Maximal correlation zones between bulk resistivity and EQ hypocenters are marked by red color.

INTERMEDIATE SCALE

Main tasks: Geophysical studies at the intermediate (concessional) scale are aimed at delineating of the potential geothermal fields and identifying the permeable zones, which could be targets for future drilling.

Main methods used: Seismics and EM; gravity and aeromagnetic surveys optionally

Seismics

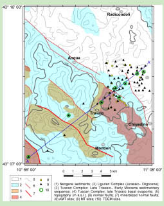
A number of seismic methods such as repeated 3D surface seismic, surface-to-borehole vertical seismic profiling and borehole-to-borehole cross well seismic are applied. Seismic methods enable to detect the stratigraphy of the area and provide a good geometrical resolution of the main lithological units.

Disadvantages of seismic methods are their weak response from permeable zones and high cost.

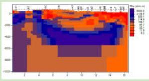
Electromagnetics

Electromagnetic techniques are extensively used for imaging geothermal regions mainly due to their ability to delineate high conductive fluid bearing areas in the earth's crust and to determine the azimuths of the fracture zones. Disadvantages of electromagnetic methods are their low geometrical resolution and noise (both geological and industrial) sensitivity.

EM MAPPING HYDROCIRCULATION ZONES

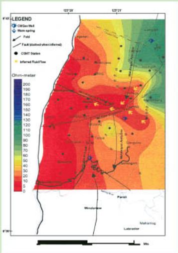


Site location map in the Travale area (Italy)



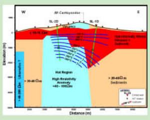
2D model along profile AA' (SW on the left, NE on the right) (Manzella et al., 2006).

EM DETECTION OF AZIMUTHS OF FRACTURE ZONES

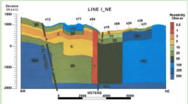


Geophysical model of the Malabuyoc thermal system at 250 m below sea level (Del Rosario et al., 2005).

EM MAPPING PERMEABLE ZONES



Resistivity structure correlated with lithology and temperature at Southern Leyte, Philippines (after Layugan et al., 2005).



Resistivity model of the Las Tres Virgenes geothermal field (Baya California Peninsula, Mexico) along line I_NE. A graben structure outlined between sites s12 and s10, is bounded by 1 Ohm·m vertical conductors presumably associated with the El Partido and El Azufre faults (after Romo et al., 2000).

LOCAL SCALE

Main tasks: Geophysical studies at the local scale are aimed at spatial delineating of the geothermal reservoir, indirect evaluation of the temperature, porosity, permeability and other parameters of the geothermal zone.

Main methods used: 3D electromagnetics and borehole geophysics (vertical seismic profiling, acoustic imaging, borehole gravimetry).

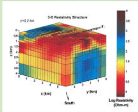
3D Electromagnetics

Modern 3-D EM modeling, imaging and inversion tools enable reconstruction of the most adequate geoelectrical structures of geothermal areas that, in turn, could be used for delineating of the reservoir and the cap layer in different geological environments.

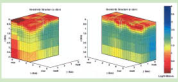
Integration of geophysical methods

Integration of the geophysical data with rock physics data, lithology, temperatures, permeability, and geological information improves the imaging of static and dynamic processes of geothermal systems. The key element in the joint interpretation could be the use of geothermal reservoir simulators to obtain a final model that complies with all the available data.

3D EM IMAGING GEOTHERMAL RESERVOIRS

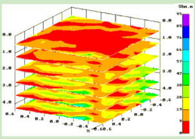


3-D resistivity model of the Ogiri geothermal zone, Japan (Uchida, 2005). At mid depths (from 400m to 800m) the whole area is conductive, while beneath 800m one can see high-resistivity anomalies, attributed to the geothermal reservoirs.

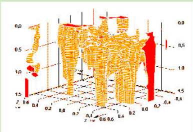


3-D resistivity model of the Pohang low-enthalpy geothermal area, Korea (Uchida et al., 2005). The survey area has underlying low resistivity layer (resistivity less than 10 Ohm.m). Below there is a high resistivity layer of approximately 100 Ohm.m, corresponding to Cretaceous sandstone/mudstone and Tertiary rhyolite intrusion. At depths greater than 3 km, a low resistivity anomaly is seen.

3D EM MAPPING CLAY CAP

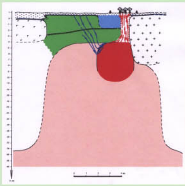


Resistivity model of the Minamikayabe geothermal zone, Japan (after Spichak, 2002)



Highly conductive cap (resistivity less than 9 Ohm.m) in the Minamikayabe geothermal area (after Spichak, 2002).

INTEGRATED MODEL OF THE GEOTHERMAL ZONE REVEALED FROM GEOPHYSICAL DATA



Conceptual model of Mutnovsky vapor-hydrothermal deposit (Kamchatka) based on electromagnetic (MT, DC, TEM), aeromagnetic, seismic and gravity data (after Spichak et al., 2007).

Pink color corresponds to partial melting while red color corresponds to melting area; green color marks rocks saturated with highly mineralized fluids; blue area is a reservoir filled with a chilled mineralized water and vapor; crosses mark heated granodiorite intrusion; dots correspond to volcanogenic sediments; red arrows mark flows of overheated vapor-gas-water mixture while blue arrows correspond to flows of cool meteoric water.

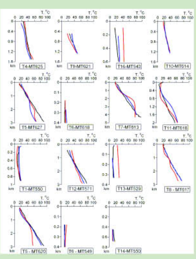
TEMPERATURE ESTIMATION BY MEANS OF INDIRECT EM GEOTHERMOMETER

A new method of indirect electromagnetic (EM) temperature estimation in the earth's interior developed recently (Spichak et al., 2007), may enable one (1) to estimate the sub-surface temperature distribution in cases when the number of temperature logs available is insufficient; (2) to perform more precise temperature estimations in extrapolation mode; (3) to monitor the temperature at depth basing on surface observations of EM field; (4) to carry out remote temperature estimations in geothermal wells with extreme conditions unsuitable for traditional geothermometers as well as in productive wells without affecting the exploitation process.

The method proposed is illustrated by the analysis of EM and temperature data measured in the northern Tien Shan and Hengill geothermal area. It is shown that using an optimal strategy for EM measurements and involvement of available temperature logs leads to reduction of the remote temperature estimation errors down to their minimal level. In particular, usage of only 6-8 temperature logs for calibration of the EM geothermometer results in 12% relative error of the temperature estimation, whereas availability of prior geological information about the region under study decreases this error up to 9%.

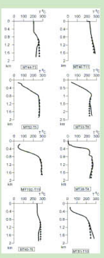
Indirect EM geothermometer may also greatly improve the temperature estimation accuracy in the case of its extrapolation both laterally and in depth. In particular, in the latter case the temperature estimation at depths 2 times bigger than the corresponding well depths results in average relative accuracy of the temperature extrapolation equal to 5.9%. This result opens the way of wide application of indirect EM geothermometer to the temperature estimation in the reservoirs located much deeper than the depths of drilled wells.

TEMPERATURE ESTIMATION BY MEANS OF EM GEOTHERMOMETER CALIBRATED BY DATA MEASURED IN OTHER WELLS



Measured and estimated temperature distributions in wells (northern Tien Shan) (Spichak et al., 2007).
Black line – measured temperature, red line – temperature model based on the temperature logs only, blue line – temperature model based on MT data.

TEMPERATURE ESTIMATION BY MEANS OF EM GEOTHERMOMETER CALIBRATED BY DATA MEASURED IN THE SAME WELL



Well logs (solid lines) and estimated temperature profiles (lines with triangles) obtained using extrapolation on the lower half of the profile by EM geothermometer calibrated on the upper half of the profile (Hengill geothermal area, Iceland) (Spichak and Zakharova, 2008).

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