

# A REVIEW OF THE RESULTS PRESENTED IN WGC 2005 CONCERNING THE INVESTIGATIONS OF ENHANCED GEOTHERMAL SYSTEMS

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During the WGC2005 held last May in Antalya the papers presented in the geophysics section, concerning geothermal geophysical surveys were as follows:

## **1. Exploration**

### **1.1 Resistivity measurements**

Resistivity measurements has been traditional a very popular method used in geothermal exploration. Its principle has been that the conductivity, ( $\sigma = 1 / \text{resistivity}$ , or the inverse of resistivity) of the subsurface formations depends on the type of rock, the minerals it includes, as well as the presence, temperature and salinity of water. It has been very successful in identifying and delineating geothermal resources; for example, the high enthalpy geothermal fields of New Zealand are characterized by low resistivity and a sharp resistivity boundary. The low resistivity of geothermal production targets is attributed to the presence of rocks with high degree of alteration, as well as to the high temperature and the salinity of the geothermal fluids.

The main methods used have been Schlumberger (DC) resistivity and the more recent Magnetotellurics (MT).

Regarding the exploration for enhanced geothermal systems, where neither altered rocks nor native geothermal fluids are present, resistivity measurements can still provide an excellent imaging of the subsurface formations and main fault zones down to depths 2-3 km. This means that subsurface formations which will be the target for engineering an artificial reservoir can be identified. Furthermore, resistivity measurements can be particularly useful when engineering an enhanced geothermal system within or close to the boundaries of a hydrothermal system, where high temperatures (150-200°C) are present at depths less than 3 km.

During the World Geothermal Congress 2005, 21 papers concerning resistivity survey were presented, of which:

- 5 papers concerned Schlumberger resistivity or similar
  - two on 1-D inversion concerning Sinai Peninsula, Egypt [1] and Kuju Volcano, Japan [2]; and
  - three on 3-D inversion concerning Cerro Prieto, Mexico [3], Sibayak, Indonesia [4] and Sumikawa, Japan [16]; the last two concern the Mise-ala-Masse technique (MAM).
- 15 papers concerned MT

- six on 1-D inversion concerning Dnieper, Ukraine [5], Takigami, Japan [7], Central Philippines [8], Mahagdong, Leyte, Philippines [9], Southern Negros, Philippines [10], and Geysir, Iceland [11];
  - five on 2-D inversion concerning East Carpathians, Ukraine [6], Takigami, Japan [7], las tres Virgenes, Mexico [12], Sabaln, Iran [13] and Afyon, Turkey [14];
  - four on 3-D inversion concerning Russia and Minamikayabe field of Japan [15], in Ogiri of southwestern Japan and Matoloko of eastern Indonesia [17], Pohang, Korea, where noise interference at frequencies 0,1-100 Hz was severe [18], and in Coso, California, USA [19]; the latter paper discusses issues related to enhanced geothermal systems and noise interference from man-made sources;
  - one on 1D-inversion CSMT in Malabuyoc low enthalpy geothermal field, Cebu, Philippines [20]; this method is also actively used for water exploration in USA.
- 1 paper concerned resistivity measured from cores taken from unaltered surface basaltic lavas (2 samples), or from deep geothermal wells corresponding either to the smectite zone (5 samples) or to the chlorite alteration zone (5 samples) in Iceland [21].

## 1.2. Heat Flow Measurements

Heat flow has been traditionally used together with resistivity in order to identify hydrothermal resources. As geothermal energy is essentially the heat of the earth, measuring heat flow towards the surface will identify regions where geothermal energy is more concentrated, e.g. areas where elevated temperatures are present in shallow depth.

Traditional methods include (i) temperature measurements in boreholes and calculation of the temperature gradient and (ii) mapping of surface manifestations (warm springs, fumaroles, mud pools, hot/steaming ground, geysers) plus measuring their temperature and flow rates. Novel methods include (i) airborne gamma ray survey, as natural radiation is one component of geothermal energy generation, (ii) airborne magnetic survey, as rocks of high temperature lose their ferromagnetic properties, and (iii) earthquake survey, as earthquake hypocenters are never encountered within partially melted rocks.

Regarding engineering future enhanced geothermal systems, heat flow measurements, can effectively identify areas where the higher temperature at depth will result in lower capital costs.

During the World Geothermal Congress 2005, 10 papers concerning heat flow surveys were presented, of which:

- 3 papers concerned flow manifestations measurements (Japanese islands [22], Kuju volcano, Japan [23], and Craters of the Moon fumarole's field in Wairakei, New Zealand [24])
- 4 papers concerned borehole temperature surveys (Dnieper, Ukraine [5], East Carpathians, Ukraine [6], Daghestan republic, Russia [26], The Geysers/Clear Lake Area, California, USA [27])
- 1 paper concerned airborne aerial gamma ray survey of Gebel Duwi Area, Egypt [28]

- 1 paper concerned airborne magnetic survey coupled with Euler method and Curie point depth estimation in the Sinai Peninsula, Egypt [1]. Curie point is defined as the surface boundary, where high temperatures at depth cause the rocks to lose their ferromagnetic properties
- 2 papers concerned earthquake surveying and determination of the depth below which partial melting of the rocks starts (Japanese islands [22], Iceland [29])

### **1.3. Gravity Measurements**

Measuring the local gravity field of the earth, provides an estimation of the distribution of subsurface rock density, especially when local geology is known. This is useful for mapping the top of a deeper formation of different density.

During the World Geothermal Congress 2005, 2 papers concerned gravity measurements in the fields Hoho Geothermal Area, Central Kyushu, Japan [30] and Rendingan-Ulubelu-Waypanas in Tanggamus Regency, Lampung, Indonesia [31].

### **1.4. Reflection Seismics**

Although reflection seismics is the primary method used for locating petroleum reservoirs, it has been also used in geothermal exploration, in order to locate major deep fault zones, especially in areas where resistivity measurements cannot penetrate down to the target depth. Deep fault zones are the primary target for production drilling, as faults tend to generate fractured permeability and provide a channel for the deeper hot fluids to rise.

Reflection seismics can effectively be applied in engineering enhanced geothermal systems in order to identify subsurface fractured zones, where enhancing existing permeability should be faster, and of lower effort and cost.

During the World Geothermal Congress 2005, 2 papers concerned reflection seismics, both in the Larderello-Travale vapor dominated geothermal field in Italy, which is operated by ENEL for power generation [32], [33].

### **1.5. Porosity**

Porosity is an essential variable for the calculation geothermal energy output, reservoir performance during exploitation and designing the geothermal plant. It is necessary for the engineering of the enhanced geothermal reservoir. During the World Geothermal Congress 2005, 2 papers concerned porosity measurements (Kuril islands, Russia [25], Iceland [21])

## **2. Reservoir monitoring during exploitation**

### **2.1. Micro Gravity Transients**

Micro Gravity transients are useful when monitoring the fluid withdrawal from a geothermal reservoir during exploitation. It has been proved that gravity transients are directly associated

to the total mass of geothermal fluid withdrawal from the system. It can provide clues such as the drop of water level and the evolution of the two phase region.

In an enhanced geothermal plant, where the water mass within the artificial reservoir remains the same this method may not prove of particular importance.

During the World Geothermal Congress 2005, 3 papers concerned micro-gravity transients They correspond to the following geothermal fields: Leyte, Philippines [34], Semarang alluvial plain in Central Java, Indonesia [35], Hatchonaru, Central Kyushu, Japan [36])

## **2.2. Micro-Seismic Activity**

Monitoring micro-seismic activity provides useful information on the location of deep fractures which may be associated with the geothermal reservoir. In addition, micro-seismic activity has also been associated with reinjection.

In enhanced geothermal systems, micro-seismic activity is associated with the hydraulic fracturing process and appears to be their only environmental impact that is worth considering. Monitoring micro-seismic activity during exploitation will provide a good assessment of the potential seismic risk, although the authors believe that the magnitude of the induced micro-earthquakes due to contraction of the rock, should not exceed the ones observed in existing hydrothermal systems.

During the World Geothermal Congress 2005, 4 papers concerned micro-seismic activity evolution. They correspond to the following geothermal fields: Mutnovsky geothermal field, Southeast of Kamchatka, Russia [37], Darajat, Java, Indonesia, where micro earthquake activity was correlated clearly with reinjection [38], Ogiri geothermal field in southern Kyushu, Japan, where microseismic activity was used to study the evolution of the two phase zone [39], and Lahendong Geothermal Field, North Sulawesi, Indonesia [40].

Micro-Gravity transients and Micro-Seismic activity monitoring are the main geophysical surveys monitoring geothermal production.

## **2.3. SP and temperature transients**

Temperature transients are an important parameter, which determines the degree of cooling that may occurs in the geothermal production field due to exploitation or reinjection. Regular temperature measurements are taken on the geothermal production wellheads, but downhole measurements in monitoring wells are also performed. Although the SP method may provide some information on main faults and alteration zones during exploration, its usefulness during production seems unclear.

Temperature transients should be monitored during the exploitation of an enhanced geothermal system, in order to determine the degree of cooling that is taking place within the artificial reservoir, which will be important after many years of exploitation in order to decide how to further engineer the plant.

During the World Geothermal Congress 2005, one paper each on SP transients concerning Mori and Matsukawa geothermal fields in Japan [41], and changes in borehole temperature at the Kuju volcano, Japan [23] were presented.

### **3. Philippines**

It is worth focusing on the case of Philippines, as they are the second geothermal power in the world with approximately 2000 MWe of installed geothermal power and the highest growth rate.

There, before 1995 the key method to geothermal exploration was the Schumberger Resistivity. This was used to delineate geothermal resources, well sitting and estimation of the plant size. They have been successful with approximately 1000 MWe installed at that time.

After 1995 they shifted to MT with 1-D inversion, due to its simplicity, easy to use, and its ability to provide reliable earth imaging at greater depths, down to 2 km. The result was to identify deeper hydrothermal resources and at greater aerial extent, which resulted in another 1000 MWe to be installed within the next 10 years. Schumberger resistivity was only able to identify shallow smectite zones of high alteration, which form the cap of the deeper geothermal reservoir. On the other hand, MT method was able to directly locate the actual deeper drilling target of intermediate resistivity, as well as several enhanced geothermal zones of high resistivity. The latter are not considered as geothermal exploration targets at present, but the authors are certain that they will become in the future. Engineering enhanced geothermal systems at these rocks of high temperature (250°C) located at depths 1,5-2,0 km, will be economically attractive.

Controlled source MT have been used in low enthalpy groundwater systems, based on US experience for water surveys.

### **4. Italy**

Italy has been the pioneer in geothermal power generation, with the first pilot plant developed in the early 1900's. Today, with more than 700 MWe of installed power, Italy is the leading European country in geothermal power generation. With its many volcanic regions, Italy is rich in geothermal potential, including enhanced geothermal systems.

Although in the geophysical section of the World Geothermal Congress Italy is represented by only two papers, both on reflection seismics, they are worth to be mentioned, as they concern depths greater than 3 km, where the imaging quality of MT method deteriorates, due to intense noise from surface sources at frequencies below 2 Hz. ENEL has successfully applied reflection seismics in order to locate deep fault zones as drilling targets at depth ~4 km. As already mentioned, faults tend to bring fluid from depth and create high permeability in their vicinity.

### **5. MT, 3-D inversion**

Papers here concerned mainly basic research. 3-D inverted MT data are theoretically more accurate than 1-D and 3-D inversion can provide a better starting point to the earth scientist to define the resistivity substructure. However, its use in the field has been limited by its complexity and the need for sophisticated computing equipment. More research is needed in inversion algorithms, elimination of noise which hinders its accuracy at lower frequencies associated with depths below 2-3 km [15], [20], and especially correlation with field data from deep wells.

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