Exploration of Geothermal Water Resources using Magnetotelluric Methods – some examples

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PBG LTD. is a leading Polish contractor with over 60 years experience in geophysical surveys for petroleum, mineral and water resources exploration.

PBG LTD. specializes in geophysical non-seismic methods. Offered services include data acquisition, processing and interpretation together with integrated interpretation of geophysical-geological data.

PBG LTD. operates high-technology geophysical equipment and use the latest professional software, and in the certain areas of operation occupies a leading position in Poland, such as in the case of specialized magnetotelluric and gravity survey, and integrated geophysical-geological interpretation for structural and deposit purposes. PBG Ltd. has skilled and qualified staff with good professional experience and international practice.
TYPES OF ELECTROMAGNETIC methods adopted by PBG Ltd.:

**Natural source**
- **MT** – magnetotellurics, frequency range 400 – 0.00005 Hz
- **AMT** – audio-frequency magnetotellurics, frequency range 10 kHz – 1 Hz

**Artificial Source**
- **CSAMT** – controlled source audio-frequency magnetotellurics, frequency range 10kHz – 1 Hz
- **TEM** – Transient Electromagnetic
- **IP** – Induced Polarization (time and frequency domain)
MAGNETOTELLURIC METHOD

The magnetotelluric (MT) method uses measurements of the natural electric (E) and magnetic (H) fields at the surface of the earth to determine the distribution of electrical conductivity within the earth. Field sources are: equivalent current systems in the magnetosphere (below 1 Hz) and lightning discharges in the earth-ionosphere cavity.

Penetration depth depends on resistivity of rocks and frequency

Typical values of resistivity of rocks

Figure by: Anna Marti, Ph.D. Thesis, modified from Palacky, 1987

Figure by: Karen Rae Christopherson, Chinook Geoconsulting, Inc. Evergreen CO USA
Basic theory

Impedance tensor:

\[
\begin{bmatrix}
E_x \\
E_y \\
\end{bmatrix} = \begin{bmatrix}
Z_{xx} & Z_{xy} \\
Z_{yx} & Z_{yy} \\
\end{bmatrix} \cdot \begin{bmatrix}
H_x \\
H_y \\
\end{bmatrix}
\]

2D solution:

If: \( Z_{xx} = Z_{yy} = 0 \) and \( Z_{xy} \neq -Z_{yx} \)

\[
Z_{xy}(\omega) = \frac{E_x(\omega)}{H_y(\omega)} \quad \Rightarrow \quad \rho_{a,xy}(\omega) = \frac{1}{\omega \mu} \left| \frac{E_x(\omega)}{H_y(\omega)} \right|^2 \quad \varphi_{a,xy}(\omega) = \tan^{-1} \left( \frac{E_x(\omega)}{H_y(\omega)} \right)
\]

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\]
MT acquisitions

Schemes of MT/AMT measurement system – soundings array

system2000.net (Phoenix Geophysics Ltd.)

Schedule of presentation:

1. Introduction
2. Basic theory
3. MT acquisition
4. Data processing
5. Geothermal environment
6. Some examples
7. Conclusions
Controlled Source Audio-frequency Magnetotellurics - CSAMT

CSAMT is an electromagnetic (EM) exploration method based on assumptions taken from magnetotellurics (MT) which uses a fixed grounded dipole as an artificial signal source. The signal strength, which is a main problem in the MT method was original motivation to develop CSAMT. The source provides a stable signal, resulting in higher-precision and faster measurements than are usually obtainable with natural-source measurements in the same spectral band.
Schedules of CSAMT measurement system
system2000.net (Phoenix Geophysics Ltd.)

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MT acquisitions

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Schemes of CSAMT measurement system
system2000.net (Phoenix Geophysics Ltd.)

Apparent resistivity:
\[ \rho_a(f) = \frac{1}{5f} \cdot \frac{AEx}{AHy} \]

Apparent phase:
\[ \phi(f) = \arg(Ex) - \arg(Hy) \]
SCHEME OF MAGNETOTELLURIC DATA ACQUISITION

Recording of time series of electric and magnetic components of natural MT field

Reciever

Time series

SCHEME OF MAGNETOTELLURIC DATA PROCESSING

Estimation of impedance tensor \([Z]\) from EM spectra and then calculation of MT apparent resistivity and impedance phase curves.

SSMT 2000: Robust Processing

MT Editor

WinGLink

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Data processing

MAGNETOTELLURIC QUALITATIVE INTERPRETATION

Analysis of MT data parameters such as polar diagrams, skew and pseudo-sections of resistivity, phase and show main features of geoelectrical structures, dimensionality etc.

MAGNETOTELLURIC QUANTITATIVE GEOLOGICAL INTERPRETATION

1D/2D and 3D forward modelling and inversions give resistivity distribution in depth domain which can be used in geological interpretation
Proposals for a solution the task of geological:

1. **1D Occam inversion (smooth inversion)**
   
PRACTICALLY INDEPENDENT OF THE SUBJECTIVE INTERPRETER, FAST BUT GENERATES A LOW-RESOLUTION MODEL FOR THE LARGER DEPTH (> 400M)

2. **2D NLCG (Non-Linear Conjugate Gradients) inversion for halfspace as starting model**
   
SIMILAR SOLUTIONS AS IN THE CASE OF 1D OCCAM INVERSION, ADAPTED FOR TWO-DIMENSIONAL STRUCTURES. SIGNIFICANT ADVANTAGE IN THE CASE OF ACQUISITION OF TWO PERPENDICULAR MEASUREMENTS OF ELECTRIC AND MAGNETIC FIELDS.

3. **2D NLCG (NON-LINEAR CONJUGATE GRADIENTS) INVERSION FOR A FIXED STARTING MODEL**
   
INTRODUCING OF A PRIORI INFORMATION CAUSES MORE ACCURATE CONTROL OF THE SOLUTION INVERSION PROBLEM. GREAT ADVANTAGES IN TERMS OF RESOLUTION, NECESSITY TO HAVE THE INFORMATION FROM BOREHOLES, SEISMIC, ETC.

4. **1D Least Squares inversion (detailed inv, LSQ)**
   
ALLOWS INTRODUCING OF A PRIORI INFORMATION FOR PARTICULAR SOUNDING. HIGH RESOLUTION MODEL AS AN OUTPUT, A VERY TIME-CONSUMING.

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Generalized model of convective hydrothermal system

Acc. Controlled Source Electromagnetic Methods In Geothermal Exploration by Stanley H. Ward
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Geothermal reservoir model in volcanic area  
*(acc. Cumming 2007)*

Distribution of resistance model in the geothermal reservoir zone  
*(acc. Cumming, 2007)*
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Geothermal reservoir model in volcanic area (acc. Cumming 2007)

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Resistivity of solutions of sodium chloride as a function of concentration and temperature (taken from Keller and Frischknecht, 1966)

Resistivity as a function of temperature at different pressures (modified from Quist ans Marshall, 1968)
Examples of application MT/AMT and CSAMT for geothermal prospecting
Examples No. 1

Detailed magnetotelluric survey (EMAP) for geothermal prospecting

Geoelectrical cross-section based on Bostick transformation show low resistivity zone connected with thermal water occurrence

Examples No. 2

Detailed CSAMT survey for geothermal prospecting

Geological cross-section and result of CSAMT 2D data inversion from survey made for recognizing fault zone connected with thermal water occurrence.

- Proposed area for the performance drillhole.
Examples No. 2

Detailed CSAMT survey for geothermal prospecting

Geological cross-section and result of CSAMT 2D data inversion from survey made for recognizing fault zone connected with thermal water occurrence.

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Examples No. 2

Detailed CSAMT survey for geothermal prospecting

Geological cross-section and result of CSAMT 2D data inversion from survey made for recognizing fault zone connected with thermal water occurrence.

LOW RESISTIVITY ZONES
– THERMAL WATER
Example from geothermal prospecting in Sudety Mts. area, Poland

Geophysical recognition of tectonic zones prospective for geothermal exploration

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Examples No. 4

Example from geothermal prospecting in Sudety Mts. area, Poland

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Example from geothermal prospecting in Polish Foredeep, Poland

Examples No. 5

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Conclusions

Summary

It was presented three EM methods for geothermal exploration: CSAMT, AMT, MT.

Choice of one of them depends on the depth range, geology, EM noise, and the required level of detail.

There is a relationship between the resistivity and temperature and/or mineralization of water.

Because AMT / MT / CSAMT is sensitive to conductivity so these methods are strongly recommended for geothermal prospecting.

Distribution of resistivity in the geological lithology shows variation depending on the porosity, fracturing, salinity and temperature of the media saturating.

So low resistivity zones indicate the best places for borehole, of course if it is justified from geological point of view (a few examples have been presented).
Thank you for your attention

Sudety Mts. area, Poland

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