Effectiveness of magnetotelluric method for geothermal exploration

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Effect of clay minerals on electrical resistivity

Montmorillonite reduces electrical resistivity more intensively than other clay minerals.

This work was for exploration of hydrothermal mineral deposits.
Resistivity decreases by more than one decade when temperature increases from 15 to 200 degrees C.

Yokoyama et al. (1983)
2D MT in Sumikawa geothermal field

Uchida et al. (1994)
Uchida et al. (1994)
Typical Resistivity of Geothermal Reservoir

**Alteration minerals**

- Glass
- Olivine
- Plagioclase
- Albite
- Epidote
- Titanite
- Wairakite
- Opales

**Schlumberger 2D model in Iceland**

- Unaltered rocks
- Smedite - zeolite zone
- Mixed layered clay zone
- Chlorite zone
- Chlorite-epidote zone

Franzson (1994)

Arnason et al. (1987)
3D MT in Ogiri Geothermal Field

Uchida (2005)

x = 150 deg.
y = 60 deg.
3D Resistivity Model, depth sections

PLAN VIEW: Case-1 (MT) ogr_42w_353, n=1%, iter=8, rms=9.71, ss=0.694

Uchida (2005)
3D MT Responses: Line-B

(b) Line-B

Static Shift

Sakkogawa F.  Pad B  Power Plant

Low resistivity

Ginyu F.

Shiramizugoe F.
Shiramizugoe

Case-1: MT sites (0.070 - 72 Hz)

Uchida (2005)
Case-1: MT sites (0.070 - 72 Hz)

Ogiri
Comparison with 2D Models (1)

2-D (TM-mode)

Uchida (2005)
Comparison with 2D Models (2)

Line-B

2-D (TM-mode)

3-D

Uchida (2005)
Shiramizugoe Field
4 wells (300 t/h steam)

Clay Cap
Ogiri Reservoir

from NEDO (2000)
Uchida (2005)
3D MT survey has rapidly expanded since late 2000s:

- USA
- Japan
- New Zealand
- Iceland
- East Africa
- Indonesia, …

3D inversion codes in WGC2015 papers:

- Siripunvaraporn et al. (2005, 2009): WSINV3DMT
- Hautot et al. (2007)
- Egbert and Kelbert (2012): ModEM
Yanaizu-Nishiyama geothermal field

65 MWe Power Plant in operation since 1995
Red dots in 2000/2001
39 stations
(26 are in the figure)

Green dots in 2010
30 stations

DC railway at 25 km distance

Uchida et al. (2015)
Time Series Data

Site 630
(x=N32° E)

10 minutes
21:00 – 21:10
23 Oct 2010

Reference site
(x=true north)

DC train

Auto-scale
Data Example

Site 630

Apparent Resistivity

Phase

Data for 4 days
3D Inversion: Area-1

Rotation = 55 deg.

51 stations, 15 freq (0.0134 - 229Hz)

- Zxy / Zyx
- Finite difference
- Static shift
- No topography

(Uchida&Sasaki, 2006)

- Forward cells: 59(x) x 57(y) x 40(z)
- Cell size (surface): 100m(x) x 100m(y) x 25m(z)
- Blocks: 17(x) x 16(y) x 18(z) = 4896
Area-1:  
3D Model  
Depth-slice sections  
Artifact?  

Uchida et al. (2015)
ynz_10_m35c (MT, rot=55deg, 15 freq) 18-layer allfreq iter=20

Area-1:

Data Fitting
Area-1: Cross section (x=1.4km, y=1.0km)

Resistivity Structure (x)

Resistivity Structure (y)

Looking from east

Uchida et al. (2015)
Rotation = 90 deg.

- 59 stations,
- 14 freq (0.0134 - 115Hz)
- Zxy / Zyx
- Finite difference
- Static shift
- No topography

- Forward cells: 83(x) x 77(y) x 40(z)
- Cell size (surface): 100m(x) x 100m(y) x 25m(z)
- Blocks: 29(x) x 26(y) x 18(z) = 13,572
Rot = 55 deg.  

Rot = 90 deg.  

Uchida et al. (2015)
Production and injection wells
Profile A-A’: Comparison with drilling data

Rot = 55 deg.

Rot = 90 deg.

Average elevation 400m assumed
Profile D-D’: Comparison with drilling data

Rot = 55 deg.

Rot = 90 deg.

Average elevation 400m assumed

Uchida et al. (2015)
Clay minerals

Upper limit of Chlorite

Uchida et al. (2015)
First full MT in NZ in 1998 by GSJ & GNS

Taupo Volcanic Zone (TVZ)

Figure 4. (a) Model of the resistivity structure derived from inversion of resistivity and phase from both the TE and TM modes. Major conductive and resistive features are labeled as C1 to C7 and R1. (b) Estimated range of resistivity for each resistivity block. The ratio of the upper to lower estimates of the resistivity is shown by gray scale. A darker color means a more reliable estimate.

Ogawa et al. (1999)
Wide MT coverage to obtain deep resistivity image and an overall geothermal model.

Bertrand et al. (2015)
Dense local MT coverage to obtain detailed resistivity image of a specific geothermal field: Ohaaki.

Bertrand et al. (2013)
3D MT in Rotorua by GNS

Fig. 11. NW–SE cross section through the 3-D resistivity model for the NW–SE profile shown in Figs. 6 and 9. Black circles show seismicity from Rannister et al. (in this issue) with events within 3.5 km of the profile projected onto the cross-section. The transitional zone where we expect magmatic fluids to interact with the surrounding meteoric water is shown schematically by hatched zones around the margins of the conductive zones. The northern margin of C3 is less well defined due to a lack of data coverage within the built up area of Rotorua; the reduced definition being indicated by the question mark.
The role of MT for geothermal exploration

- MT is the most important geophysical tool for geothermal exploration.
- 2D model is useful only when real geologic structure is close to 2D; but often gives false anomalies for deep structure.
- 3D model is needed in all exploration for reliable interpretation, although it requires longer field measurement and intensive computation time for interpretation.
- Many trials of inversion are necessary to obtain satisfactory model.

Message from Yanaizu-Nishiyama MT data

- The inversion result that only utilized the dense MT stations over the geothermal field (Area-1) produced artifacts along the edge of the interpretation zone, probably caused by anomalous structure that exists at the edge or just outside of the target area.
- Inclusion of outside MT stations (Area-2) in the 3D inversion can reduce such artifacts and improve the model reliability at a deeper part of the target area.
Issues of 3D MT inversion to be solved for geothermal application soon.

- Topography must be included.
- Four components of the impedance and two components of the vertical transfer function should be considered.
- Static shift and galvanic distortion should be included.