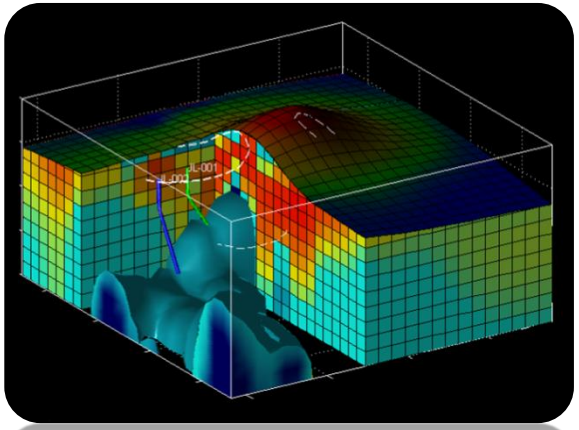
Training for Trainers

MAGNETOTELLURIC TECHNOLOGY FOR GEOTHERMAL EXPLORATION



Dr. Eng. Yunus Daud, Dipl. Geotherm. Tech., M.Sc.

Training for Trainers – Magnetotelluric (MT) Technology for Geothermal Exploration
Margo Hotel, Jakarta. 25th – 30th July 2016

UNDERSTANDING ELECTRICAL PROPERTIES OF ROCK FORMATION

Conduction Mechanisms in Earth Materials

1. Electronic Conduction

Electronic conduction occurs in pure metals. The charge carriers are electrons that exist as a gas between ions and can move very easily through the metal. Typically very low resistivity (~ 1.6 10^{-8} Ωm)

2. Semiconductors

Semi conduction occurs in minerals such as sulphides. Here the charge carriers are electrons, ions or holes. The resistivity is usually higher (typically 10^{-3} to 10^{-5} Ωm). This type of conduction occurs in igneous rocks and usually shows a temperature dependence of the form:

$$\rho \approx e^{\frac{E}{kT}}$$

where *T* is the temperature in *K, E* is an activation energy and *k* is the Boltzmann constant.

3. Ionic Conduction in Liquids

In liquids (aqueous fluids or molten materials) the ions can freely move. As the salinity of a brine increases, the resistivity decreases as more charge carriers become available.

Electrical Properties of Rock Formation

- A useful empirical relationship between **bulk resistivity (ρ), porosity (φ), water saturation (*Sw) and fluid* resistivity (ρ*w) has been widely used (Archies law):***

$$\rho = a\rho_w \phi^{-n} S_w^{-m}$$

- where a and n are constants (approximately 0.6 to 1.6 and 2 respectively) that are related to the character of the porosity.
- At saturations greater than 25%, m ≅ n
- It has been practical to measure ρ and ρ_w in the laboratory so the ratio ρ / ρ_w (commonly referred to as the formation factor - F) is a useful relationship that combines the other terms

Electrical Properties of Rock Formation

- More usefully, Caldwell et al (1986) report a modification of Archie's equation that includes a component for conduction by **clay minerals** within the matrix:

$$\rho = a\rho_w \phi^{-n} S_w{}^{-m} \left(1 + KC\rho_w\right)^{-1}$$

- where Sw is water saturation proportion in pores, C is the proportion of clay minerals in the matrix, and K is a constant according to the type of clay minerals present.

Electrical Properties of Rock Formation

- Because conduction within electrolytes is by ionic processes, electrolyteresistivity is directly related to viscosity whichdecreases with temperature. Consequently ionic and semi-conductingmaterials both have an inverse exponential dependence ofresistivity with temperature of the form:

$$\rho = \rho_0 e^{\varepsilon/RT}$$

ε isanactivationenergy (ineV)

R isBoltzman'sconstant (0,8617x10-4 eV/oK)

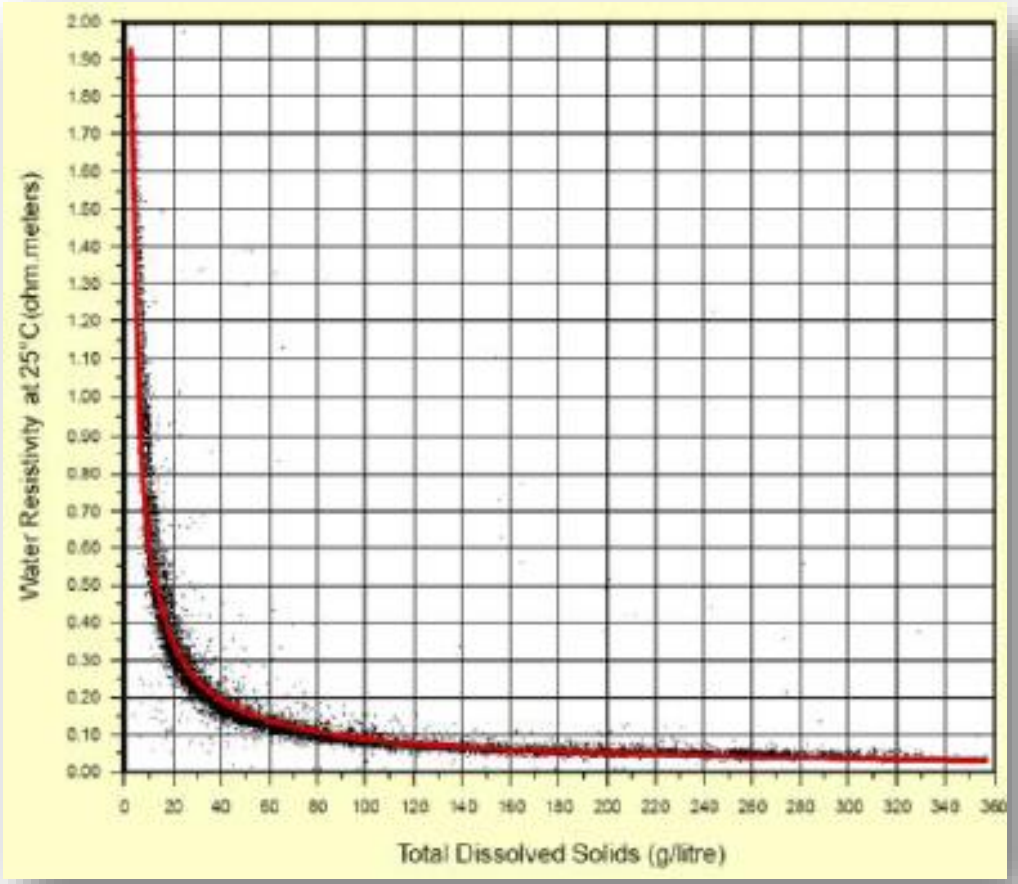
Electrical Properties of Rock Formation

- Empirical studies (Block, 2001) show that the resistivity of brines (ρw) in the Alberta Basin varies as:

$$\rho_w = 4.5\, TDS^{-0.85}$$

- where TDS is the amount of **total dissolved solids** in g/litre.

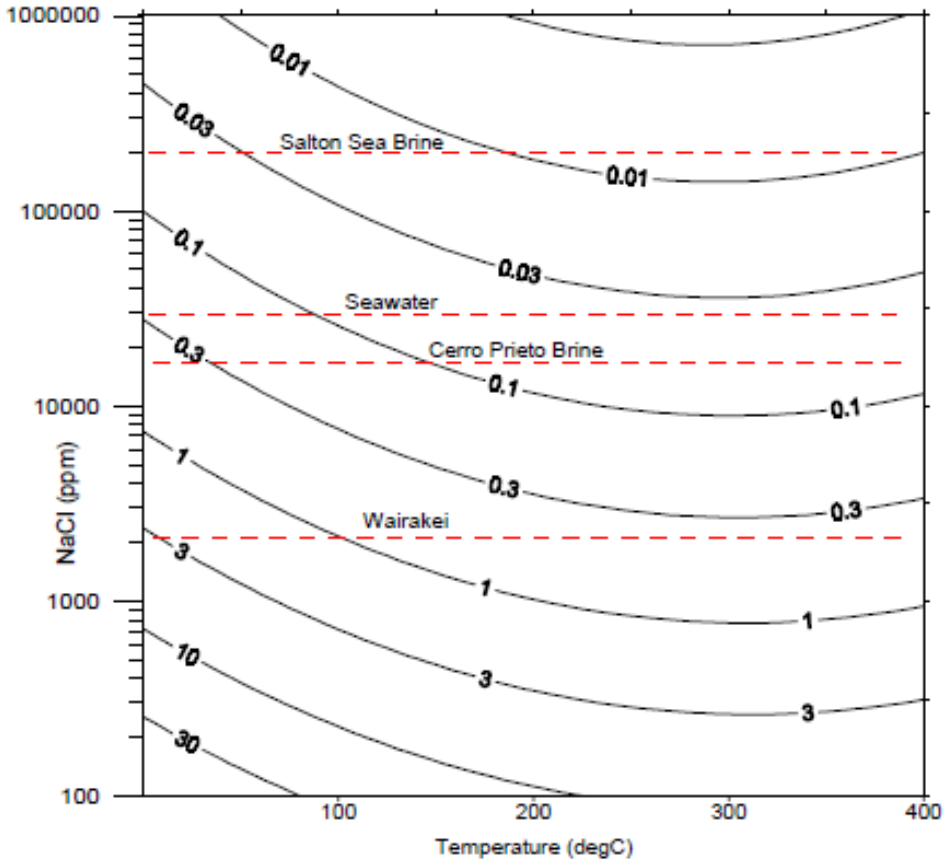
- Seawater has around 30 g/litre, and this can also be expressed as 30,000 ppm.



Ussher et al., 2000)

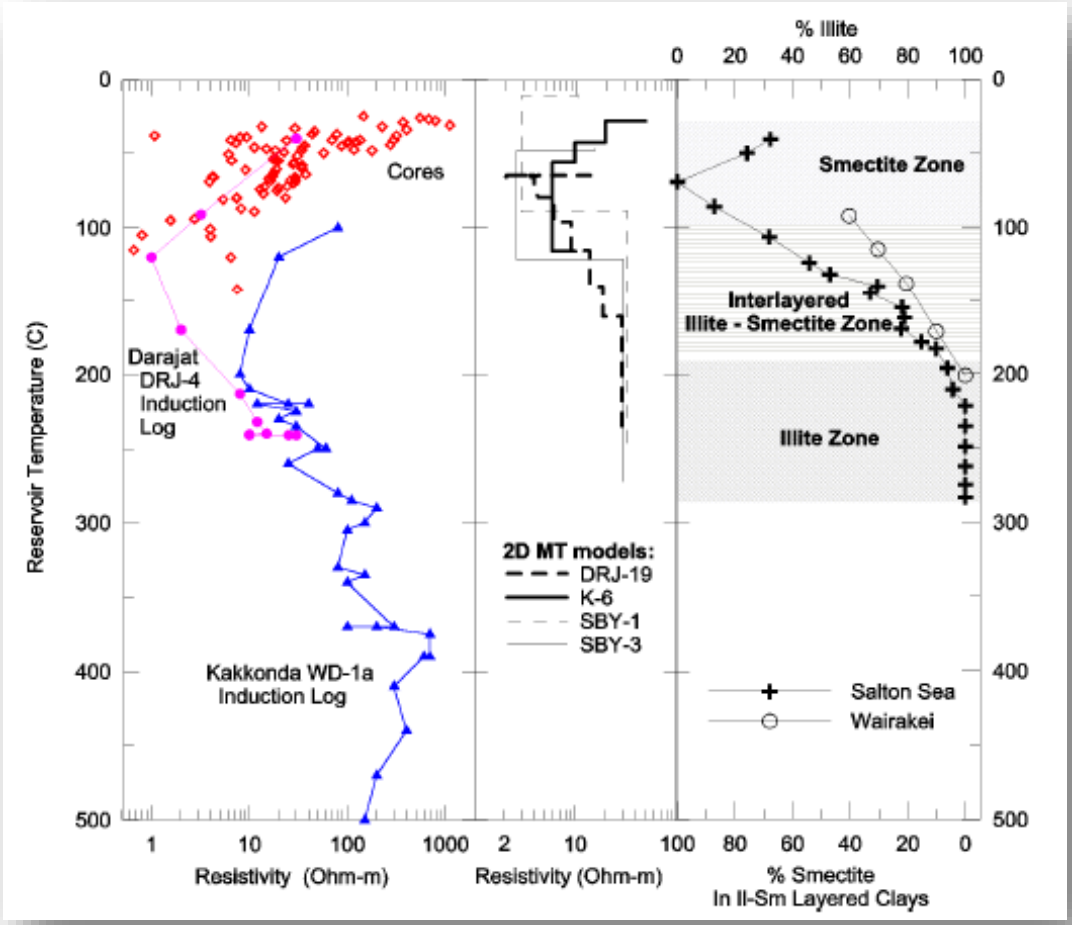
Electrical Properties of Rock Formation

- Variation of resistivity (in Ωm) of NaCl solutions from measurements of Ucok et al. (1980). The salinity of several well known geothermal fields are shown for reference.



Ussher et al., 2000)

Example of Resistivity Profile in Geothermal



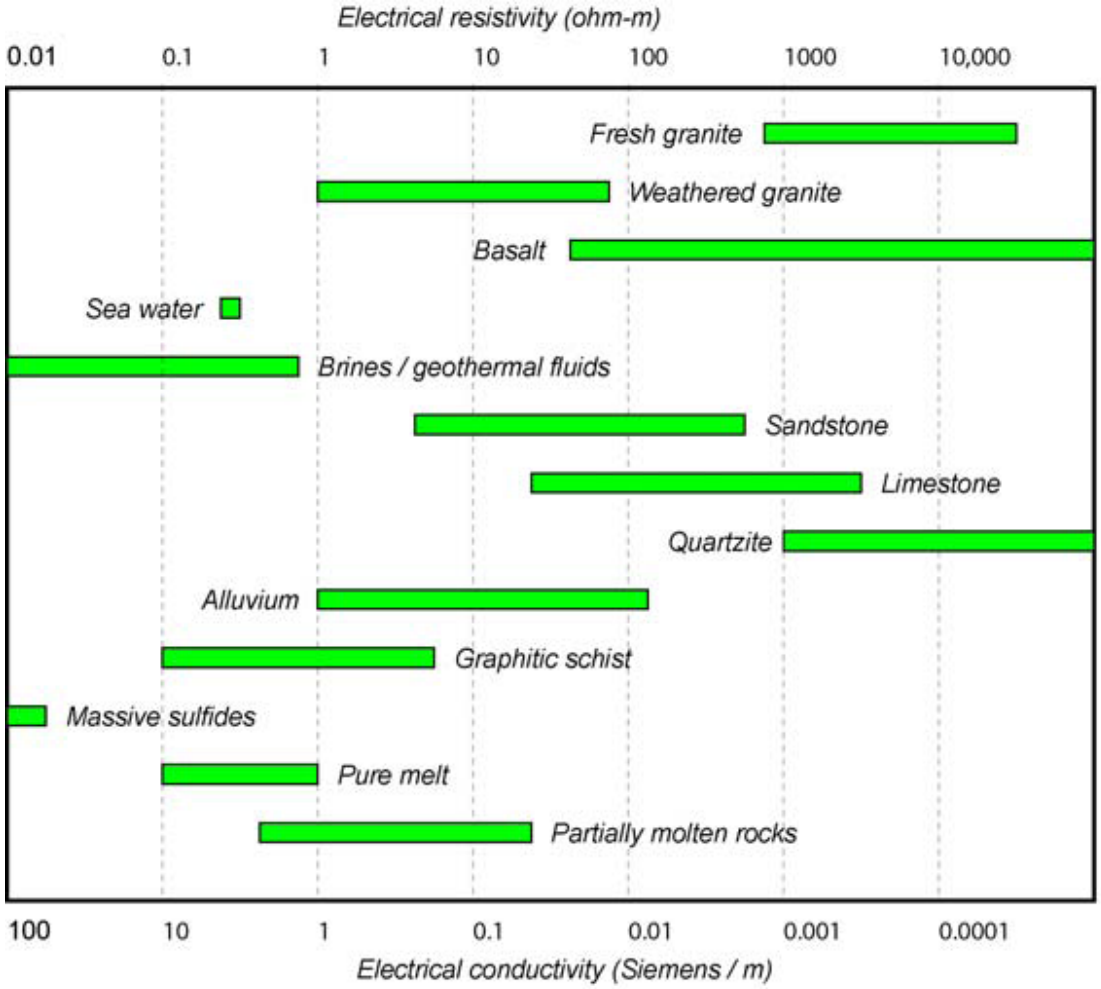
Ussher et al., 2000)

Electrical Properties of Rock Formation

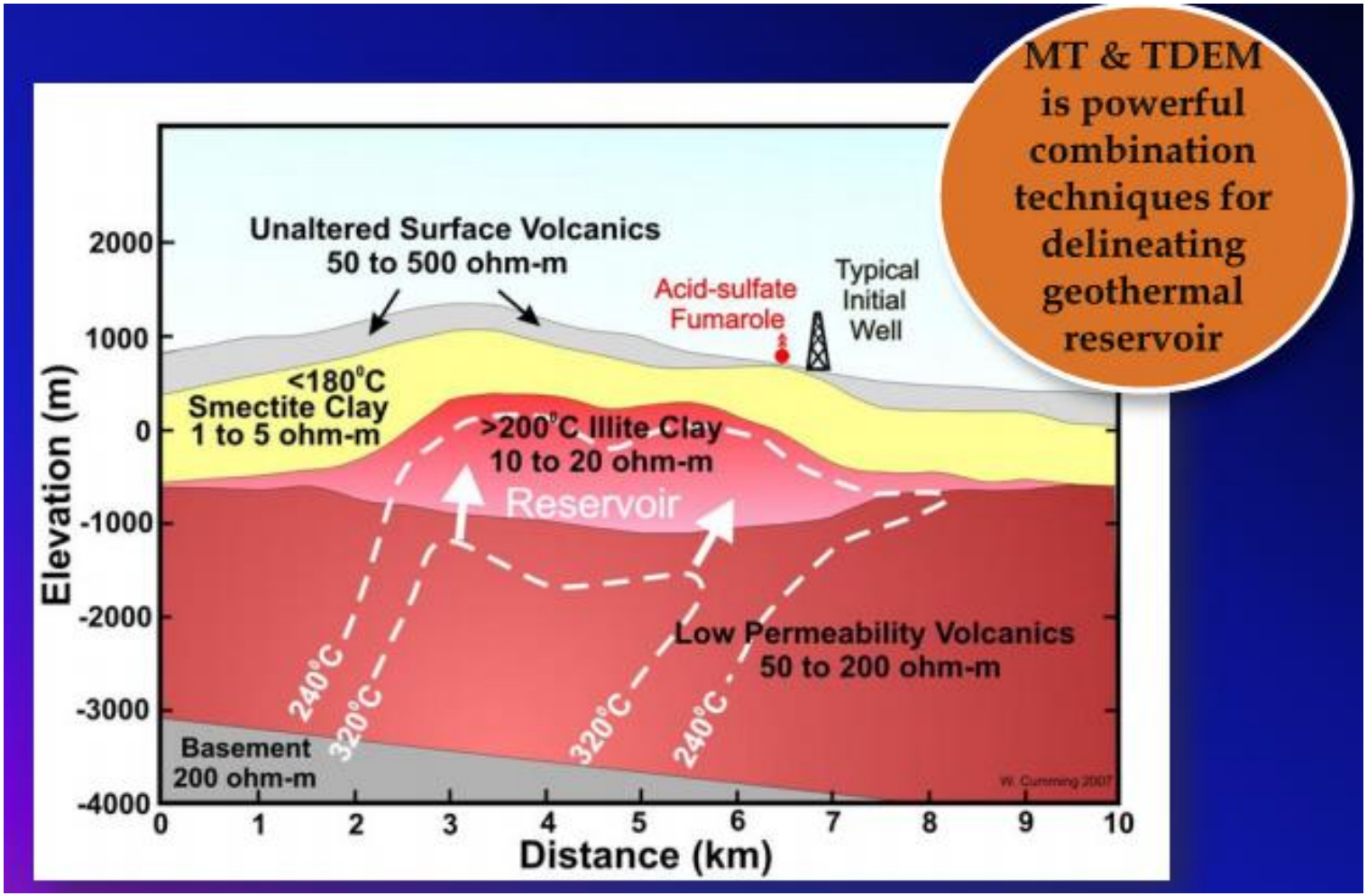
Factors that will **DECREASE the resistivity of a rock:**
(a) Add more pore fluid
(b) Increase the salinity of the pore fluid - more ions to conduct electricity
(c) Fracture rock to create extra pathways for current flow
(d) Add clay minerals
(e) Keep fluid content constant, but improve interconnection between pores
(f) Increase the temperature

Factors that will **INCREASE the resistivity of a rock:**
(a) Remove pore fluid
(b) Lower salinity of pore fluid
(c) Compaction - less pathways for electric current flow
(d) Lithification - block pores by deposition of minerals
(e) Keep fluid content constant, but decrease connection between pores
(f) Decrease the temperature

Electrical Properties of Rock Formation



Geology Model



BASIC PRINCIPLE OF ELECTROMAGNETIC (EM) METHODS

Introduction

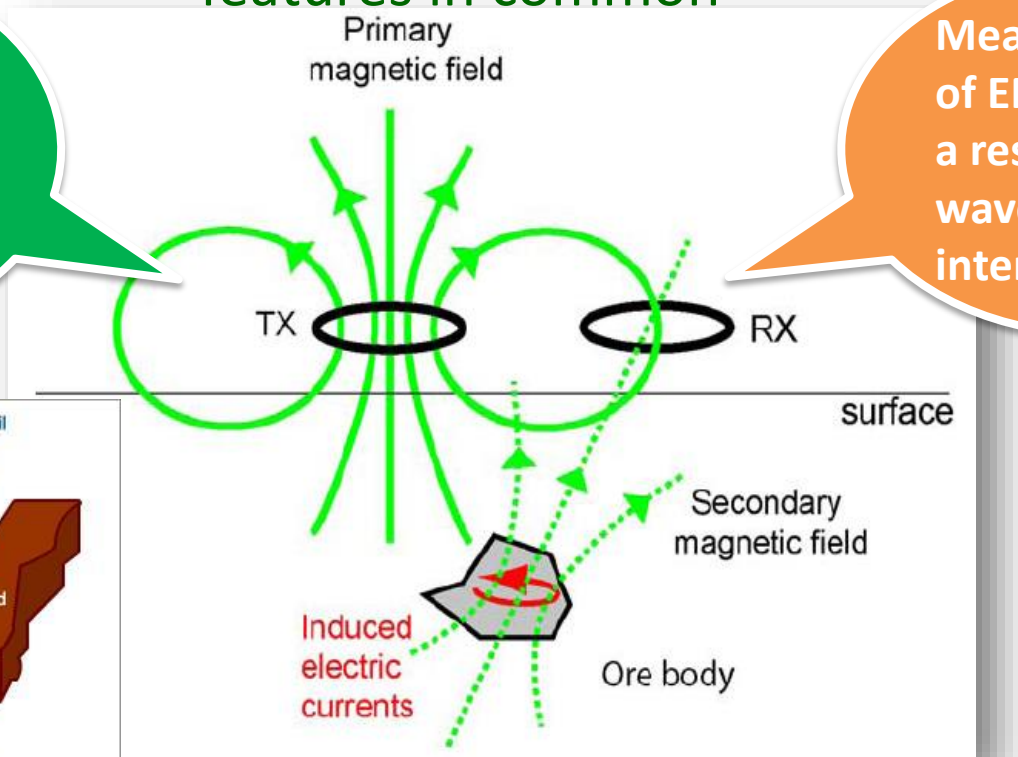
- **History**
  - **MT (Low Frequency 300-0.001 Hz)** : Cagniard (1953), Kato and Kikuchi (1950), Rikitake (1950,1951), and Tikonov (1950)
  - **AMT (10 Hz – 10 kHz)** : 1960
  - **CSAMT (2 kHz – 1 Hz)** : Goldstein (1971), David Strangway (1975), Zonge (1980)

- **Worldwide applications**
  - MT has been popular for **geothermal exploration**, mineral exploration, hydrocarbon exploration and regional geophysical mapping.
  - It is used in oil exploration for low-cost reconnaissance of sedimentary basins and for exploration in areas where seismic surveys are difficult because of severe topography or the presence high-impedance volcanic rocks near the surface.

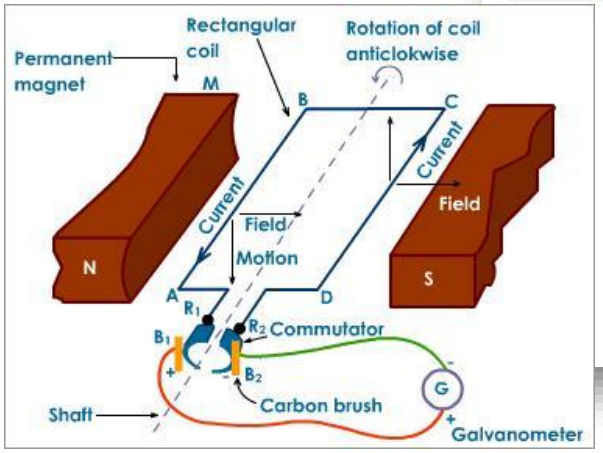
Principle of EM Exploration

Electromagnetic (EM) methods have the following features in common

A primary EM field can be man made or natural



Measurement of EM fields as a result of EM wave – rock interactions

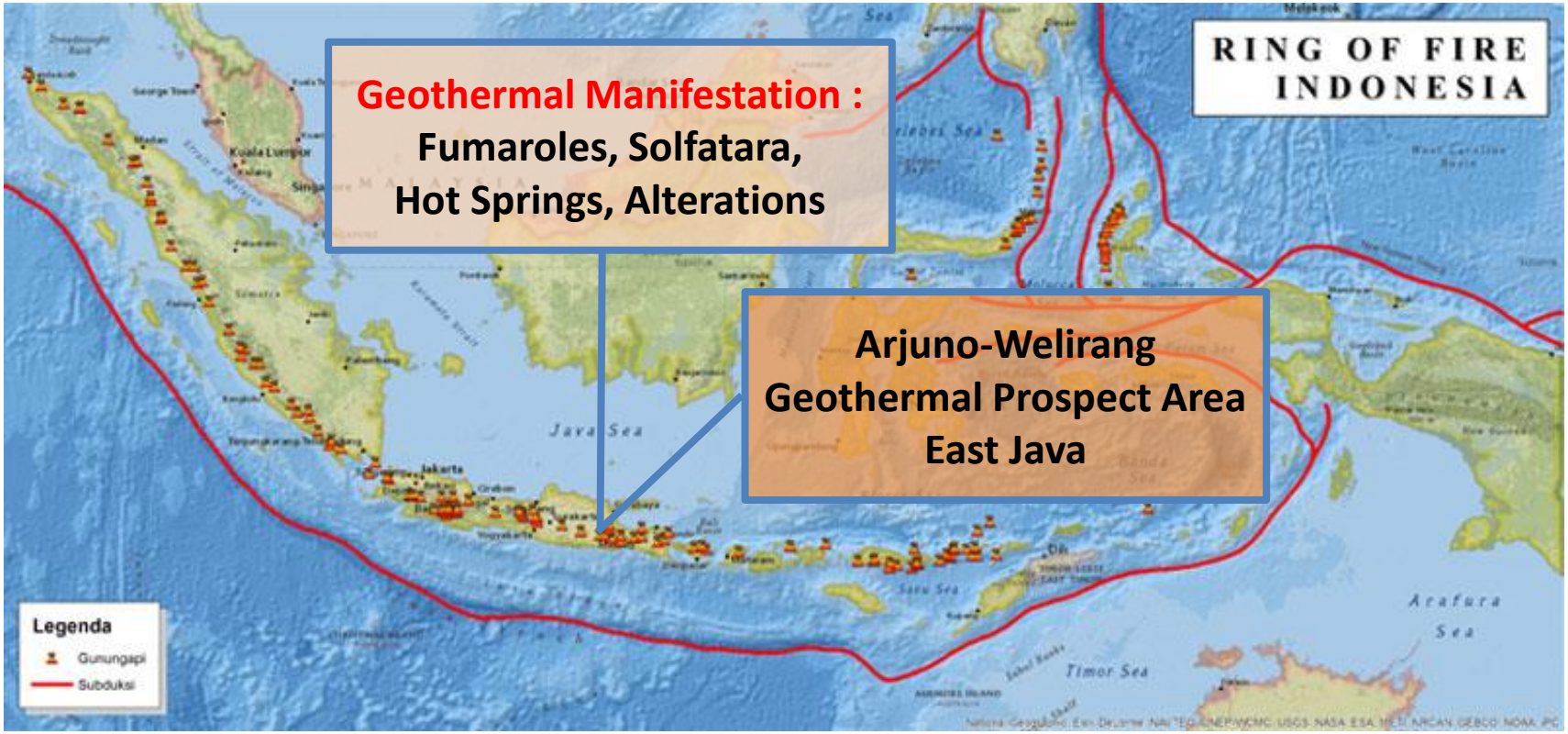


Electromagnetic Methods

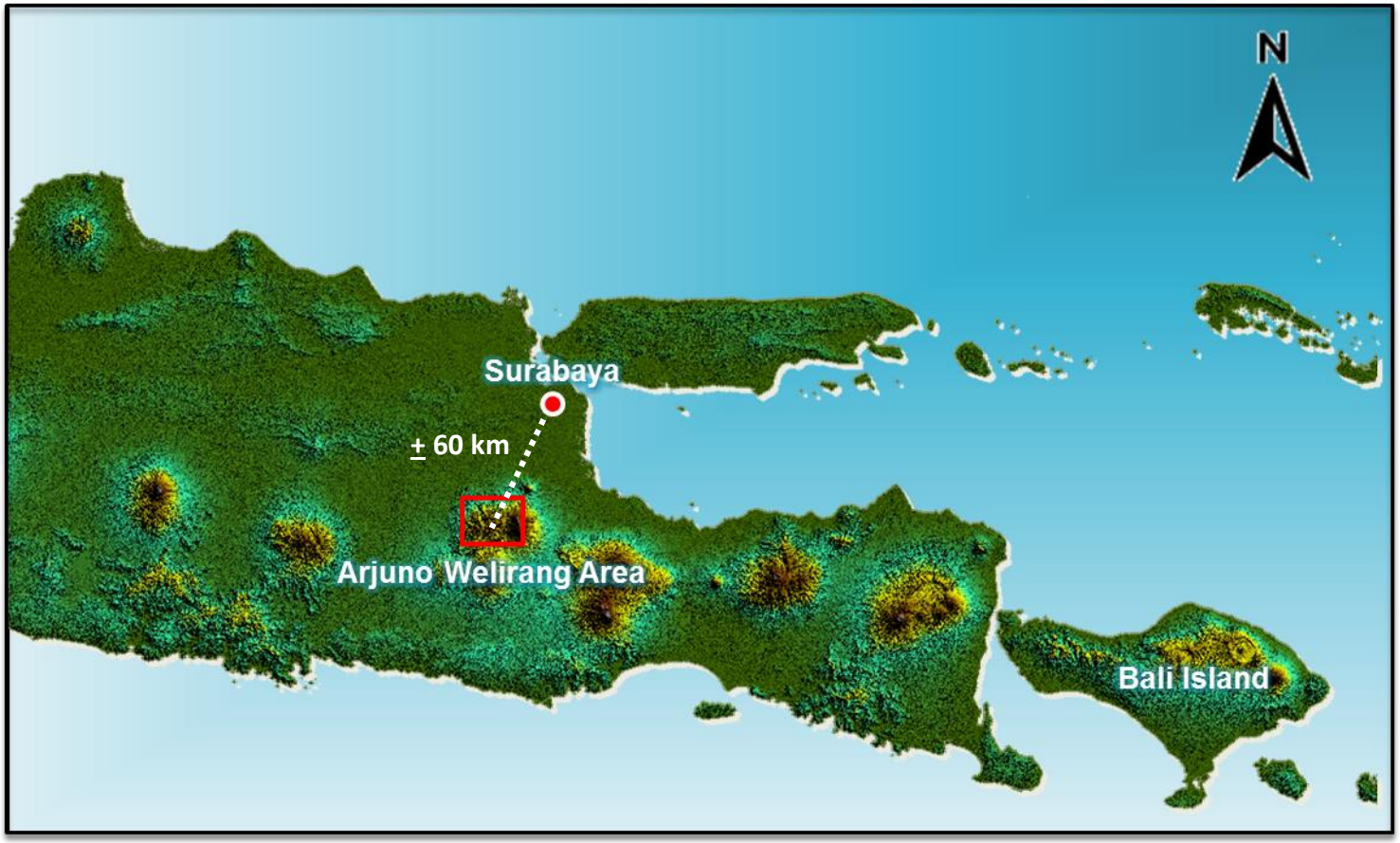
No	Type of EM Method	Passive or Active	Source	Frequency	Depth	Application
1	MT	Passive	Solar Wind Lightning	Low	100 m – 100 km	Geothermal Hydrocarbon Mineral Large scale geological features
2	CSAMT/ CSEM	Active	Grounded Dipole Source	High	< 3 km	Geothermal Hydrocarbon Mineral
3	TDEM	Active	Transmitting Loop	High	< 500 m	MT Static Shift Correction

CASE STUDY:
MT Investigation in Arjuno-Welirang Volcanic Geothermal System

Arjuno-Welirang Geothermal Prospect Area

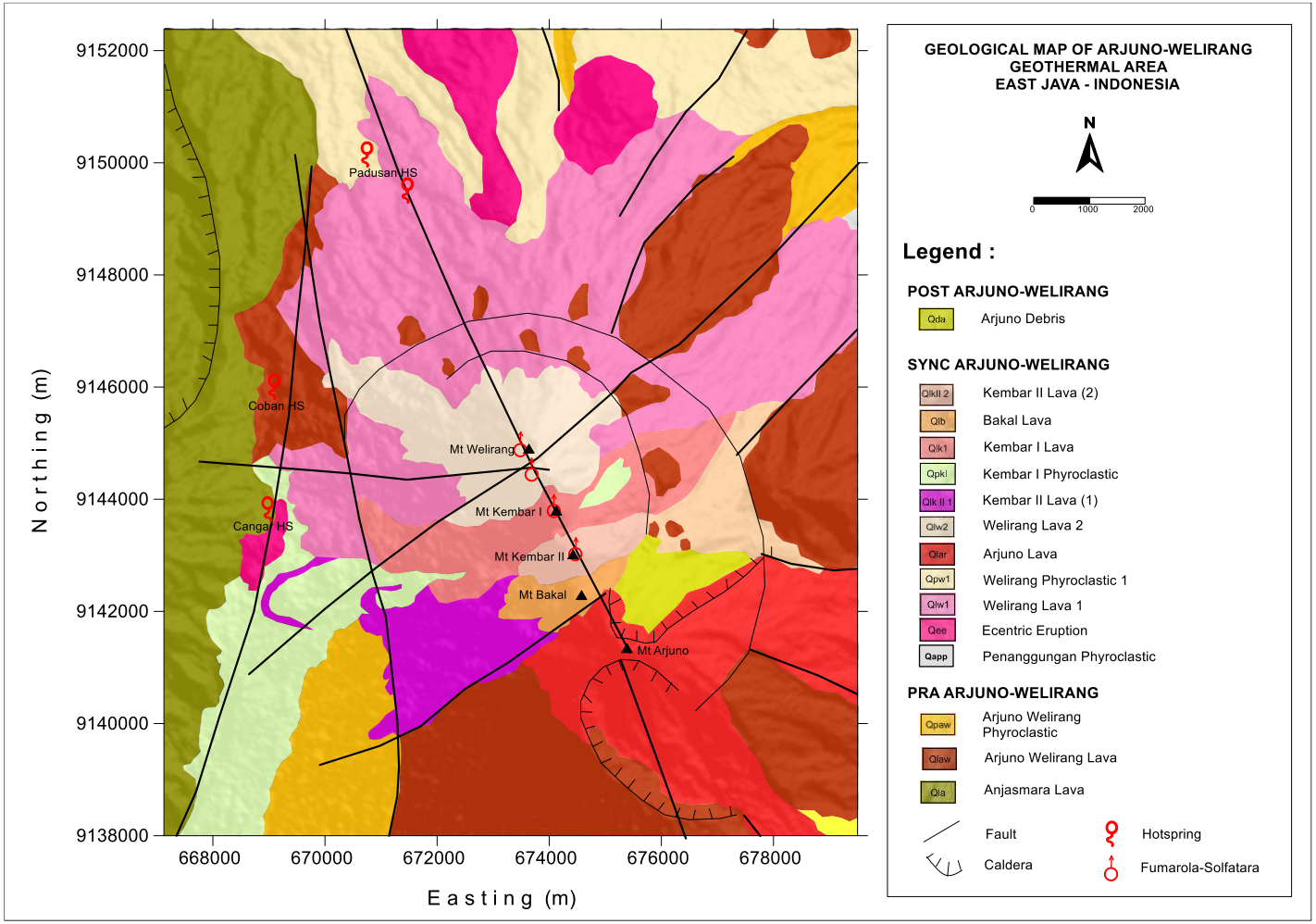


Location of the Arjuno-Welirang Geothermal Prospect Area



FIELD REVIEW

Geological Setting

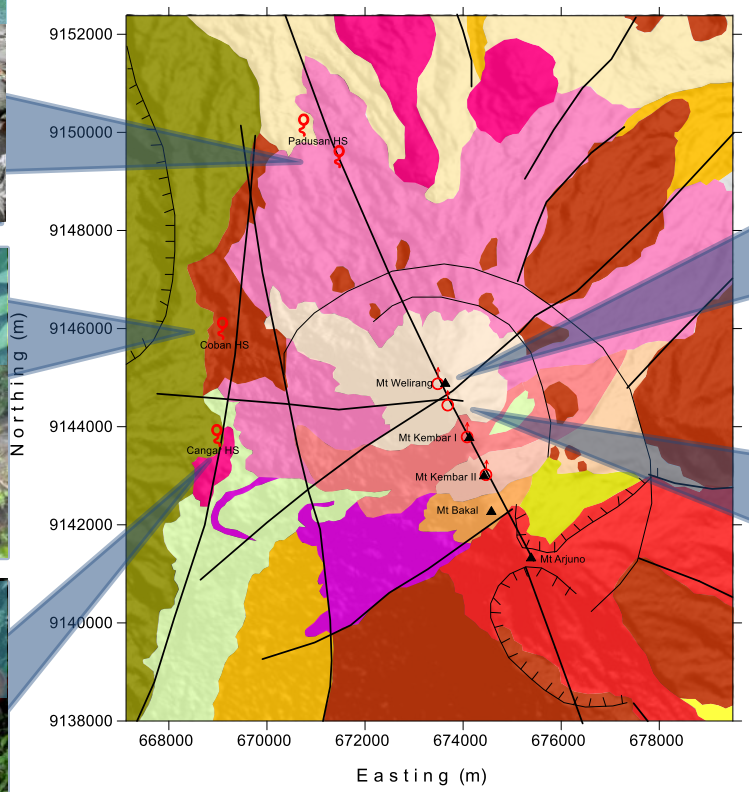


Surface Manifestation

Padusan HS - Bicarbonate
50 dan 55°C, pH 5,8 – 6,3

Coban HS - Bicarbonate
39°C, pH 6,4

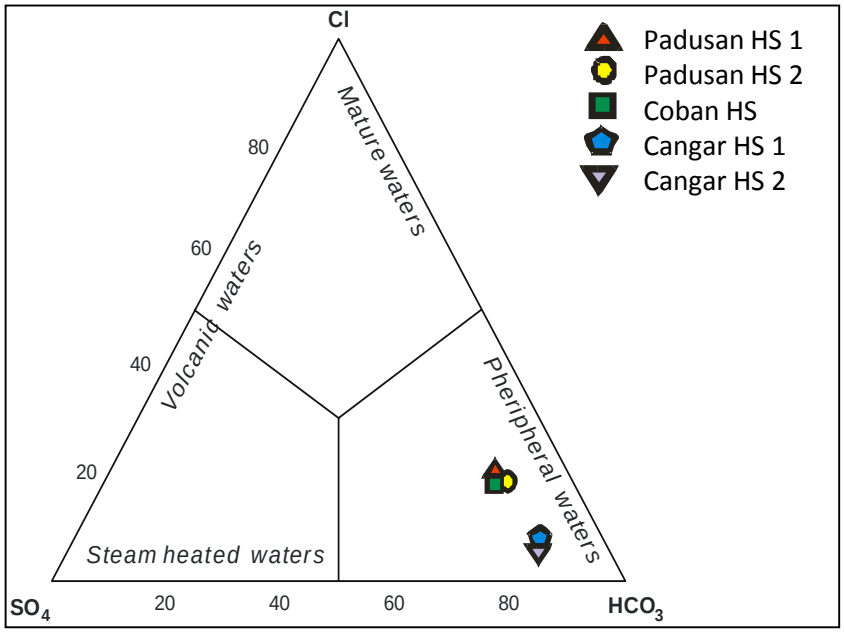
Cangar HS - Bicarbonate
48 dan 54°C, pH 5.9

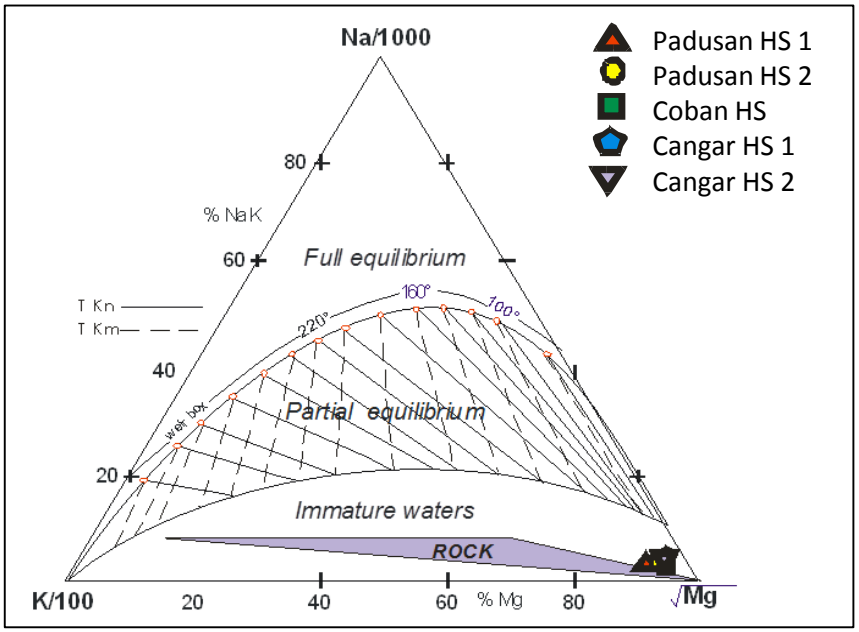


Solfatara

Fumarol
94,1 – 137,5 °C

Geochemical Data



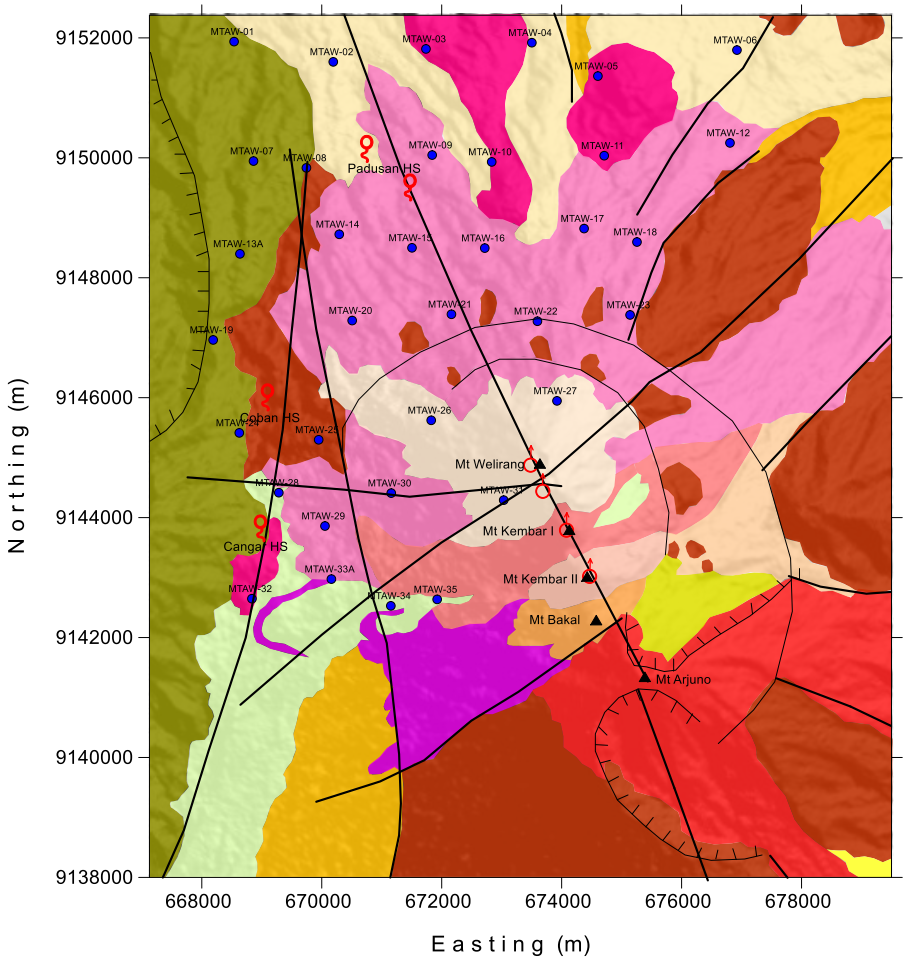


Triangular diagram Cl-SO_4-HCO_3 (left) and Na-K-Mg (right)
for the waters of Arjuno-Welirang geothermal area(PSDG, 2010)

Reservoir Temperature

- SiO_2 Geothermometer = 176^oC
- Na/K Geothermometer = 313^oC
- CO_2 Geothermometer = 260^oC

MT Station Distribution

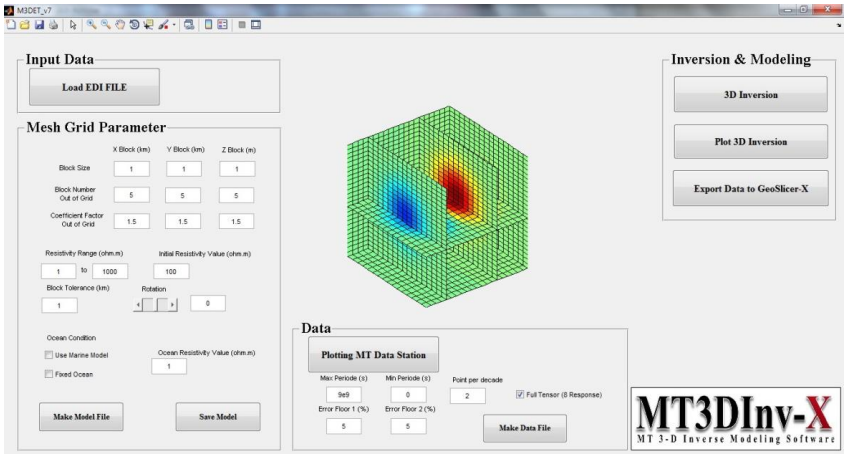


MT Data Acqutition of Arjuno-Welirang Geothermal Area

- MT data acquistion was carried out by Center for Geological Resources of the Ministry of Energy and Mineral Resources (MEMR) in 2010.
- Total Stations : 35
- Spacing : 1-2 km.
- Instrumentations : MTU-5A, Phoenix

3-D MT Inversion

Software



- MT3DInv-X has been developed by PT. NewQuest Geotechnology.
- This software utilises algorithm of data space Occam's Inversion to perform 3-D inversion process effectively.
- The result of 3-D Inversion of MT data visualized using the GeoSlicer-X software that previously developed by PT. NewQuest Geotechnology.

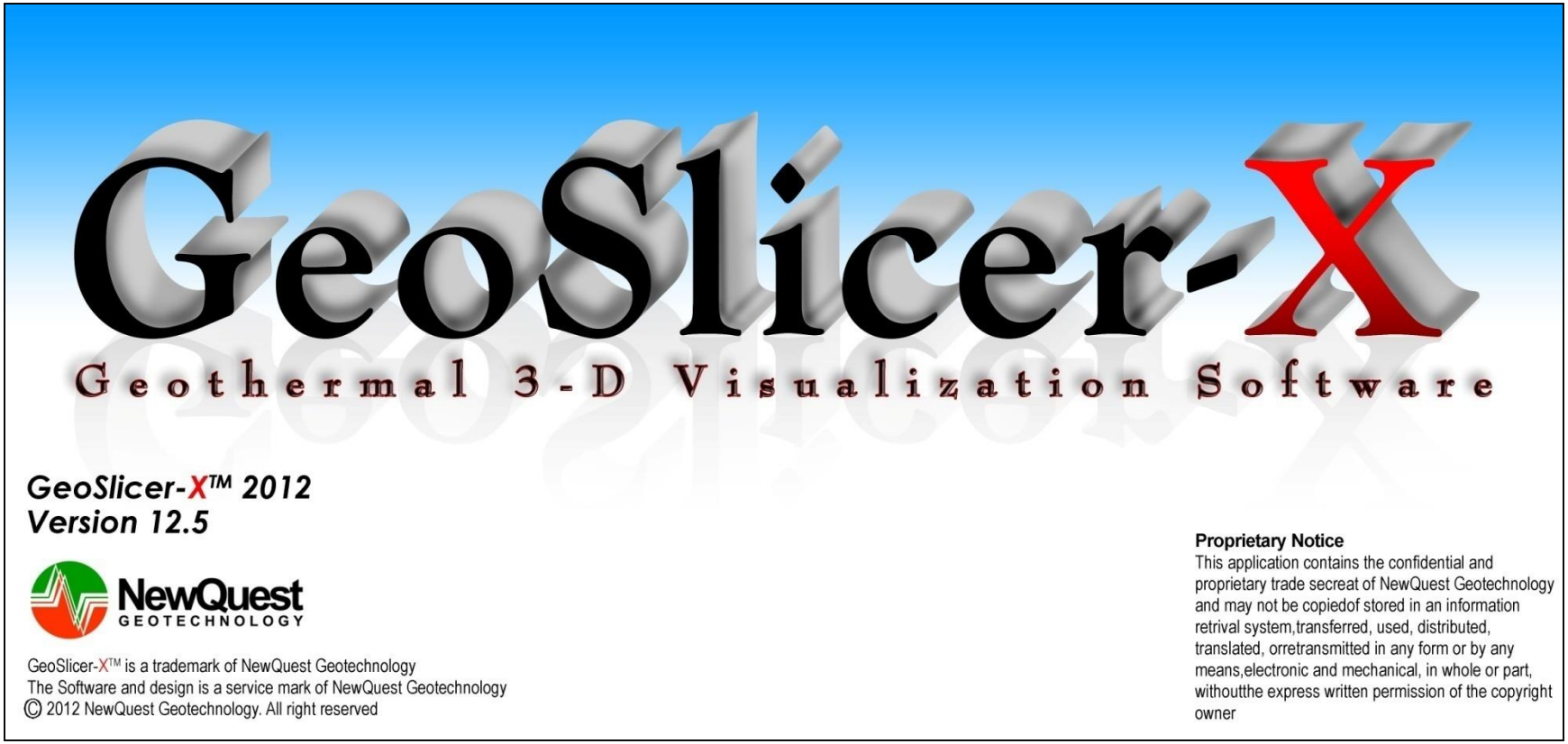
3-D Inversion Parameter

Mesh Grid Parameter	
Block Size (x, y, z)	500 m , 500 m, 10 m
Padding Factor (x, y, z)	1.5 , 1.5 , 1.5
Total Number of Model Blocks	M = 30 x 30 x 22 = 19,800
Initial Model	100 ohm-m homogeneous half-space
Data Input	
Number of Station	80 Station
Impedance Tensor	Zxx.real, Zxx.,imag, Zxy.real, Zxy.,imag, Zyx.real, Zyx.,imag, Zyy.real, Zyy.,imag (8 response)
Number of Periodes / Frequency Ranges	9 periodes / 100 – 0.01 Hz
Error Floor (Zxy-Zyx / Zxx-Zyy)	5 % / 5 %
Total Number of Data	N = 34 x 9 x 8 = 2,448

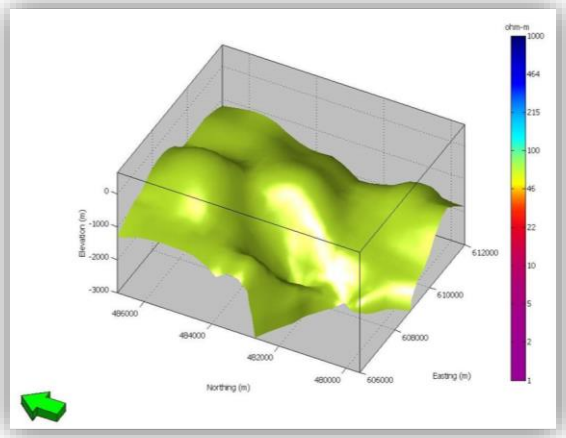
3-D Inversion Process

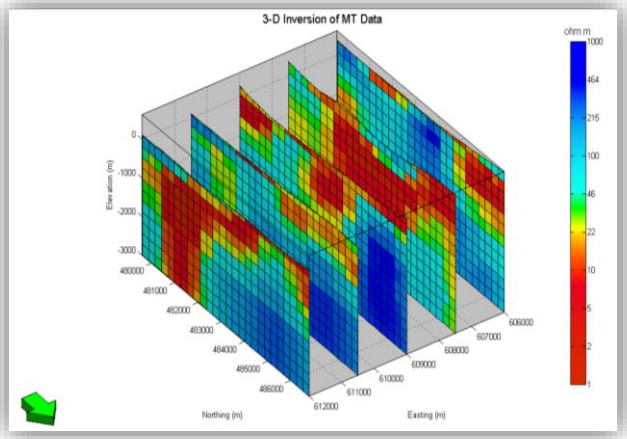
- The 3-D MT inversion process was run on PC Intel Pentium core i7 with 16 GB of RAM.
- For once iteration it took about 2 hours and the total time to reach 34th iteration was about 68 hours.
- The final RMS misfit achieved was 10.8%.

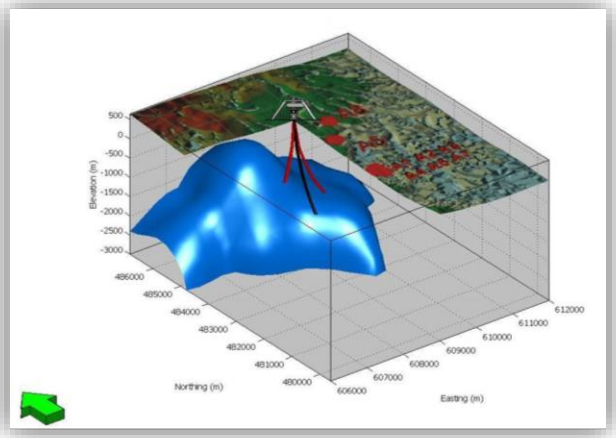
3-D Visualization Software

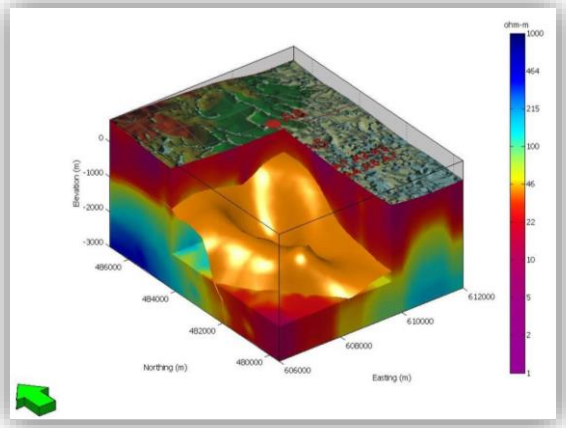


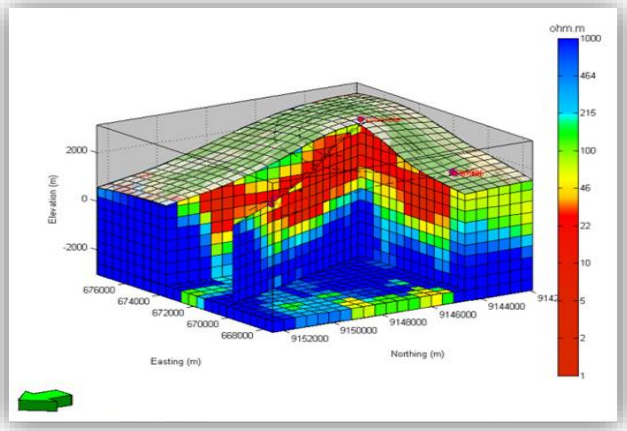
3-D Visualization Software

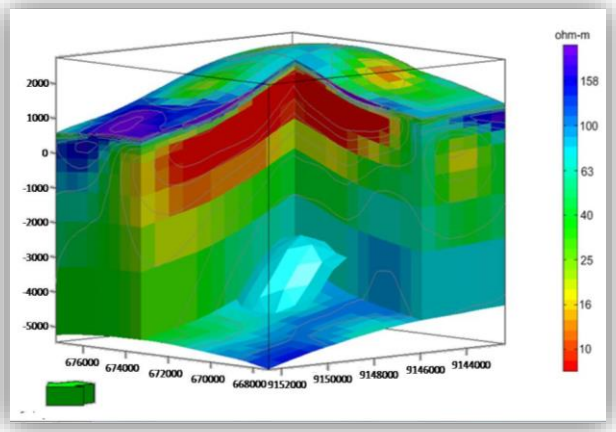




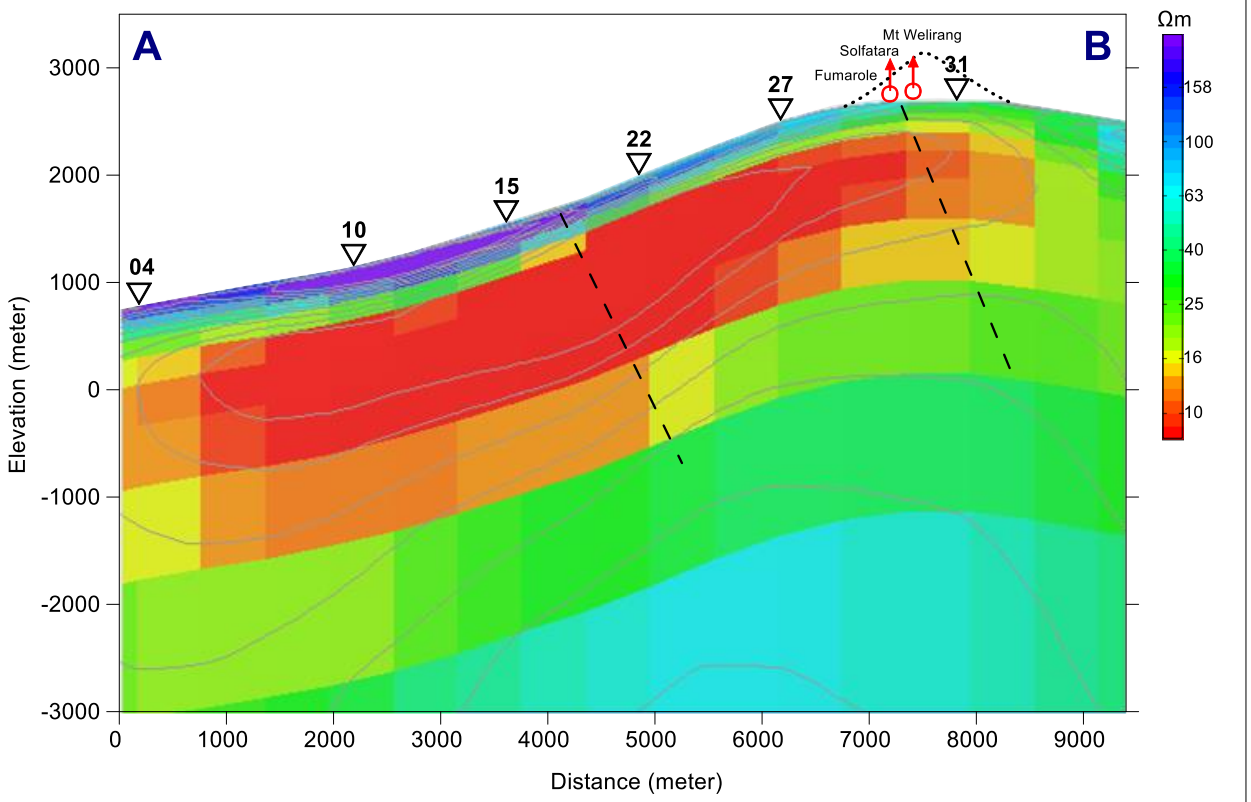








Resistivity Section of Line AB



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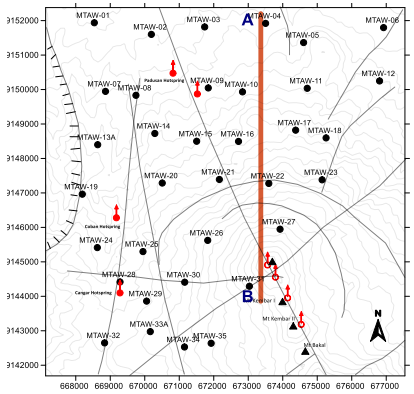
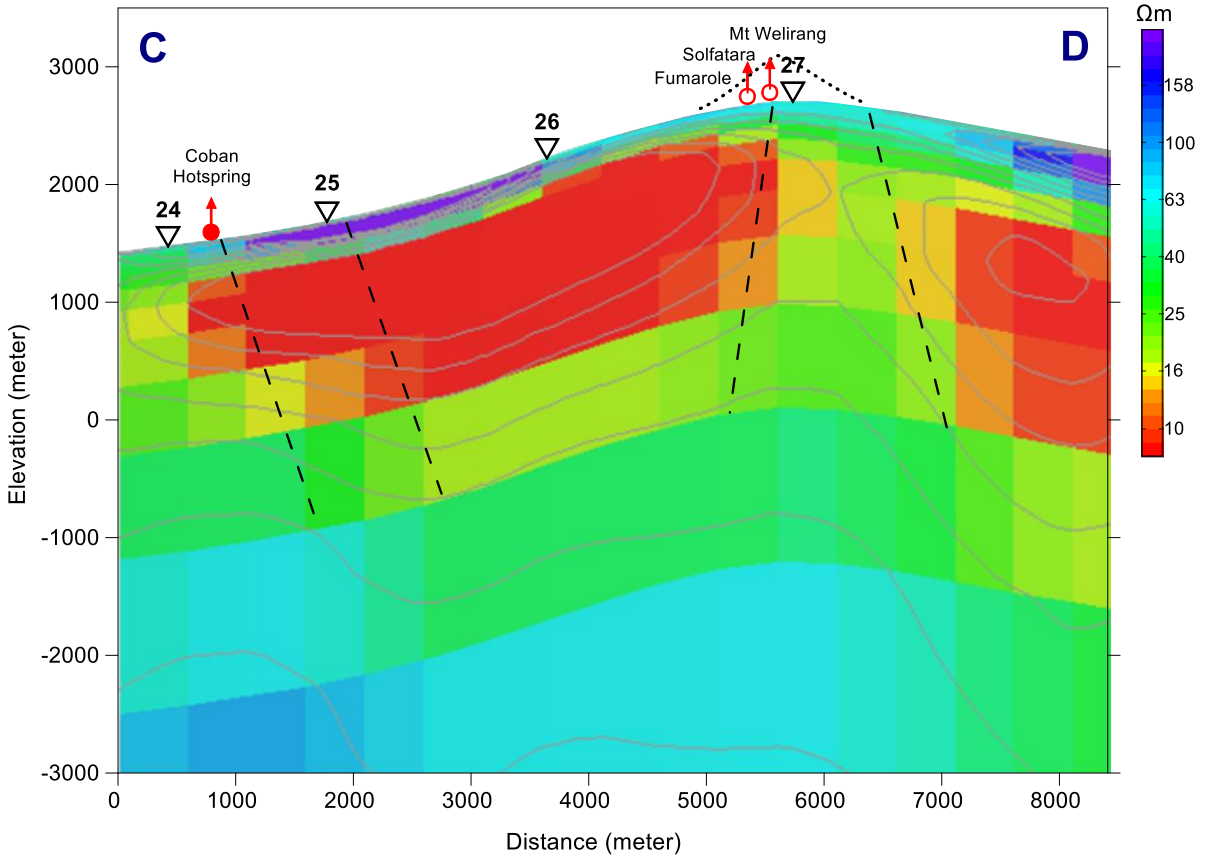
Resistivity Section of Line AB
Derived from 3-D Inversion



Resistivity Sectionof Line CD



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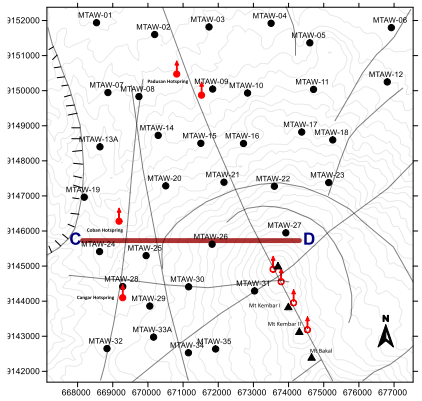
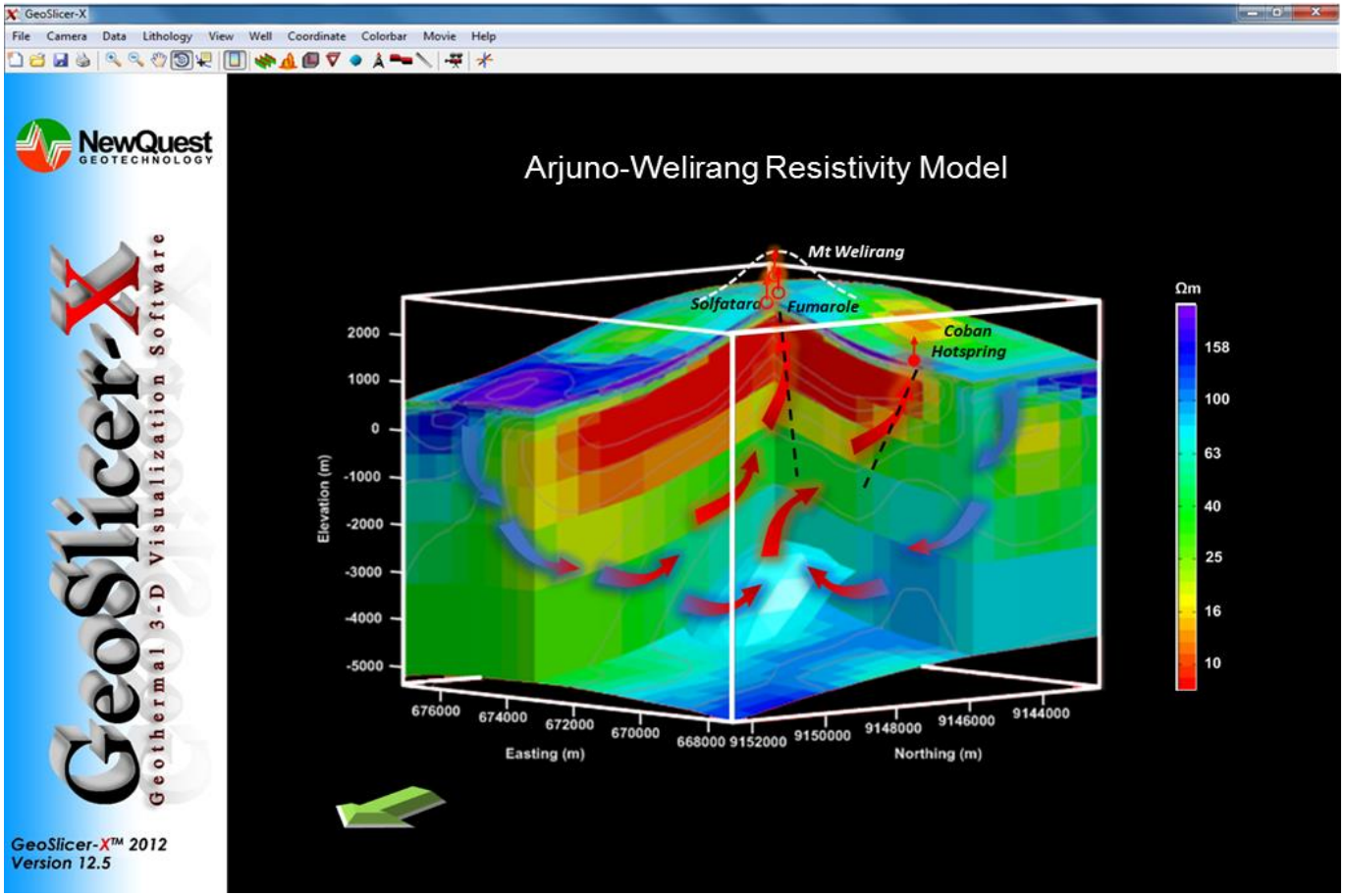
Resistivity Section of Line CD Derived from 3-D Inversion

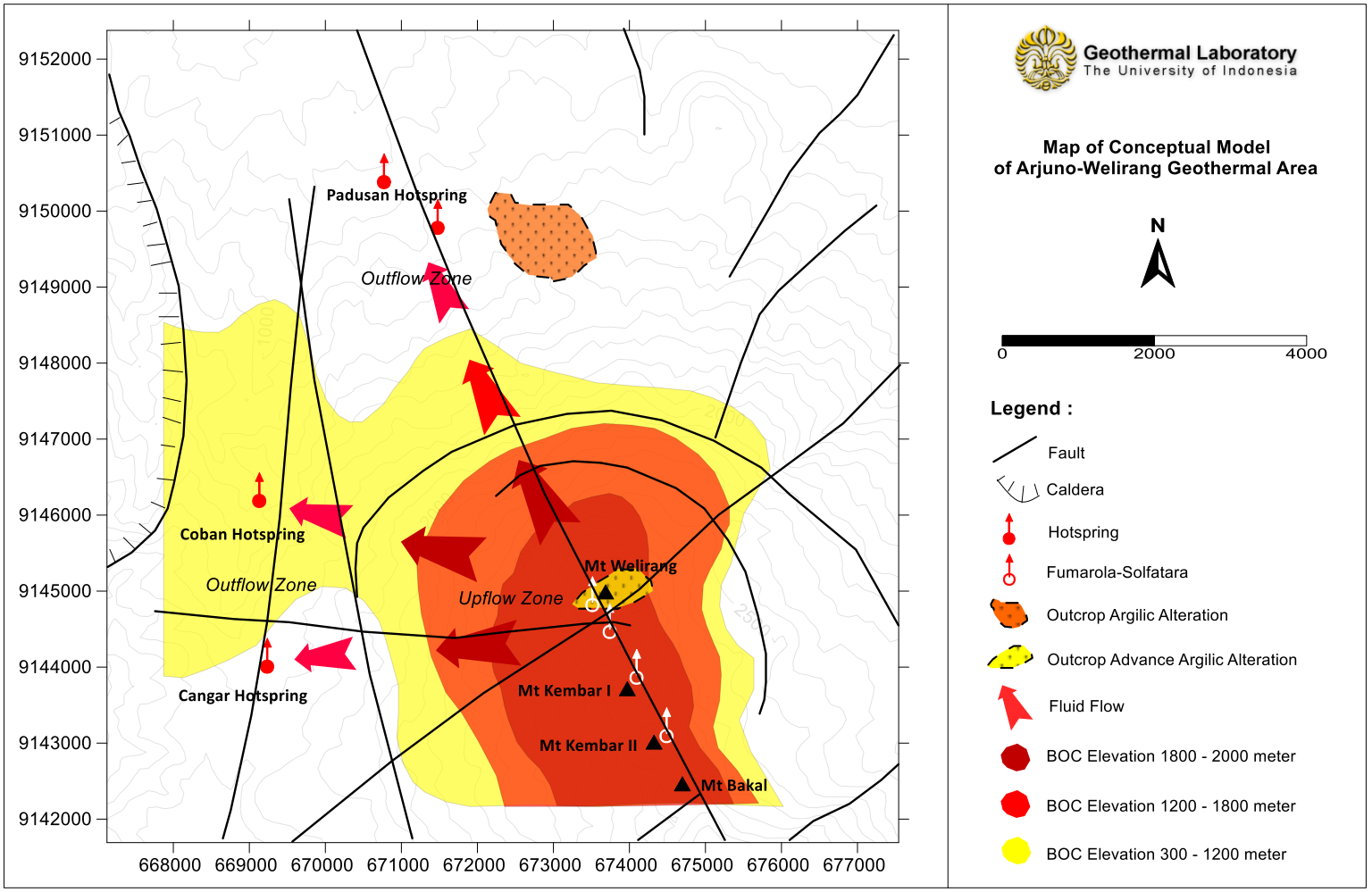


3-D Visualization

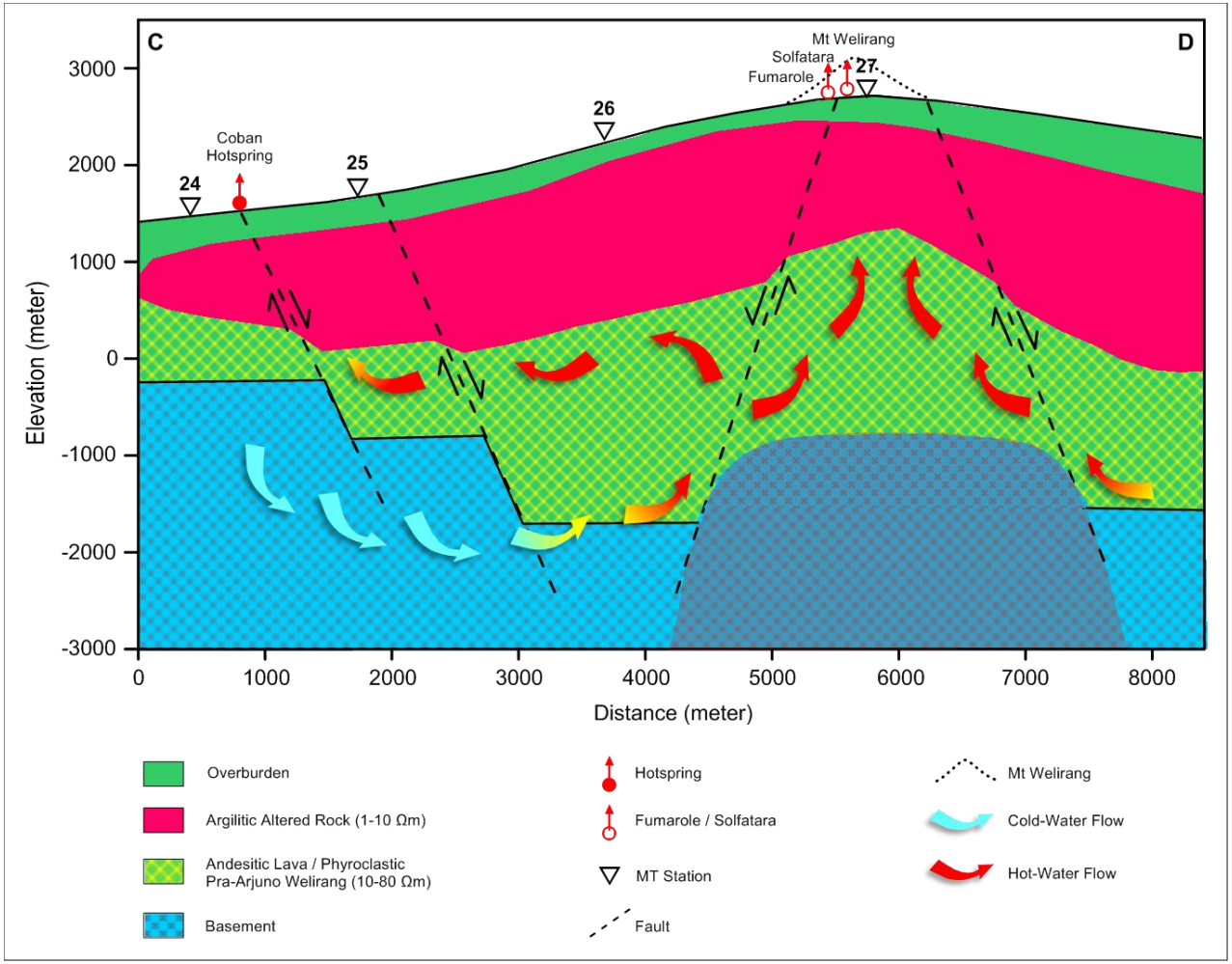


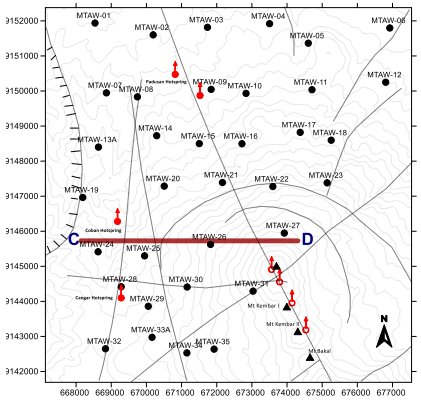
Integrated Intepretation

Conceptual Model Represented by BOC Elevation Contour and Hydrogeology Map of the Arjuno-Welirang Geothermal Area



Conceptual Model of the Arjuno-Welirang Geothermal System



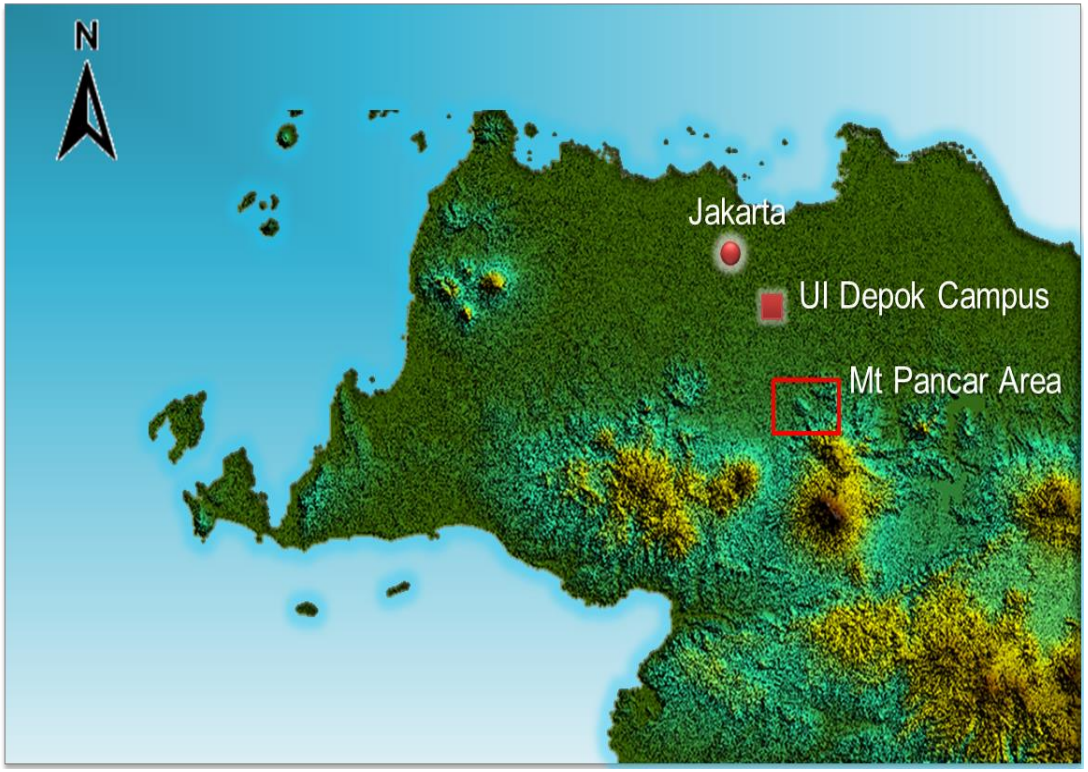


CASE STUDY:
MT and Gravity Survey in Mt. Pancar Geothermal Prospect

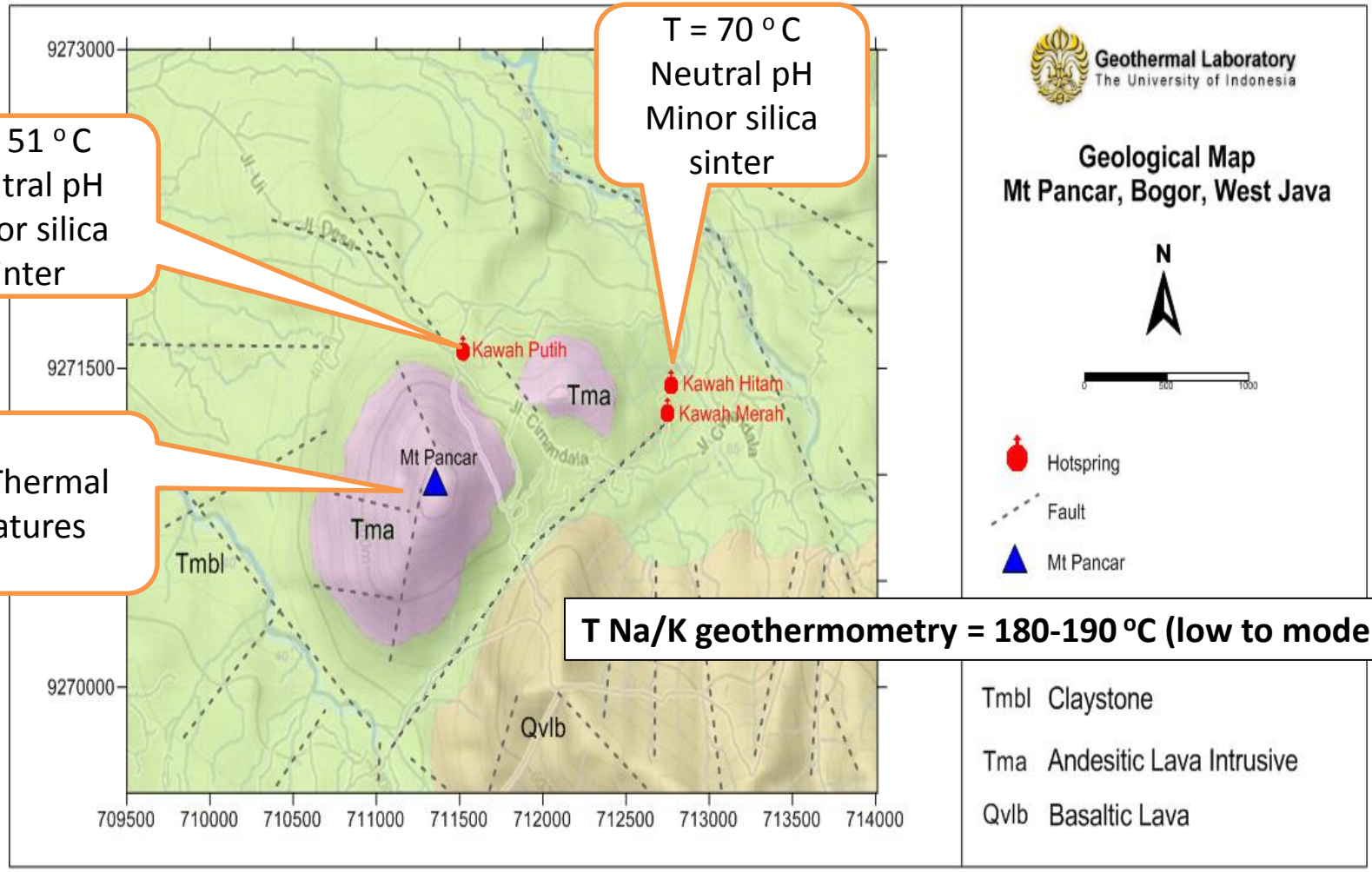
FIELD REVIEW

- Mt Pancar geothermal prospect is located in the Bogor District, West Java Province, Indonesia about 40 km to the south of Jakarta.

- The location can be reached from UI Depok campus about 90 minutes.



Geological Map of Mt Pancar Geothermal Prospect Area

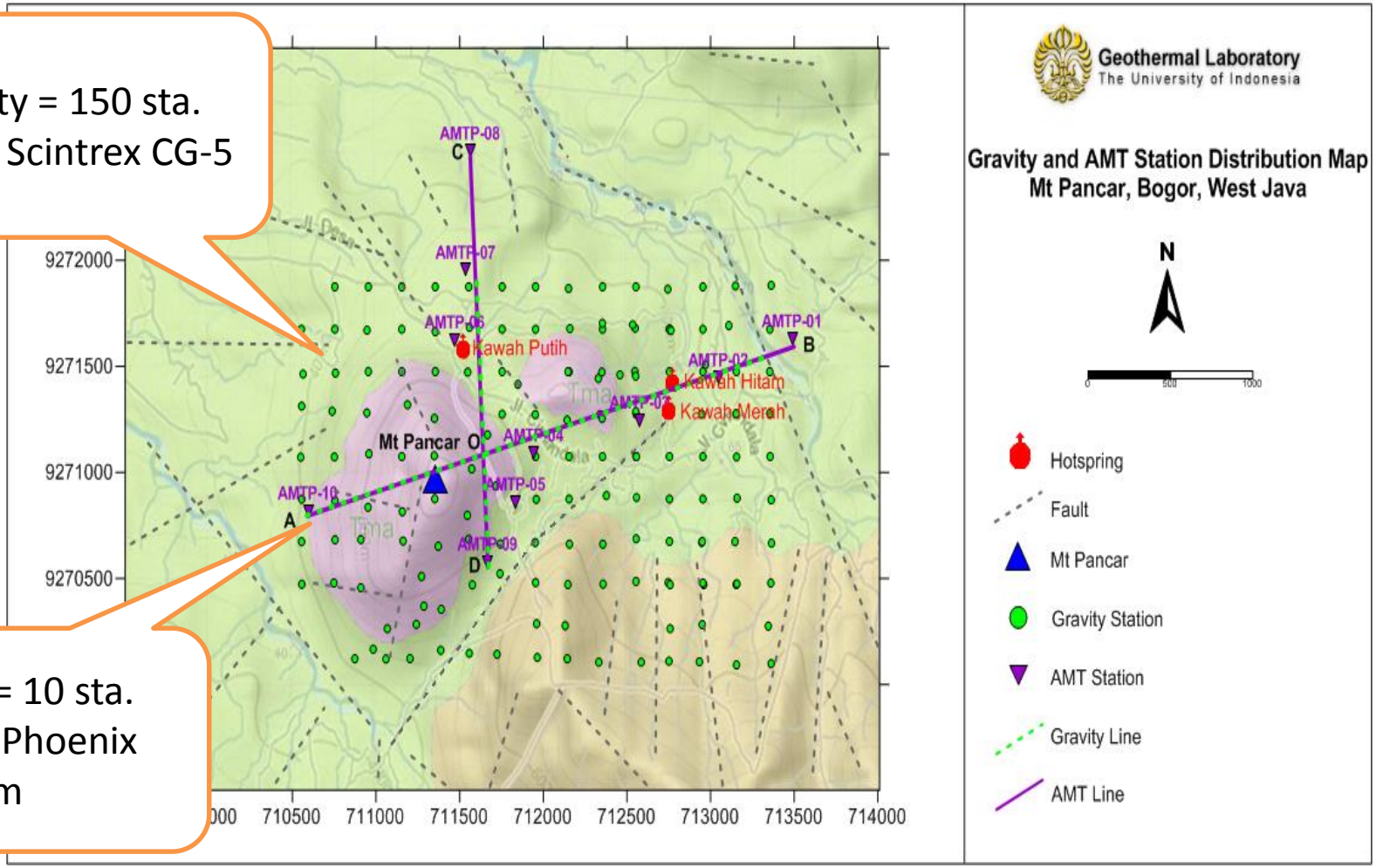


T Na/K geothermometry = 180-190 °C (low to moderate T)

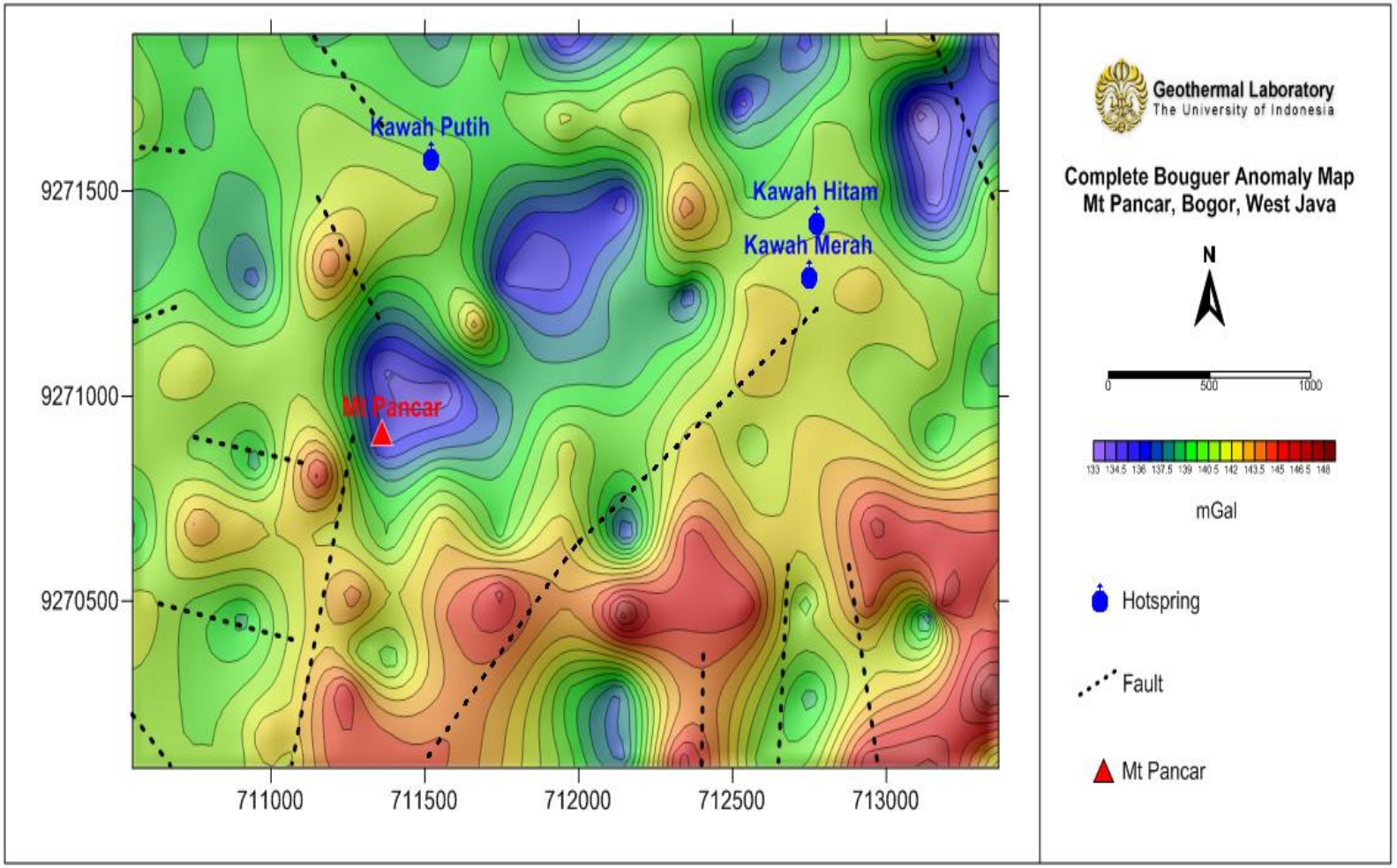
Distribution of Gravity and AMT Data

Gravity = 150 sta. using Scintrex CG-5

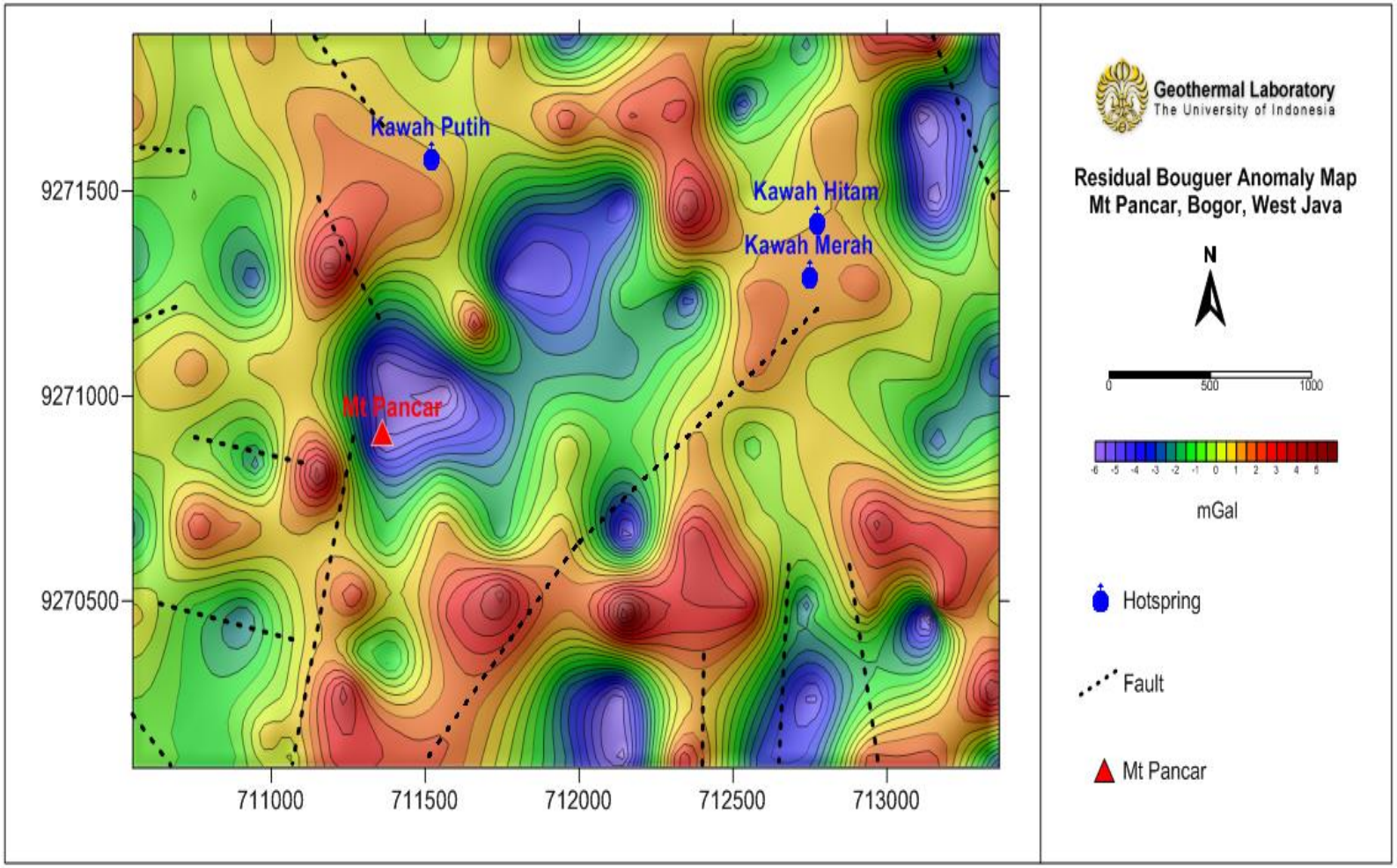
AMT = 10 sta. using Phoenix System



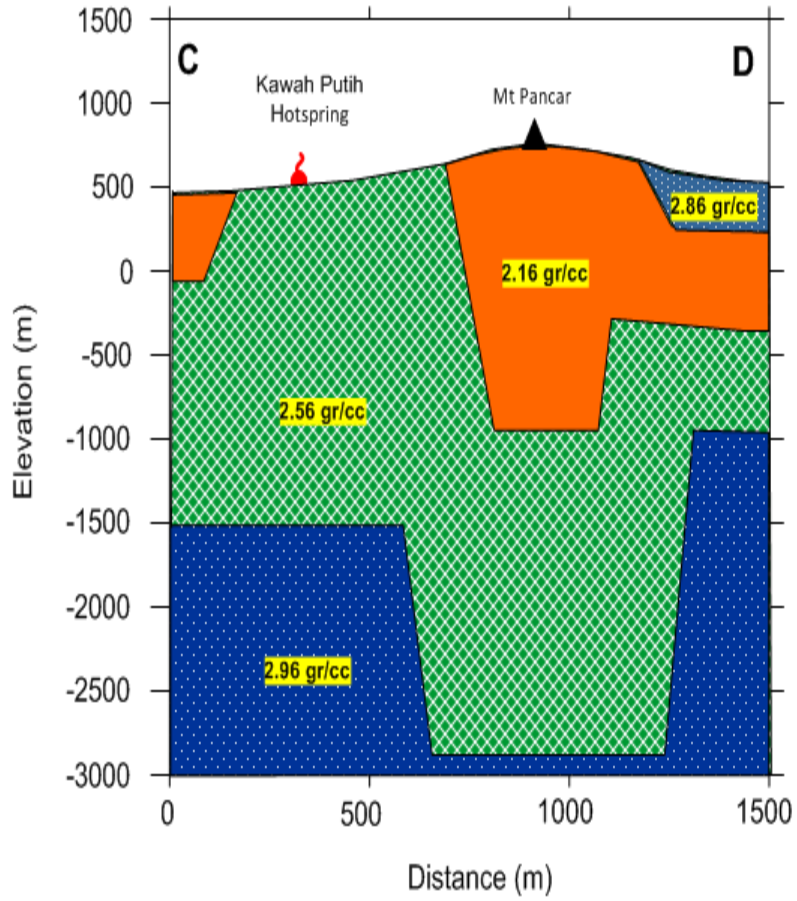
RESULTS AND DISCUSSION



Residual Bouguer Anomaly Map



Gravity Section of Line AB



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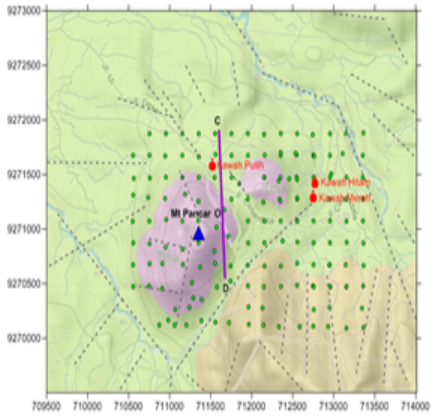
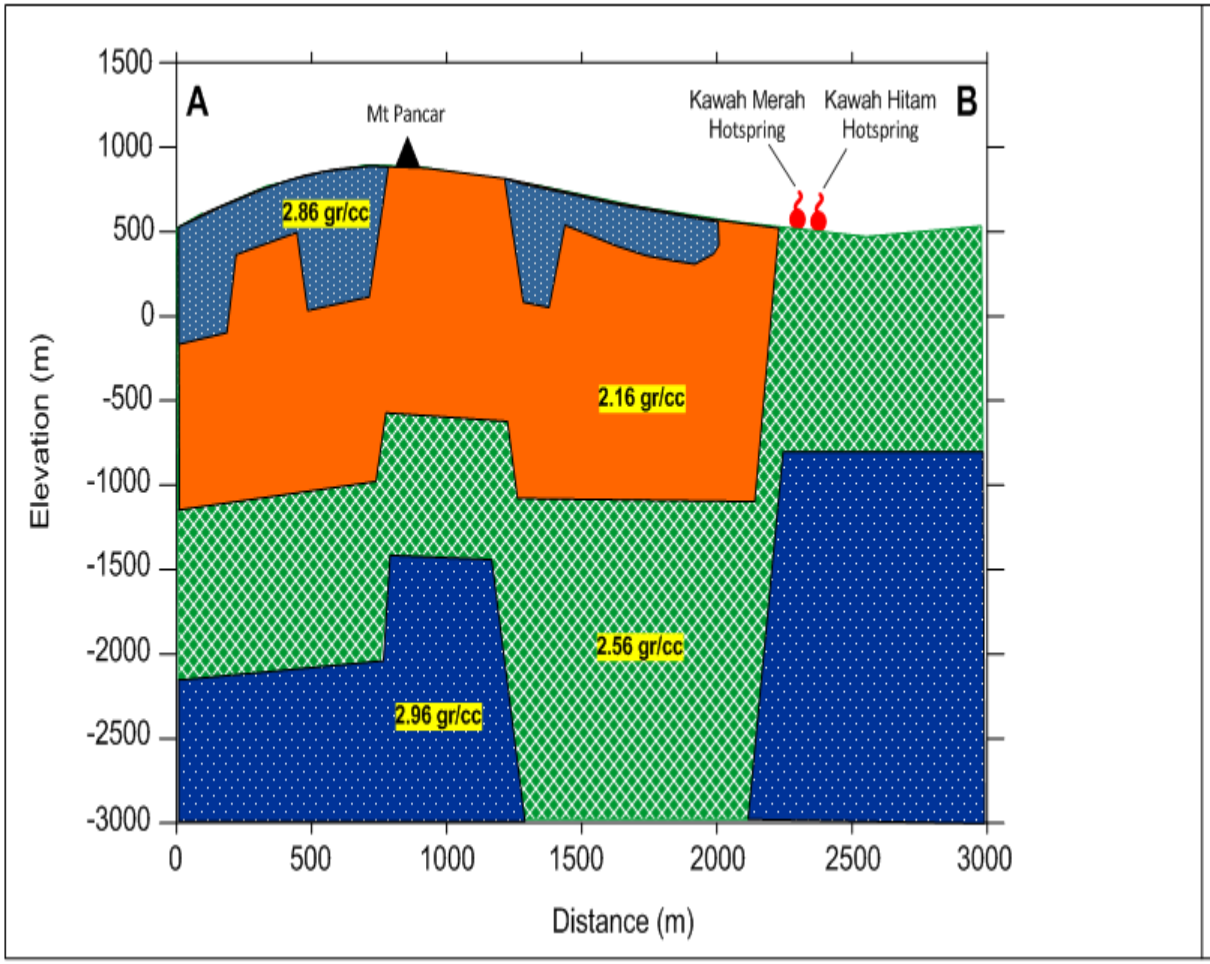
Gravity Section of Line CD



Gravity Section of Line AB



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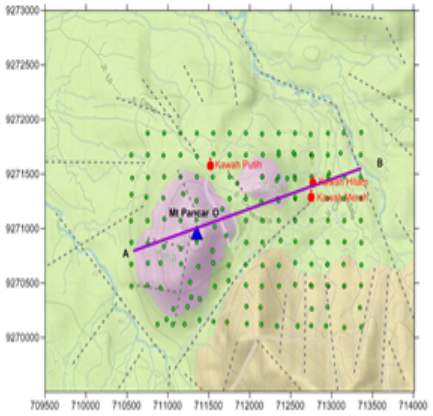
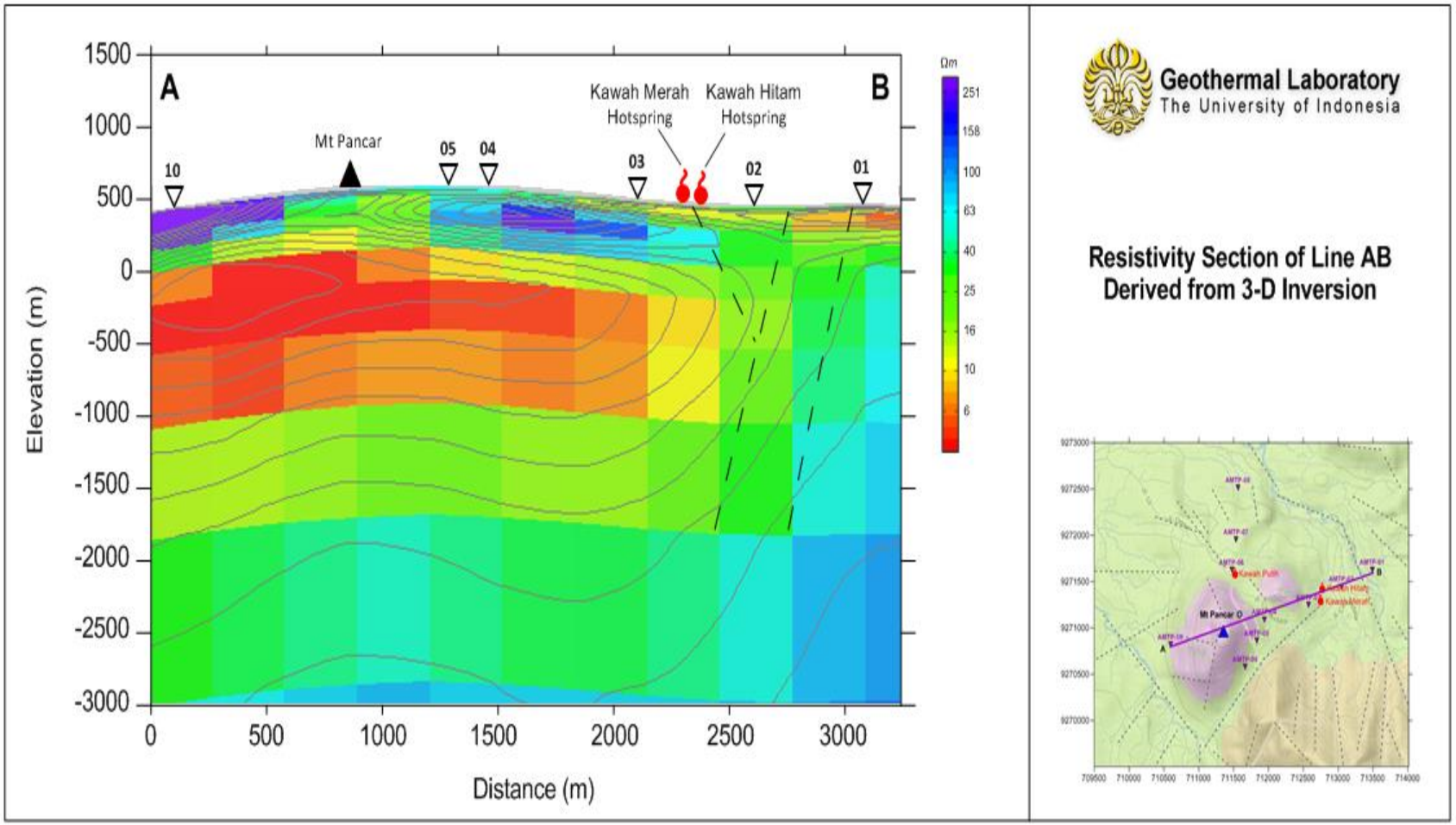
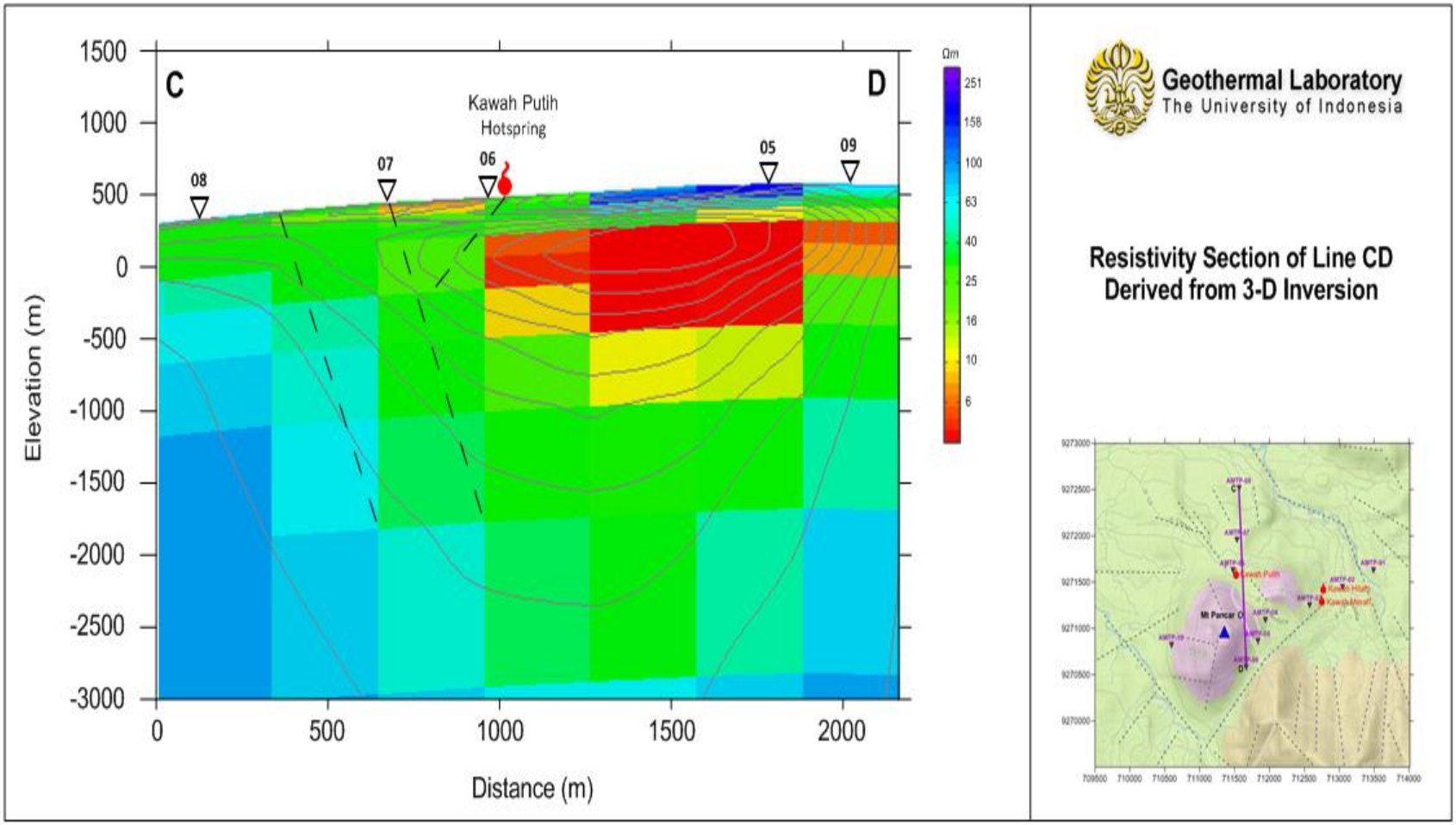
Gravity Section of Line AB



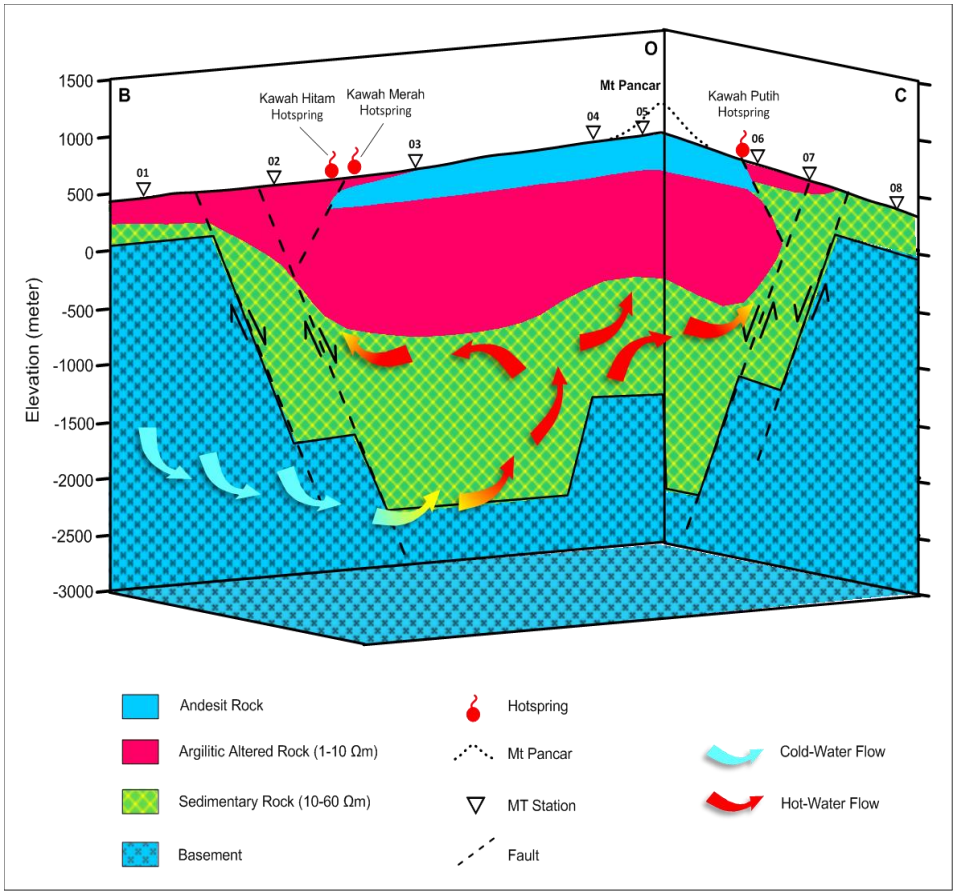
Resistivity Section of Line AB

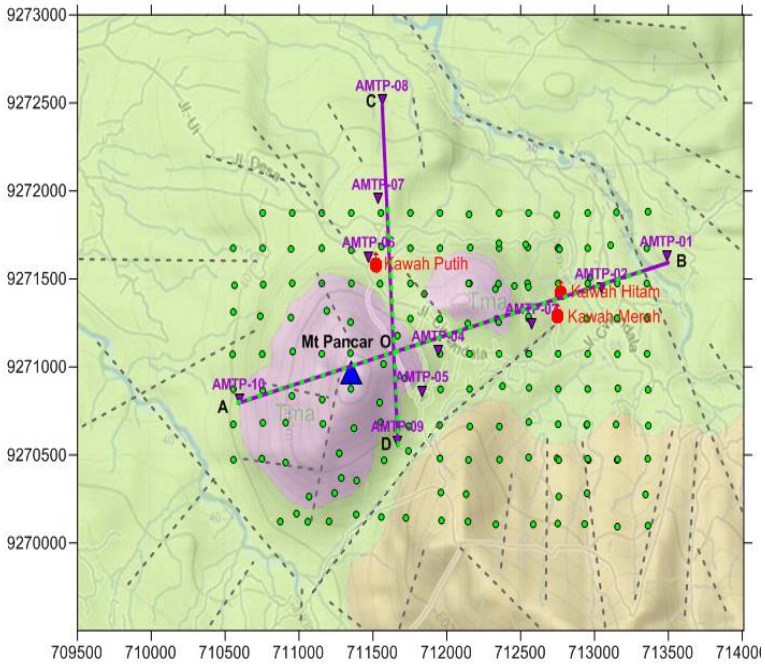


Resistivity Section of Line CD



Conceptual Model of Mt Pancar Area





Training for Trainers

MAGNETOTELLURIC TECHNOLOGY FOR GEOTHERMAL EXPLORATION

THANK YOU

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