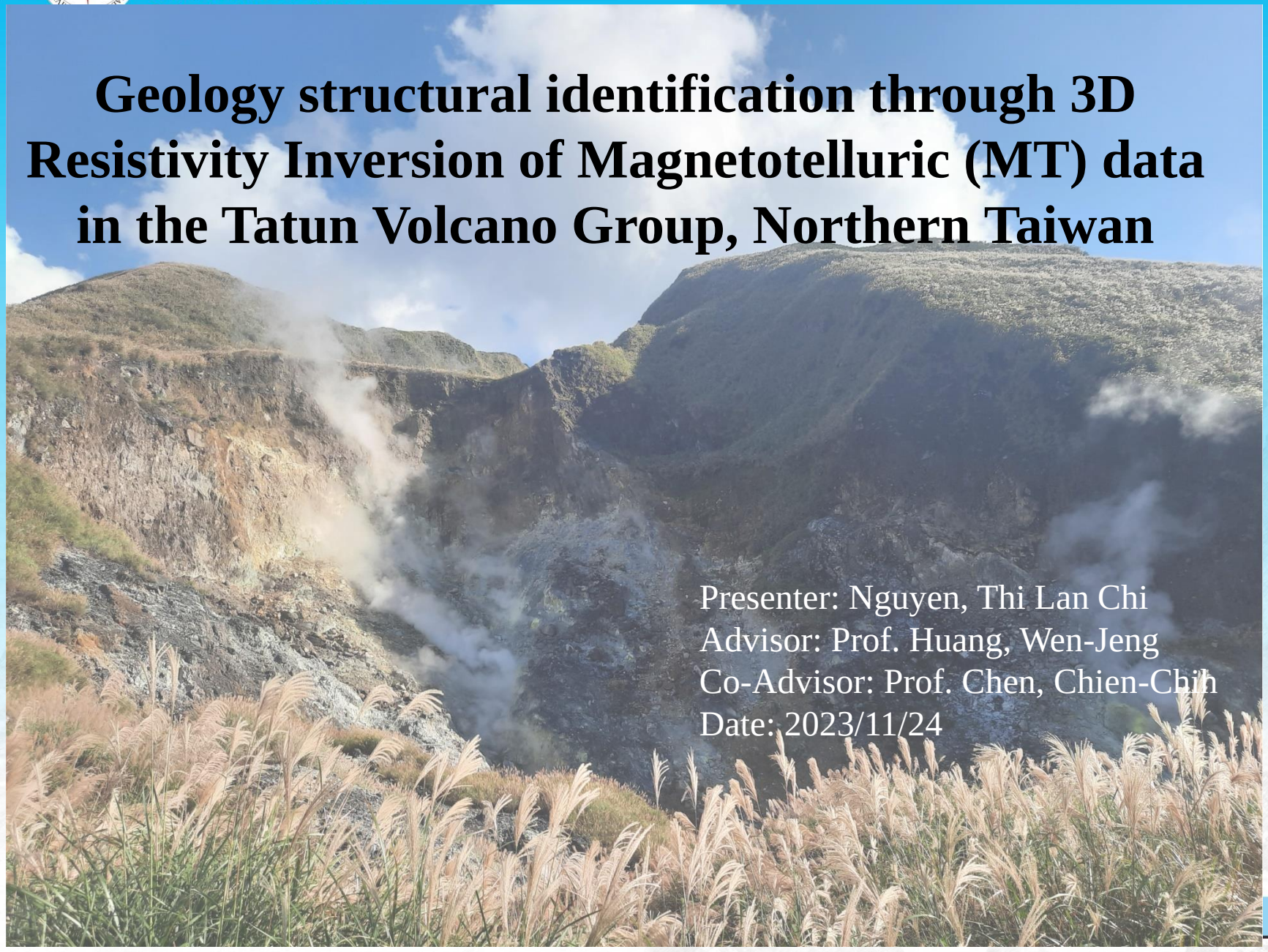
國立中央大學
應用地質研究所
National Central University

Geology structural identification through 3D Resistivity Inversion of Magnetotelluric (MT) data in the Tatun Volcano Group, Northern Taiwan



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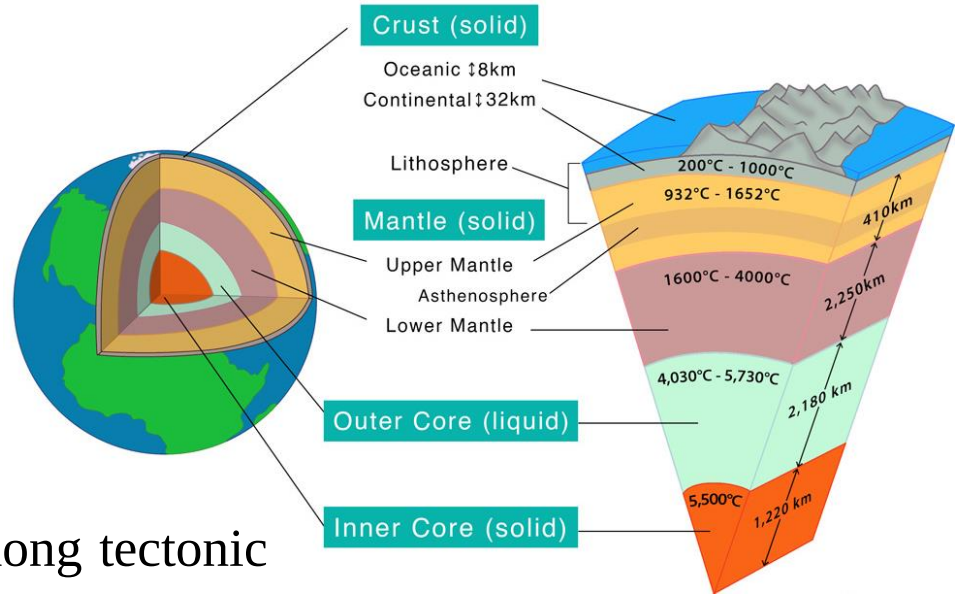
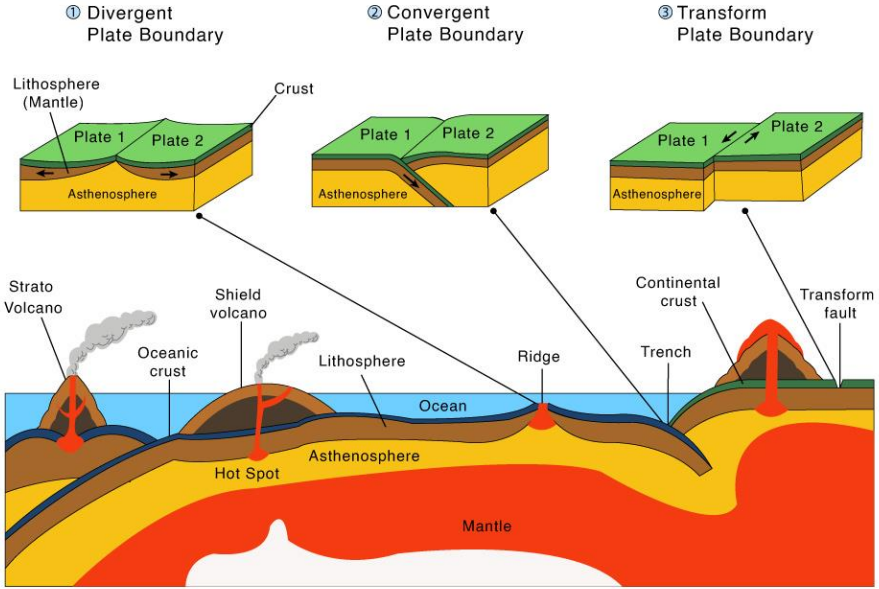
Advisor: Prof. Huang, Wen-Jeng
Co-Advisor: Prof. Chen, Chien-Chih
Date: 2023/11/24

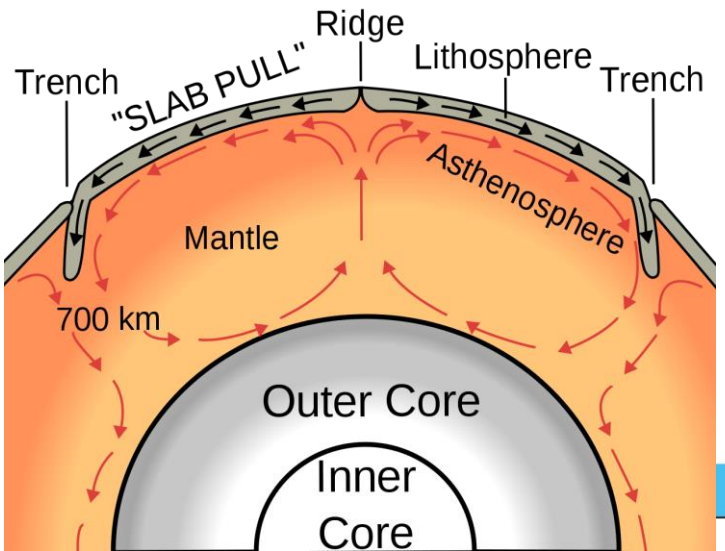
Introduction

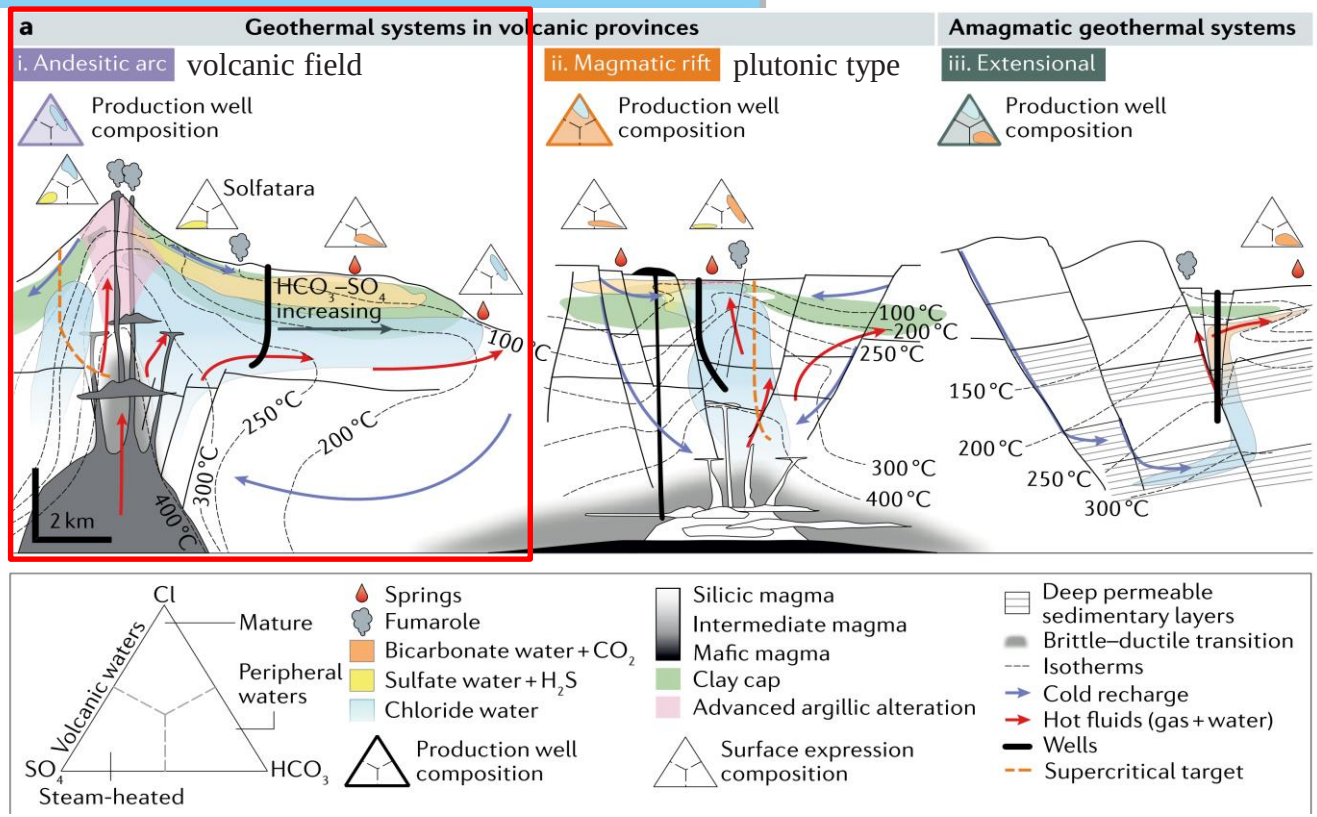
What is geothermal energy?

- Geothermal energy is the heat from the earth
- The heat increase with depth
- Geothermal energy is exposed to the surface as a result of Earth's cooling mechanism (Convection process)
- The geothermal tends to be strongest along tectonic plate boundaries







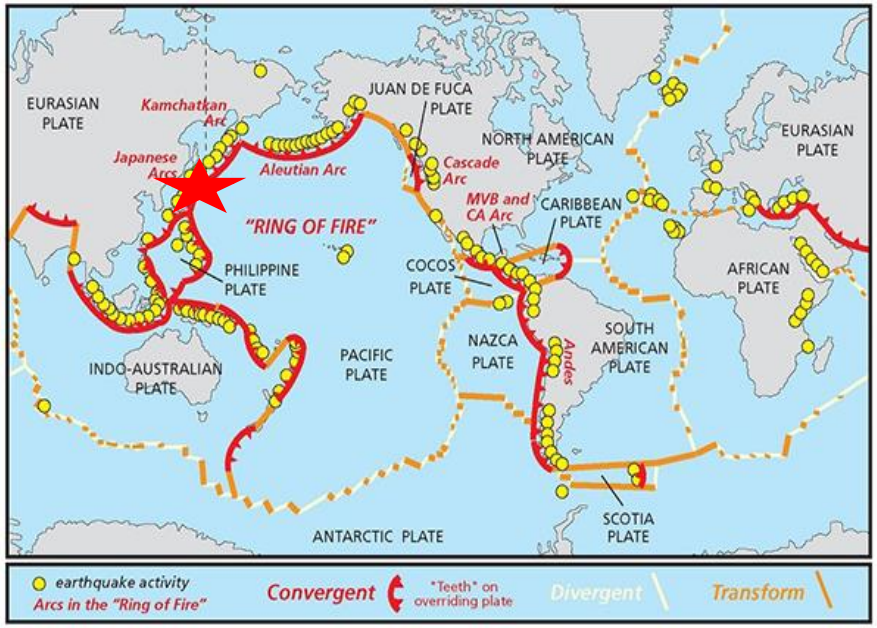


Egbert Jolie et., al 2021

	Volcanic field type	Plutonic type	Extensional domain type
2	*Java-Kamojang*	*Larderello*	*Bradys (Basin and Range)*
3	Magmatic arcs Mid oceanic ridges Hot spots	Young orogens Post-orogenic phase	Metamorphic core complexes Back-arc extension Pull-apart basins Intracontinental rifts
	Magma chamber, intrusion	Young intrusion+extension	Thinned crust → elevated heatflow
4	Active magmatism (volcanism)	Recent plutonism	Active extensional domain
5	Convection dominated systems		
6	- / +	Fault controlled / Magmatic	+ / -

I.S. Moeck , 2014

Geological background



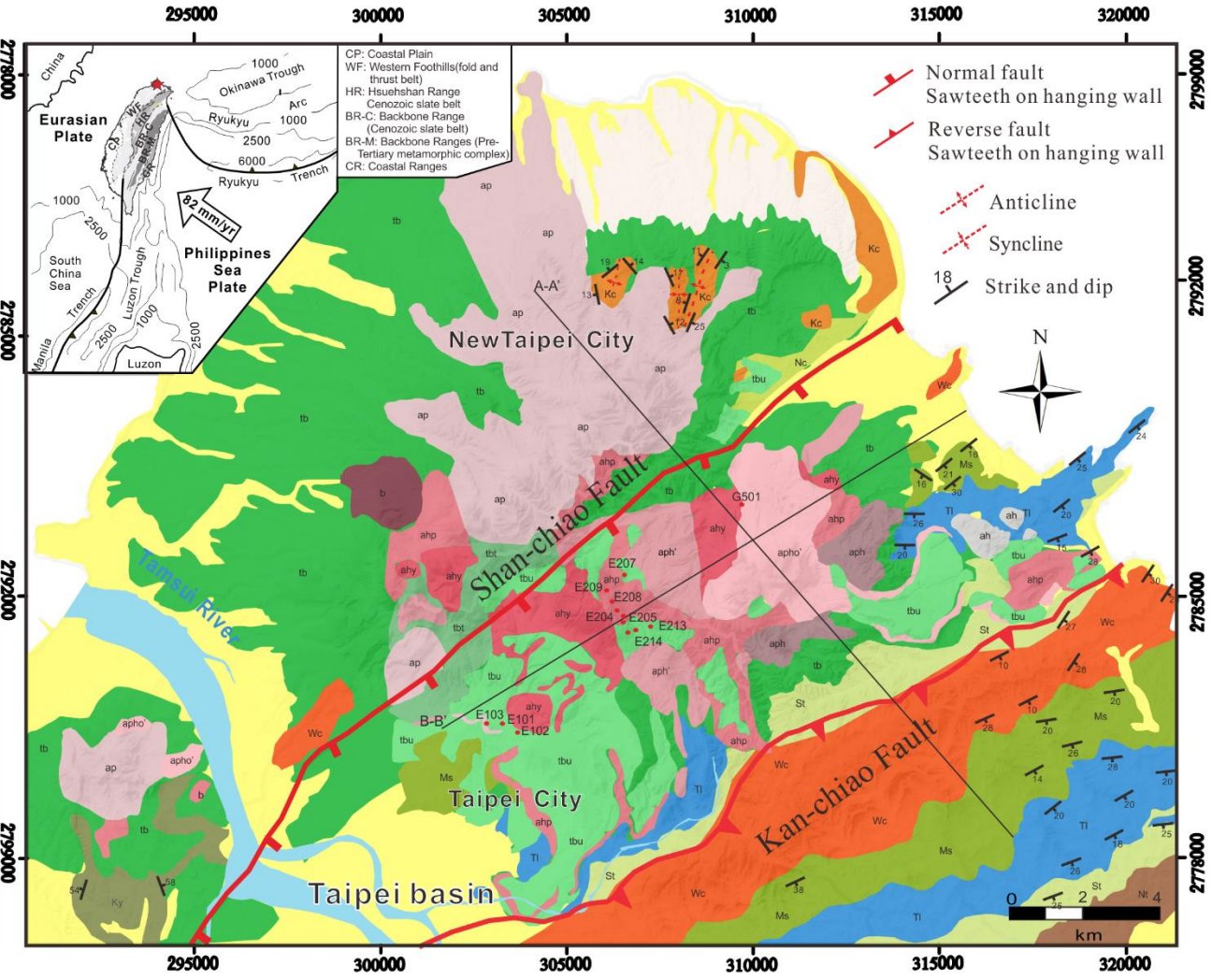
- Most of Taiwan is currently undergoing crustal shortening
- Northern Taiwan is experiencing extensional deformation.

- The TVG multi-vent volcano group covers an area of approximately 400 km^2 on the northern tip of Taiwan.
- The TVG is composed of more than 20 Quaternary-age volcanoes.

Taiwanese Ministry of Science and Technology
https://www.youtube.com/watch?v=M5rnPO1h-ro&t=1s&ab_channel=sunartscience

Regional geology

Tatun Volcano Group (TVG)



Legend

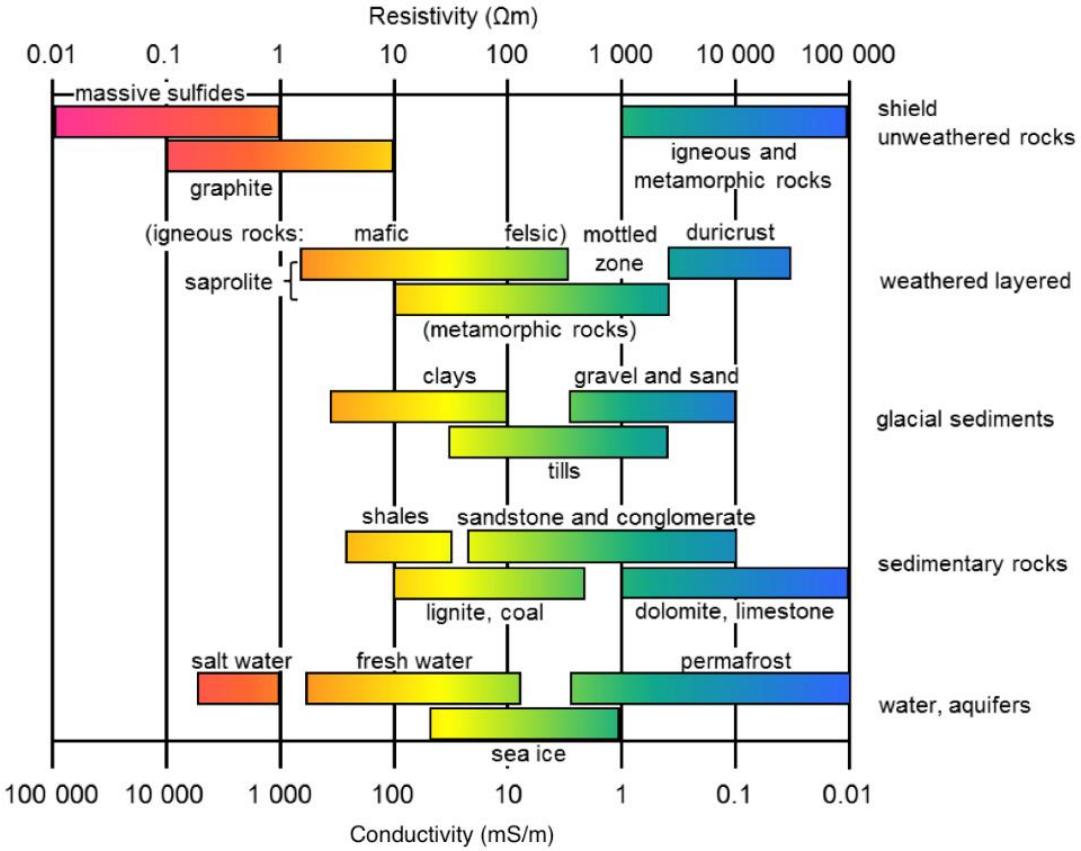
- Recent
  - Alluvium
- Pleitocene Pliocene
  - Tks — Hsiangshan Facies Toukoshan Formation
  - Kc — Kuechulin Formation
- Miocene
  - Nc — Shangfuchi Sandstone Nanchuang Formation
  - Nt — Nankang-Tsoho Formation
  - St — Shinti Formation
  - Tl — Taliao Formation
  - Ms — Mushan Formation
  - Wc — Wuchihshan Formation
- Pleitocene
  - Pyroclastic
  - Lava Flows
    - ah — Horblende andesite
    - ahy — Hypersthene hornblence andesite
    - ahp — Two-pyrocene hornblende Andesite
    - aph — Hornblende two-pyrocene andesite
    - aph' — Hornblende-bearing two-pyrocene andesite
    - ap — Two-pyrocene andesite
    - apho' — Olivine-bearing hornblende two-pyrocene andesite
    - b — Basal
  - Tuff Breccias
    - tbu — Upper tuff breccia
    - tb — Tatunshan tuff breccia
    - tbt — Lower tuff breccia

Introduction

Resistivity of Earth material

Resistivity is one of the most variable physical properties of materials and has proven to be the most useful geophysical parameter in the search for geothermal resources.

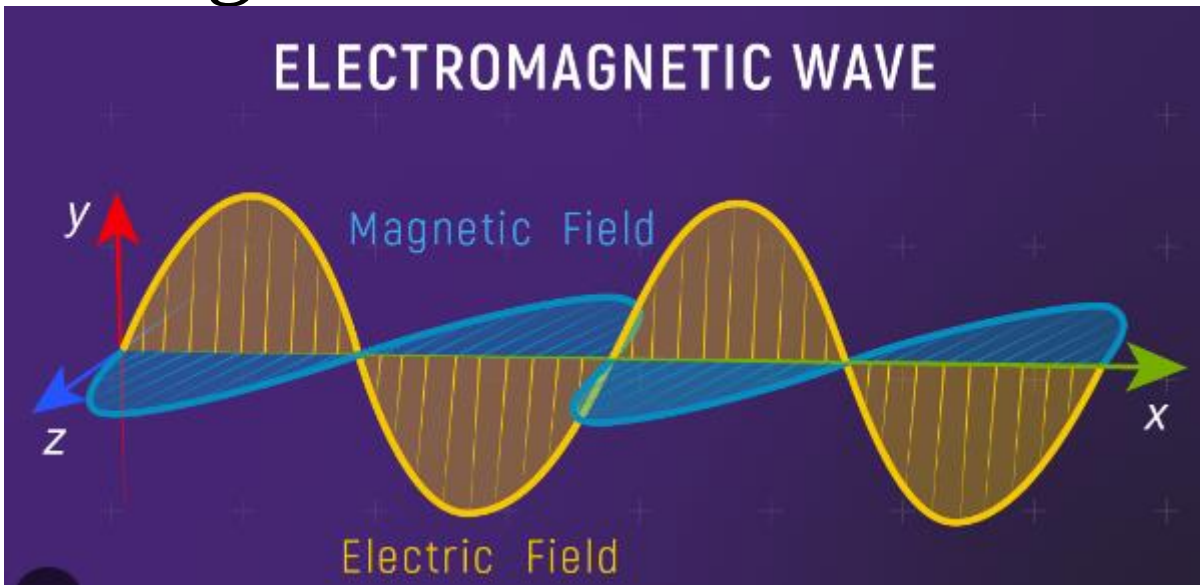
Mineralogy, temperature,… affected to resistivity

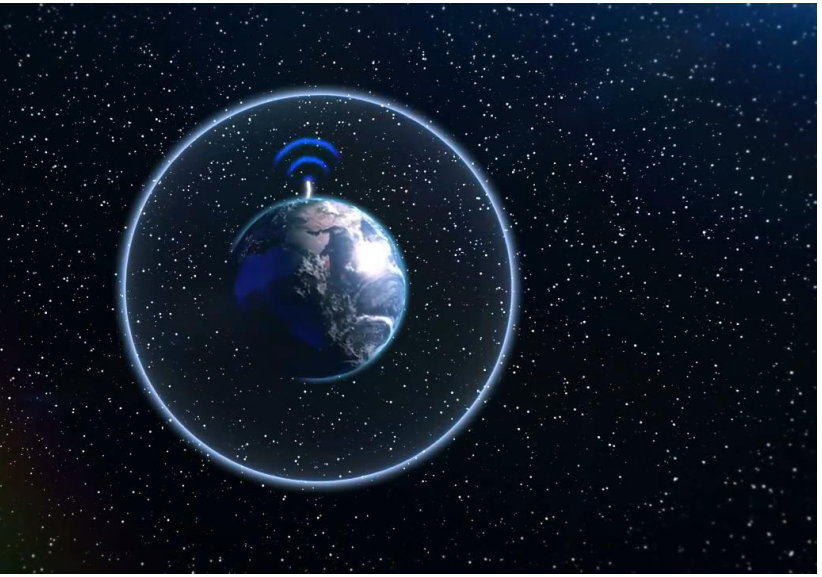


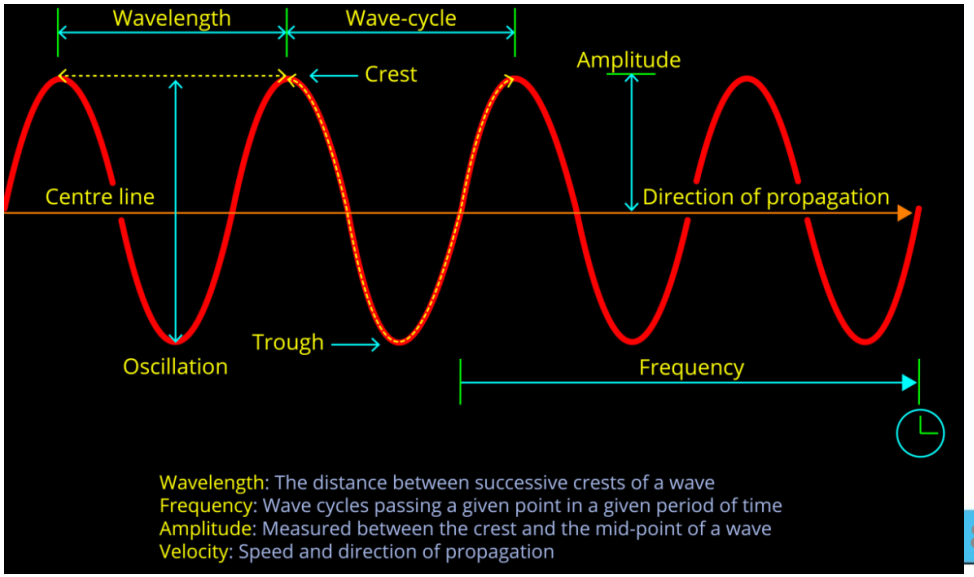
Basic principle of Magnetotelluric

Magnetotellurics (MT) is a passive EM (electromagnetic) geophysical method that uses natural time variations of the Earth's **magnetic** and **electric fields** to measure the electrical resistivity of the sub-surface.

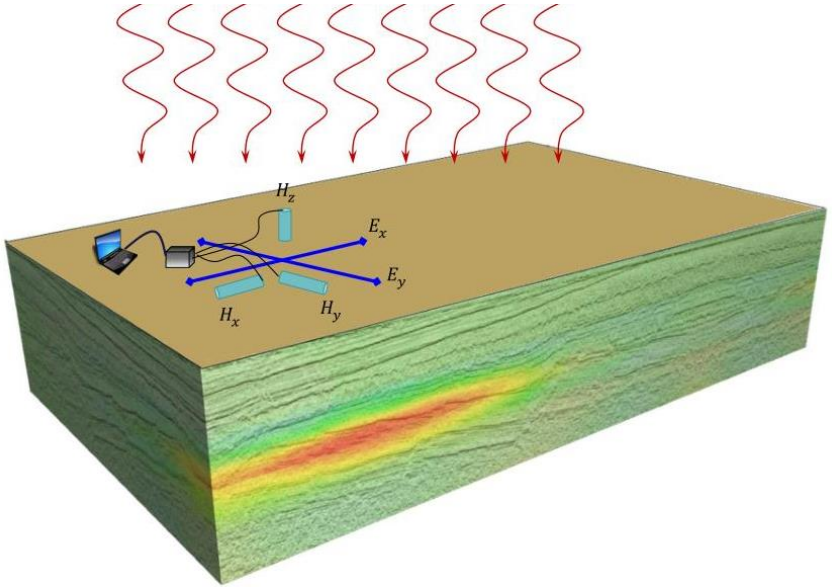
Signal: ~0-10kHz







How to measure the resistivity of the Earth with MT



ρ_a → Apparent Resistivity (Ω.m)
δ → depth of penetration (m)
E_x → electric field component (V/m)
H_y → magnetic field components (A/m)
μ → magnetic permeability of the medium (H/m)
f → frequency (Hz)
ω → angular frequency (rad/s)

μ_r = Relative Permeability (usually 1)

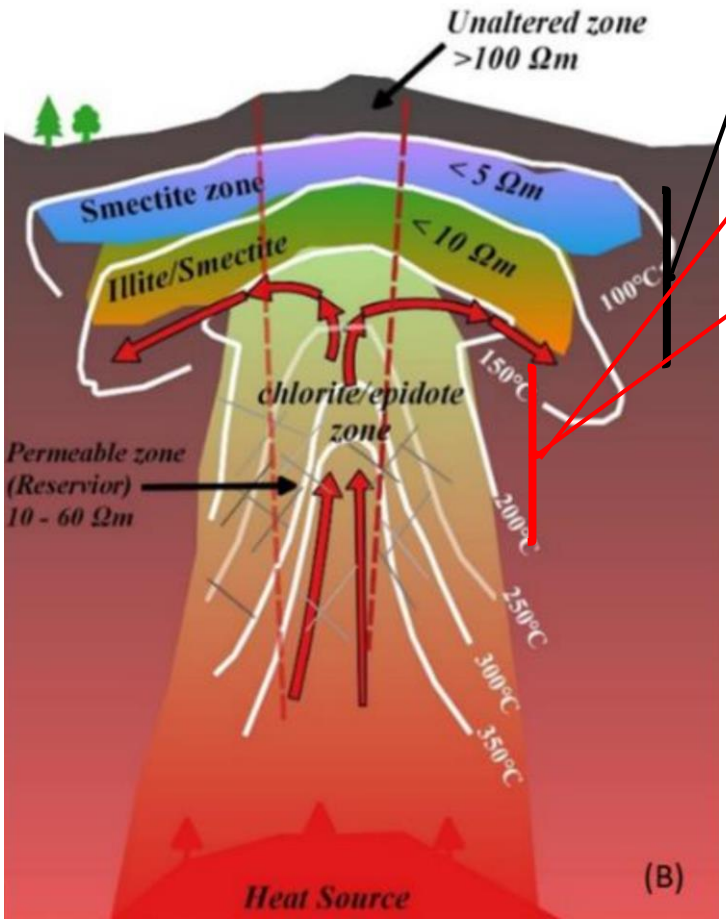
μ_o = Permeability Constant = $4\pi \times 10^{-7}$

Maxwell's equations:

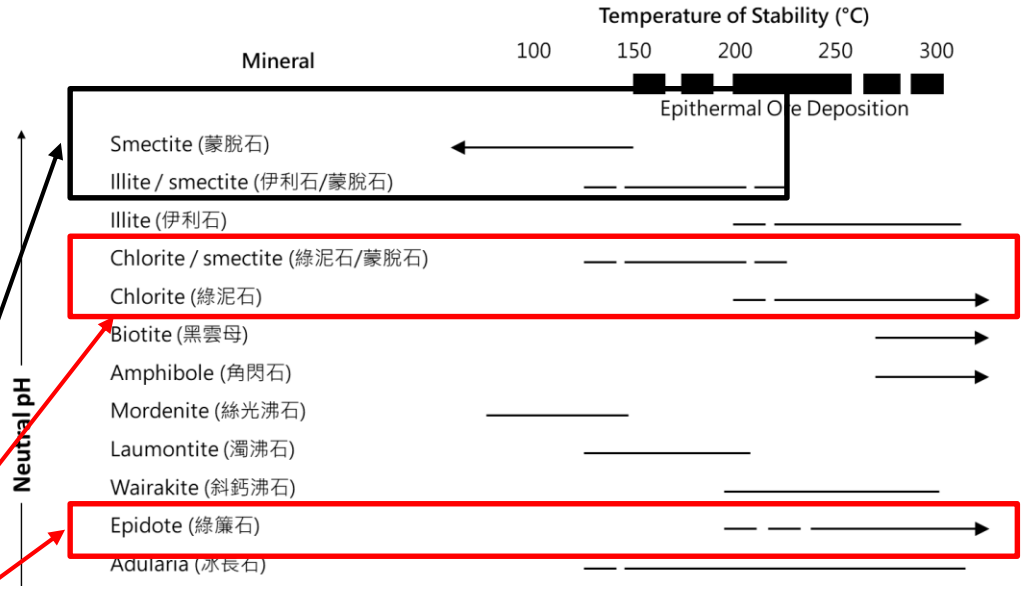
$$\rho_a = \frac{1}{\omega\mu_0}\left|\frac{E_x}{H_y}\right|^2$$

$$Skin\ Depth = \delta = \sqrt{\frac{\rho_a}{\pi f \mu}} = \sqrt{\frac{\rho_a}{\pi f \mu_r \mu_o}} = 500 * \sqrt{\rho_a / f}$$

MT role in geothermal exploration



Johnston et al. (1992) and Cumming (2009)



Geothermal system (volcanic type conceptual model):

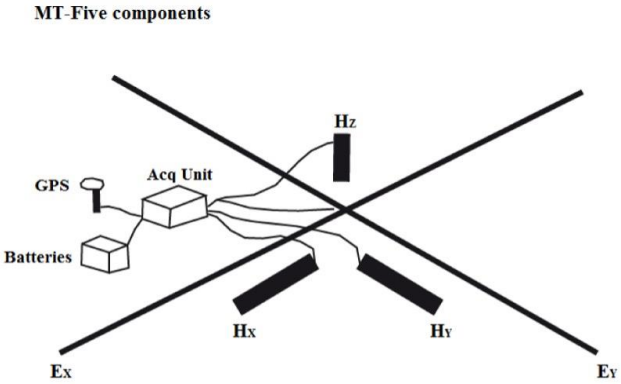
- Clay cap: smectite and illite zone low resistivity (<10 Ωm)
- Reservoir: chlorite and epidote (related to high-temperature mineral low resistivity but slightly higher than clay cap (10-60 Ωm)

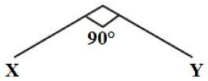
The main target for MT investigation

Purpose

- Understanding the TVG structural geology through the Resistivity model
- Locating the heat source and estimating the boundaries of the TGV geothermal system.
- Point out the most appropriate sites to develop the geothermal power plant

Methodologies: MT





- ITRI data
- Computational Geophysical Research Group

Raw MT data

EMPower

- Remove noise
- Modify Sounding curve

Create files for Inversion

3D gird

ModEM

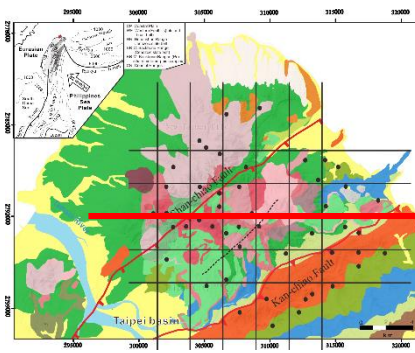
Inversion

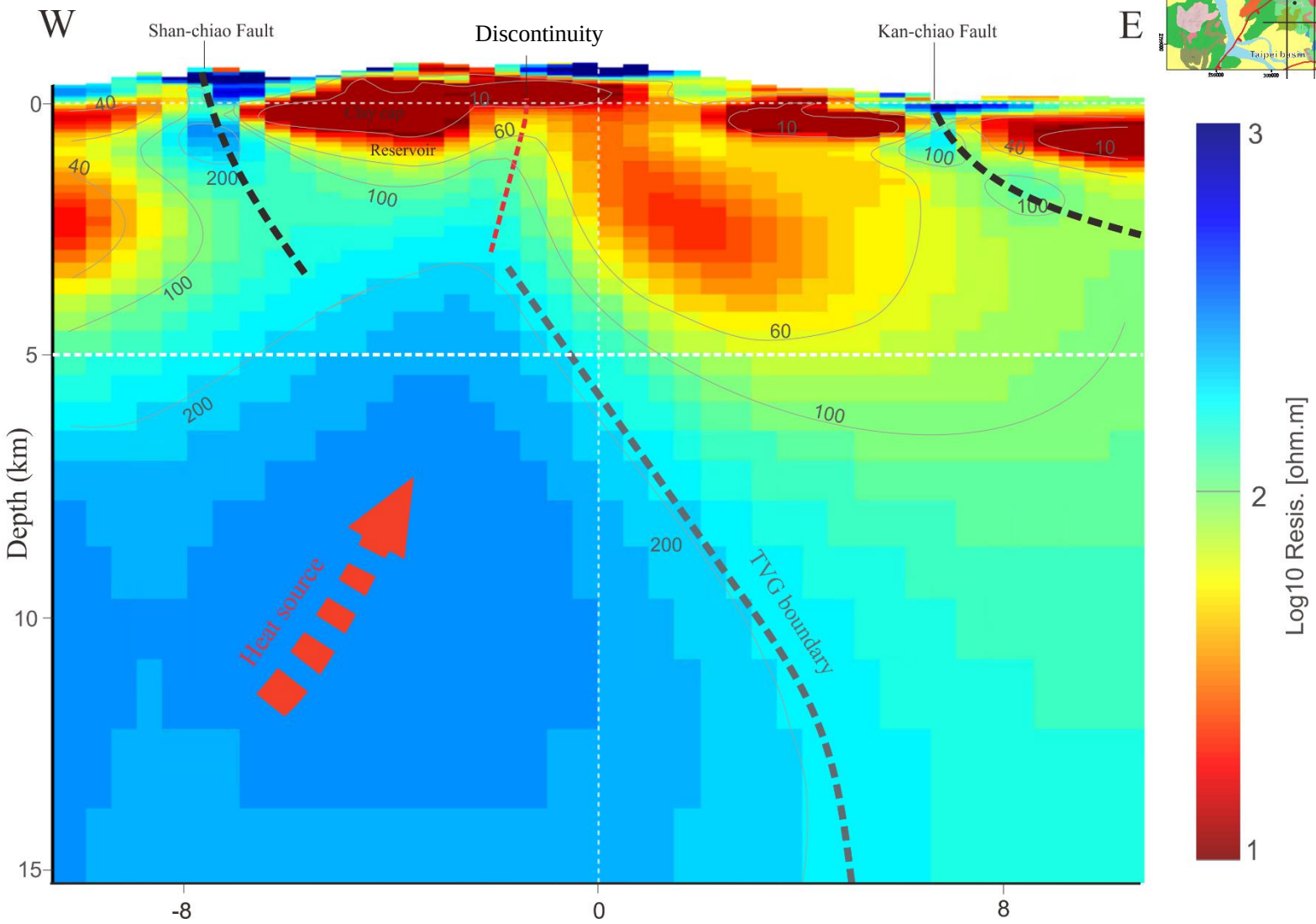
Plot results

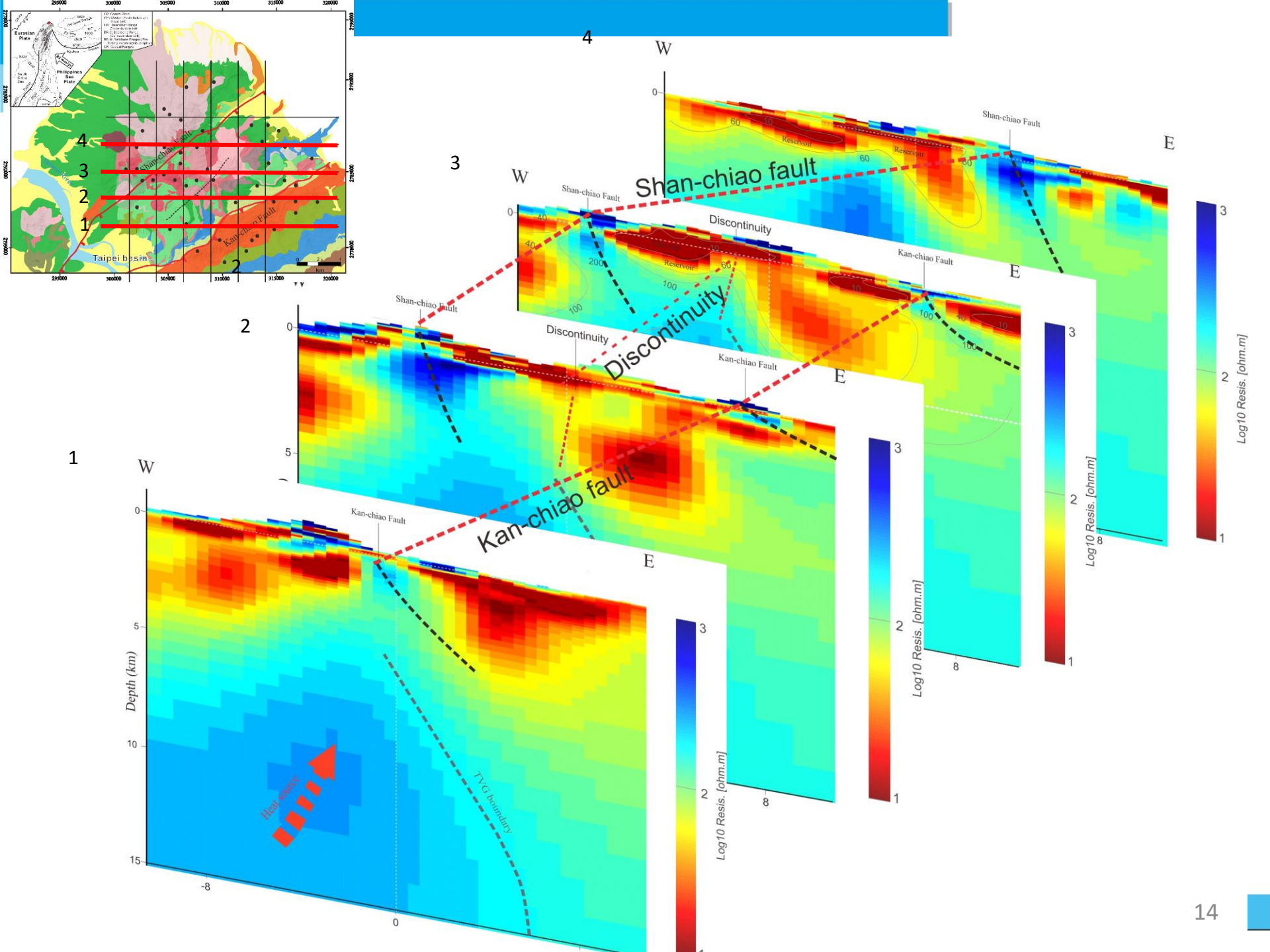
3D gird

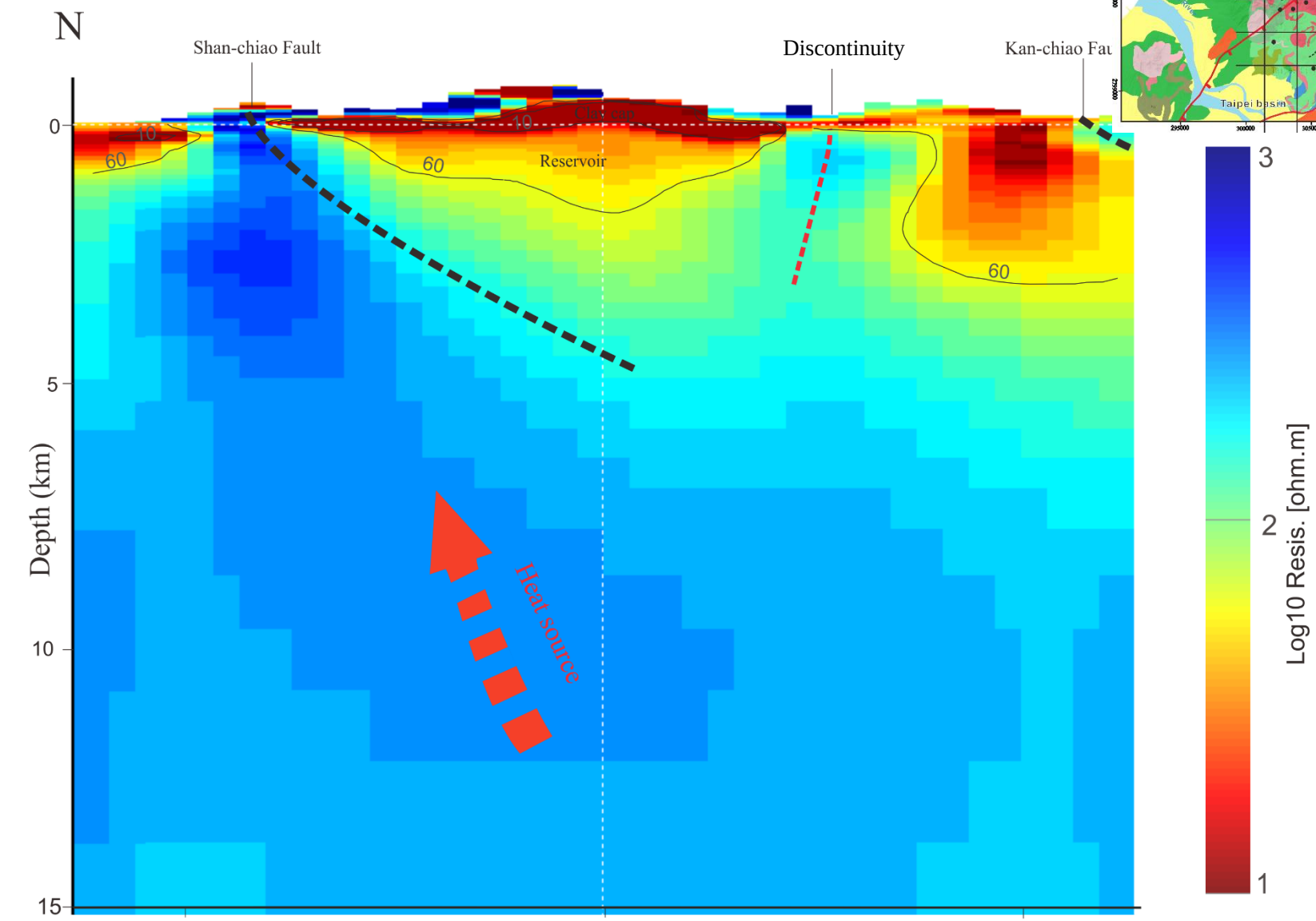
Note: A remote reference site was use in order to remove electromagnetic noise from the electromagnetic signal at each measuring station (Yamashita, 2013)

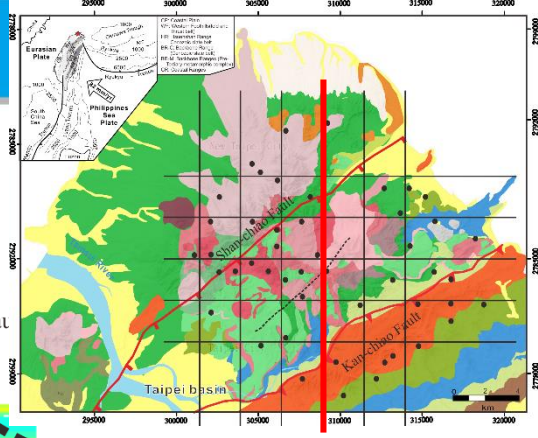
Results

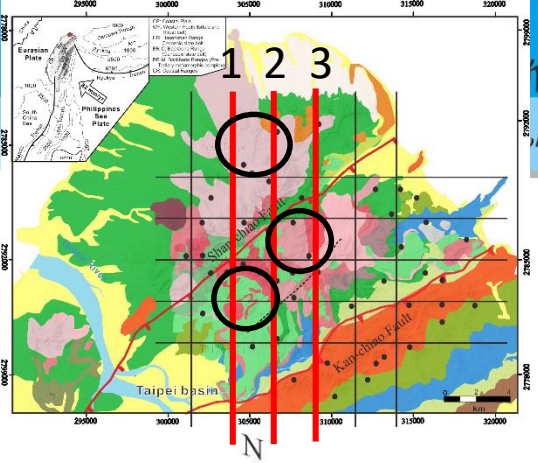


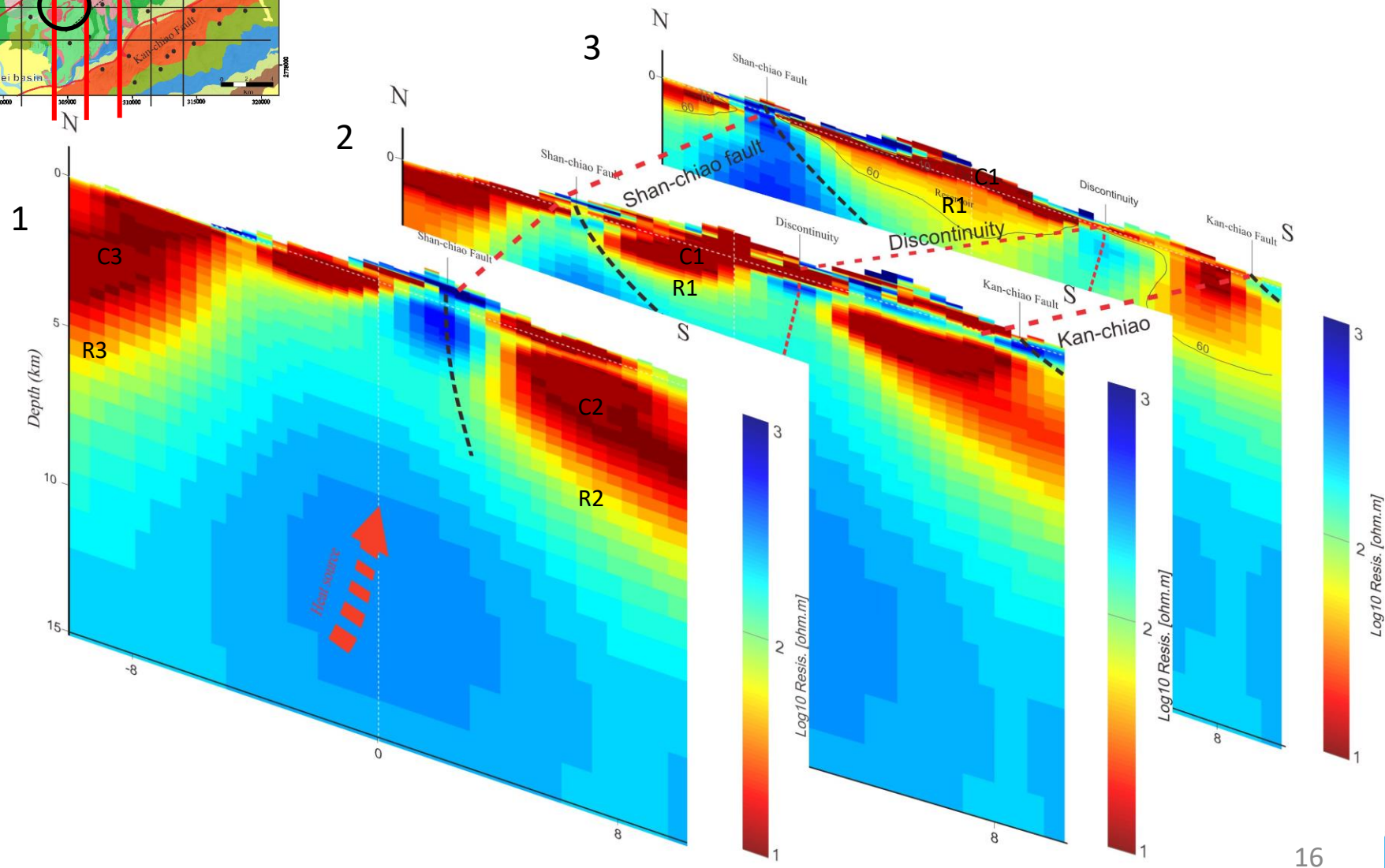

W
E
Shan-chiao Fault
Discontinuity
Kan-chiao Fault
Clay cap
Reservoir
Heat source
TVG boundary
Depth (km)
0
5
10
15
-8
0
8
40
10
60
200
100
Log10 Resis. [ohm.m]
3
2
1

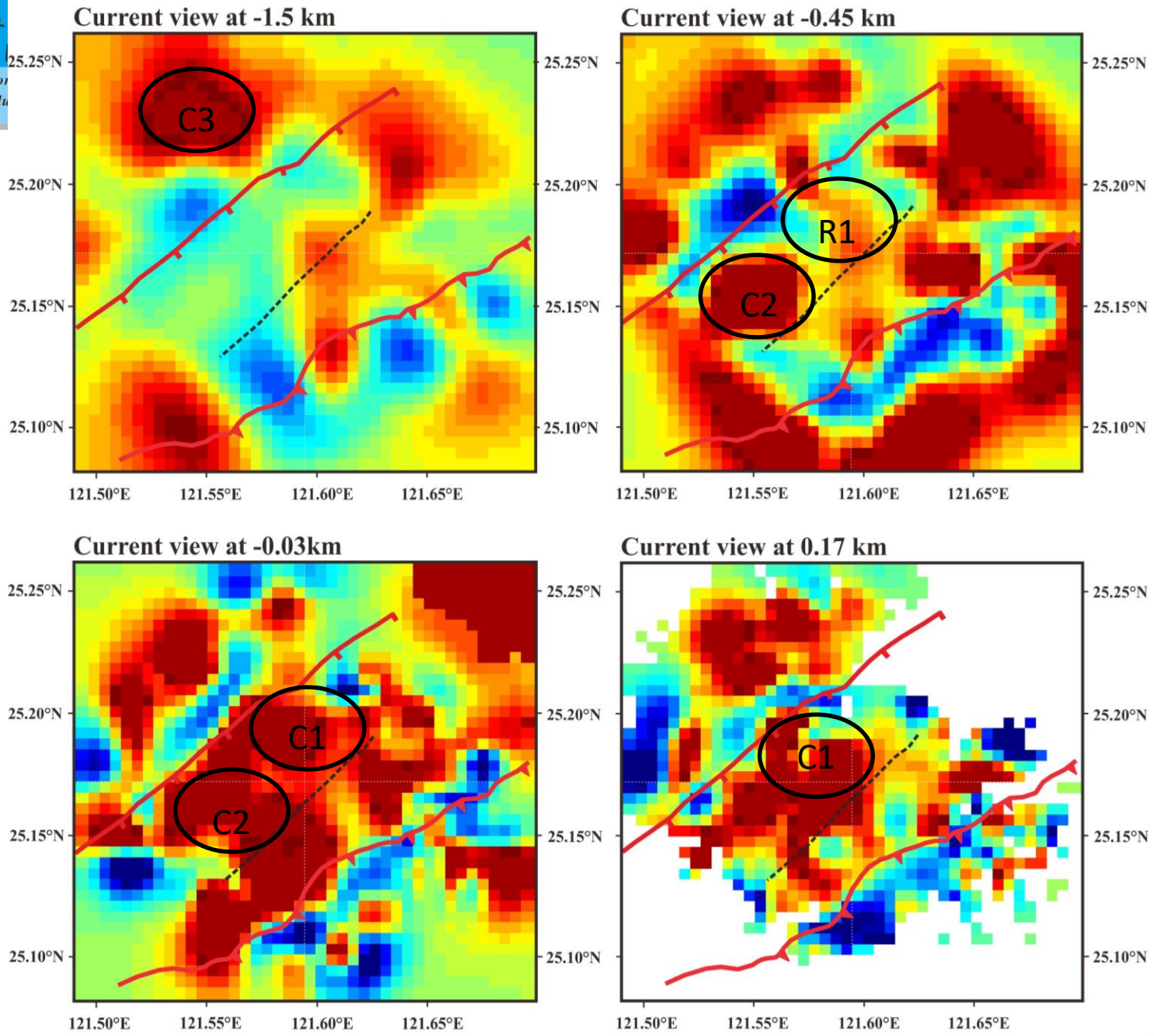

Eurasian Plate
Philippines Sea Plate
Shanchiao fault
Kanchiao Fault
Taipei basin
4
3
2
1
Shan-chiao fault
Discontinuity
Kan-chiao fault
Shan-chiao Fault
Kan-chiao Fault
Reservoir
W
E
Depth (km)
Heat source
TVG boundary
Log10 Resis. [ohm.m]


N
Shan-chiao Fault
Discontinuity
Kan-chiao Fau
Clay cap
Reservoir
10
60
Heat source
Depth (km)
0
5
10
15
-8
0
8
Log10 Resis. [ohm.m]
3
2
1


Eurasian Plate
Philippines Sea Plate
Shanchiao Fault
Kanchiao Fault
Taipei basin

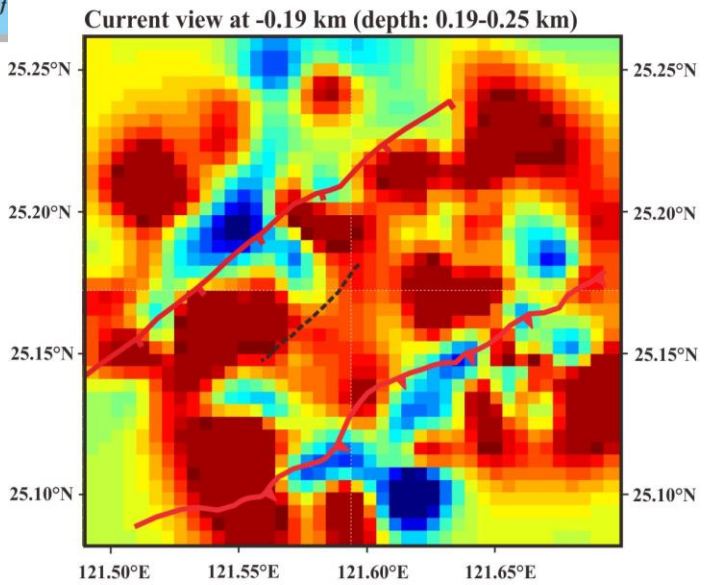

1
2
3
Eurasian Plate
Philippines Sea Plate
Shan-chiao Fault
Kan-chiao Fault
Taipei basin
N

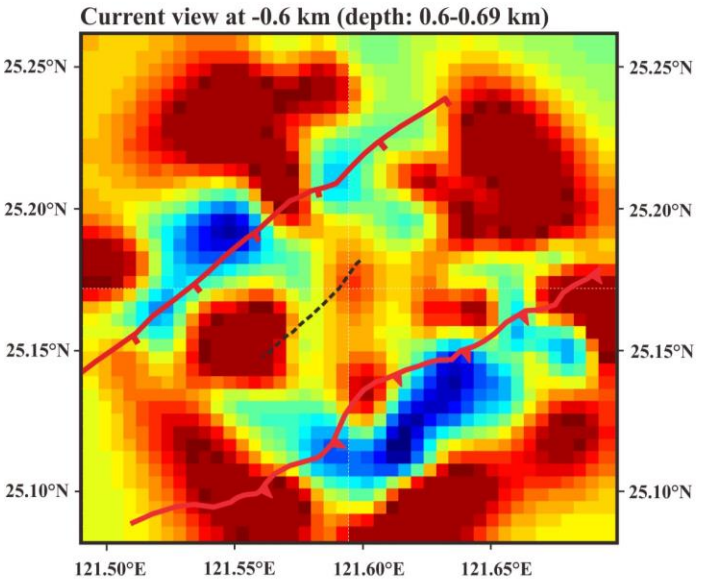

1
2
3
N
S
Shan-chiao Fault
Shan-chiao fault
Kan-chiao Fault
Kan-chiao
Discontinuity
C1
C2
C3
R1
R2
R3
Depth (km)
Log10 Resis. [ohm.m]
Reference


Current view at -1.5 km
C3
Current view at -0.45 km
R1
C2
Current view at -0.03km
C1
C2
Current view at 0.17 km
C1
25.25°N
25.20°N
25.15°N
25.10°N
121.50°E
121.55°E
121.60°E
121.65°E
1
2
3
Log10 Resis. [ohm m]

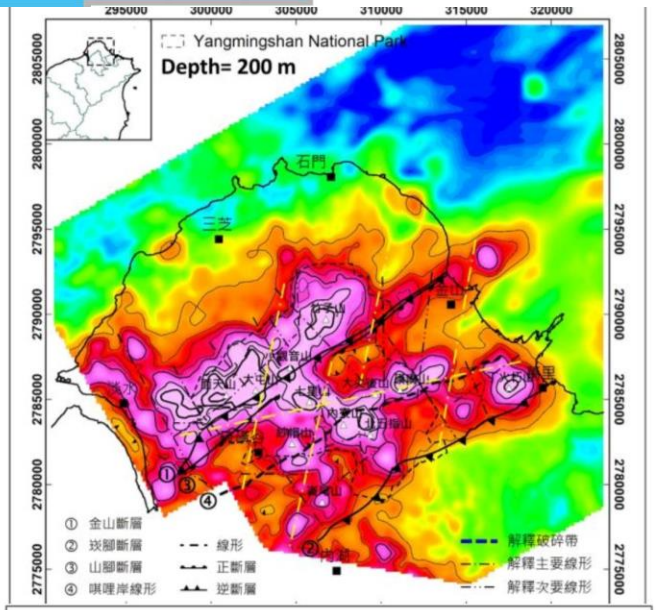
MT and airborne magnetic survey

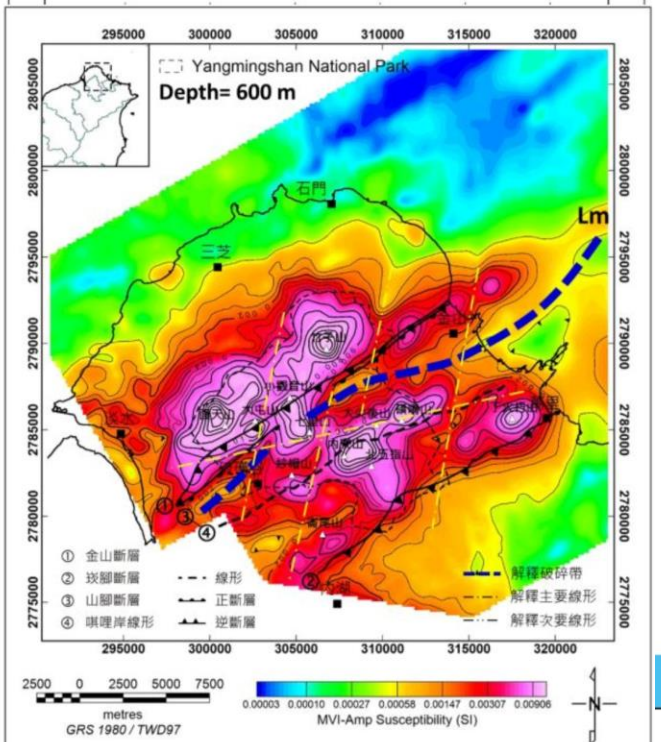
Current MT



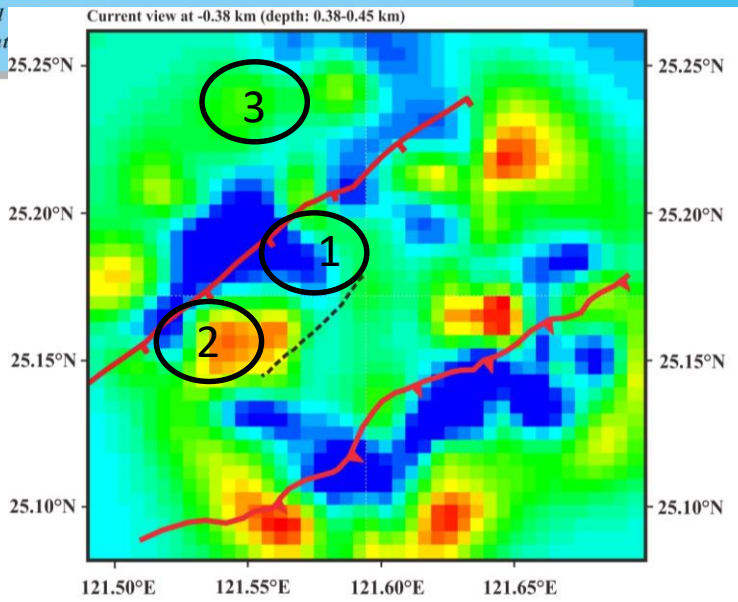


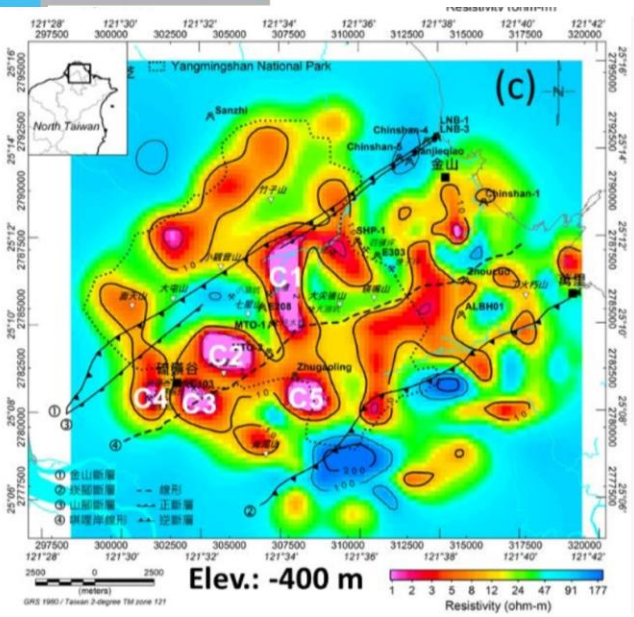
Airborne magnetic survey

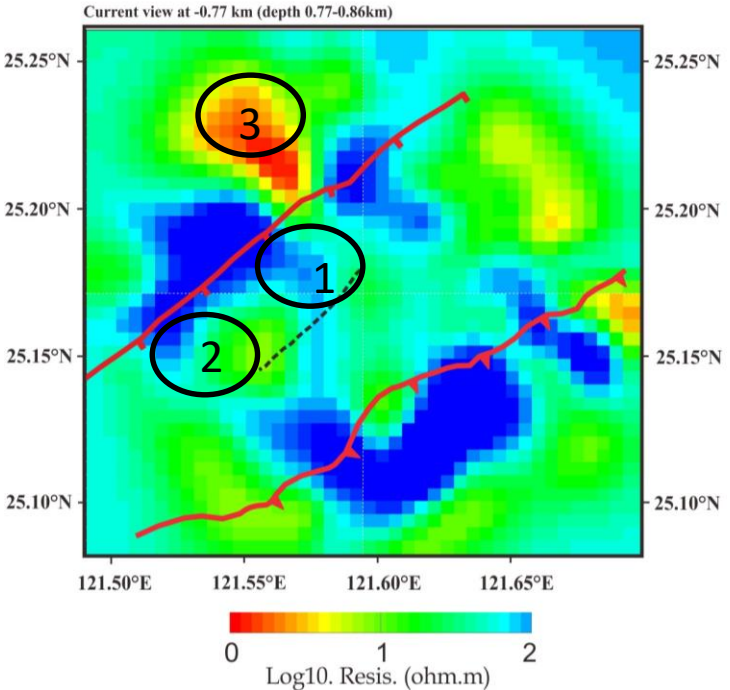


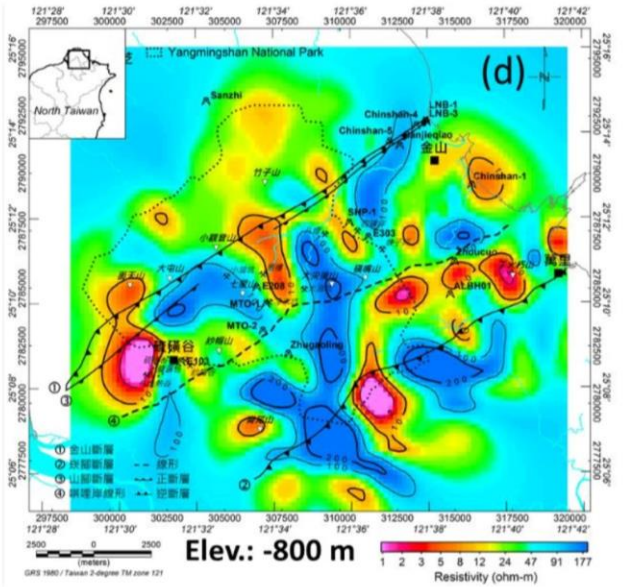


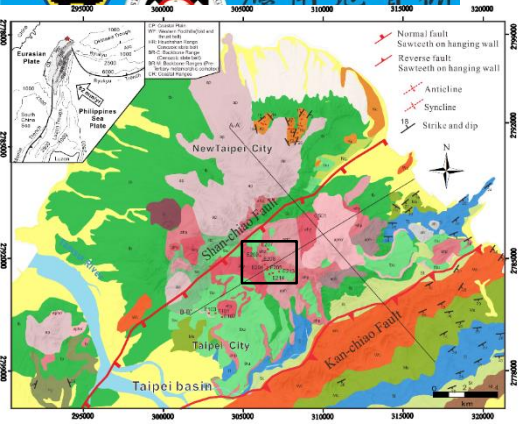
Current MT results and previous results



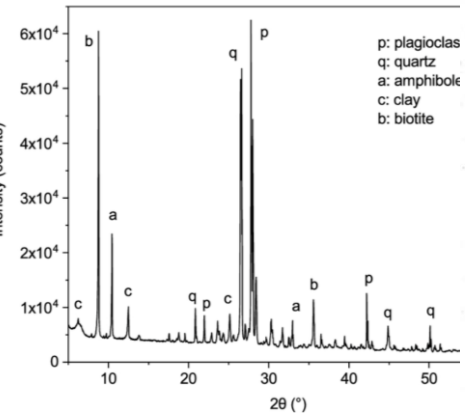




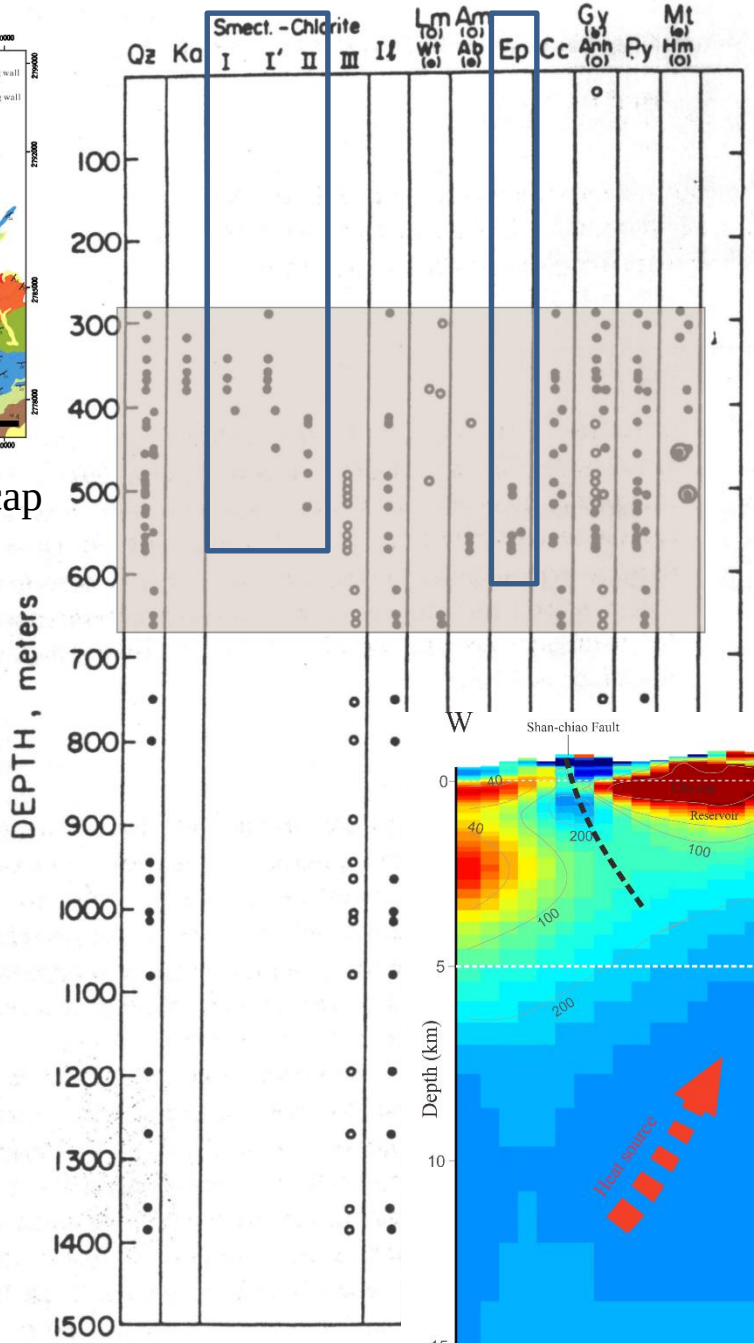


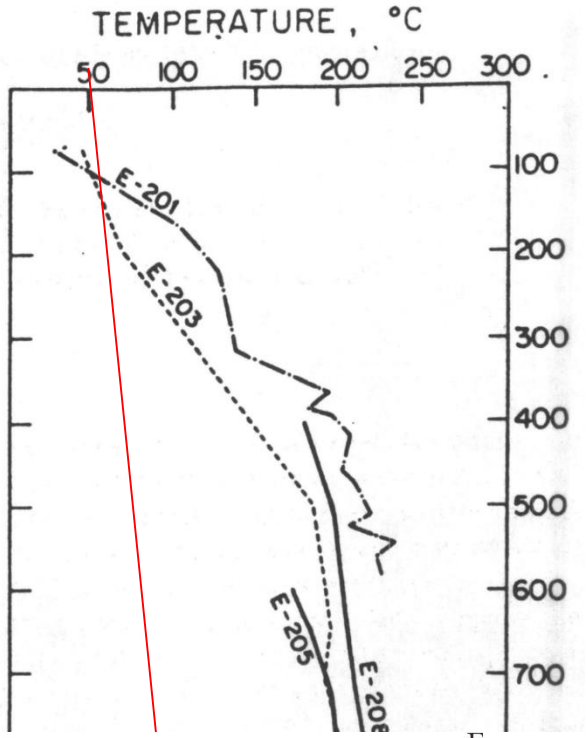


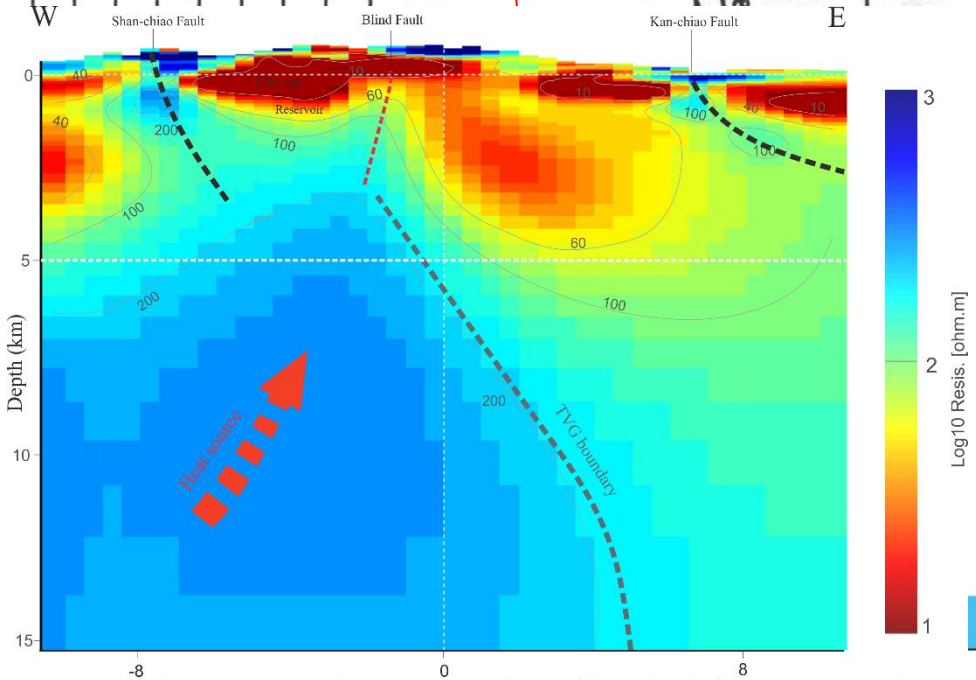
Clay cap



I: alkaline montmorillonite
I': Smectite (with mordenite and clinoptilolite)
II: Smectite-chlorite with laumotite
III: wairakite
Qz: Quartz
Ka: Kaolinite
Il: Illite
Lm: Laumotite, Wt: wairakite, Am: Analcime, Ab: Albite, Ep: Epidote, Cc: Calcite, Gy: Gypsum, Anh: anhudrite, Py: Pyrite, Mt: Magnetite, Hm: Hemaite







Summary

- Improve the MT resistivity result
- Detect a Discontinuity between Shan-chiao fault and Kan-chiao faults
- Point out 3 areas that have high potential to develop Geothermal Power plant
- Indicated the heat source with high resistivity located 5 km beneath the SW of TVG

Current and Future work

- Compare current MT resistivity results and ITRI (MT resistivity, airborne magnetic survey) results

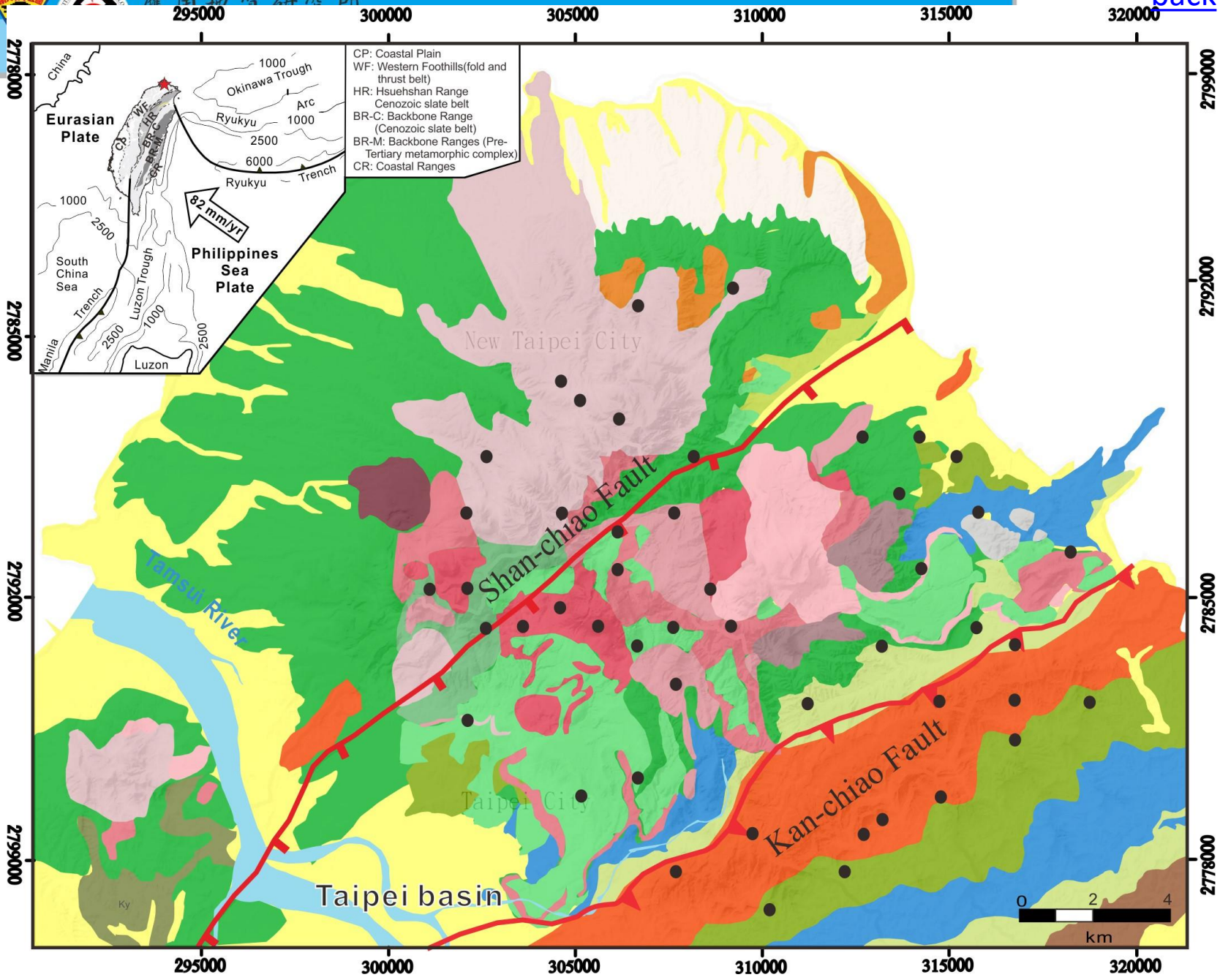
⇒ Plot results and export cross-sections flowing NE-SW and NW-SE directions

- Combine MT resistivity results and seismic velocity (Vp/Vs ratio) results to indicate the magma chamber position.

Thanks for your attention!

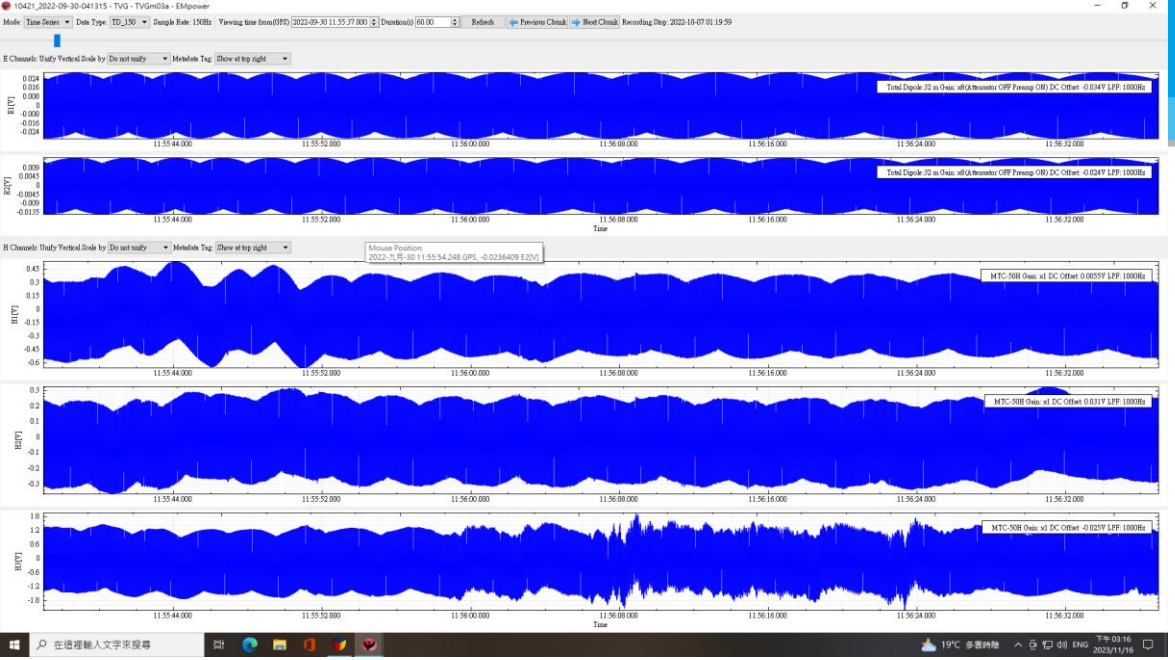
Qixingshan main peak

back

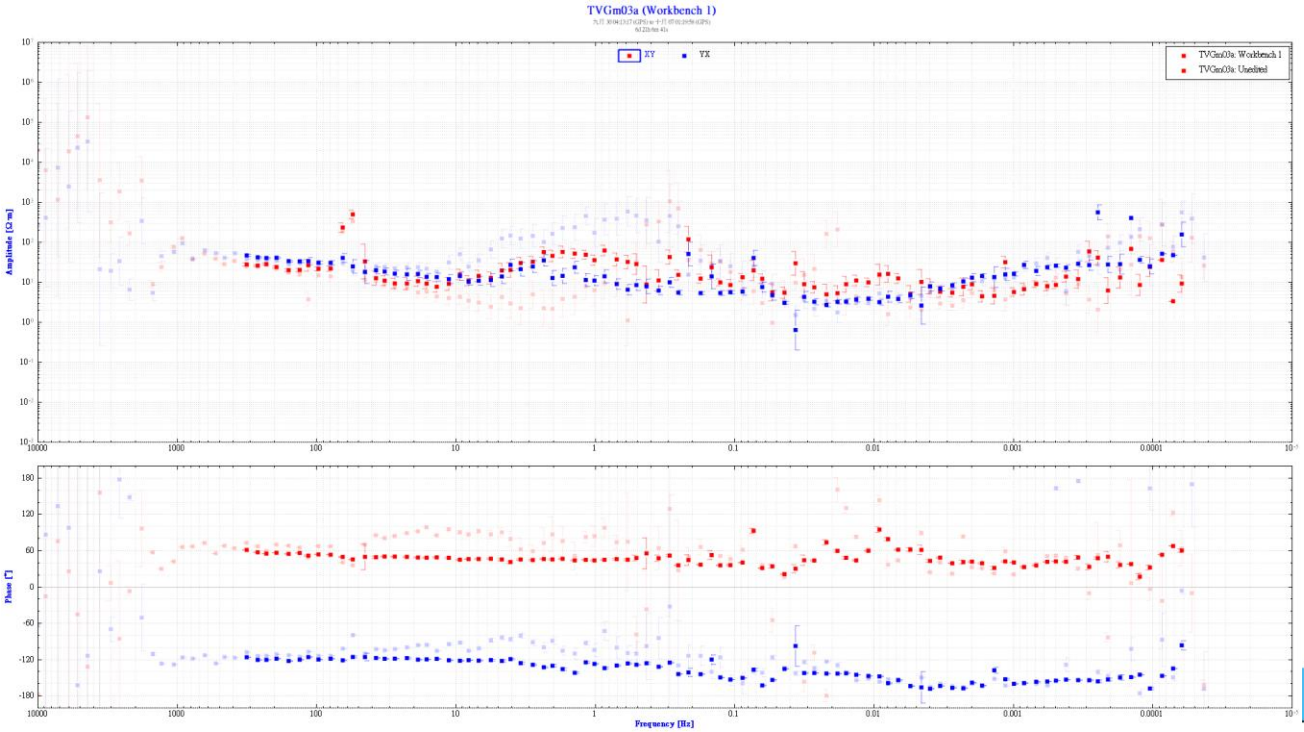

295000
300000
305000
310000
315000
320000
2778000
2785000
2792000
2799000
CP: Coastal Plain
WF: Western Foothills(fold and thrust belt)
HR: Hsuehshan Range Cenozoic slate belt
BR-C: Backbone Range (Cenozoic slate belt)
BR-M: Backbone Ranges (Pre-Tertiary metamorphic complex)
CR: Coastal Ranges
China
Eurasian Plate
Okinawa Trough
Ryukyu
Arc
Trench
82 mm/yr
Philippines Sea Plate
South China Sea
Luzon Trough
Manila
Luzon
New Taipei City
Shan-chiao Fault
Tamsui River
Taipei City
Kan-chiao Fault
Taipei basin
Ky
0
2
4
km

Back

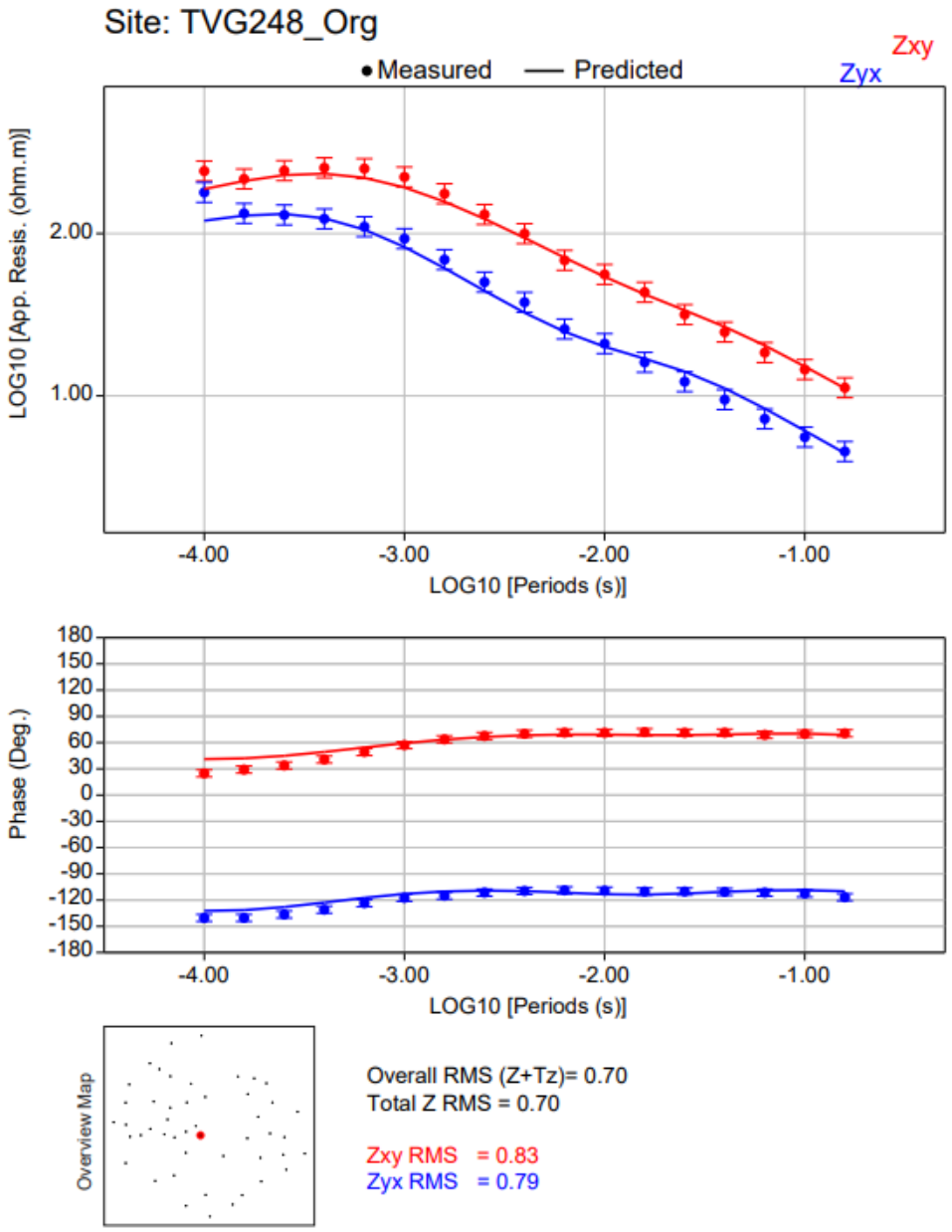
Time series analysis



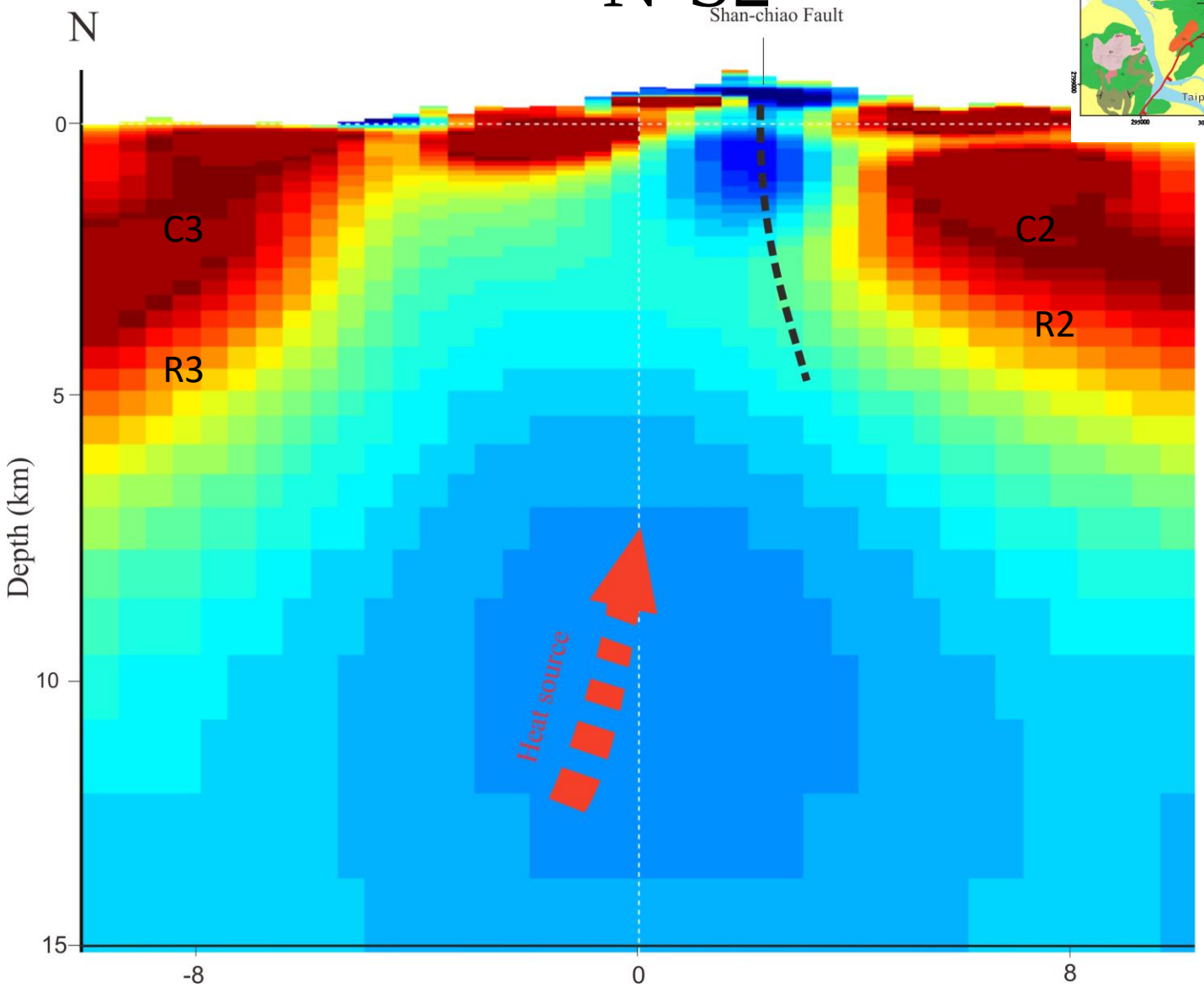
Frequency modulation

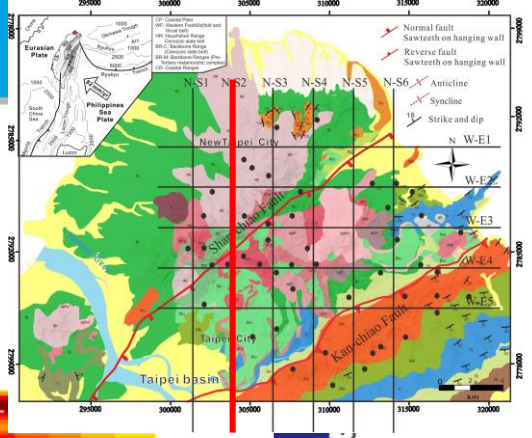


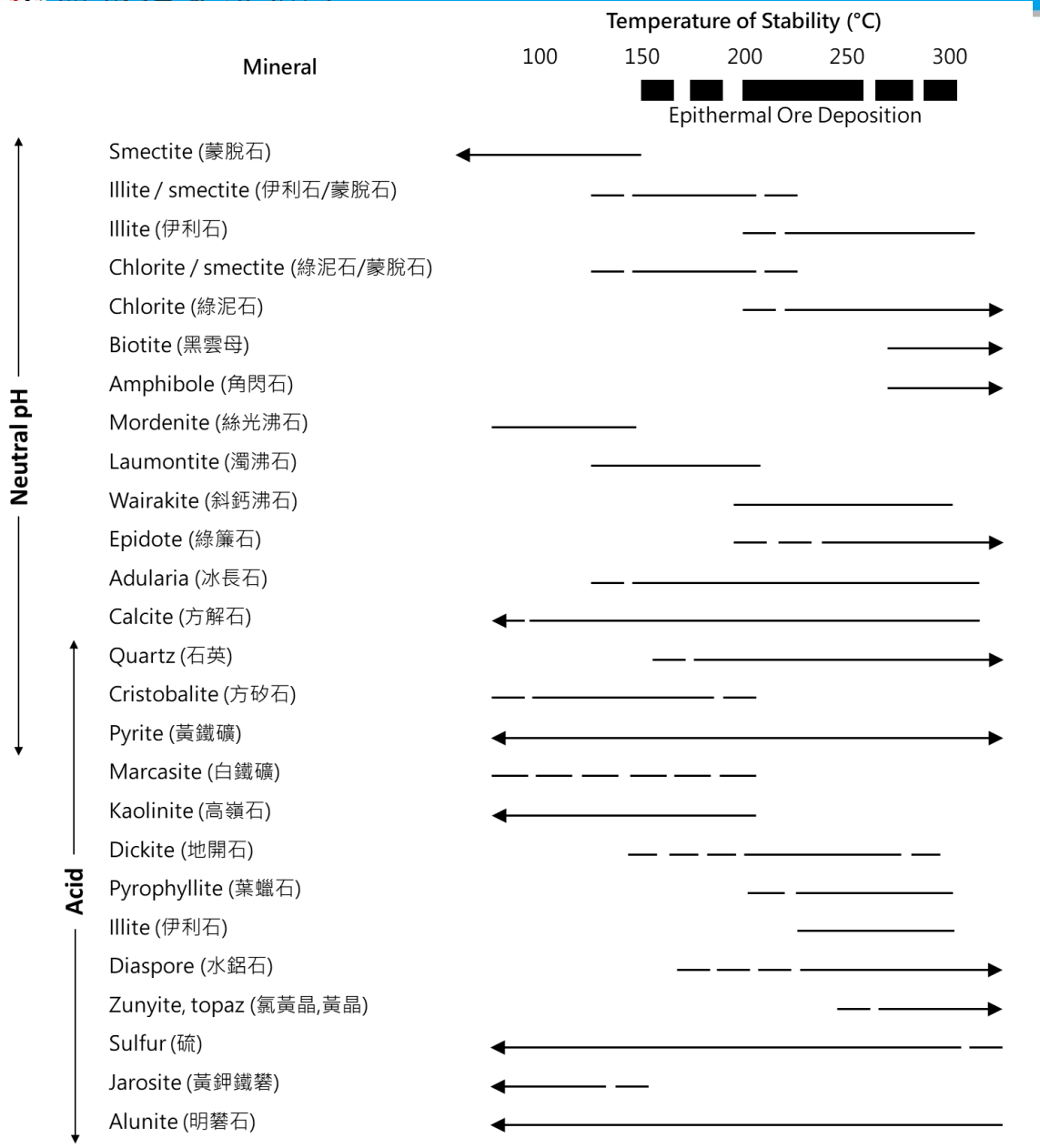
back


Site: TVG248_Org
Measured
Predicted
Zxy
Zyx
LOG10 [App. Resis. (ohm.m)]
2.00
1.00
-4.00
-3.00
-2.00
-1.00
LOG10 [Periods (s)]
Phase (Deg.)
180
150
120
90
60
30
0
-30
-60
-90
-120
-150
-180
-4.00
-3.00
-2.00
-1.00
LOG10 [Periods (s)]
Overview Map
Overall RMS (Z+Tz)= 0.70
Total Z RMS = 0.70
Zxy RMS = 0.83
Zyx RMS = 0.79

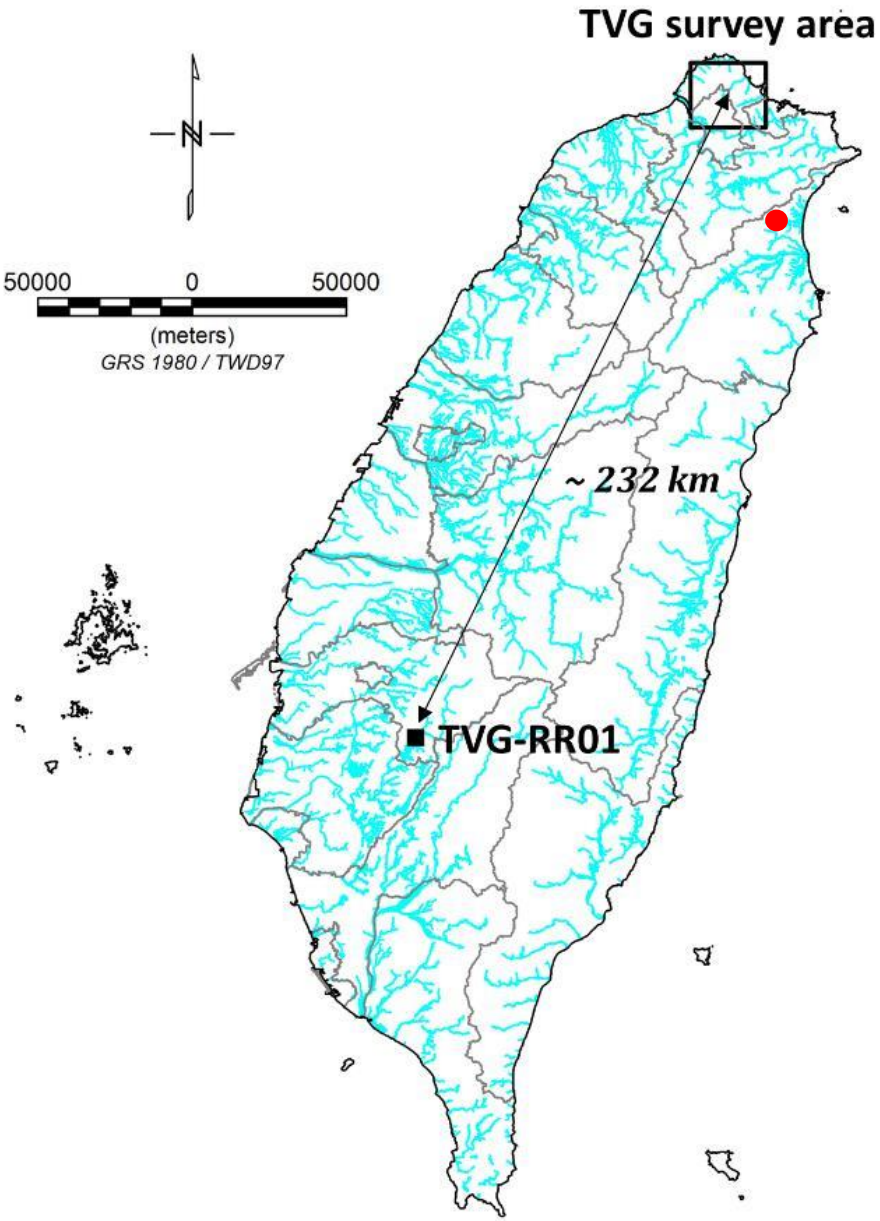
N-S2

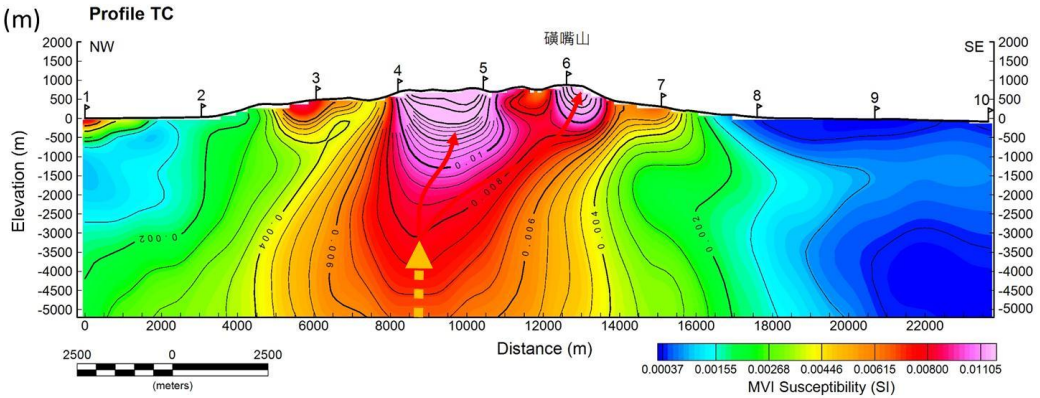

N
Shan-chiao Fault
0
5
10
15
Depth (km)
C3
R3
C2
R2
Heat source
-8
0
8
3
2
1
Log10 Resis. [ohm.m]

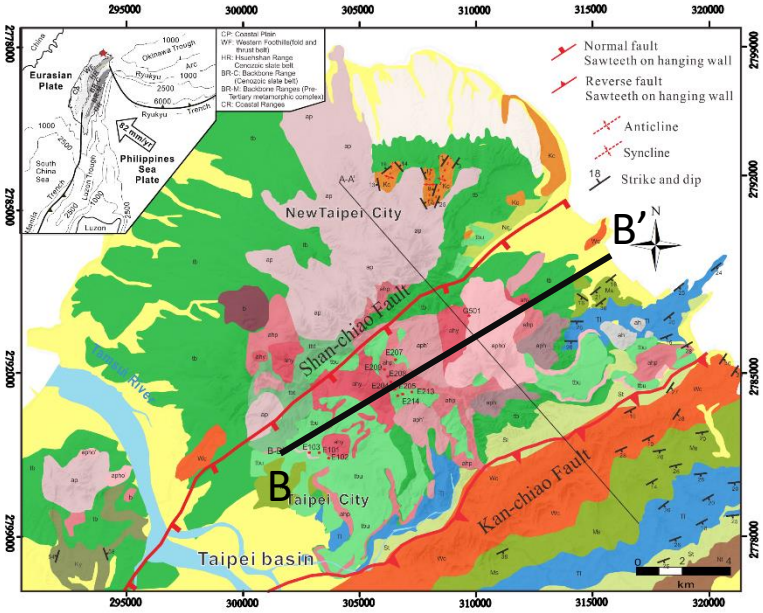

Eurasian Plate
Philippines Sea Plate
N-S1
N-S2
N-S3
N-S4
N-S5
N-S6
Normal fault
Sawteeth on hanging wall
Reverse fault
Sawteeth on hanging wall
Anticline
Syncline
Strike and dip
W-E1
W-E2
W-E3
W-E4
W-E5
New Taipei City
Taipei City
Taipei basin
Shan-chiao Fault
Kan-chiao Fault

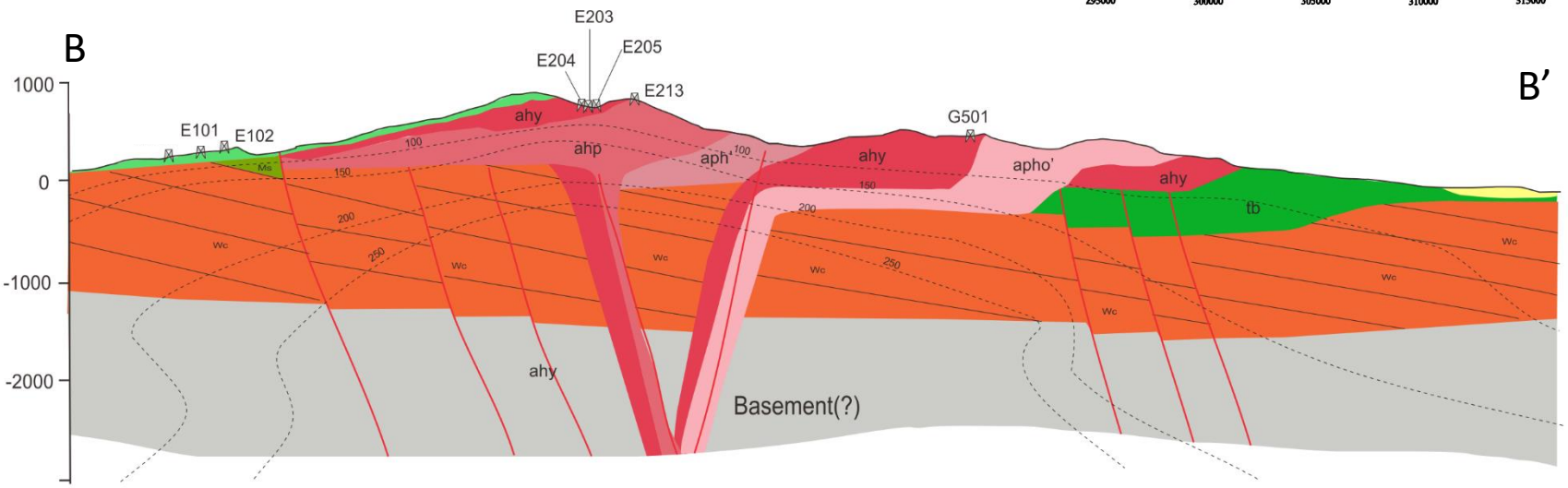

Temperature of Stability (°C)
Mineral
100
150
200
250
300
Epithermal Ore Deposition
Neutral pH
Acid
Smectite (蒙脫石)
Illite / smectite (伊利石/蒙脫石)
Illite (伊利石)
Chlorite / smectite (綠泥石/蒙脫石)
Chlorite (綠泥石)
Biotite (黑雲母)
Amphibole (角閃石)
Mordenite (絲光沸石)
Laumontite (濁沸石)
Wairakite (斜鈣沸石)
Epidote (綠簾石)
Adularia (冰長石)
Calcite (方解石)
Quartz (石英)
Cristobalite (方矽石)
Pyrite (黃鐵礦)
Marcasite (白鐵礦)
Kaolinite (高嶺石)
Dickite (地開石)
Pyrophyllite (葉蠟石)
Illite (伊利石)
Diaspore (水鋁石)
Zunyite, topaz (氯黃晶,黃晶)
Sulfur (硫)
Jarosite (黃鉀鐵礬)
Alunite (明礬石)

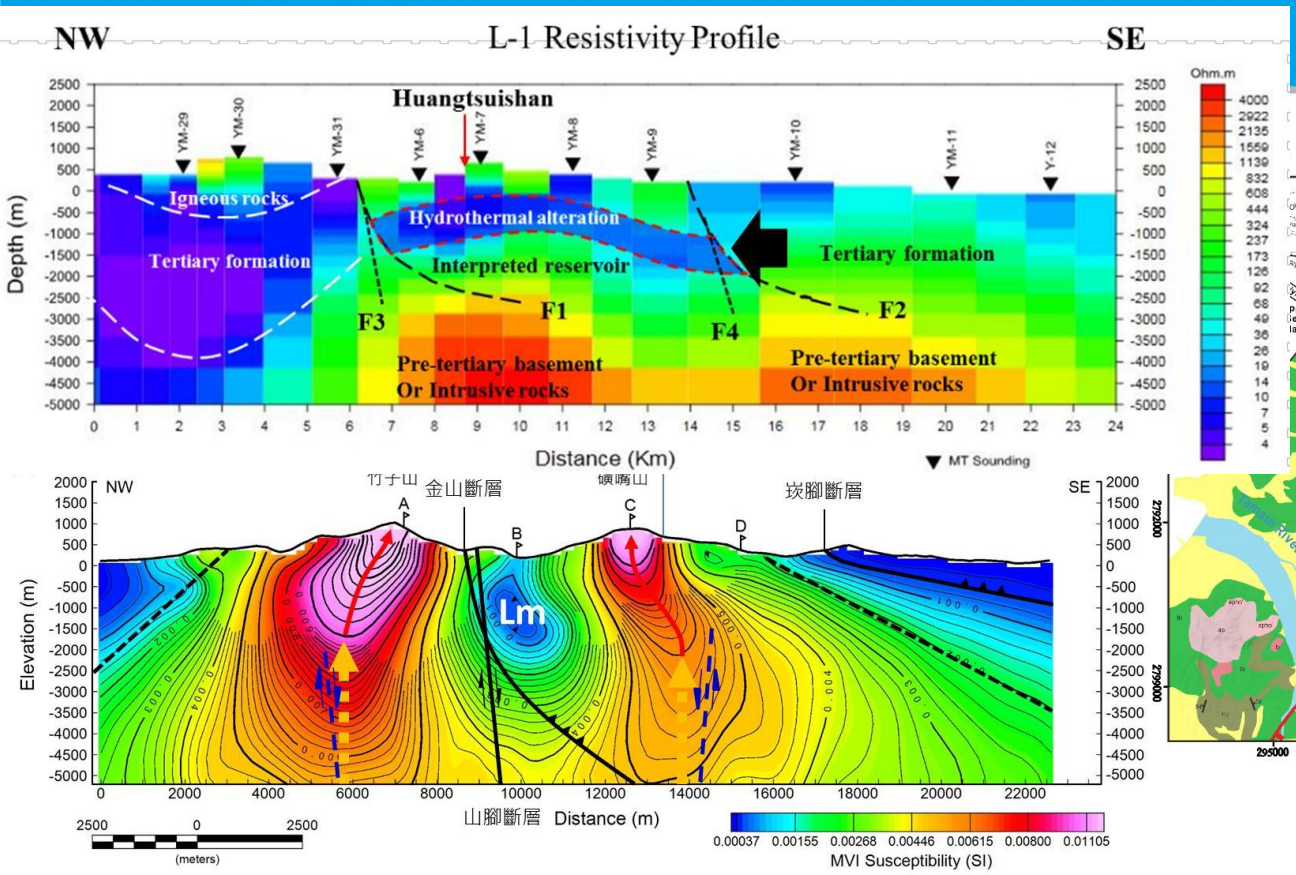

TikTok
@1day50videos


TVG survey area
N
50000
0
50000
(meters)
GRS 1980 / TWD97
~ 232 km
TVG-RR01

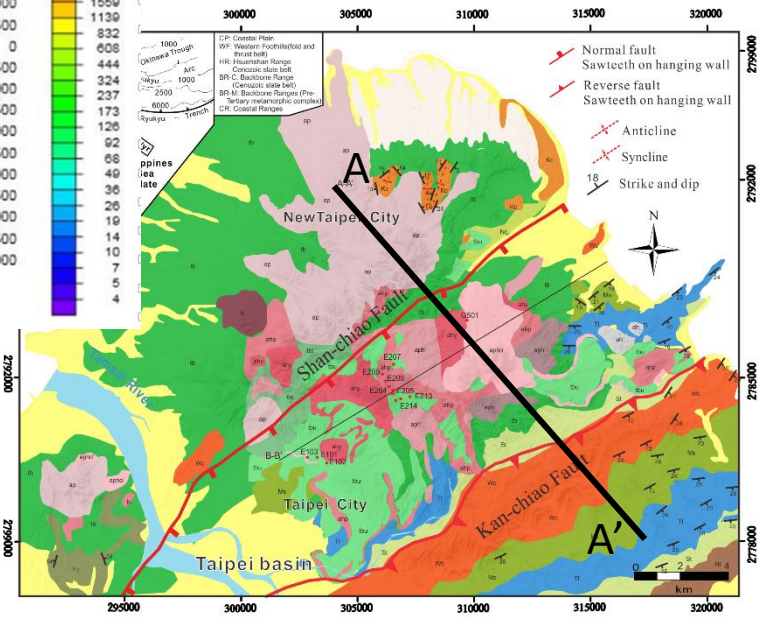

(m)
Profile TC
NW
SE
礦嘴山
Elevation (m)
Distance (m)
(meters)
MVI Susceptibility (SI)
0.00037 0.00155 0.00268 0.00446 0.00615 0.00800 0.01105

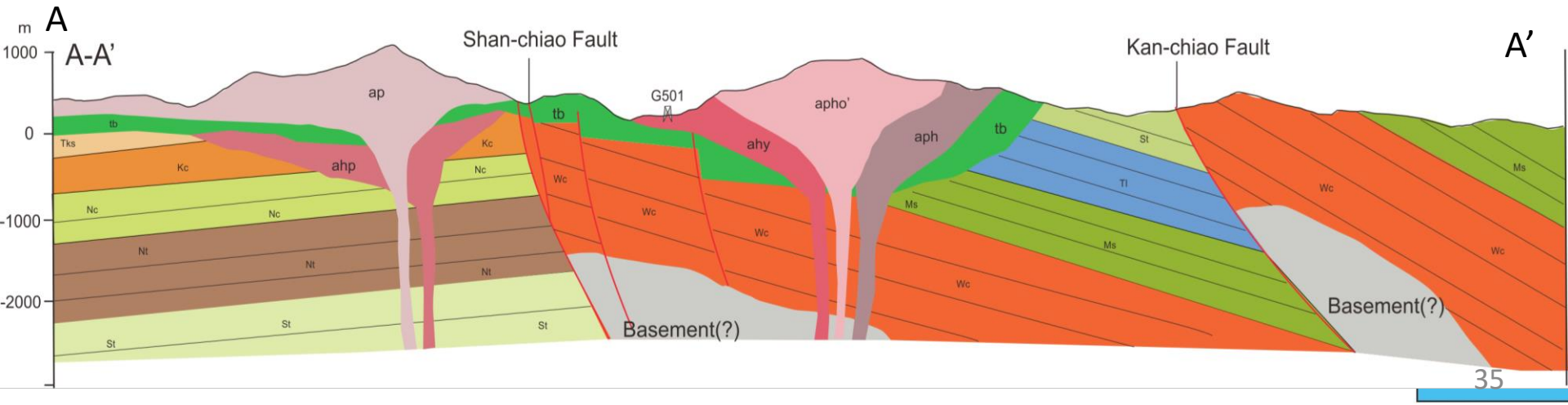

Eurasian Plate
Philippines Sea Plate
Normal fault
Sawteeth on hanging wall
Reverse fault
Sawteeth on hanging wall
Anticline
Syncline
Strike and dip
NewTaipei City
Shan-chiao Fault
Kan-chiao Fault
Taipei City
Taipei basin
B
B'
A
A'
km

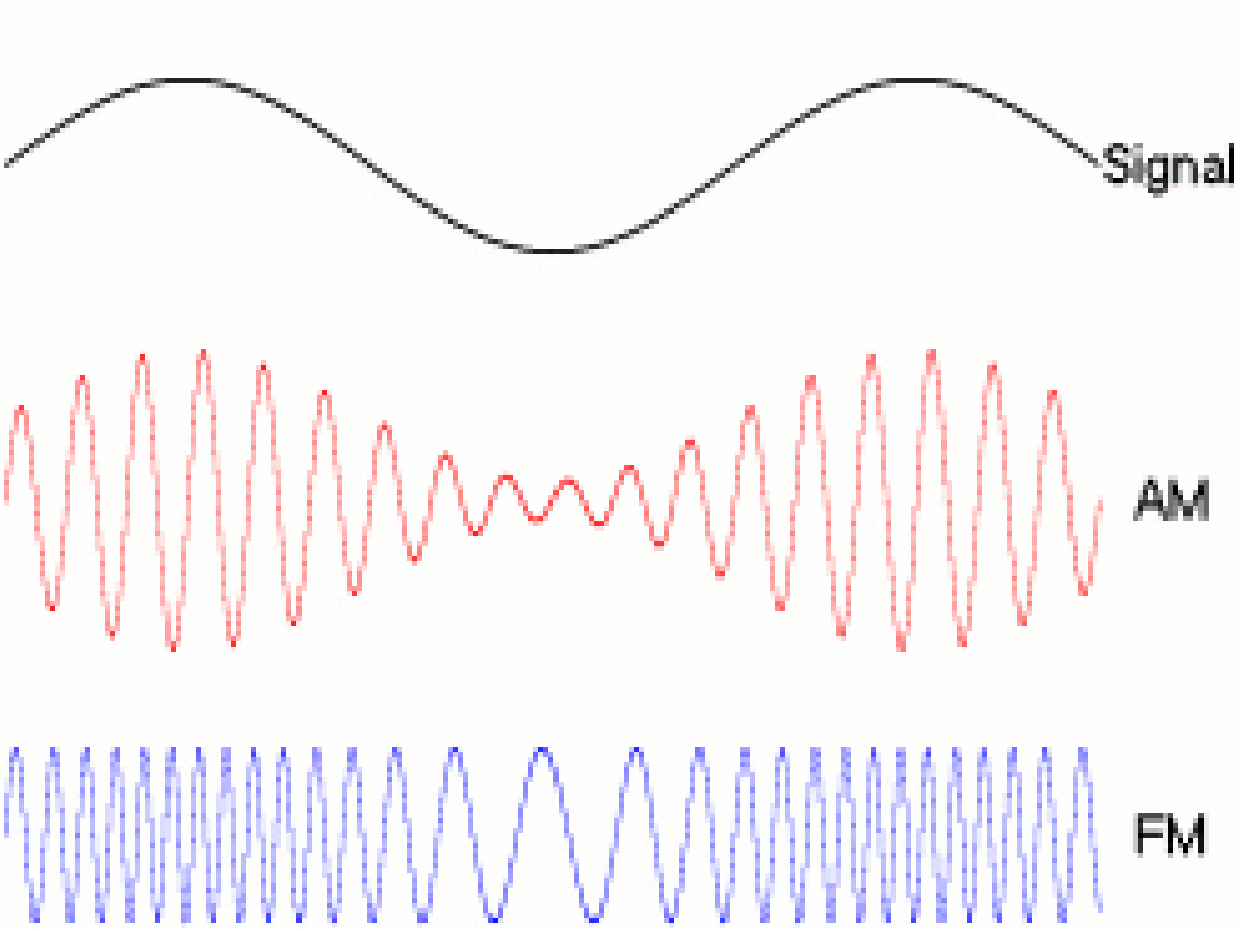

B
B'
E101
E102
E203
E204
E205
E213
G501
ahy
ahp
aph'
apho'
tb
Wc
Basement(?)


NW
L-1 Resistivity Profile
SE
Huangtsuishan
YM-29
YM-30
YM-31
YM-6
YM-7
YM-8
YM-9
YM-10
YM-11
Y-12
Igneous rocks
Tertiary formation
Hydrothermal alteration
Interpreted reservoir
F1
F2
F3
F4
Tertiary formation
Pre-tertiary basement
Or Intrusive rocks
Pre-tertiary basement
Or Intrusive rocks
Depth (m)
Distance (Km)
Ohm.m
4000
2922
2135
1559
1139
832
608
444
324
237
173
126
92
68
49
36
26
19
14
10
7
5
4

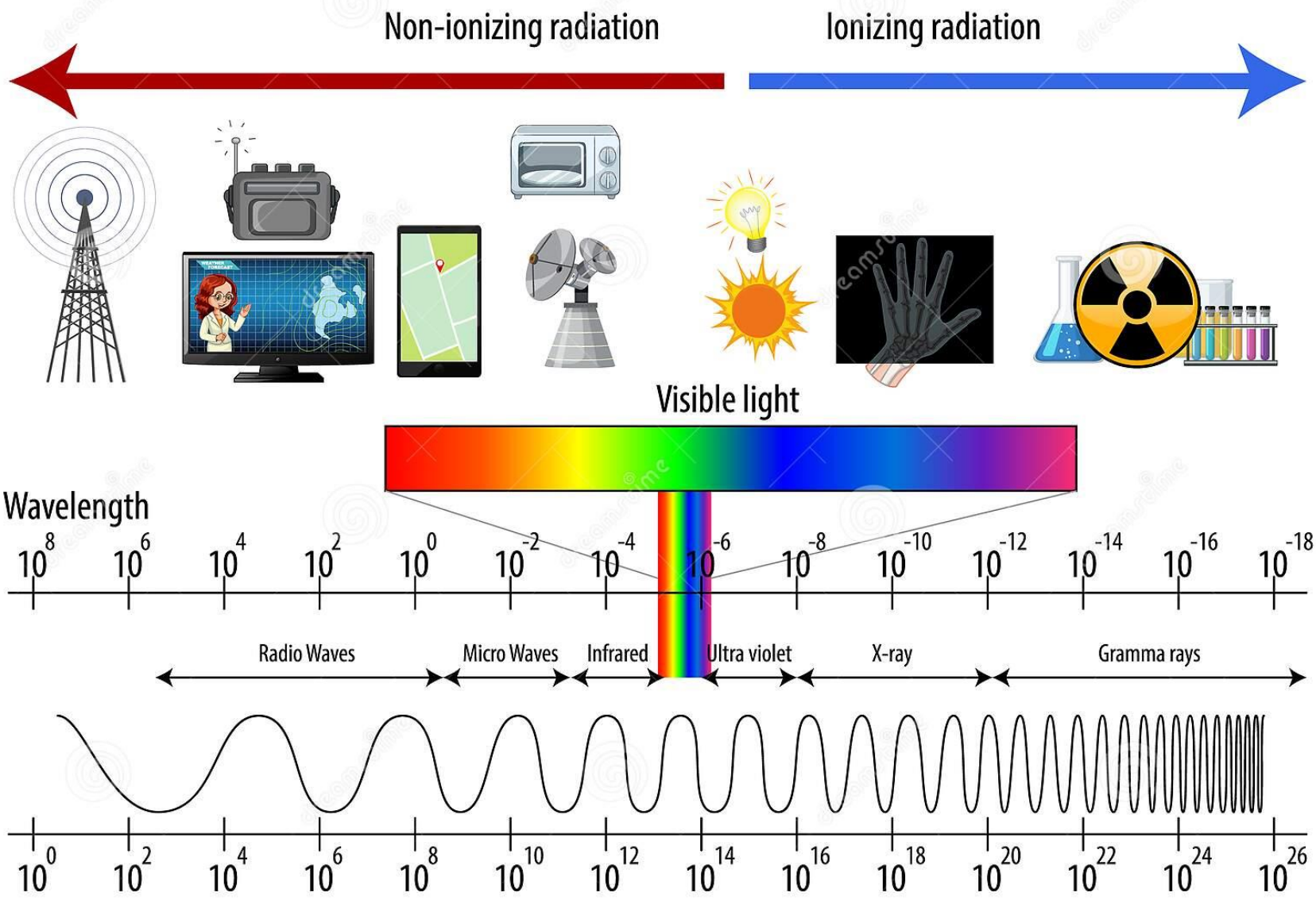
NW
竹子山
金山斷層
噴嘴山
崁腳斷層
SE
A
B
C
D
Lm
Elevation (m)
山腳斷層
Distance (m)
2500
0
2500
(meters)
0.00037
0.00155
0.00268
0.00446
0.00615
0.00800
0.01105
MVI Susceptibility (SI)


Normal fault
Sawteeth on hanging wall
Reverse fault
Sawteeth on hanging wall
Anticline
Syncline
Strike and dip
A
A'
NewTaipei City
Taipei City
Taipei basin
Shan-chiao Fault
Kan-chiao Fault
Tamsui River
km


m
A
A-A'
Shan-chiao Fault
Kan-chiao Fault
A'
ap
tb
G501
apho'
ahy
aph
ahp
Tks
Kc
Nc
Nt
St
Wc
Ms
TI
Basement(?)
Basement(?)


Signal
AM
FM

THE ELECTROMAGNETIC SPECTRUM



File Edit Search View Encoding Language Settings Tools Macro Run Plugins Window ?

Measured_data_file.dat | model_file.mod

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> exp(+i\omega t)
> []
> 0
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> 23 40
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1.000000E-04  TVG201_Org   25.140694   121.520058   -3247.498   -7747.498   -174.000   TY   -4.884869E-02   2.211639E-01    3.000000E-2
1.580000E-04  TVG201_Org   25.140694   121.520058   -3247.498   -7747.498   -174.000   TX   9.098639E-02    2.019319E-01    3.000000E-2
1.580000E-04  TVG201_Org   25.140694   121.520058   -3247.498   -7747.498   -174.000   TY   -1.319815E-01   3.275134E-01    3.000000E-2
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1.585000E-03  TVG202_Org   25.126110   121.546669   -5247.498   -4747.498   -224.000
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1.584890E-01  TVG204_Org   25.105806   121.574448   -7247.498   -2247.498   -374.000
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File Edit Search View Encoding Language Settings Tools Macro Run Plugins Window ?

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11649.040 8960.799 6892.922 5302.248 4078.652 3137.425 2413.404 1856.465 1428.050 1098.500 845.000 650.000 500.000
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3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.9143
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3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.9143
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3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.9143
3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.9143
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3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.9143
3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.9143
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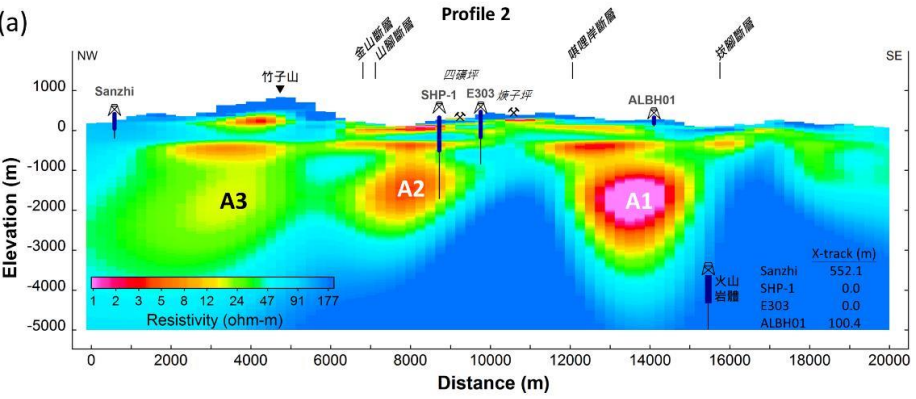
3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.9143
3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.9143
3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.9143
3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.9143
3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.9143
3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.9143
3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.9143
3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.9143
3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.9143
3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.9143
3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.9143
3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.91439E+01 3.9143
```

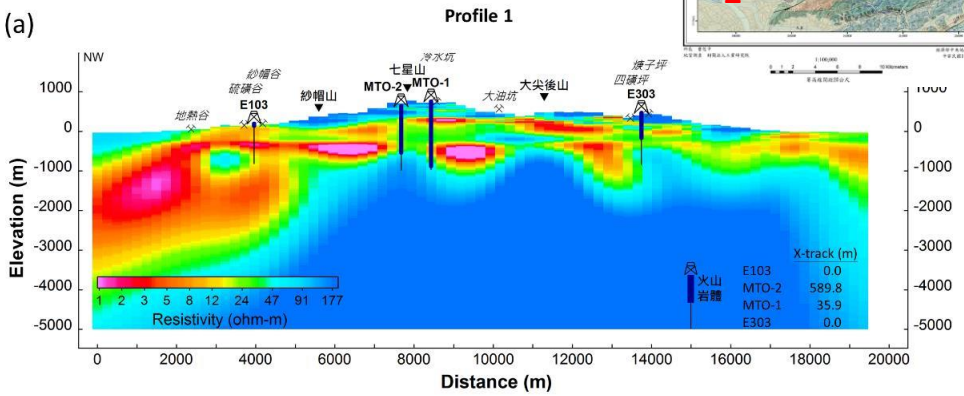

2
1

back

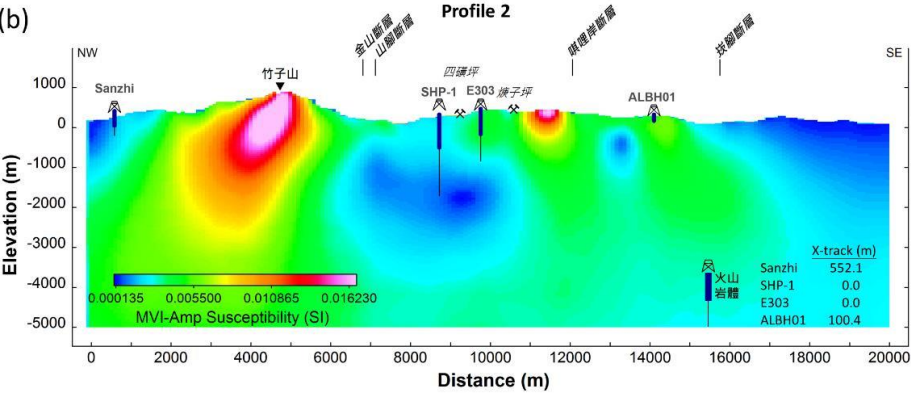
(a)


Profile 2
NW
SE
Sanzhi
竹子山
金山斷層
山腳斷層
四磺坪
SHP-1
E303
旗子坪
ALBH01
旗裡岸斷層
枝柳斷層
A3
A2
A1
Elevation (m)
Distance (m)
Resistivity (ohm-m)
1 2 3 5 8 12 24 47 91 177
X-track (m)
Sanzhi 552.1
SHP-1 0.0
E303 0.0
ALBH01 100.4
火山岩體

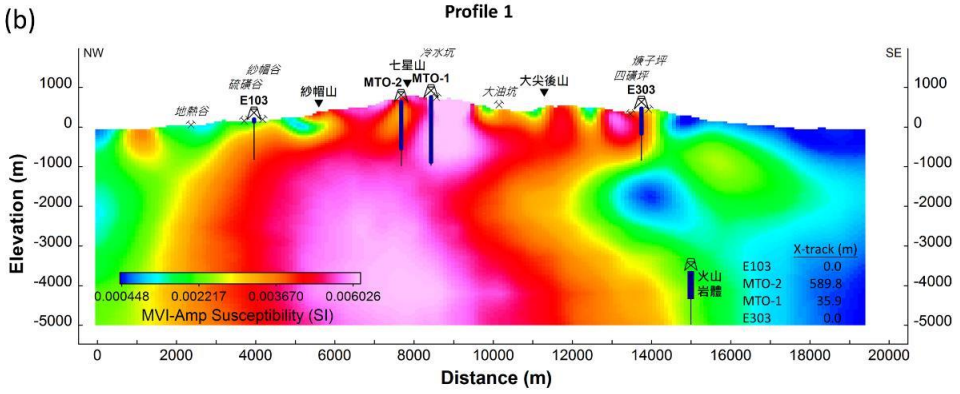
(a)


Profile 1
NW
SE
地熱谷
紗帽谷
硫磺谷
E103
紗帽山
七星山
MTO-2
MTO-1
冷水坑
大油坑
大尖後山
旗子坪
四磺坪
E303
Elevation (m)
Distance (m)
Resistivity (ohm-m)
1 2 3 5 8 12 24 47 91 177
X-track (m)
E103 0.0
MTO-2 589.8
MTO-1 35.9
E303 0.0
火山岩體

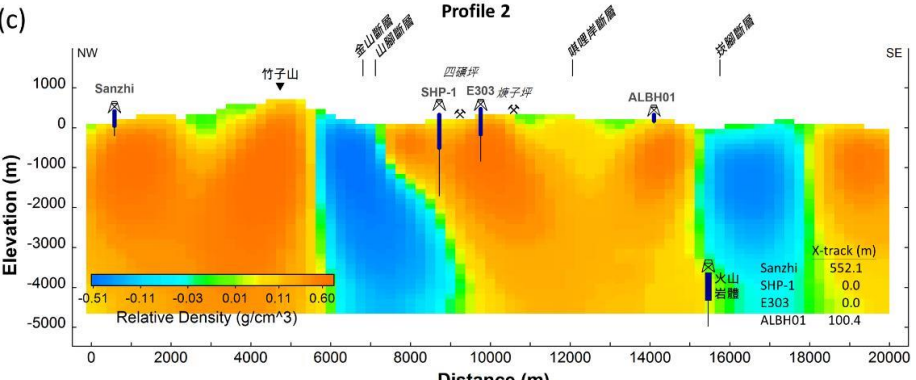
(b)


Profile 2
NW
SE
Sanzhi
竹子山
金山斷層
山腳斷層
四磺坪
SHP-1
E303
旗子坪
ALBH01
旗裡岸斷層
枝柳斷層
Elevation (m)
Distance (m)
MVI-Amp Susceptibility (SI)
0.000135 0.005500 0.010865 0.016230
X-track (m)
Sanzhi 552.1
SHP-1 0.0
E303 0.0
ALBH01 100.4
火山岩體

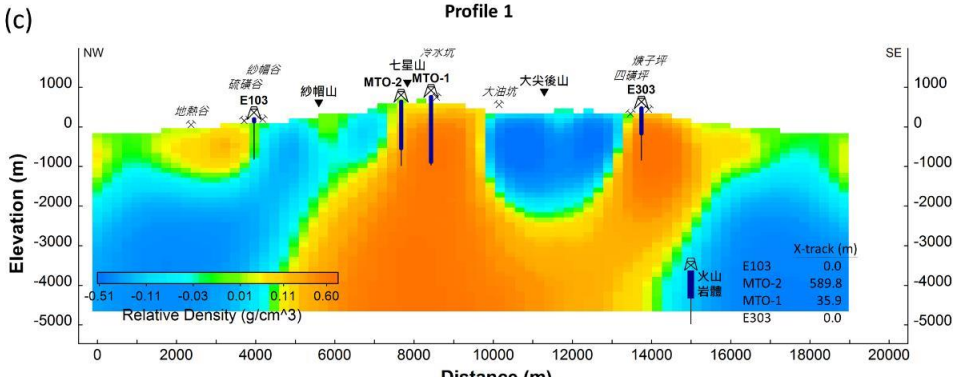
(b)

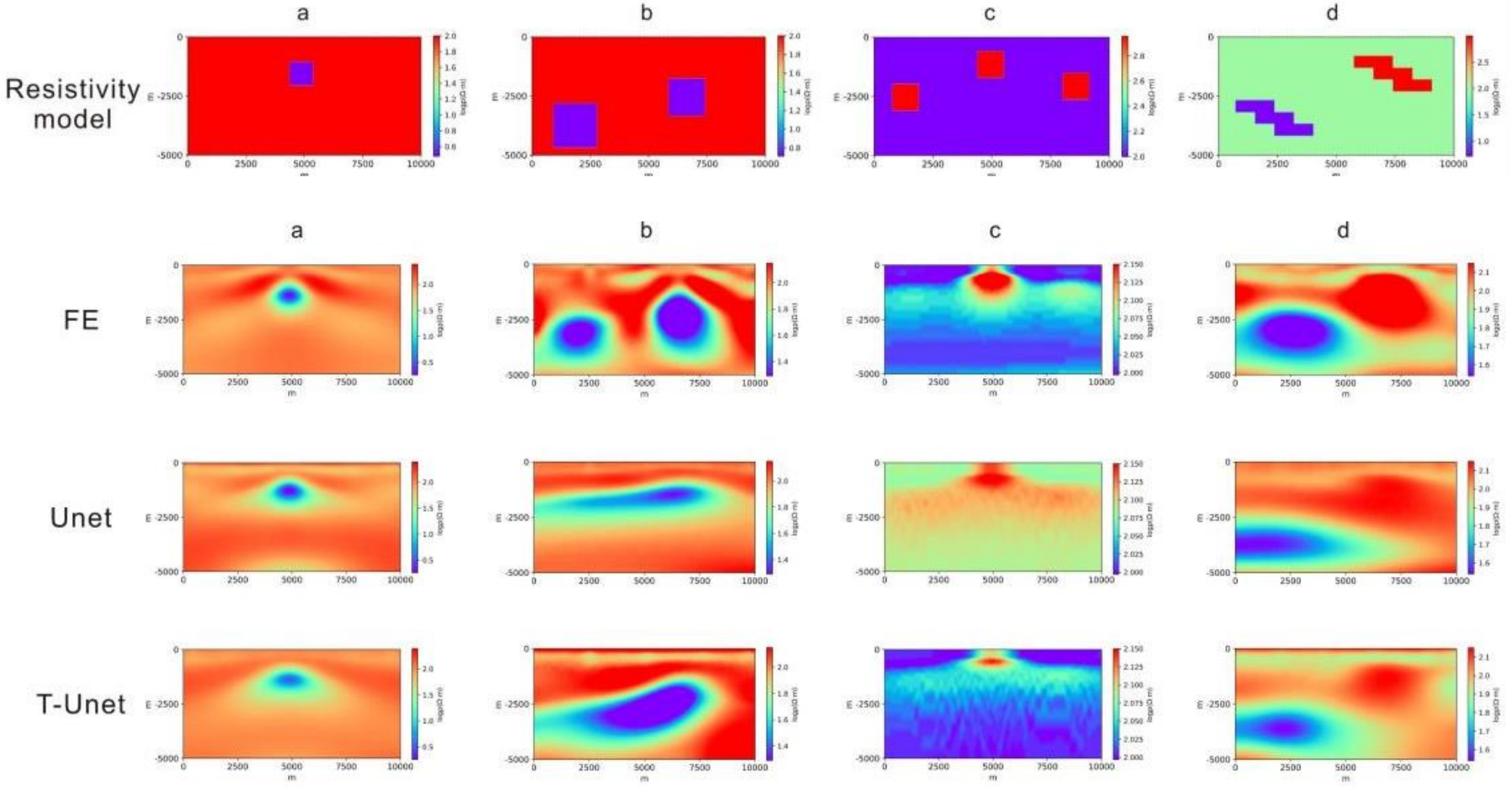

Profile 1
NW
SE
地熱谷
紗帽谷
硫磺谷
E103
紗帽山
七星山
MTO-2
MTO-1
冷水坑
大油坑
大尖後山
旗子坪
四磺坪
E303
Elevation (m)
Distance (m)
MVI-Amp Susceptibility (SI)
0.000448 0.002217 0.003670 0.006026
X-track (m)
E103 0.0
MTO-2 589.8
MTO-1 35.9
E303 0.0
火山岩體

(c)


Profile 2
NW
SE
Sanzhi
竹子山
金山斷層
山腳斷層
四磺坪
SHP-1
E303
旗子坪
ALBH01
旗裡岸斷層
枝柳斷層
Elevation (m)
Distance (m)
Relative Density (g/cm^3)
-0.51 -0.11 -0.03 0.01 0.11 0.60
X-track (m)
Sanzhi 552.1
SHP-1 0.0
E303 0.0
ALBH01 100.4
火山岩體

(c)


Profile 1
NW
SE
地熱谷
紗帽谷
硫磺谷
E103
紗帽山
七星山
MTO-2
MTO-1
冷水坑
大油坑
大尖後山
旗子坪
四磺坪
E303
Elevation (m)
Distance (m)
Relative Density (g/cm^3)
-0.51 -0.11 -0.03 0.01 0.11 0.60
X-track (m)
E103 0.0
MTO-2 589.8
MTO-1 35.9
E303 0.0
火山岩體



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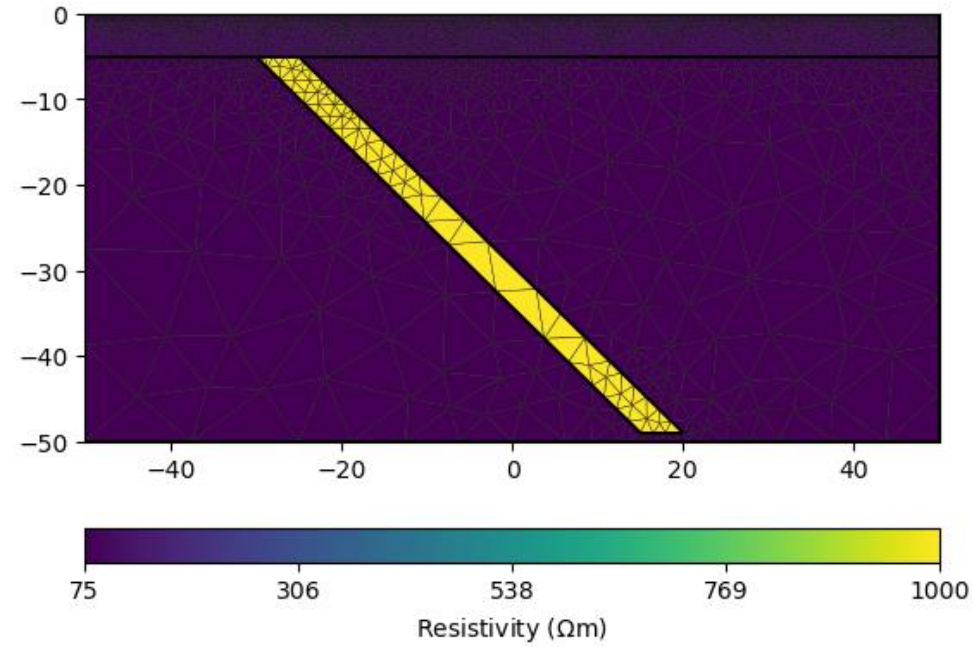
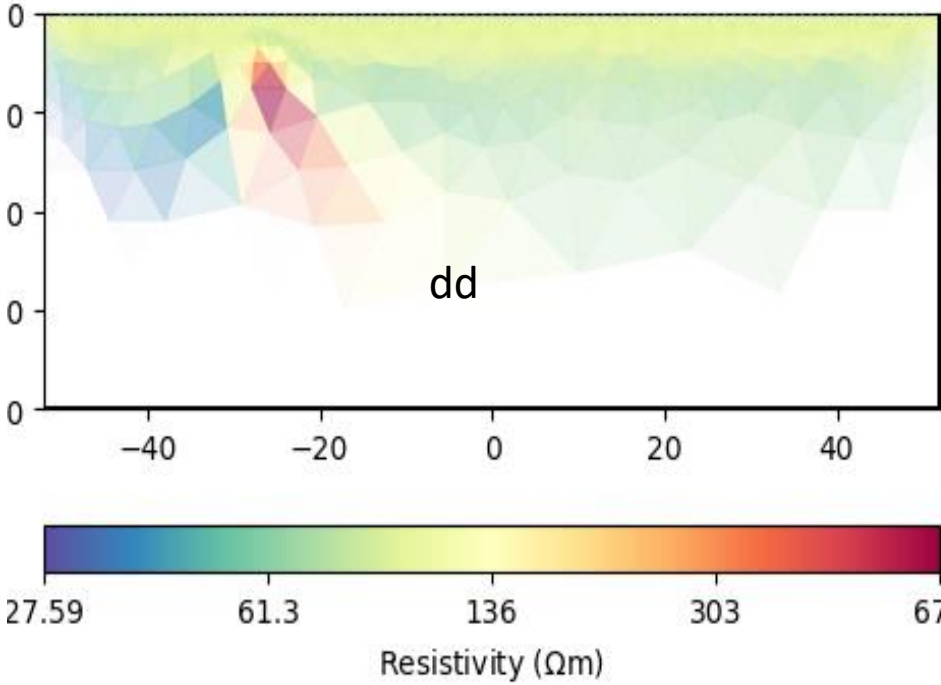

0
−10
−20
−30
−40
−50
−40
−20
0
20
40
75
306
538
769
1000
Resistivity (Ωm)


0
0
0
0
0
dd
−40
−20
0
20
40
27.59
61.3
136
303
67
Resistivity (Ωm)