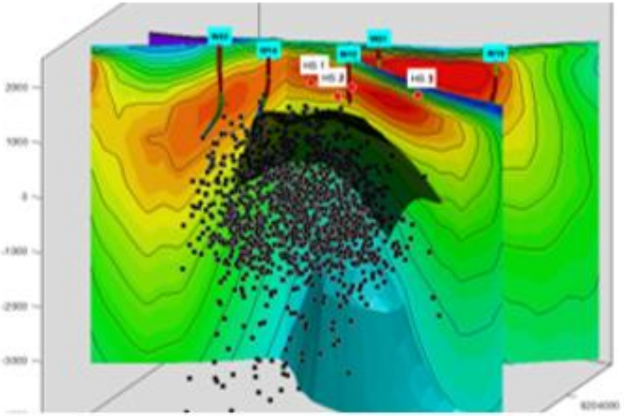
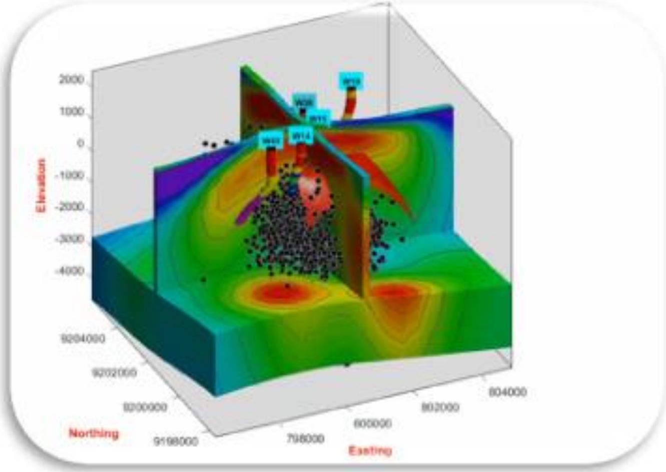
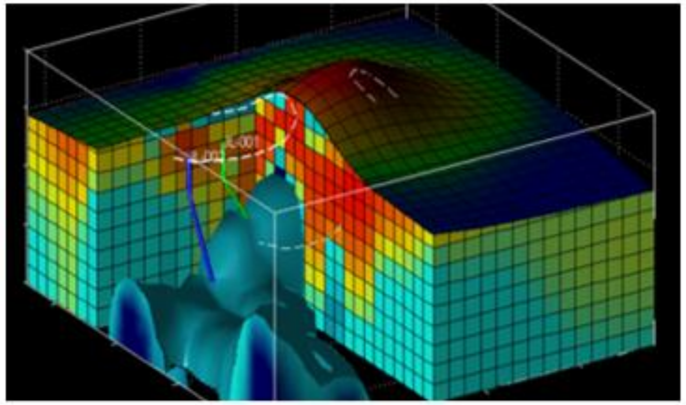
EMinars Series 2 MTNet 25 May 2022

MAGNETOTELLURIC STUDIES FOR THE EXPLORATION OF GEOTHERMAL RESOURCES IN INDONESIA







Dr. Yunus Daud
Head of Geothermal Research Center (GRC) – Universitas Indonesia
Founder of PT NewQuest Geotechnology

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OUTLINE OF PRESENTATION

1. **Introduction**
   - Indonesia: A Country Blessed with Geothermal Resources
   - Geothermal Resources and Characteristics of Indonesia
   - Geothermal Development in Indonesia
   - Recent Geothermal Exploration Challenges in Indonesia
2. **MT Roles in Geothermal Exploration**
   a. MT Can Reconstruct A Geothermal System Model
   b. MT Can Delineate Boundary of Reservoir
   c. MT Can Delineate Well Target Zones
   d. MT Can Be Optimized For Achieving Exploration Targets
   e. MT Technology Workflow
   f. Challenges in Applying MT Technology (Successful and Unsuccessful Drilling Targets)
3. **MT Application in the Challenging "Hidden" Geothermal Reservoir**
   - Overview of Geothermal Field – Geological & Geochemical Background
   - Remote Sensing Data Interpretation
   - MT Data Reprocessing & 3D Inversion
   - After Reservoir Confirmation Based on Slim-Hole Drilling
4. **Valuable Lessons Learned from MT Applications in Indonesia**

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NewQuest GEOTECHNOLOGY

INTRODUCTION

Indonesia: A Country Blessed with Geothermal Resources

10 Years of Contributions

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Indonesia: A Country Blessed with Geothermal Resources

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Indonesia: A Country Blessed with Geothermal Resources

- Located along *Ring of Fire.*
- Abundant geothermal resources and become one of the world largest geothermal potential.
- Indonesia is the 2nd largest of geothermal producer after the USA.

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INTRODUCTION

Geothermal Resources and Characteristics of Indonesia

10 Years of Contributions

Distribution of Geotermal Resources in Indonesia

Potential (*reserves+resources*) = **9.339** MWe + **14.626.5** MWe = **23.965,5 MWe** (MEMR, 2019).
Already utilized of 2.276 MWe (9.5% of the total geothermal resources).

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GEOTHERMAL RESOURCES OF INDONESIA

No	Major Islands	Locations	Resources (MW)					Total Resources (MW)	Installed Capacity (MW)
			Speculative	Hypothetical	Reserves				
					Possible	Probable	Proven		
1	Sumatera	101	2.276	1.557	3.735	1.040,7	1.070,3	9.679	887,4
2	Jawa	73	1.265	1.190	3.414	418	1.820	8.107	1.253,8
3	Bali	6	70	21	104	110	30	335	0
4	Nusa Tenggara	31	190	148	892	121	12.5	1.363,5	12,5
5	Kalimantan	14	151	18	13	0	0	182	0
6	Sulawesi	90	1.365	362	1.041	180	120	3.068	120
7	Maluku	33	560	91	497	6	2	1.156	0
8	Papua	3	75	0	0	0	0	75	0
	Total	**351**	**5.952**	**3.387**	**9.696**	**1.875,7**	**3.054,8**	**23.965,5**	**2.276**
			9.339		**14.626,5**				
			23.965,5						

Classified based on SNI 6009:2017
Reference: Geological Agency - MEMR, 2019

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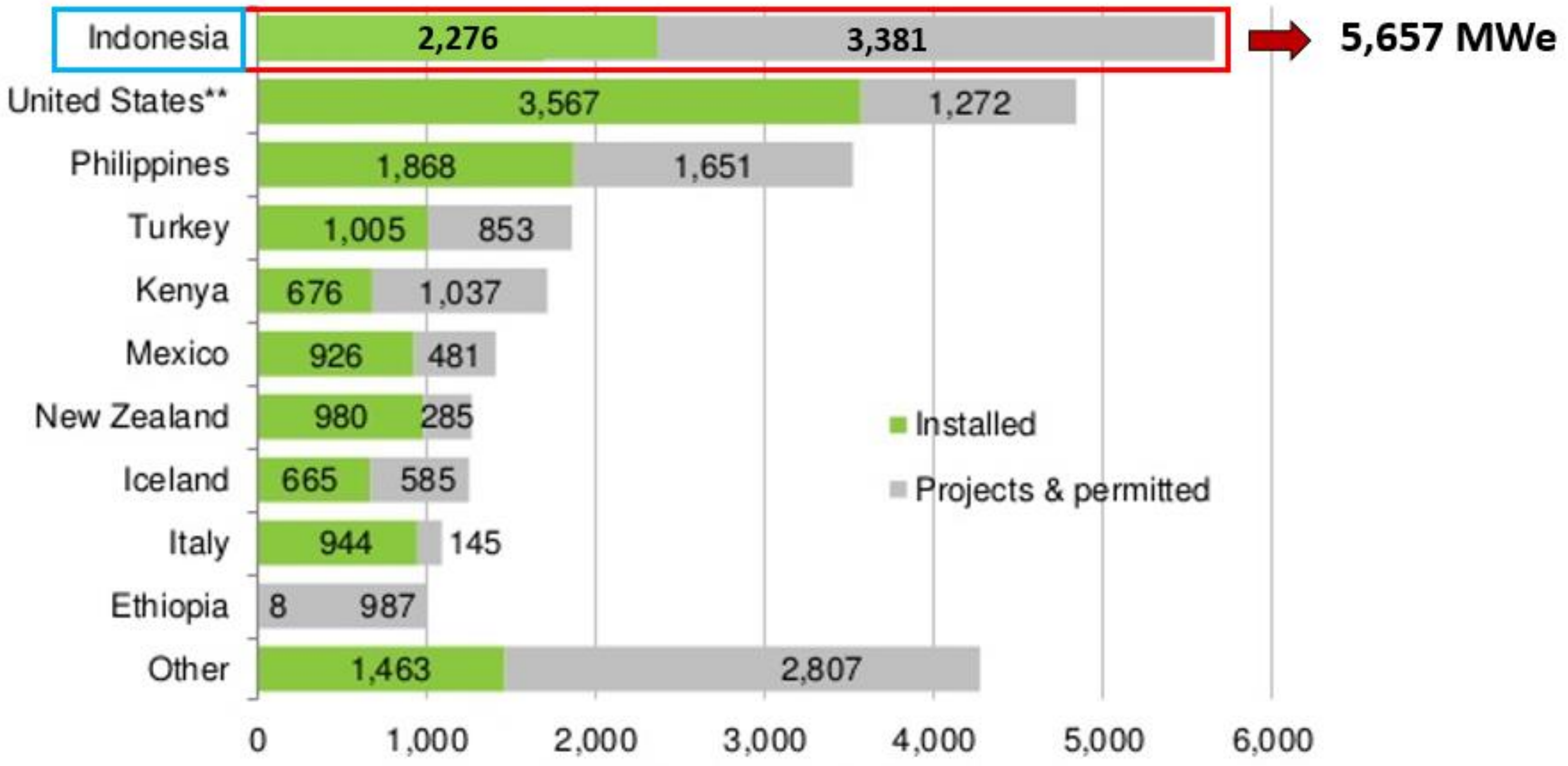
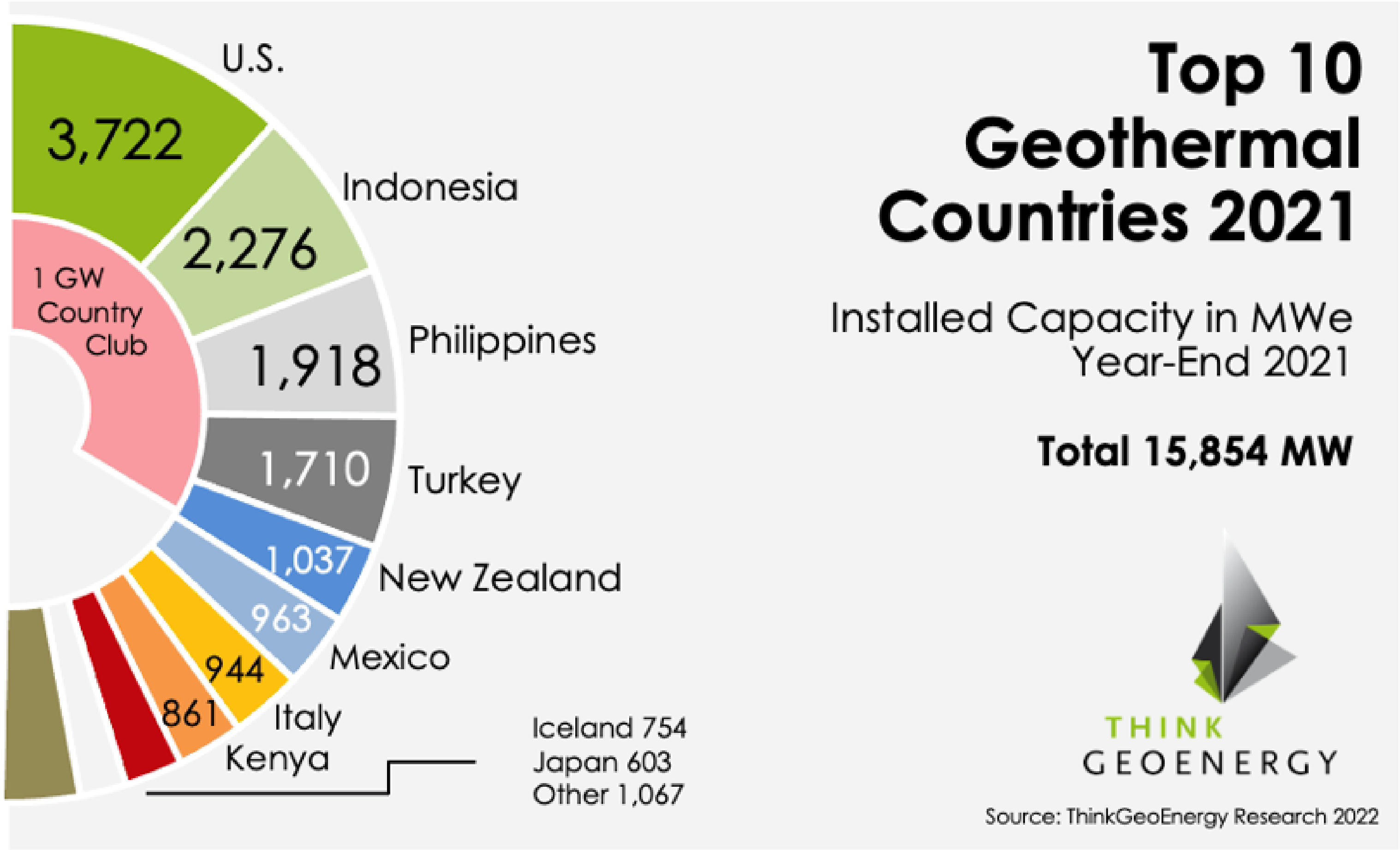
TOP 10 GEOTHERMAL COUNTRIES

Installed Capacity & Projects – MW (2021)

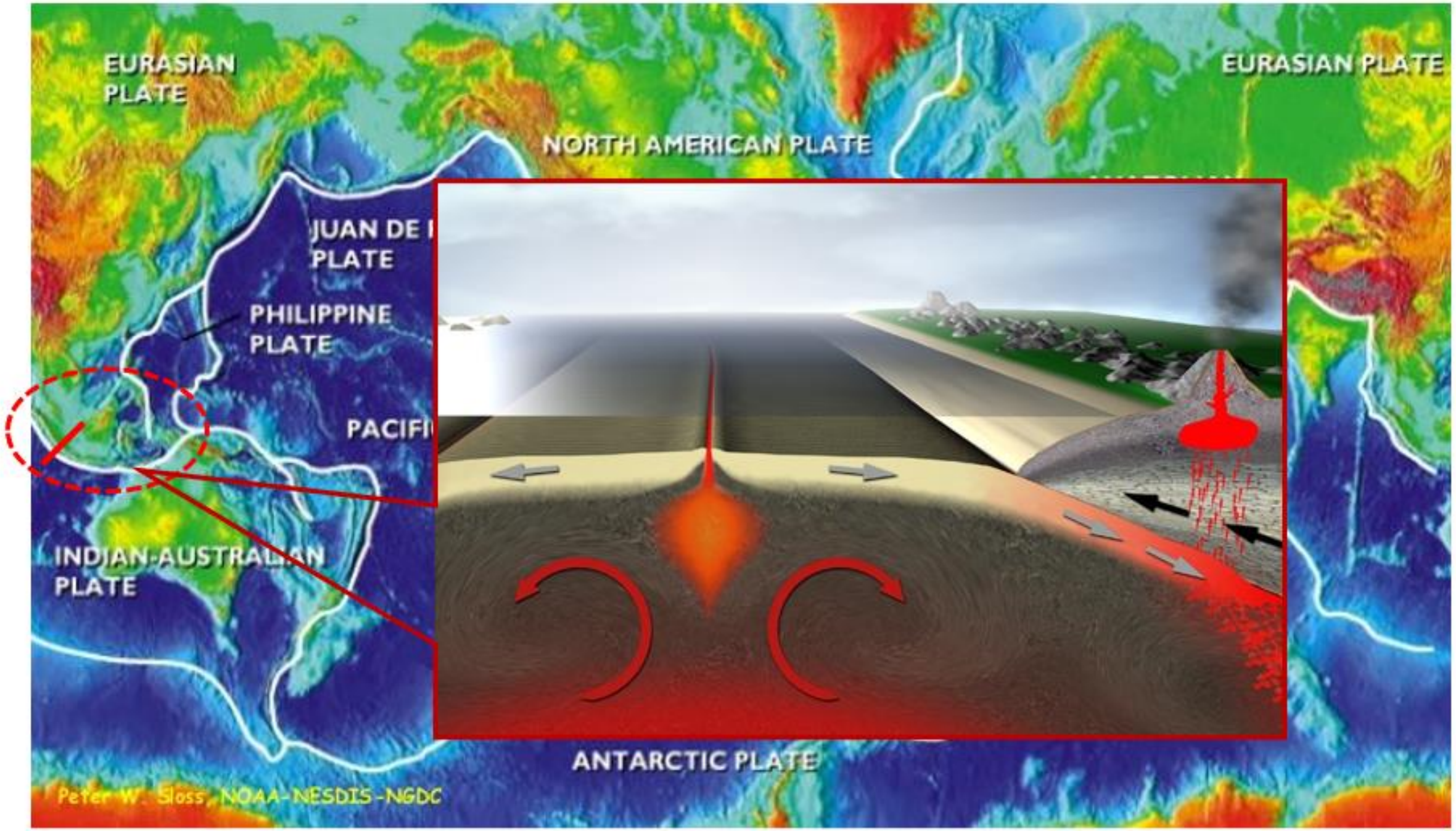


Source: ThinkGeoEnergy Research (2017), GEA (2016), IGA (2015)

Towards the Biggest Producer

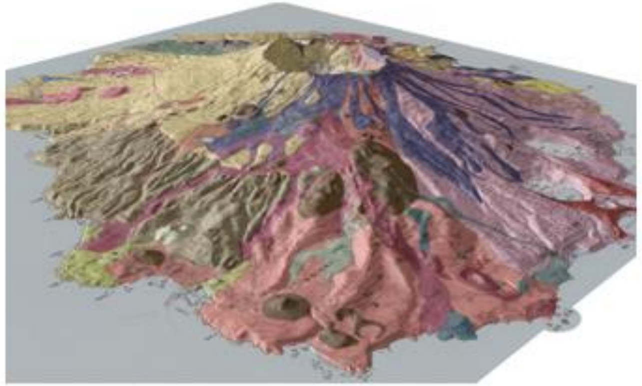


Geothermal Resources and Characteristics of Indonesia



- Geothermal resources in Indonesia are associated with subduction zone.
- Mostly volcanic hosted geothermal systems.
- Some are non-volcanic geothermal systems (fault controlled, granitic rock, etc.).

Geothermal Resources and Characteristics of Indonesia



✓ ***Located on the mountainous terrain***

✓ ***Deep & Concealed Reservoir (1-3 km)***

✓ ***Complex Geological Structure***

✓ ***Located in high dense forest***

- Therefore, exploration activity should be conducted **carefully and properly** to avoid unsuccessful exploration drilling.
- **MT technology** plays an important role in contributing the **successful exploration program**.

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INTRODUCTION

Recent Geothermal Exploration Challenges in Indonesia

10 Years of Contributions

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Recent Geothermal Exploration Challenges

1. Most typical “ideal” geothermal systems have been developed

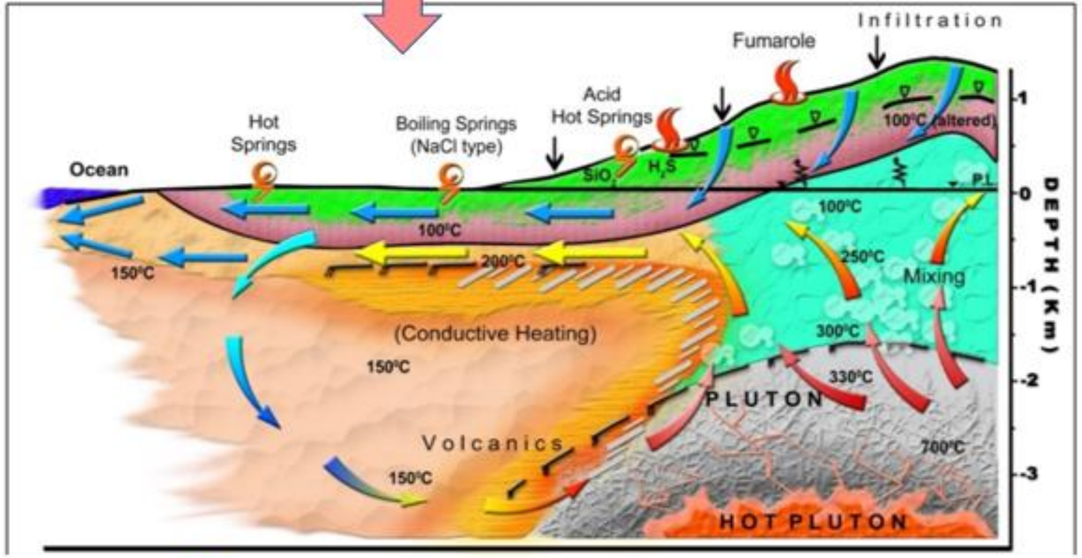
<u>Characteristics</u>

- **Impressive Surface Manifestations :**
  - **Upflow**
    - Fumaroles
    - Steam heated acid hot springs
    - Steaming grounds
  - **Outflow :**
    - Neutral-Chloride hot springs

<u>Field Examples :</u>

- Salak, Ulubelu, Wayang Windu, Lahendong, and other similar fields.

Most the “ideal” systems have been developed.



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Recent Geothermal Exploration Challenges

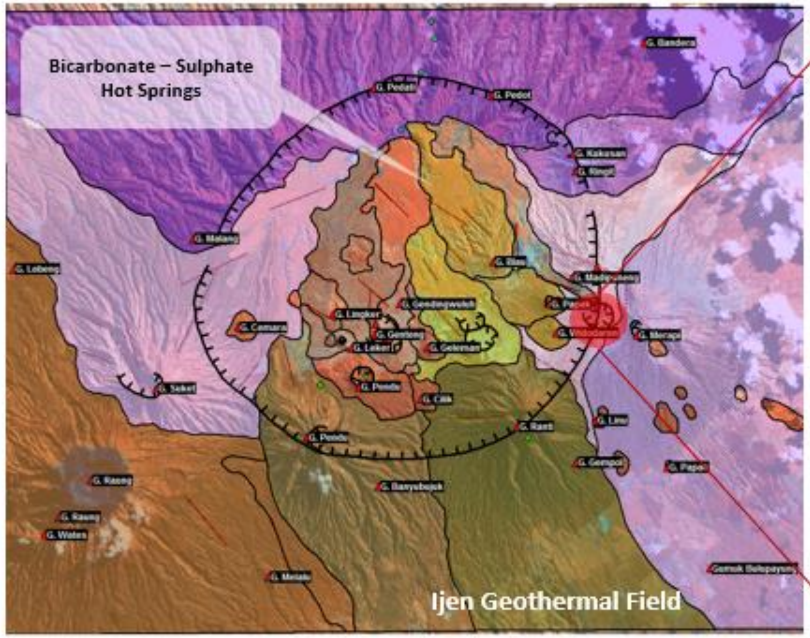
2. Undeveloped "Challenging" Geothermal Systems (Type #1)

<u>Characteristics</u>

- **Magmatic Surface Manifestations :**
  - Such as magmatic fumaroles & solfataras in the summit crater
  - Strongly acidic crater lakes
- Be careful with acid vapor core
- Challenging to find neutral reservoir

<u>Field Examples :</u>

- Kawah-Ijen & Arjuno-Welirang (East Java), Tangkuban Parahu (West Java).

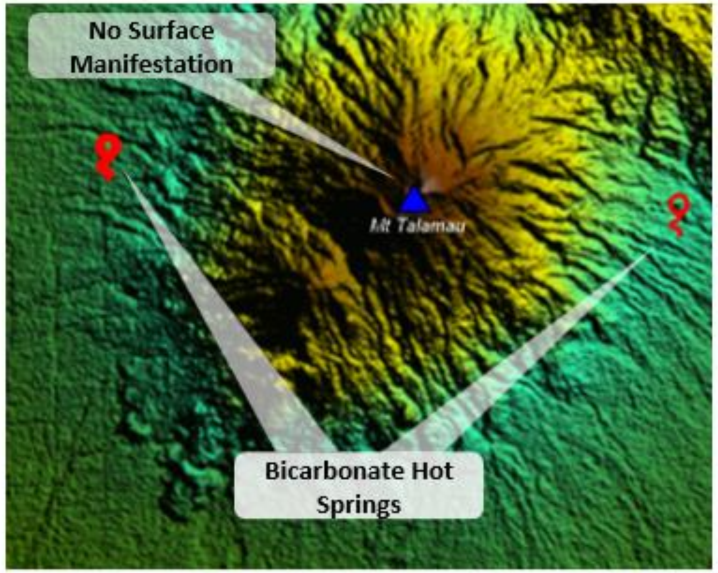


Recent Geothermal Exploration Challenges

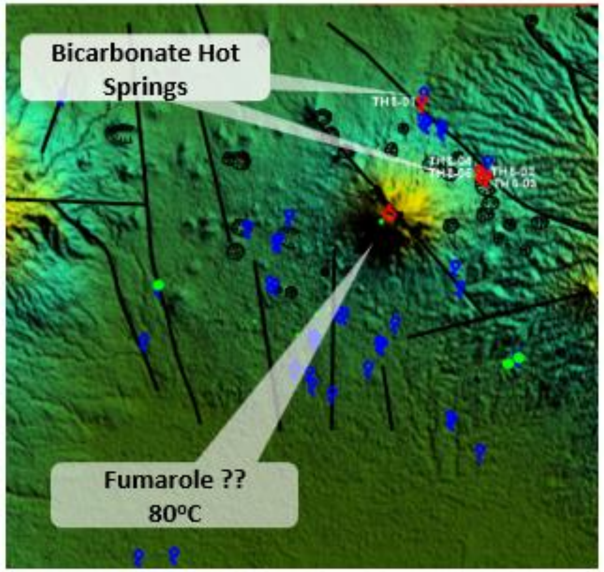
2. Undeveloped “Challenging” Geothermal Systems (Type #2)

Characteristics

- **Unimpressive Surface Manifestations**
  - Hosted by tertiary or late quaternary volcanic products
  - No indications on the surface of high temperature in the reservoir
  - Low temperature hot springs on the foothills (outflow) without impressive manifestations (geothermal fumaroles)



Talamau Geothermal Field



Tiris Geothermal Field

Field Examples :

- Many such geothermal areas in Indonesia (Eg. Talamau - West Sumatera, Tiris -East Java).

Recent Geothermal Exploration Challenges

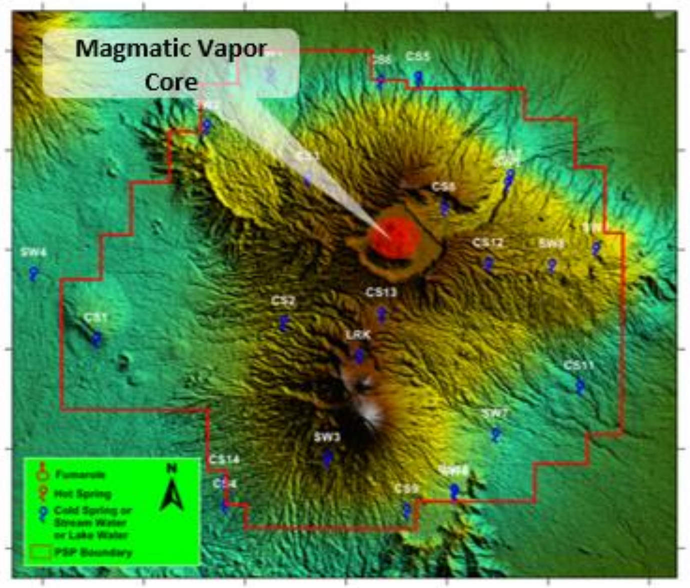
2. Undeveloped "Challenging" Geothermal Systems (Type #3)

Characteristics

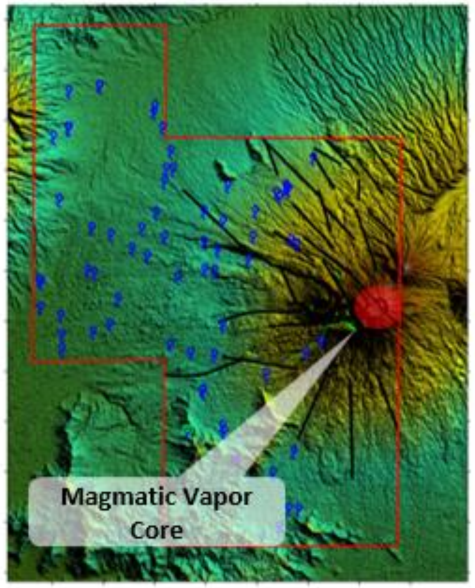
- **Poor Surface Manifestations**
- Almost no surface manifestations found except on the summit indicating there is possible geothermal system in the subsurface (degassing crater).

Field Examples :

- Bromo & Raung in East Java.



Bromo Geothermal Field



Raung Geothermal Field

Recent Geothermal Exploration Challenges

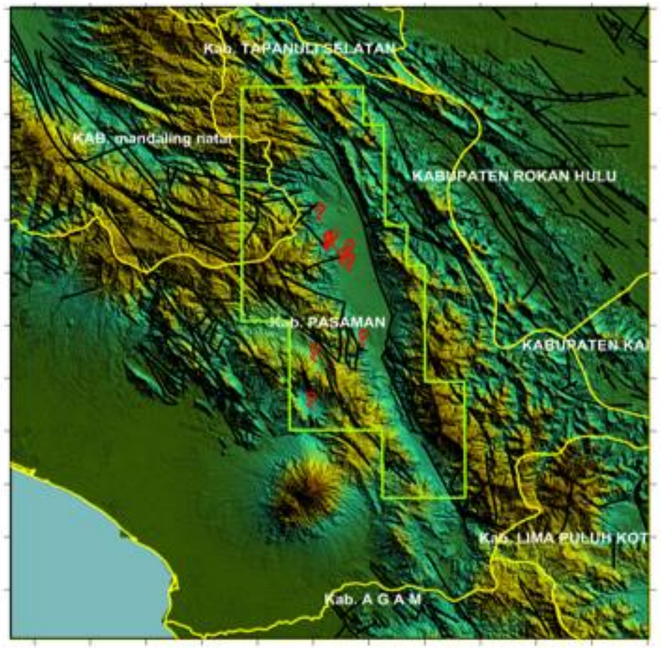
2. Undeveloped "Challenging" Geothermal Systems (Type #4)

Characteristics

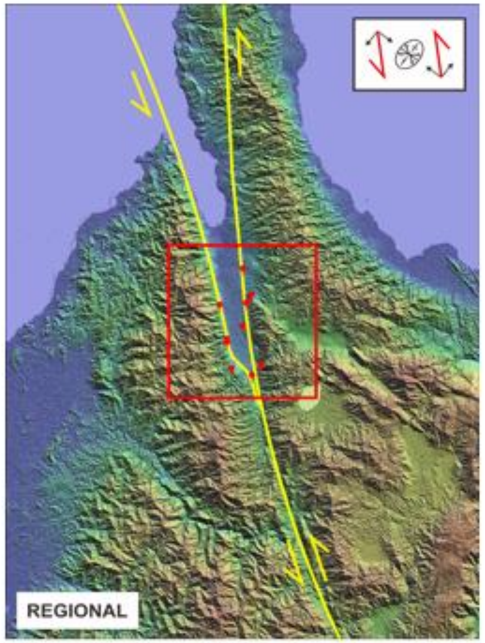
- **Non-volcanic geothermal system**
  - Typical tectonic geothermal systems with low-moderate temperature
  - Surface Manifestations usually hot springs and altered grounds found along fault structures.

Field Examples :

- Simisuh-Pasaman-Cubadak (West Java), Bora-Pulu & Marana (Central Sulawesi).



Simisuh – Pasaman – Cubadak



Bora-Pulu - Marana

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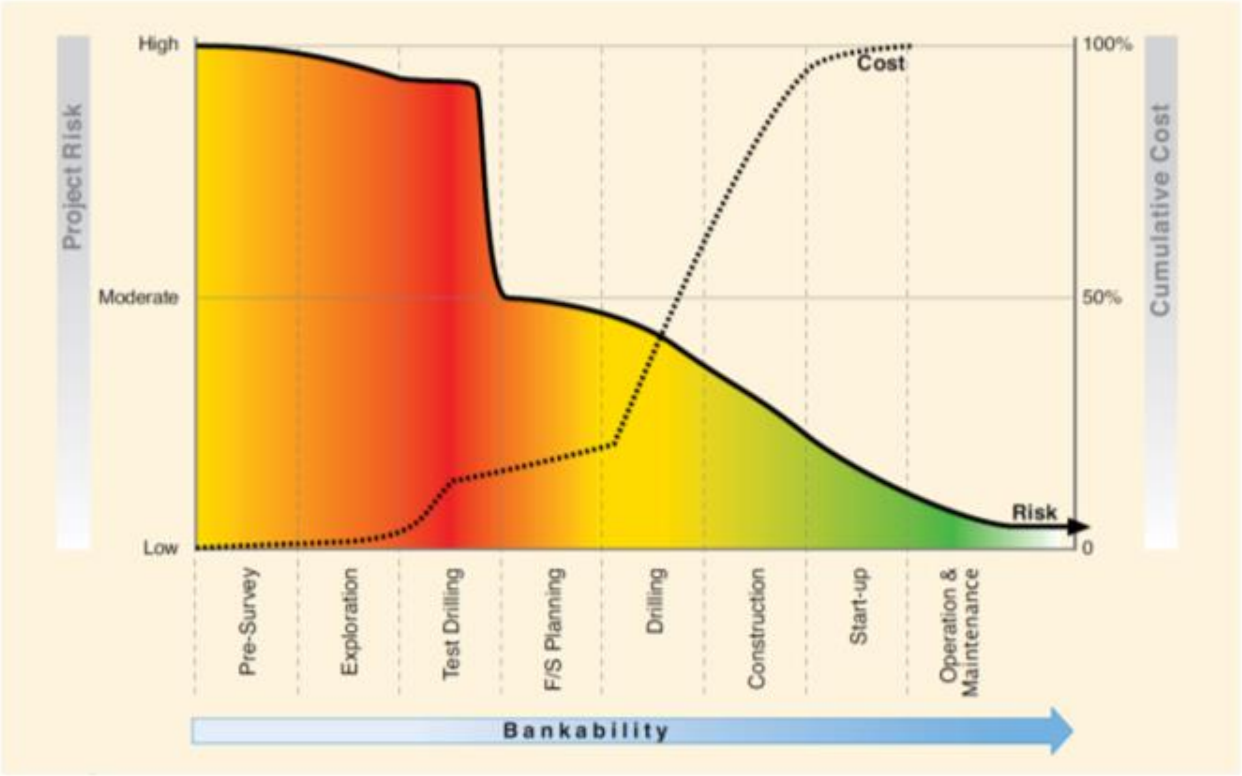
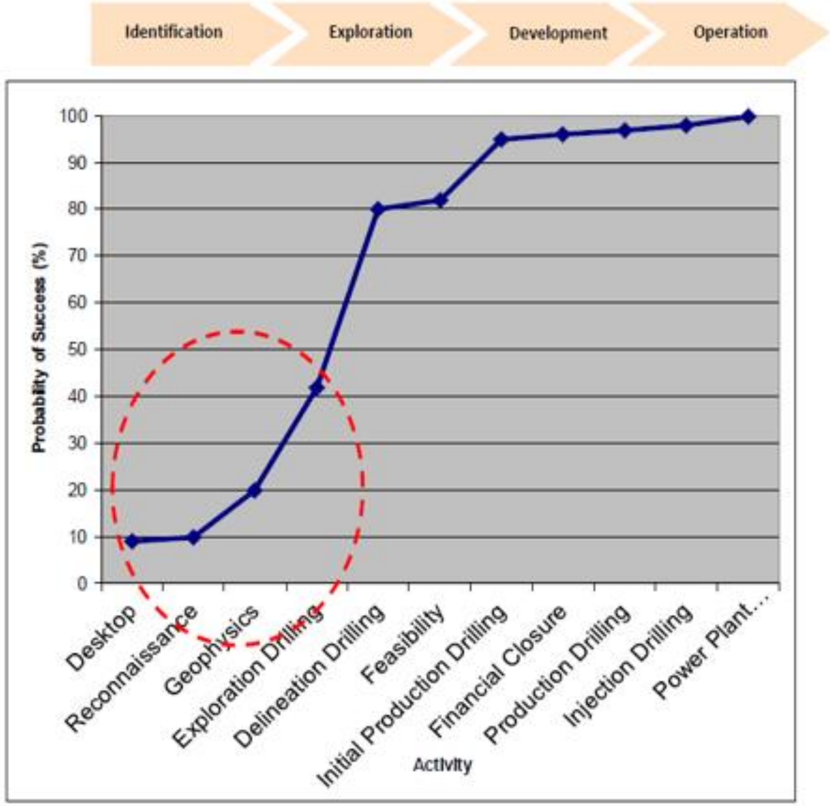
Recent Geothermal Exploration Challenges

3. High Exploration Risk and Low Probability of Success

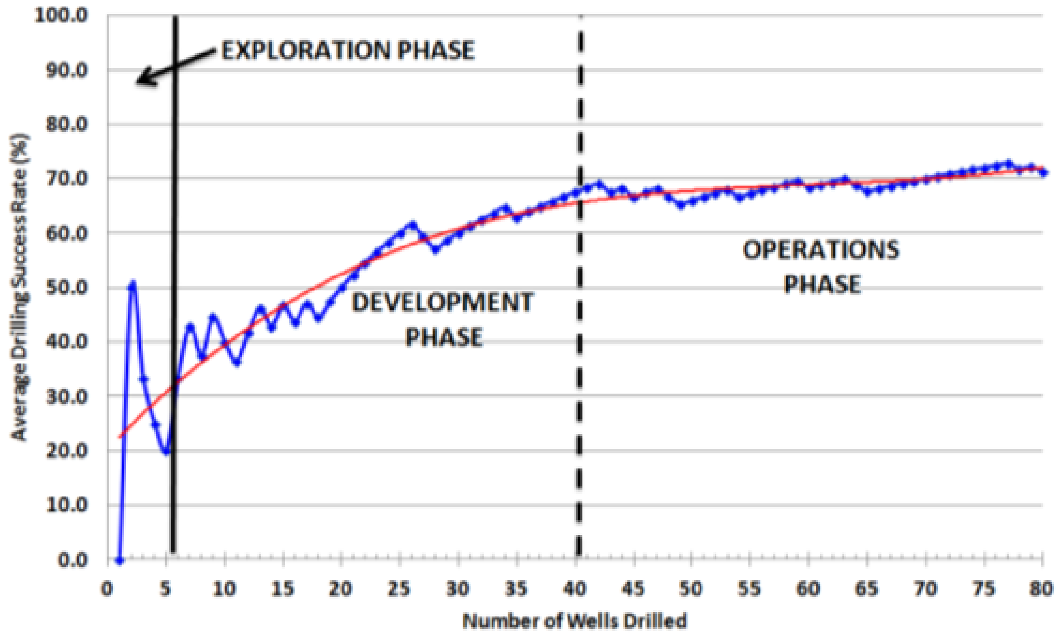




Source: ESMAP World Bank Geothermal Handbook 2012

Recent Geothermal Exploration Challenges

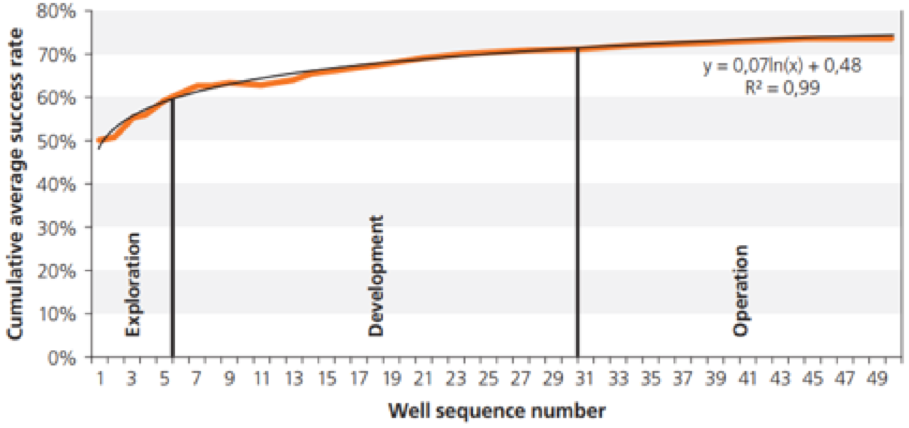
4. Drilling Success Ratio (DSR) in Indonesia and Worldwide



Average Drilling Success Rate vs. Number of Wells Drilled in the Kamojang Field, Indonesia (Sanyal & Morrow, 2012)

Ministry of Energy and Mineral Resources also estimates drilling success ratio from the latest 5 geothermal exploration drilling, that is about 33 to 67%.

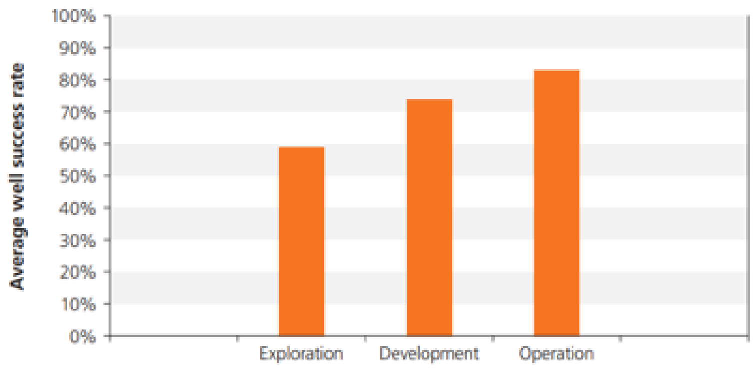
Cumulative average well success rates



- ❑ 1st well: **50%,**
- ❑ 1st 5 wells: **59%**
- ❑ 1st 30 wells: **71%**

.. continues beyond the 50th well.

Average well success rate, by project phase



- ❑ Exploration Phase: **59%**
- ❑ Development Phase: **74%**
- ❑ Operation Phase: **83%**

(IFC, 2013)

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MT ROLES IN GEOTHERMAL EXPLORATION

10 Years of Contributions

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MT Roles in Geothermal Exploration

Typical exploration questions:

Where is the center of reservoir?

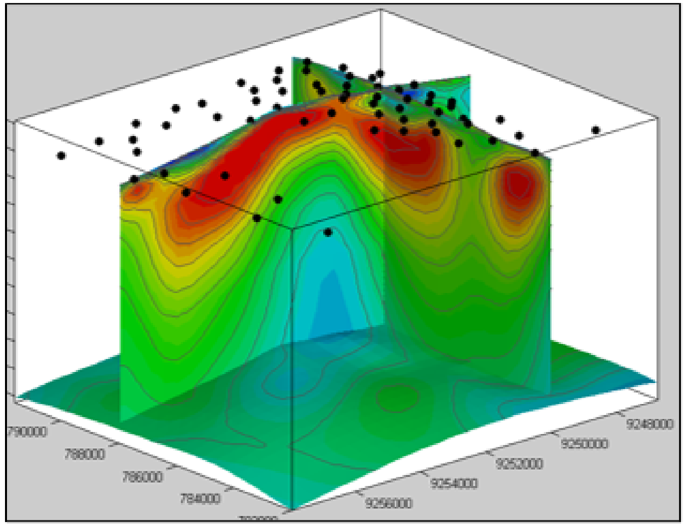
What is the area extent of reservoir?

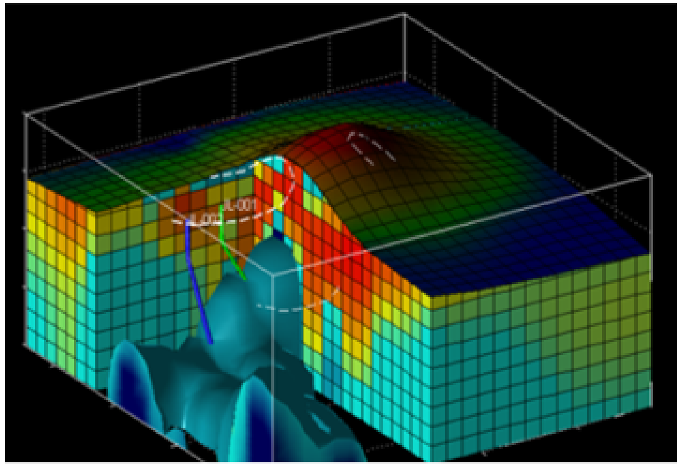
What is the depth of reservoir?

Can major structural features be recognised?

Can outflow structure be identified?

Can MT technology answer these questions?





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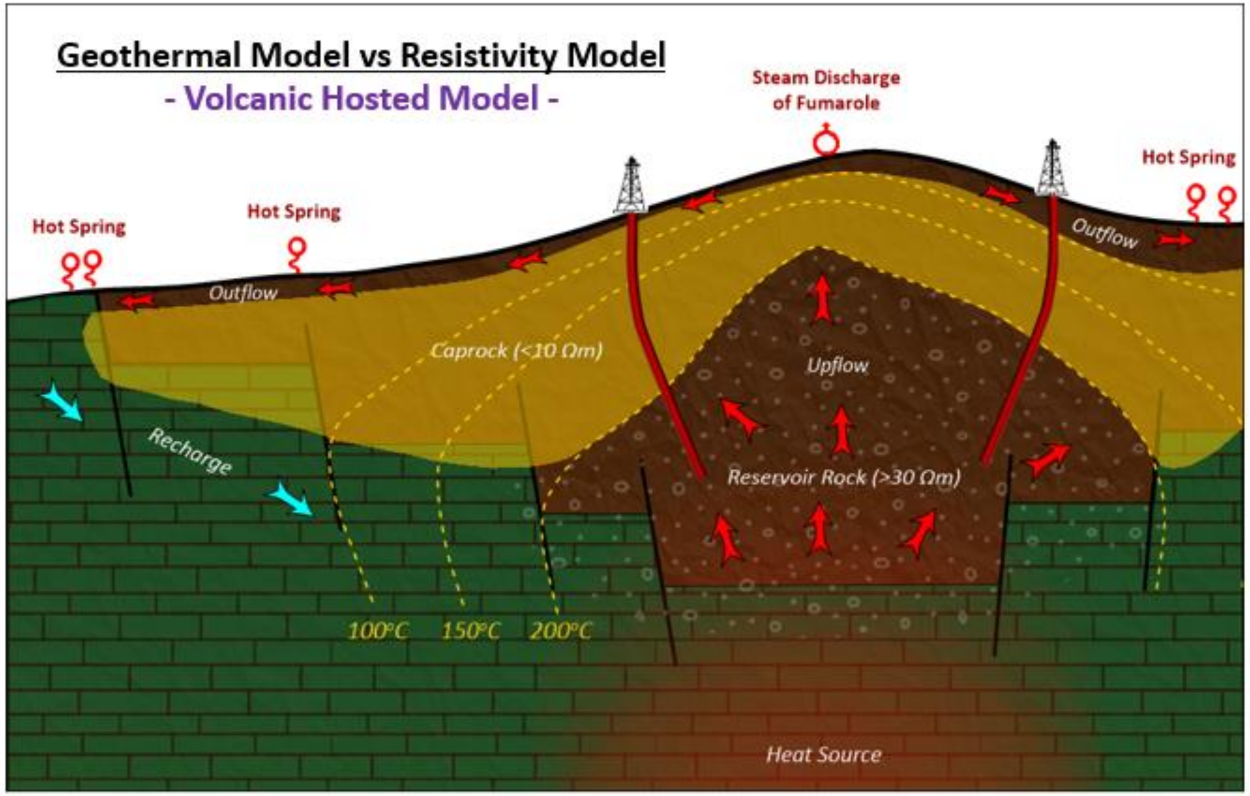
MT ROLES IN GEOTHERMAL EXPLORATION

MT can reconstruct a geothermal system model

10 Years of Contributions

MT Roles in Geothermal Exploration

a. MT can reconstruct a geothermal system model



- **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

- **Geothermal system**: high salinity, clay alteration, high temperature ➔
  - **Lower overall resistivity of rocks**
  - Clay cap (cap rock) has **lowest** resistivity (< 10 ohm-m)
  - Reservoir has low resistivity but **slightly higher** than resistivity of clay cap (> 30 ohm-m)
  - Basement or hot rock has highest resistivity (> 100 ohm-m)
  - **Main target for MT investigation**
  - Proper MT Technology can **delineate geothermal system model and guide well target zones.**

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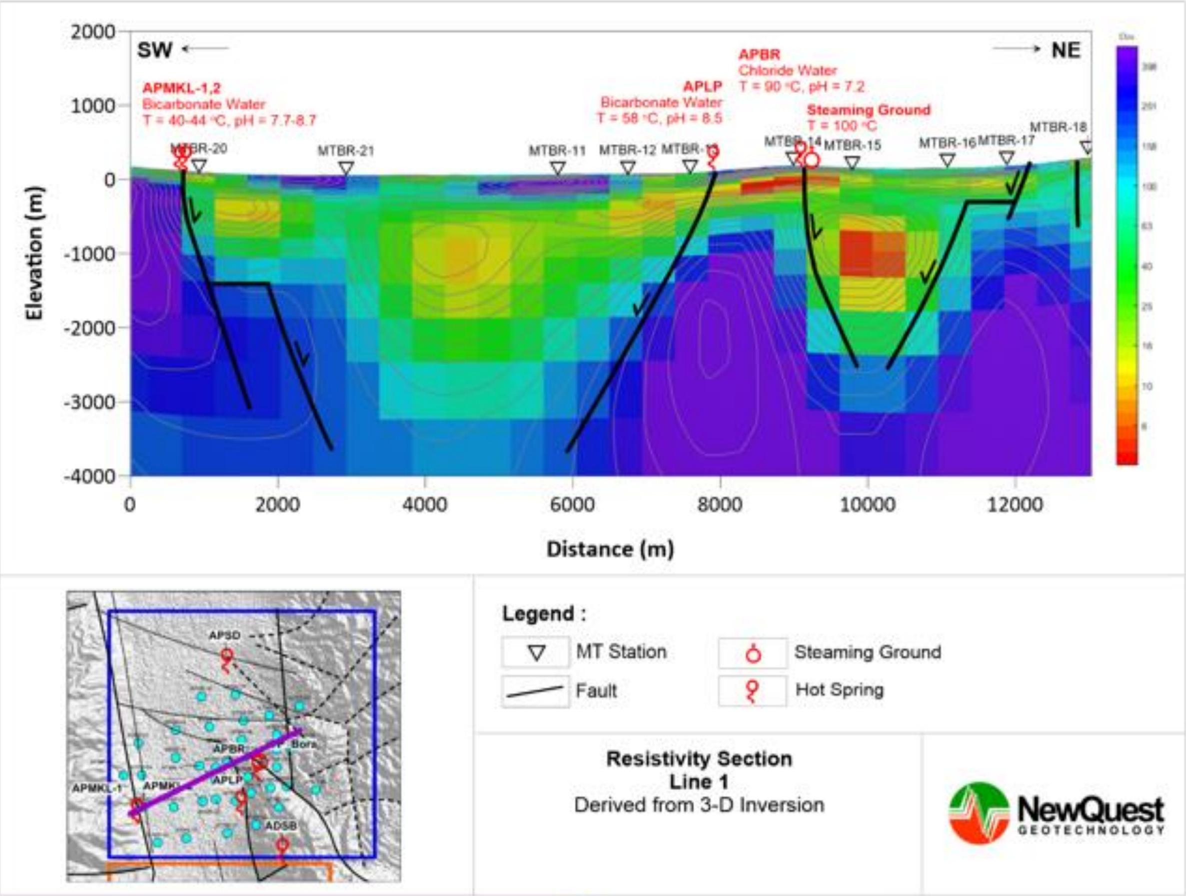
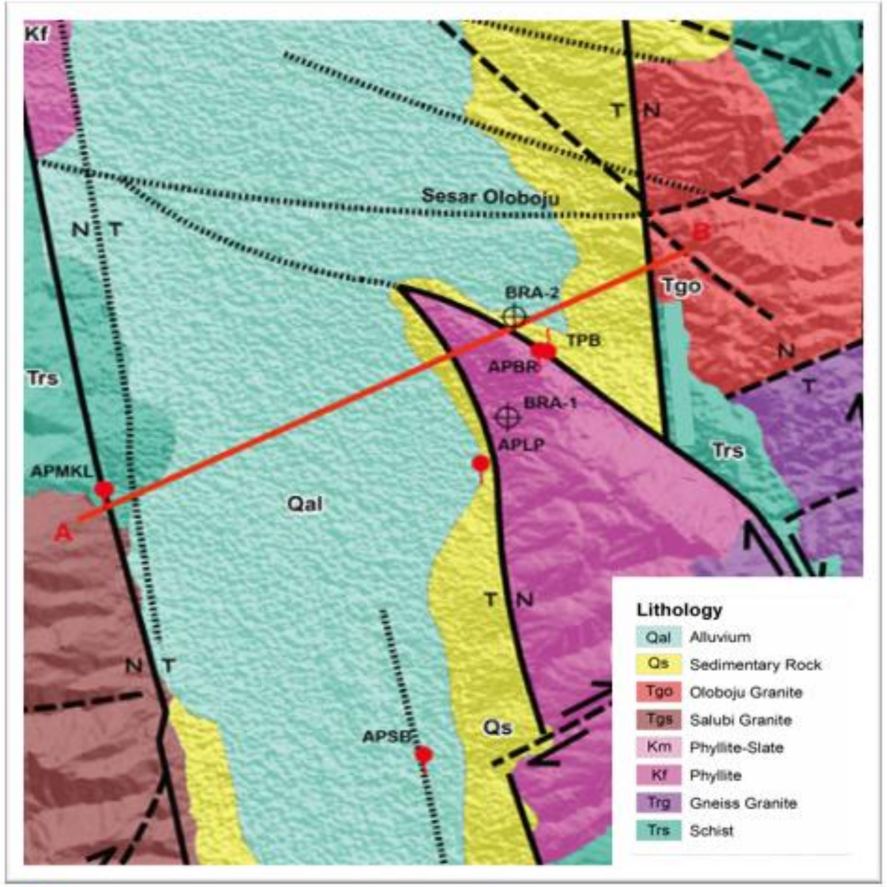
MT Role in Geothermal Exploration

a. MT can reconstruct a geothermal system model

Geothermal Model vs Resistivity Model

- Fault-Controlled Model -



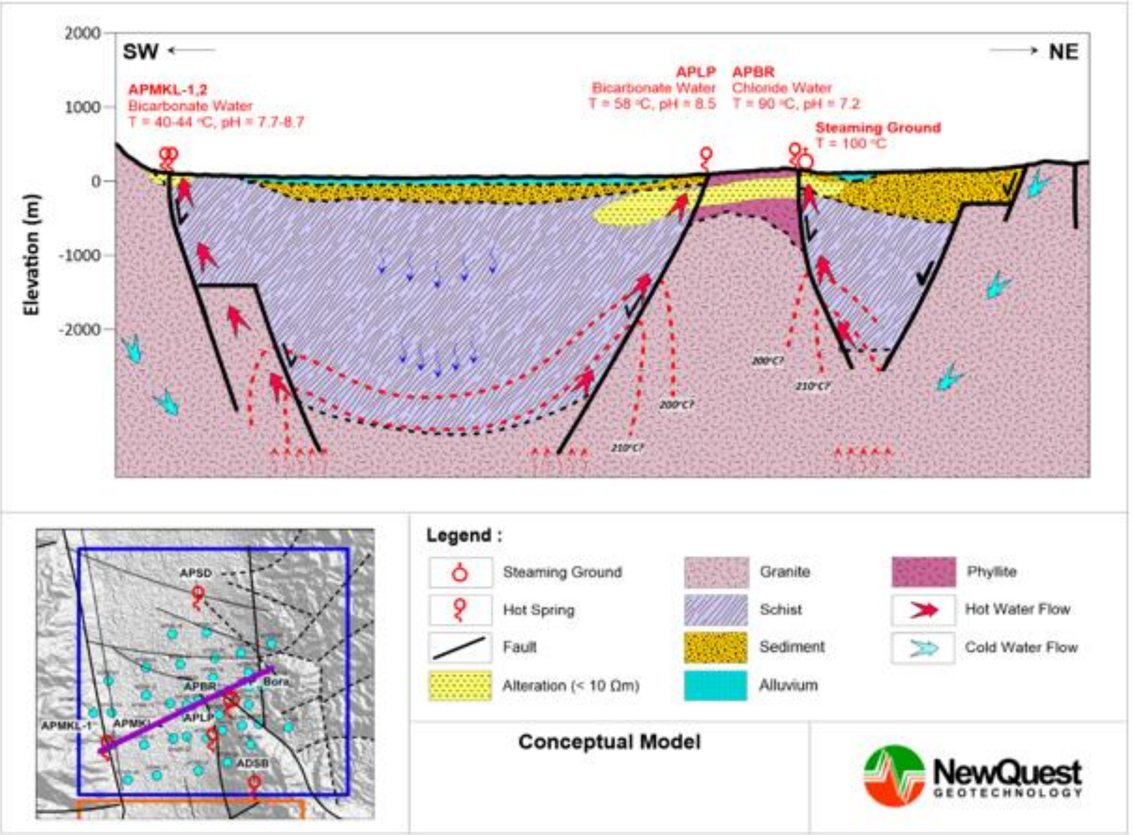


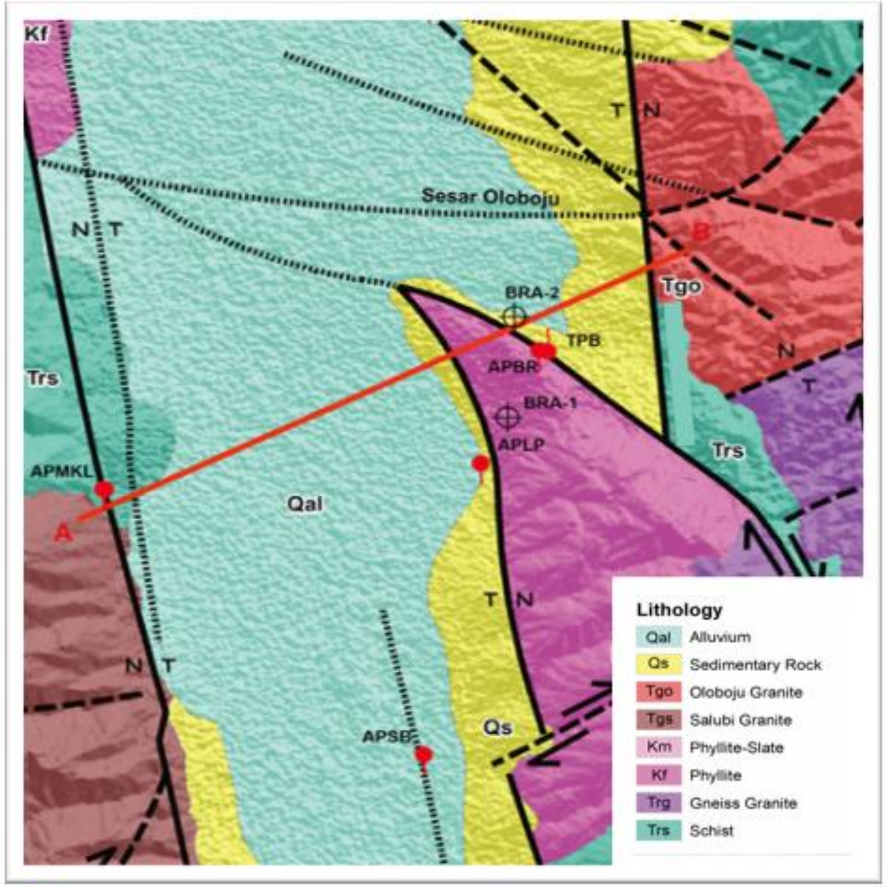
MT Roles in Geothermal Exploration

a. MT can reconstruct a geothermal system model

Geothermal Model vs Resistivity Model

- Fault-Controlled Model -





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MT ROLES IN GEOTHERMAL EXPLORATION

MT can delineate boundary of reservoir

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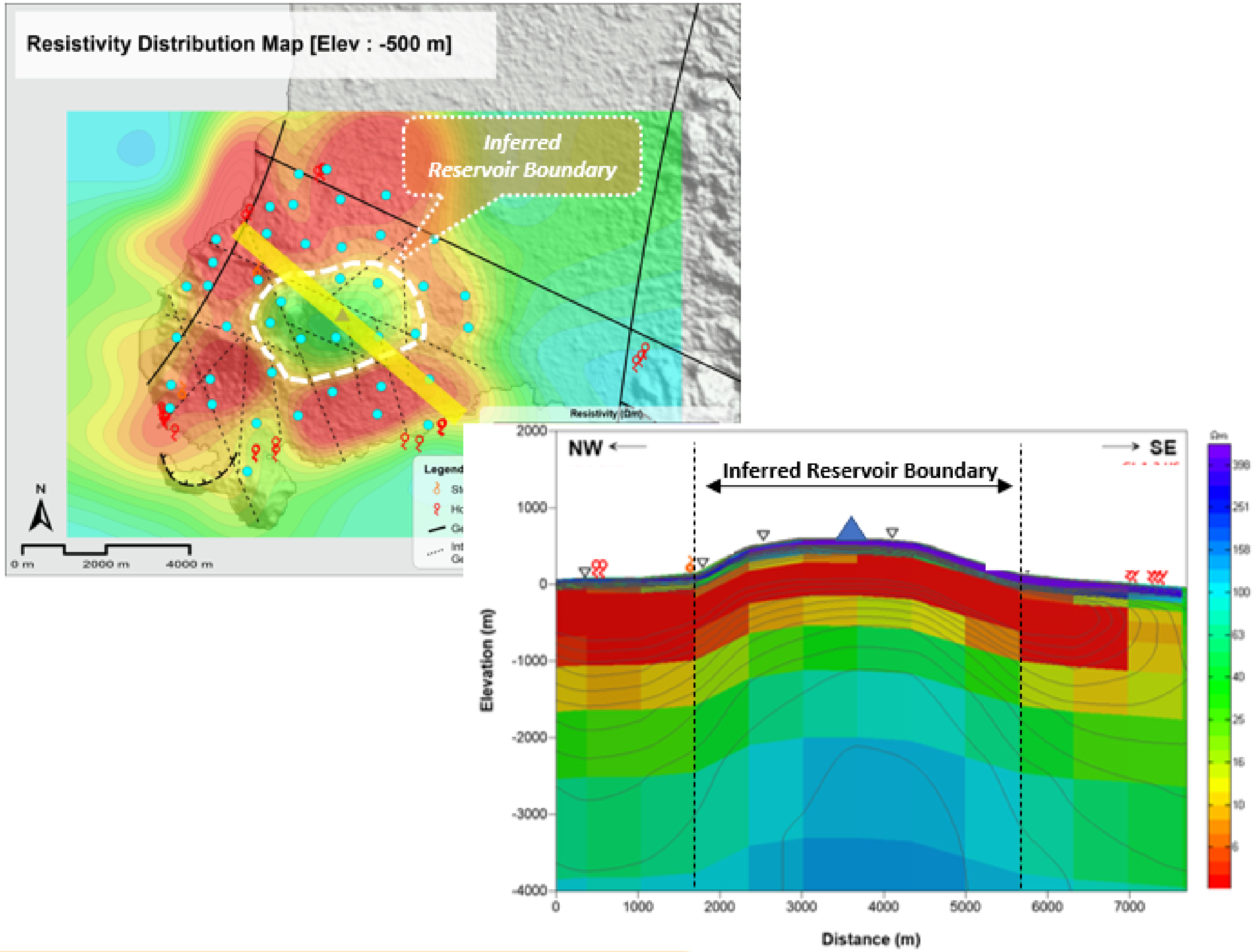
MT Roles in Geothermal Exploration

b. MT can delineate boundary of reservoir



- ❑ **"Economic" Geothermal Reservoir:** high temperature, high permeability, benign fluid in the range of economic well depth.

- ❑ **Reservoir Boundary:** decreasing (reverse) temperature, "impermeable" geological structure/formation, represented by:
  - Thickening of conductive layer (<10 ohm-m)
  - Resistivity contrast between slightly higher resistivity (20-100 ohm-m) and very high resistivity (more than 200 ohm) formations
  - Steep gradient of BOC contour.

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MT ROLES IN GEOTHERMAL EXPLORATION

MT can delineate well target zones

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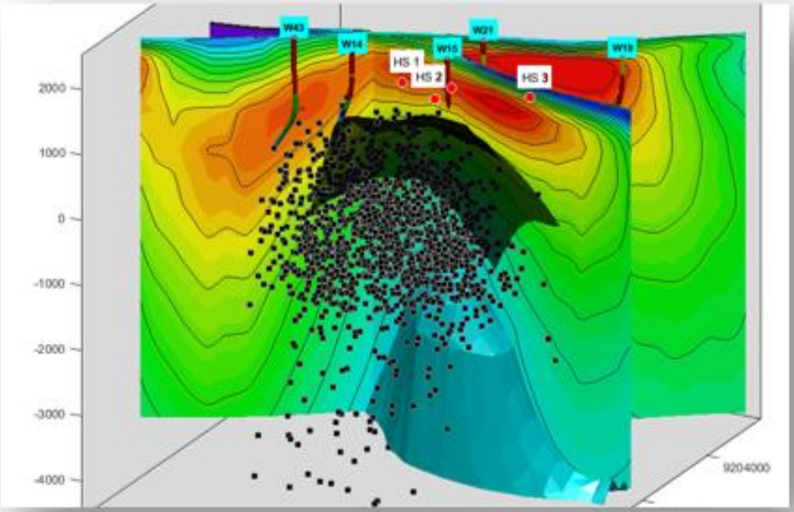
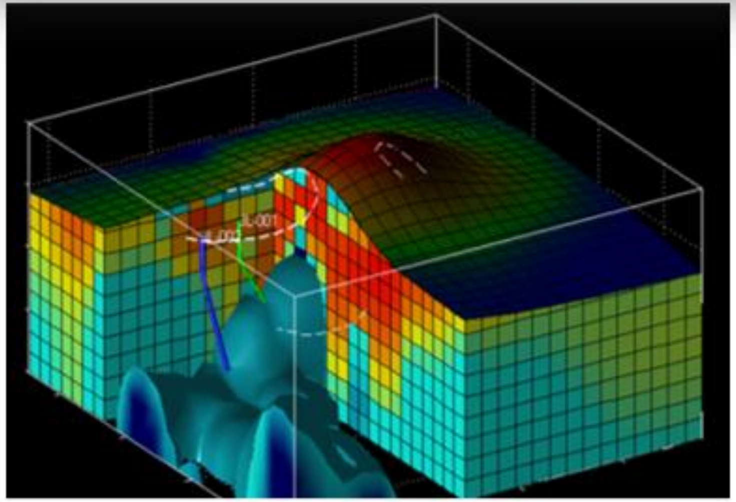
MT Roles in Geothermal Exploration

c. MT can delineate well target zones

- **Proper MT technology can guide well target zones (high T, high K, benign fluid)**
- MT is an **inexpensive method compared to drilling**
    - ✓ *100 MT stations = about 4 % of one Drilling Price*
- Even, MT Technology can **cover wider target area than Drilling**
- **Priority to optimize MT role <u>before drilling campaign.</u>**





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MT ROLES IN GEOTHERMAL EXPLORATION

MT can be optimised for achieving exploration targets

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MT Roles in Geothermal Exploration

d. MT can be optimised for achieving exploration targets

Exploration Target \ Methods	Geology	Geochemistry	Geophysics: Gravity	Geophysics: MT	Geophysics: Passive Seismic
Heat Source	Strong	None	Weak	Strong	Strong
Reservoir Host Rock	Strong	Moderate	Weak	Weak	Weak
Permeability Indication	Moderate	Weak	Weak	Moderate	Strong
Upflow - Outflow	Weak	Strong	Weak	Strong	Weak
Top of Reservoir	None	None	None	Strong	None
Reservoir Boundary	None	None	Weak	Strong	None
Resource Size	Weak	None	Weak	Strong	None
Regional/Local Structure	Strong	None	Strong	Moderate	Weak

Degree of Capability: None Weak Moderate Strong

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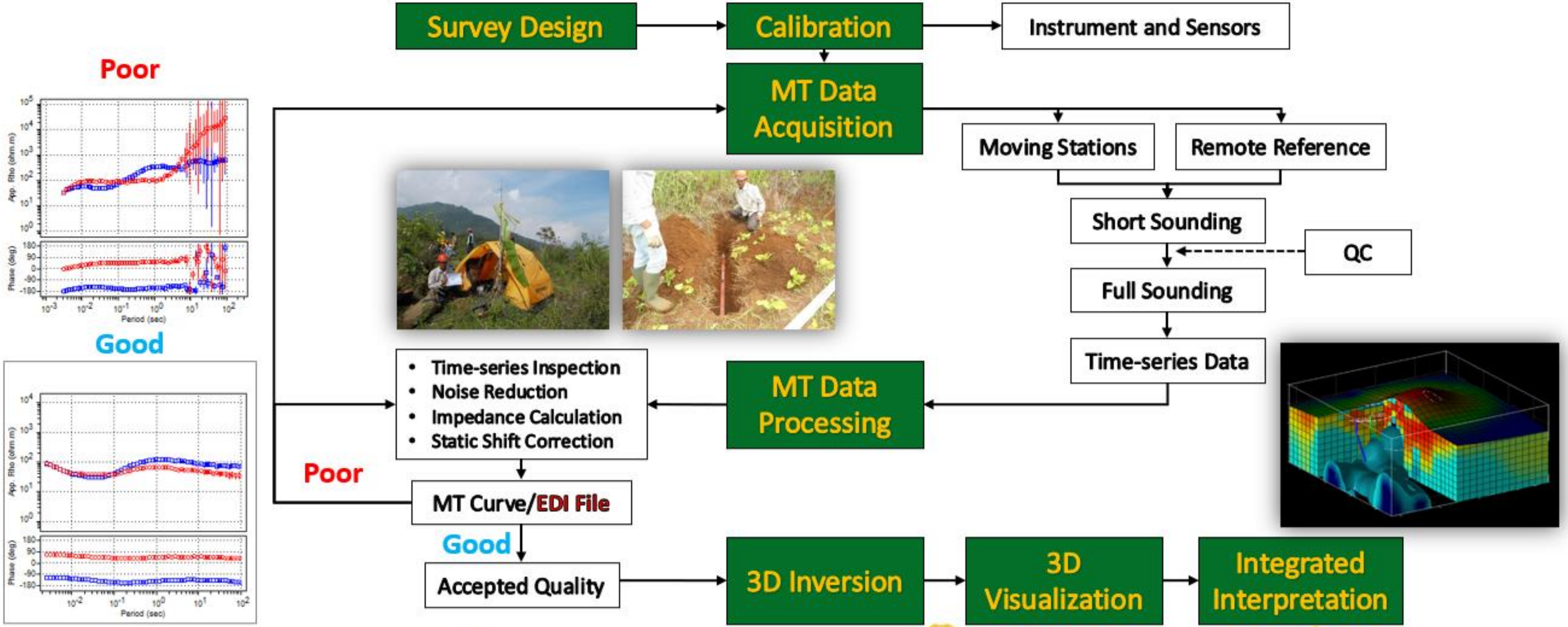
MT ROLES IN GEOTHERMAL EXPLORATION

MT Technology Workflow

10 Years of Contributions

MT Role in Geothermal Exploration

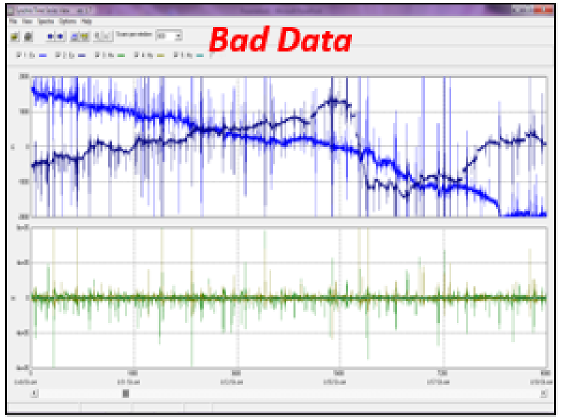
e. MT Technology Workflow

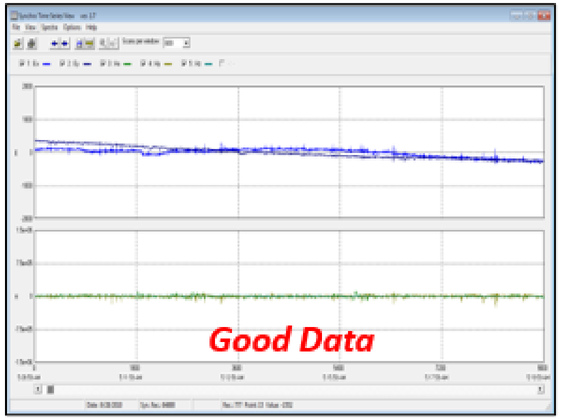


Time-series Inspection → Noise Reduction → Impedance Calculation → Static-shift Correction

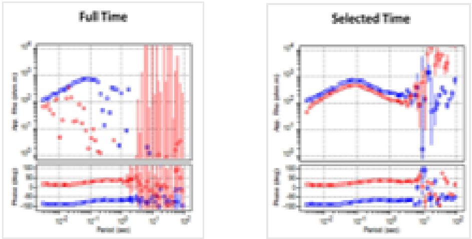
Time-series Inspection	Noise Reduction	Impedance Calculation	Static-shift Correction
Amplitude (Spike) *Power Spectra (Power Line Noise)* *Coherency*	*Time-series selection* *Noise Filters* *Remote Reference*	*Robust Processing* *Crosspower selection* *Apparent Resistivity & Phase Curve*	*TDEM Data* *Geostatistical Method*

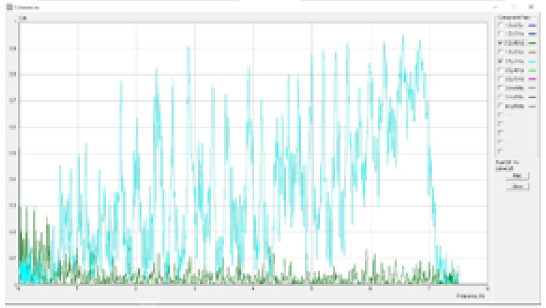
Time-series Inspection

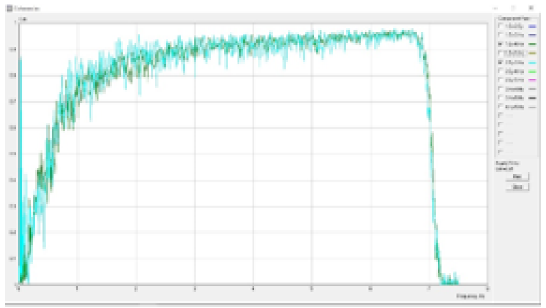




Noise Reduction



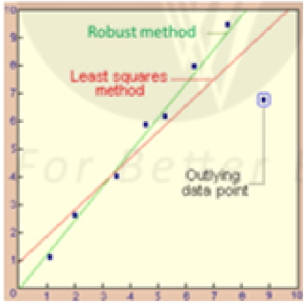




Impedance Calculation

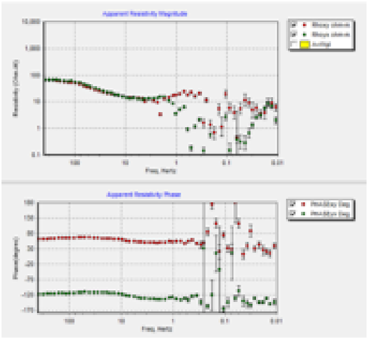
$$Z_{xy} = \frac{E_x}{H_y} \qquad \rho_{xy} = \frac{1}{\omega\mu_o}\left|\frac{E_x}{H_y}\right|^2$$

$$\emptyset_{xy} = tan^{-1}|Z_{xy}|^2$$

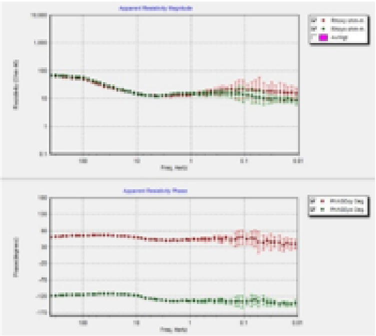


Crosspower Selection

Before



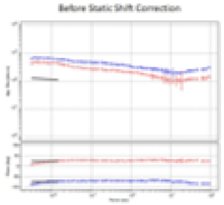
After



Static Shift Correction

- Static Correction
  - TDEM Data
  - Geostatistical Method
    - CoKriging
    - Averaging

Before



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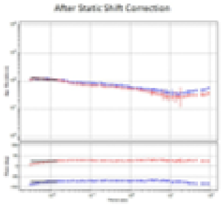

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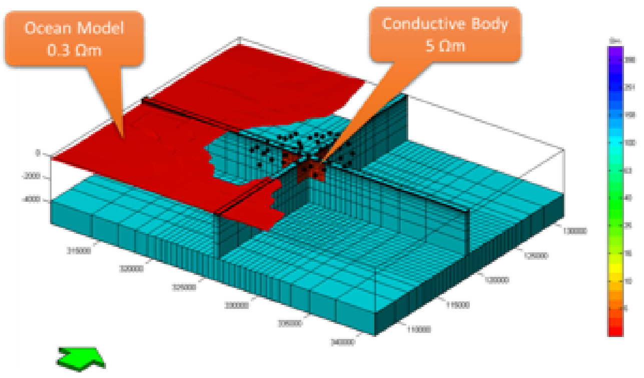
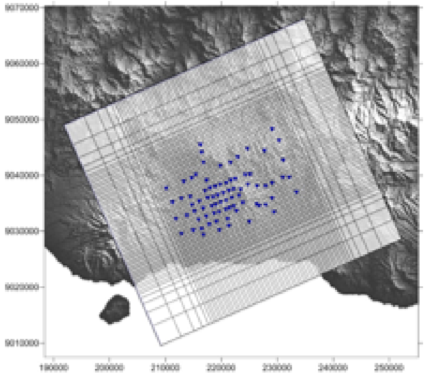
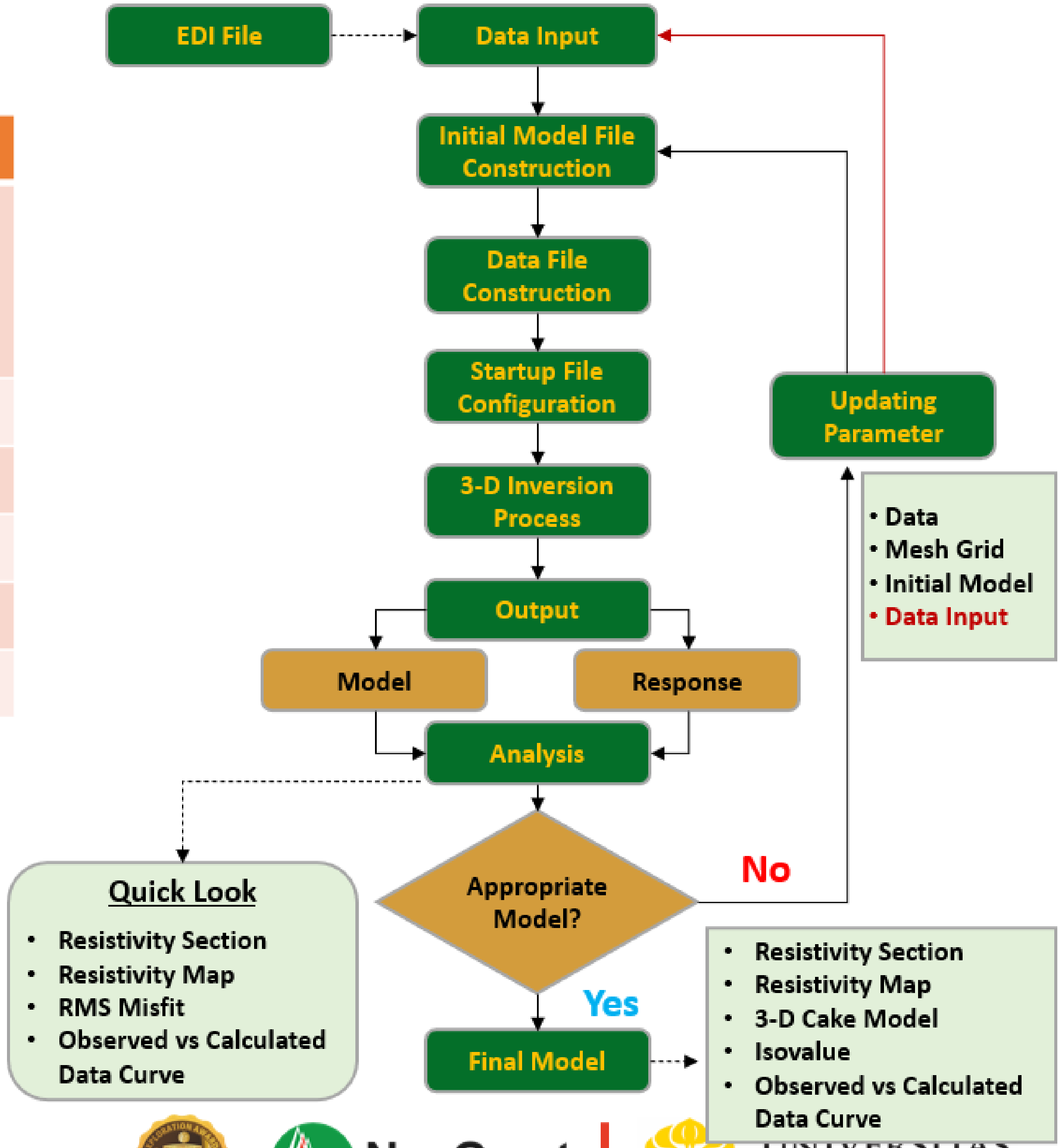
3-D Inversion Features & Procedure

No	Feature	Note
1	Algorithm	❑ Data space conjugate gradients (Siripunvaraporn and Egbert, 2007) ❑ Non-linear conjugate gradients (NLCG) (Egbert and Kelbert (2012)
2	Input Data	EDI File (Tensor Impedance, Tipper)
3	Topography	Included or Flat
4	Ocean/Prior Model	Available
5	Grid Rotation	Available
6	Output Data	XYZ Value, Mackie Out







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MT ROLES IN GEOTHERMAL EXPLORATION

Challenges in Applying MT Technology
(Successful and Unsuccessful Drilling Target)

10 Years of Contributions

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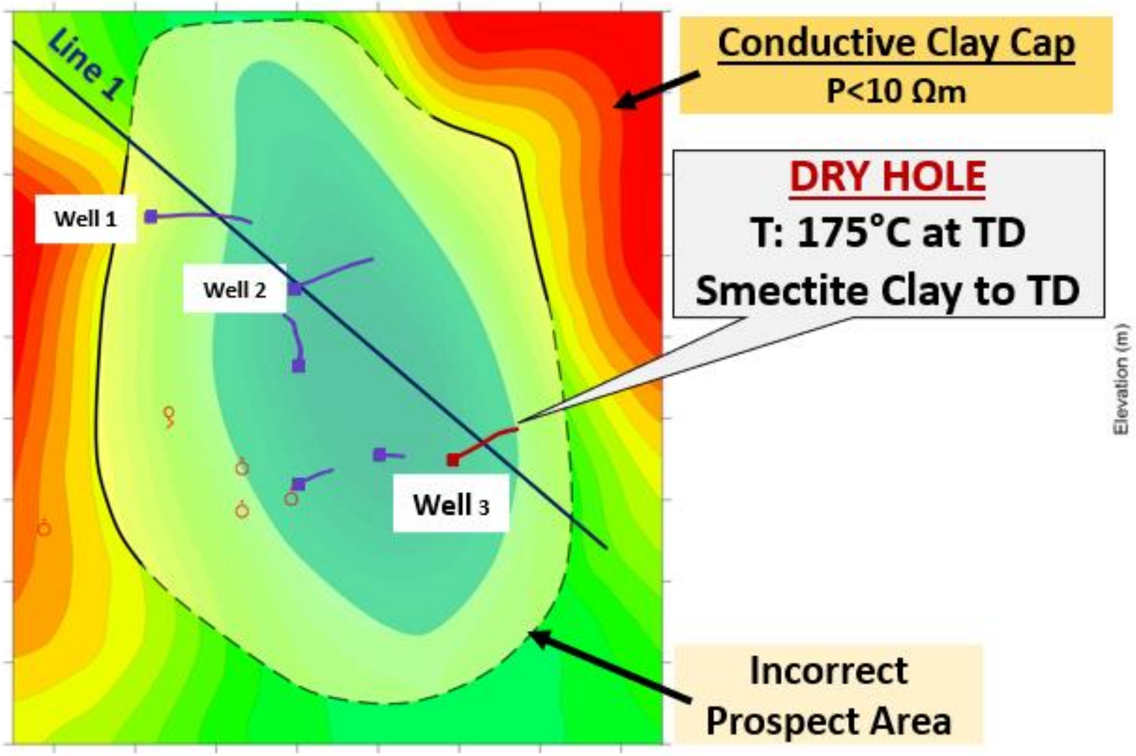
MT Roles in Geothermal Exploration

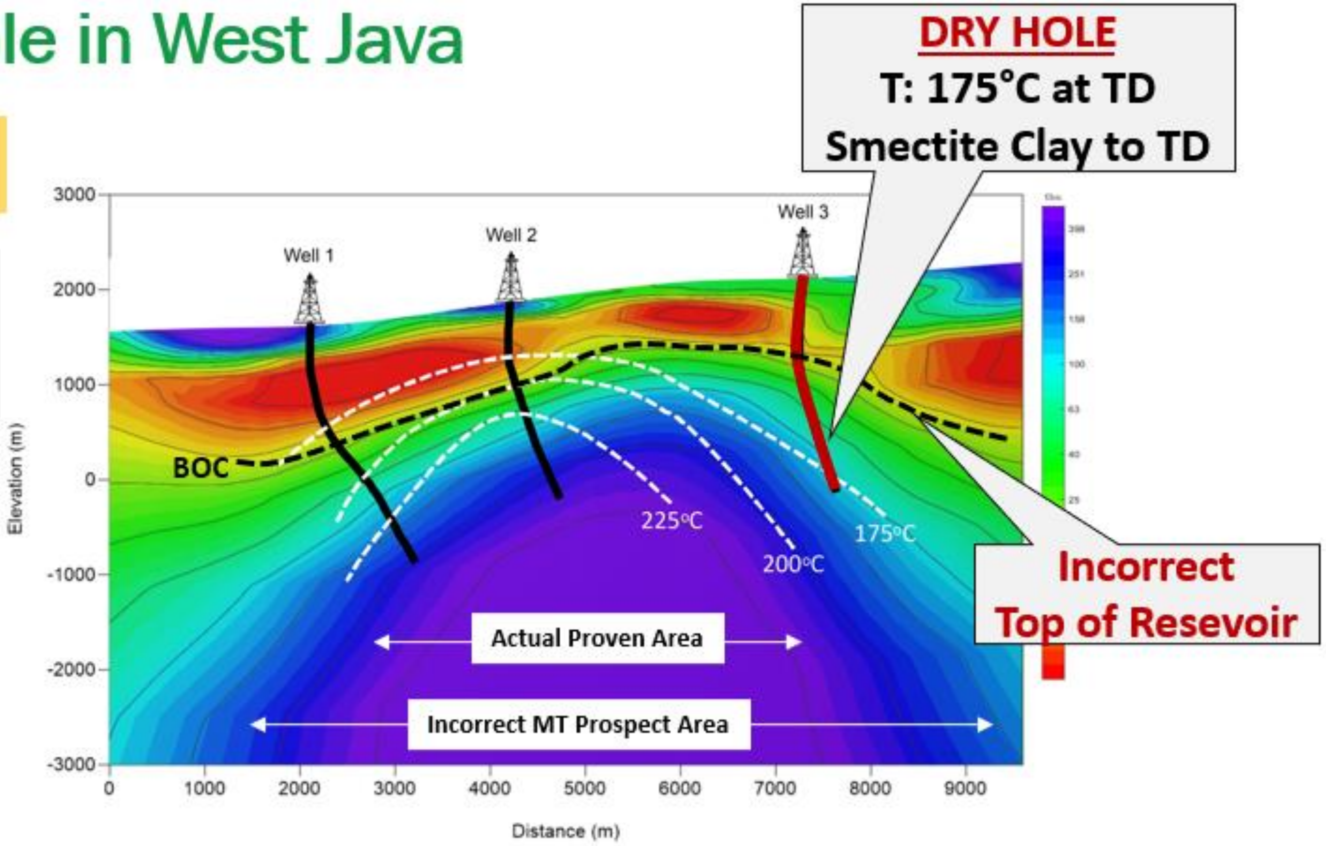
f. Challenges in Applying MT Technology (Successful & Unsuccessful Drilling Targets)

- **MT sensors (E in mV; H in nT) are very sensitive to the EM noises**
  - Cultural EM noises: powerline noise, electronic devices machines, car/train, etc.
  - Natural EM noises: active faults, tremor, moving trees near sensors, etc.
  - Needs understanding of the **noise characteristics** and **how to reduce it.**
  - **Careful MT Data Processing** must be done to get **Clean & Genuine MT Signal**.
- MT technology follows **EM principle** and naturally **a tensor.** So, **3D inversion is most suitable with the EM principles**. Need better **understanding of the Modelling Schemes.**
- **Incorrect use of MT technology** can cause **errors in determining subsurface drilling targets.**
- **Successful & unsuccessful drilling targets** can be learned from the following examples:

Un-successful Drillings Due to Incorrect Use of MT Technology

1st Example in West Java



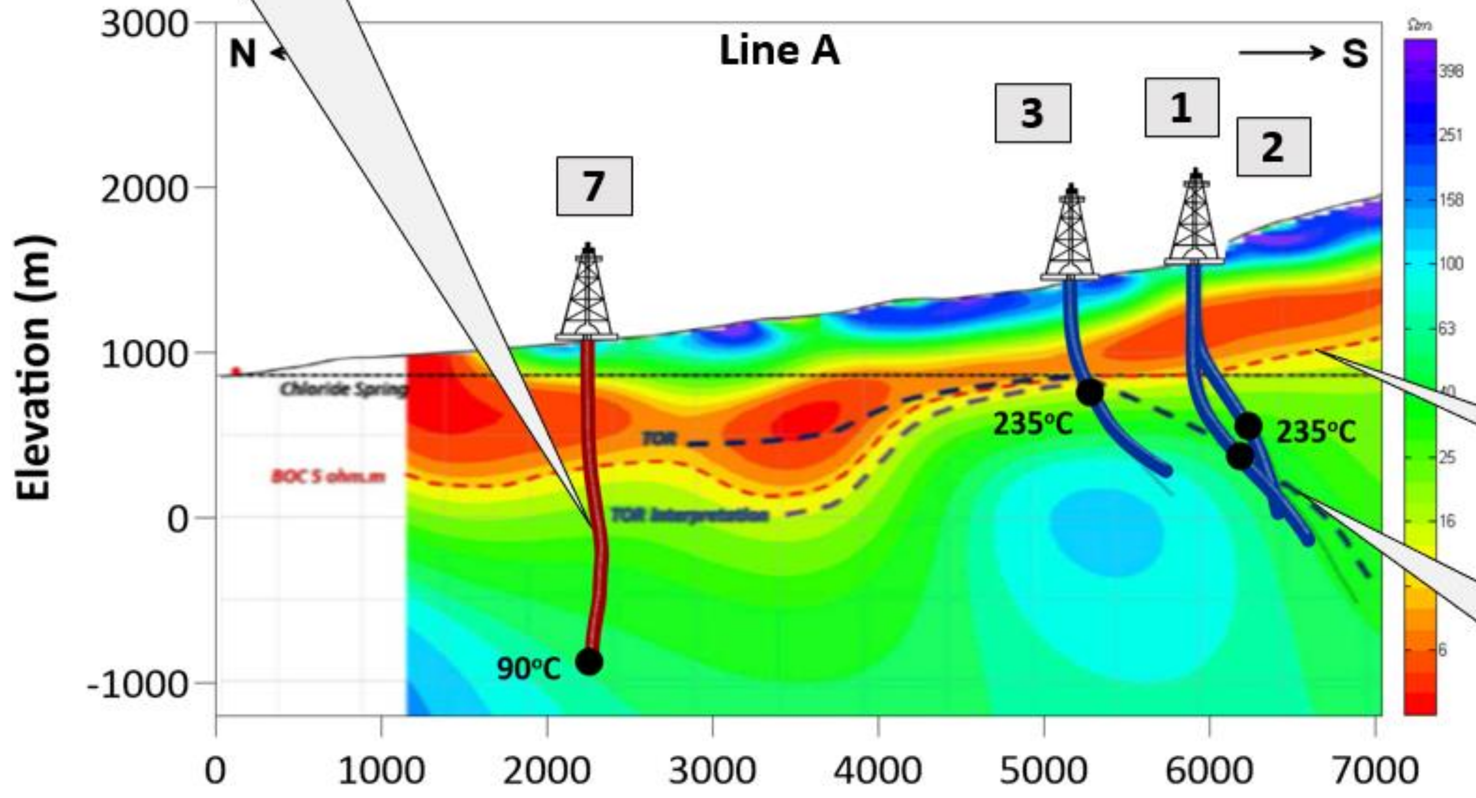


The MT Model give incorrect **MT prospect area** and has **contradiction with drilling data & reservoir simulation** results

Un-successful Drillings Due to Incorrect Use of MT Technology

2nd Example in West Sumatera

DRY HOLE
T: 90°C at TD



Disagreement between Base of Conductor (BOC) and Actual Top of Reservoir (TOR)

Incorrect Top of Resevoir Based on MT Data

Top of Resevoir Based on Drilling Data

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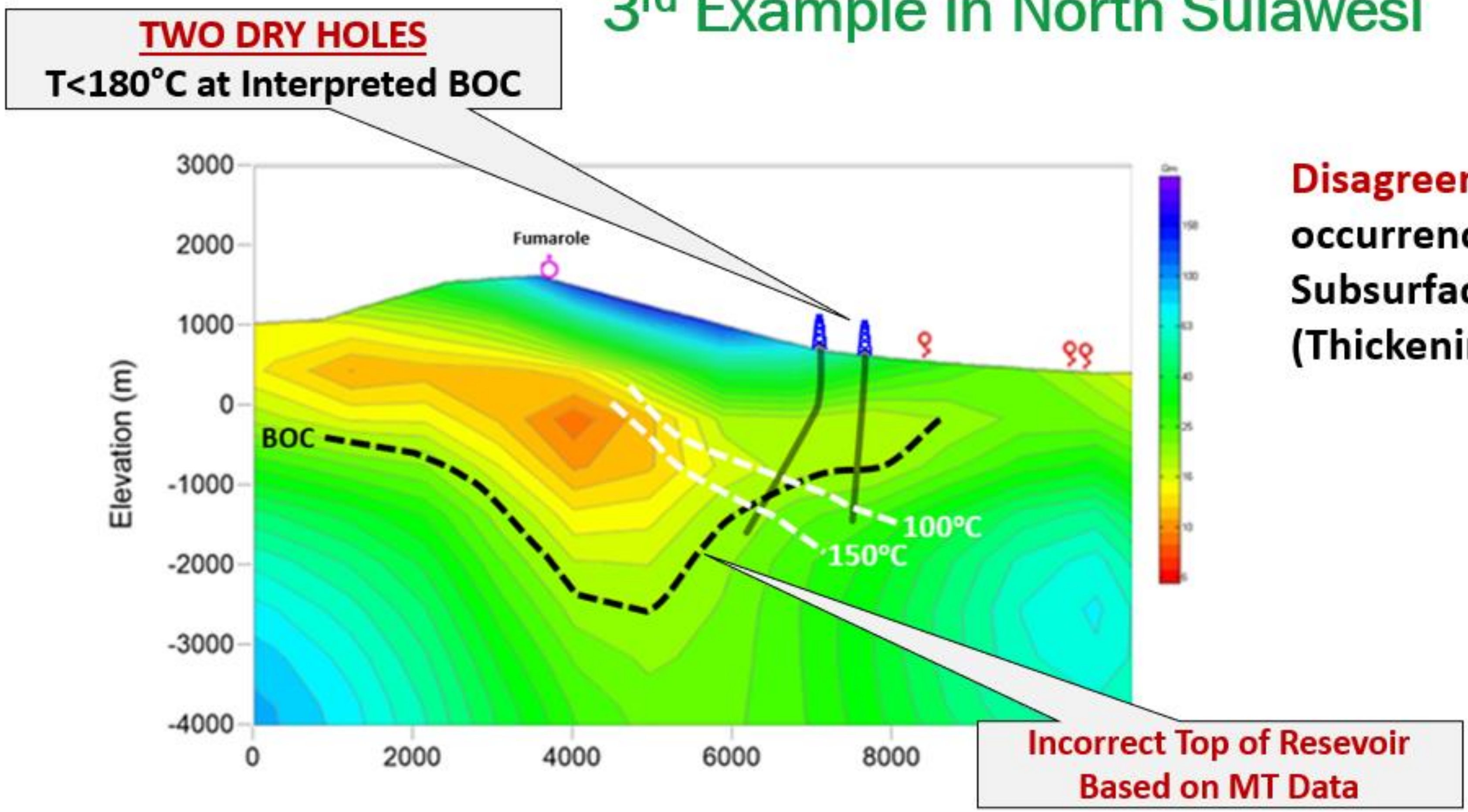
Un-successful Drillings Due to Incorrect Use of MT Technology

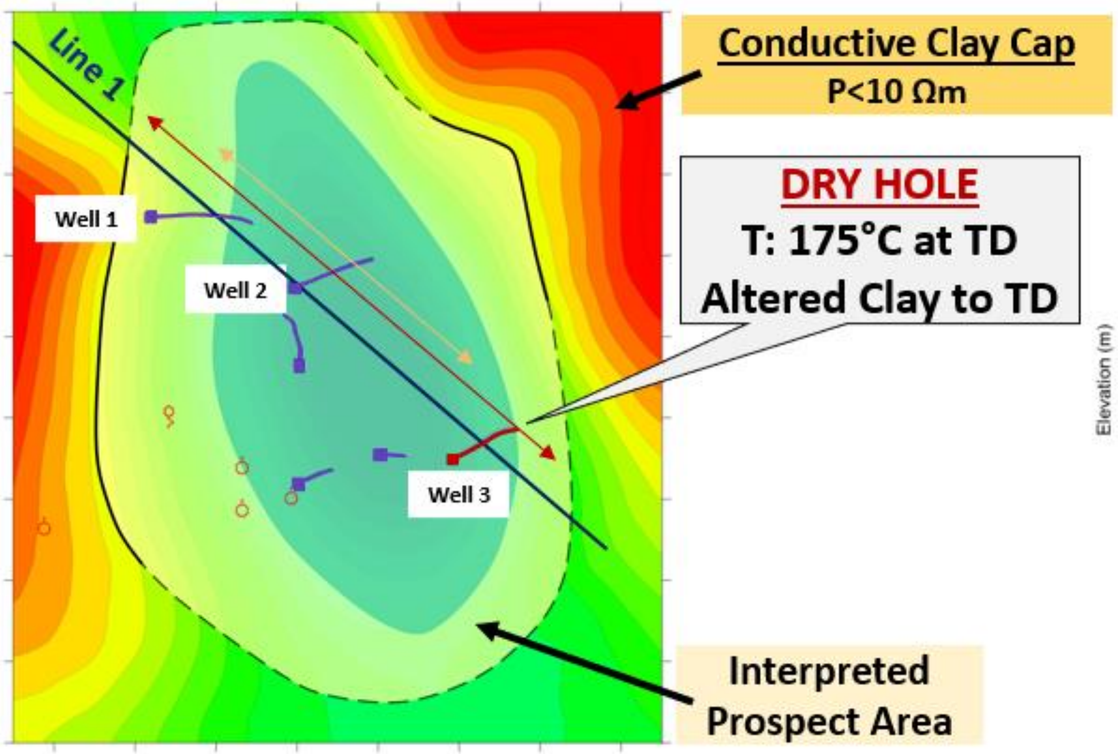
3rd Example in North Sulawesi

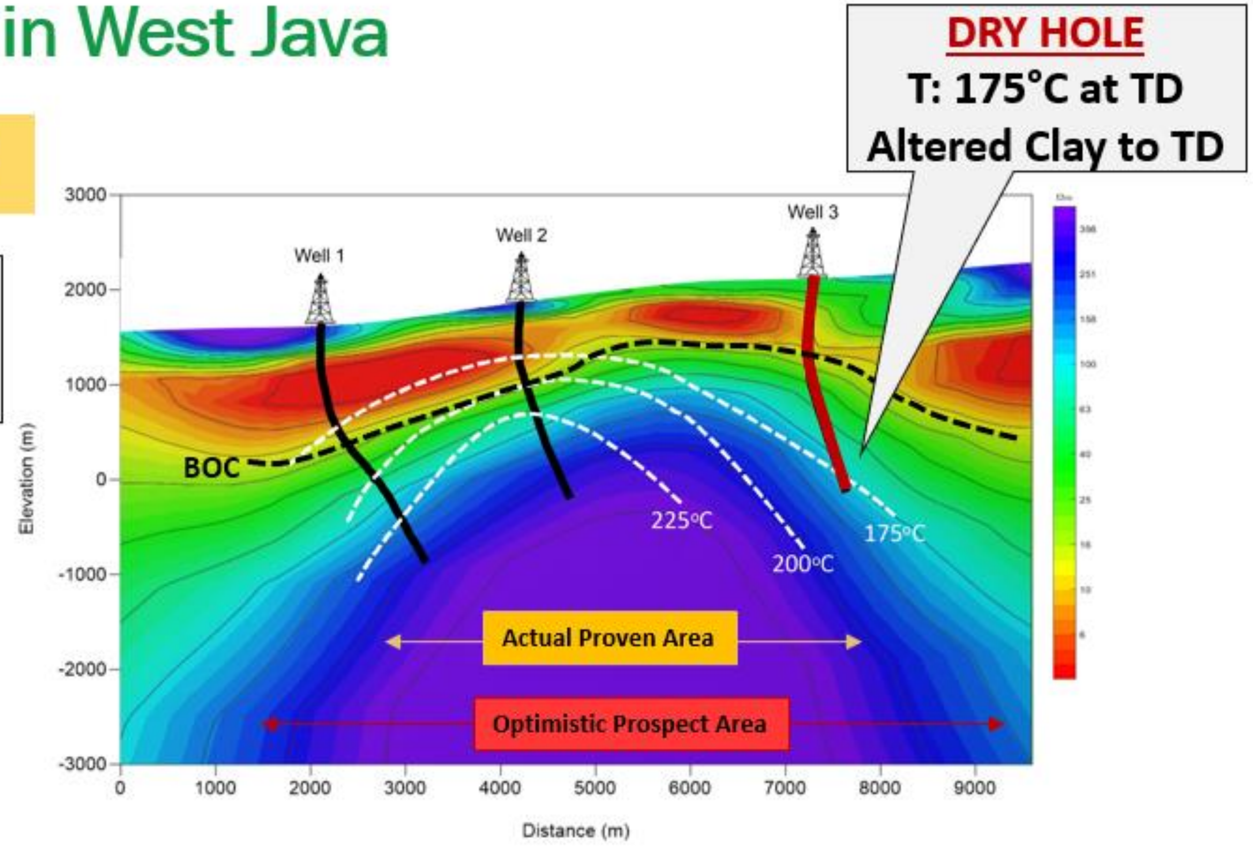


Disagreement between Fumarole occurrence (indicated upflow) and Subsurface Resistivity Structure (Thickening of Conductive Layer)

Before Reprocessing & Remodelling of MT Data

1st Example in West Java

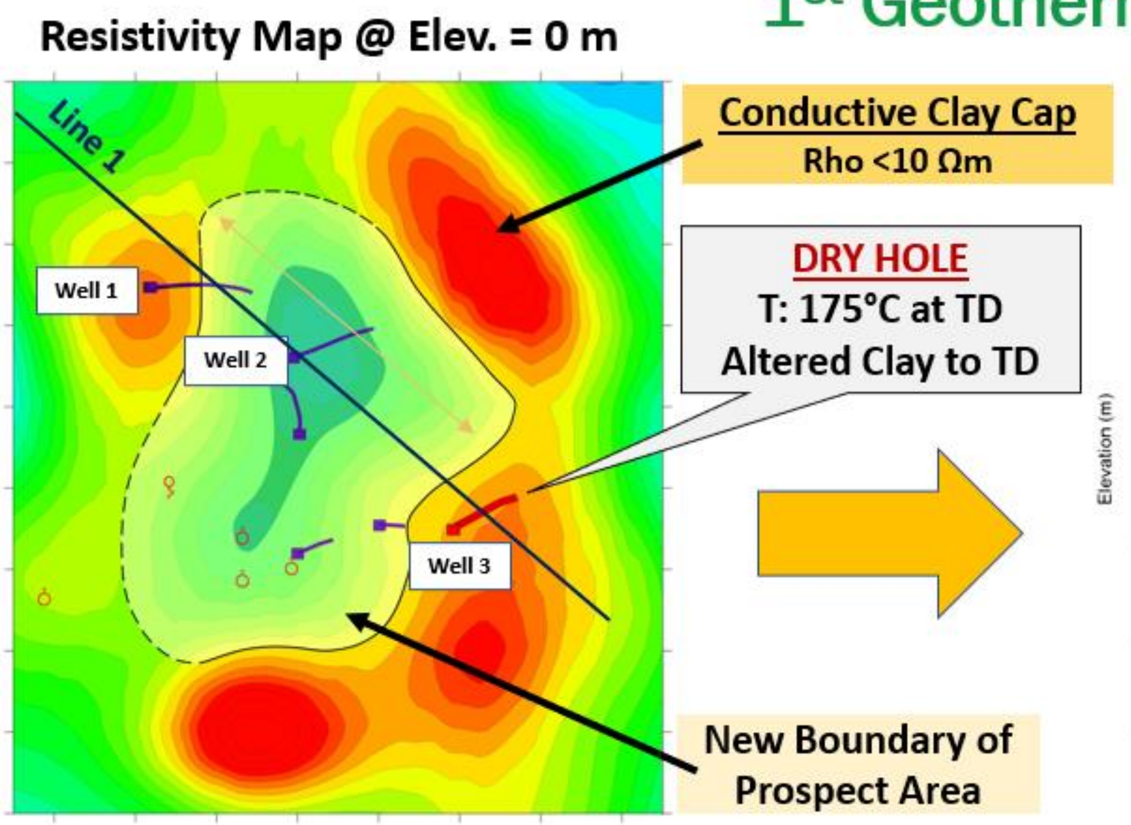


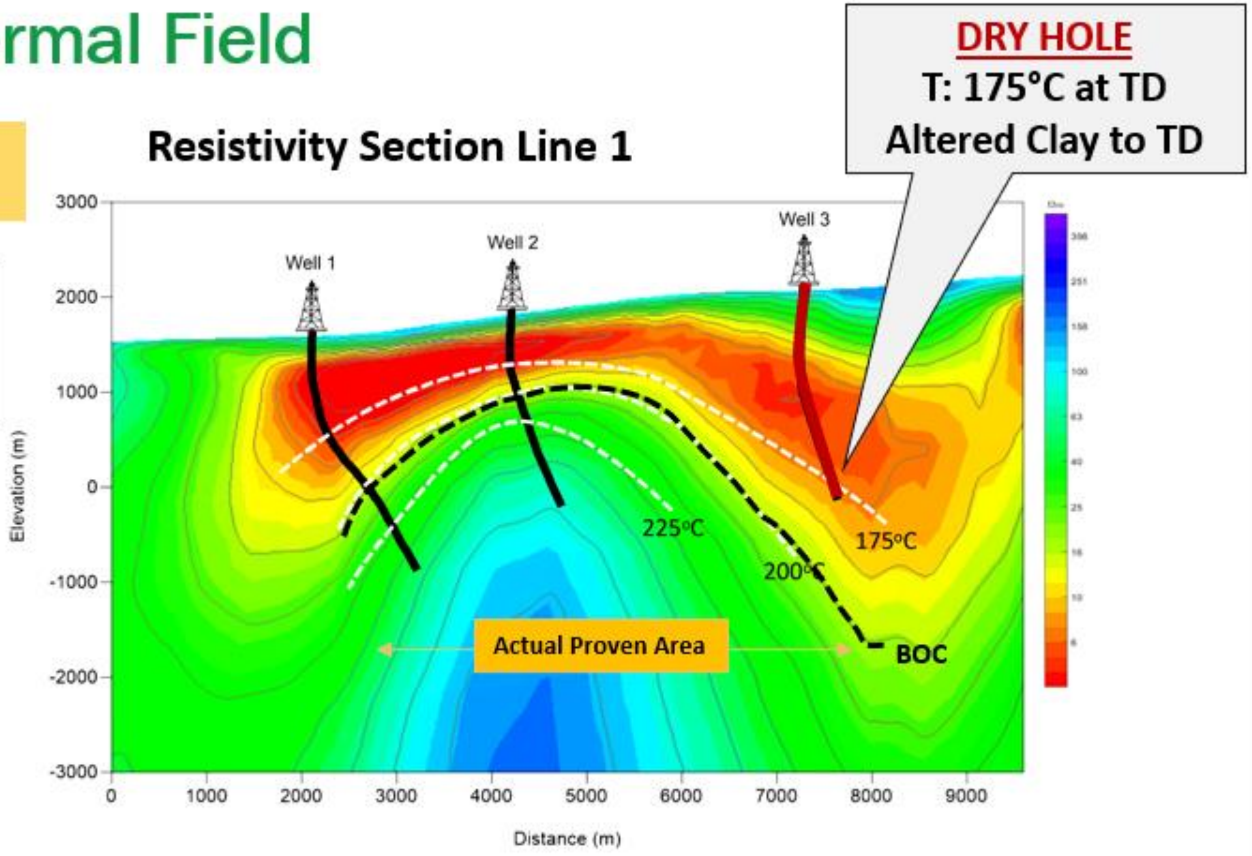


The MT Model give incorrect prospect area and has contradiction with drilling data & Reservoir Simulation result

After Reprocessing & Remodelling of MT Data

1st Geothermal Field

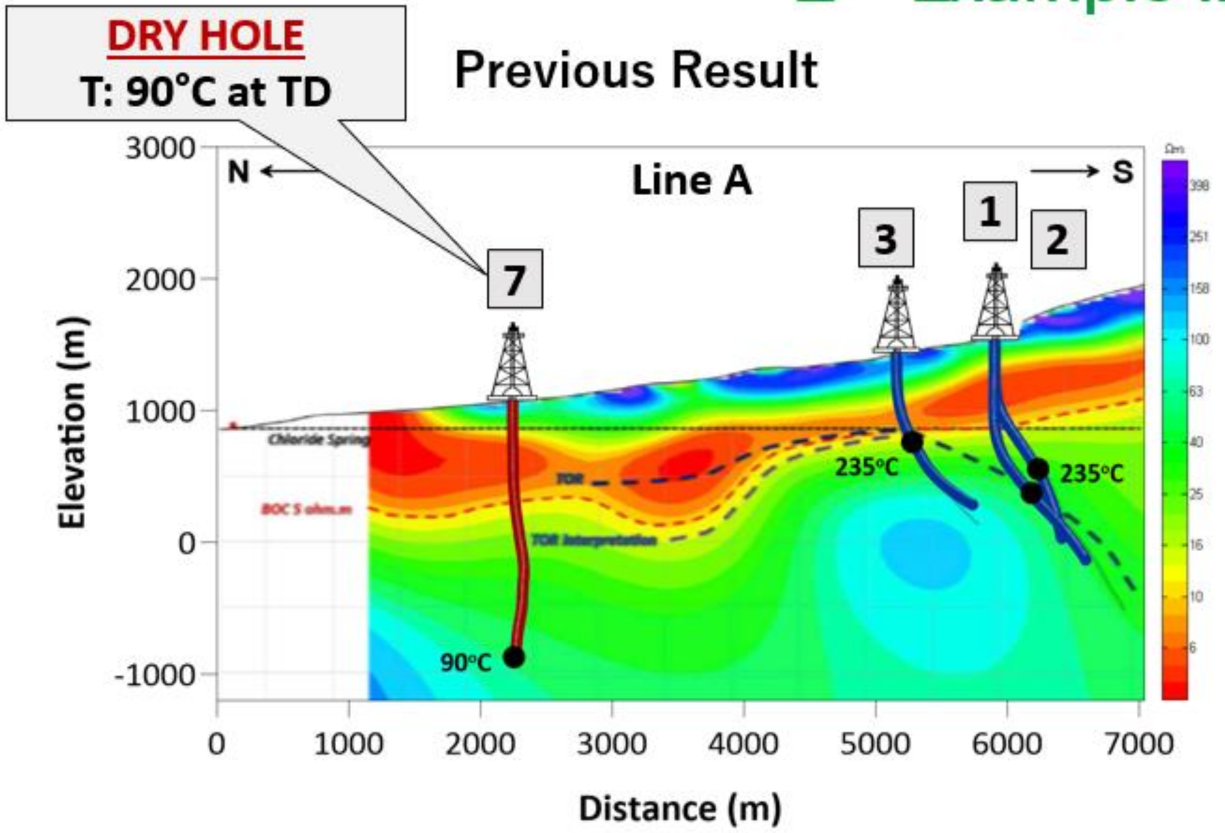


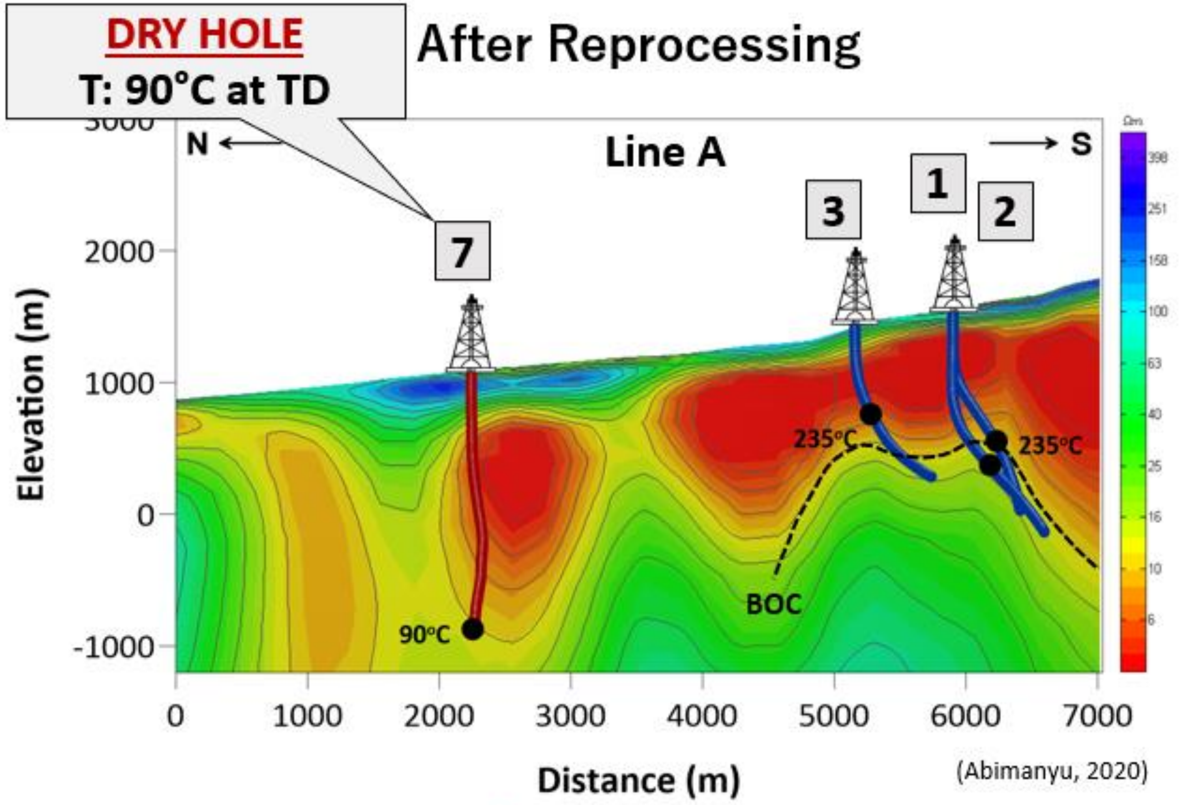


New MT model has good agreement with all drilling data

After Reprocessing & Remodelling of MT Data

2nd Example in West Sumatera





(Abimanyu, 2020)

Disagreement between Base of Conductor (BOC) and Actual Top of Reservoir (TOR)

New MT model has good agreement with TOR from drilling data as well as thickening of conductive layer in unsuccessful well

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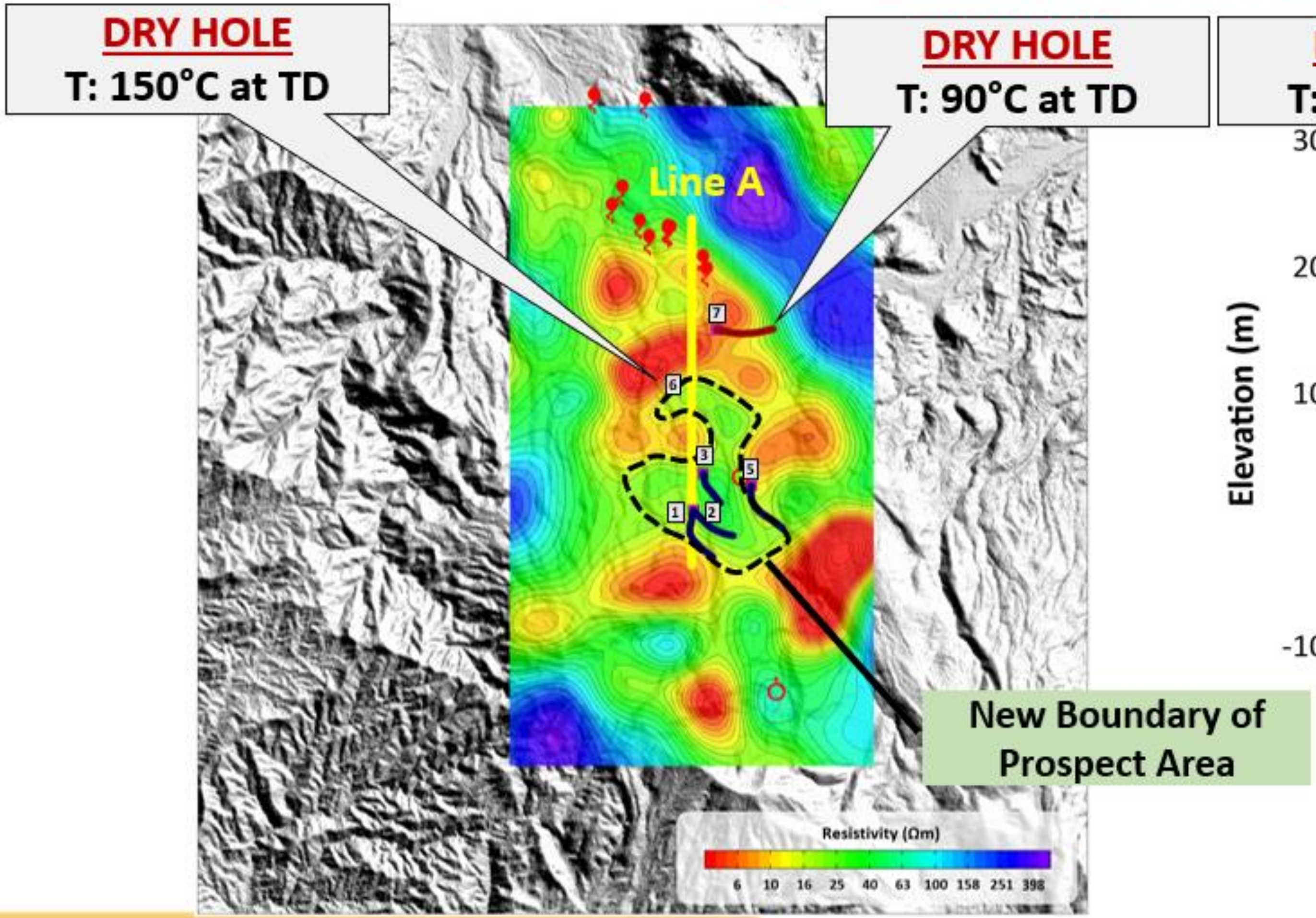
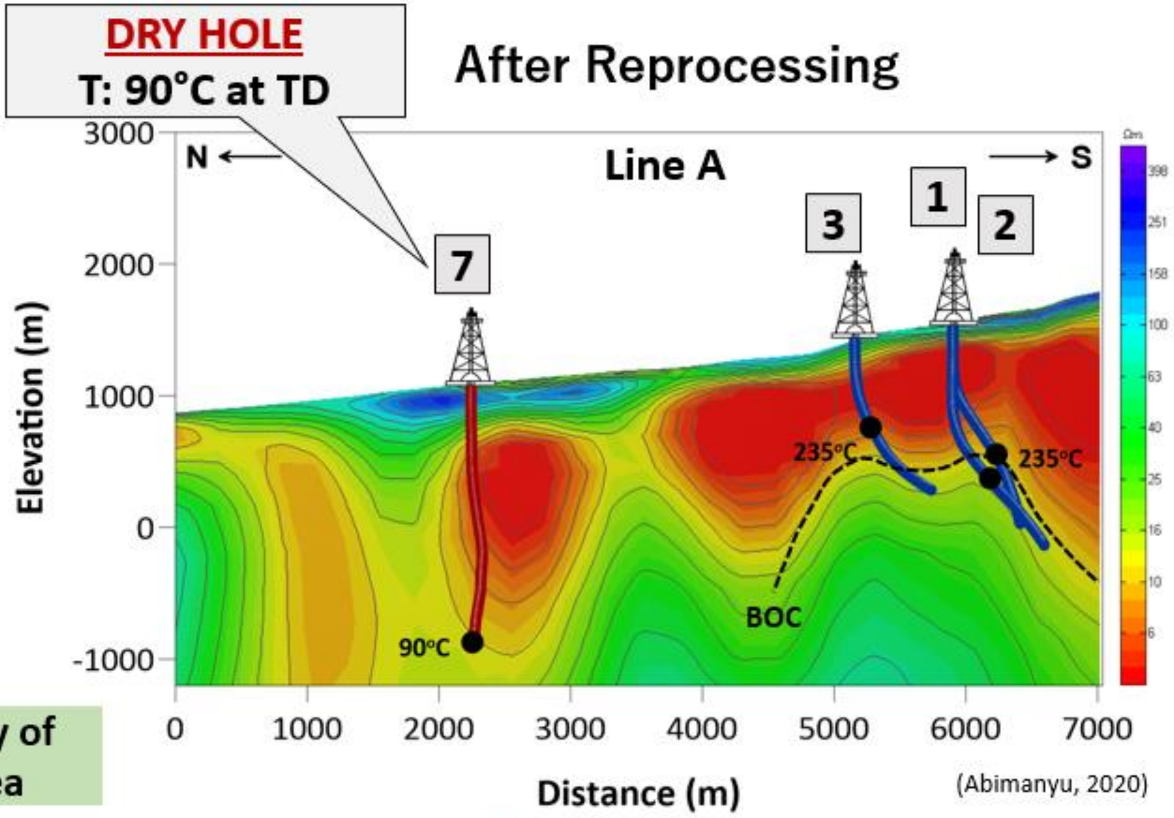
After Reprocessing & Remodelling of MT Data

2nd Example in West Sumatera





New MT model has **good agreement** with TOR from drilling data as well as thickening of conductive layer in unsuccessful well

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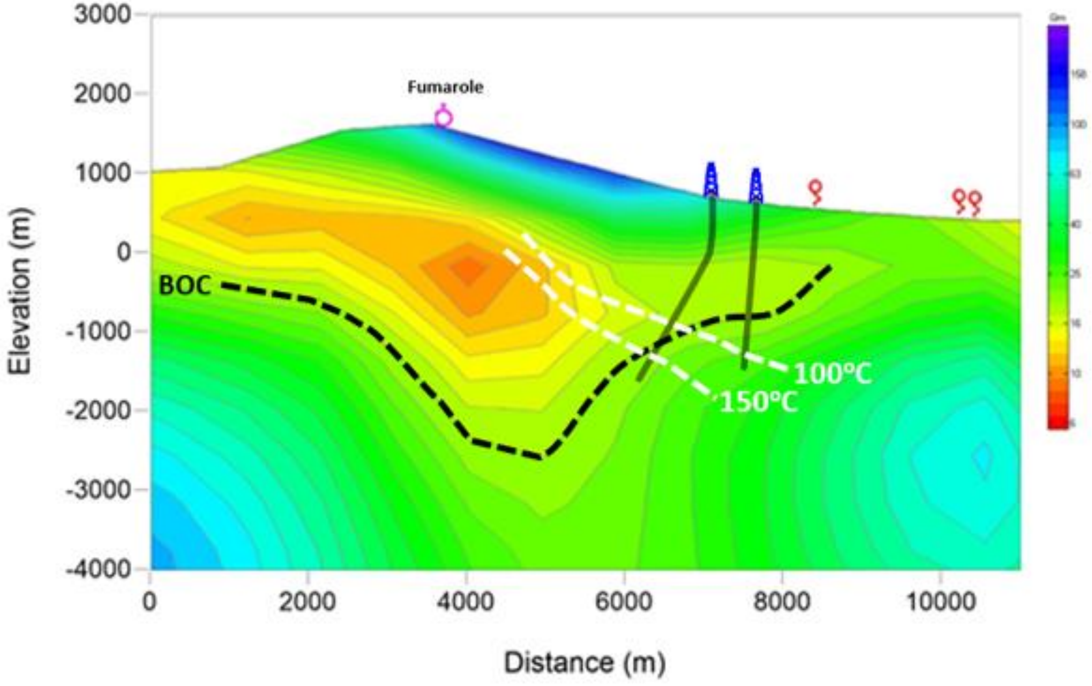
After Reprocessing & Remodelling of MT Data

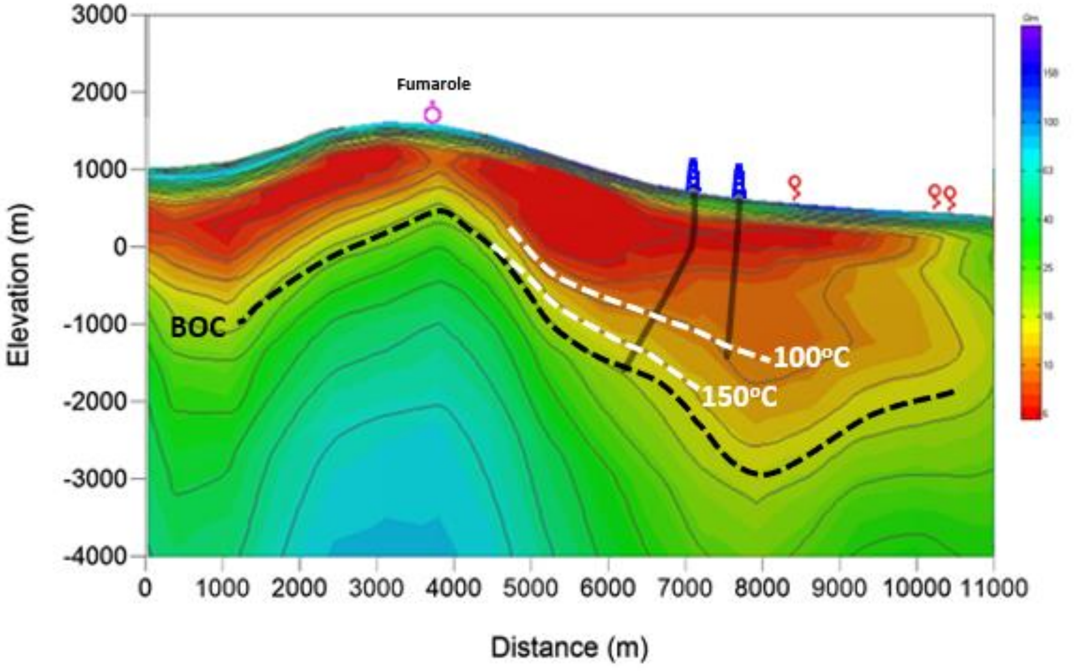
3rd Example in North Sulawesi

Previous Result



3D MT model is contradictive with well data

After Reprocessing



New 3D MT model has good agreement with well data

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MT APPLICATION IN THE CHALLENGING “HIDDEN” GEOTHERMAL RESERVOIR

- Overview of the Geothermal Field – Geological & Geochemical Background

10 Years of Contributions

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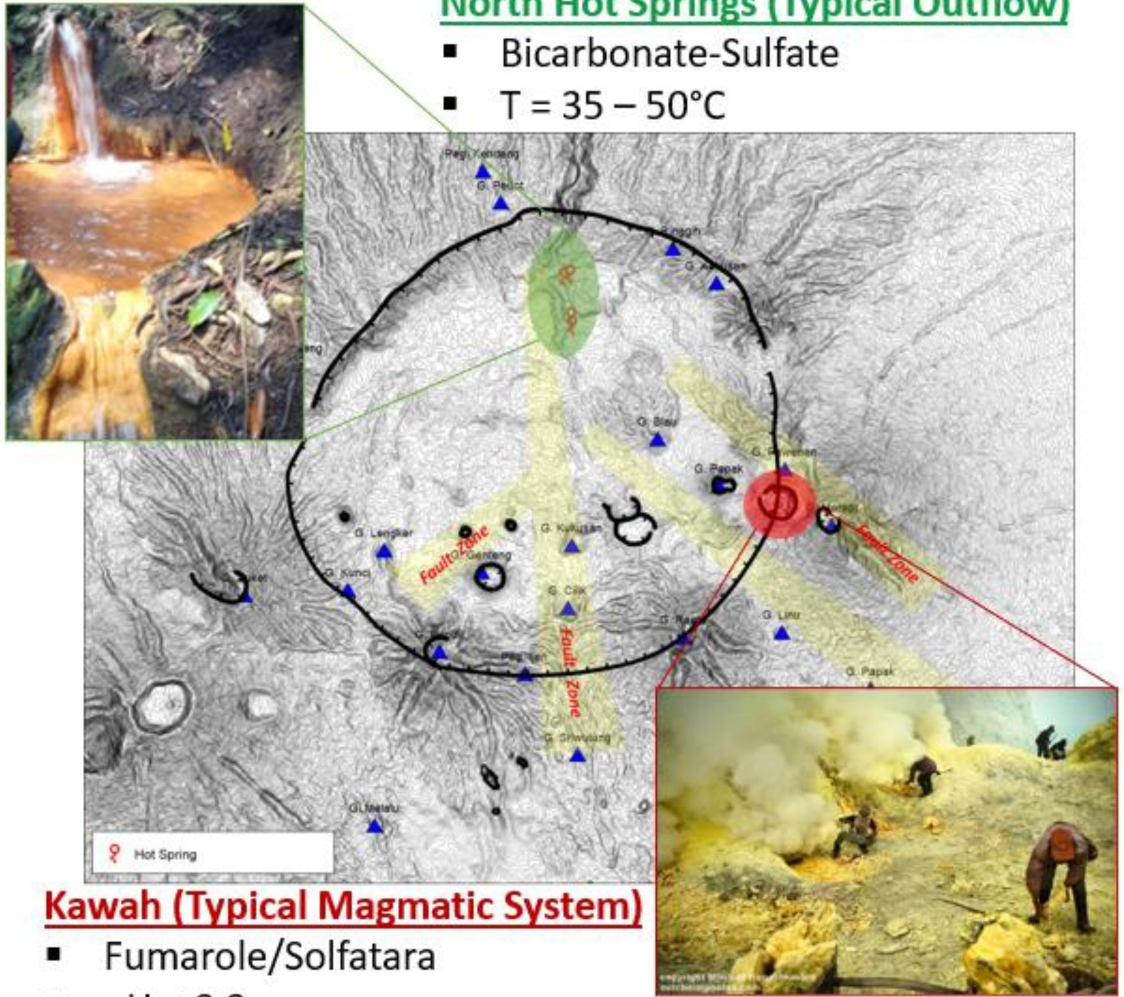
Overview of the Geothermal Field – Geological & Geochemical Background

- ❑ The geothermal area is located inside **a big caldera (about 15 km diameter) and covered by thick lava**, so indication of geological structure in the surface is **challenging (hard to observe)**. So, **remote sensing data** should be optimized **for identifying the geological structures (and then permeable zone).**

- ❑ Furthermore, the presence of geothermal system is only characterized by **unimpressive surface manifestations** in the northern caldera margins (low T bicarbonate hot springs with travertine deposition). Such **immature water** could not be utilized for temperature assessment. So, **geochemistry doesn't work.**



North Hot Springs (Typical Outflow)
- Bicarbonate-Sulfate
- T = 35 – 50°C

Kawah (Typical Magmatic System)
- Fumarole/Solfatara
- pH < 0.3

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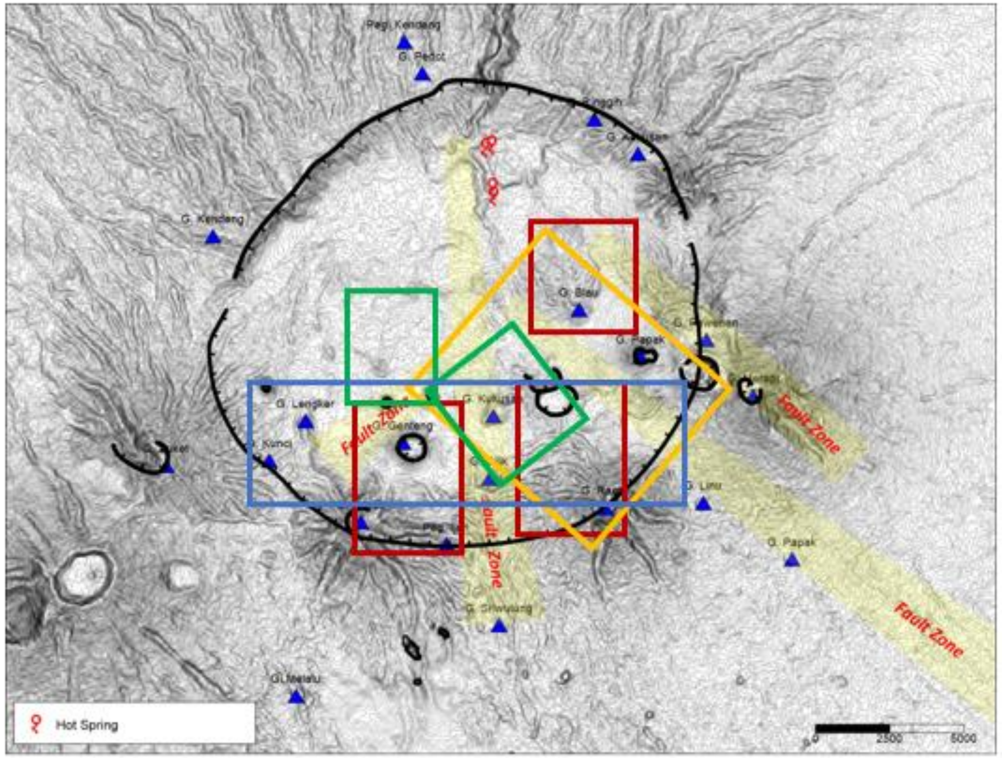
Overview of the Geothermal Field – Geological & Geochemical Background

- Based on the conditions, **MT data is the only "tool"** to reveal the subsurface **"well target zones" (high T & high K).** However, the results of MT studies conducted by previous several works showed **different well target zones**.
- **So, the company was confused to decide the right place for exploration drilling.**
- **<u>How to solve this problem?</u>**
  - ***<u>Remote Sensing</u> studies for delineating geological structure & permeable zones***
  - ***Reprocessing of the <u>existing raw (time series)</u> MT data, then doing 3D inversion***



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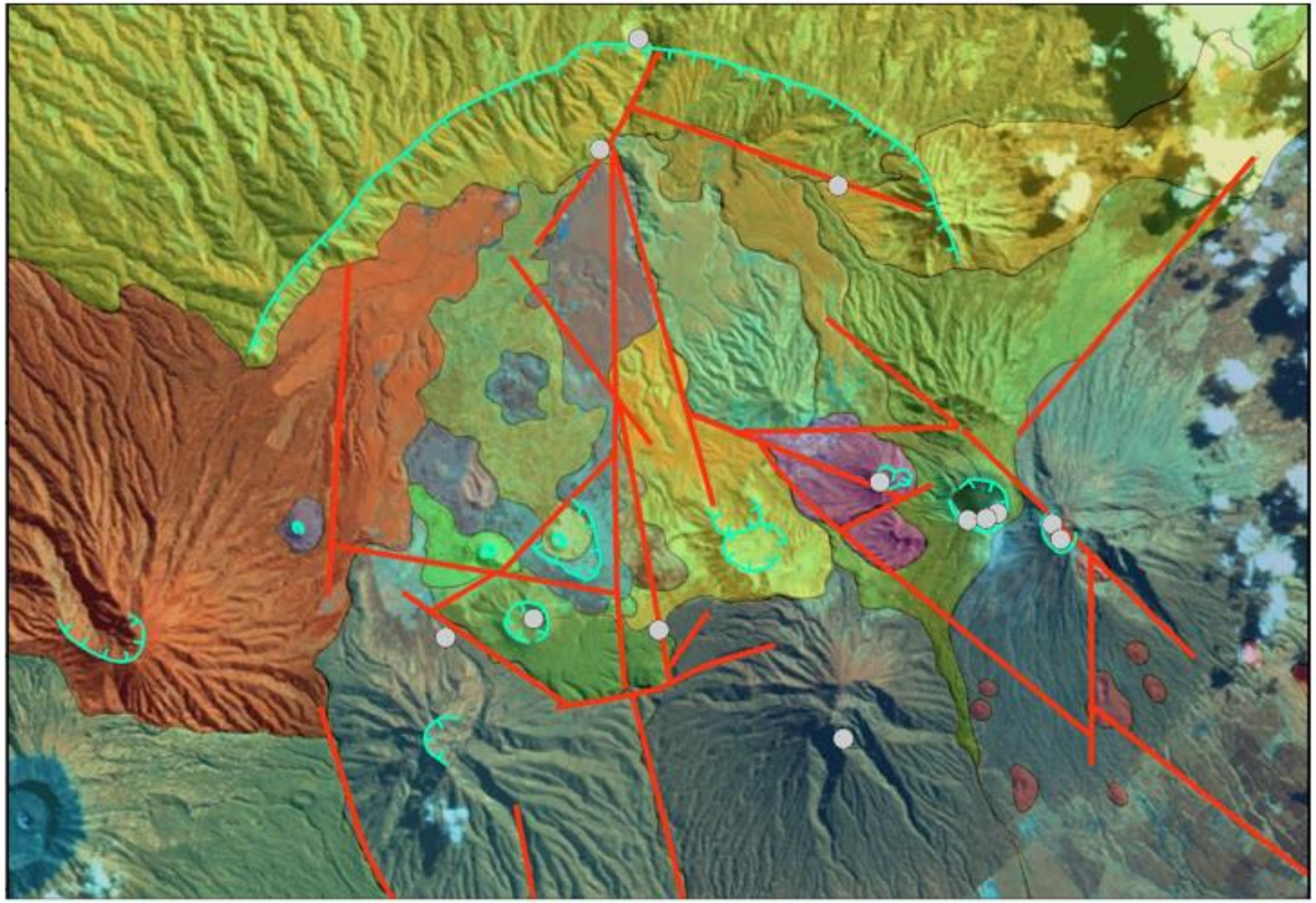
Remote Sensing Data Interpretation

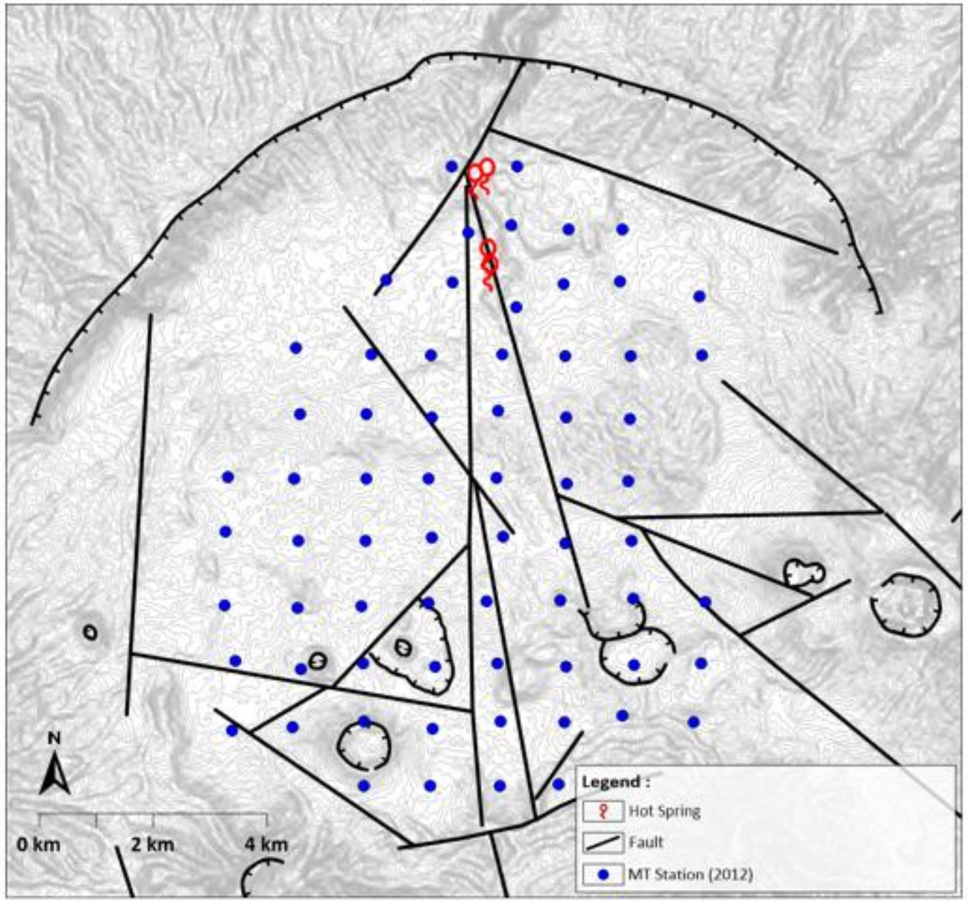


- ❑ Remote Sensing data for identifying possible altered grounds.
- ❑ Remote Sensing data for delineating surface lithology based on observation of lithological unit and possible eruption center.
- ❑ Remote Sensing data for delineating surface geological structures (caldera margins and fault structures).
- ❑ Geological Map based on Remote Sensing data interpretation.

MT Data Reprocessing & 3D Inversion

STEPS CONDUCTED:

- Reprocessing of the existing raw (time series) MT data, resulting 98% Good to Excellent quality, with 2 Fair quality data.



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MT Data Reprocessing & 3D Inversion

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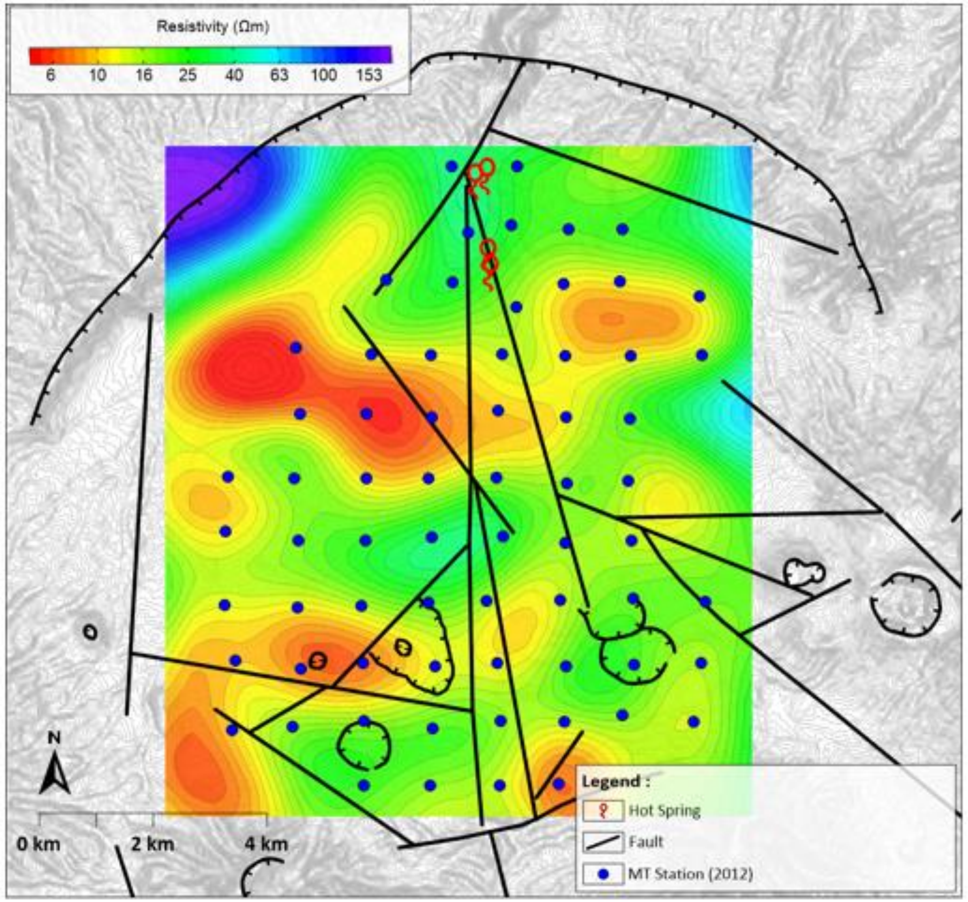
- Reprocessing of the existing raw (time series) MT data, resulting 98% Good to Excellent quality, with 2 Fair quality data.
- Doing 3D Inversion of the reprocessed MT data



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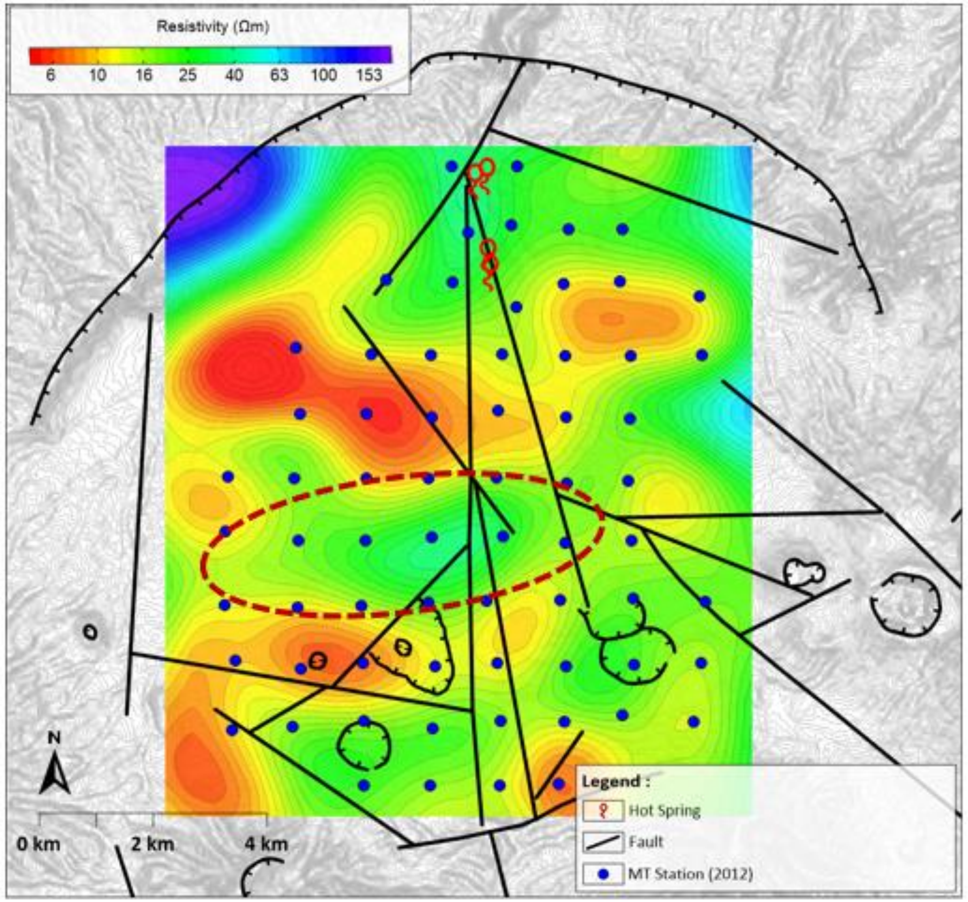

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MT Data Reprocessing & 3D Inversion

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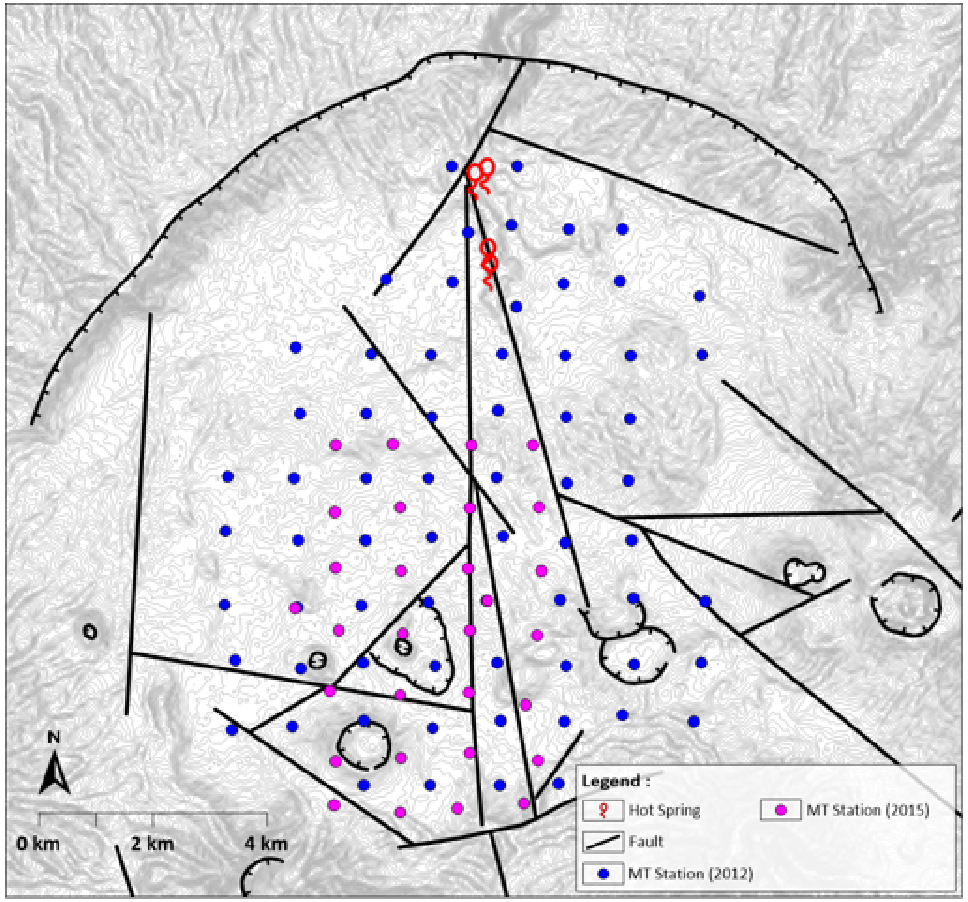
- Doing 3D Inversion of the reprocessed MT data
- Discovering an indicated prospect zone in the center of the survey area
- Conducting additional MT data acquisitions to "infill" the MT data distribution as well as re-sounding 2 Fair quality MT data within the prospect zone ➔ **to ensure the "reservoir zone".**



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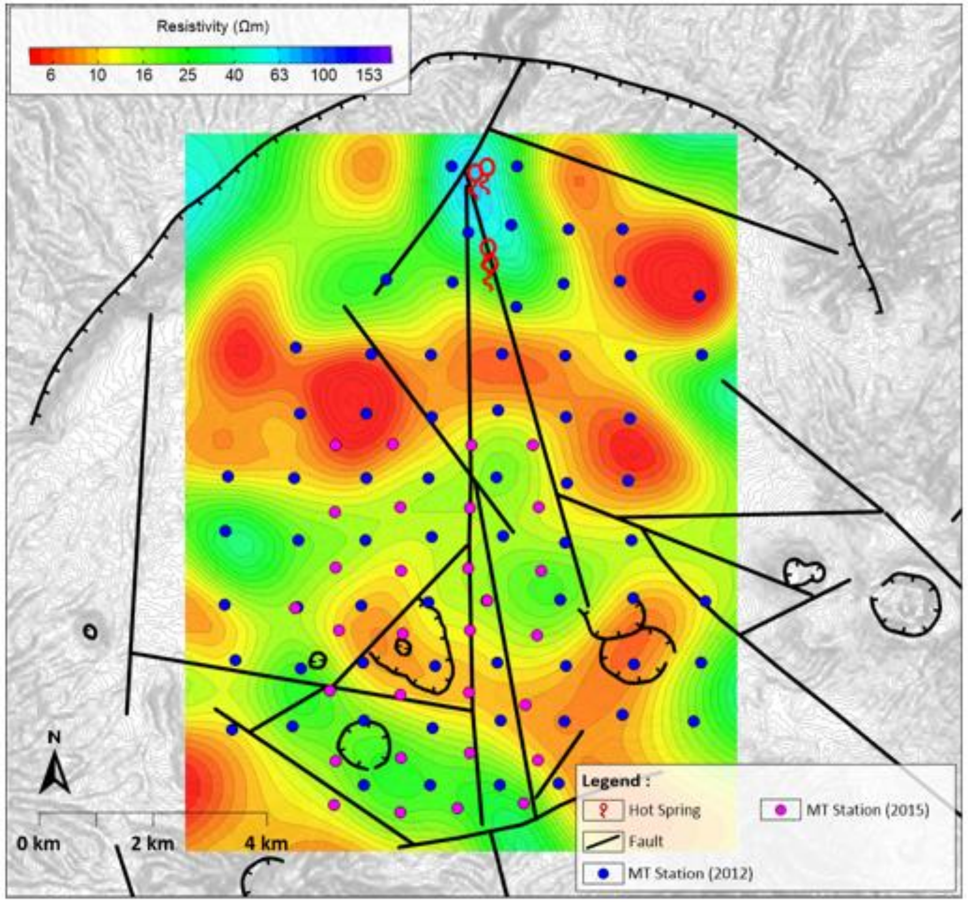
- Updating 3D Inversion for both existing & new MT data



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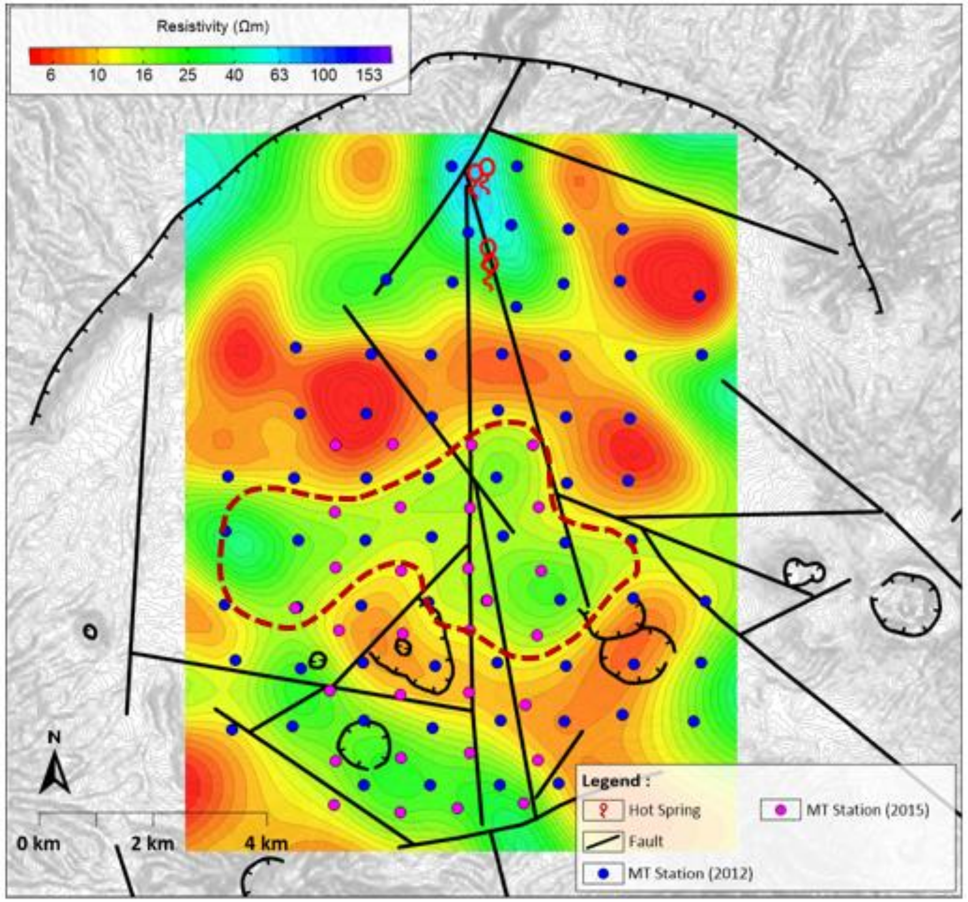
- Updating 3D Inversion for both existing & new MT data
- Delineating the main prospect zone



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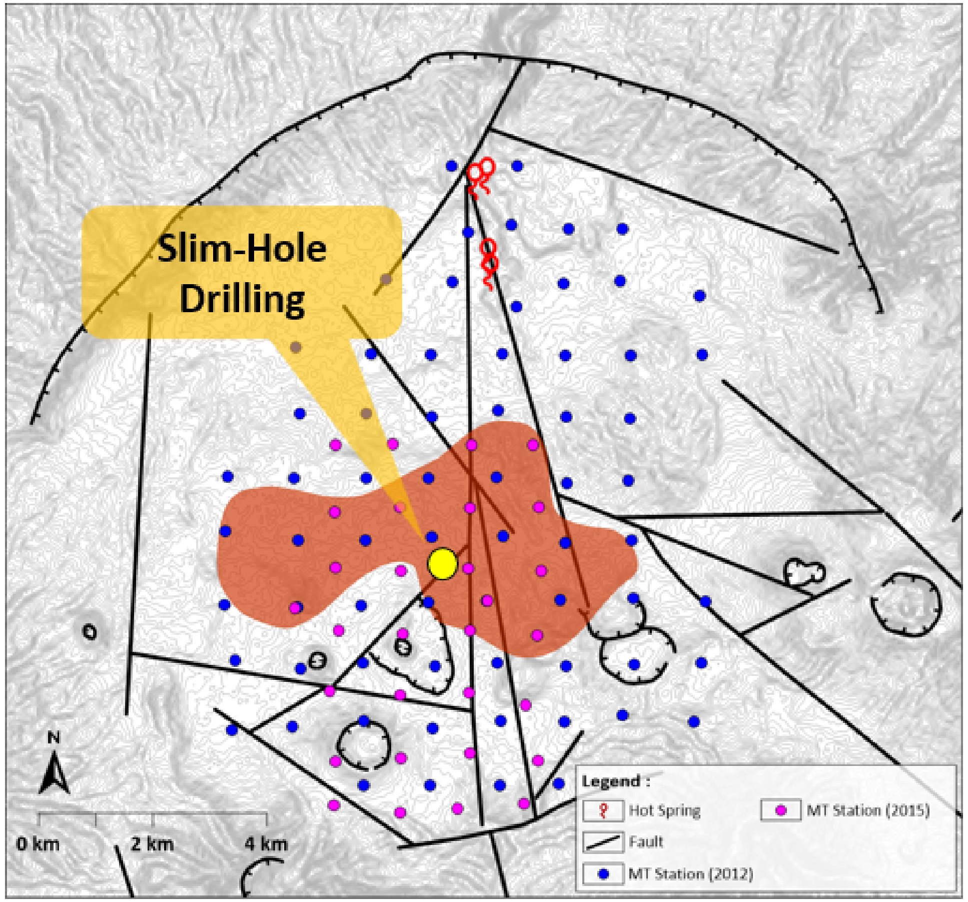
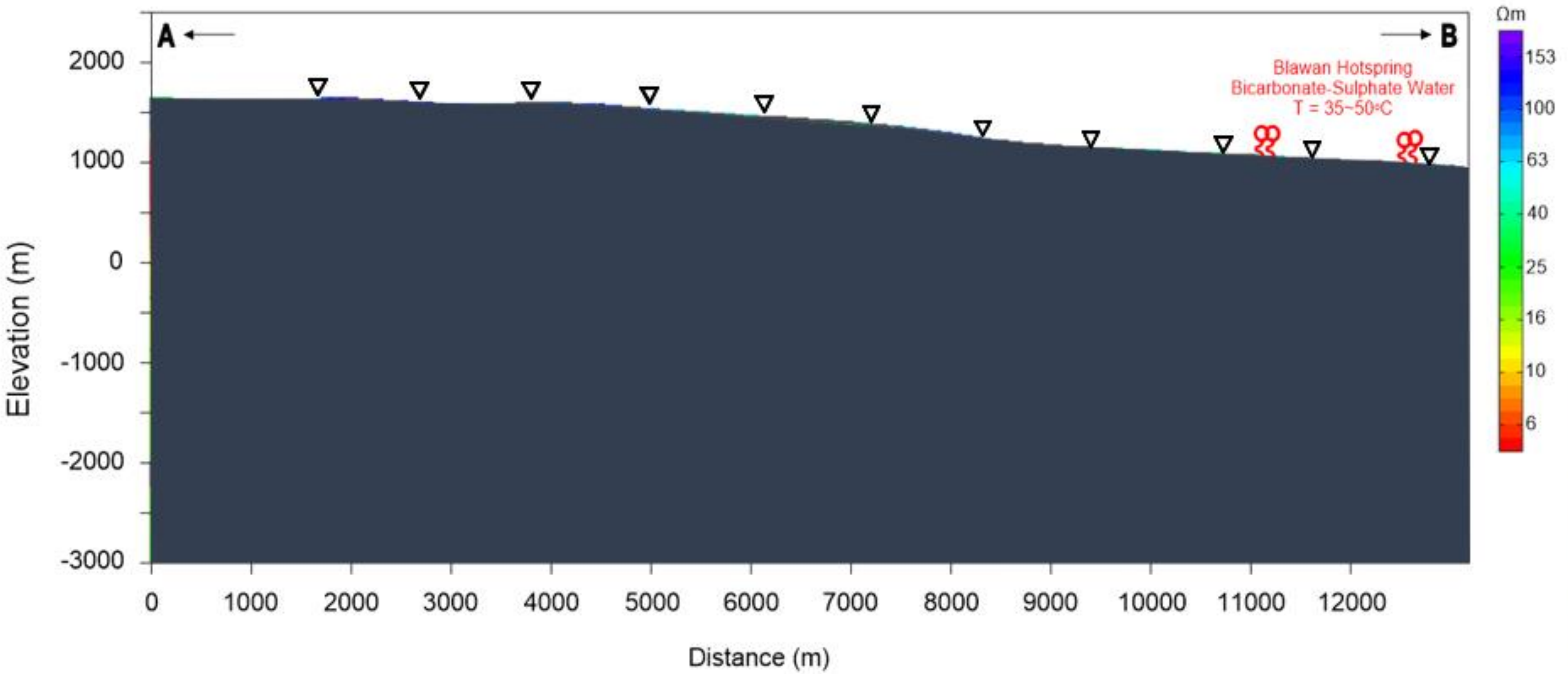
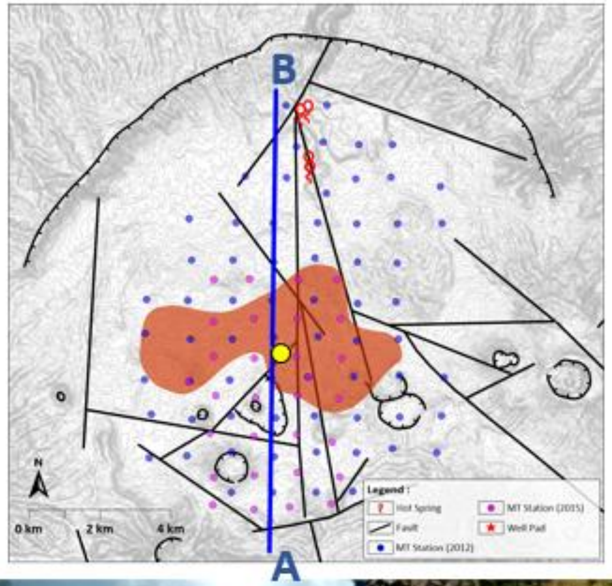
- Updating 3D Inversion for both existing & new MT data
- Delineating the main prospect zone
- Recommending **"slim-hole" drilling to prove the "reservoir zone".**



Successful Drillings Guided by MT Technology in A "Hidden" System





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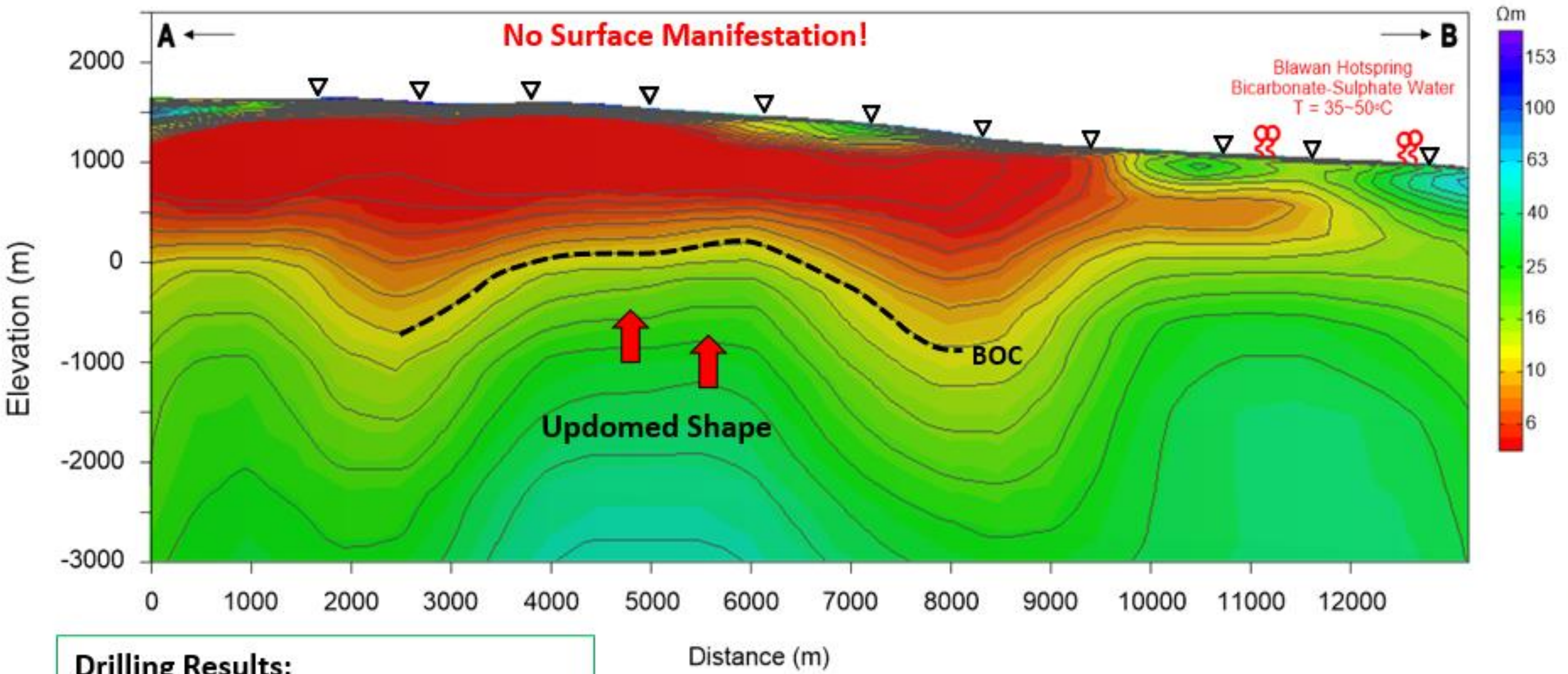
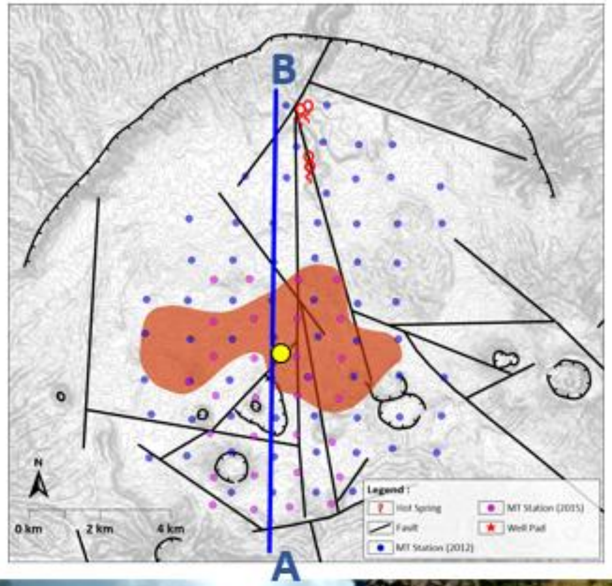
Successful Drillings Guided by MT Technology in A "Hidden" System





Drilling Results:

- Total Depth (TD) = 2000 meter
- Temperature @TD = 291°C
- Neutral Fluid

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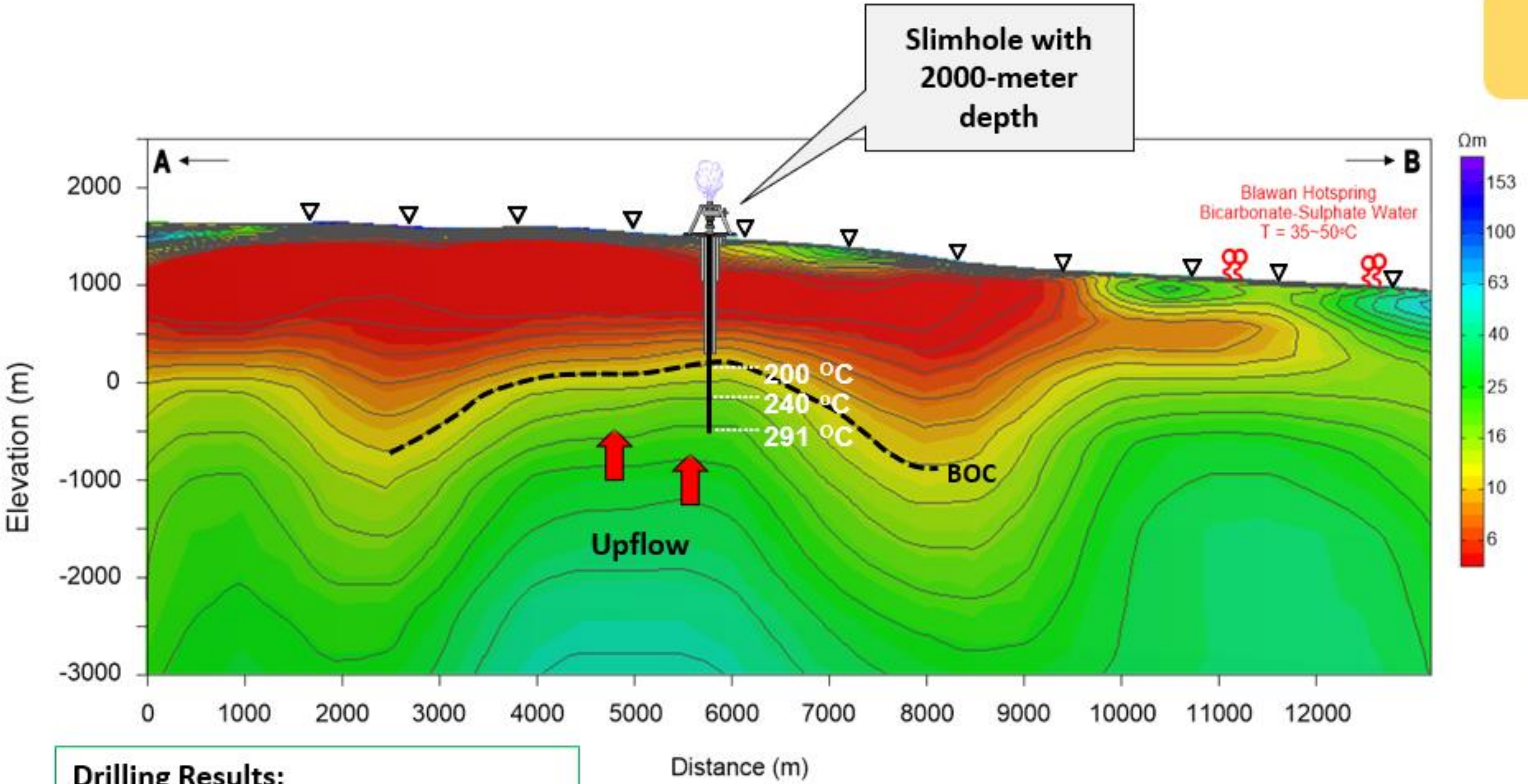
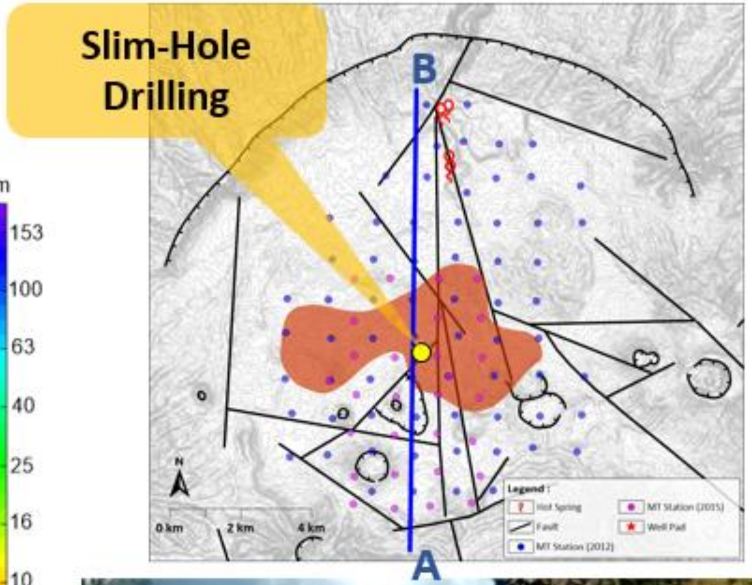
Successful Drillings Guided by MT Technology in A "Hidden" System





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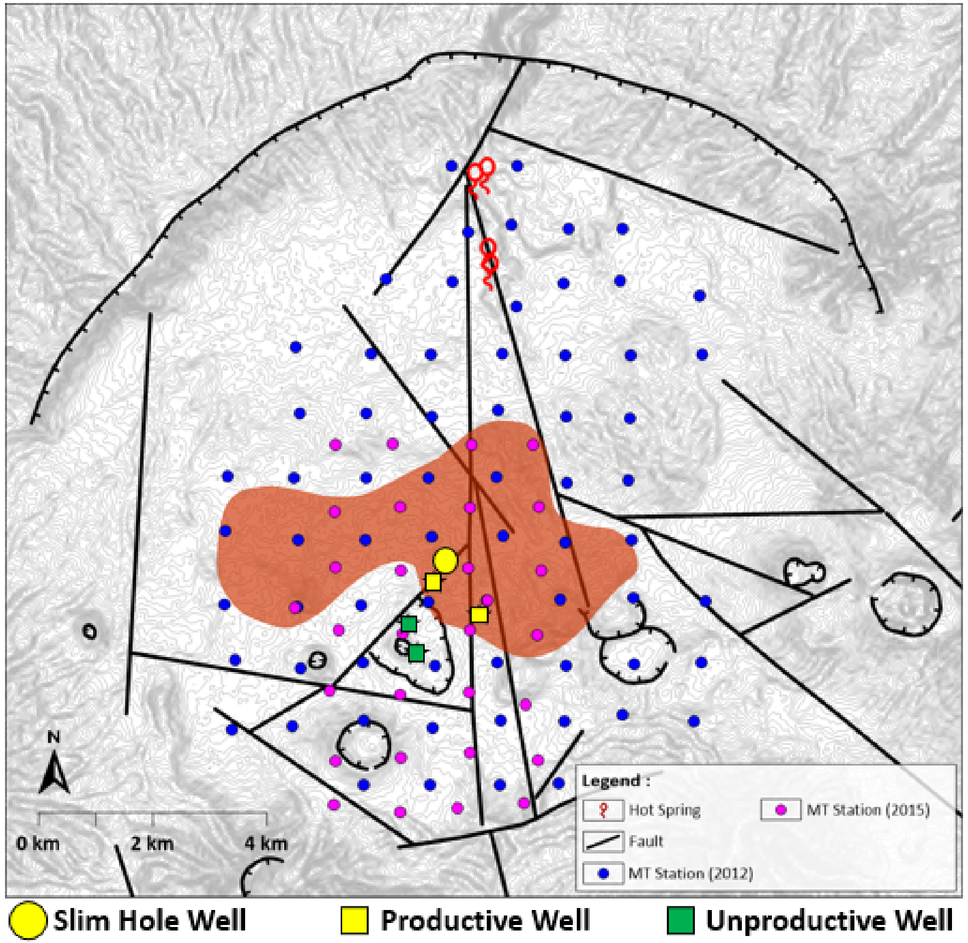
After Reservoir Confirmation based on Slim Hole Drilling

- During the field development phase, there was a change in the field development approach in line with the management change.
- The MT data was reprocessed, remodeled, and reinterpreted by **other parties**. Then, **four wells were recommended based on that works.**
- Two wells were reported to be **successful**, but the other two unfortunately were **unsuccessful**.
- After conducting independent-evaluation, we found that the overall drilling results show good correlation with our **MT Model (Prospect Area)**.
- Two wells **(yellow square)** drilled **inside** the delineated **prospect area show productive high temperature result.**
- While the other 2 wells (**green square)** drilled **outside our prospect area**, show **unproductive** result.



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VALUABLE LESSONS LEARNED FROM MT APPLICATIONS IN INDONESIA

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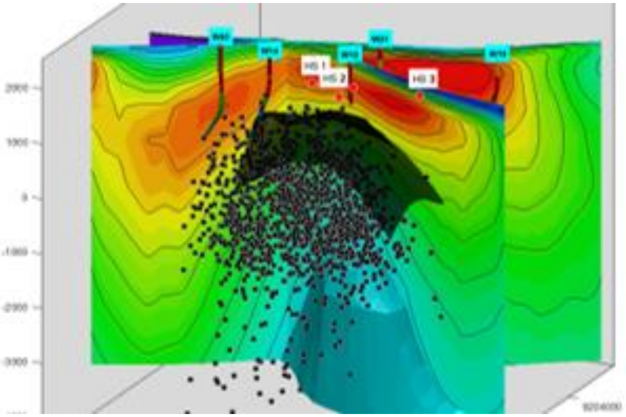
VALUABLE LESSONS LEARNED FROM MT APPLICATIONS IN INDONESIA

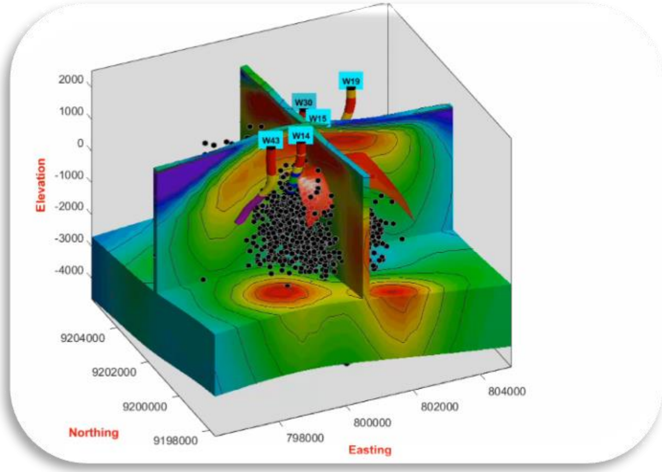
- **Magnetotelluric (MT) imaging** is a powerful technology to reconstruct a **geothermal system model** based on **resistivity distribution** to guide **in locating drilling target**
- Since Indonesia is blessed with huge geothermal resources, **MT technology has big opportunity** to be widely used and plays an important role in million-dollar decisions.
- However, **MT technology** must be used **carefully and properly**. **Incorrect use of MT technology** can lead to generate **pitfalls in MT model and geothermal conceptual model,** and finally **errors in determining drilling targets.**
- **Drilling data** both **successful and unsuccessful** is a tremendous asset that can be utilized **to evaluate the application of MT technology**.
- Further **improvement** should then be carried out **continuously** to get **better and more accurate MT technology**.
- Accordingly, we should be able to take many **lessons** from the **"MT vs Drilling"** journey by utilizing these **valuable drilling data** in order **to increase drilling success ratio**, especially in **the geothermal exploration stage.**

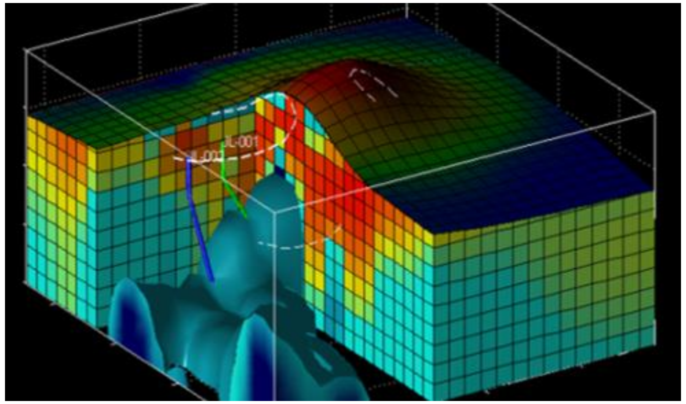
EMinars Series 2 MTNet 25 May 2022

THANK YOU

MAGNETOTELLURIC STUDIES FOR THE EXPLORATION OF GEOTHERMAL RESOURCES IN INDONESIA







Dr. Yunus Daud

Head of Geothermal Research Center, Universitas Indonesia & Founder of PT NewQuest Geotechnology

ydaud@sci.ui.ac.id or ydaud@newquest-geotechnology.com

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