King Fahd University of Petroleum
and Minerals - KFUPM
College of Petroleum Engineering
and Geosciences - CPG
Department of Geosciences

focusing on the energy transition with
emphasis on geothermal and reservoir
monitoring EOR

Fluid monitoring using joint EM and Seismic methods

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WHY do we present this !!

Carbonate reservoir characterization is challenging because,

- the reservoirs has **secondary porosity/fractures**
- seismic is challenged by high velocities.
- we want the **fluids** (oil, gas, brine, etc.)

Characterizing fractures needs permeability → necessity of directional sensitivity

INTEGRATING **surface** and **borehole** geophysical methods. M**icroseismic** with non-seismic (**electromagnetic - passive & active**) & **gravity** leads to fracture characterization & fluid flow direction

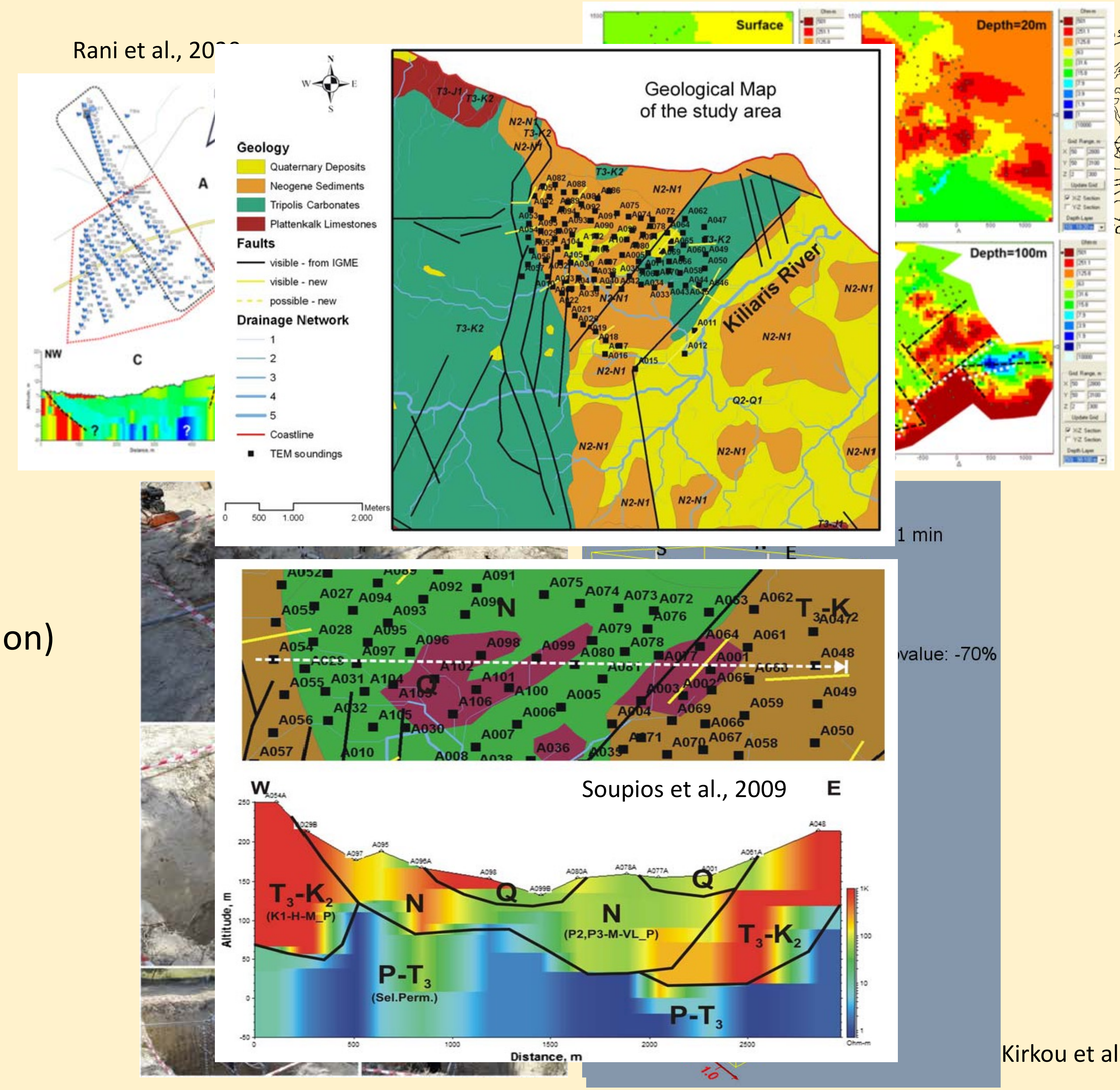
Seismic delineates **geometric boundaries**, EM gives **fluids** from resistive (hydrocarbons) to water (conductive). Gravity senses **density contrasts** between fluids, gas & rock matrix.

OBJECTIVES are:

- **to understand injected fluid (front) movement/distribution**
- **to depict flow pattern of fluids**
- **to define fluid interactions at reservoir level**
- **to build a reservoir static/dynamic model**

Overview

- Reservoir characterization/monitoring
  - Fractures
  - Fluids
  - Lithology
- Phases of work
  1. Feasibility study + noise test
  2. Proof-of-Concept (Data acquisition, Processing/Interpretation & Integration)
  3. Case histories (if 1 & 2 are positive)
- Instrumentation - KFUPM
- Examples, applicability, efficiency
- Conclusions

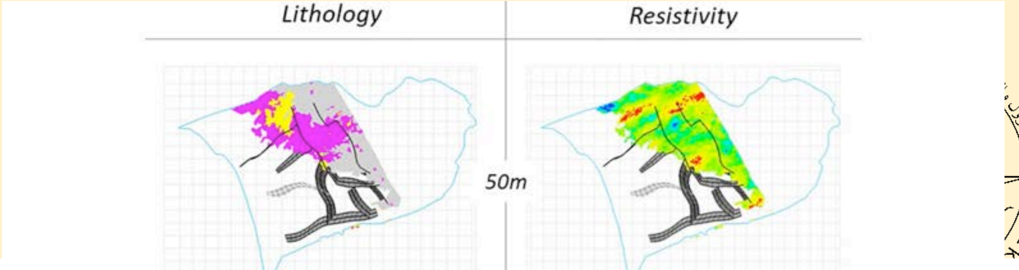


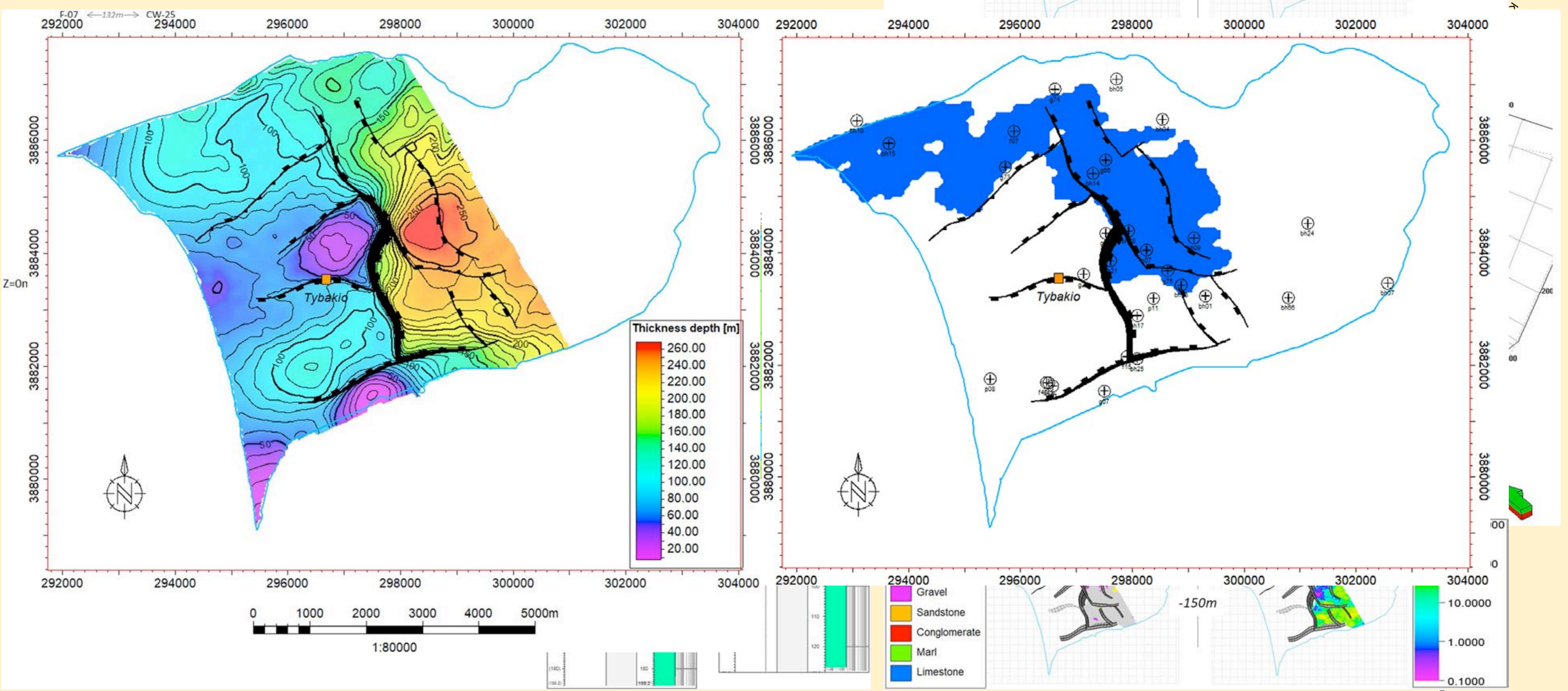
Rani et al., 20..

Soupios et al., 2009

Kirkou et al., 2022

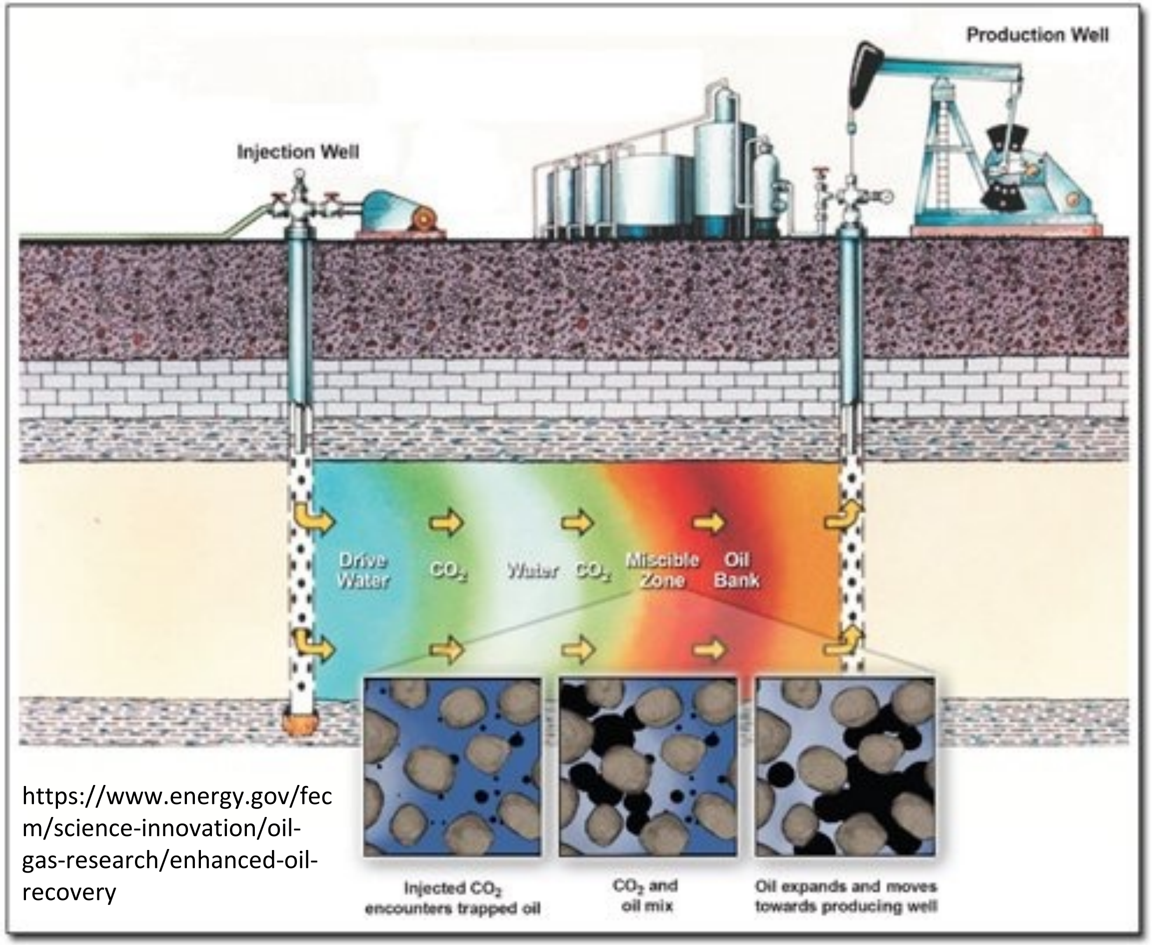
Reservoir characterization/monitoring





Panagopoulos et al., 2021

Phases of work (1)



https://www.energy.gov/fecm/science-innovation/oil-gas-research/enhanced-oil-recovery

During the EOR (WAG (Water Alternating Gas) (HC gas) or CO_2) → to **improve the flood mobility** → to **squeeze more oil** out of the reservoir (>recovery factor).

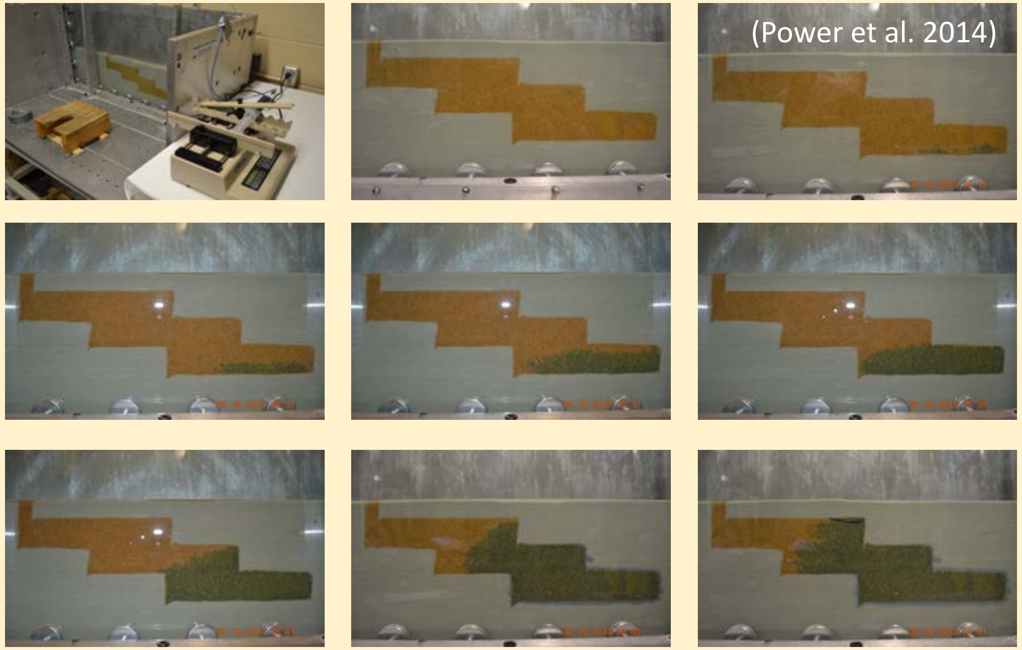
A <u>monitoring scheme</u> starts → **field characterization** (reservoir properties) → accurate **fluid mapping** (dynamic, ≈ 100 m/year)

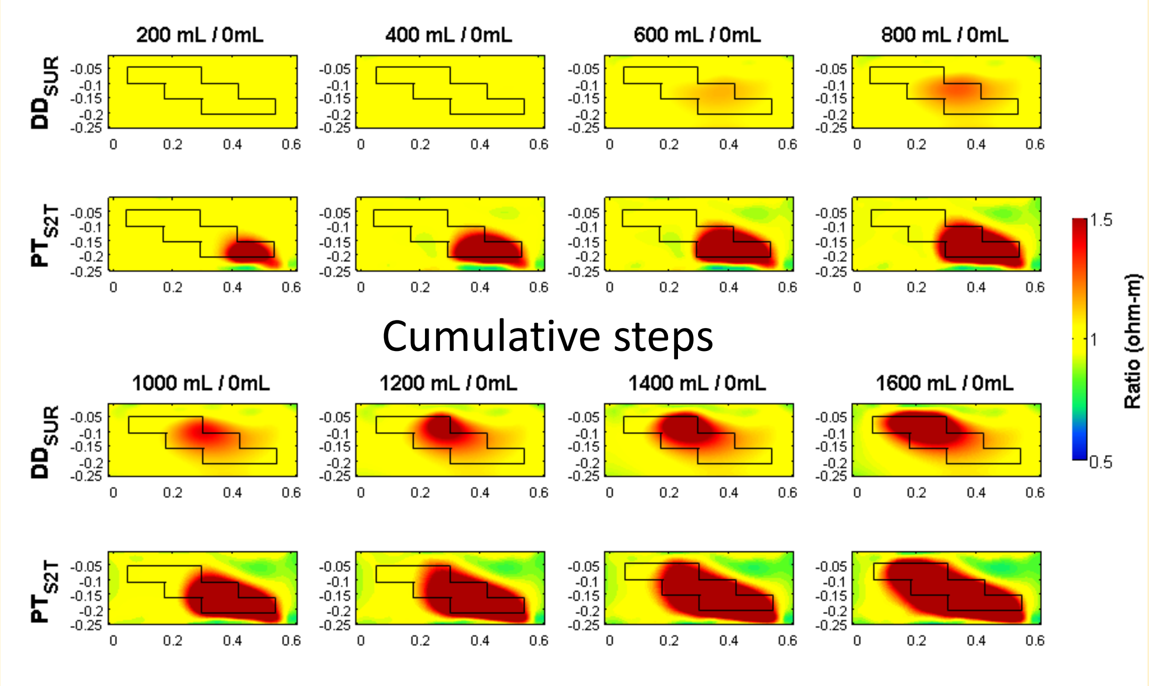
Before time-lapse monitoring (flooding), a **baseline is required (the initial model)**.

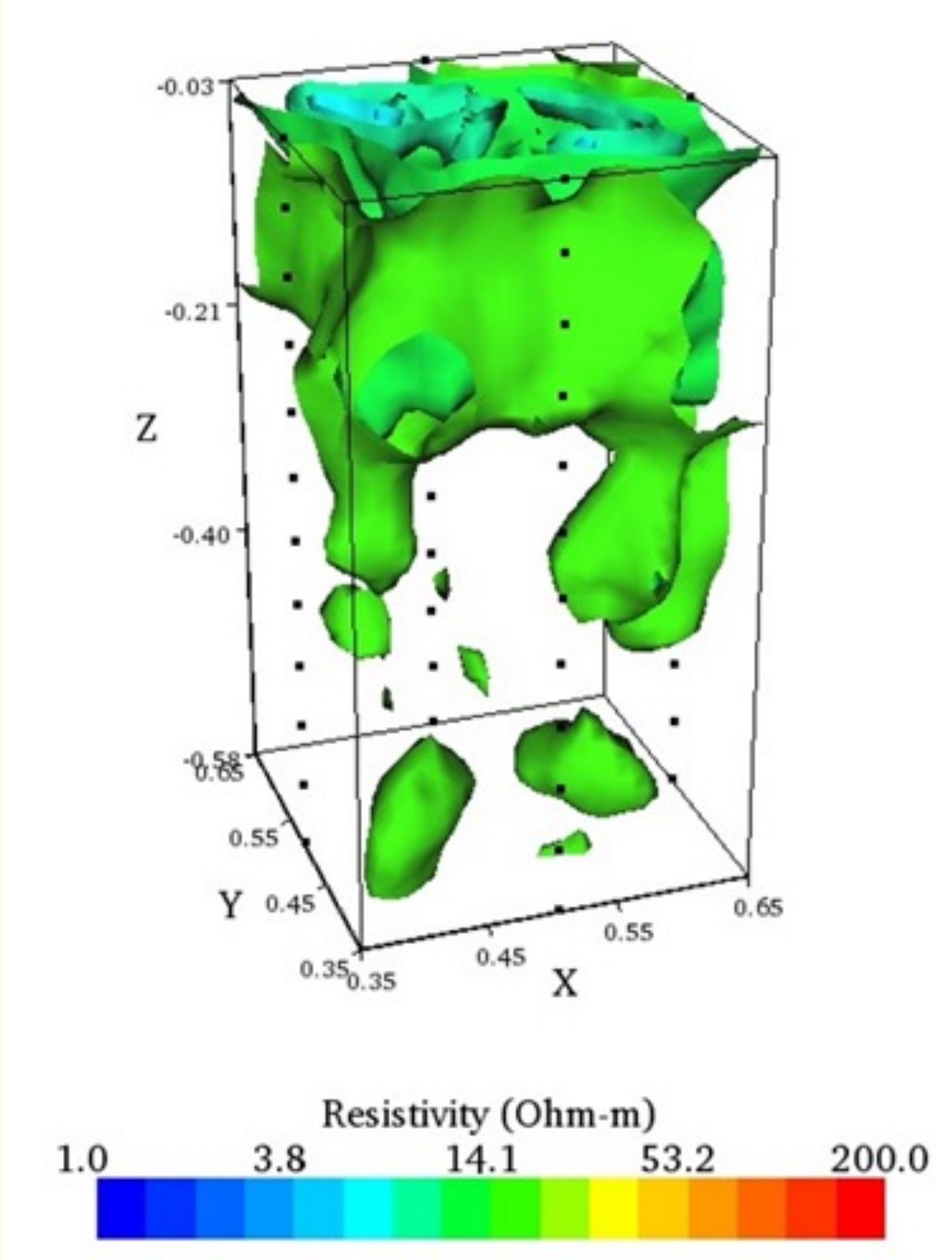
DETECT/MONITOR FLUIDS

Phases of work (2)

Baseline and Time-lapse images







(Seferou et al., 2011)

Phases of work (3)

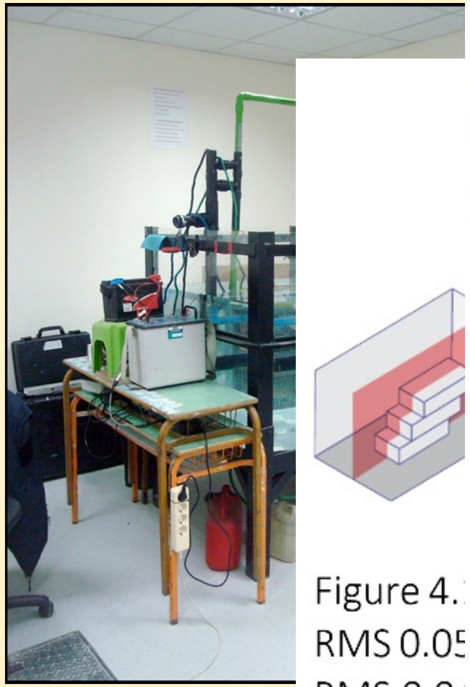


Figure 4.
RMS 0.05
RMS 0.04

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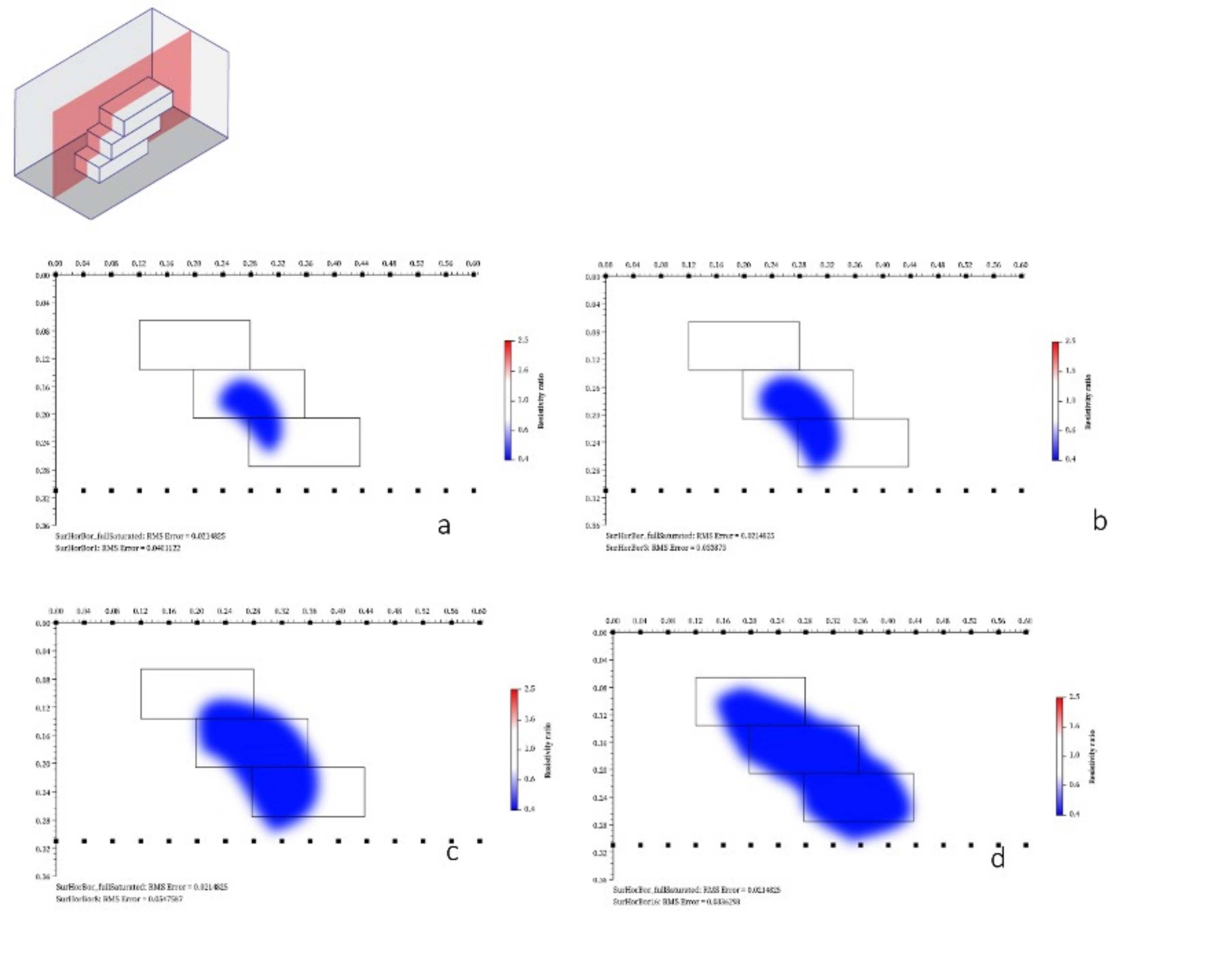


Figure 4.12: a) Time lapse ratio No T1/T0; b) Time lapse ratio No T3/T0; c) Time lapse ratio No T8/T0; d) Time lapse ratio No T16/T0.

(Kirkou et al., 2022)

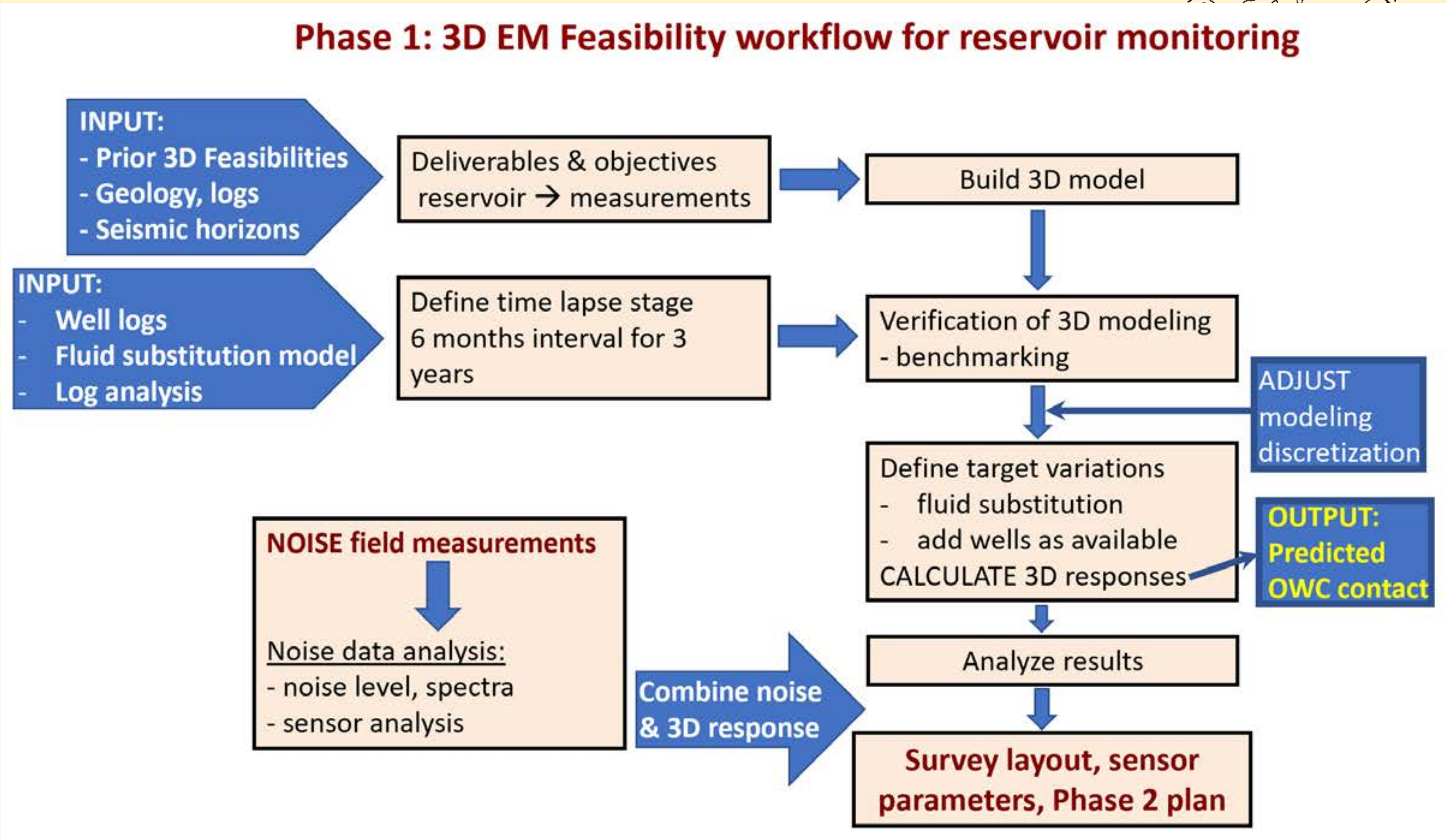
Phases of work (4)

Any project is divided into **3 phases**,

<u>Phase</u> **1**: **3D Feasibility**

a. <u>Tasks:</u> 3D modeling based on prior info (geology, logs, reservoir simulator, etc.)
b. <u>Deliverables:</u> 3D Feasibility (time-lapse), **On-site noise test**, **Proof-of-concept pilot plan/survey design**
c. <u>Milestones:</u> Measurable variation of **signal above the noise level**
d. <u>Break Point:</u> **Target response** (reservoir parameters' variation) cannot be extracted from noise test.

C and D are link Phase 1 and 2



Phases of work (5)

<u>Phase</u> 2:

Proof-of-concept - **Can we see reservoir parameter variations?**

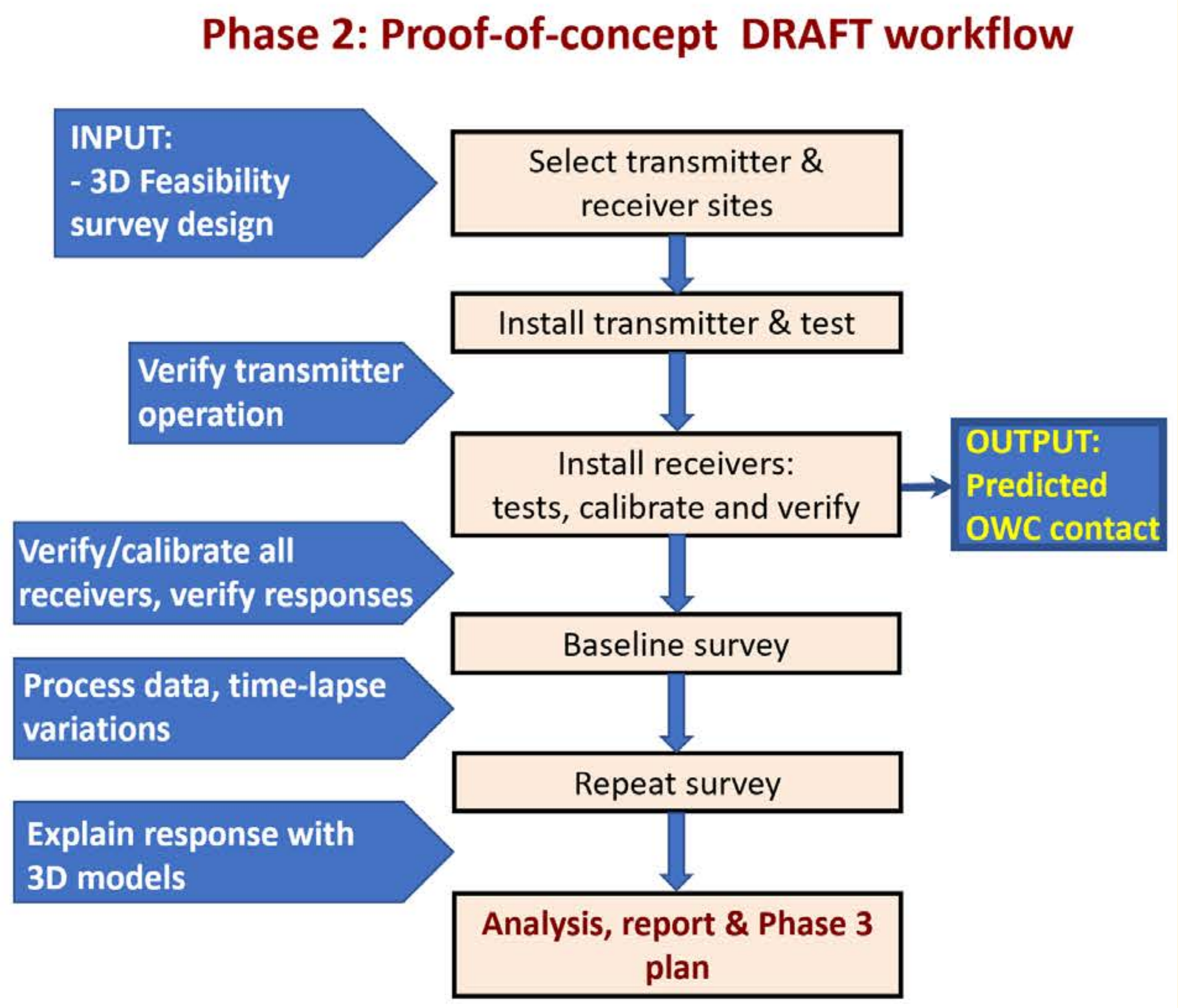
a. <u>Tasks:</u>
   i. **Test measurement during a single injection phase (baseline, post-injection)**, EM-continuous, Gravity – 2 surveys)

b. <u>Deliverables:</u> Survey data, data processing, time-lapse analysis

c. <u>Milestones:</u> We can see the reservoir's parameters variation in the individual datasets.

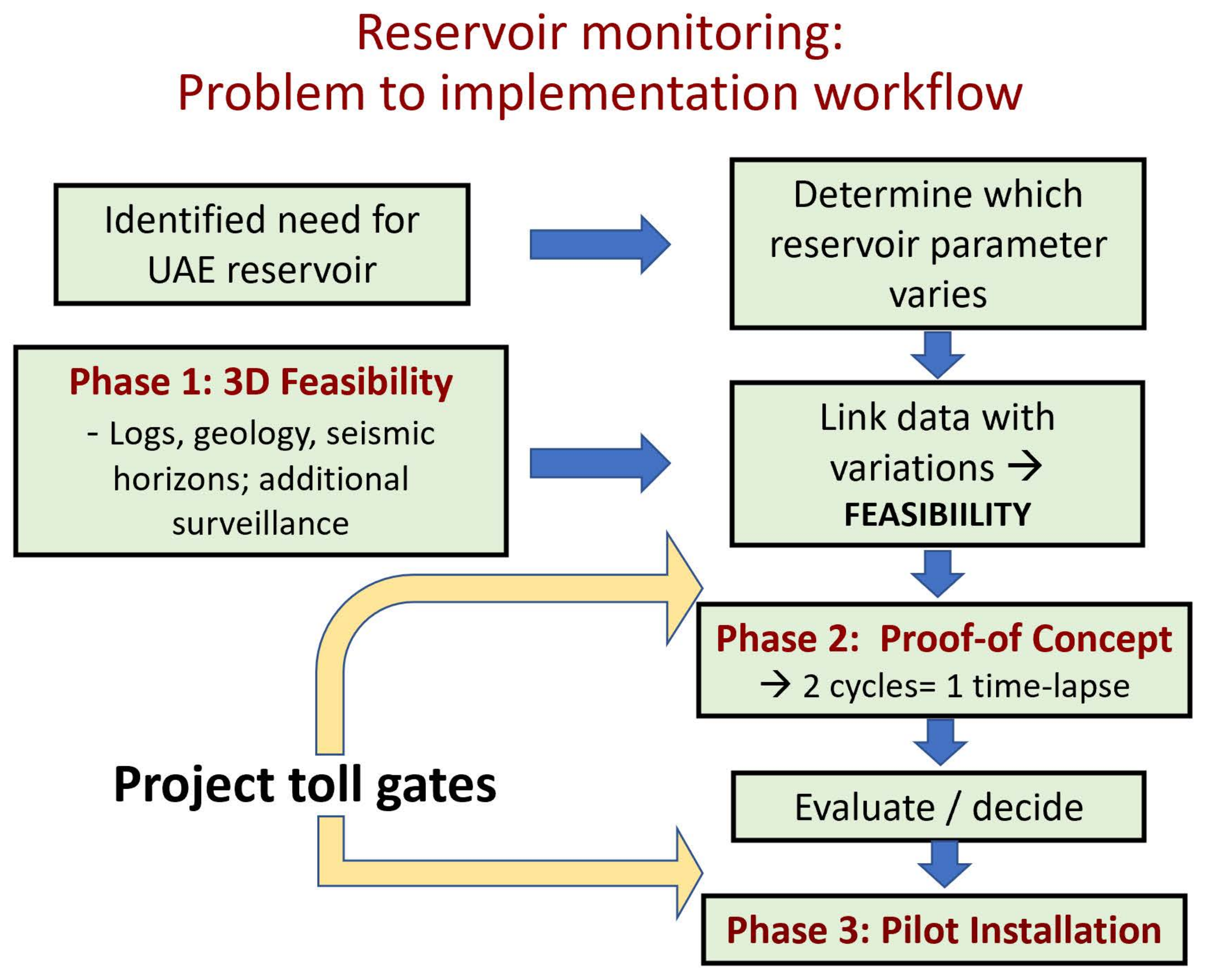
d. <u>Break Point:</u> There is limited variation of the geophysical responses with petrophysical variations

e. <u>Decision Point:</u> If results are positive, decide on field pilot within this project or a separate one .



Phases of work (6)

<u>Phase</u> 3: Field pilot study (if Phases 1 and 2 are positive)



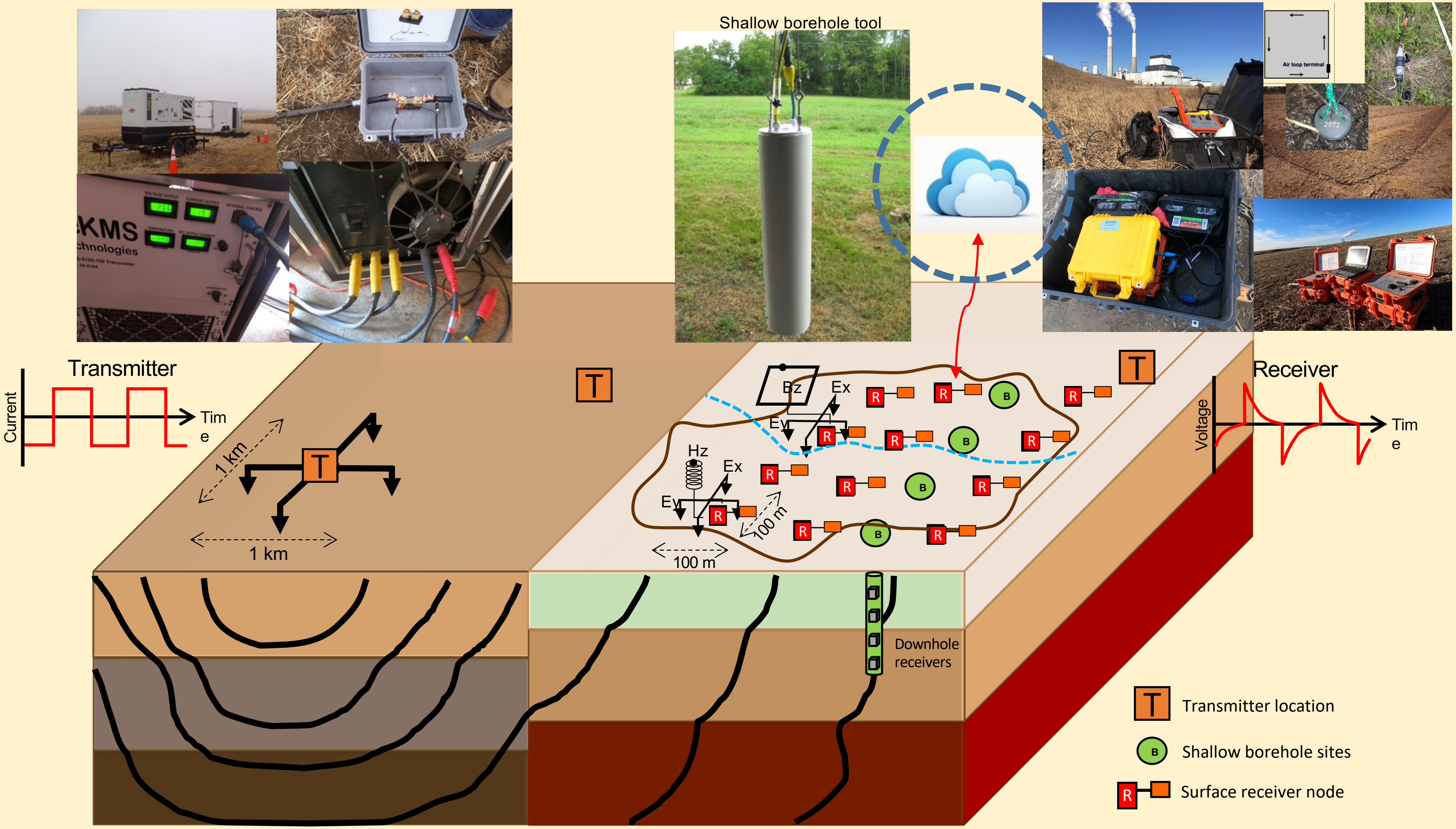
Instrumentation (1)

KFUPM CSEM system

A multi-function transmitter is ruggedized, portable, compact yet providing reliable maximum output power of **150 KVA** + **5 sets of sensors** (wireless). In additional to **Time domain** , it can do **Frequency domain** and **Time Frequency EM (TFEM)**

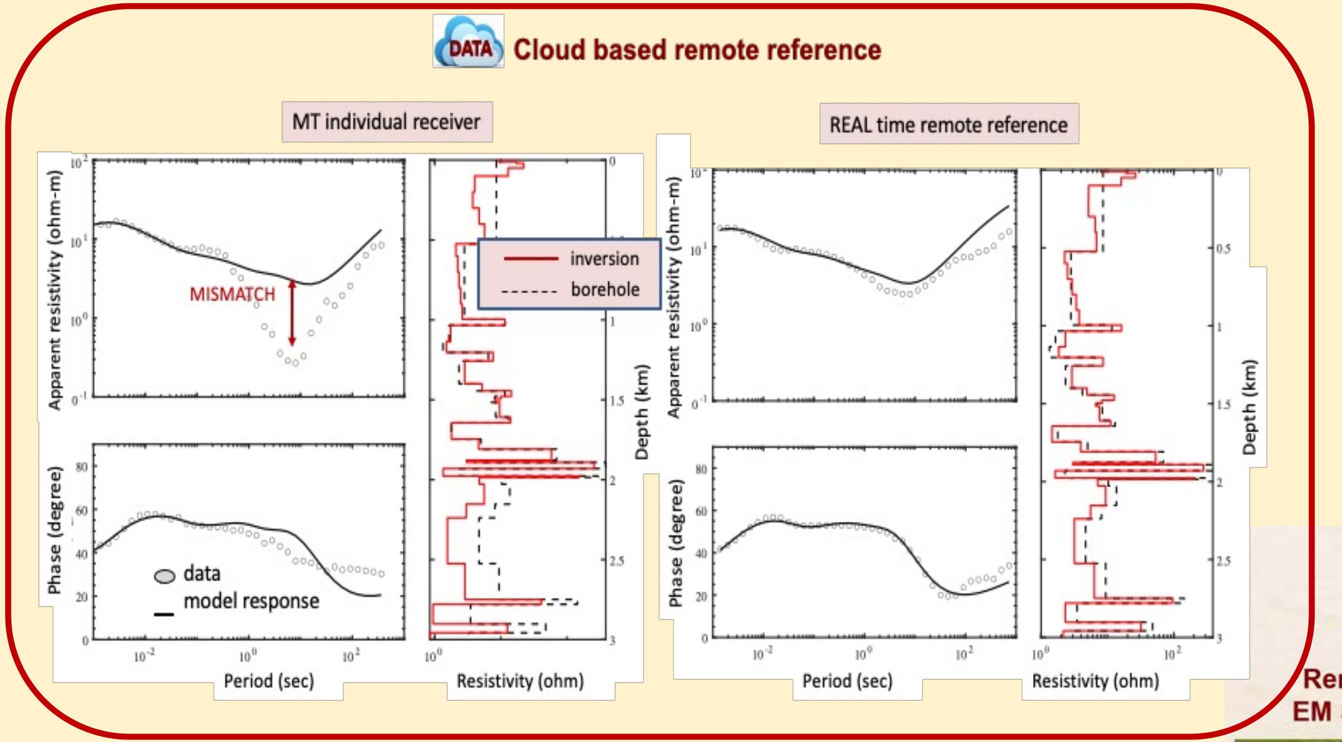
CSAMT, MT, TDEM, Long Offset TEM-LOTEM, IP

Instrumentation & optimum configuration (2)



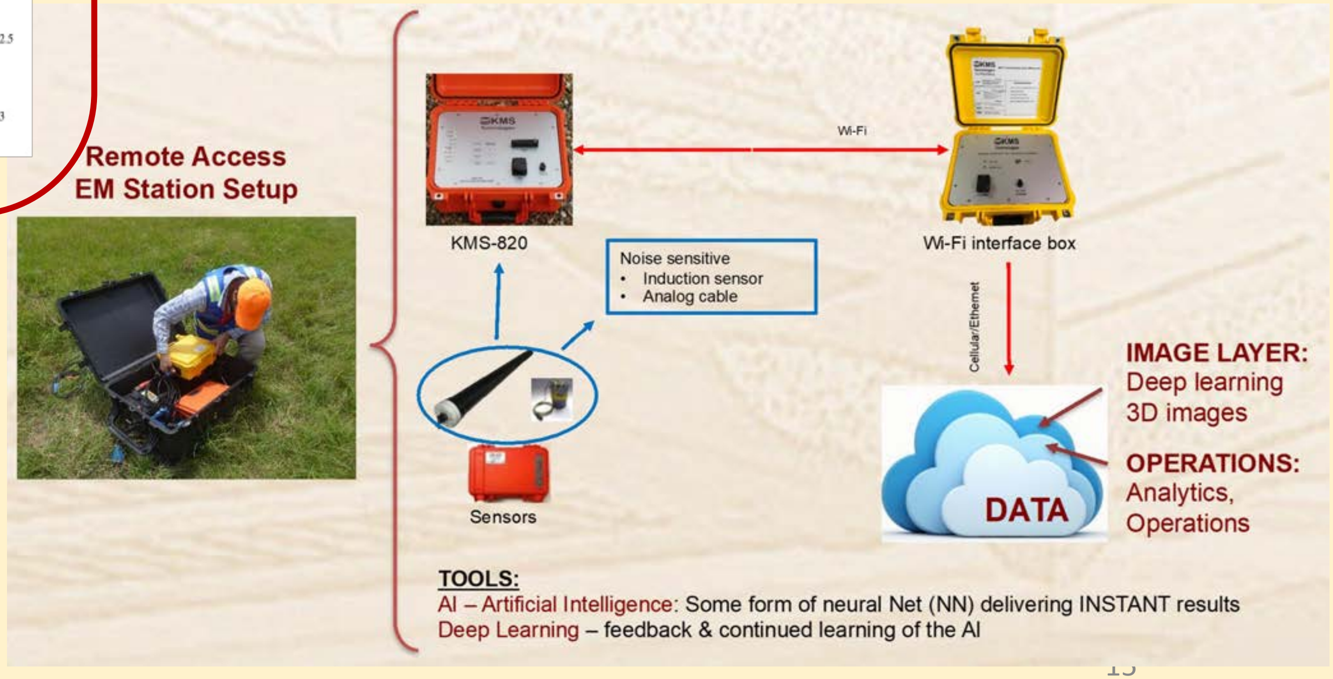
Modified after Hoerdt

Instrumentation, remote reference & capabilities (3)

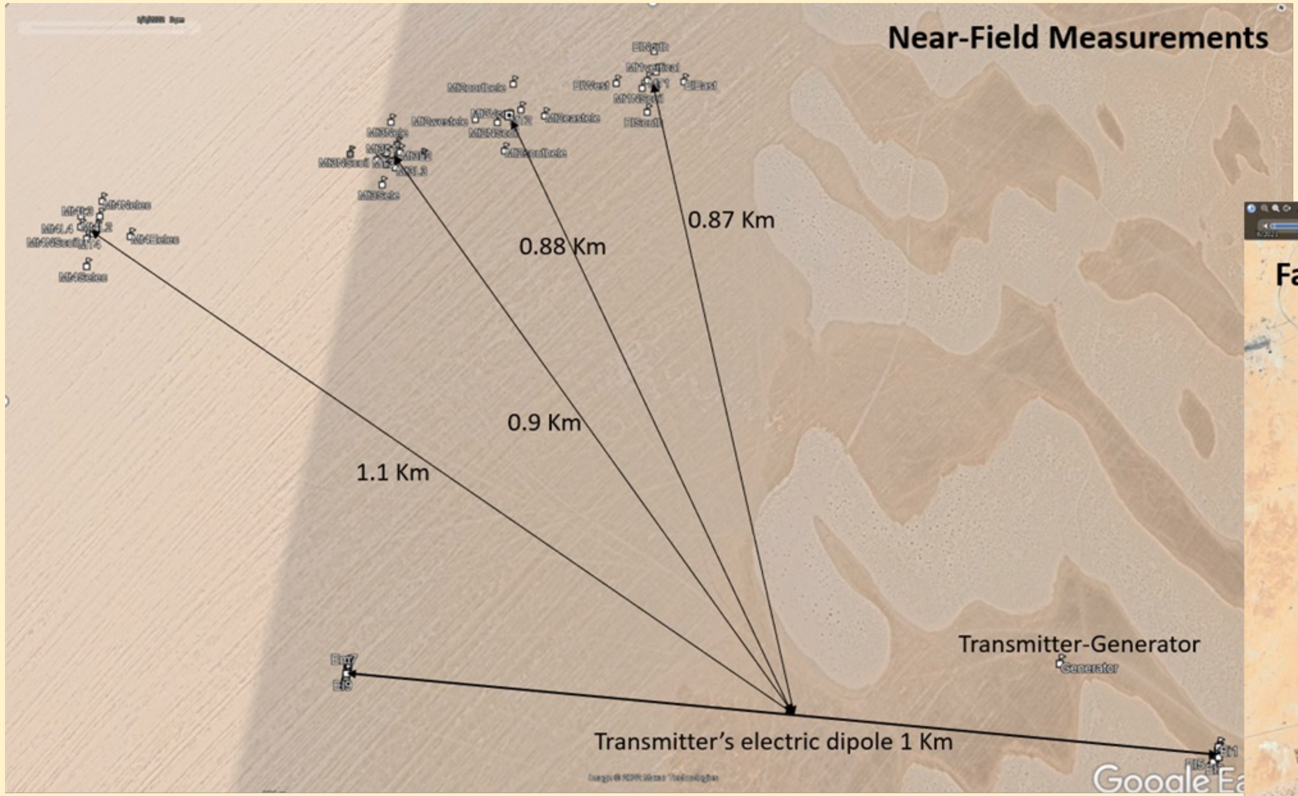


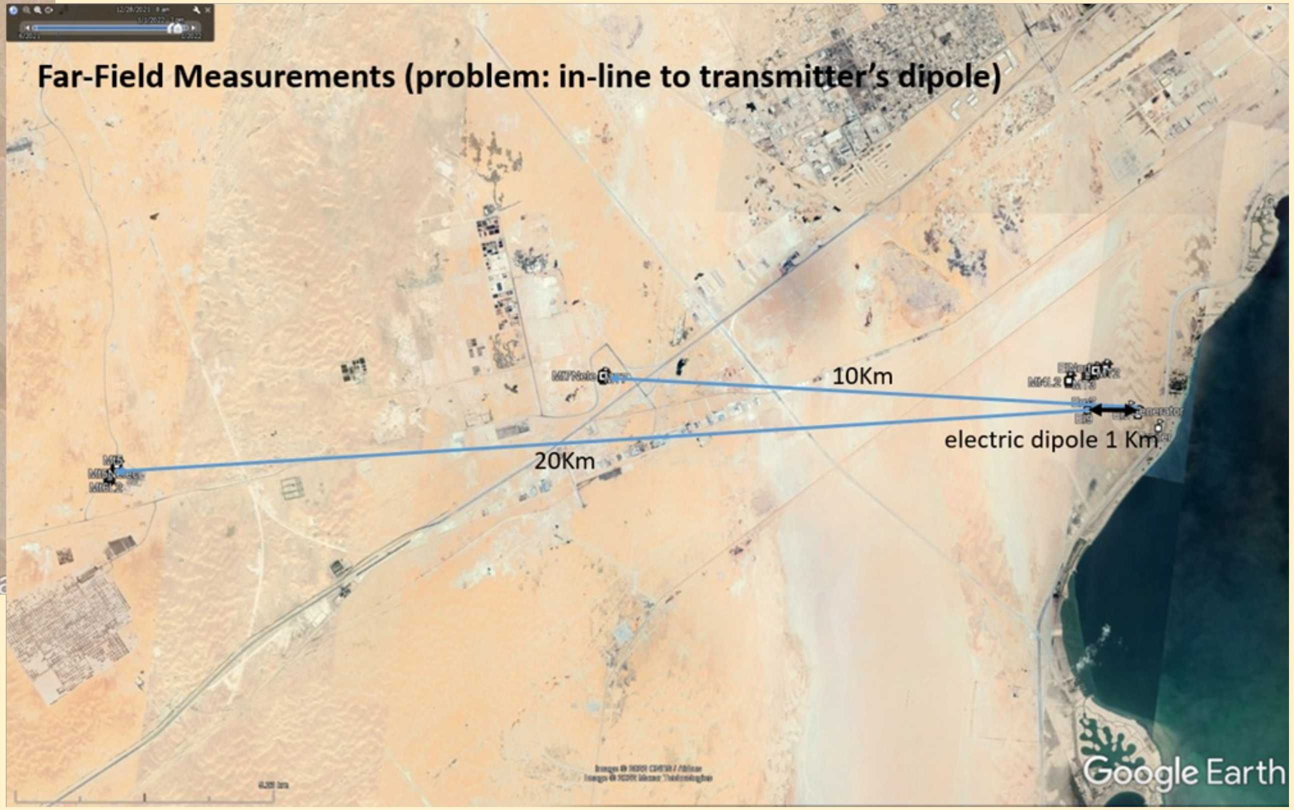
After Barajas-Olalde et al., 2021

MT QA via Cloud: Quality Assurance RR (1400 miles) & 3D model



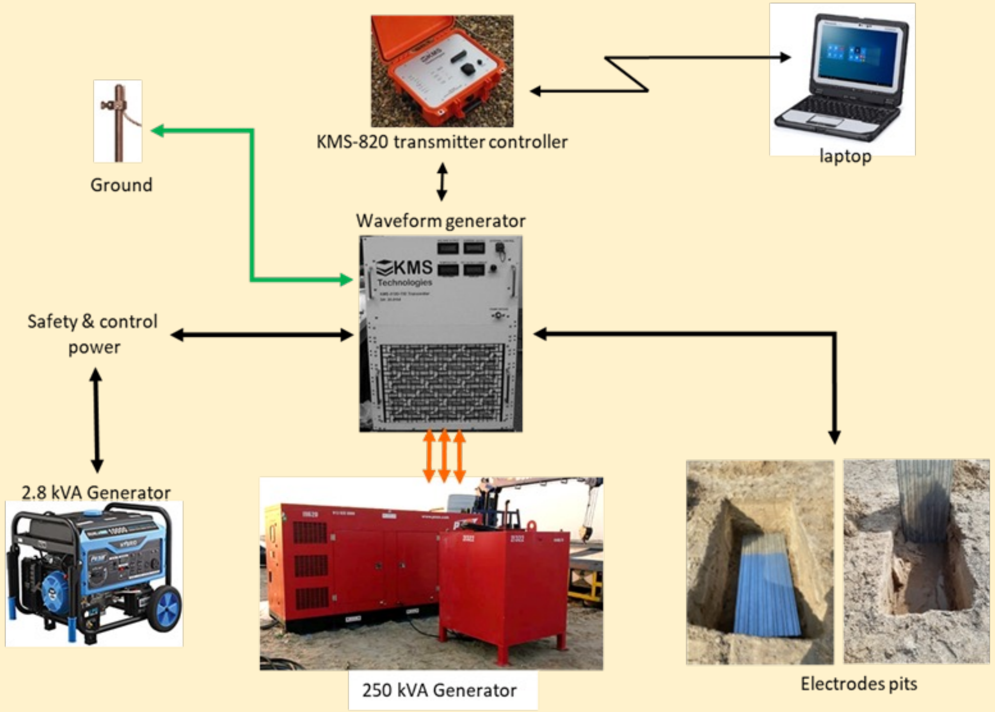
Instrumentation (CSEM), remote reference & capabilities





FIELDWORK – Dec. 28th 2021 – Jan. 2nd 2022

Instrumentation (CSEM), remote reference & capabilities



Instrumentation (CSEM), remote reference & capabilities

FIELDWORK – Dec. 28th – Jan. 2nd

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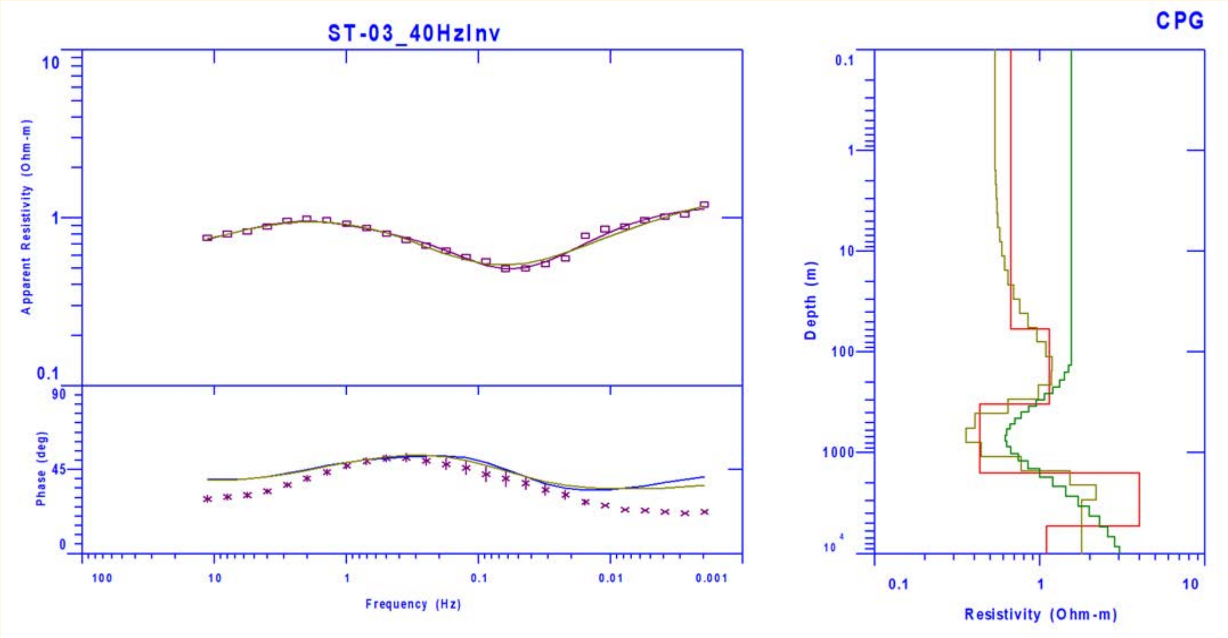
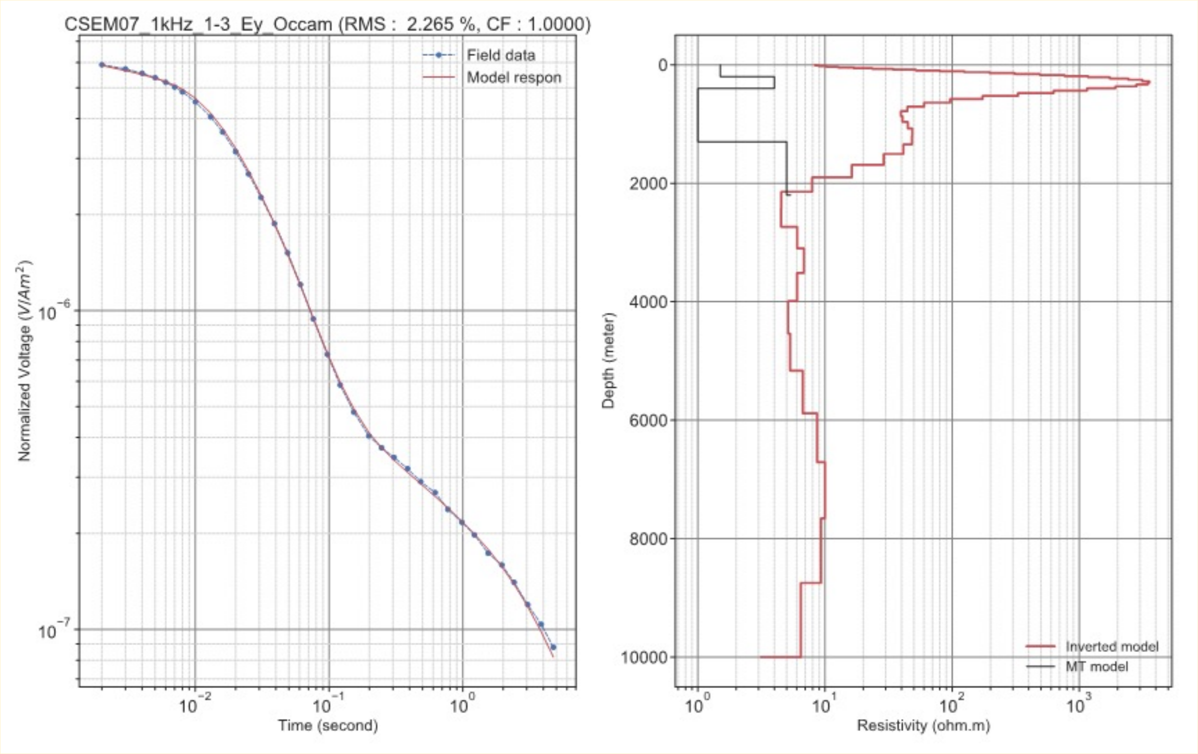
Instrumentation (CSEM), remote reference & capabilities



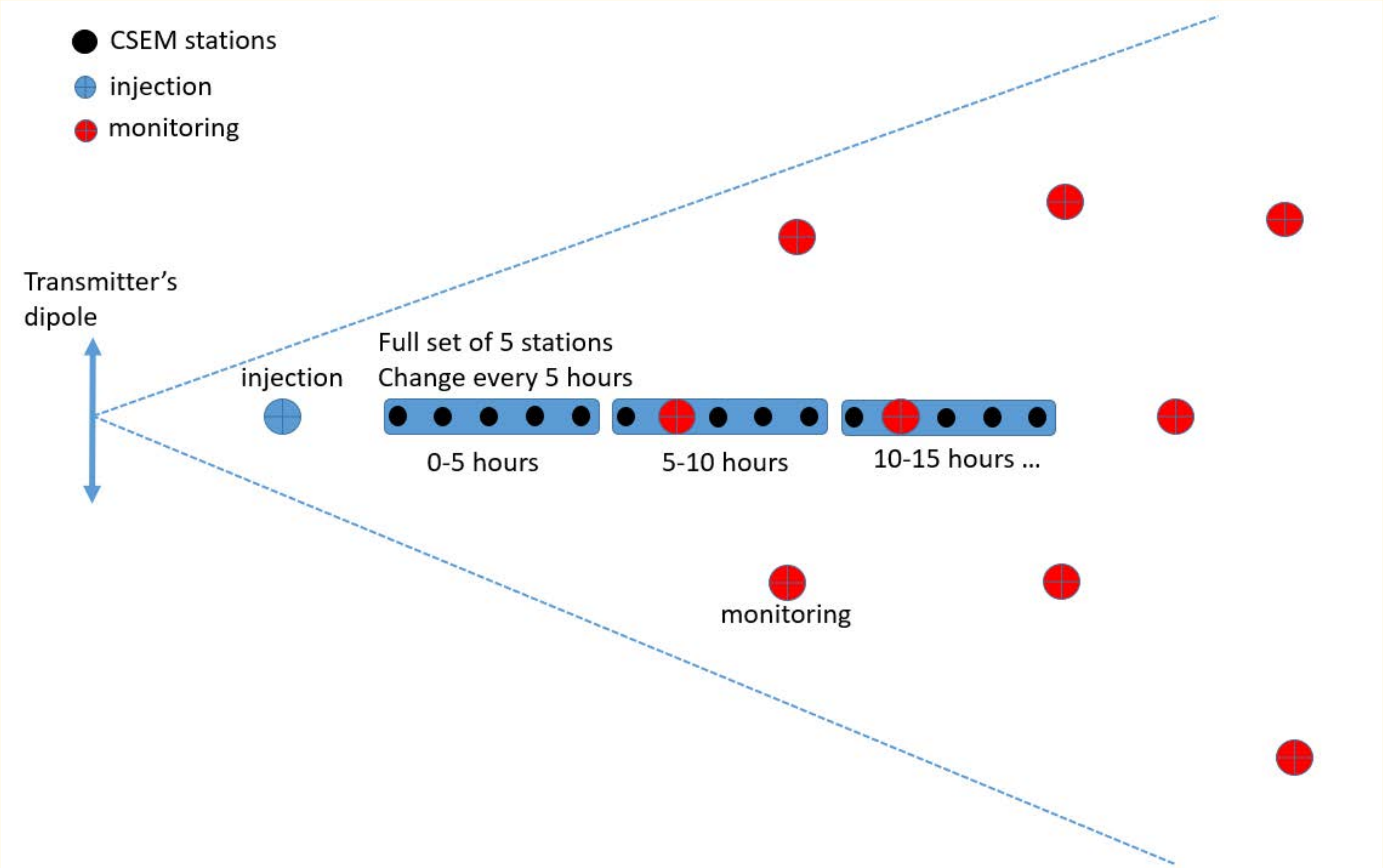
Processing – 1D – Near Field

Processing – 1D – Far Field (ST7, 20 km from source)



Instrumentation (CSEM), remote reference & capabilities

FLOOD monitoring – EOR @ ARAMCO test field



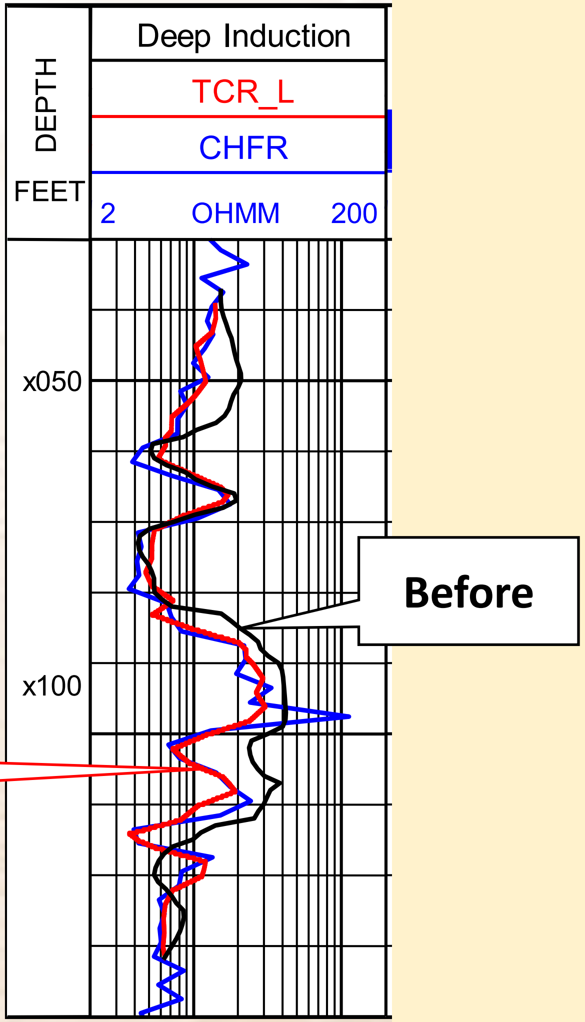
Examples, Applicability, Efficiency (1)

Example from Venezuela (Chevron)

Case study: Time lapse EM

Steam flood reduced 80 Ω-m reservoir resistivity to 40 Ω-m

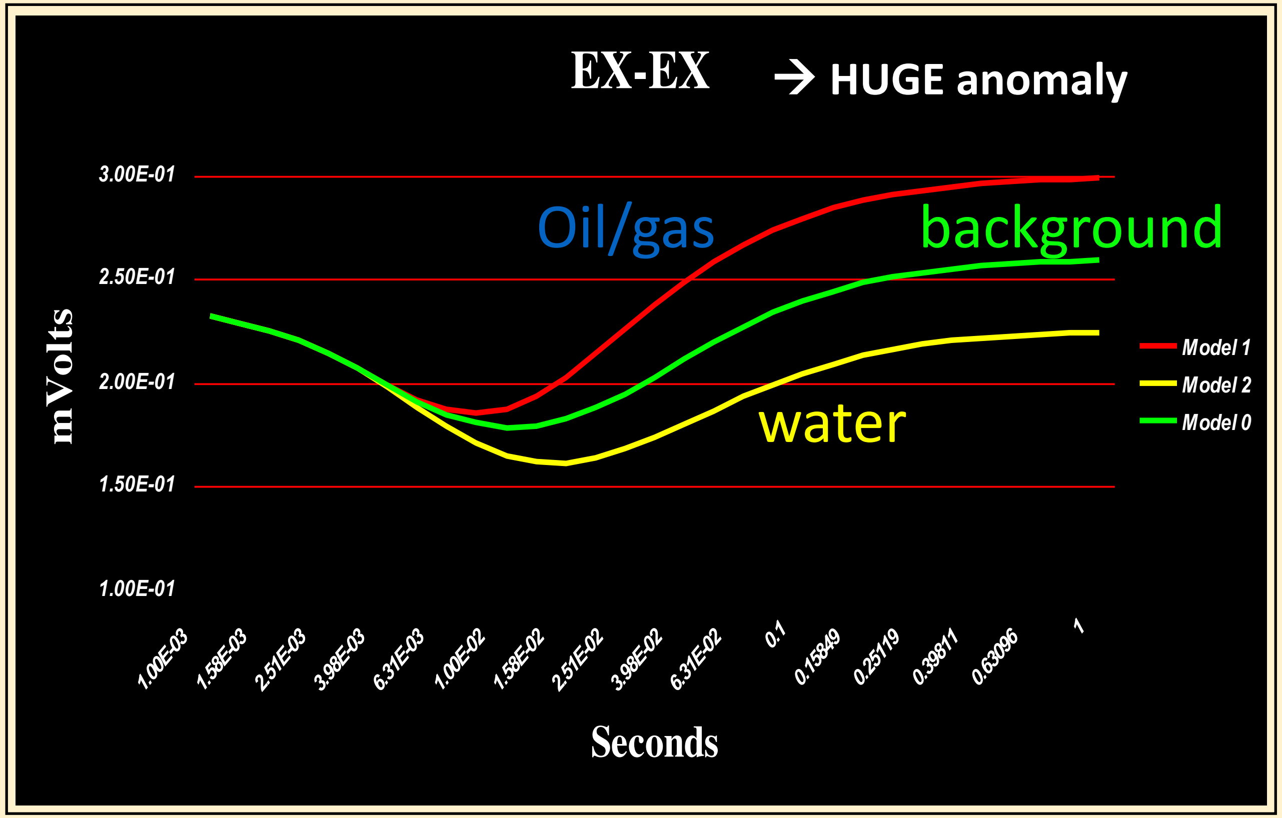
We CAN detect this change with EM !



After Zhou, et al, 2002

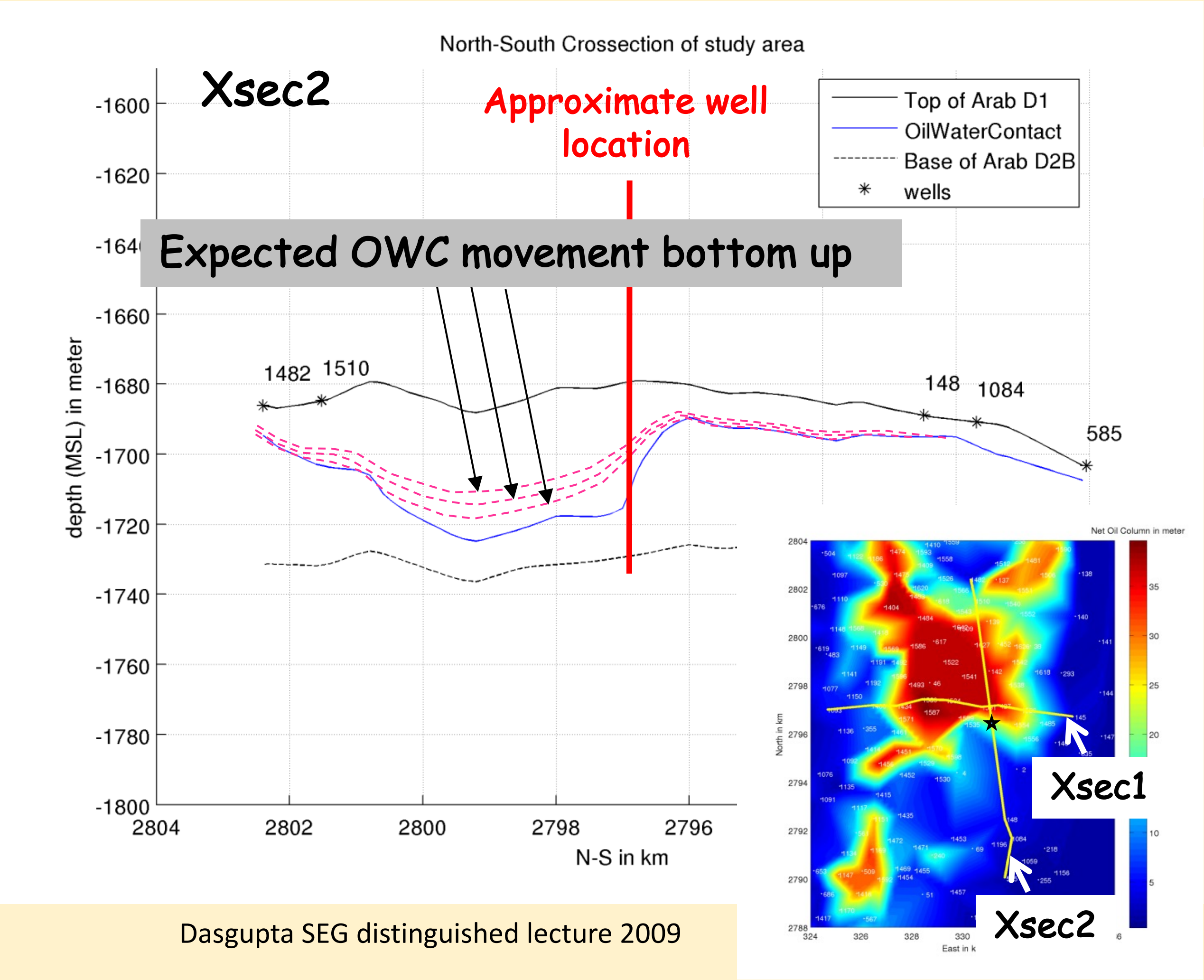
Steam-flooding makes local changes in resistivity that are large enough to be easily detected.

E-field transients as a function of time. The different in measured signal is in millivolts and easily detectable.

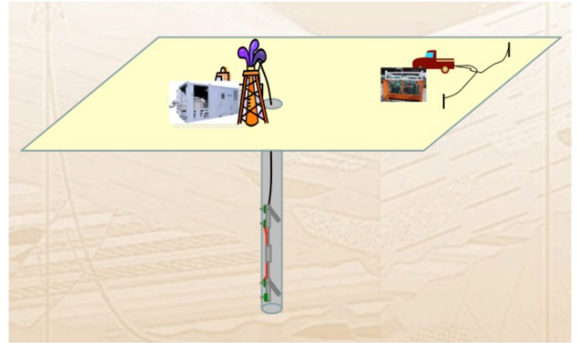


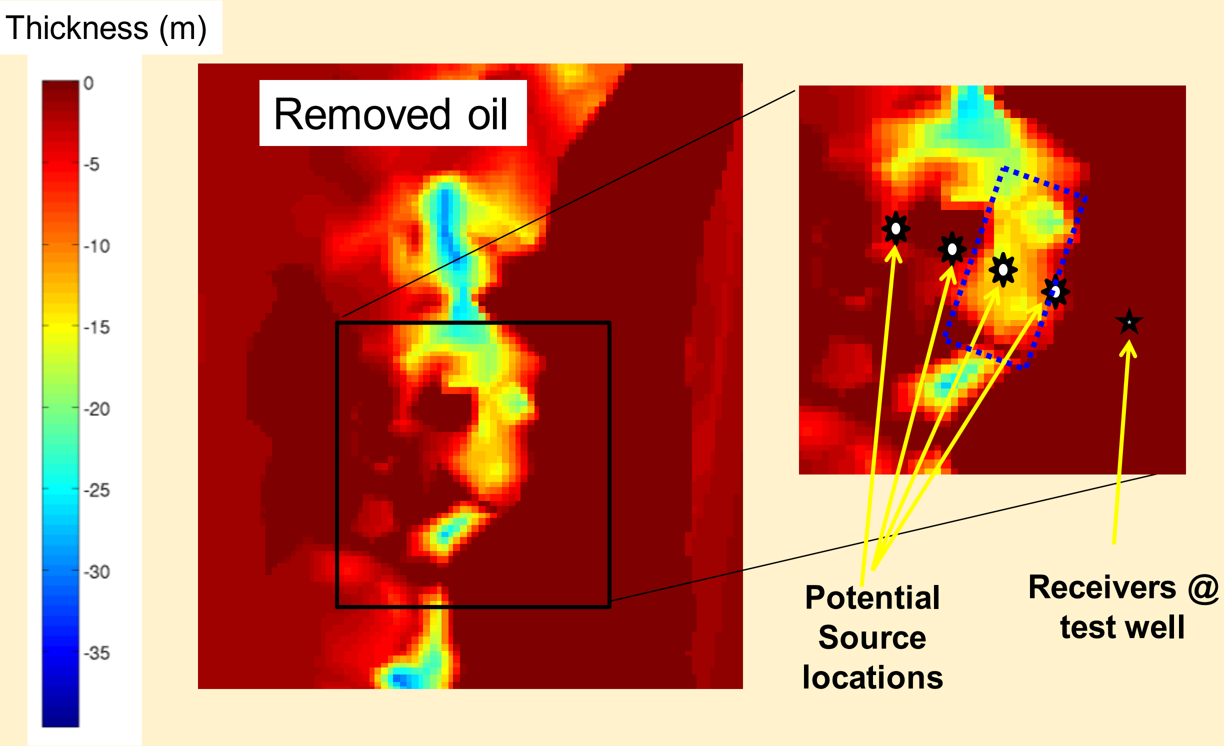
Examples, Applicability, Efficiency (2)

Ghawar model building: North-south cross-section



Dasgupta SEG distinguished lecture 2009

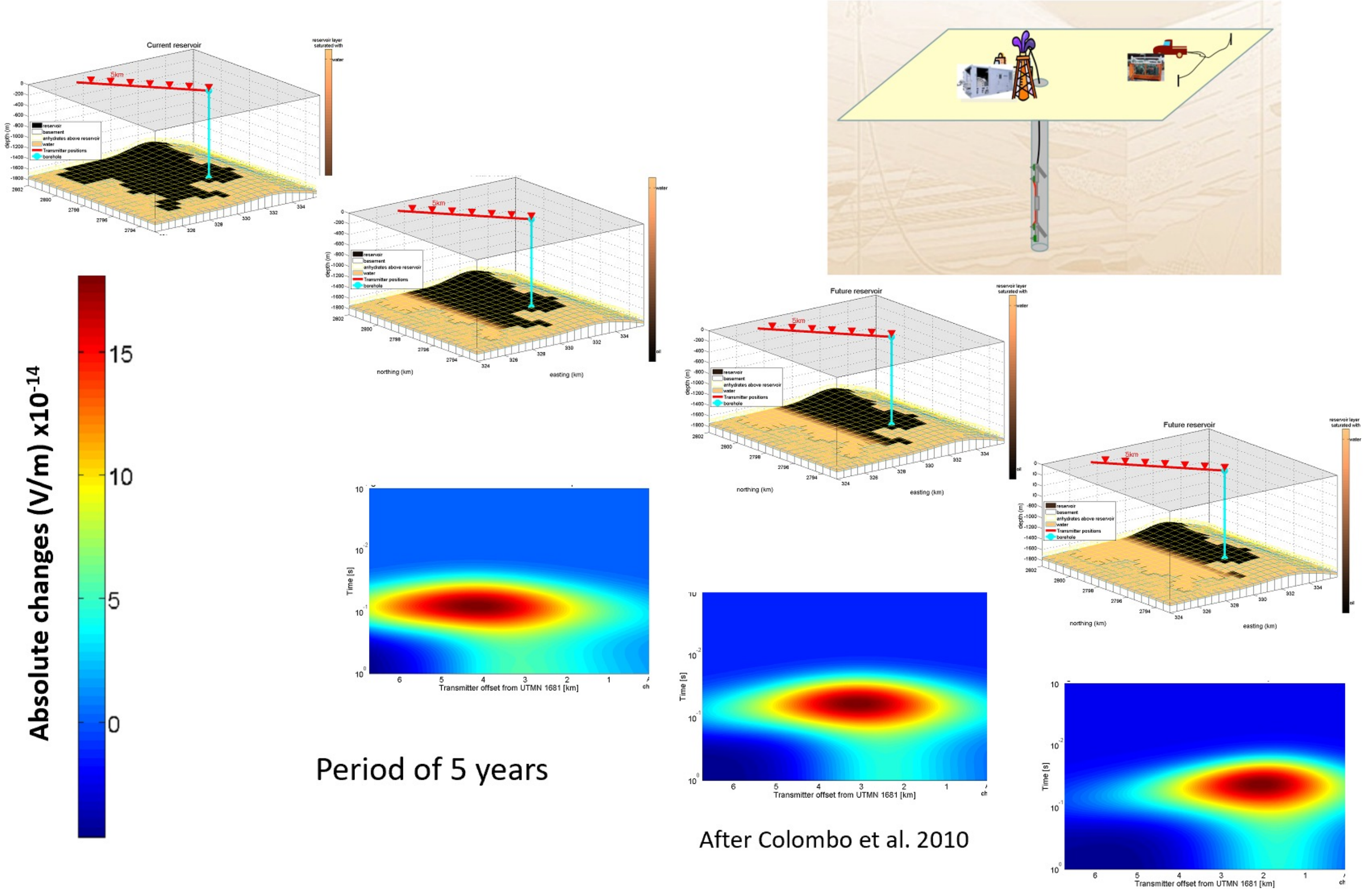




After Colombo et al., 2010

Examples, Applicability, Efficiency (3)

Example Phase 1 output after 3D modeling:
Reservoir models, time-lapse resistivity section, surface & borehole



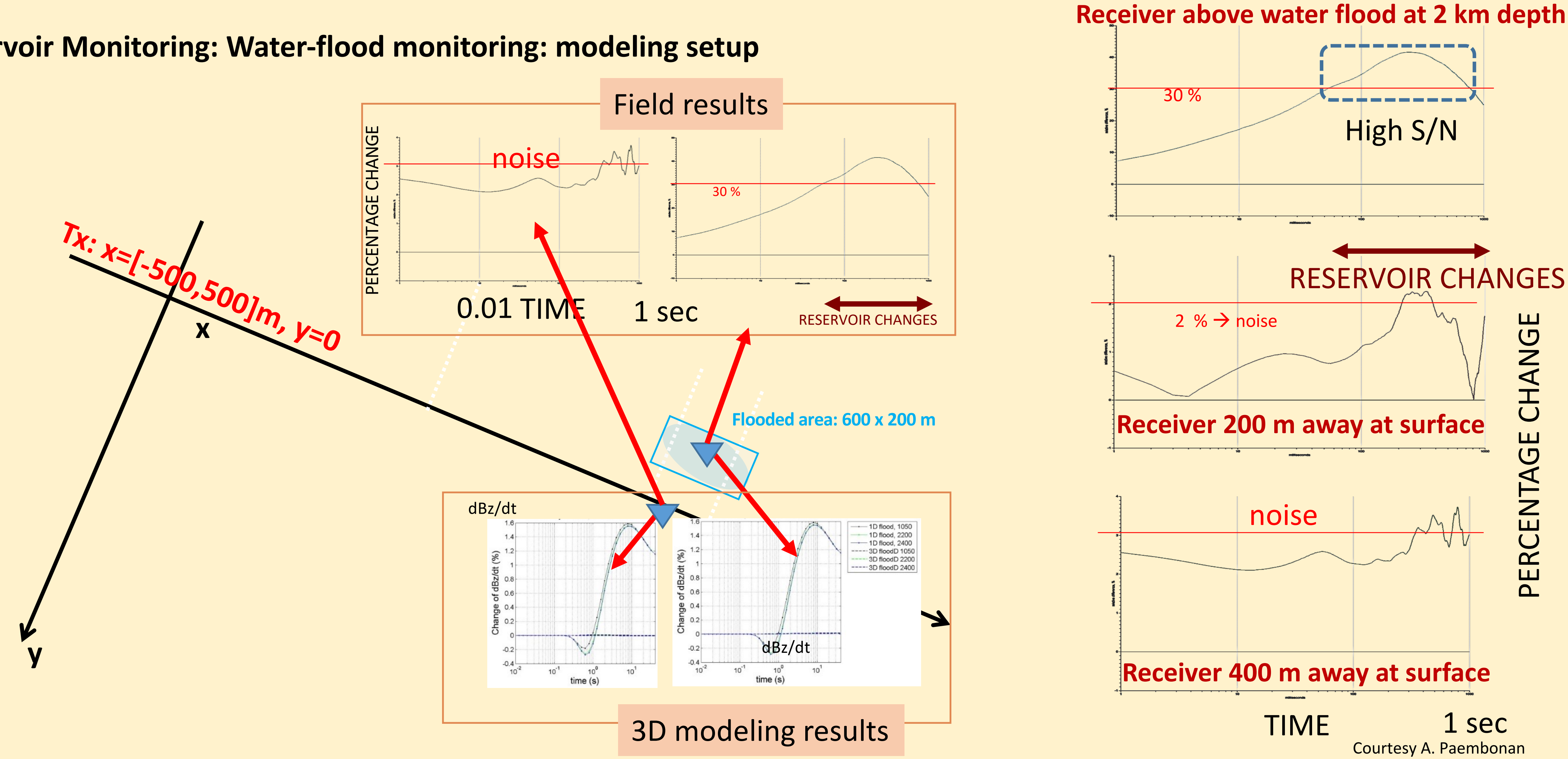
Period of 5 years

After Colombo et al. 2010

Four different reservoir states several years apart. They indicated that the changes increase with encroaching waterflood.

Examples, Applicability, Efficiency (4)

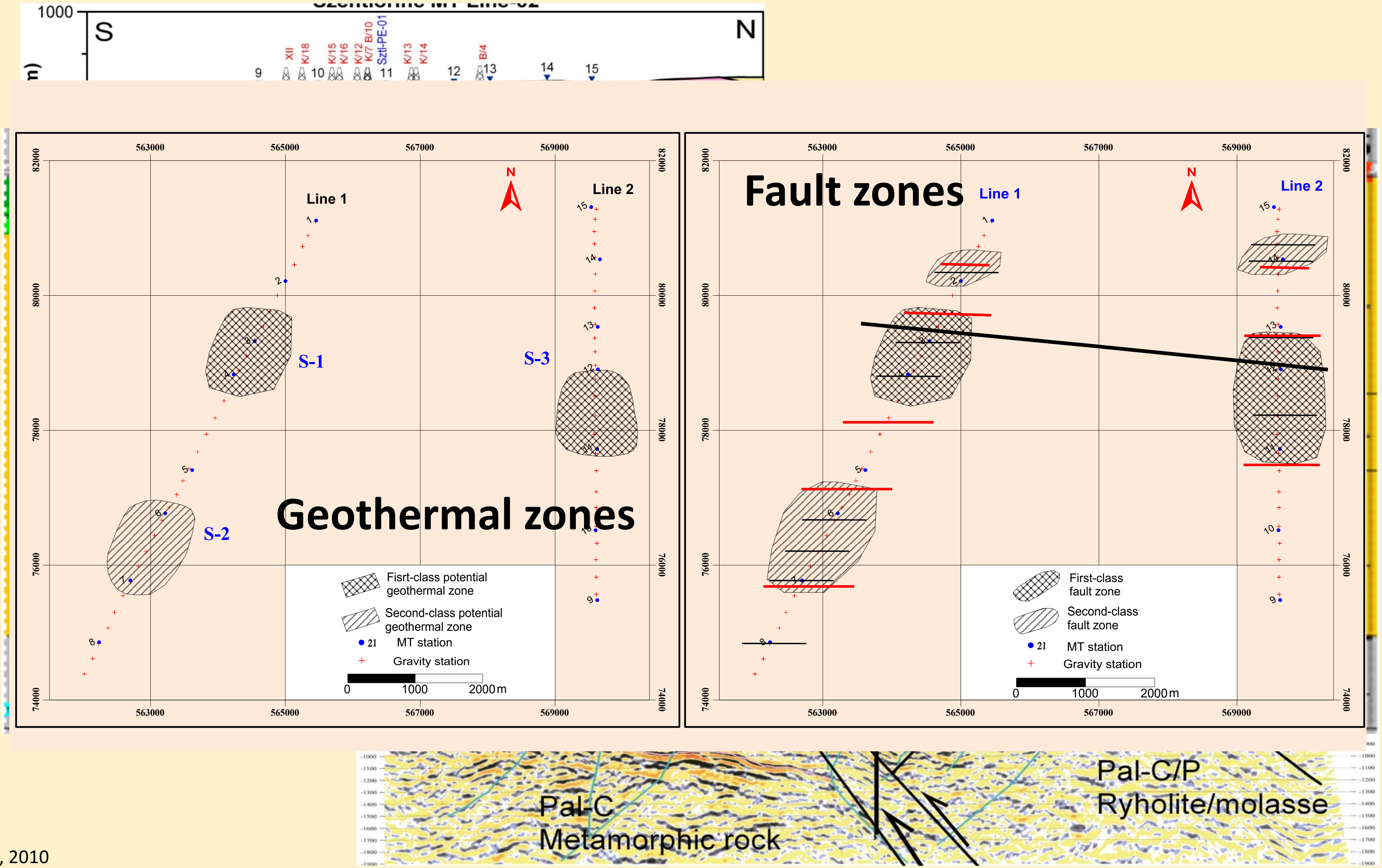
Reservoir Monitoring: Water-flood monitoring: modeling setup



Courtesy A. Paembonan

Examples, Applicability, Efficiency (6)

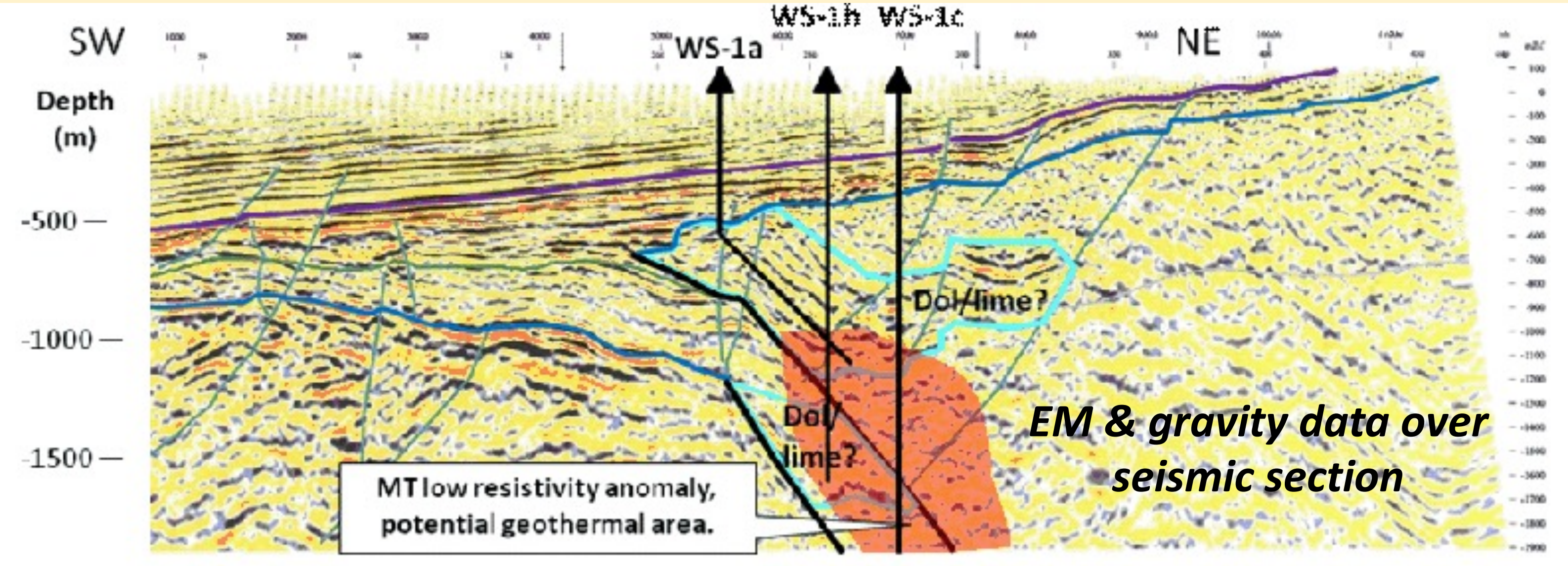
Geothermal Exploration in Hungary



After Yu et al., 2010

Examples, Applicability, Efficiency (7)

Geothermal Exploration in Hungary



Total success!
(4 MW)

After Yu et al., 2010

Examples, Applicability, Efficiency

Geothermal Exploration (May 13-22, 2022)
MT/AMT/Gravity/Geological survey

Examples, Applicability, Efficiency

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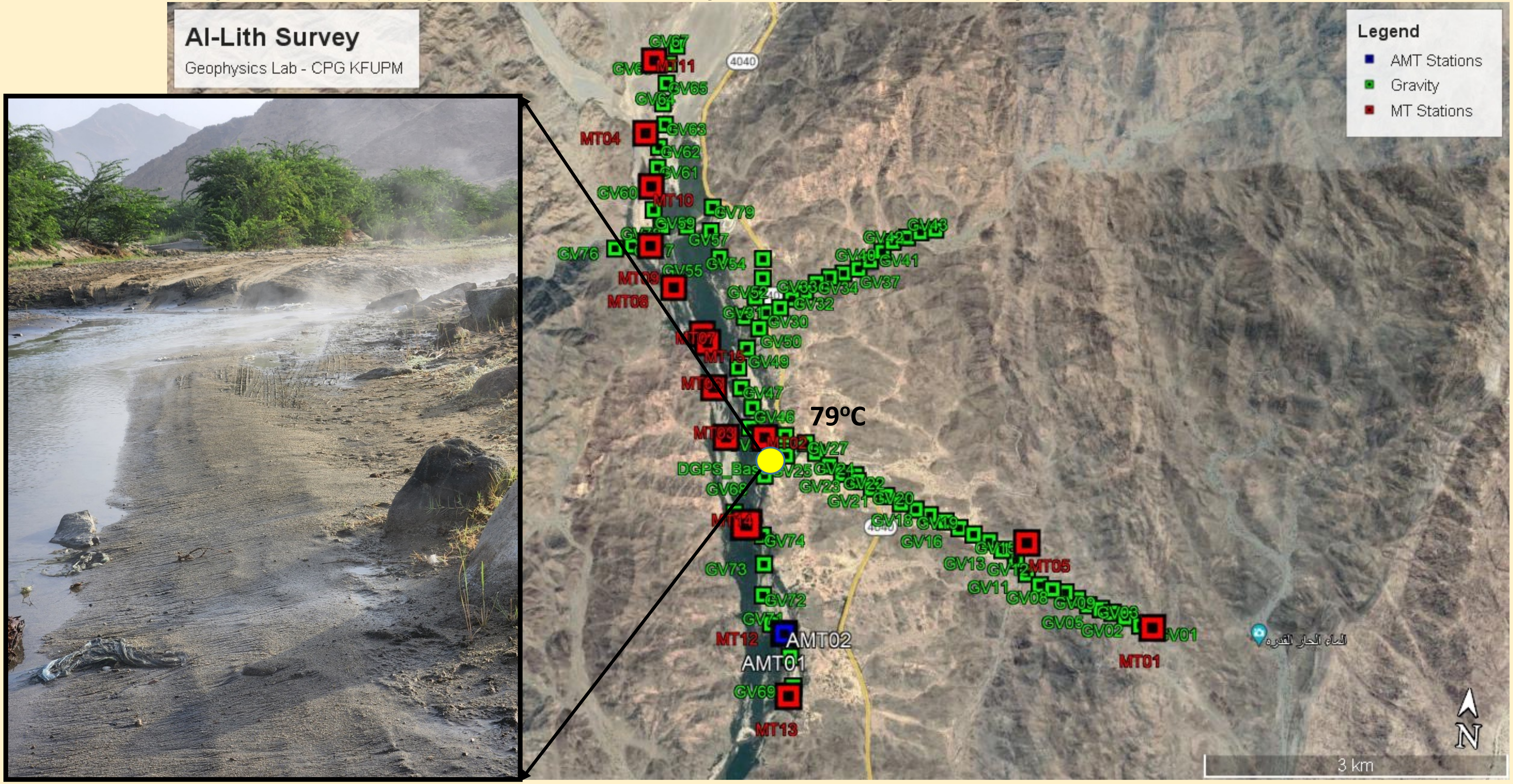
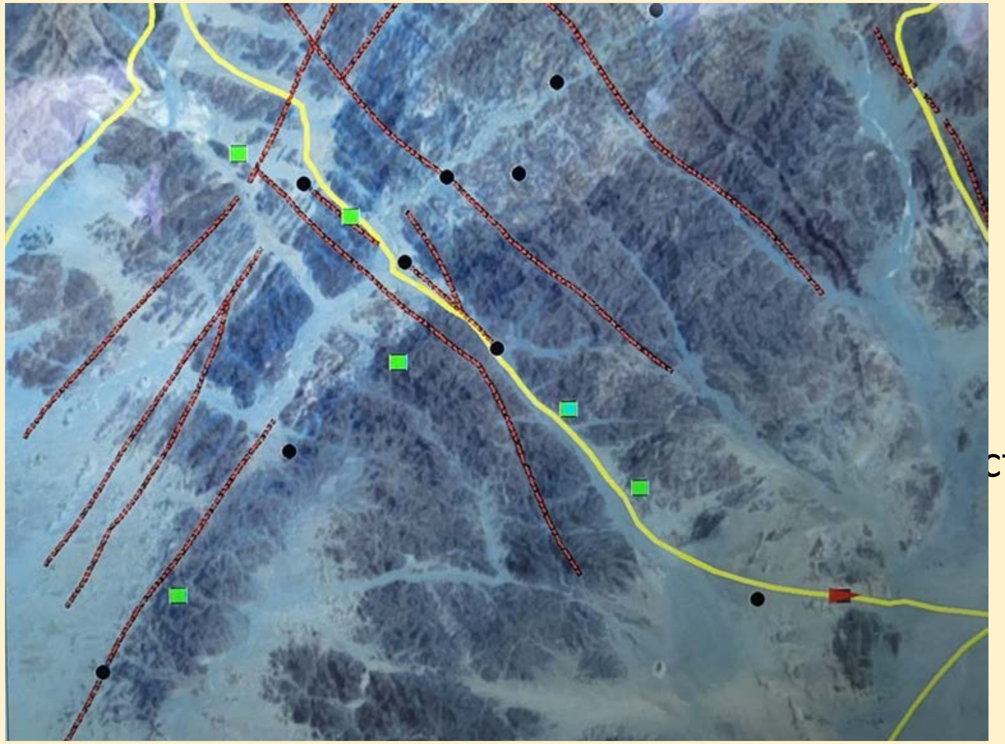
Examples, Applicability, Efficiency

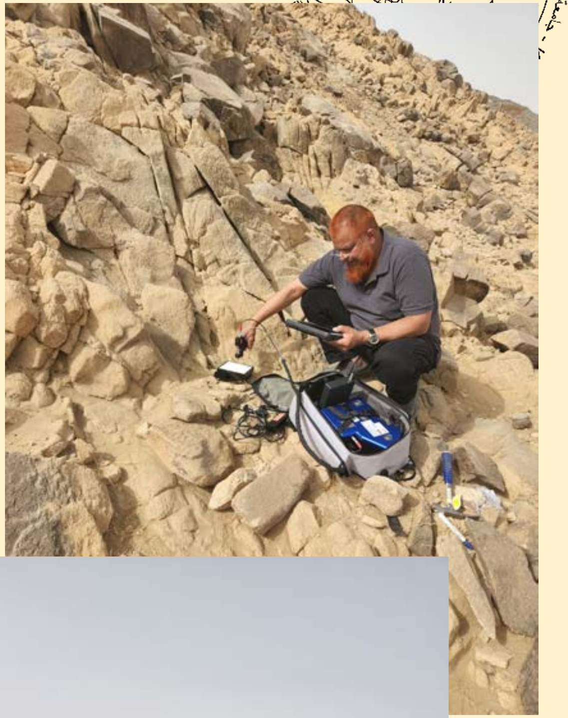
Geothermal Exploration (May 13-22) - FINAL experimental geometry



Examples, Applicability, Efficiency

Geothermal Exploration (May 13-22)

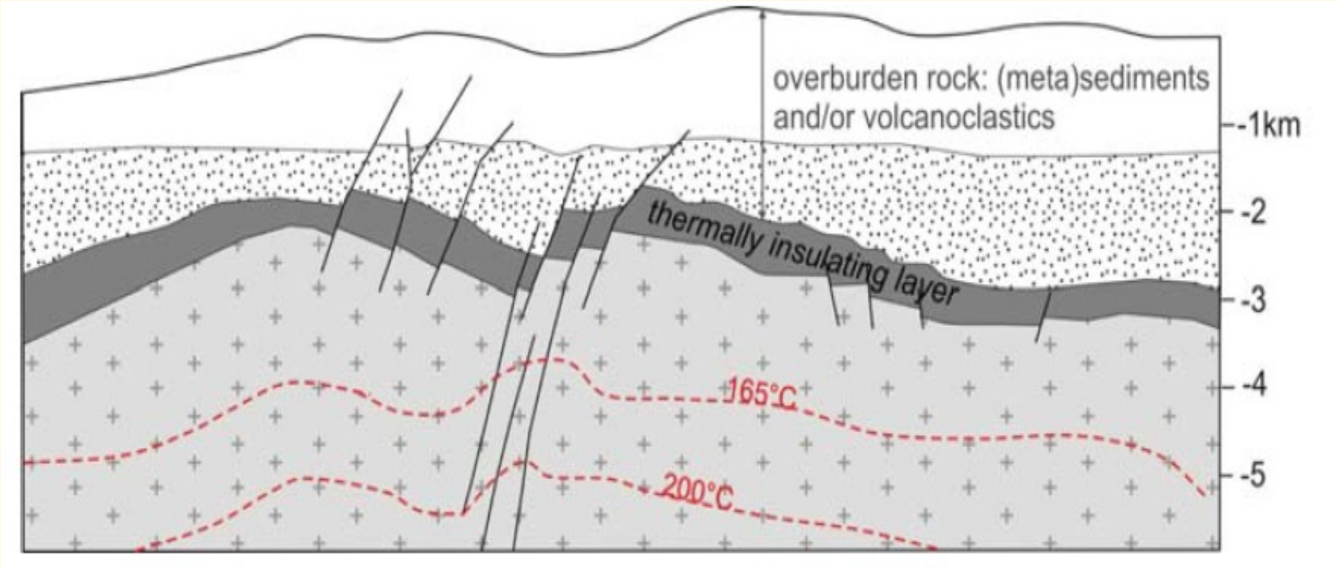


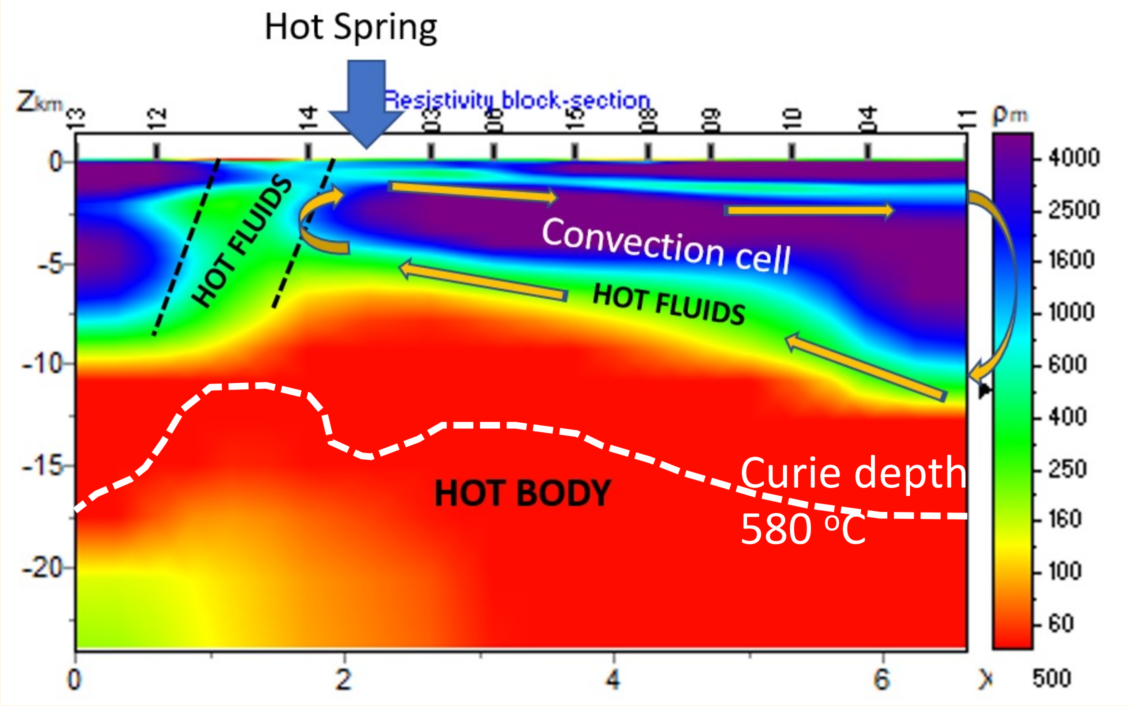


- Ground truthing of the geological map and tectonic features.
- Record of spectral signatures of different geological units.

Examples, Applicability, Efficiency

Geothermal Exploration (May 13-22)





Use of **aeromagnetic data** (SGS) to estimate the **Curie depth estimations** (the isotherm of 580 ºC). This, with the surface temperature as reported from different publications/reports can give me an average estimate of the,

Geothermal Gradient $\frac{\partial T}{\partial z} = \frac{T_{Curie} - T_{surface}}{z_b} \quad \left(\text{in } \frac{°C}{km}\right)$

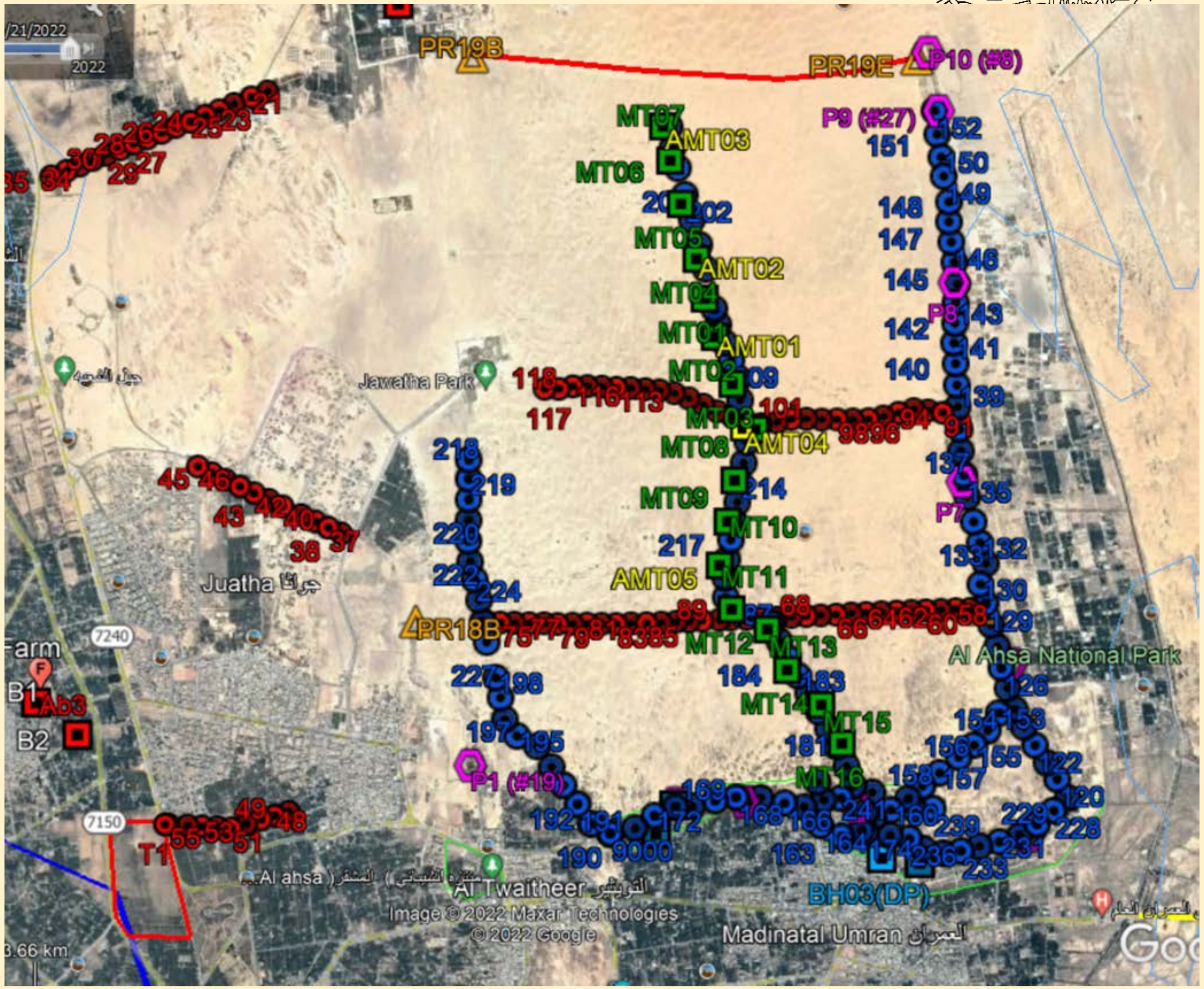
Heat Flow $Hf = k * \frac{\partial T}{\partial z} \quad \left(\text{in } \frac{mW}{m^2}\right)$

k=thermal conductivity

Examples, Applicability, Efficiency

Shallow Geothermal Exploration
(June 10-22, 2022)

16 MT stations
6 AMT stations
242 gravity stations
10 water boreholes
1.2 Km seismic
2 GPR profiles



CONCLUSIONS

- CSEM is well suited for fluid imaging
- Depth 1 to 6 km requires high power Tx (150 KVA)
- O&G, Geothermal: use in exploration & production
- CO2 storage: monitoring & with seismic for seal integrity
  - Combined seismic/EM Same crew = > 50% saving
  - Same instruments record microseismic/EM acquisition
- Interpretation/integration
  - CSEM: 3D anisotropic model available
  - Integrated interpretation
- **MUST: Calibrate – calibrate - calibrate**

Future plans:

- Implement more ML/AI
- Acquire denser data: Seismic & EM
- Use EM for monitoring
- Integrate surface with borehole
- Integrate land & marine