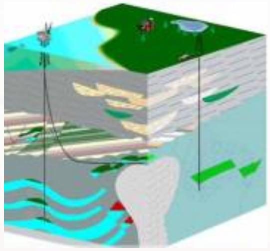


Novel integrated array EM for the different lifecycles of a geothermal prospect

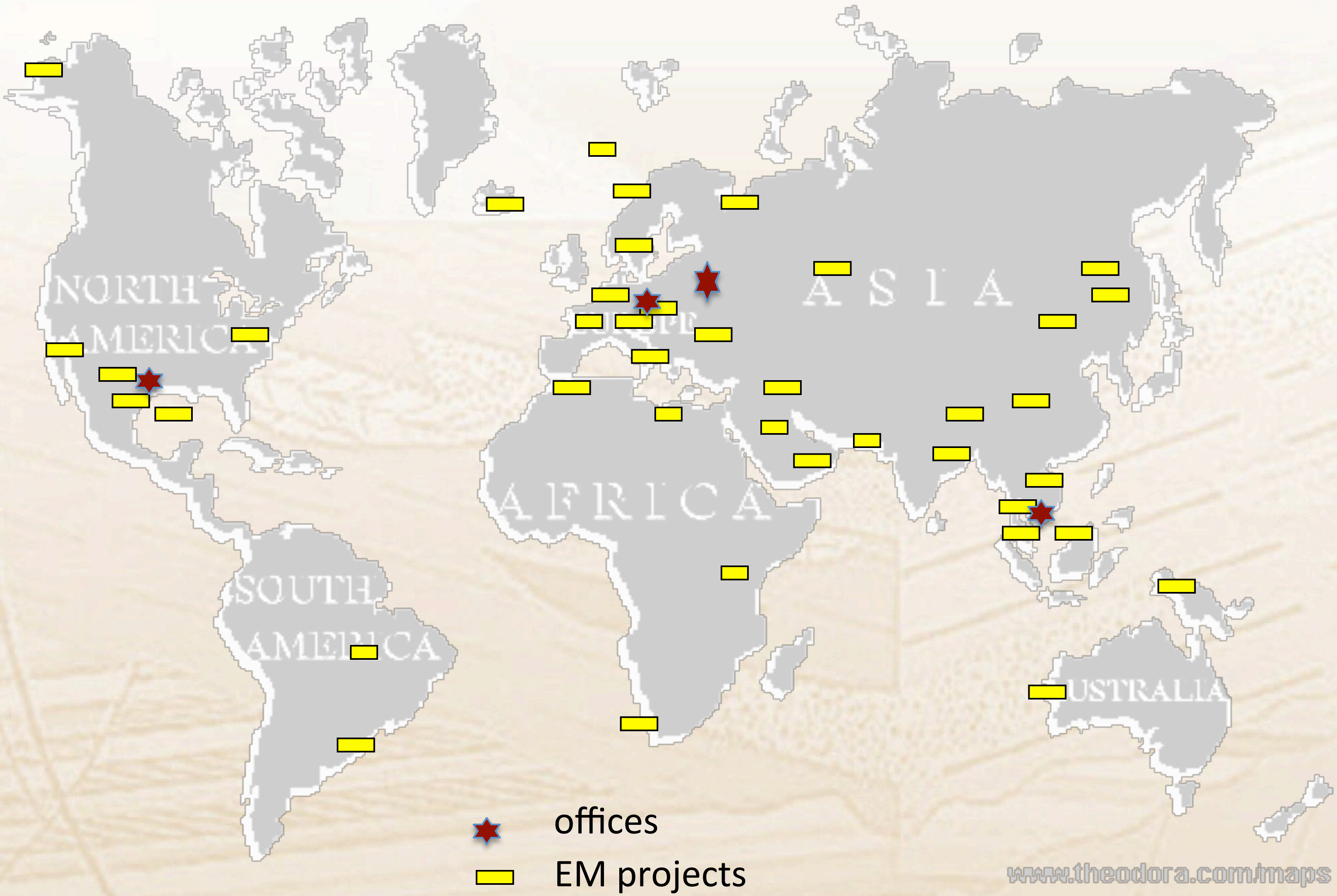
KMS Technologies

February 2015

KMS history

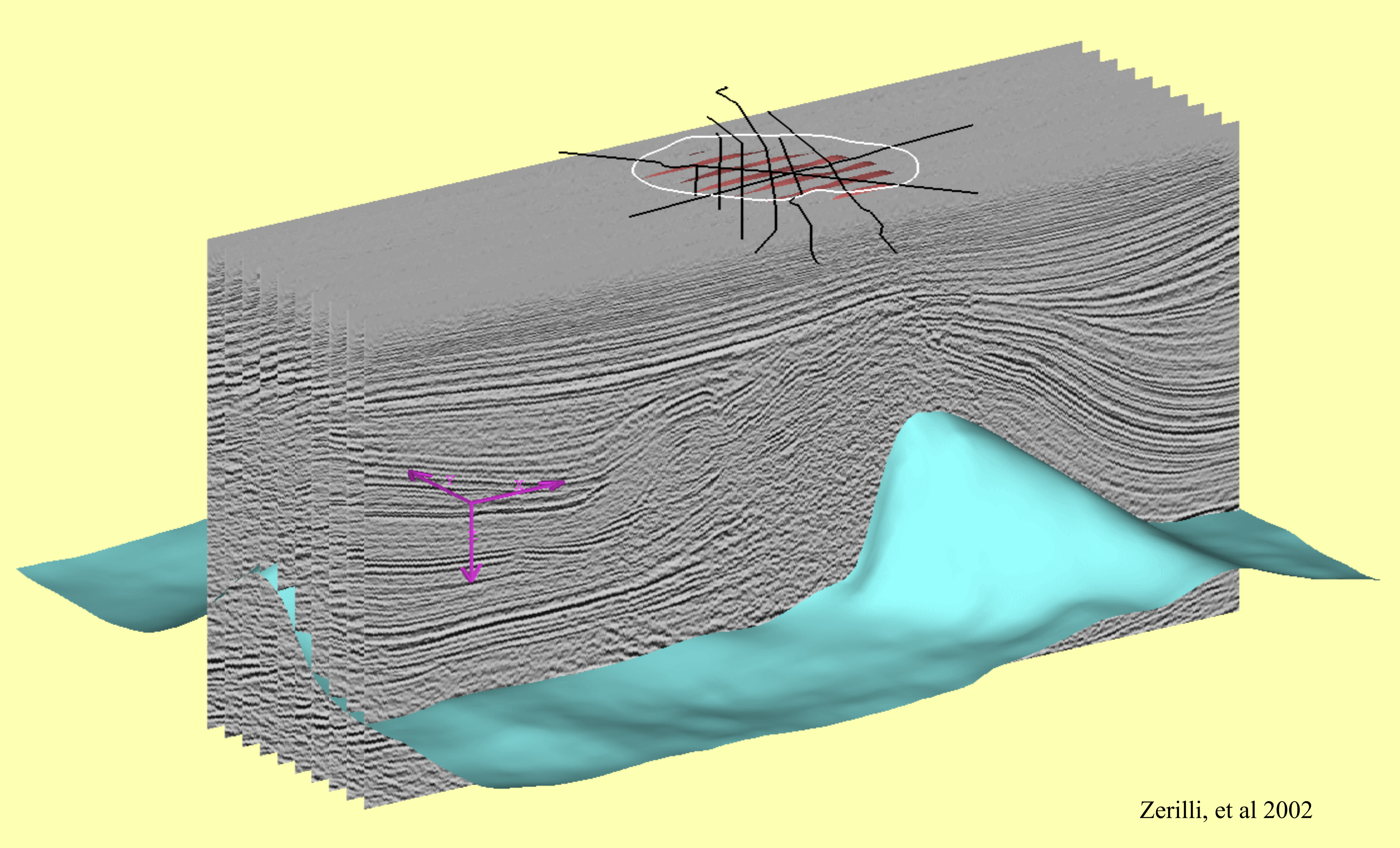
- Started in 1999 as technology development Group for Agip/ENI & Shell
- Strong in new technology development (EM emphasis)
- Initial borehole tools →
- Geothermal acquisition services →
- Marine EM →
- Since 2010: hardware manufacturer with global presence
- Today Monitoring → Strategic MOU with PTTEP

KMS track record since 1999: EM only



Fully integrated Hi-res MT, gravity & seismic: Highlight

Dense acquisition (Δx = 50 m) → better images



Zerilli, et al 2002

How do we get there? EM methods review

- Magnetotellurics – **passive method**
  - **Good for basin structure, obver-thrust, sub-basalt, sub-salt**
- Controlled Source Electromagnetics (CSEM)

  more detail than magnetotellurics & noisy environment
  - Time domain EM – a single signal generating event
    - Similar to seismic (acquisition & processing)
  - Frequency domain EM – a fixed frequency continuous event

New ARRAY acquisition → better images

- Wireless (long range & WIFI)
- True array system
- Large dynamic range (up to 32 bits)
- High bandwidth (DC to 50 kHZ)

Geothermal relevant EM lifecycles

EM has been the geophysical workhorse for the geothermal industry

Exploration

- MT is first choice
- Integration
- Target well location

Pre-drilling

- Detailed EM (CSEM)
- Baseline survey
- Risk control
- Facility estimation

Development

- Monitor (induced seismicity)
- Addition wells (calibration & integration)
- Cost reduction

Production

- Environ. Compliance
- Control reservoir flow

Geothermal relevant Examples of integrated EM

Exploration
- Iceland
- Hungary

Pre-drilling
- Urach, Germany
- Hawaii, USA

Development
- Monitor (induced seismicity)
- Imperial Valley, CA

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- Ghawar field, Saudi
- Kuwait

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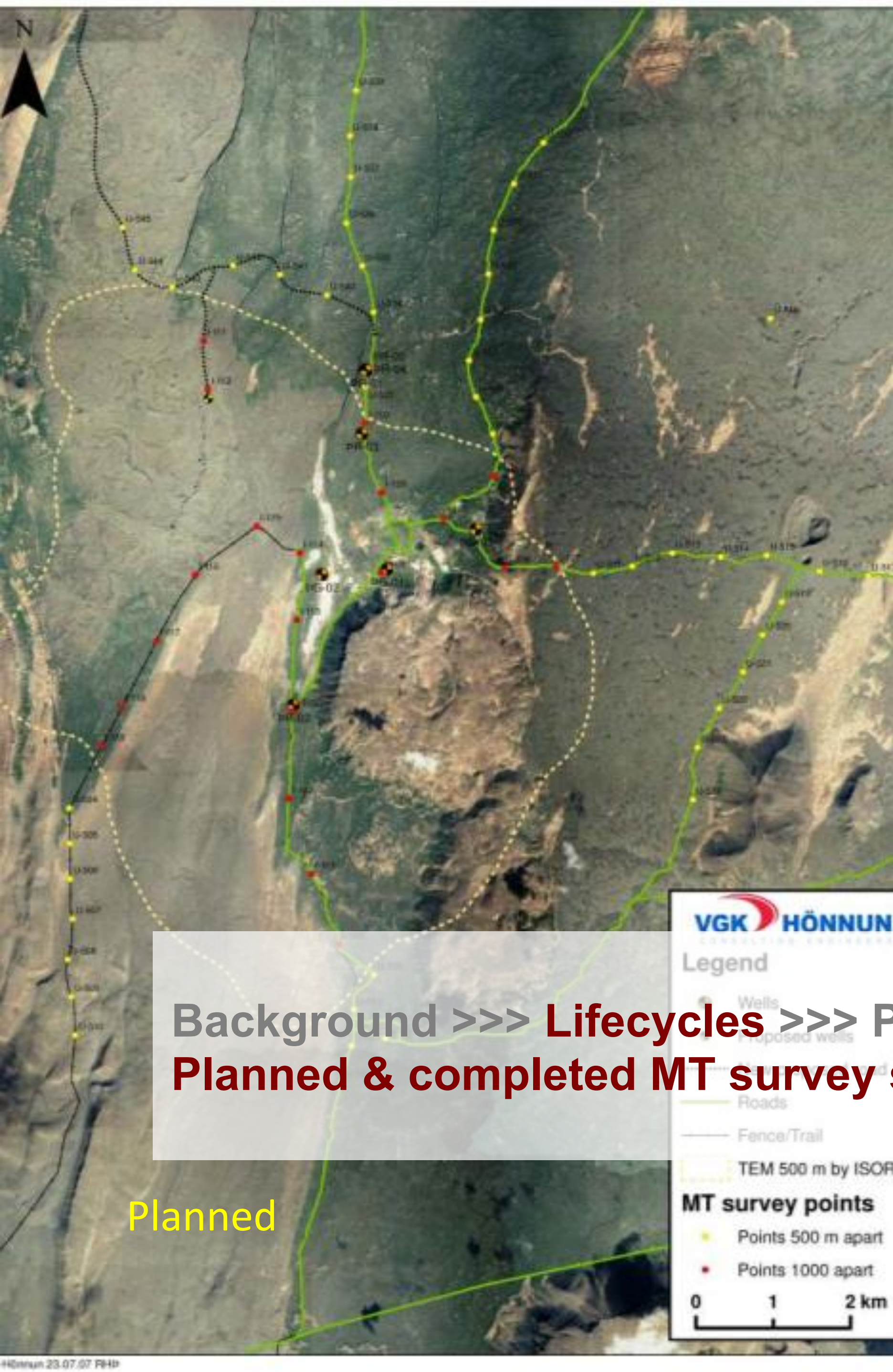
- Environ. Compliance
- Control reservoir flow

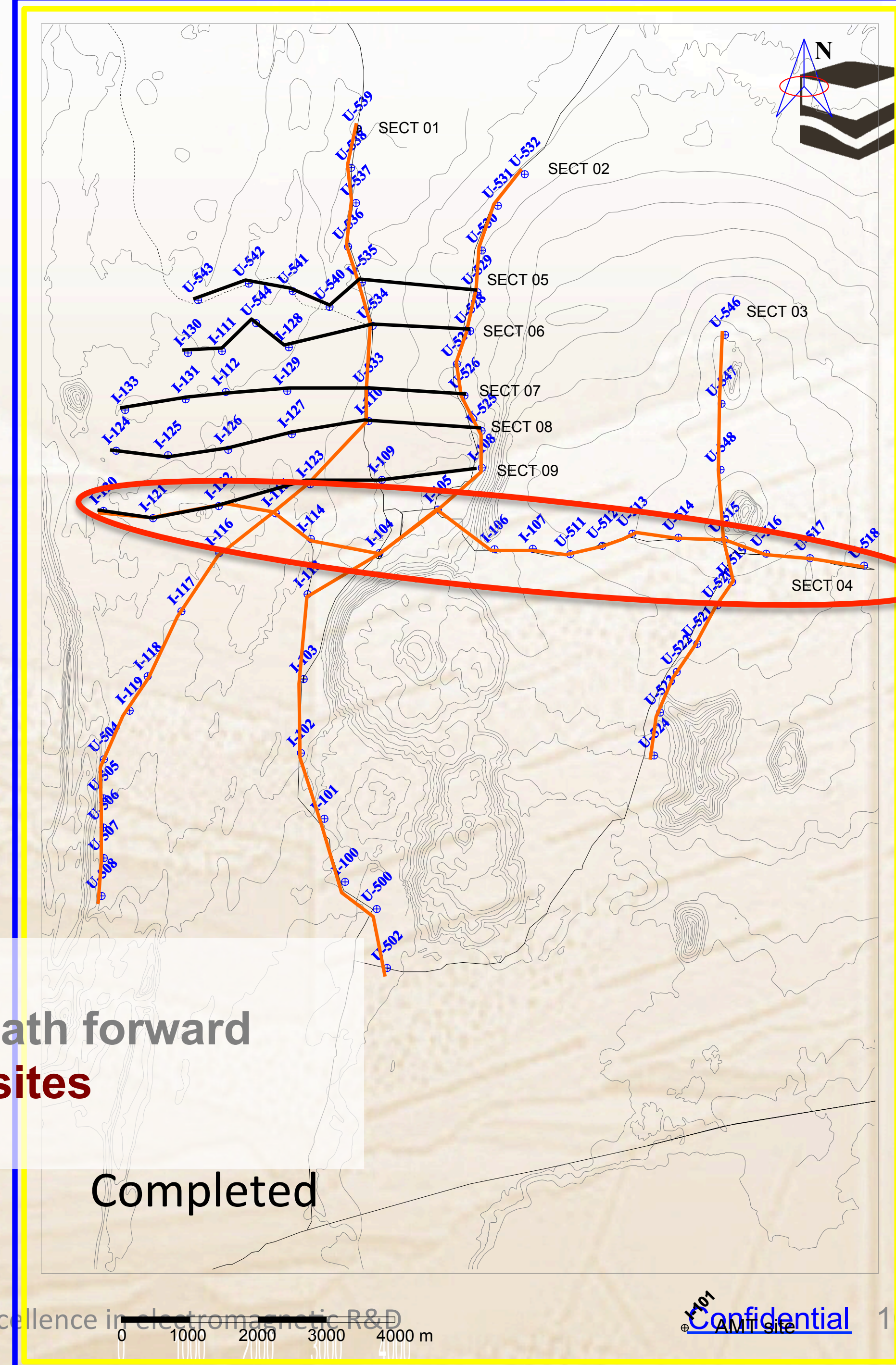
Iceland: punch line

- All volcanic material
- Target: find additional reservoir to feed power plant
- Survey mapped resistive & conductive targets
- MT data to be integrated with TEM & all others data

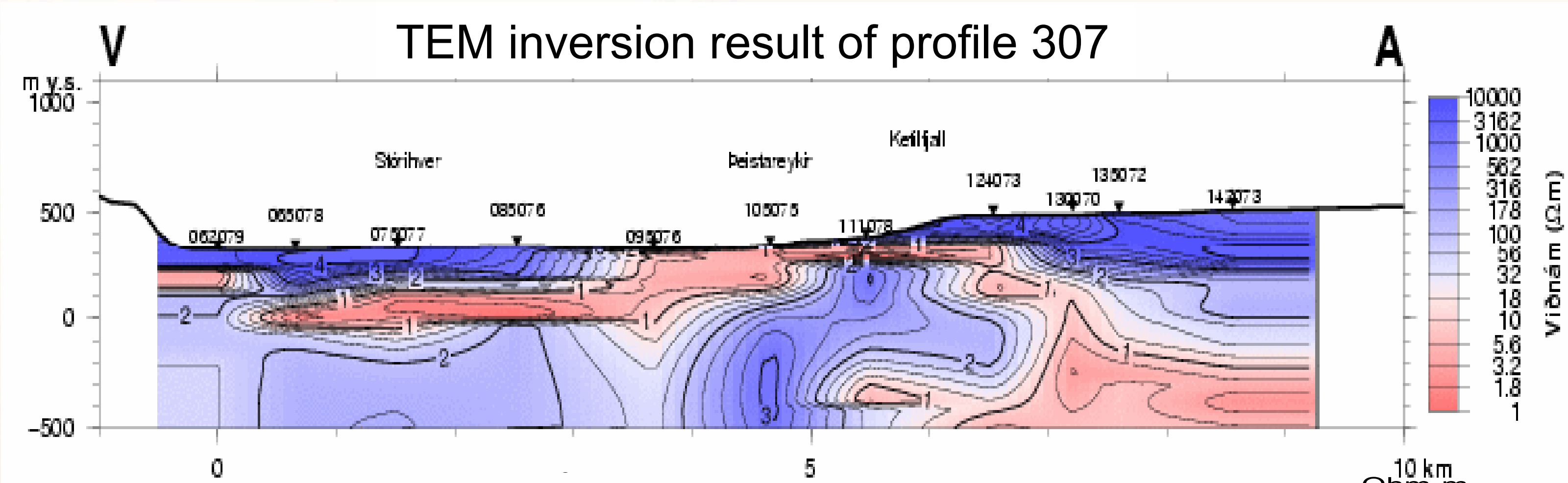
Background >>> **Lifecycles** >>> Path forward

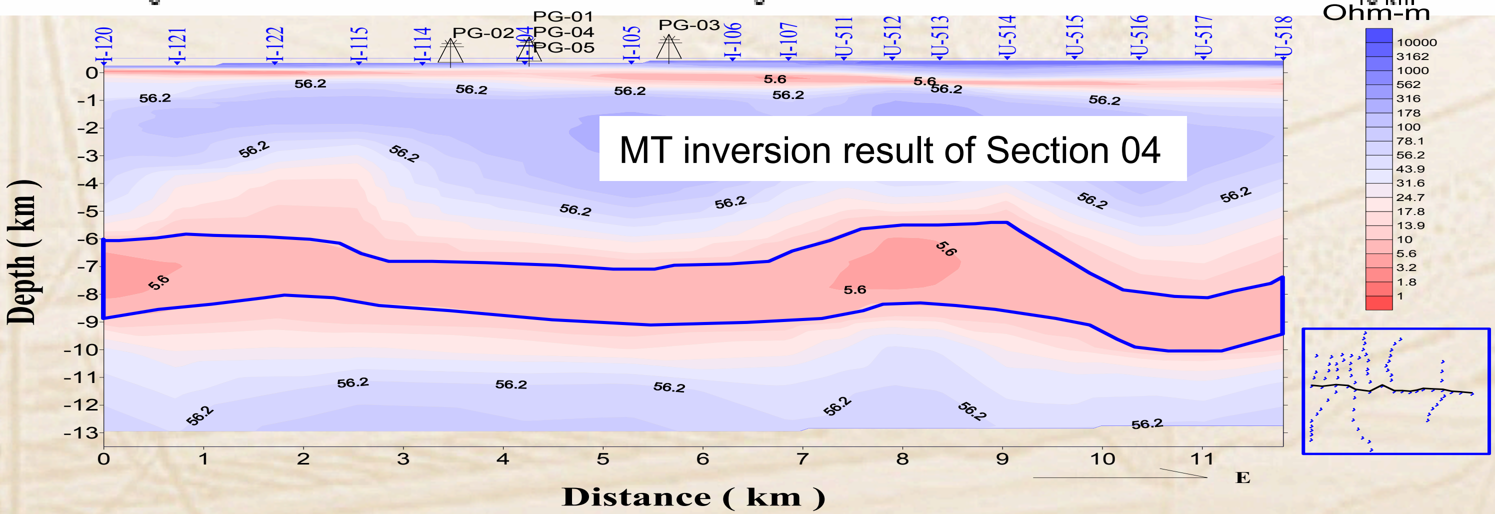
Planned & completed MT survey sites





Iceland: TEM & MT results – interpretation integrated

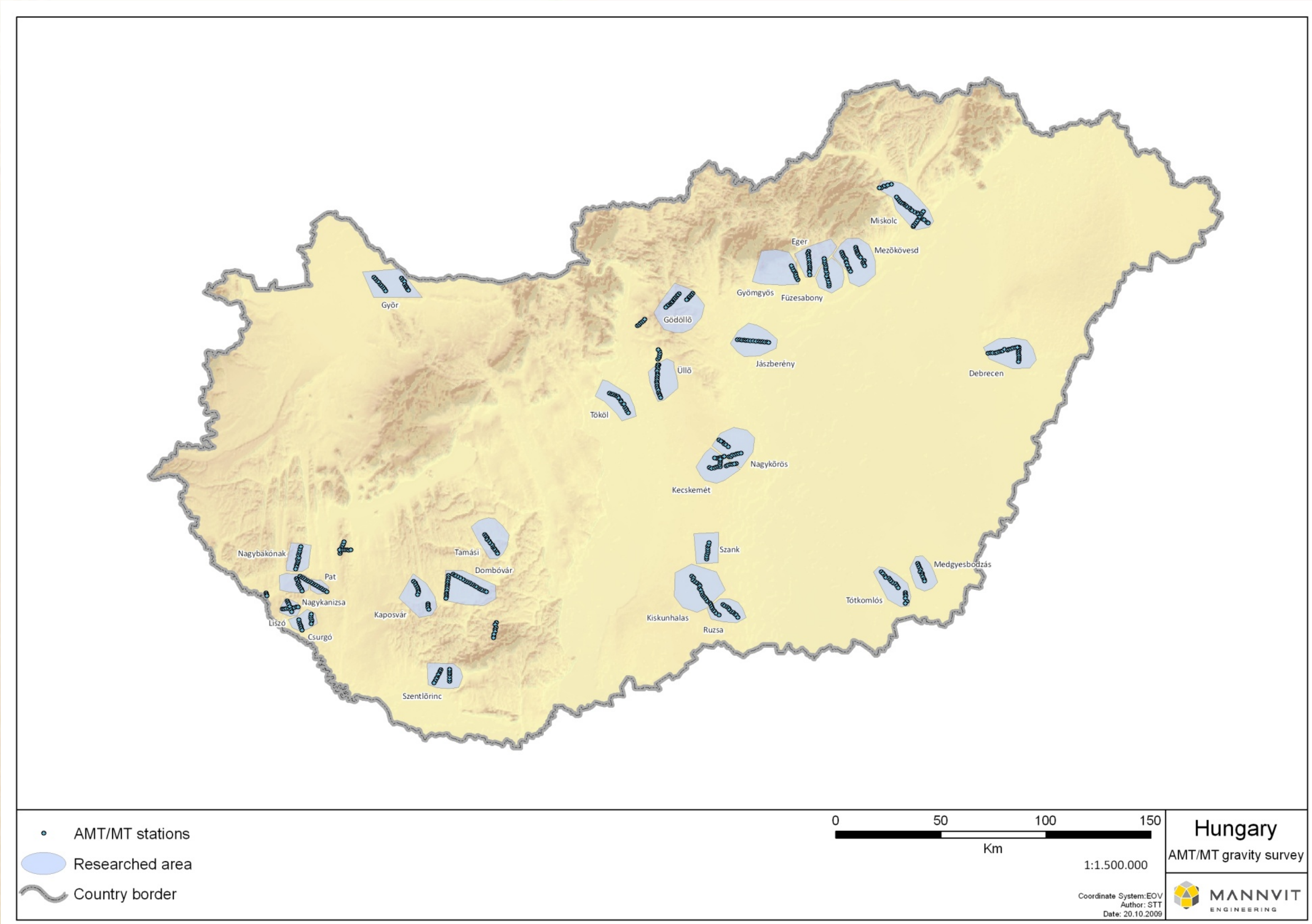




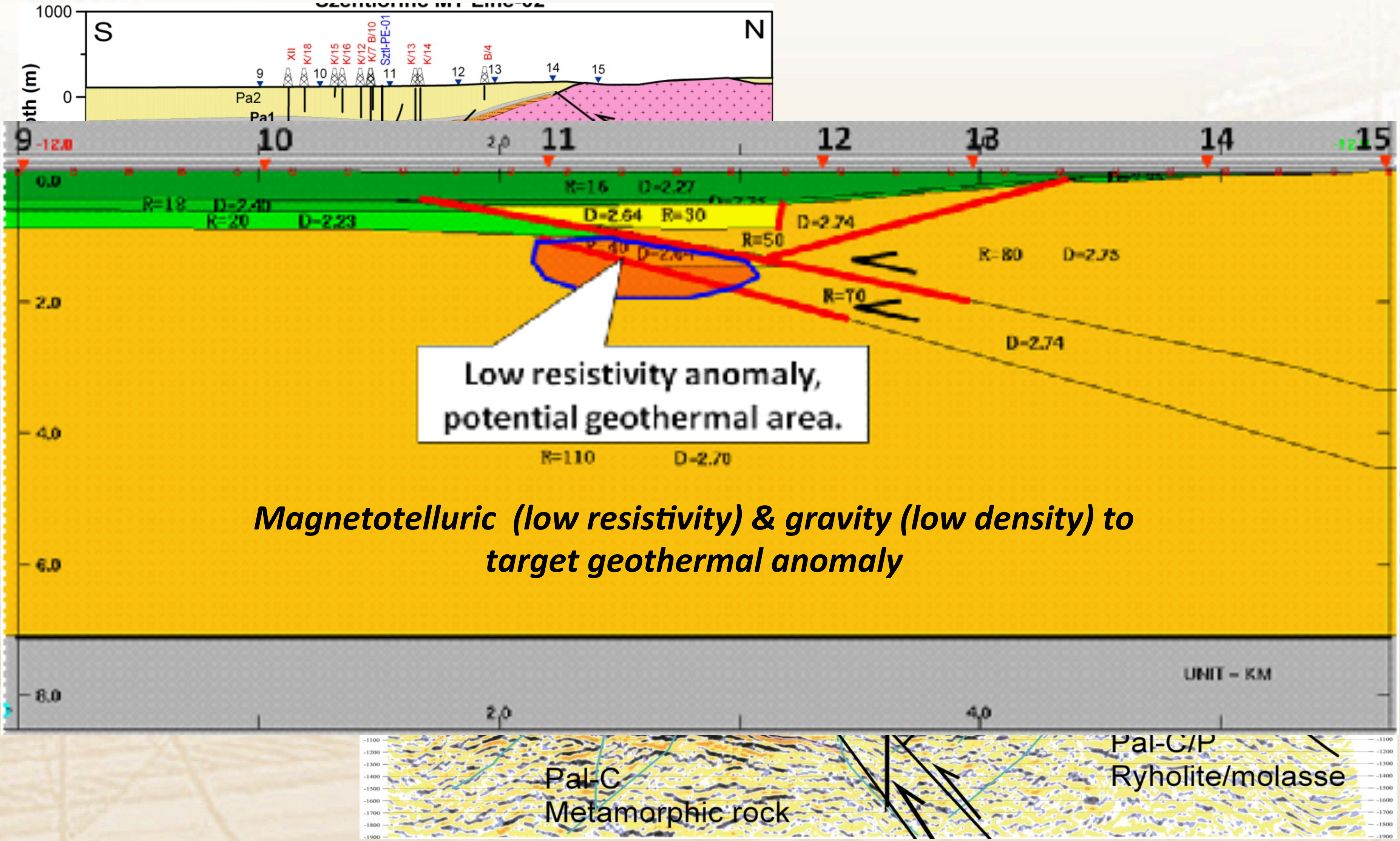
Hungary: punch line

- Hungary is rich in low heat entropy geothermal resources.
- Reliability of previous data was poor.
- Earlier surveys were not aimed for geothermal exploration.
- MT & gravity survey was performed for potential geothermal evaluation areas.
- Integrated interpretation helps to select drilling location.
- Drilling result showed success on 1st evaluation well → 4 MW
- More drilling is ongoing & planned.

Hungary AMT/MT & gravity survey map



Hungary: Integrated interpretation



MT instrument field calibration

Field gravity survey calibration

Hungary Gravity Base Network Data

<u>4145. Csákán</u>
Y= 513 961;
X= 133 820;
Elevation: 126.653 m
g = 980 718.679 mgal

Geothermal drilling success! 4 MW

Video is at www. KMStechnologies.com

Hungary conclusions

- Interpreted two 1st-class (deep faults) & one 2nd-class (shallow faults) potential geothermal zones in Szentlörine survey area;
- Anomalies buried at depth between 1,000 m ~ 2,000 m;
- Conductive heat flow from magma through sediments to surface is main geothermal source;
- Deep fault may extend through crust & reach mantle;
- Successfully drilled 1st evaluation well near Szl in 09/2009;
- 85°C hot water with peak heating capacity of 4 MW at depths of 1,620 to 1,790 m;
- The total project scope: Possible to supply 700,000 homes in Hungary with geothermal energy within next decade.

Geothermal relevant Examples of integrated EM

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- Hungary

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- Hawaii, USA

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- Imperial Valley, CA

- Monitor (induced seismicity)
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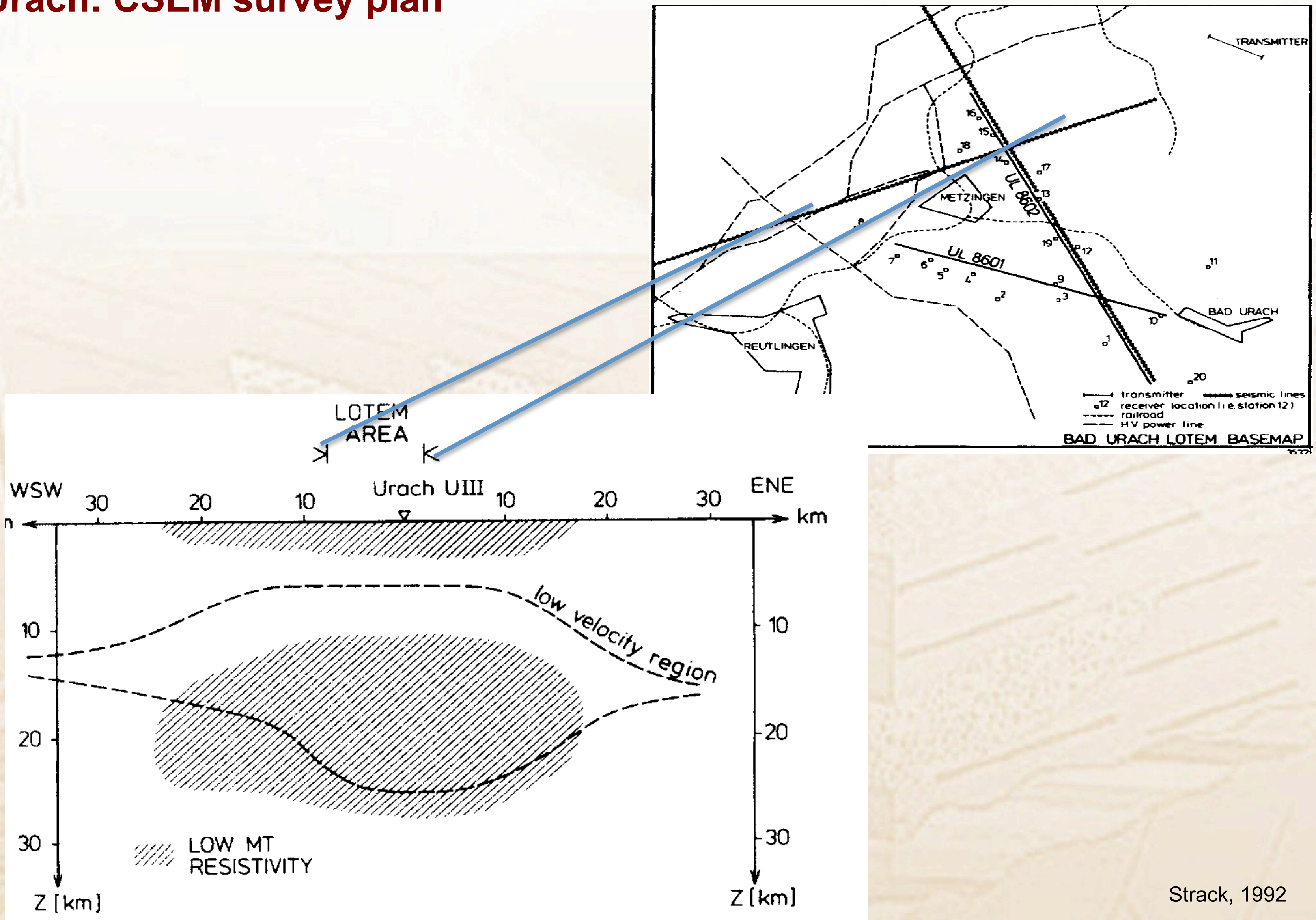
- Ghawar field, Saudi
- Kuwait

- Environ. Compliance
- Control reservoir flow

Urach geothermal area

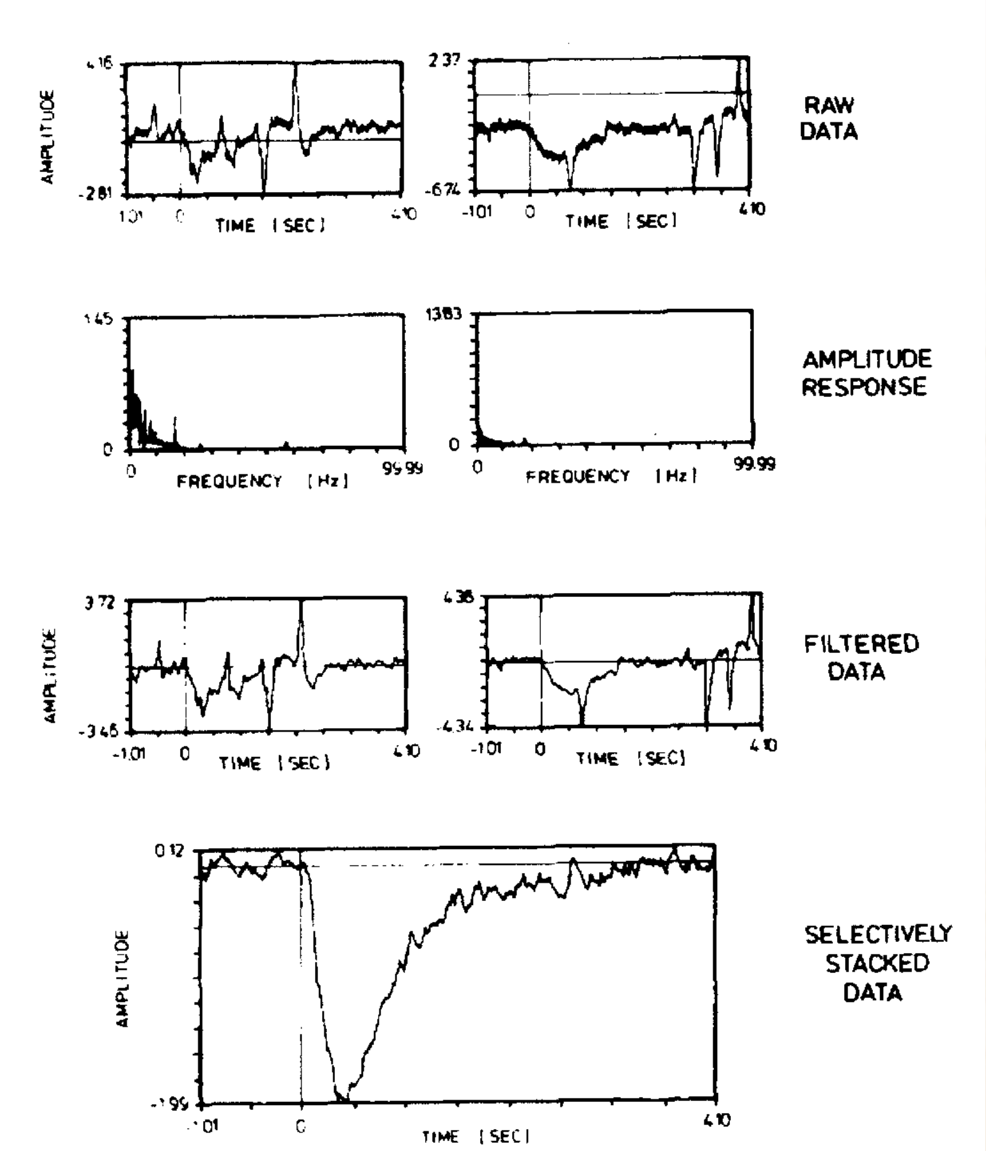
- A low velocity anomaly is known
- A low resitivity anomaly is known from MT, depth to top is mostly unknown
- Objective tCSEM™: Define top of low resistivity zone better.
- Problem: a lot of electrical noise

Urach: CSEM survey plan



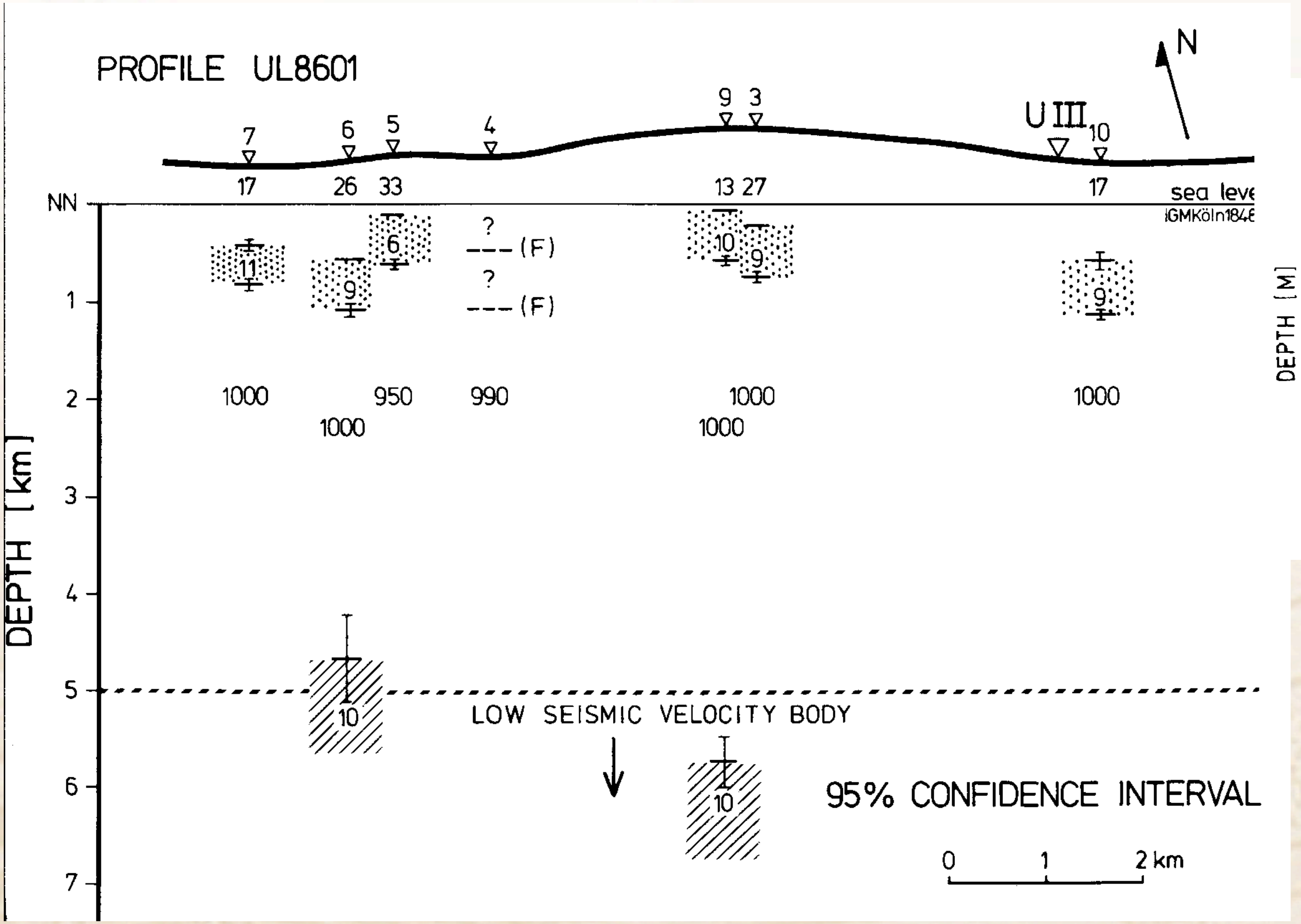
Strack, 1992

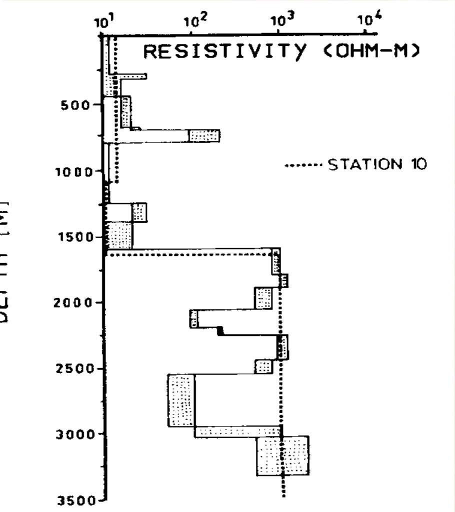
Urach: processing example (6)



Strack, 1992

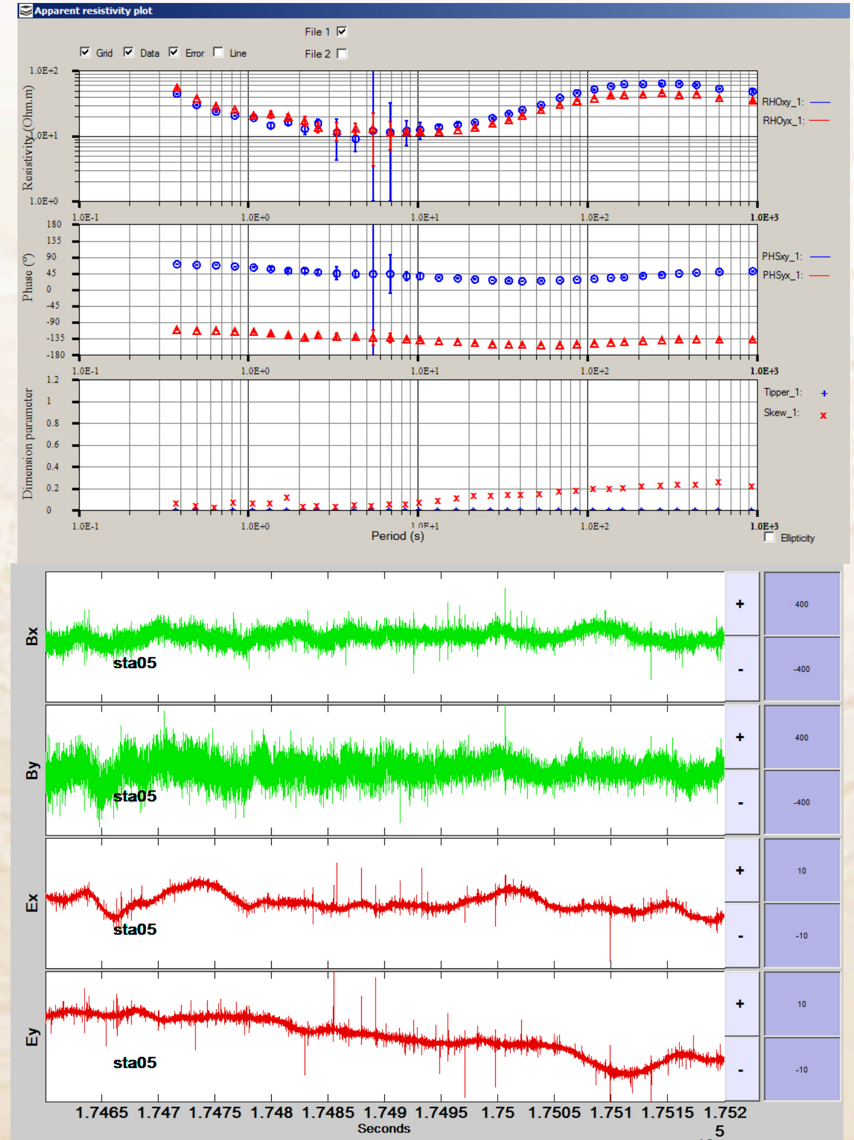
Urach: interpreted section & log





Strack, 1992

University of Hawaii geothermal project: KMS 820 data



Courtesy E. Gaspericova 2012, LBL-NL

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Why EM & Seismic are complimentary

- **Seismic** detects container **boundaries**, **EM** the **fluids** inside
- Determining composition, boundaries and movement
- Best quality data! - both
- Combination of Seismic and EM offer best solution
- EM has proven as valid DHI (Direct Hydrocarbon Indicator)

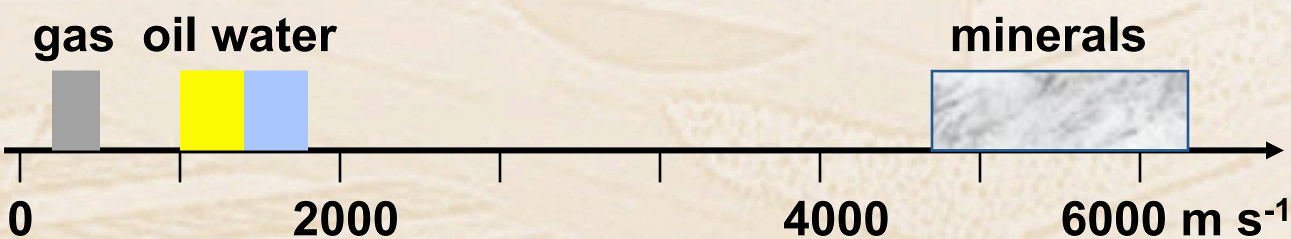
SENSOR CAPABILITY	RESOLVING POWER				
	Distance	Fluid	Surface-to-surface	Borehole-to-surface	Borehole
Seismic	Excellent	Poor	Excellent	Excellent	Ok (more noise)
EM	Ok (5% of depth)	Excellent (water to HC)	Ok	Excellent	Excellent (less noise & distance)
Gravity	Poor	Ok (oil to gas)	Poor	Poor (no source)	Poor (no source)
Strongest Synergy	Seismic	EM/seismic	Seismic/EM/gravity	Seismic/EM	Seismic/EM/gravity

Elastic properties of rock constituents

Mean values & overview

	V_P (m/s)	V_S (m/s)
Rock forming minerals:		
Quartz	6000	4100
Calcite	6600	3400
Dolomite	7300	4000
Pore fluids:		
Water	1450 … 1700	no
Oil	1000 … 1400	shear
Gas	300 … 400	wave

Very similar

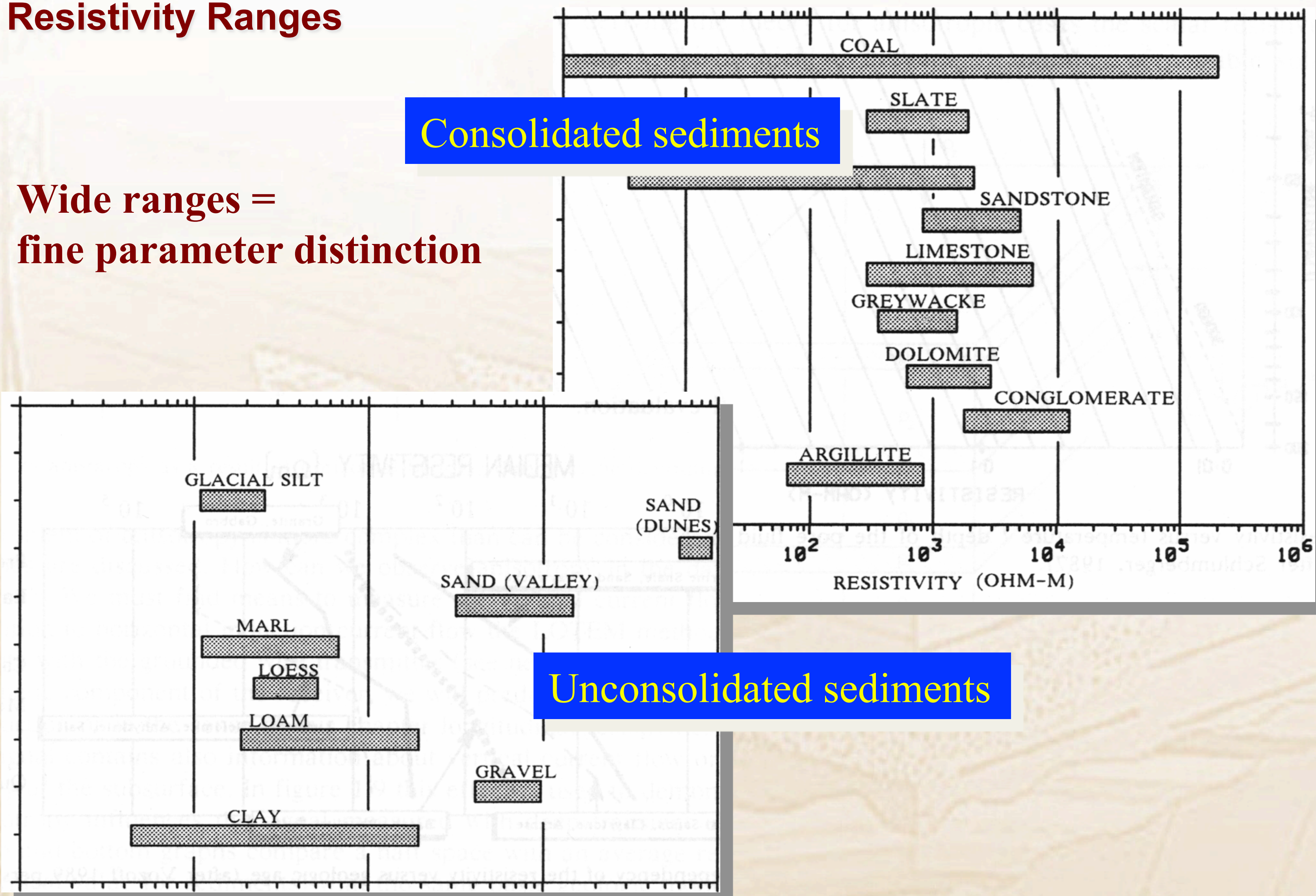


→ Velocity decreases with increasing porosity

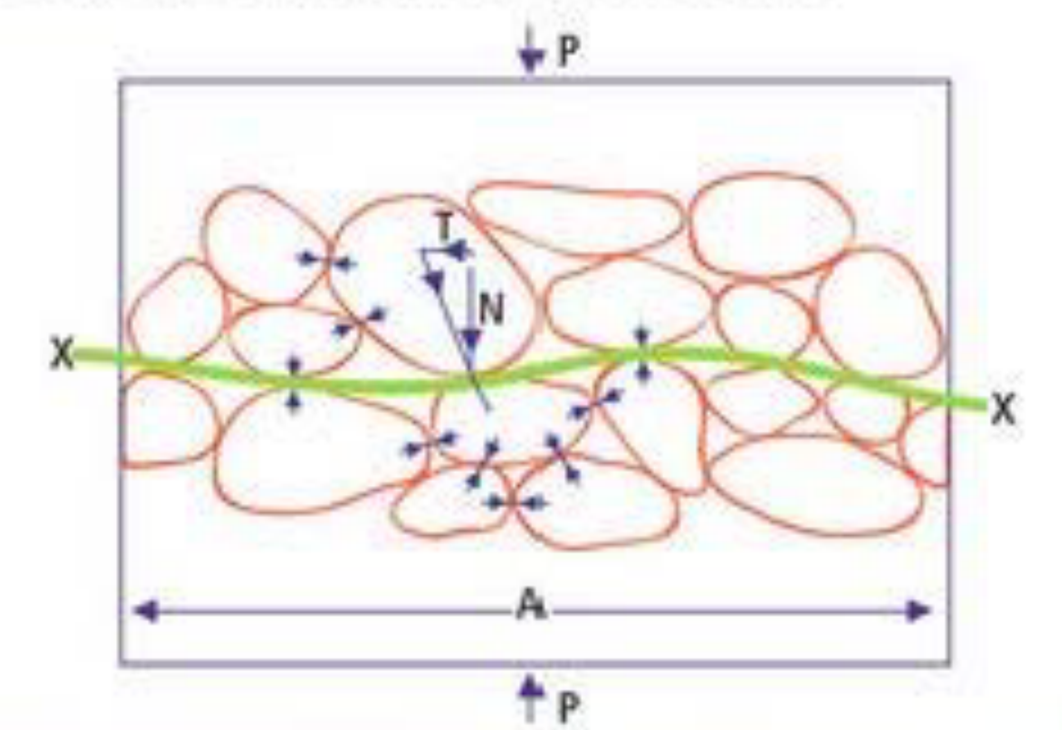
SYS99

Resistivity Ranges

Wide ranges =
fine parameter distinction



Reservoirs seal: EM & microseismic - effective stress



- Overburden & fluid stress in balance
- When fluid pressure too high →quick sand
- Seal BRITTLE → porosity reduction → resistivity increase
- Seal FRACTURE →porosity increase→ **resistivity increase**
- Microseismic signature from fracturing
- EM responds to fluid movements →
- EM signature from brittle & fracturing

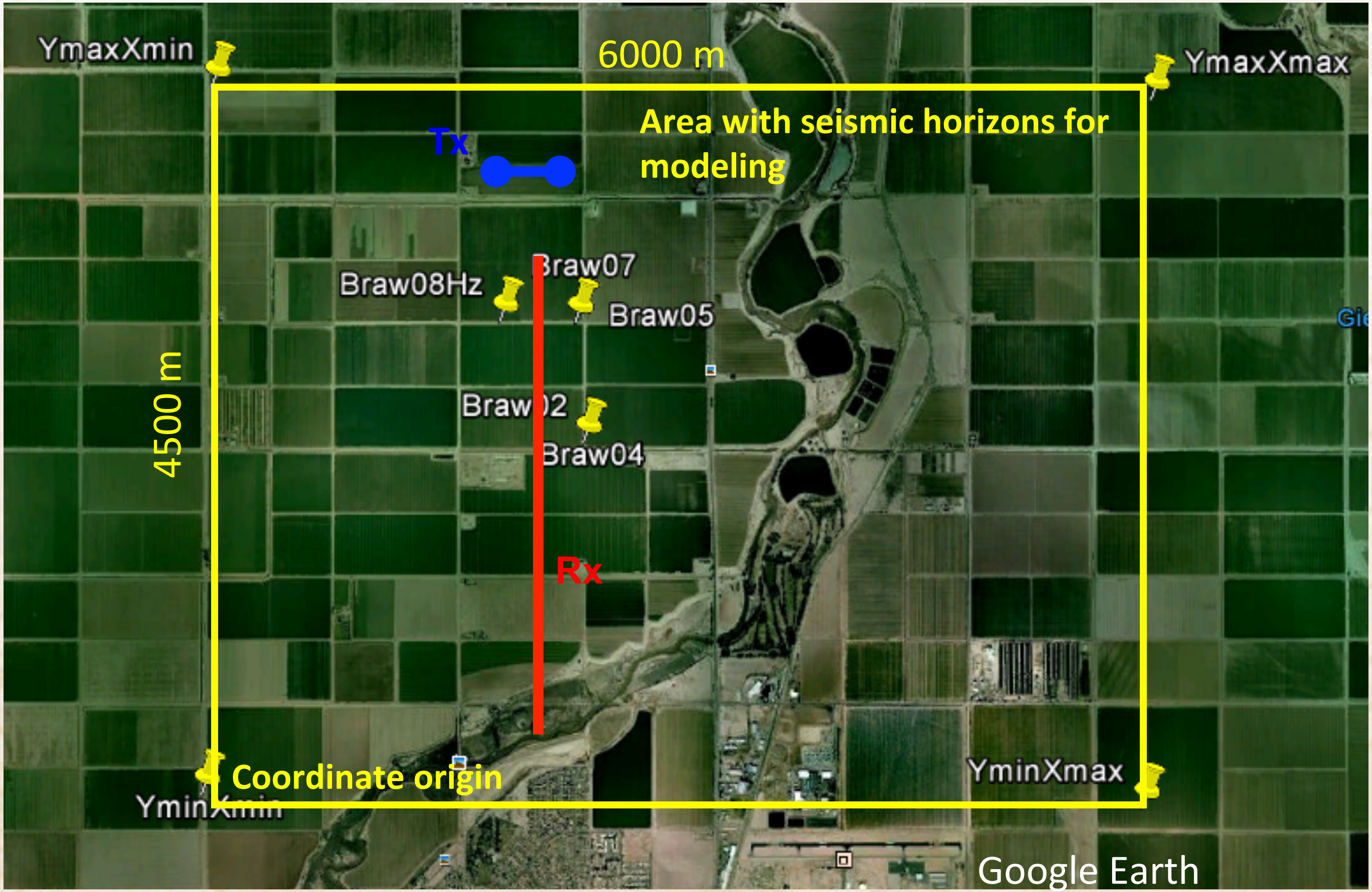
After Carlson, 2013

Feasibility case history: Imperial Valley, CA - Brawley punch line

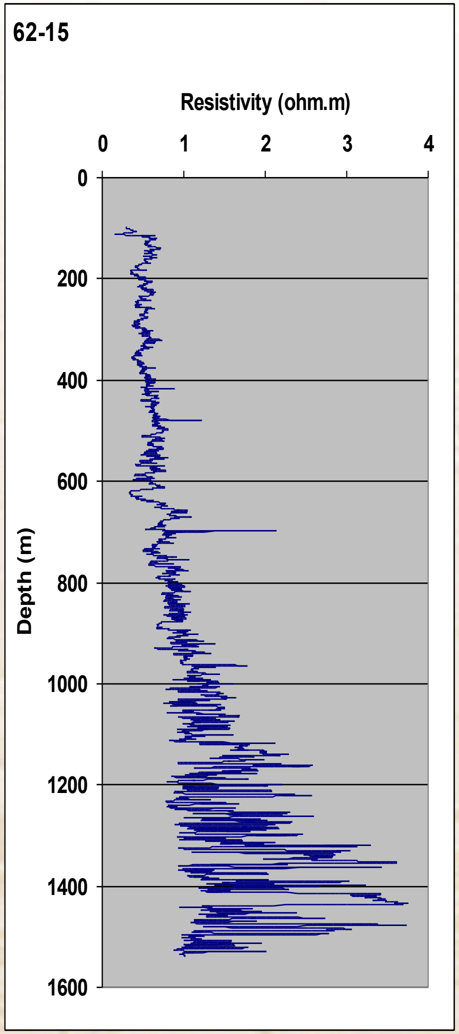
- Geothermal power plant producing since 1980s
- Production in decline; needs to go to 50 MW
- 30 years of microseismic monitoring – no answers
- Low resistivity low contrast environment
- Little information about the reservoir sweet spots.
- Carried out EM feasibility to monitor sweat spots in reservoir

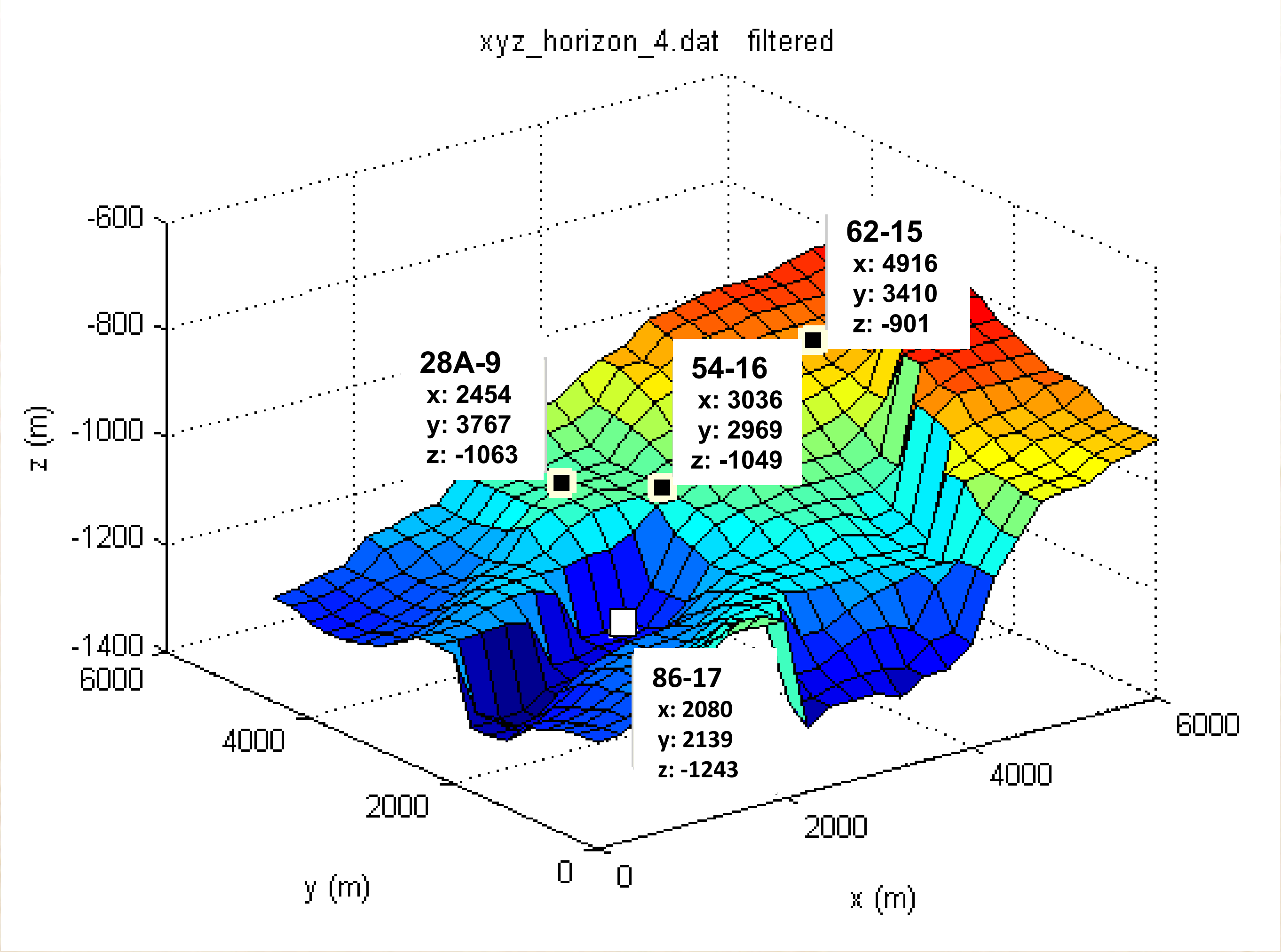
Imperial Valley: Area with seismic horizons

Transmitter Tx and receiver profile Rx



Imperial Valley: INPUT DATA: seismic horizon 4 with well positions

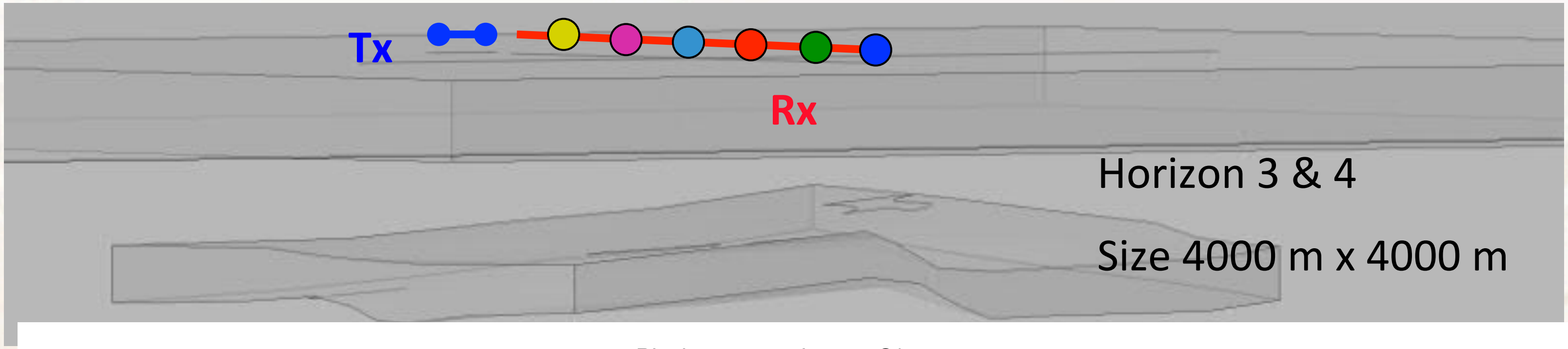


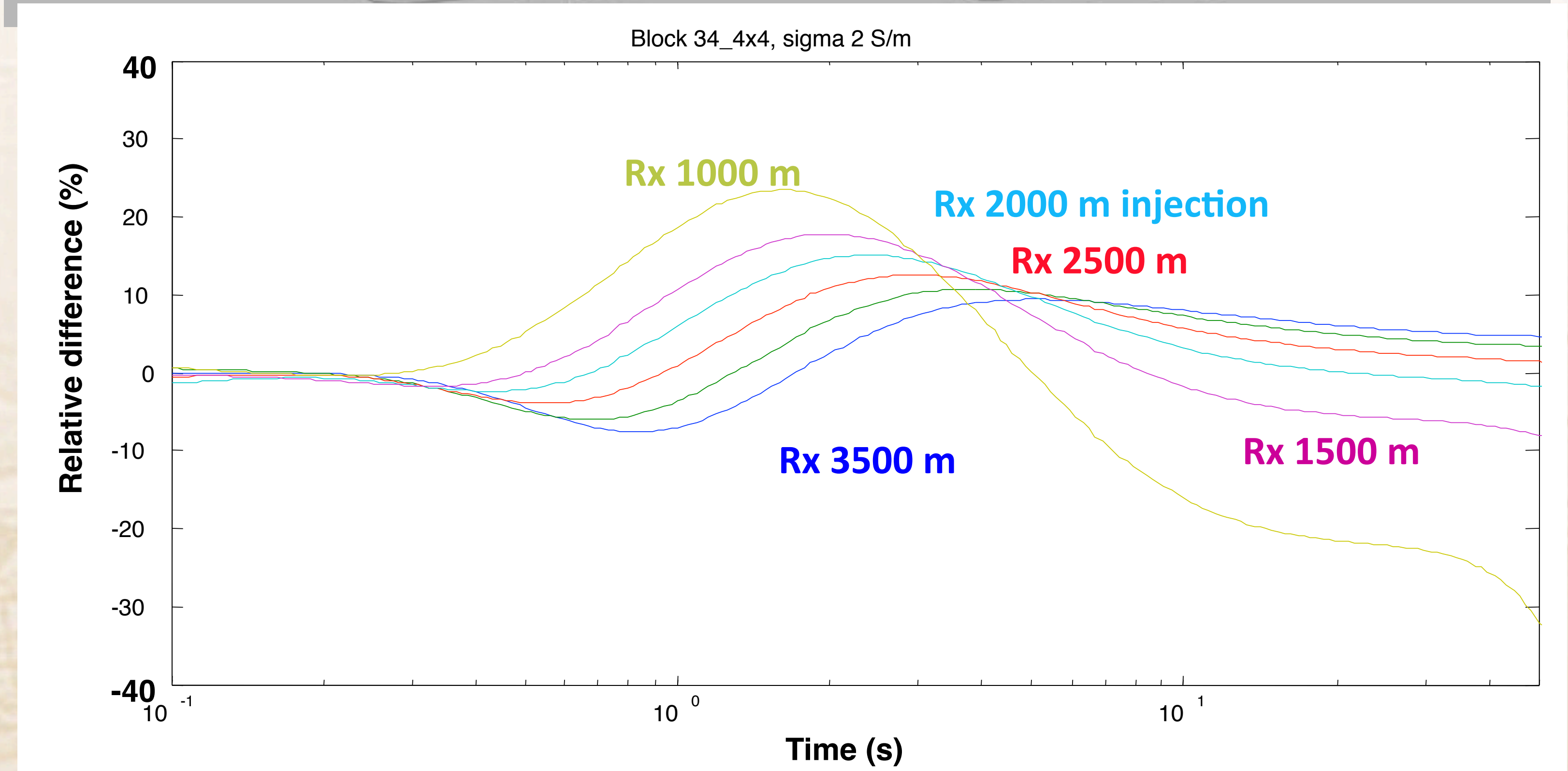


Imperial Valley: Workflow

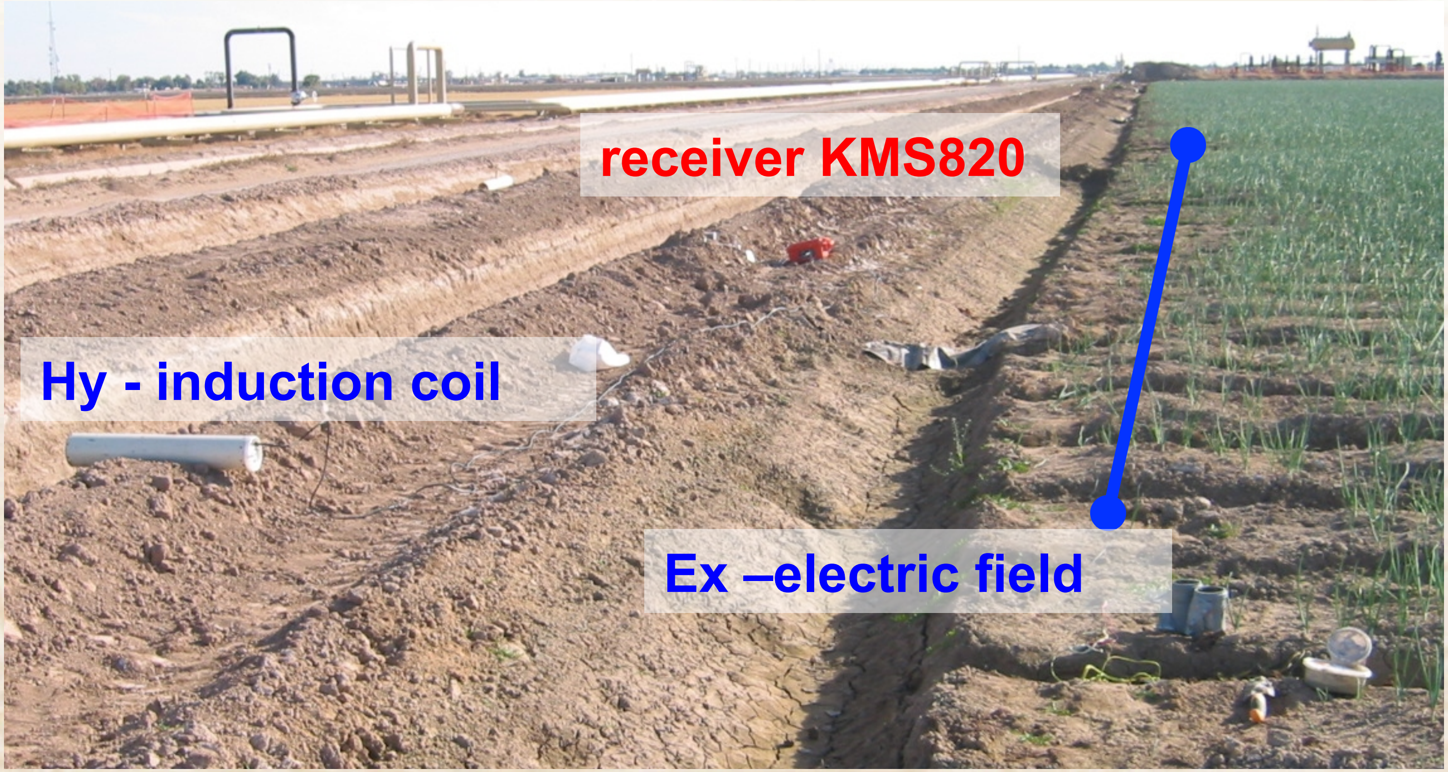
- Reference model: conductive background (1 ohm.m)
- Build 3D model, after verification add seismic reservoir layers, model and calculate DIFFERENCE from baseline
- FIRST: compare different reservoir sizes (production depletion)
  - Small – medium – large reservoirs
- SECOND: verify that voltage can be measured → signal

Imperial Valley: 3D reservoir: relative difference, LARGE block

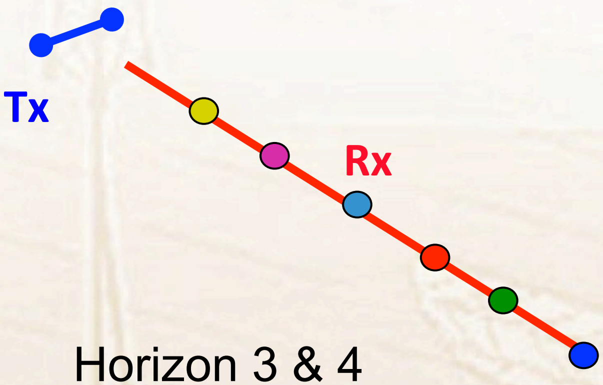




Imperial Valley: Noise test setup



Imperial Valley: RESULT: transients with expected noise levels / Tx current



Horizon 3 & 4

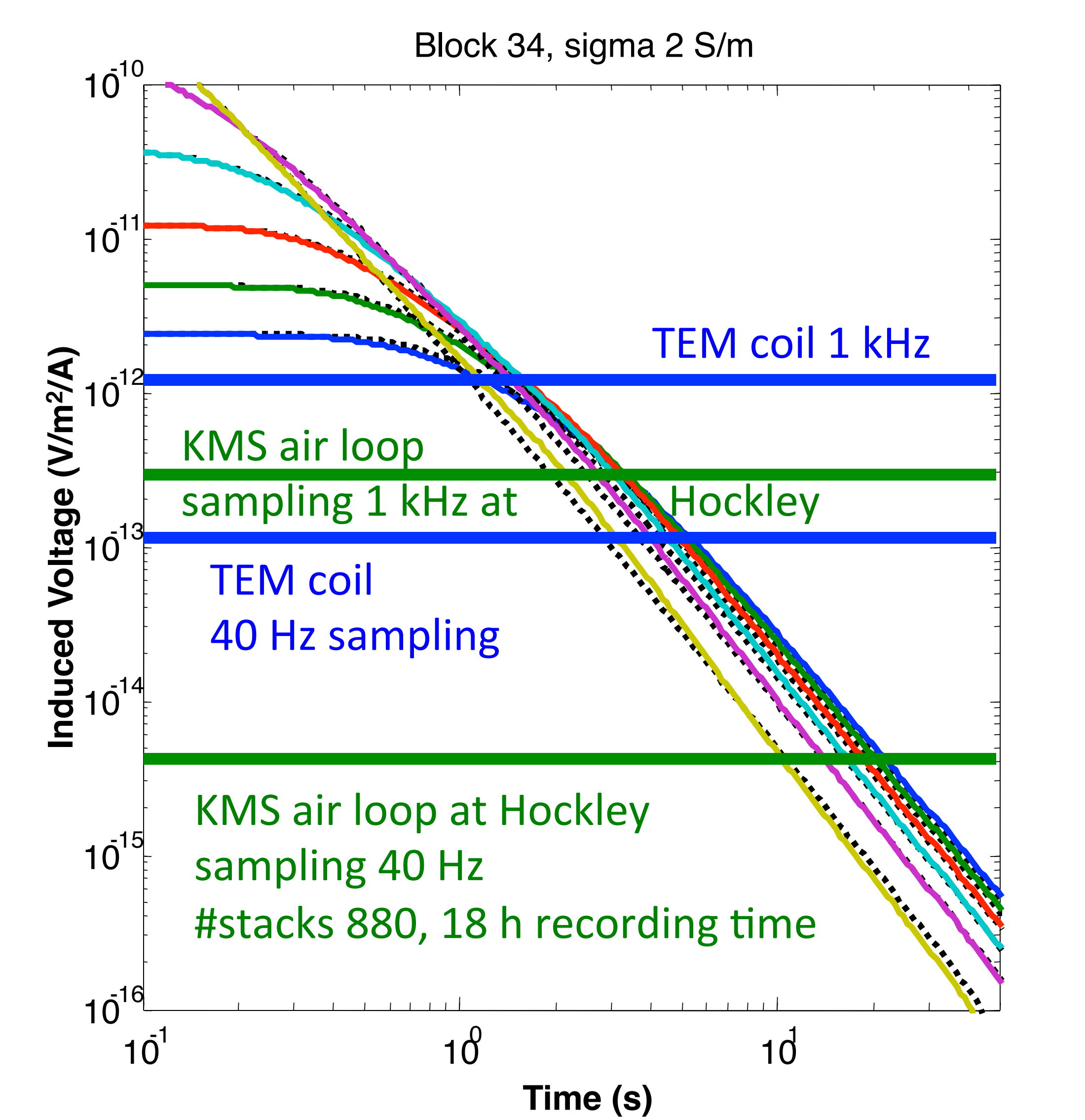
size 6000 m x 4500 m

whole block

Tx -current:

300 A
2x longer than 200 m
2x switch step over

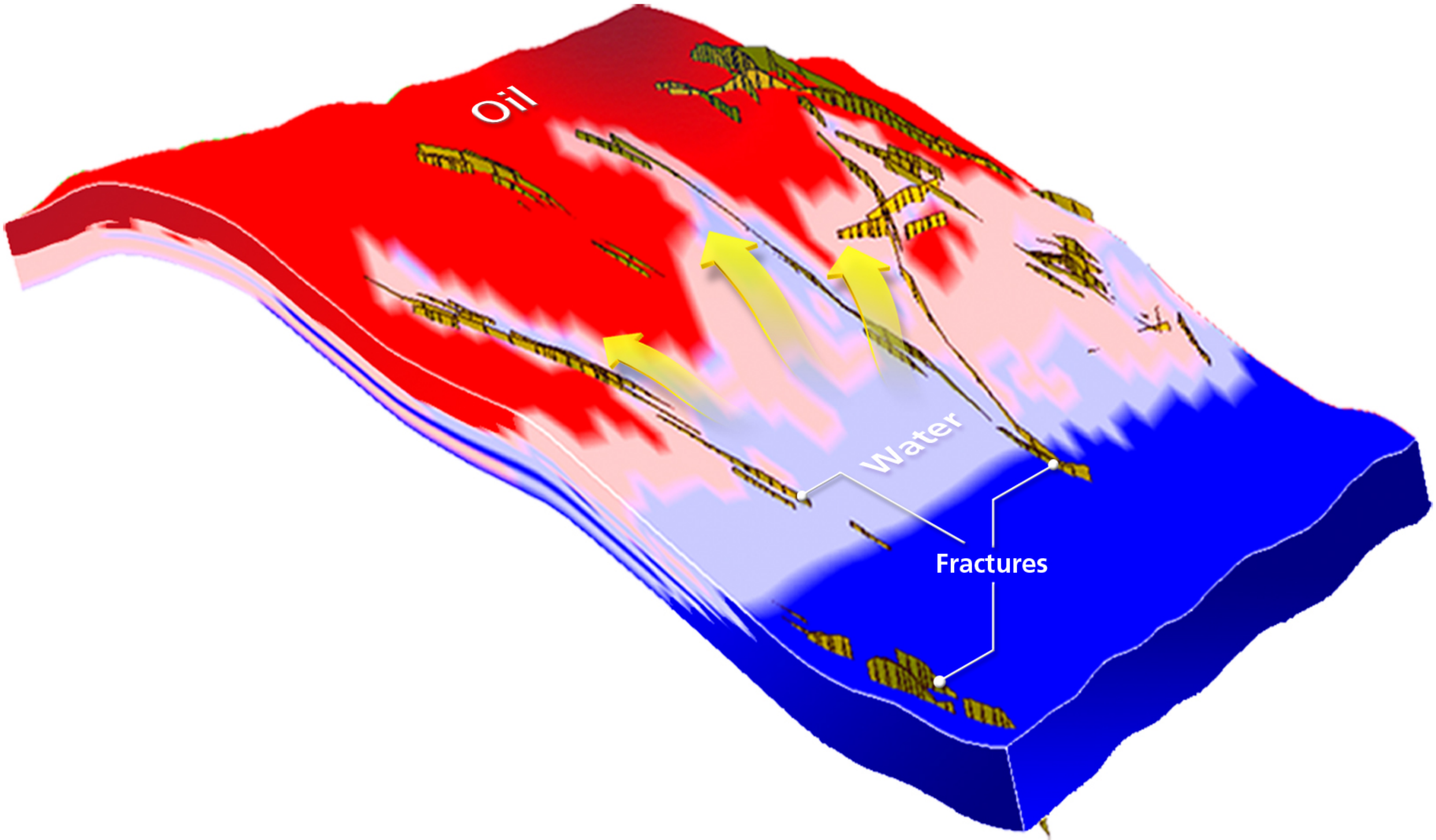
= 1200 A



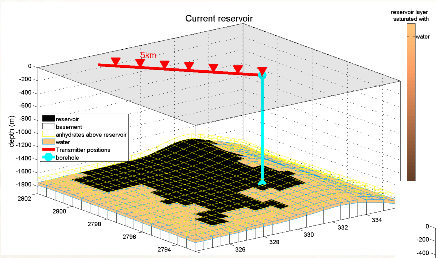
Geothermal relevant Examples of integrated EM

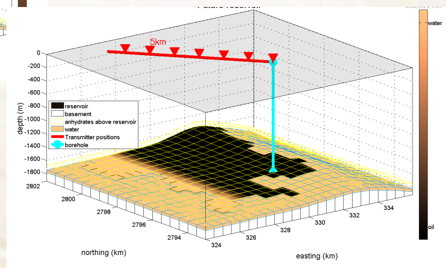
Exploration	Pre-drilling	Development	Production
• Iceland • Hungary	• Urach, Germany • Hawaii, USA	• Monitor (induced seismicity) • Imperial Valley, CA	• Ghawar field, Saudi • Kuwait
• MT is first choice • Integration • Target well location	• Detailed EM (CSEM) • Baseline survey • Risk control • Facility estimation	• Monitor (induced seismicity) • Addition wells (calibration & integration) • Cost reduction	• Environ. Compliance • Control reservoir flow

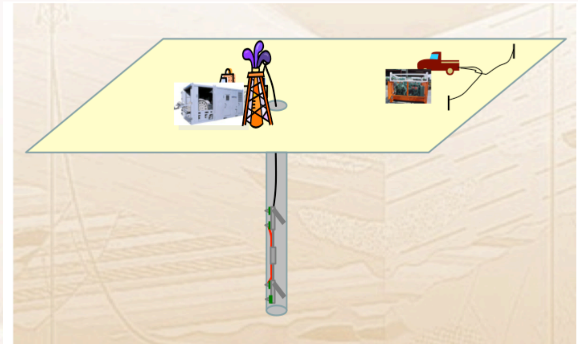
Ghawar: Fluid displacement heterogeneity

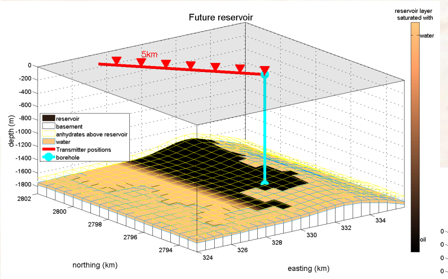


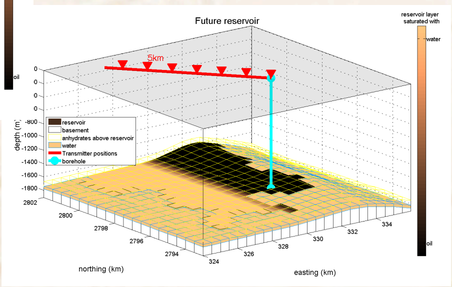
Ghawar: ADD BOREHOLE: Integration!

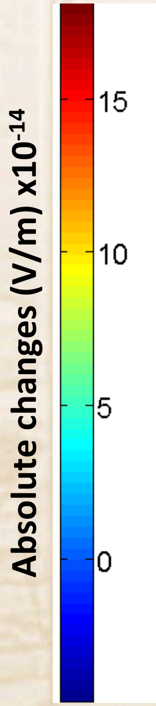


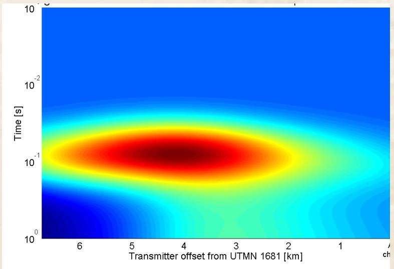




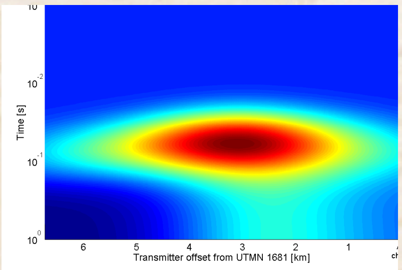


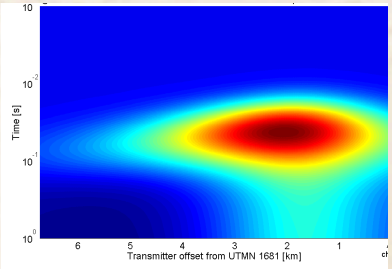






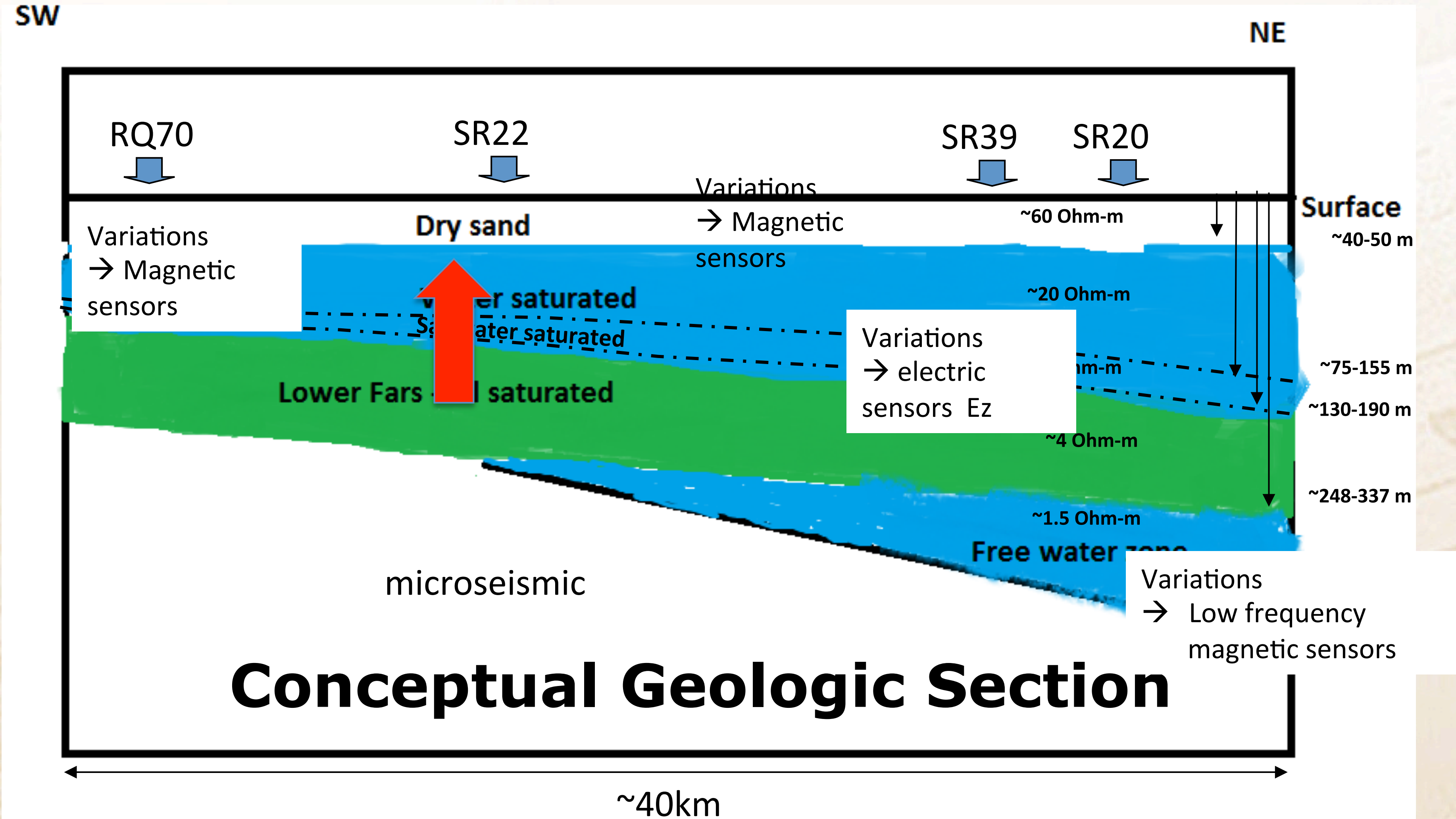
Period of 5 years





After Colombo et al. 2010

Kuwait: geologic sections & objectives



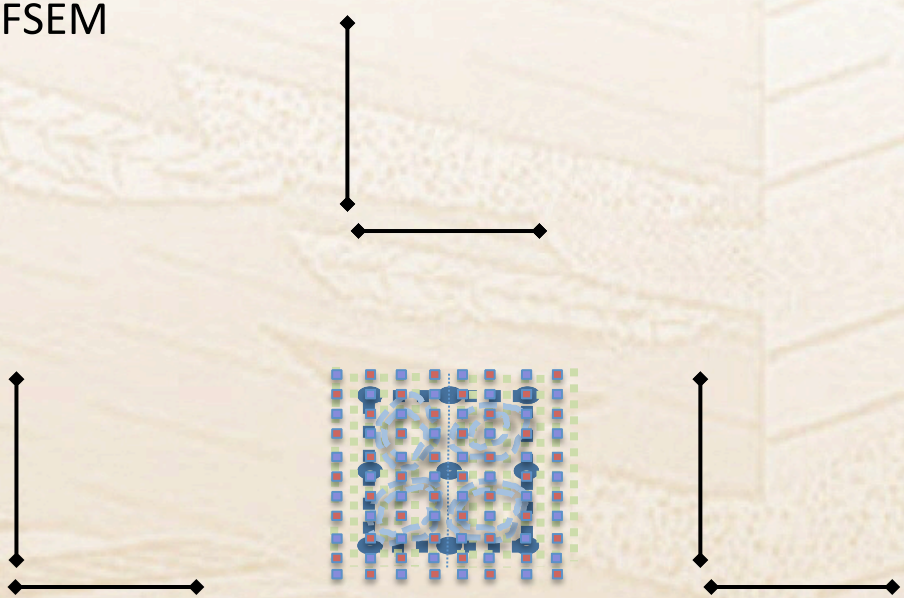
Kuwait: Line layout

Tx length 500 m

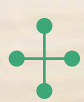
Offsets: 500 - 750 m (TEM)

moving for FSEM

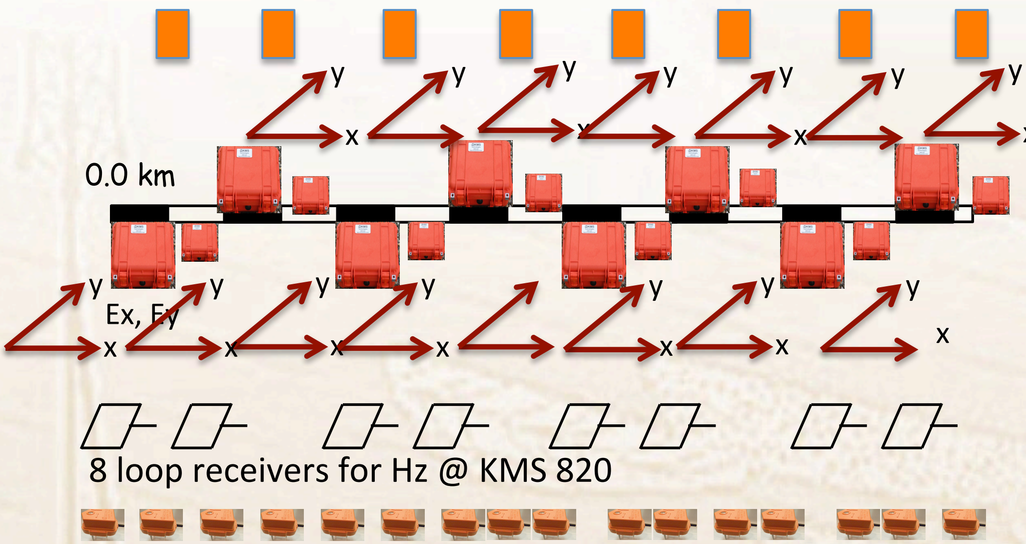
- Transmitters may be ‘L’ shape , inline or broadside
- Consecutive survey may use subset transmitters



Rx reference (possible)



Kuwait: Line layout



8 KMS-029 fluxgate sensor, between KMS 820 site & 831

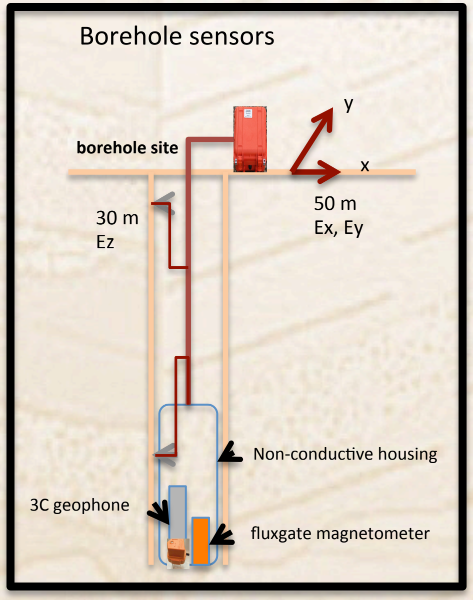
8 KMS 820 acquisition system

8 KMS 831-6; 32-bit interface , 6 channels used @ 100 m intermediate sites

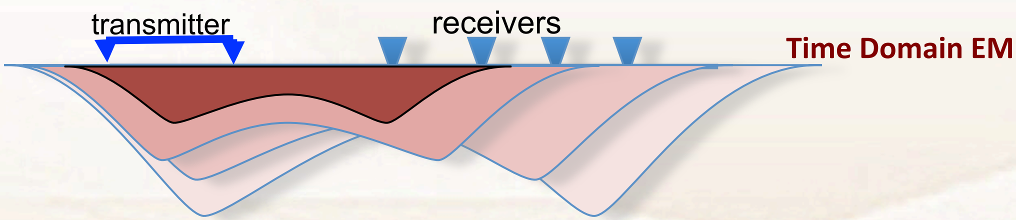
16 Ex & Ey dipole 50 m @ every site

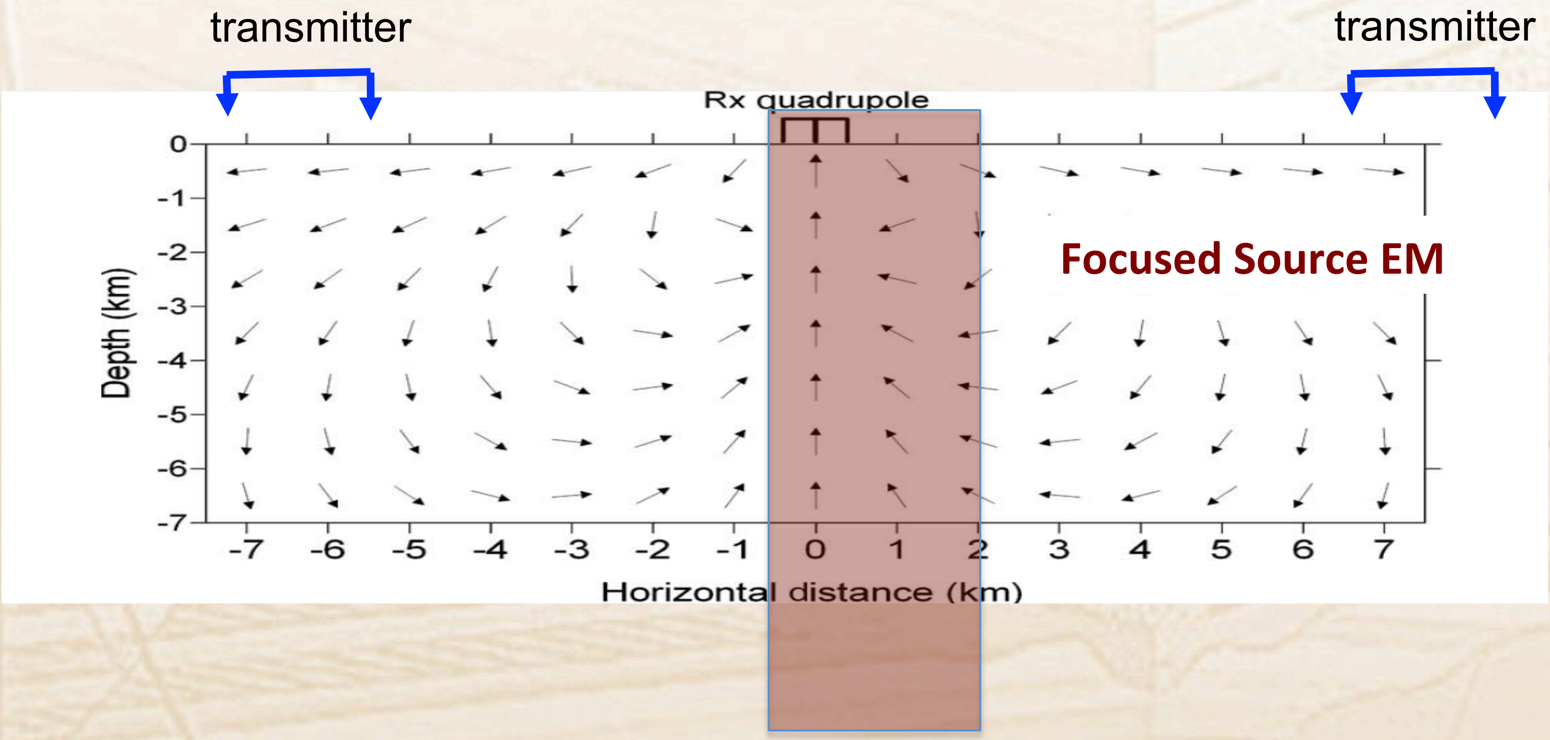
8 loop receivers for Hz @ KMS 820

16 3C geophones at every location



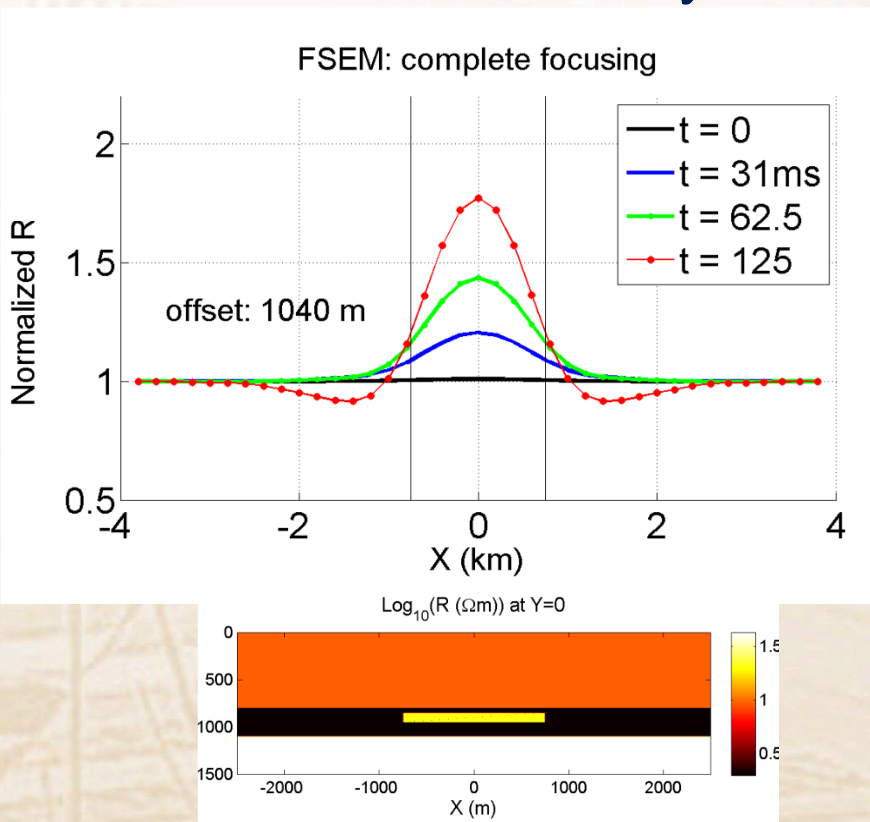
Kuwait test TEM versus Focused Source EM



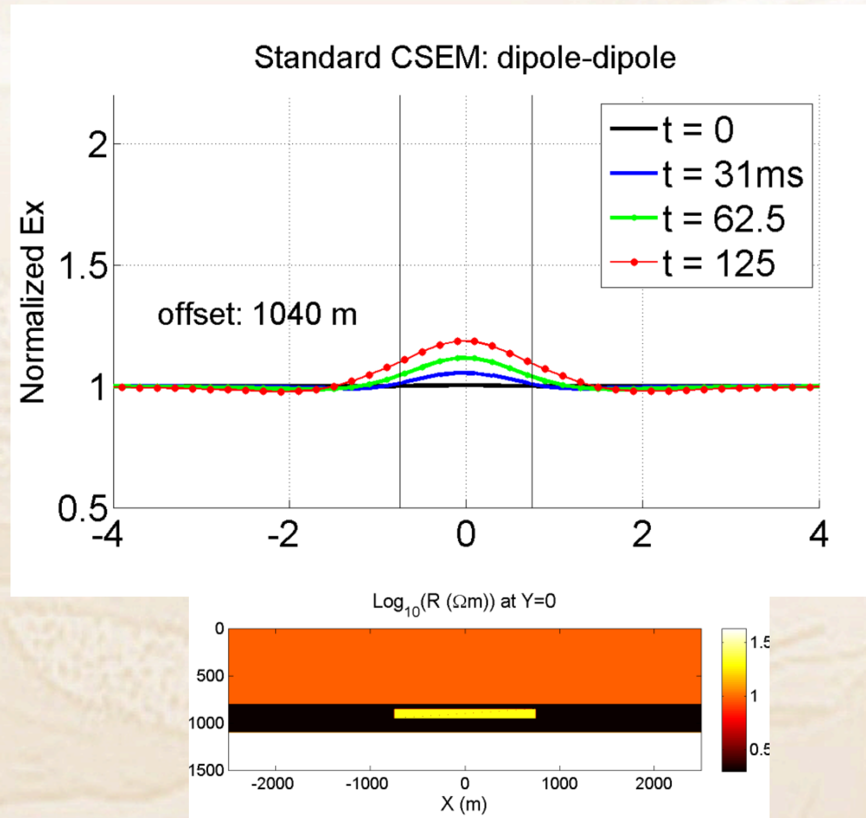


Kuwait test TEM versus Focused Source EM expected results

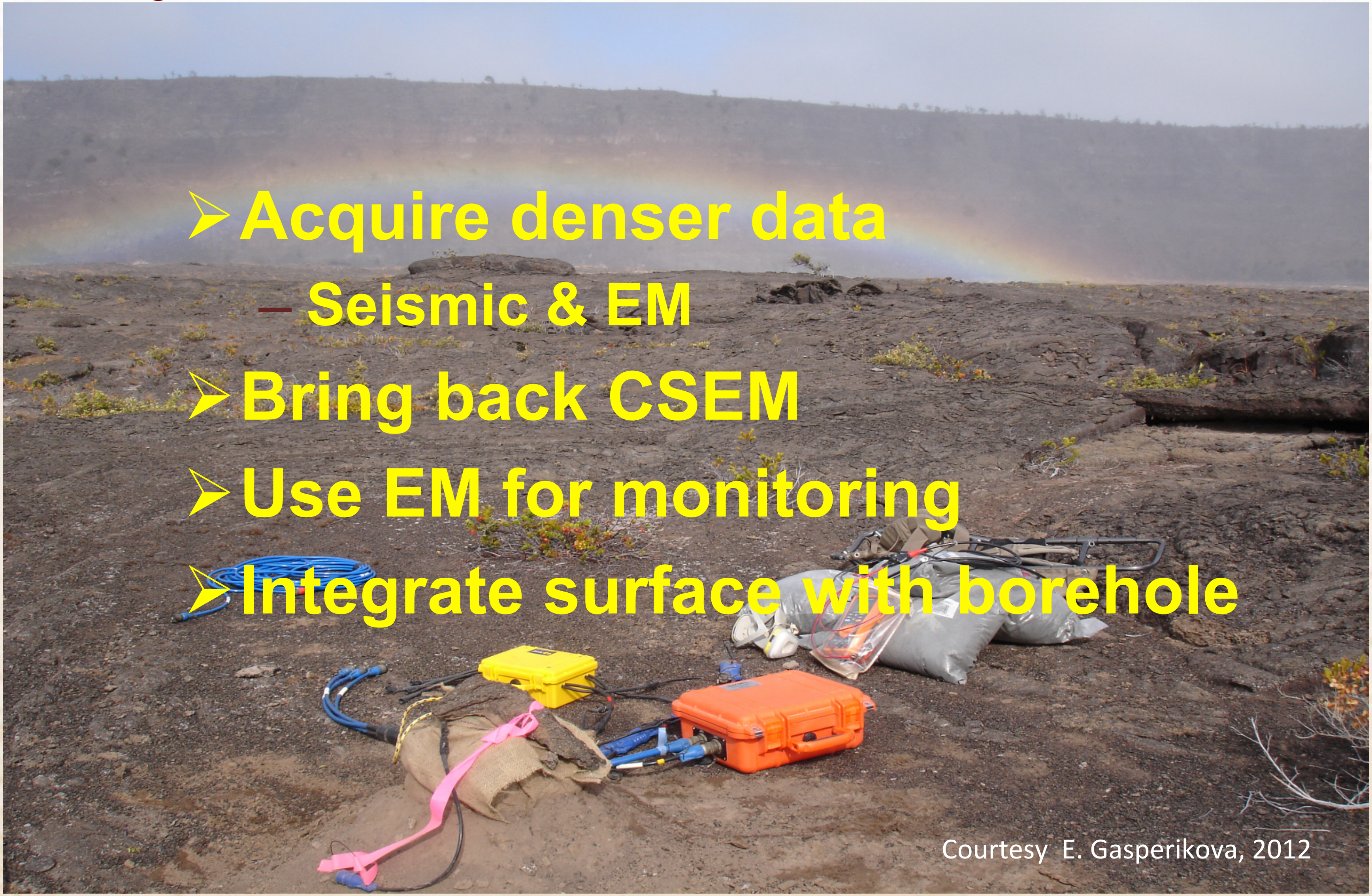
FOCUSED: Anomaly ~75%



Anomaly ~20%



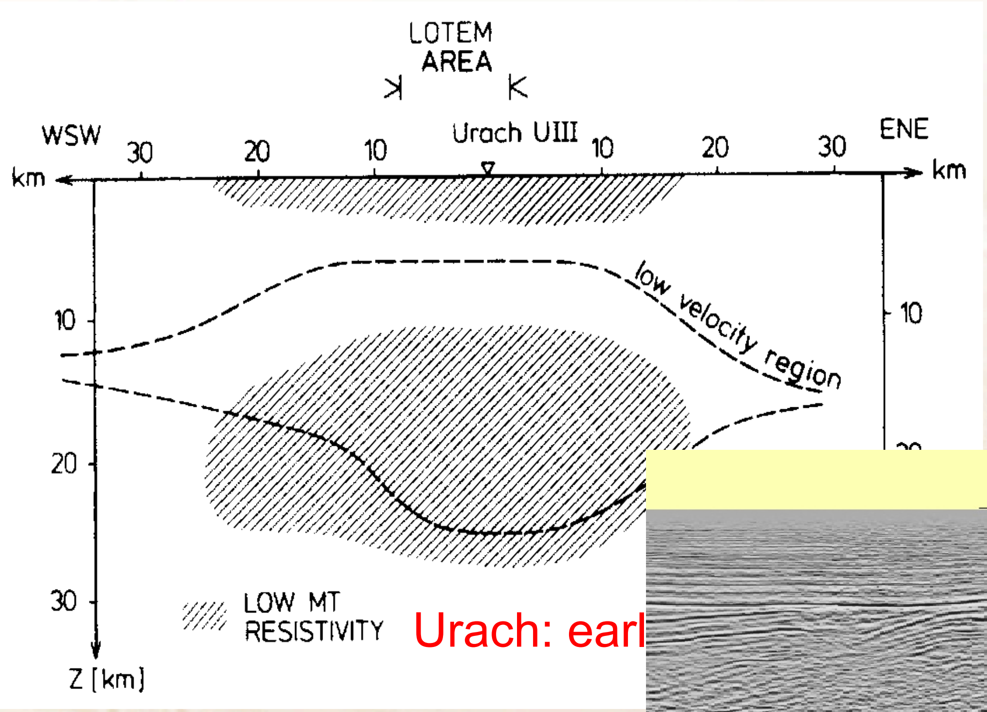
EM for geothermal will



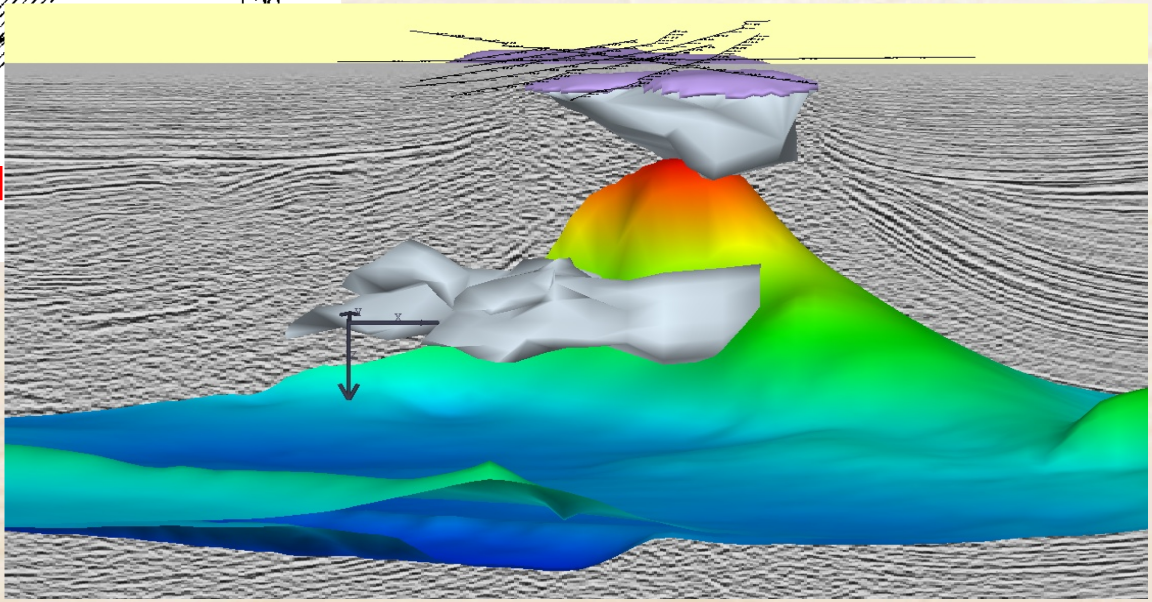
- Acquire denser data
  - Seismic & EM
- Bring back CSEM
- Use EM for monitoring
- Integrate surface with borehole

Courtesy E. Gasperikova, 2012

MT: 30 years of progress



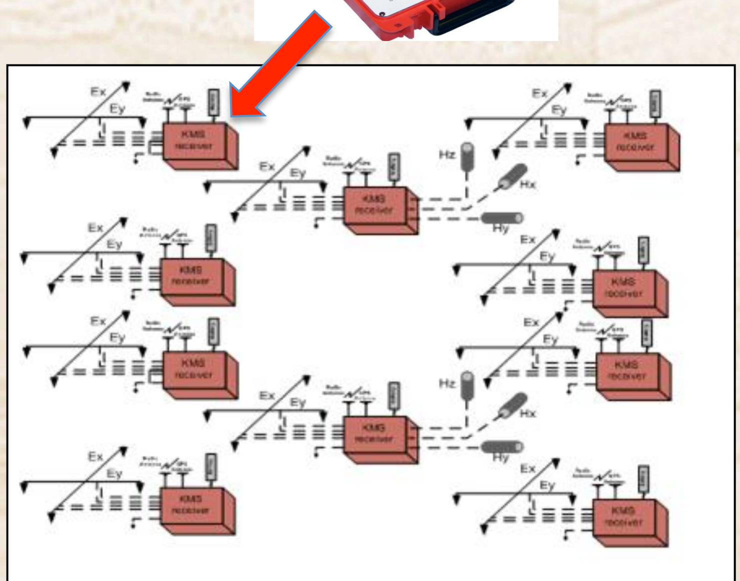
Urach: earl



MT: 2002 vintage

UNPUBLISHED,
courtesy RWE-Dea

1981



3D receiver bin

Handheld QA/Qc

2010