3D Real-Time Inversion of Ultra-Deep Resistivity Logging-While-Drilling

Glenn Wilson & Nigel Clegg

MTnet EMinar – 9 February 2022

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Overview

- Introduction to Logging-While-Drilling
- Ultra-Deep Resistivity
- Inversion
  - 1D $\rightarrow$ 2.5D $\rightarrow$ 3D
- Case Studies

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Acknowledgements

- Halliburton
  - Alban Duriez, Geosteering Manager
  - Neila Kadri, Strategic Business Manager – LWD
  - Sperry Drilling Technology
- Computational Geoscience
  - Eldad Haber
  - Dave Marchant
  - Nigel Phillips
- Halliburton & various operators for permission to publish

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Logging-While-Drilling

Azimuthal Gamma Ray
- Detects natural radiation in rocks (K-U-Th)
- Total or spectral count
- Lithology indication

Directional Sensors
- Navigation
- Orientation

Resistivity
- Azimuthal or non-azimuthal
- Resistivity is related to fluid saturation and porosity

Azimuthal Density / Neutron Porosity

Nuclear tools
- Density – Compton scattering of gamma rays for density
- Neutron porosity – neutron backscattering for porosity
- Mineralogy – backscatted gamma ray spectra from neutron activation
- Chemical or neutron generator sources

Sonic
- Azimuthal
- Slowness (velocity) is related to rock mechanics

Formation Pressure and Fluid Sampling
- Direct sampling of fluids and pressures

Magnetic Resonance Imaging
- Porosity
- Fluid discrimination

Telemetry
- Mud pulse
- EM
- Wired Pipe

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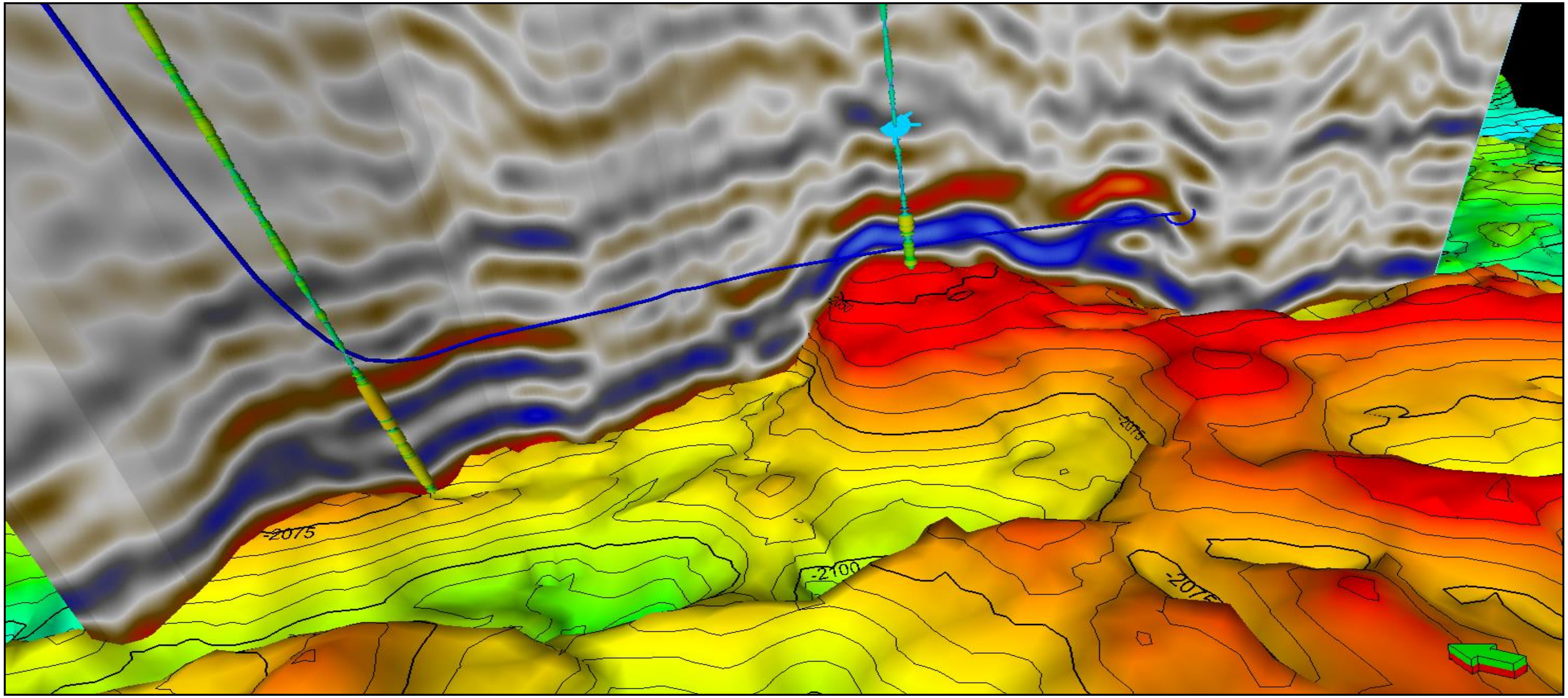
Subsurface Resolution



Sinha, S., Clegg, N., Beset, K., Kristoffersen, I., Kolsto, S., and Marchant, D., “Optimized well planning using 3D EM inversion results.” Paper presented at Abu Dhabi International Petroleum Exhibition and Conference, Virtual, November 2020. doi: https://doi.org/10.2118/202606-MS

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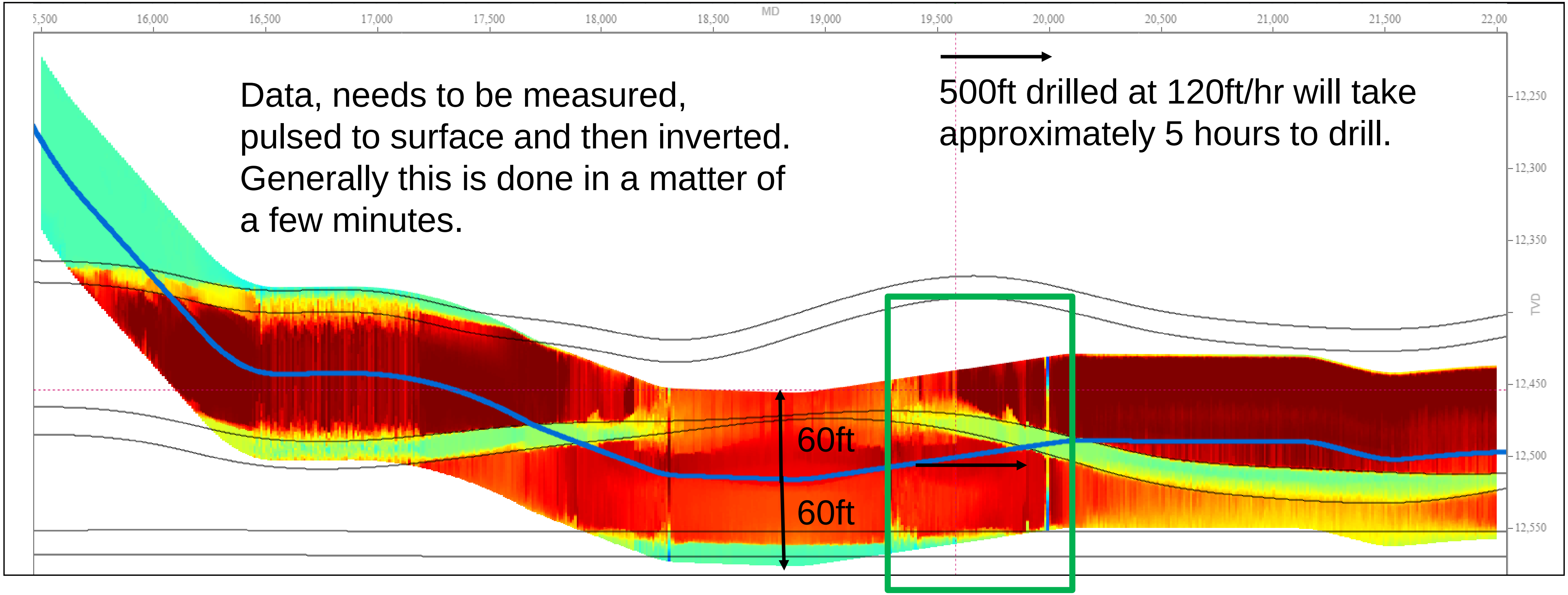
Timing Constraints on Well Construction



- Geosteering decisions need to be made quickly. To avoid this exit smoothly a decision needs to be made early, ideally in the first 50 to 100 ft.
- At best a decision needs to be made in the first 30 mins.
- These decisions are made following trends in data, not on 1 data point.

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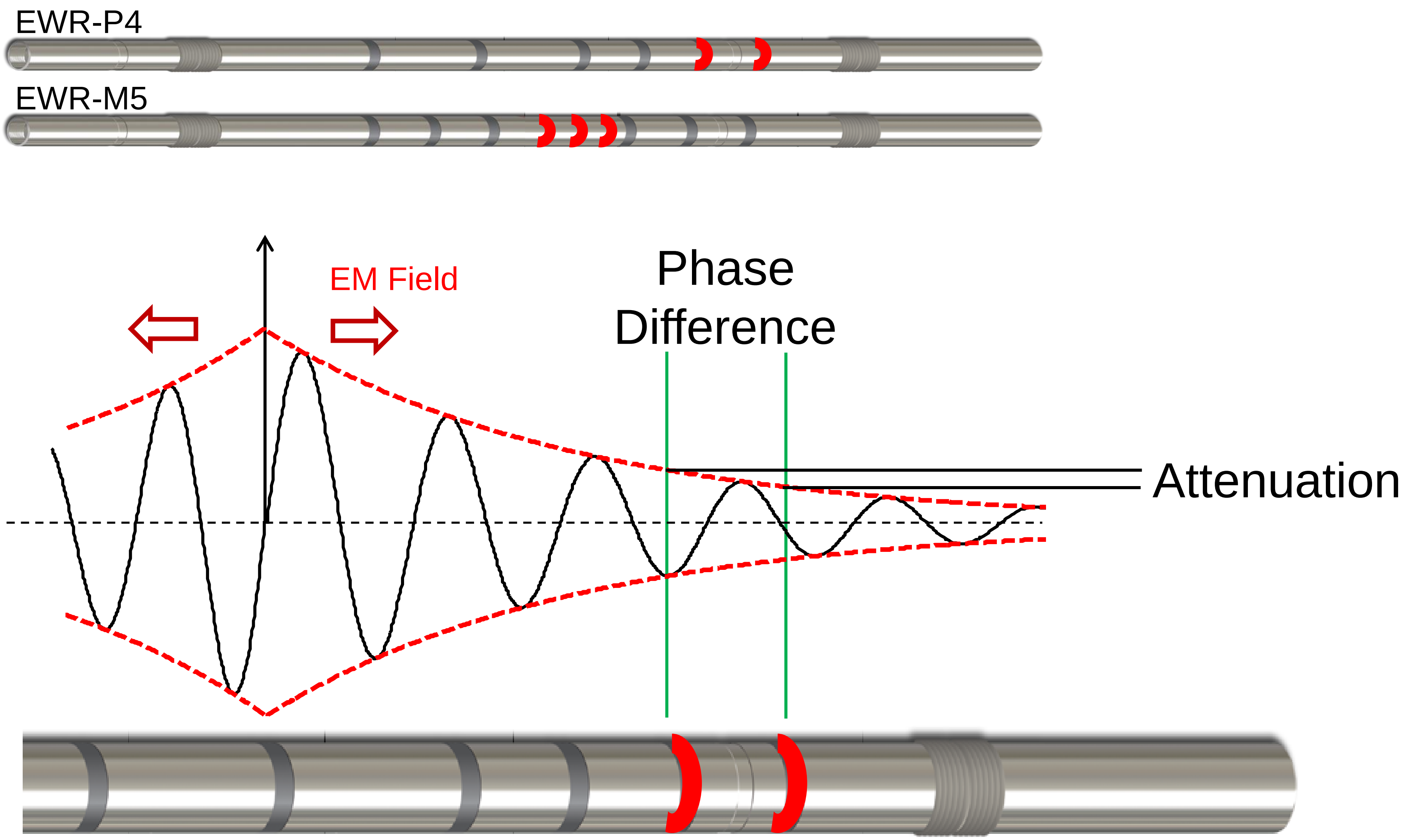
Resistivity Logging-While-Drilling



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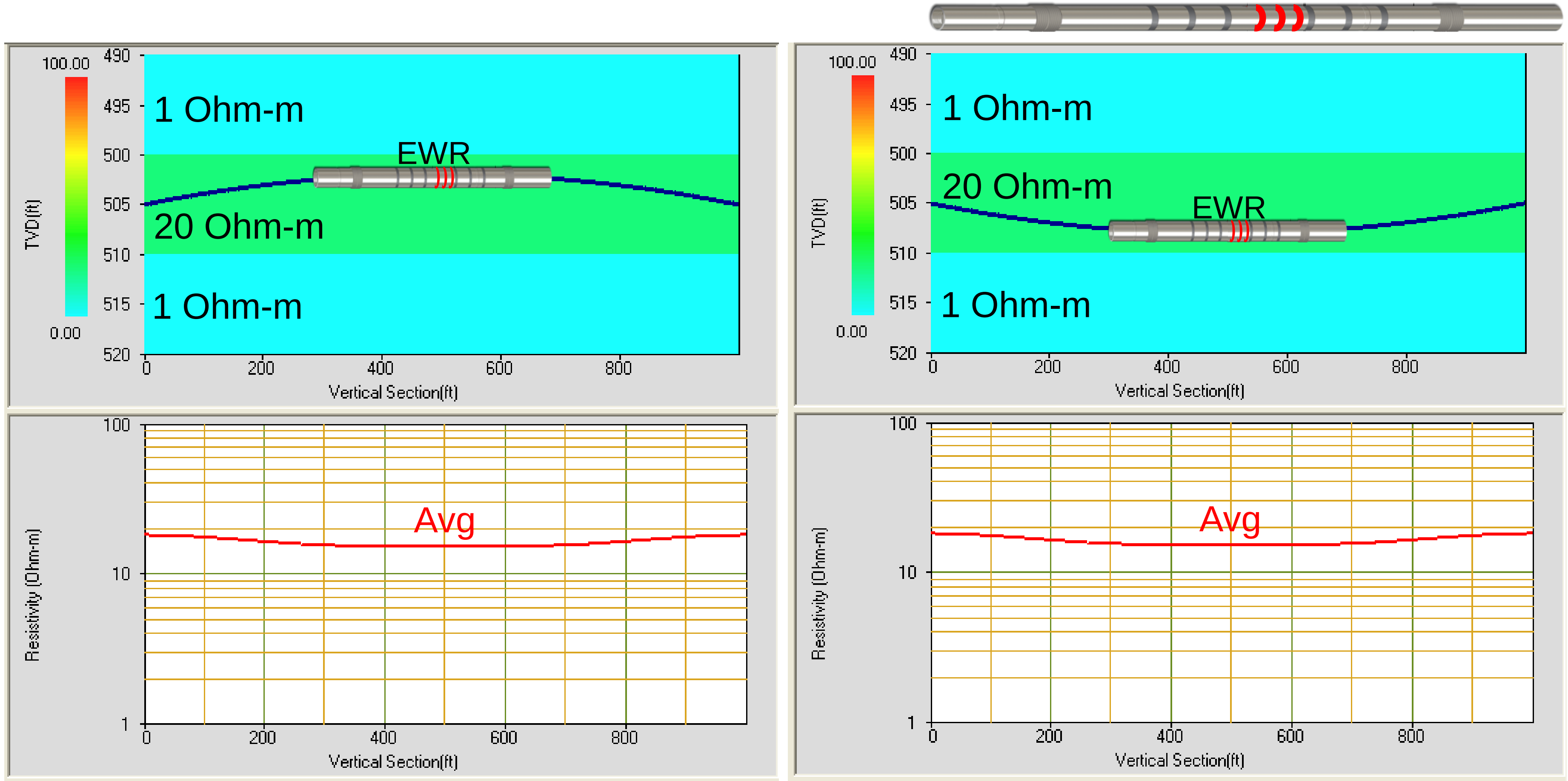
Resistivity Logging-While-Drilling

EWR 500 KHz, 32 inch



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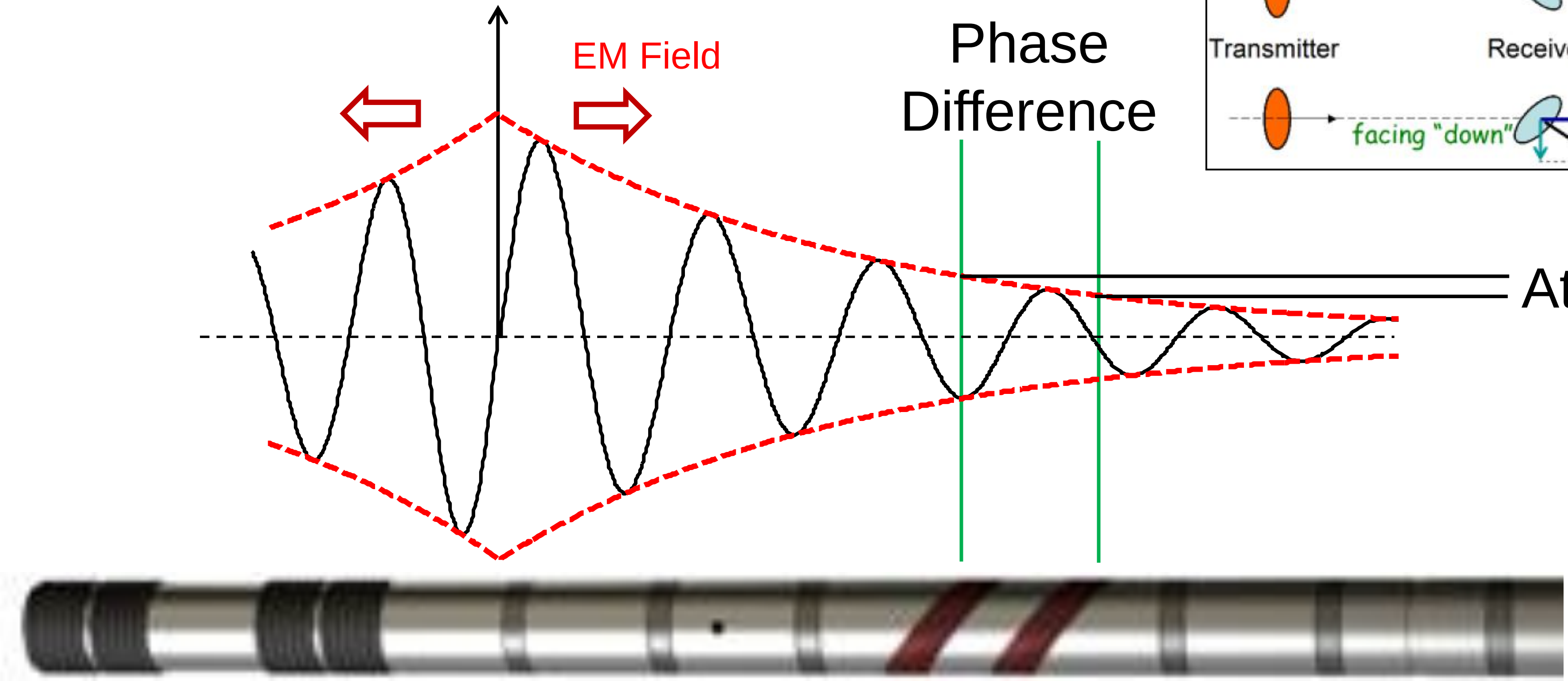
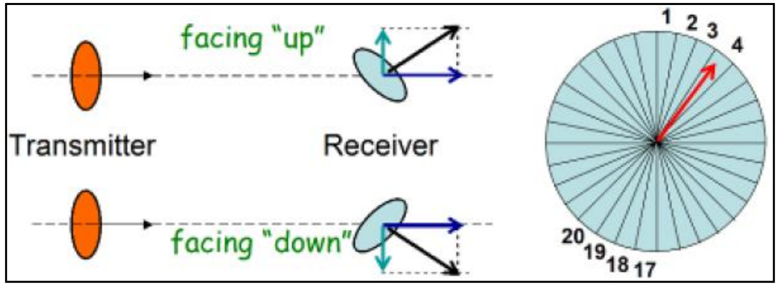
Resistivity Logging-While-Drilling

ADR





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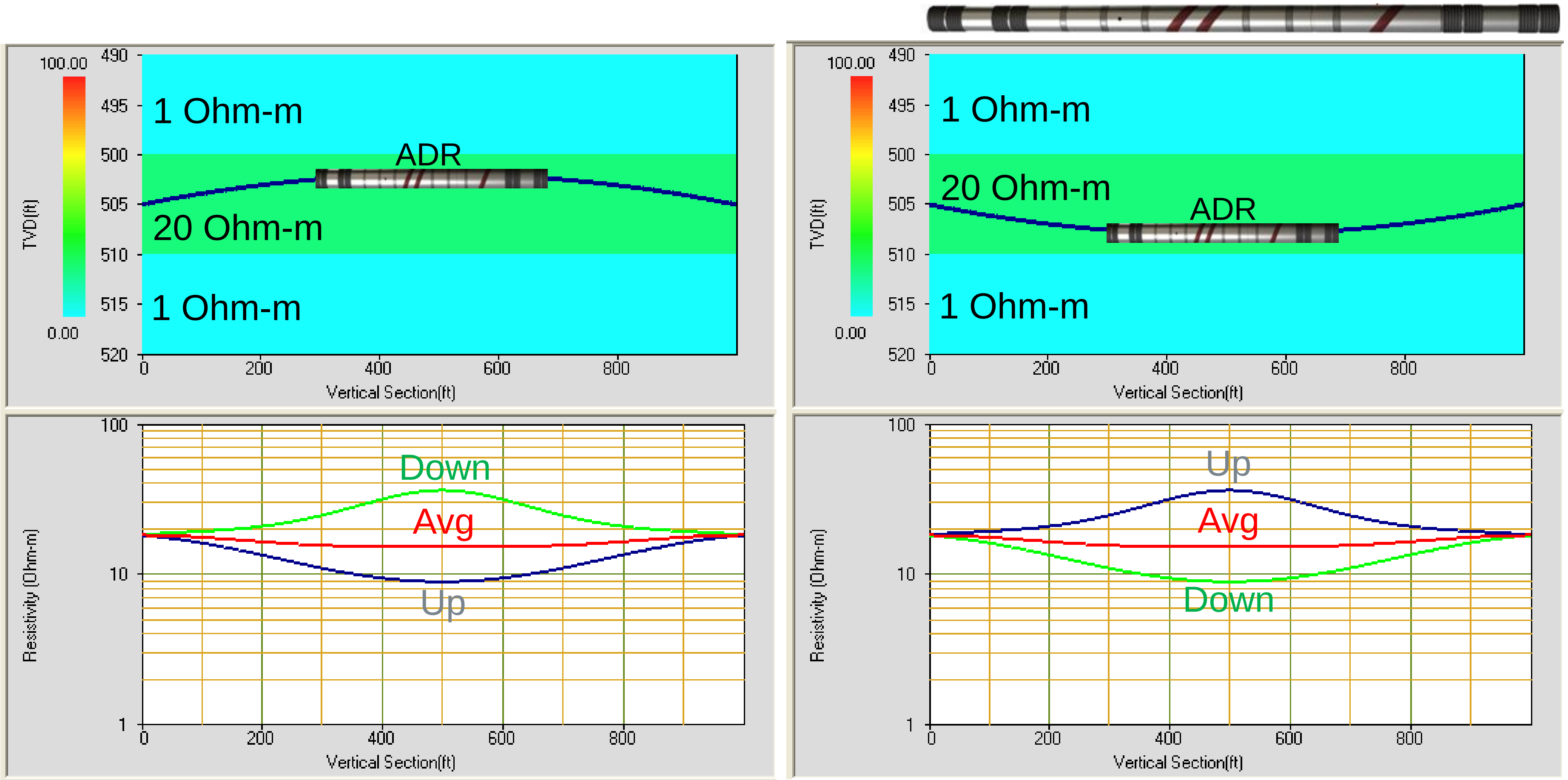
Resistivity Logging-While-Drilling

ADR 500 KHz, 32 inch



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Ultra-Deep Resistivity Logging-While-Drilling

Other LWD Tools

Typically ALD™ and CTN™ for reservoir evaluation, doubling as spacers for EarthStar™ antennas

Transmitter Sub

Multiple, low-frequency firings for maximum formation penetration

Receiver Subs

Azimuthally sensitive measurements, spaced 25 to 125 ft. from transmitter for maximum depth of investigation

Other LWD Tools

Typically ADR™ azimuthal resistivity geosteering sensor for near-wellbore detail

Raw Data

Downhole Processing

$$\begin{bmatrix} Z_{XX} & Z_{XY} & Z_{XZ} \\ Z_{YX} & Z_{YY} & Z_{YZ} \\ Z_{ZX} & Z_{ZY} & Z_{ZZ} \end{bmatrix}$$

Telemetry

Surface Processing & Inversion

Geosteering

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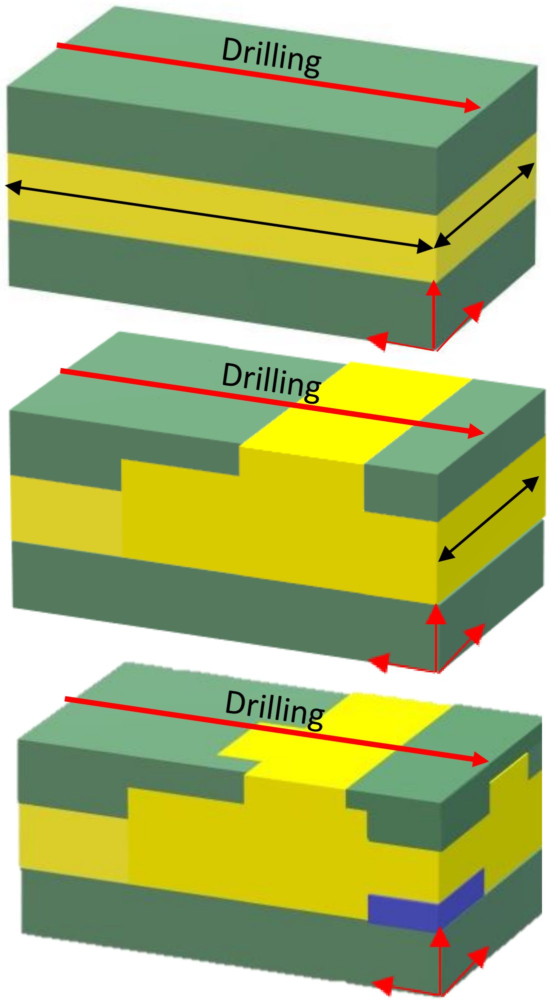
Inversion Dimensionality

1D

2D

3D



- 1D inversion assumes changes only happen above and below the wellbore
- 2.5D inversion assumes a plane of infinite strike, so changes happen above/below the wellbore and along the wellbore
- 3D inversion permits changes in all directions

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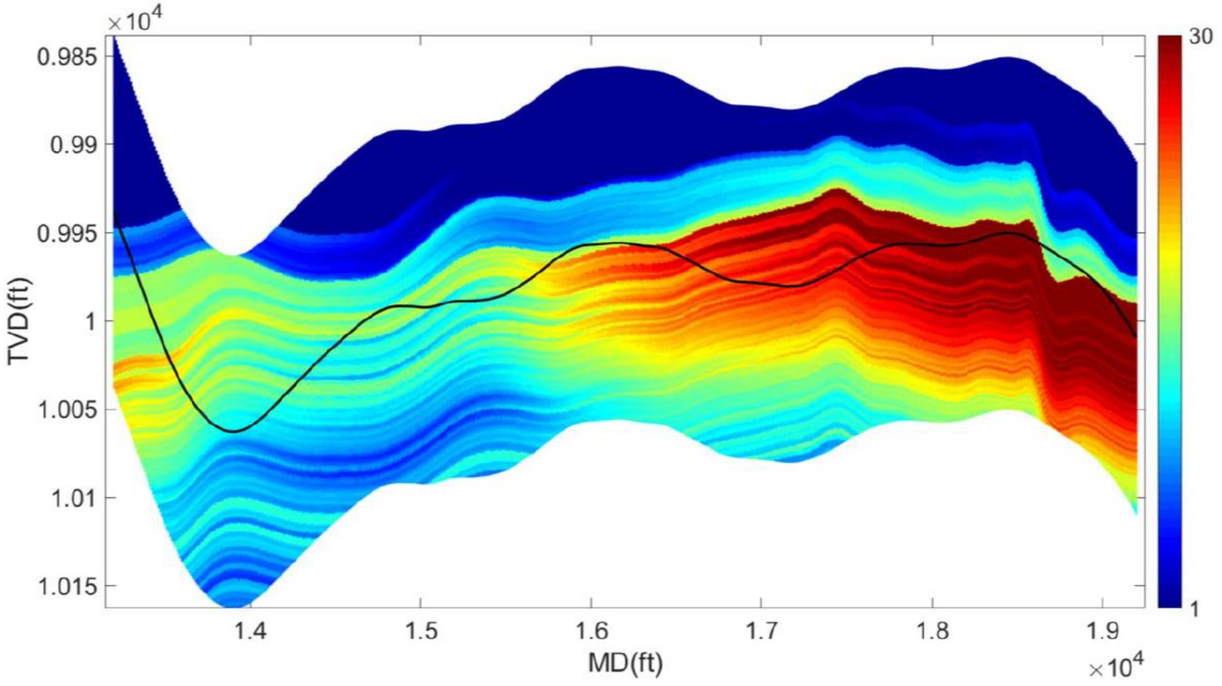
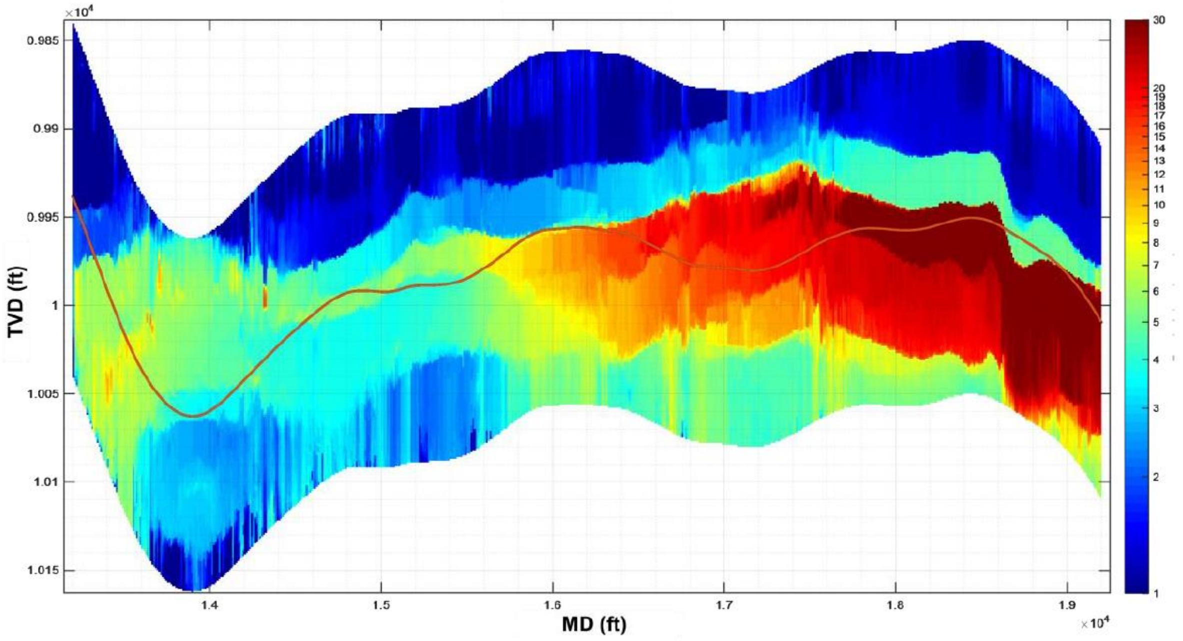
1D Inversion for Ultra-Deep Resistivity

Multi-layer pre-well model



1D inversion of pre-well model



Wu et al., 2018, SPWLA

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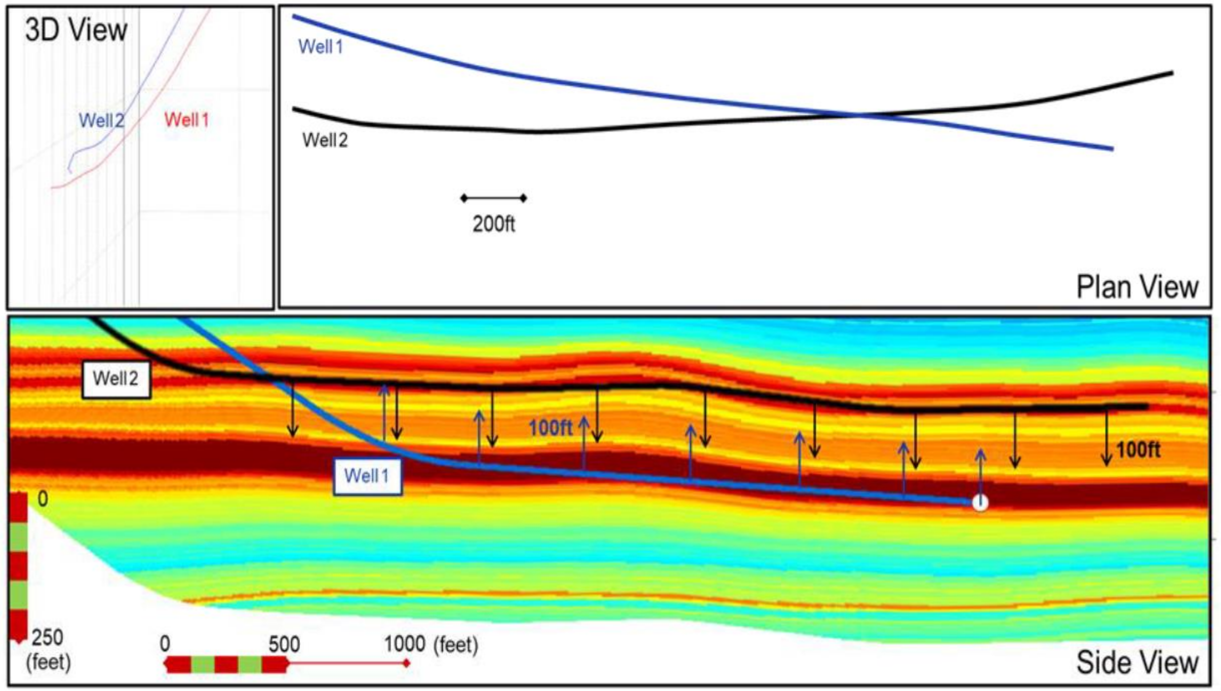
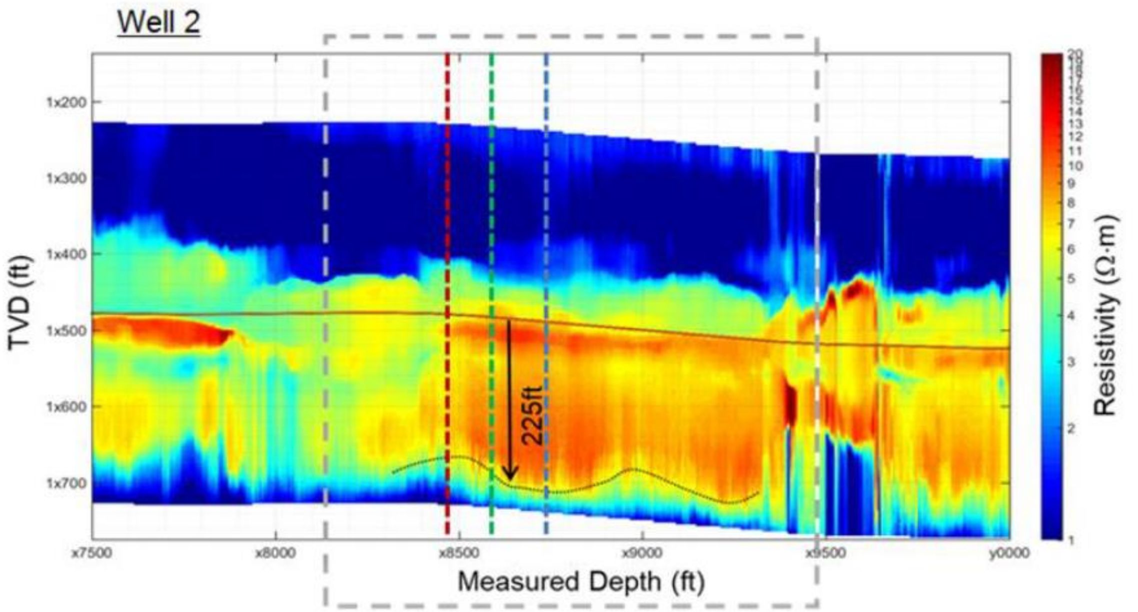
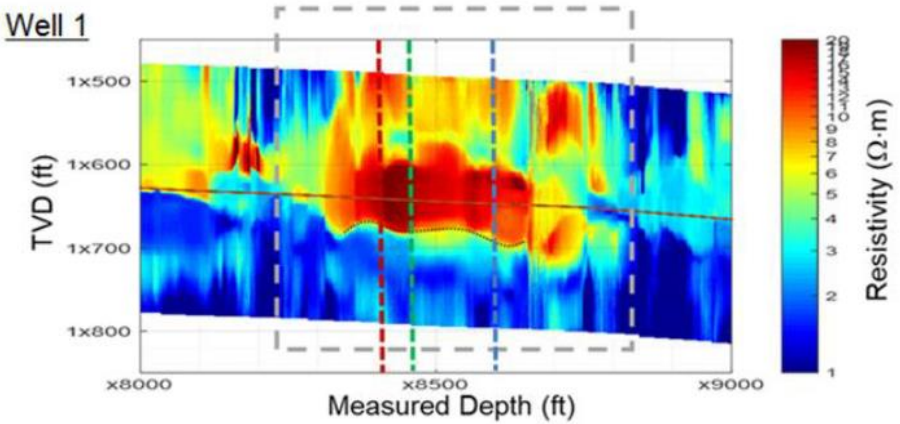
1D Inversion for Ultra-Deep Resistivity

Wu et al., 2018, SPWLA







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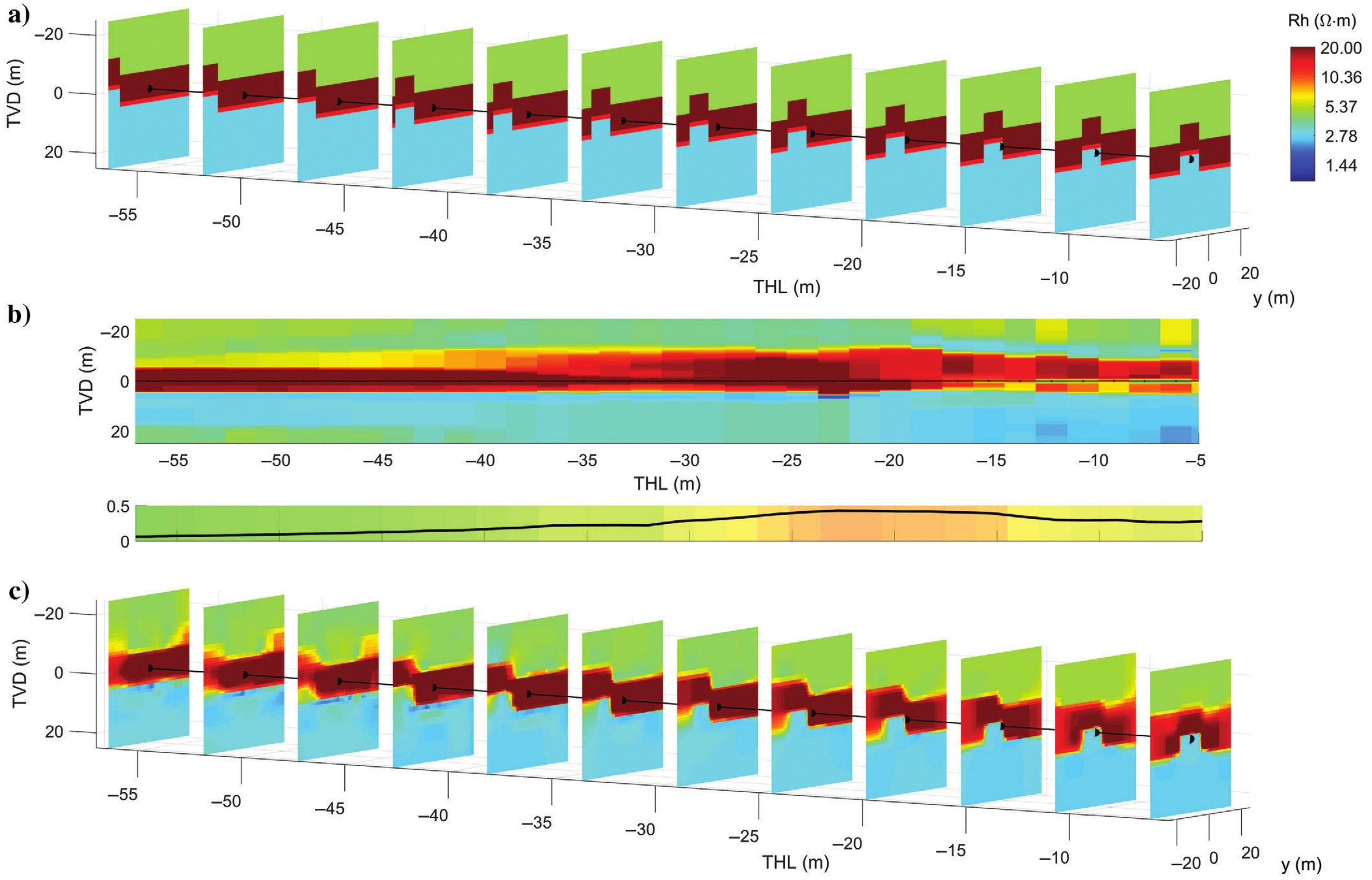
2.5D Inversion for Ultra-Deep Resistivity



Thiel & Omeragic, 2019, Geophysics

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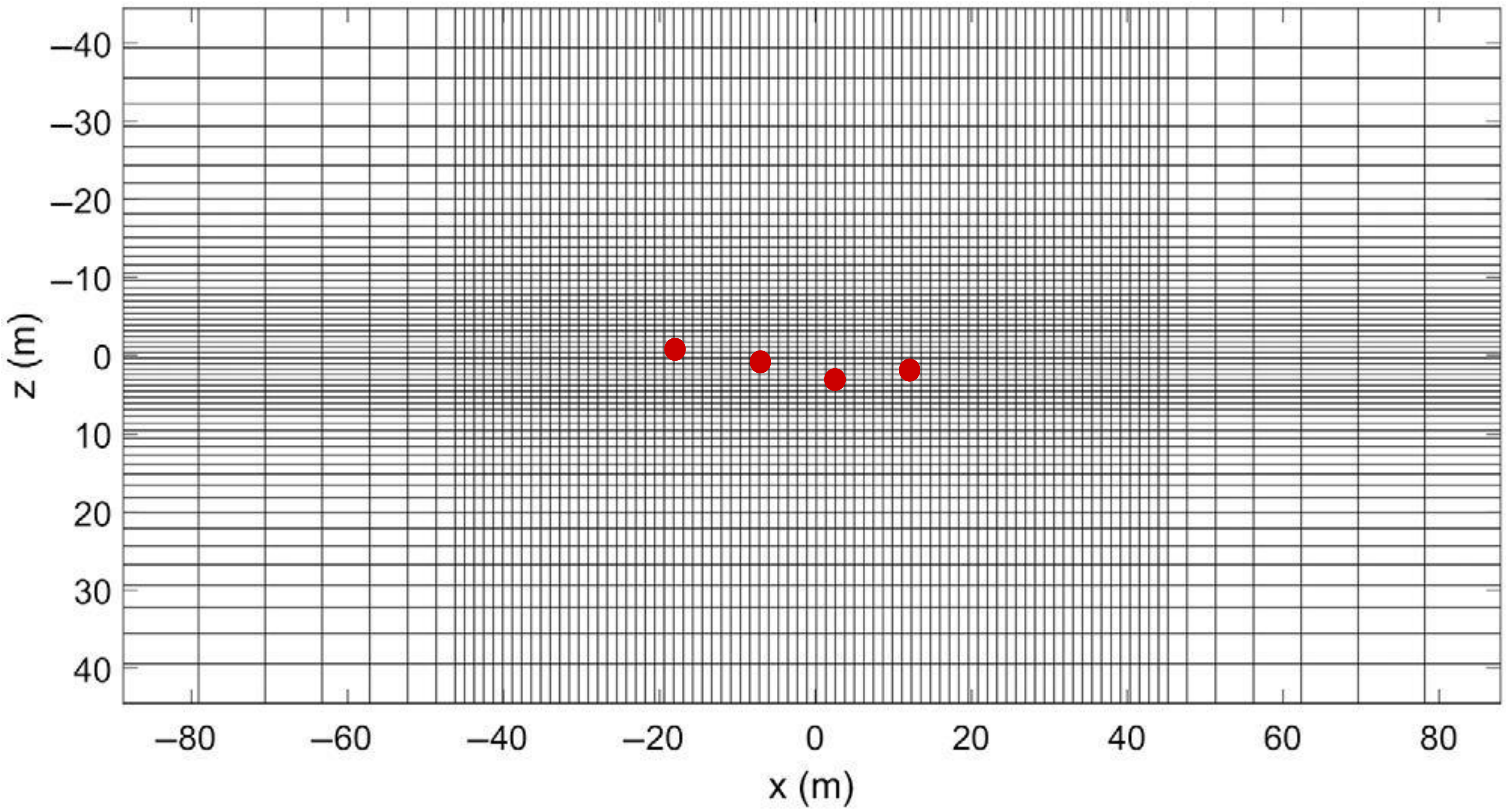
3D Inversion for Multi-Source Surveys



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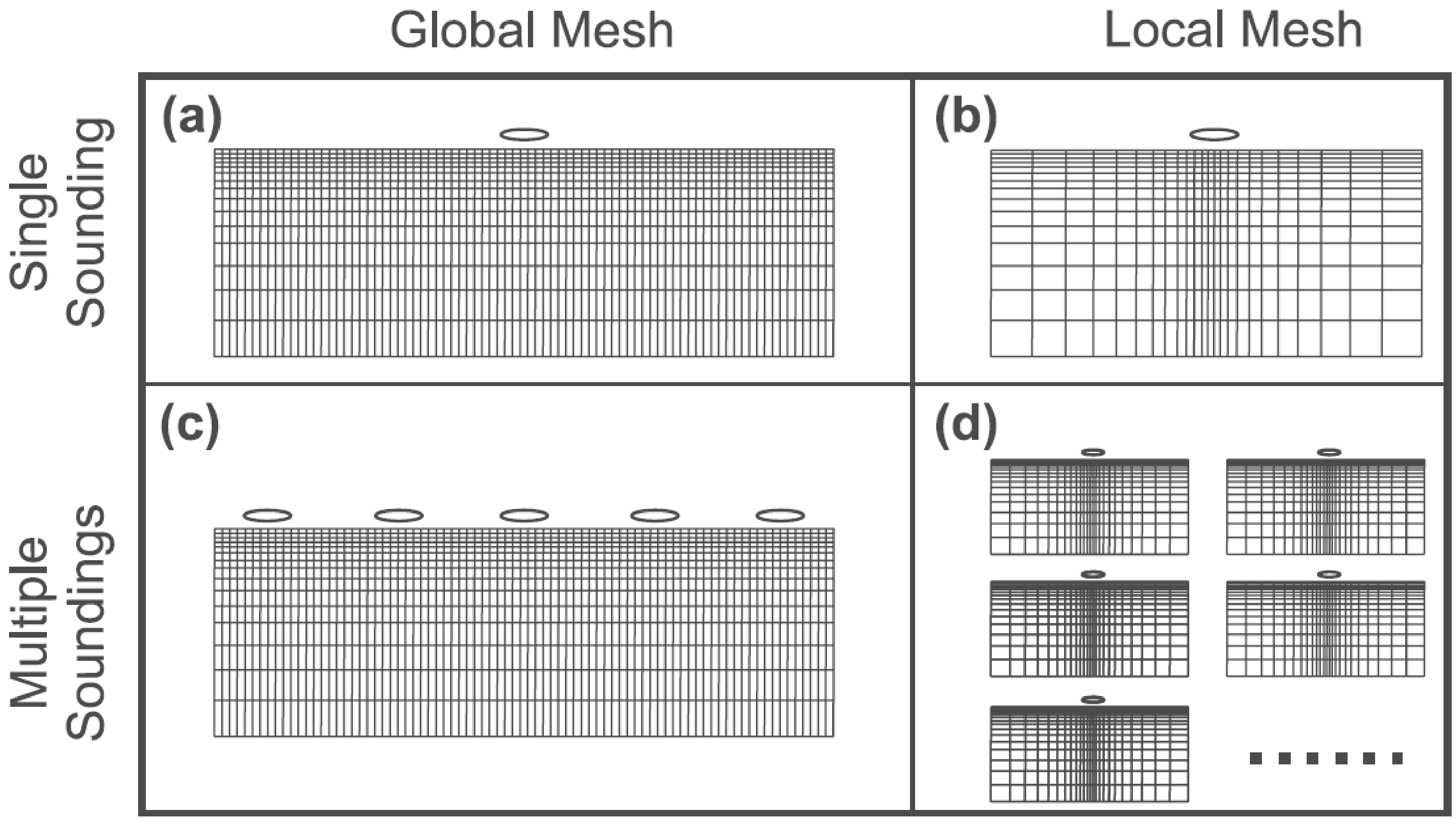
3D Inversion for Multi-Source Surveys: Decouple Grids



Commer & Newman, 2008, GJI
Yang et al., 2014, GJI

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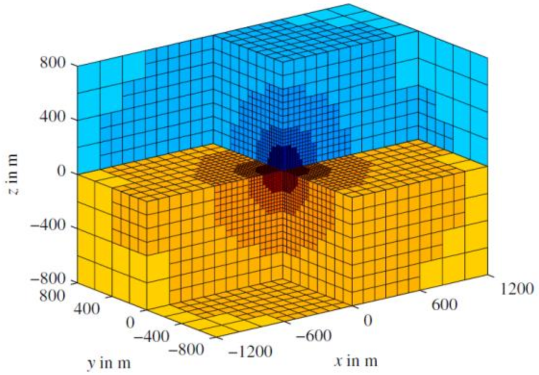
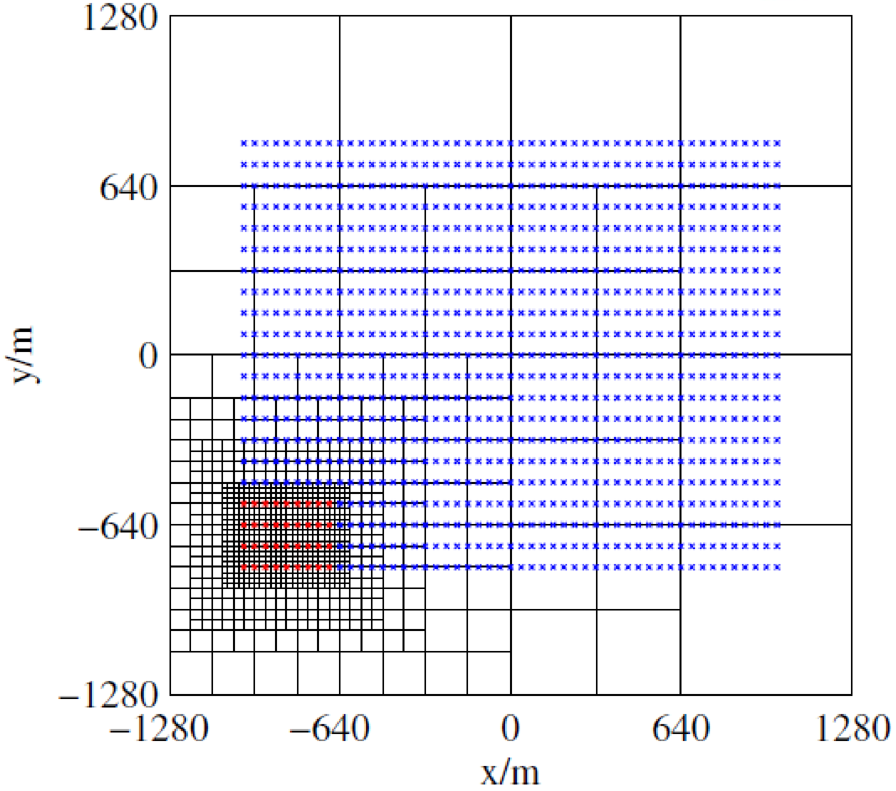
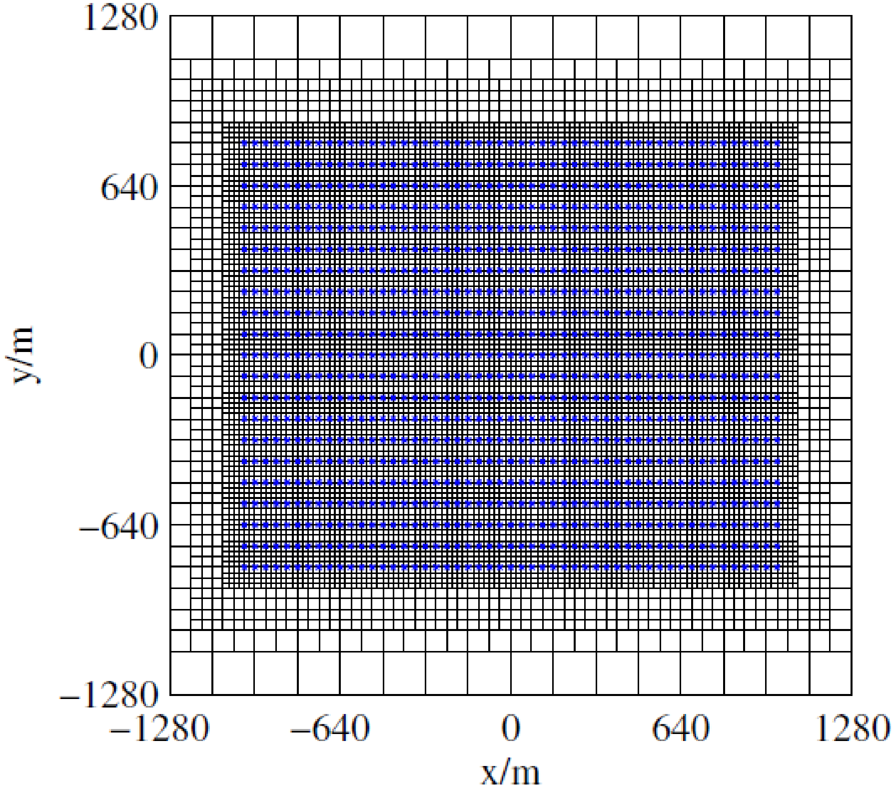
3D Inversion for Multi-Source Surveys: Decouple Grids & OcTree







Haber & Schwarzbach, 2014, Inv. Prob.

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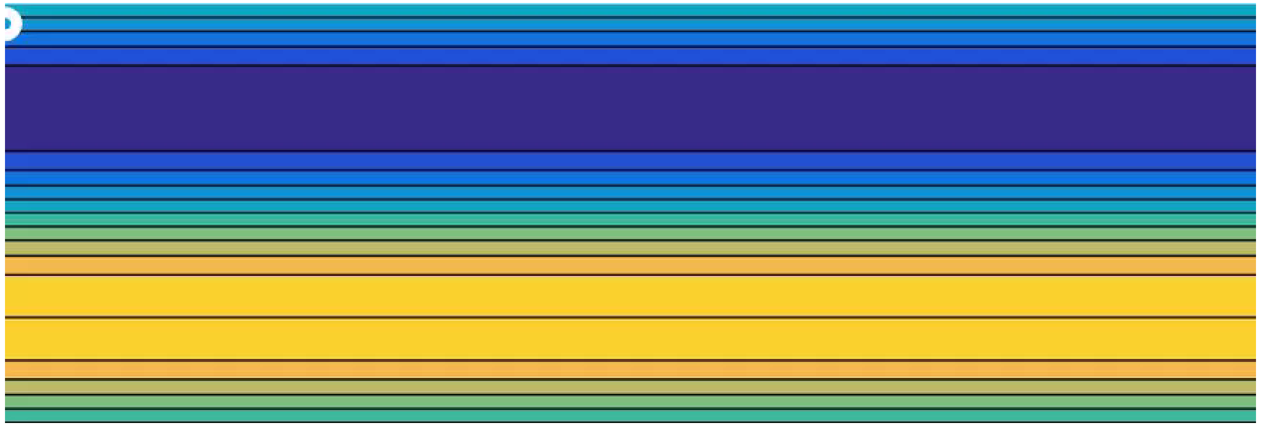
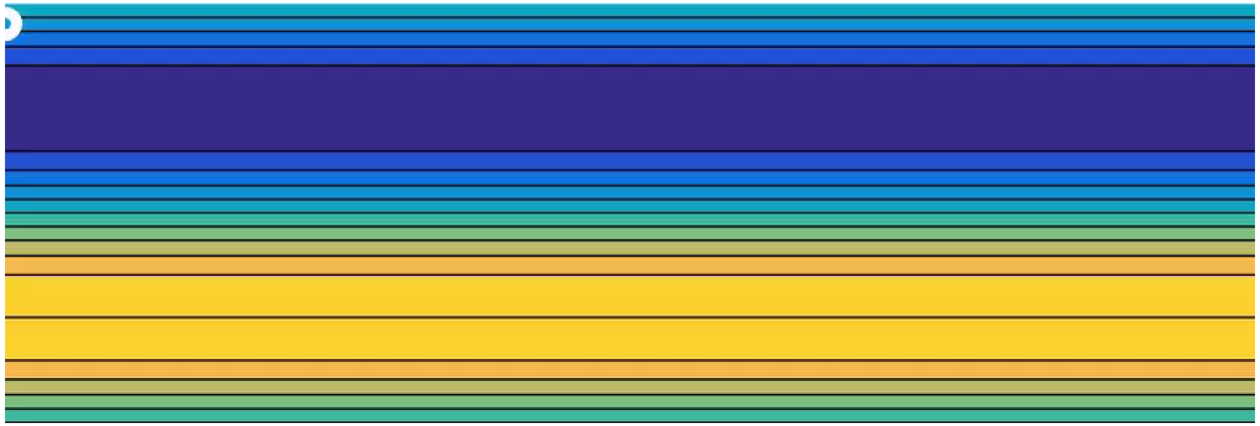
3D Inversion for Multi-Source Surveys: Use All or Local Data?

Standard Inversion



$$min \sum ||d_j^{obs} - d_j^{pred}(\sigma)||^2 + \alpha R(\sigma, \nabla\sigma)$$

Inversion with Local Data



$$min \sum_{j=1}^{N} || d_j^{obs} - d_j^{pred}(\sigma)||^2 + \alpha R_N(\sigma - \sigma_{N-1}, \nabla(\sigma - \sigma_{N-1}))$$

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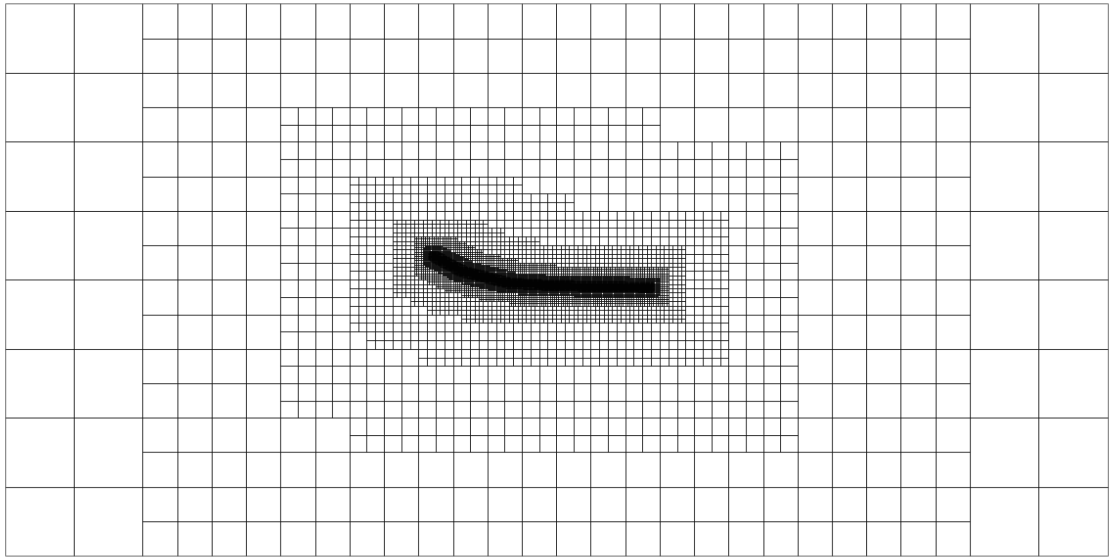
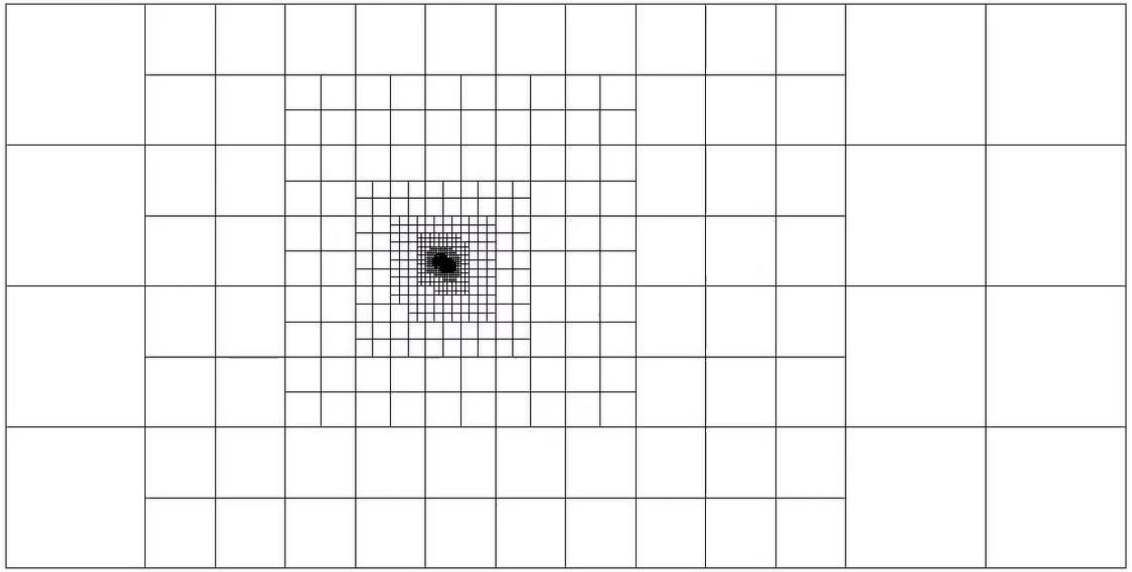
3D Inversion for Dynamic Multi-Source Surveys: Decouple Grids & OcTree





Wilson et al., 2019, SPE ATCE

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But… “Real-time 3D inversion is impossible!”

	1D	2.5D	3D OcTree	Standard 3D
Degrees of Freedom	nLayers x nFT x nHankle ~ 30K	nX x nZ x nKy ~ 100k+	30-50K	500K+
Run Time	Seconds	Hours	Seconds	Hours to Days
Parallelization	✓	✓	✓	✓
Geological Complexity	X	✓	✓	✓
Anisotropy	✓	✓	✓	✓

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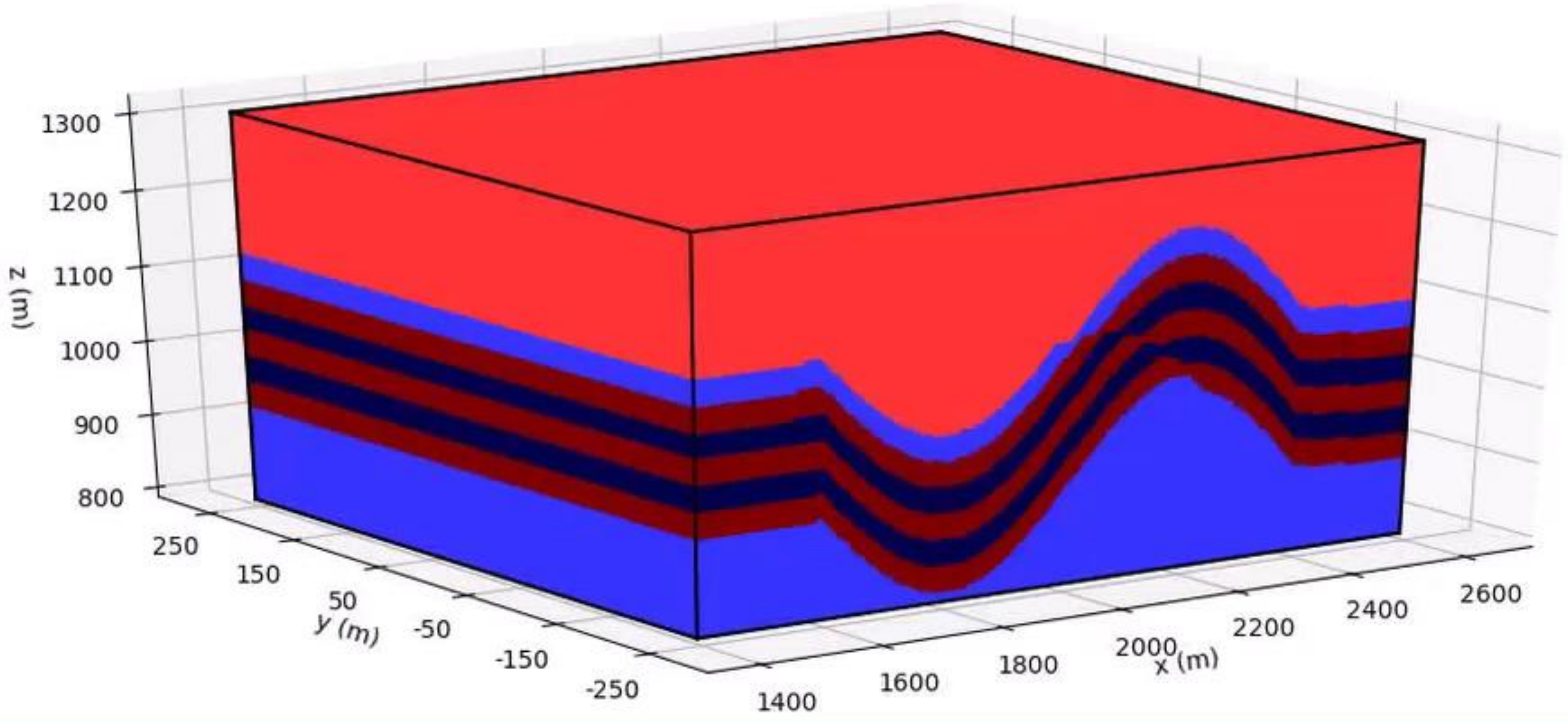
3D Inversion for Ultra-Deep Resistivity: Model Study



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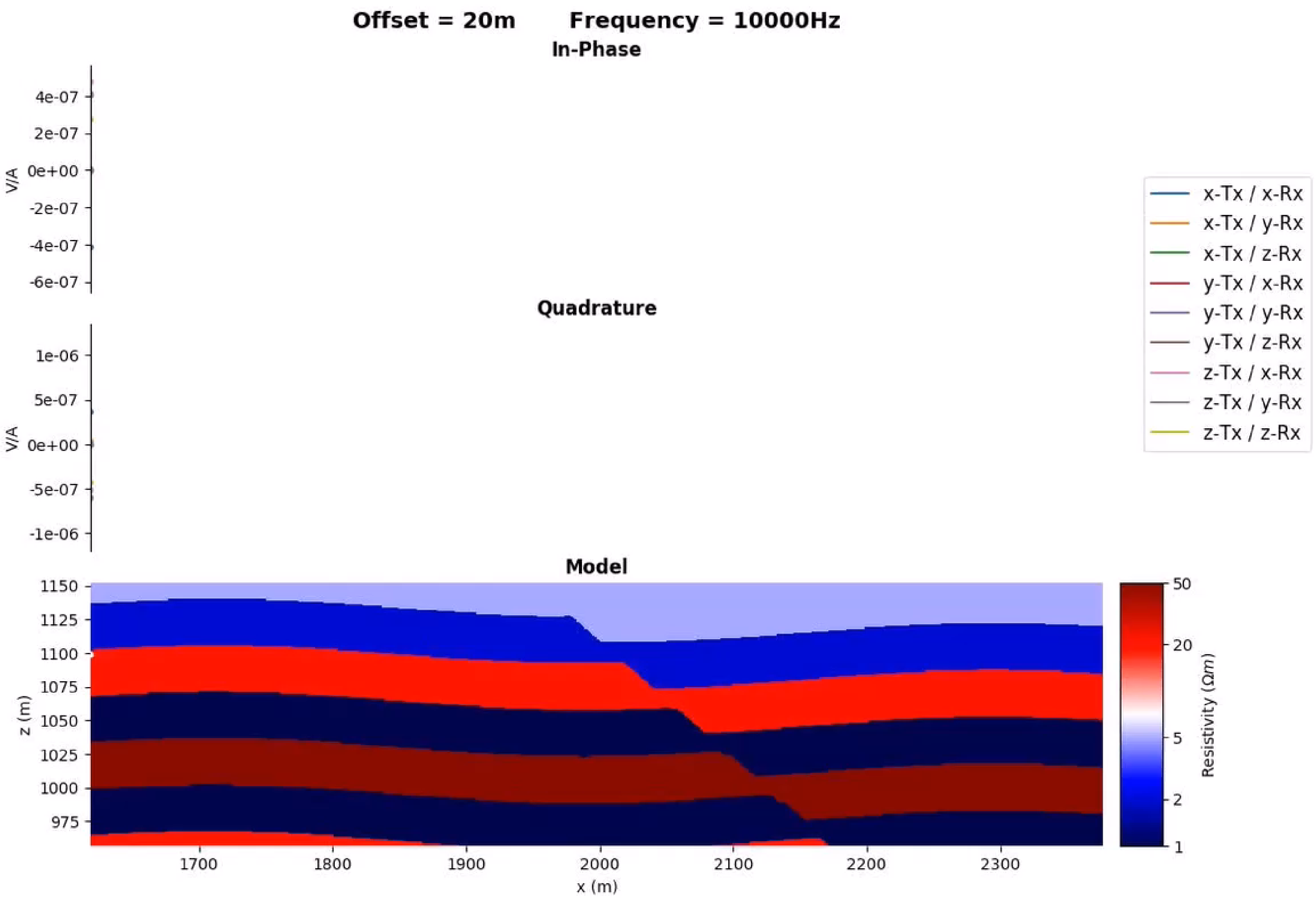
3D Inversion for Ultra-Deep Resistivity: Model Study



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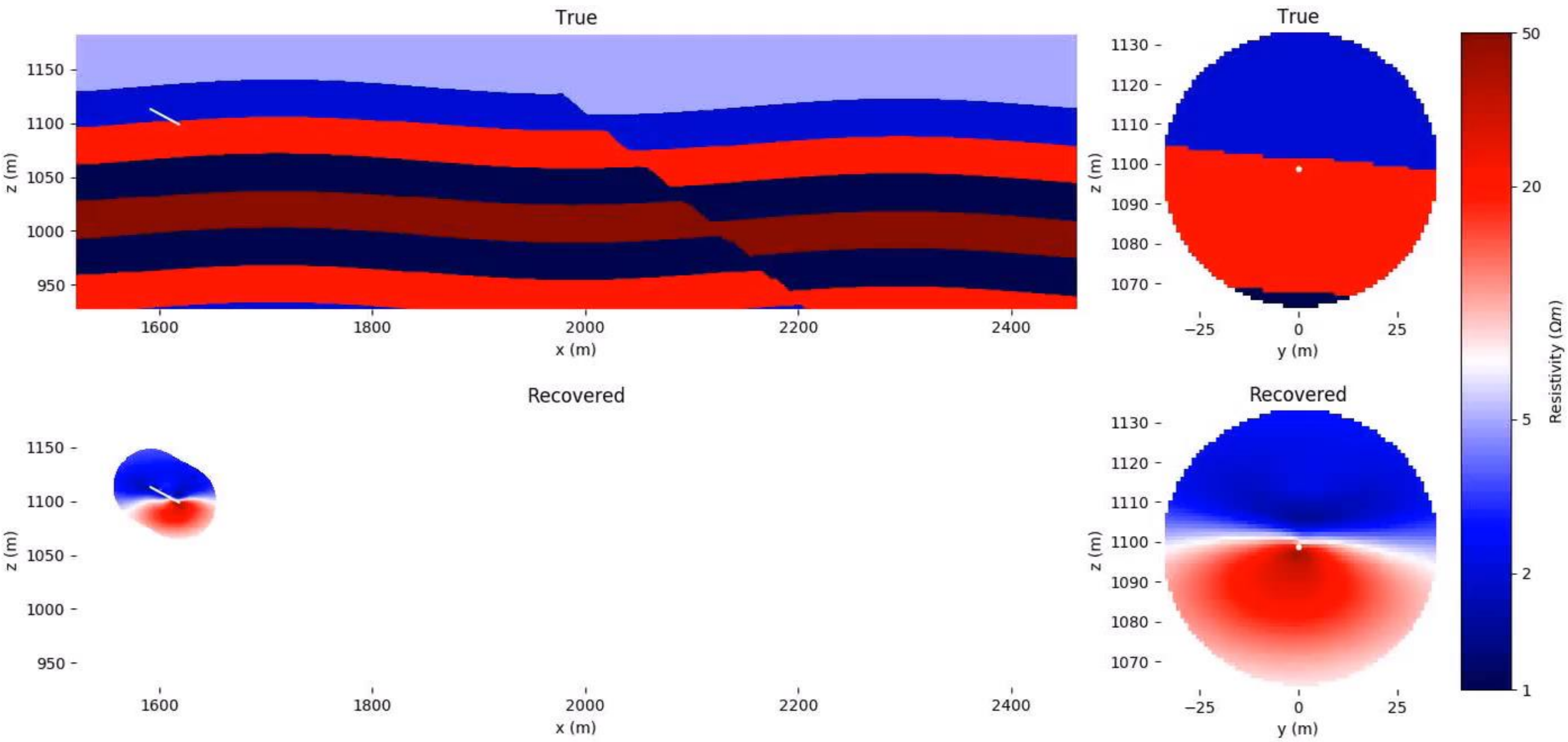
3D Inversion for Ultra-Deep Resistivity: Model Study



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New 3D LWD technology provides detailed representation of subsurface structures
Jeff Grable, Halliburton
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Halliburton releases 3D logging-while-drilling technology for oil and gas industry
Created: Thursday, 18 July 2019 05:43
Oil field service company Halliburton has introduced 3D reservoir mapping, a new logging-while-drilling (LWD) capability that provides a detailed representation of subsurface structures to improve well placement in complex reservoirs
3D inversion, an advanced reservoir mapping process, reveals
OE OFFSHORE ENGINEER
THE FUTURE OF OFFSHORE ENERGY & TECHNOLOGY.
REGIONS ENERGY GEOSCIENCE ENGINEERING TECHNOLOGY VESSELS SUBSEA
3D Inversion Helps Tackle Complex Reservoirs
Jennifer Pallanich, Contributor
Jennifer Pallanich is a veteran oil and gas journalist based in Houston....
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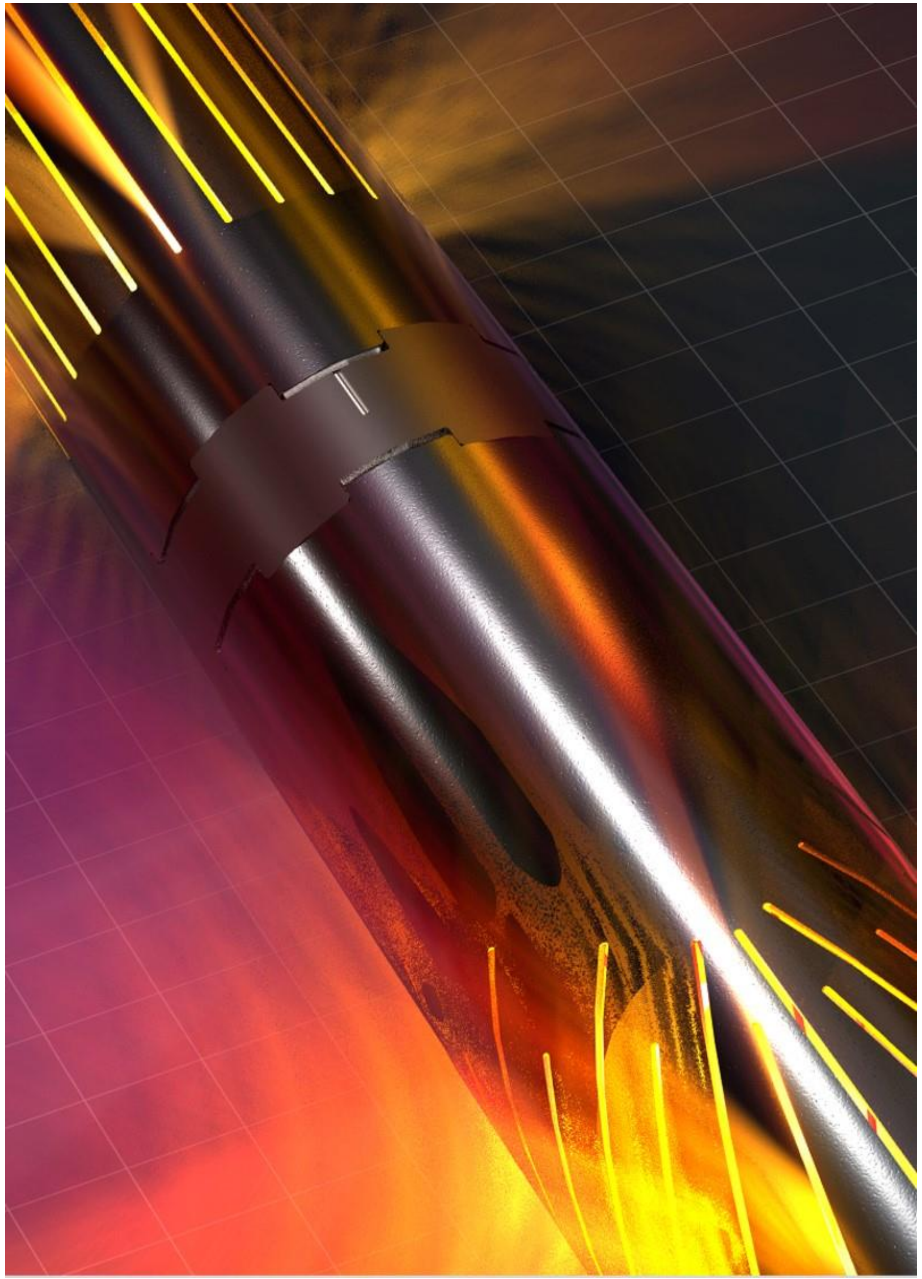

Tracking Injection Water

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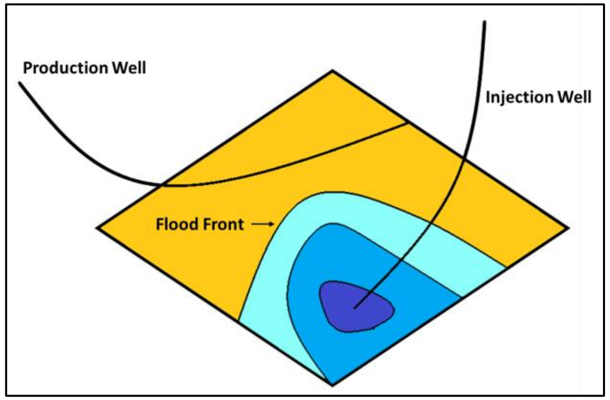
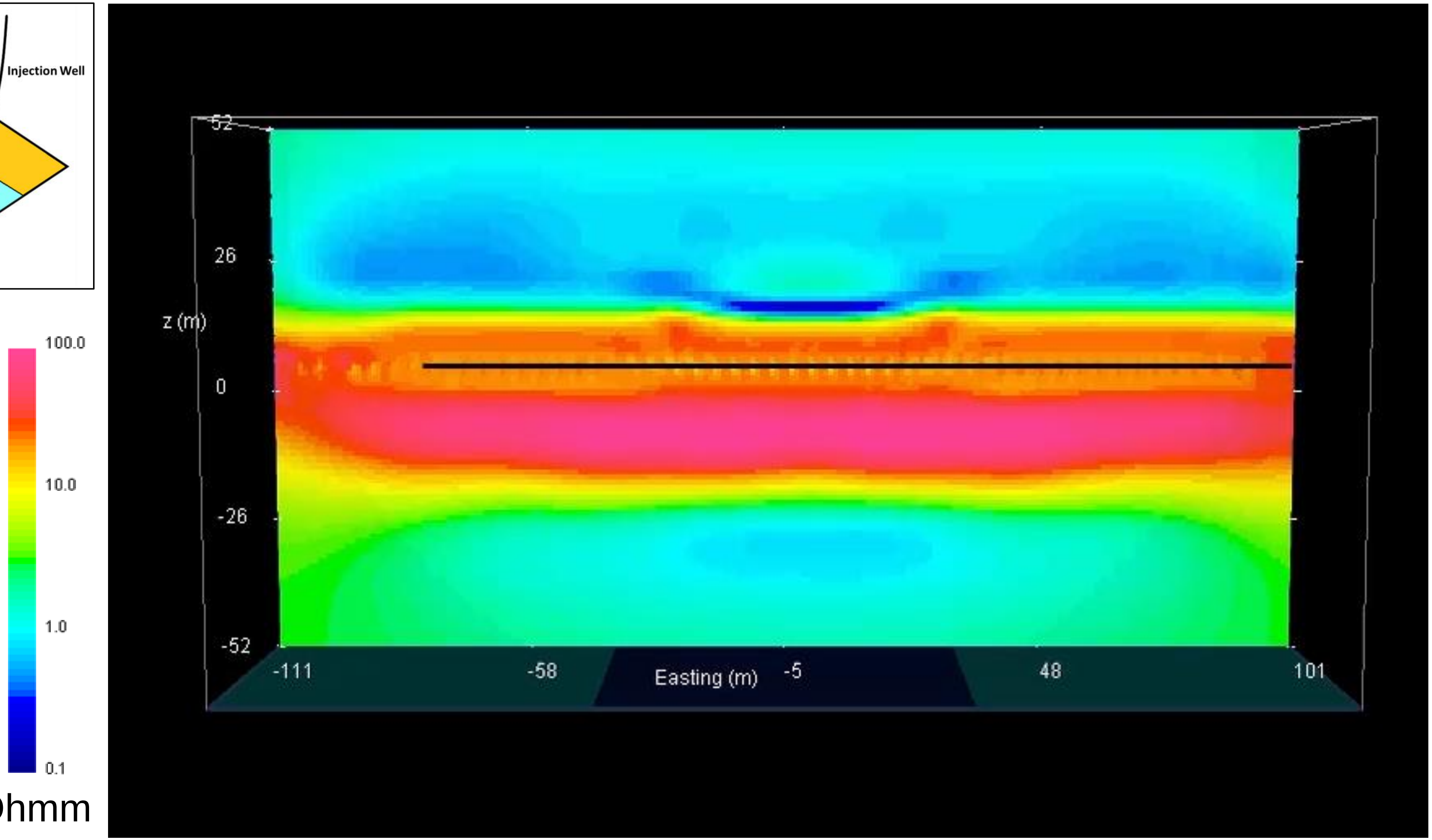
Why is 3D Inversion so Important?



Water injected to push hydrocarbons towards the production well



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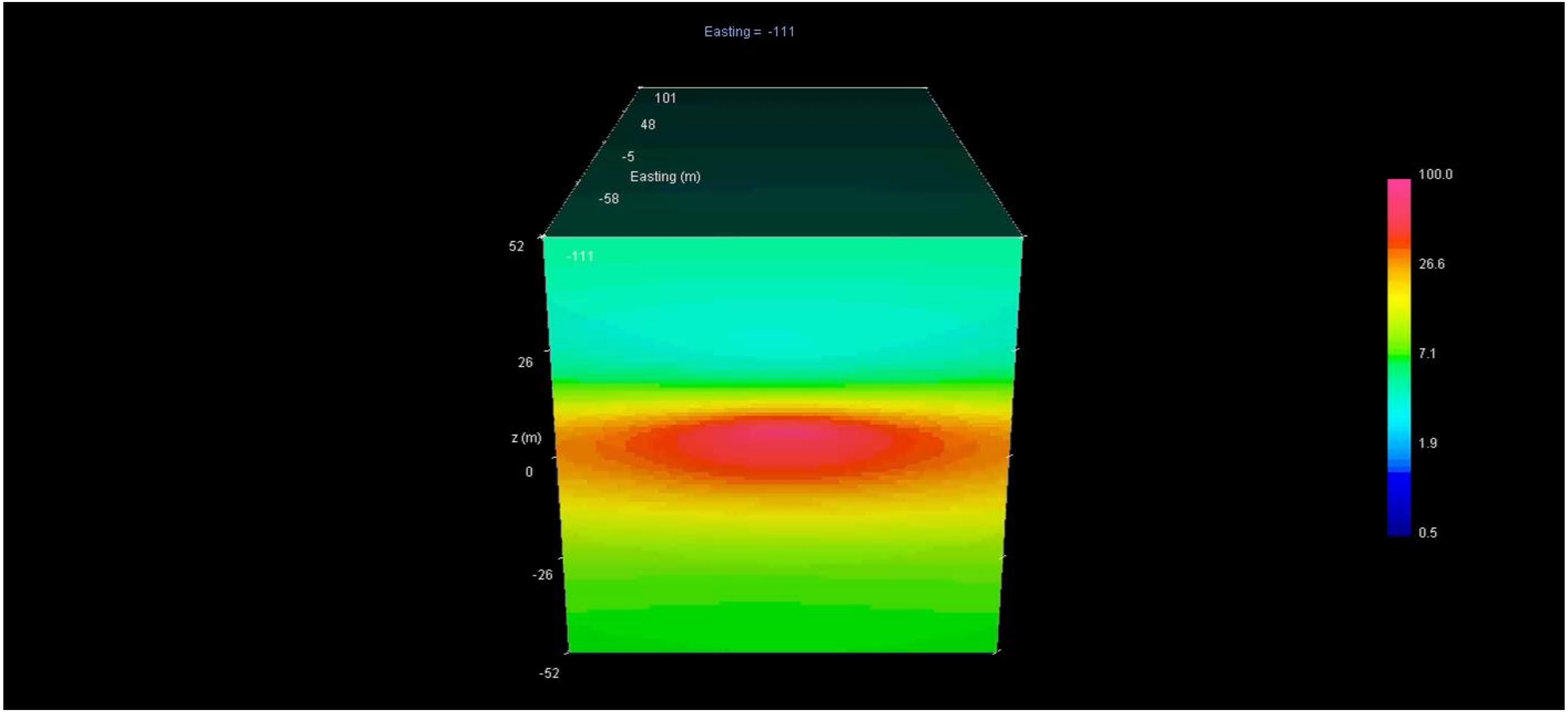
View while drilling



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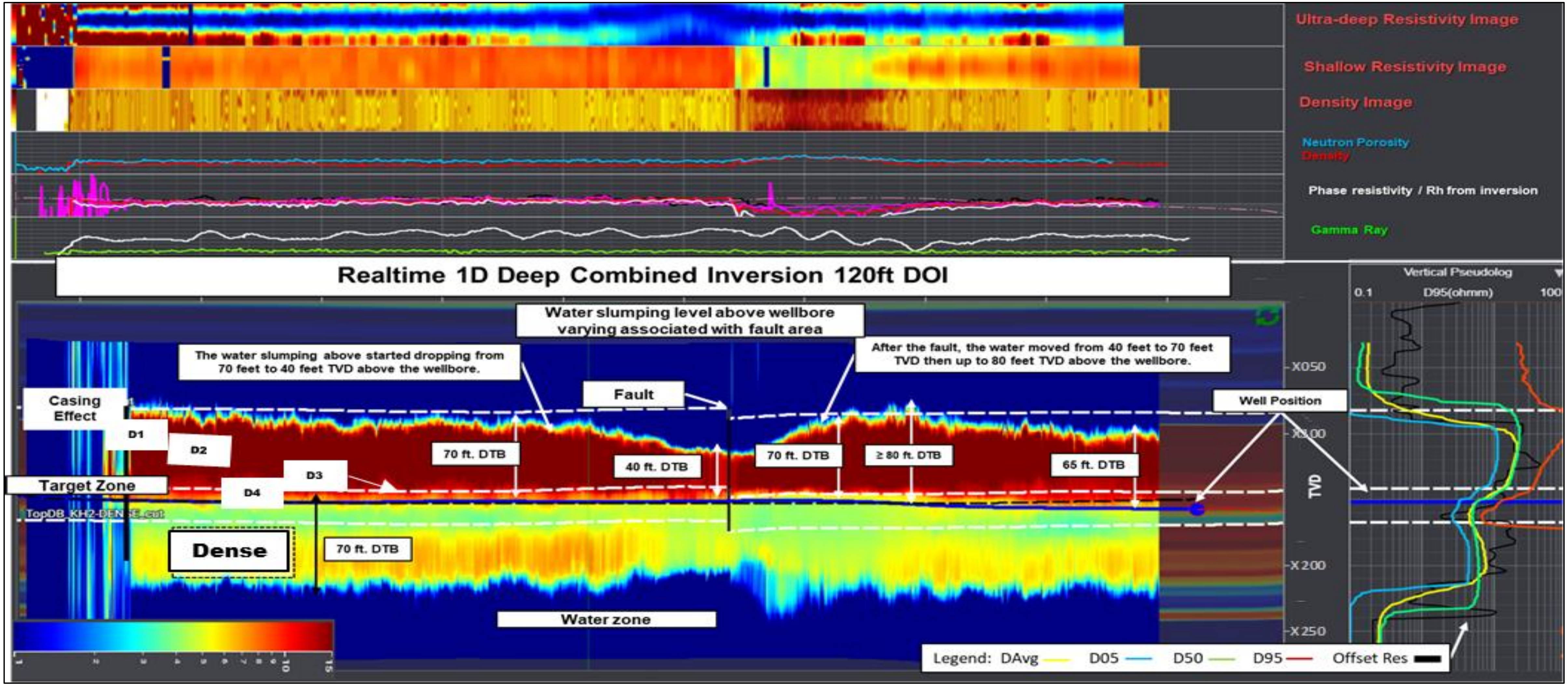
Case Study – Water Slumping UAE



Maniesh Singh, Parmanand Dhermeshwar Thakur, Mariam N. M. Al Baloushi, Haitham Ali Al Saadi, Maisoon M. Al Mansoori, Ahmed S. Al Mesafri, Saif Al Arfi, Vikram K. Pandey, Alaa Al Shalabi, Flavien Maire, Ernesto L. Barragan Chang, Maher M. Kenawy, Mouza Ali Al Nuaimi, Douglas Boyd, Nader Gerges, Wael Fares, Eduard Bikchandaev, Nigel Clegg, Arthur Walmsley, Ahmet Aki. Real-Time 3D Ultra Deep Directional Electromagnetic LWD Inversions: An Innovative Approach for Geosteering and Geomapping Water Slumping Movement Around Sub-Seismic Fault, Onshore Abu Dhabi. Paper presented at the Abu Dhabi International Petroleum Exhibition & Conference, November 15–18, 2021. DOI: https://doi.org/10.2118/207478-MS.

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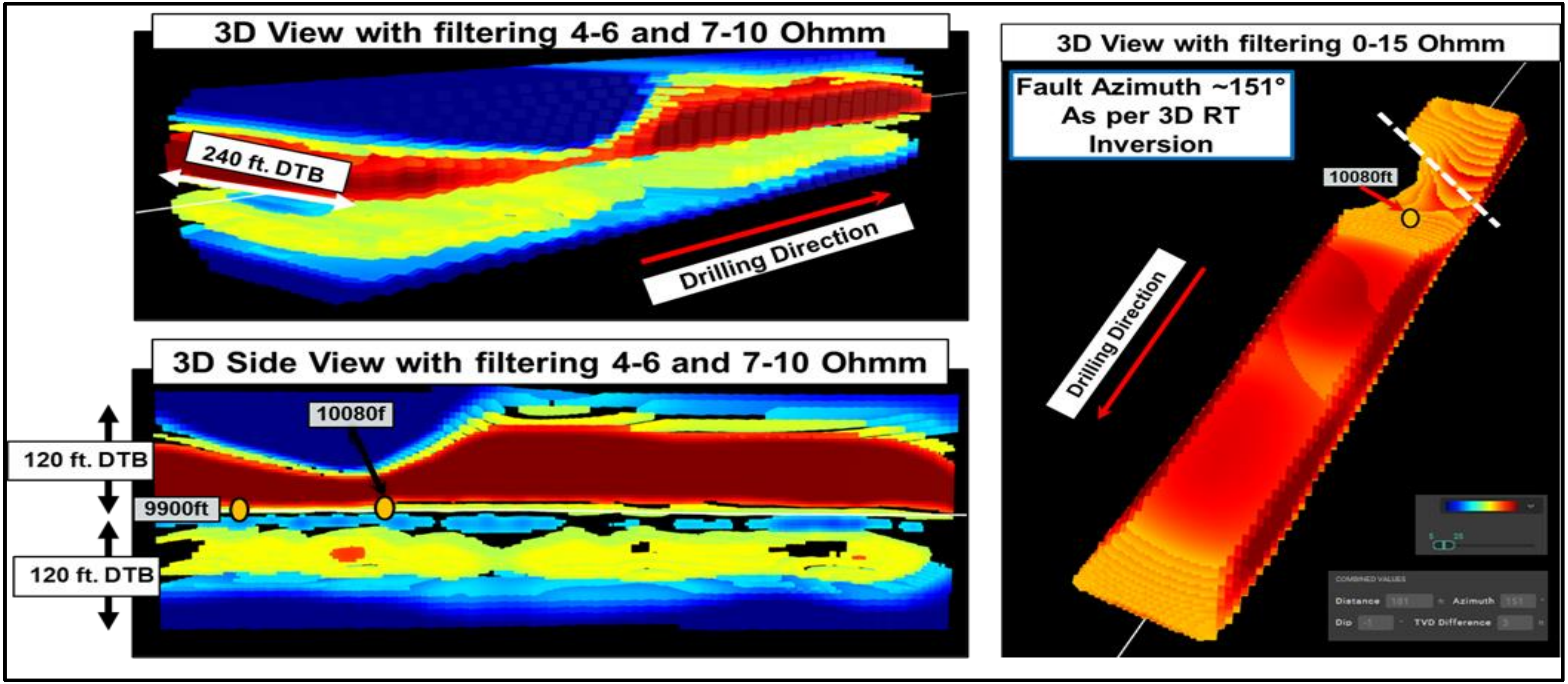
Case Study – Water Slumping UAE



Maniesh Singh, Parmanand Dhermeshwar Thakur, Mariam N. M. Al Baloushi, Haitham Ali Al Saadi, Maisoon M. Al Mansoori, Ahmed S. Al Mesafri, Saif Al Arfi, Vikram K. Pandey, Alaa Al Shalabi, Flavien Maire, Ernesto L. Barragan Chang, Maher M. Kenawy, Mouza Ali Al Nuaimi, Douglas Boyd, Nader Gerges, Wael Fares, Eduard Bikchandaev, Nigel Clegg, Arthur Walmsley, Ahmet Aki. Real-Time 3D Ultra Deep Directional Electromagnetic LWD Inversions: An Innovative Approach for Geosteering and Geomapping Water Slumping Movement Around Sub-Seismic Fault, Onshore Abu Dhabi. Paper presented at the Abu Dhabi International Petroleum Exhibition & Conference, November 15–18, 2021. DOI: https://doi.org/10.2118/207478-MS.

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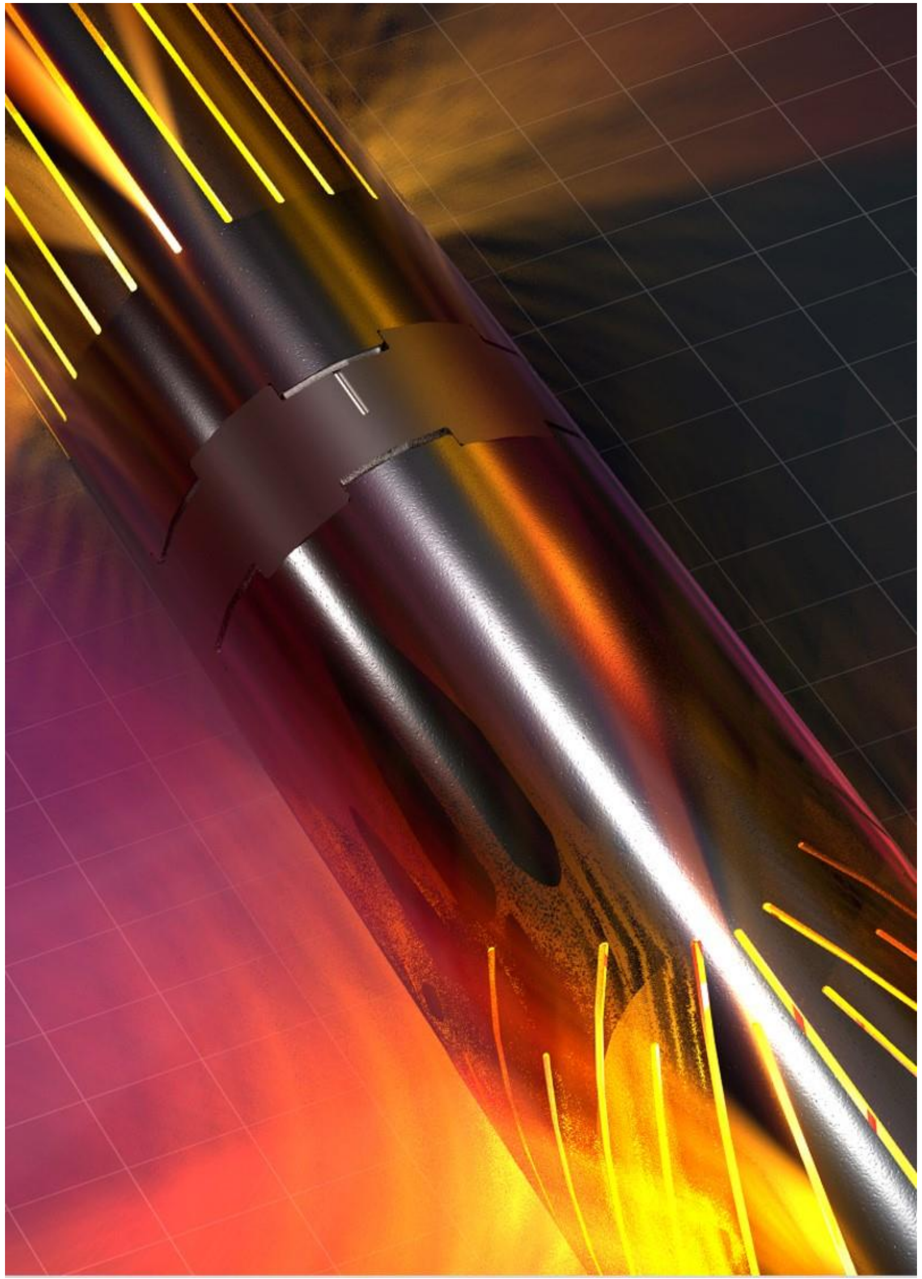

Turbidite Sands

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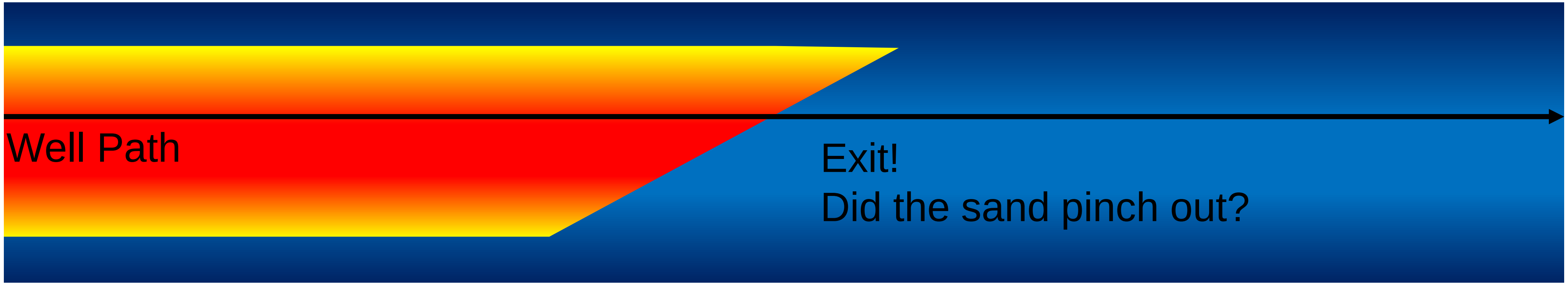
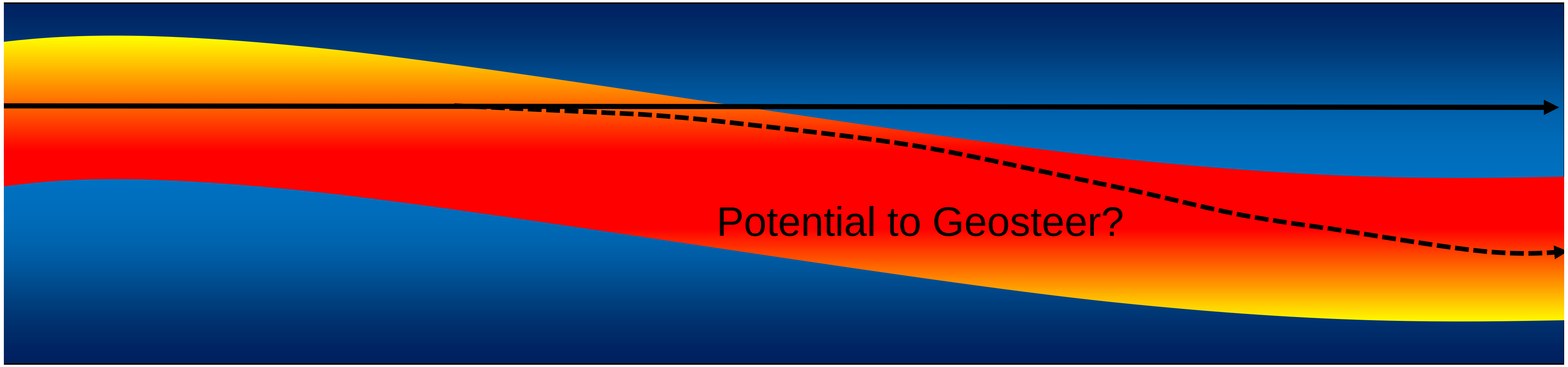
Channel Sand

Side View (1D)



Side-track? Missed Pay?

Plan View



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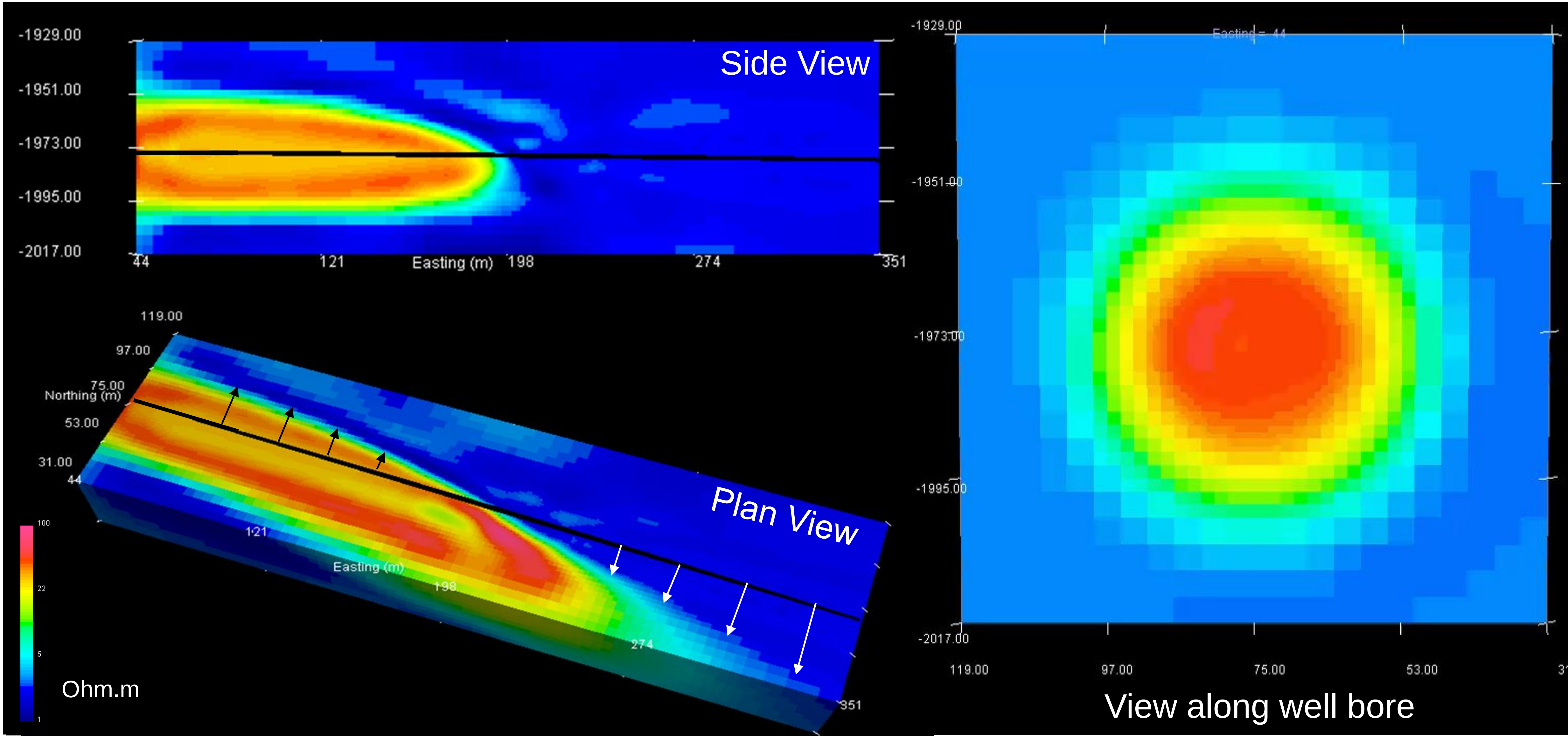
Exiting a Channel Sand



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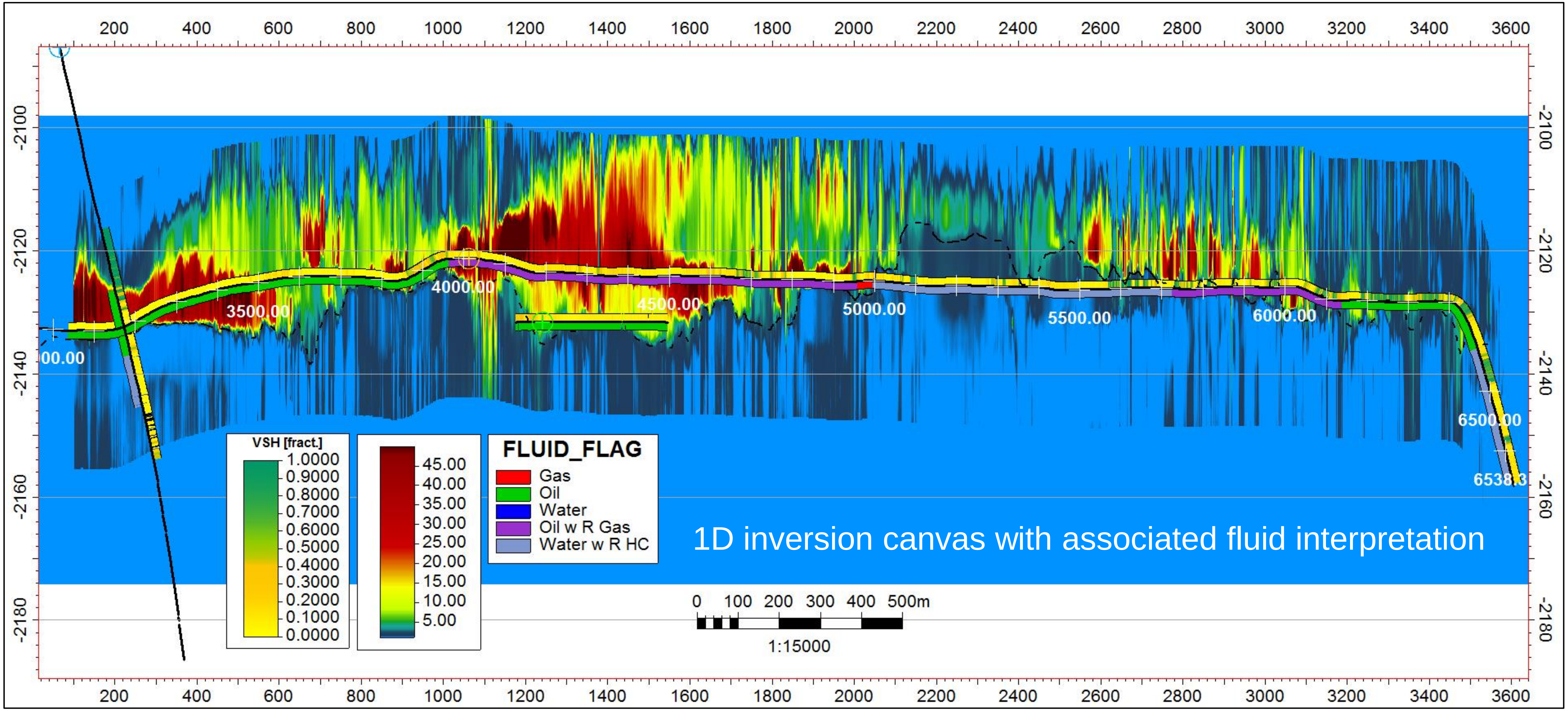
Case Study: Complex Turbidite Reservoir, Norwegian Continental Shelf



Wilson, G., Marchant, D., Haber, E., Clegg, N., Zurcher, D., Rawsthorne, L., & Kunnas, J. (2019, September 23). Real-Time 3D Inversion of Ultra-Deep Resistivity Logging-While-Drilling Data. Society of Petroleum Engineers. doi:10.2118/196141-MS

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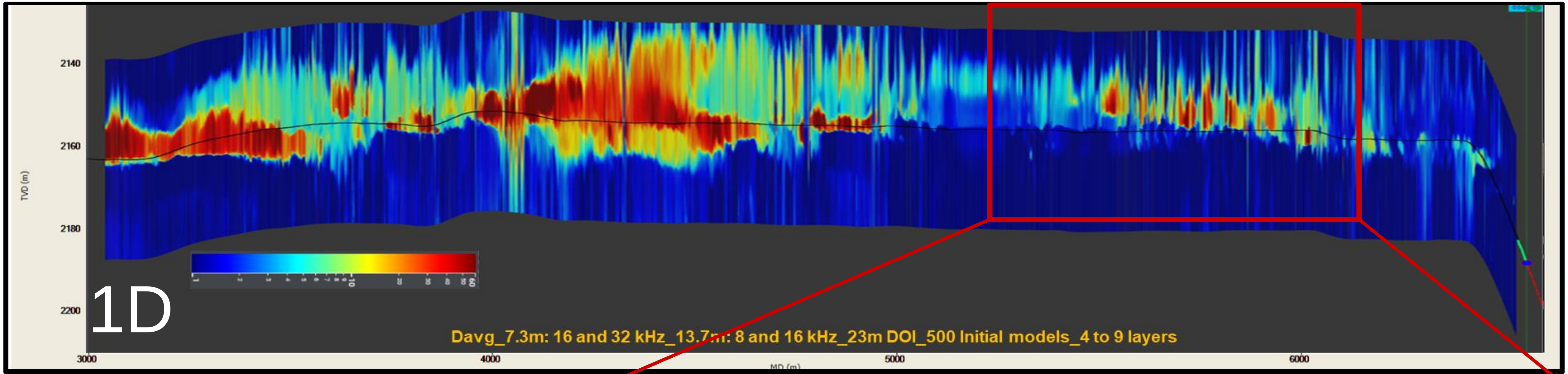
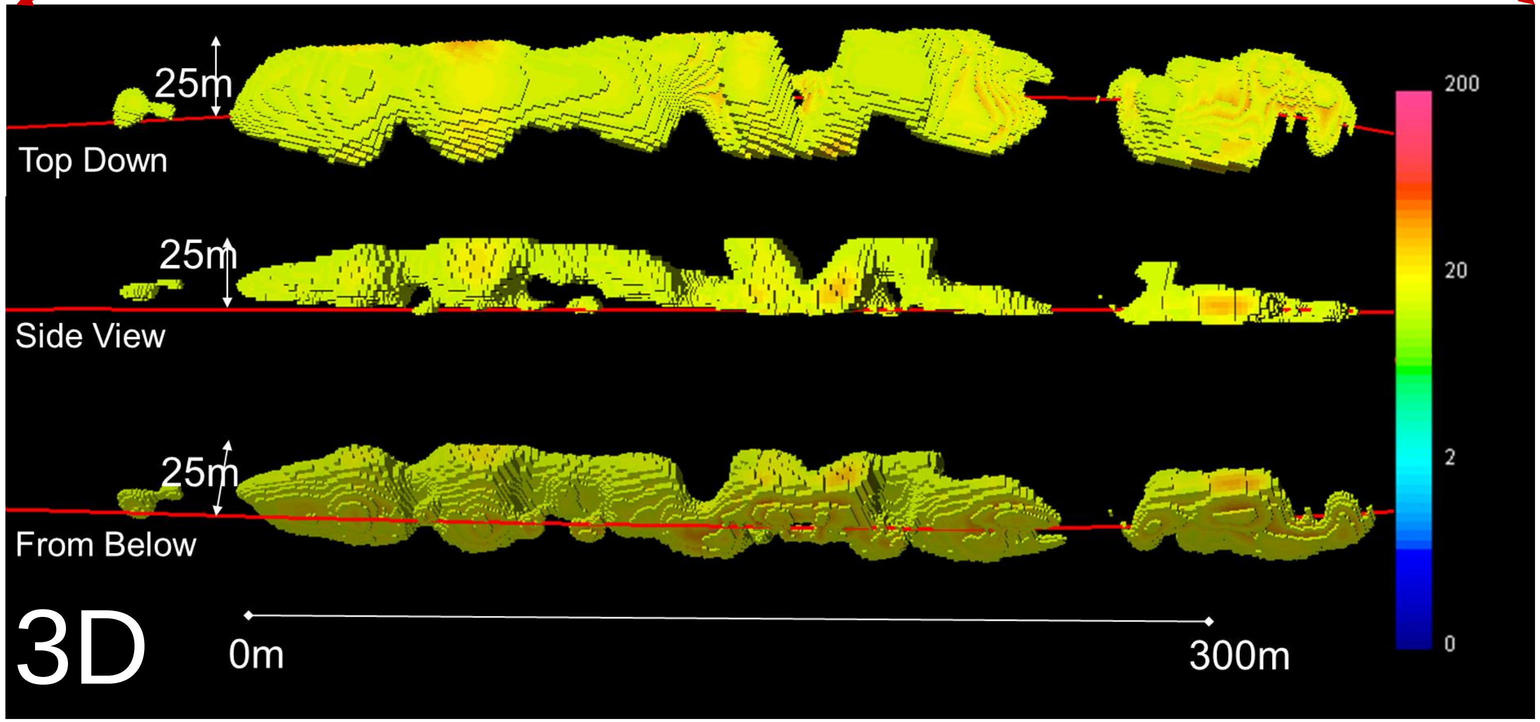


3D Inversion



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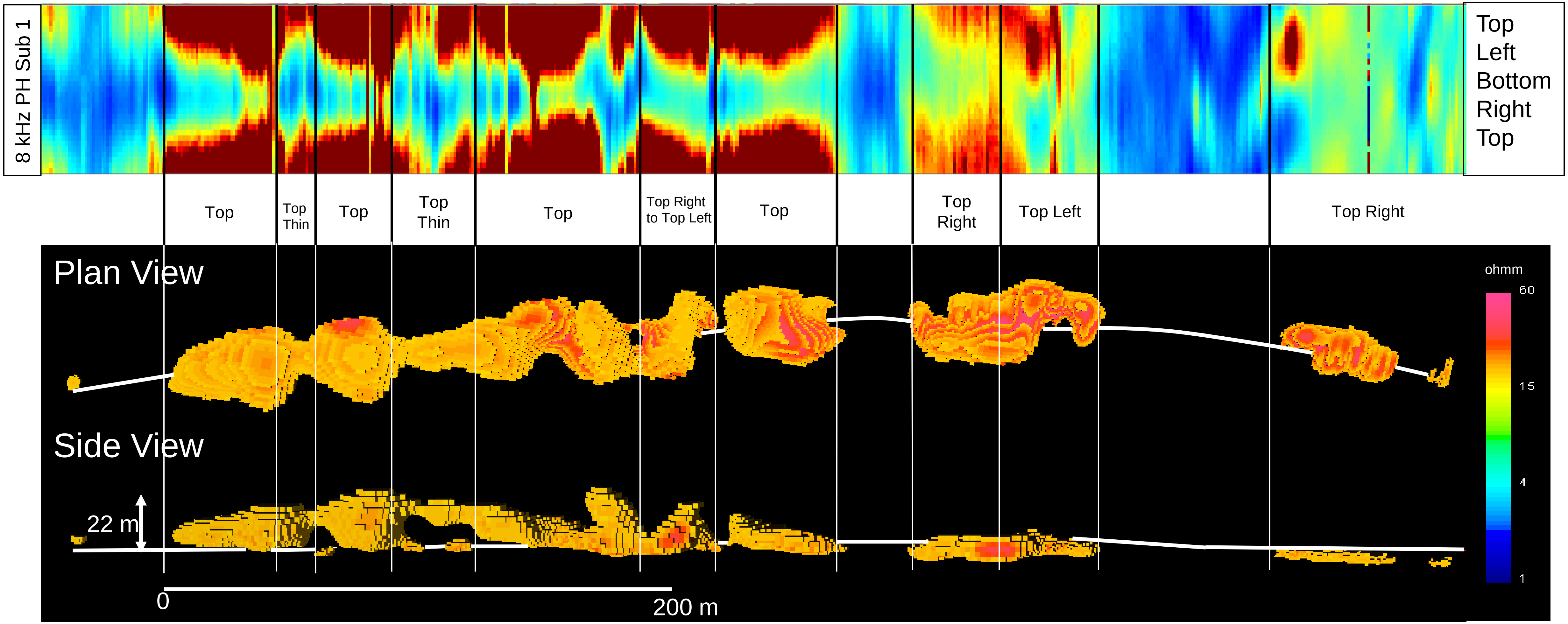
Verification



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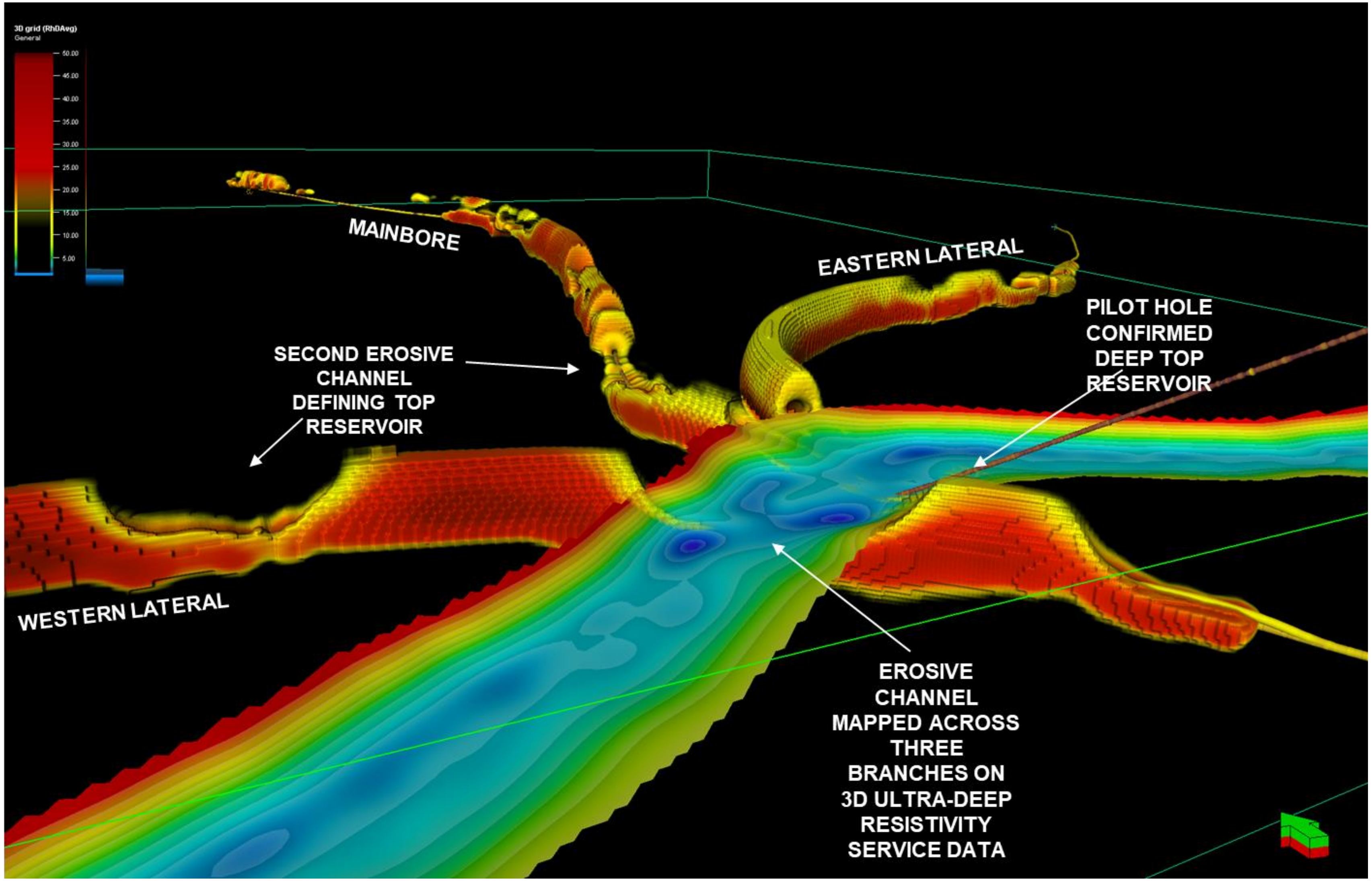
3D Inversion of Ultra-Deep Resistivity Data from Multi-Lateral Wells Integrated with Seismic Data

Mapping erosive turbidite channel that defines the top reservoir, confirmed with pilot hole



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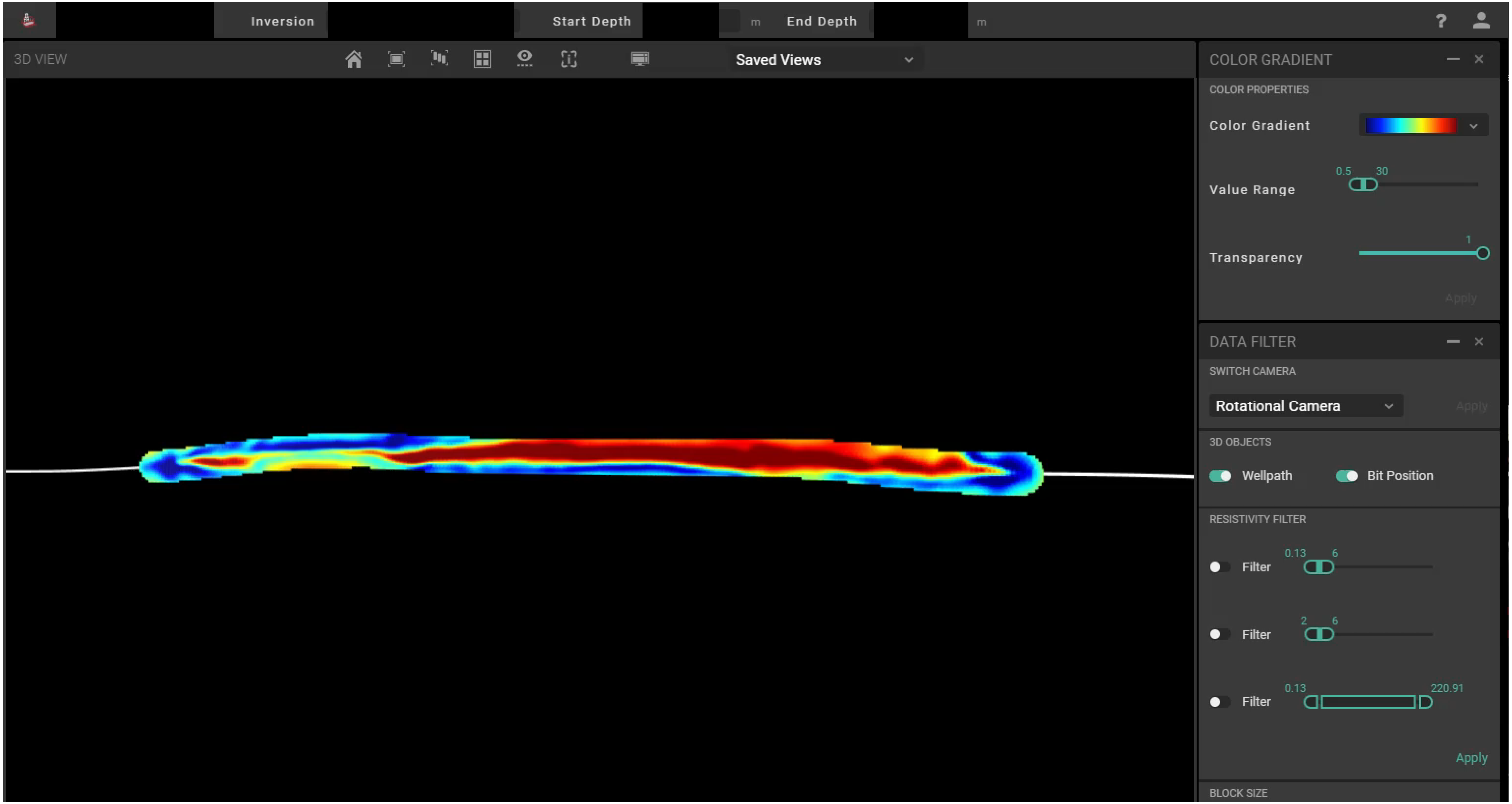
EarthStar® 3D Real Time Inversion



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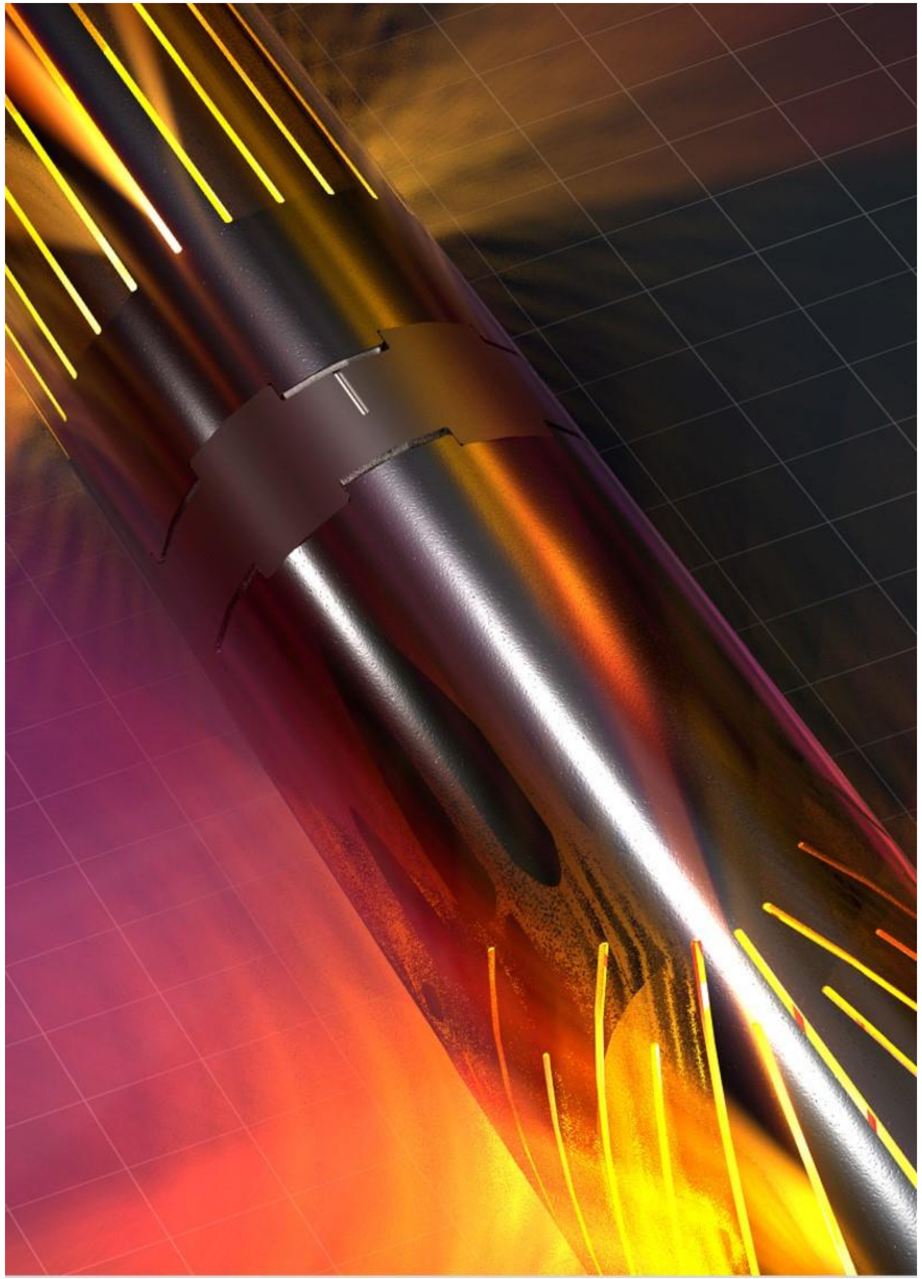

Landing Operations

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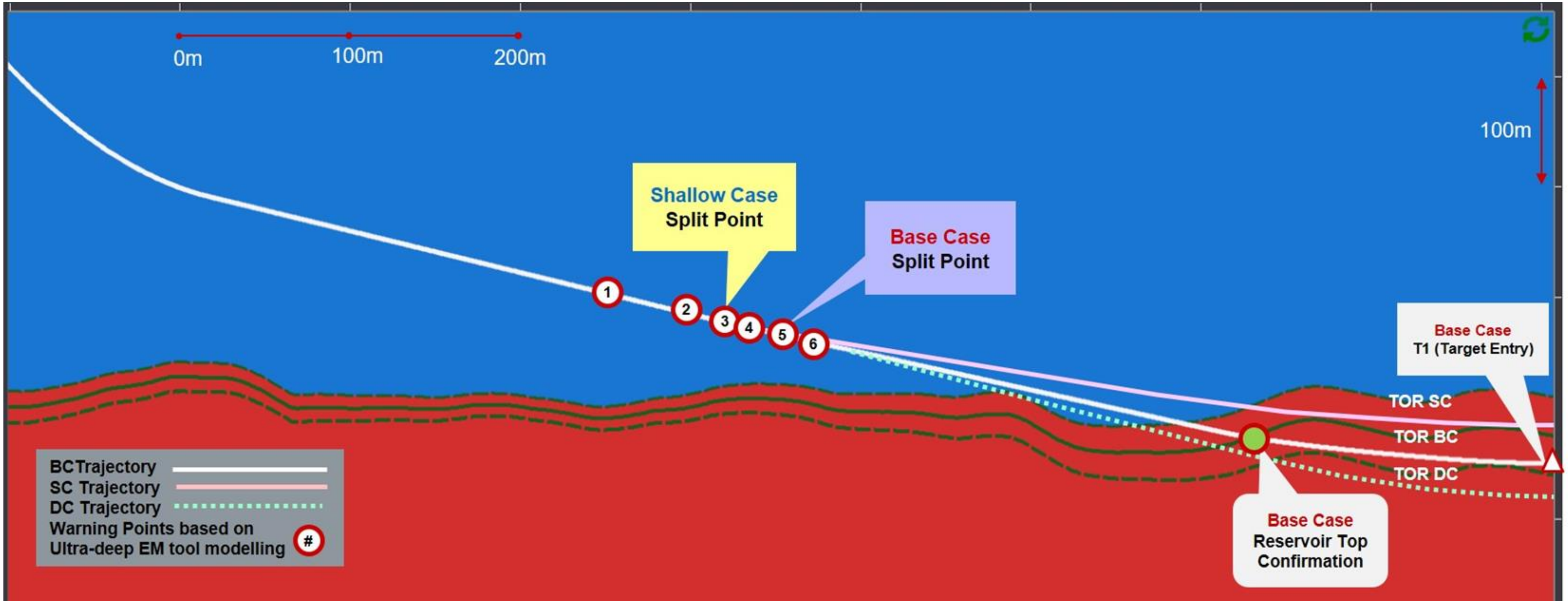
Pre-Drill Scenarios



Clegg, N., Domingues, A. B., Ameneiro Paredes, R., Gardner, N., Mendoza Barrón, V., Rowden, E., and Marchant, D. "Mapping Complex Geological Surface Morphology During Landing Operations Using 3-D Inversion of Ultra-Deep Electromagnetic LWD Data." Paper presented at the Offshore Technology Conference, Virtual and Houston, Texas, August 2021. doi: https://doi.org/10.4043/31216-MS

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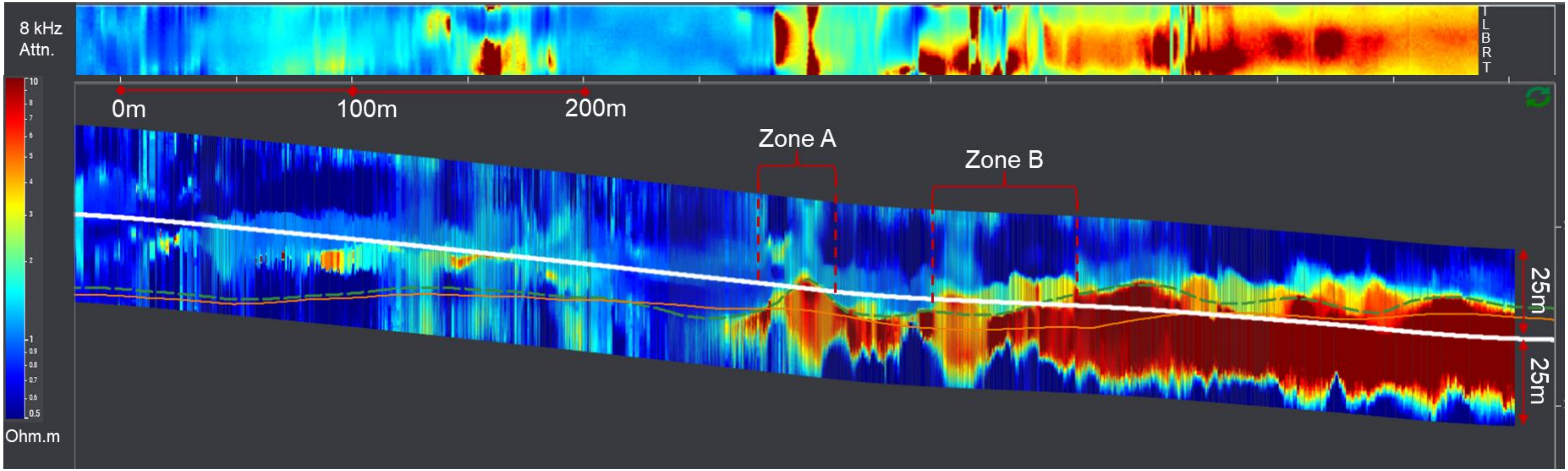
1D Inversion and Azimuthal Resistivity Image



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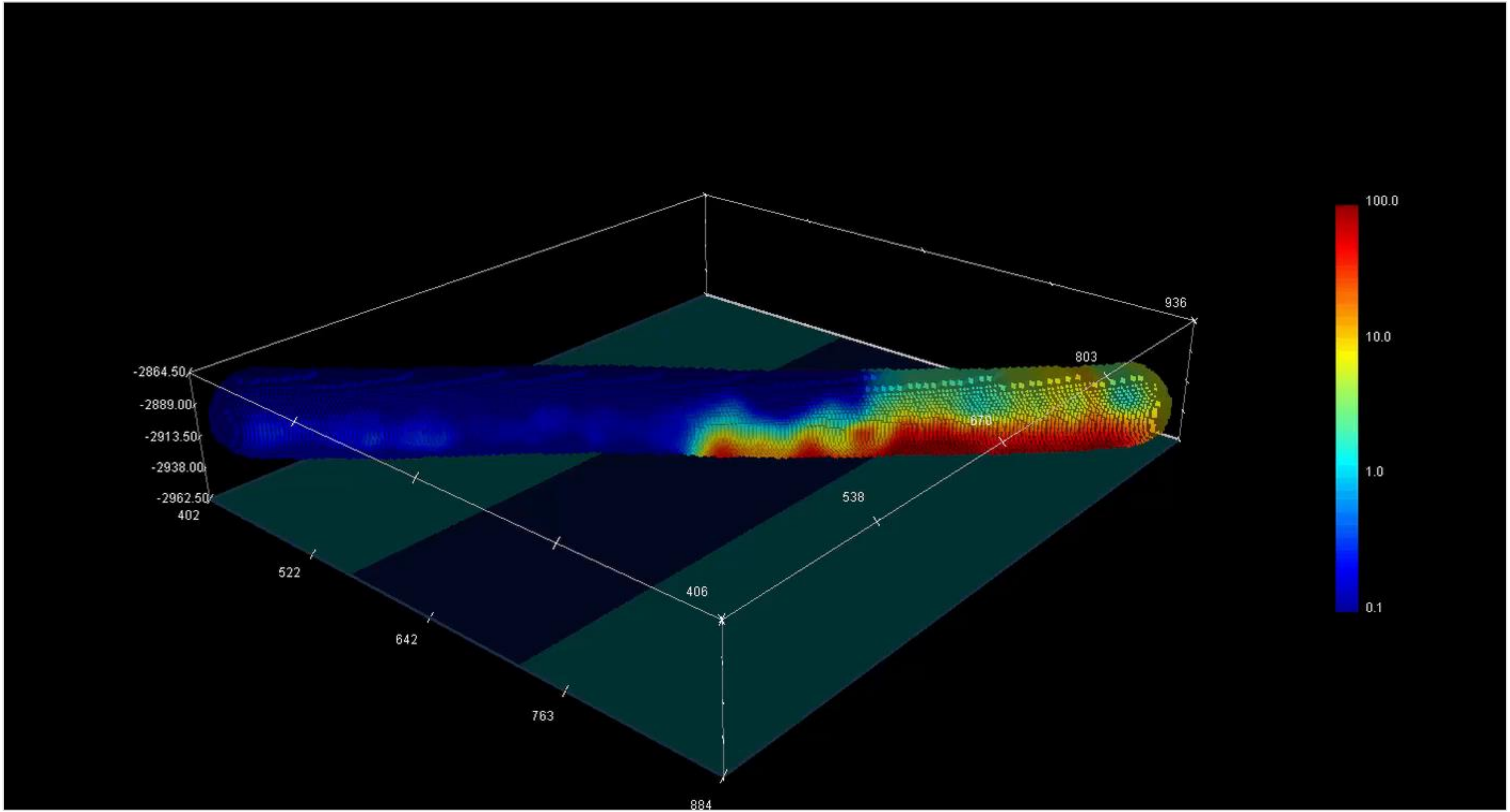
3D Inversion Results



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Conclusions

- Logging-while-drilling operations require real-time analysis to impact drilling and completion decisions
- Ultra-deep resistivity is important for landing, geosteering, and geostopping operations
- 3D inversion captures full geological complexity
  - No approximations in modeling per se
  - OcTree enables real-time 3D inversion
- Many case studies to validate results and value to well construction

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