ZTMT2DIV: Two-dimensional Joint Inversion of ZTEM and MT Plane-Wave EM Data Including Topography

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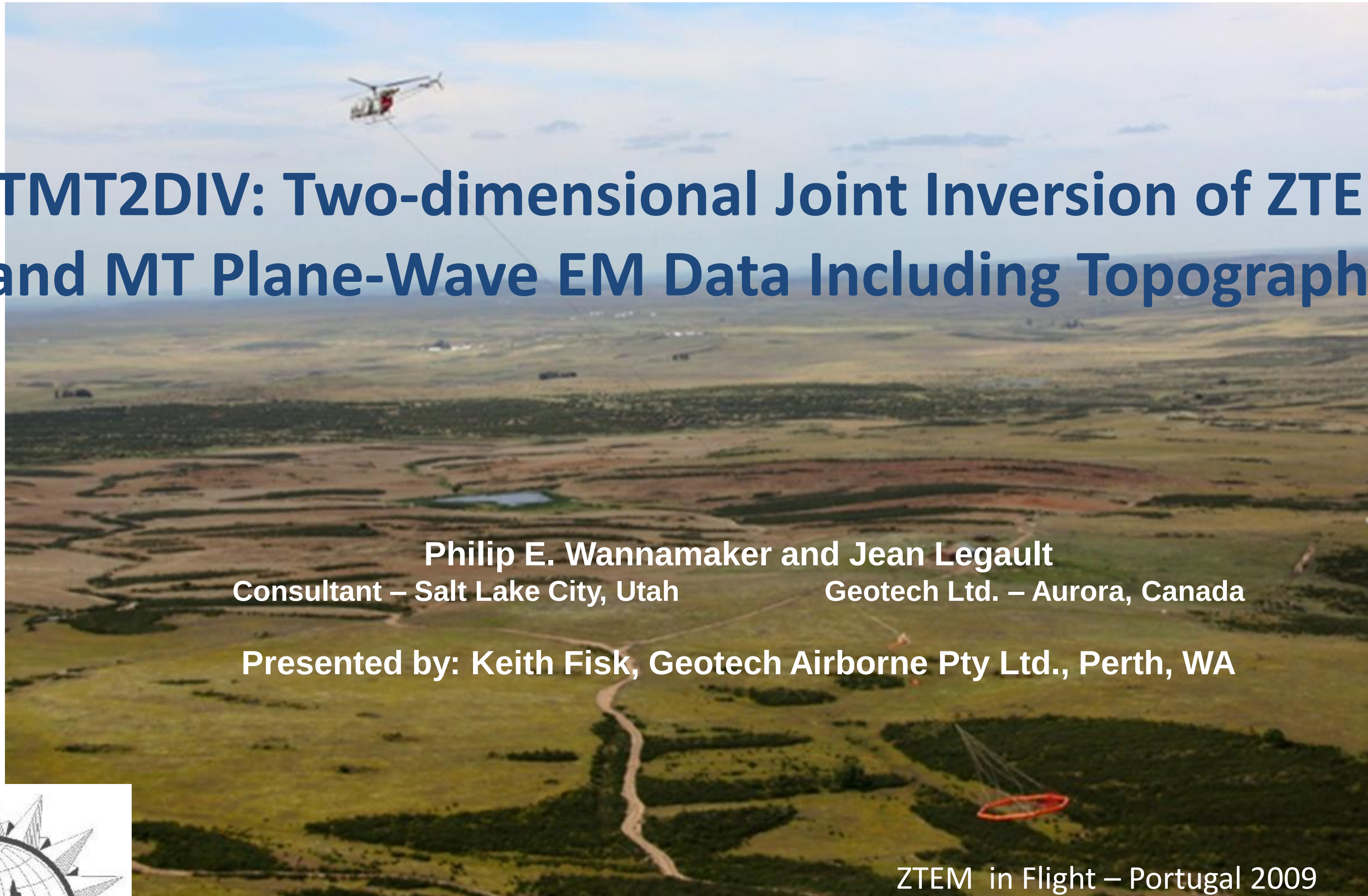

ZTEM in Flight – Portugal 2009

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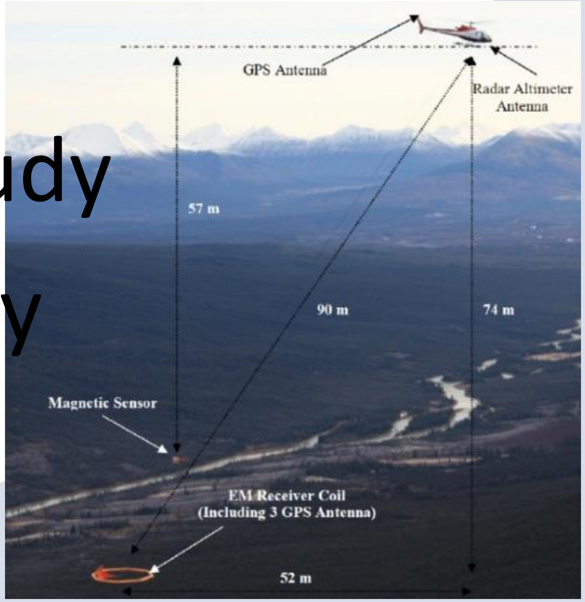
2nd Presentation: "Geophysical Inversion for Mineral Explorers", Perth, WA, 2nd Sept., 2014

Outline

- Introduction
- ZTEM and MT Basic Principles
- ZTEM Apriori Model Effects
- Joint MT-ZTEM Inversion
- Joint MT-ZTEM Model Study
- Joint MT-ZTEM Case Study
- Conclusions

ZTEM AEM System



SAGEEP 2014
March 16-20

Introduction

- ZTEM data provide excellent mapping of lateral resistivity contrasts – Fast and Low Cost.
- Quantitative resistivity model attained with suitable constraints (resolution depends on apriori start model).
- MT method provides quantitative resistivity independently due to E-fields and H-fields.
- Full airborne MT remains a technological challenge – Ground MT acquisition Slow and High Cost.
- Motivated to examine improvement to ZTEM resolution (depth, resistivity) by incorporating sparse MT measurements + Joint Inversion code.

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AIRBORNE GEOPHYSICAL SURVEYS

ZTEM & MT – Basic Principles

- MT and ZTEM in same family of plane-wave EM techniques.
- Measurement of electric (E) and/or magnetic (H) fields close to the Earth's surface
- MT stands for **M**agneto**t**ellurics – ground EM method
- ZTEM stands for **Z**-axis **T**ipper **E**lectro**m**agnetics – airborne EM method
- Magnetotellurics - ground version of ZTEM (plus electric fields).
- Frequency range determines depth of investigation
- ZTEM: 720-30 Hz (up to 2km), MT-AMT: 10,000-0.0001Hz (surface down to upper mantle)

GEOTECH
AIRBORNE GEOPHYSICAL SURVEYS

ZTEM & MT – Basic Principles

ZTEM-MT Tipper Comparison

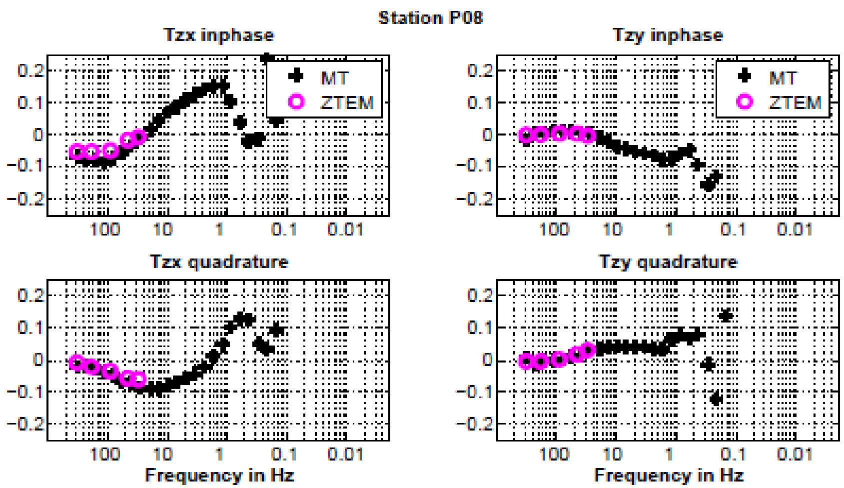


Figure : Components of tipper, estimated from ZTEM and MT at one station

ZTEM-MT 3D Inversion Comparison

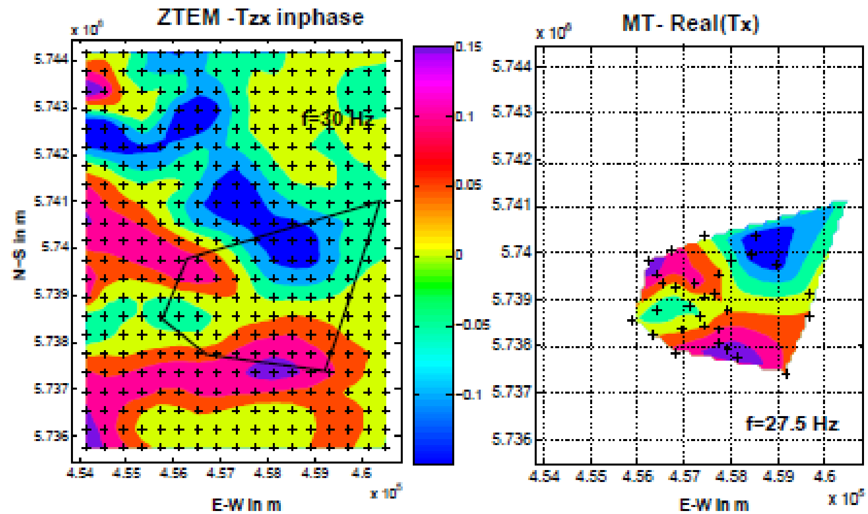


Figure : Tx real part from ZTEM (left) and MT (right)

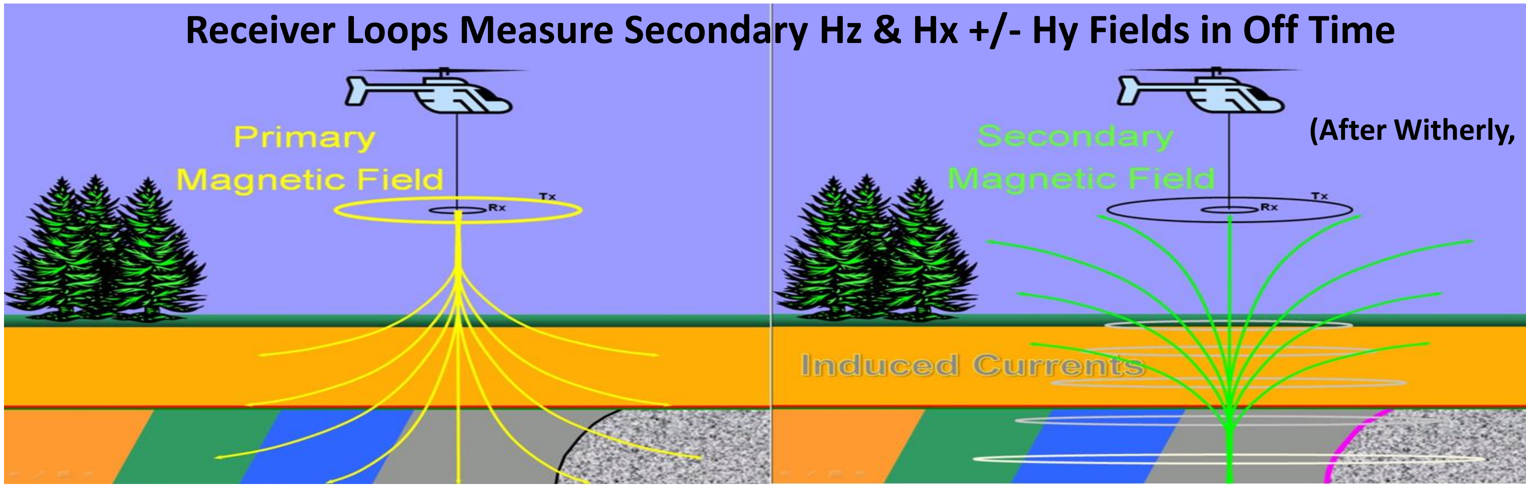
Highlighting Identical Nature of ZTEM & MT Measurements and Relative Accuracy Demonstrated in 3D Inversion Results

(after Hubert et al, PDAC 2013)

ZTEM Basic Principles

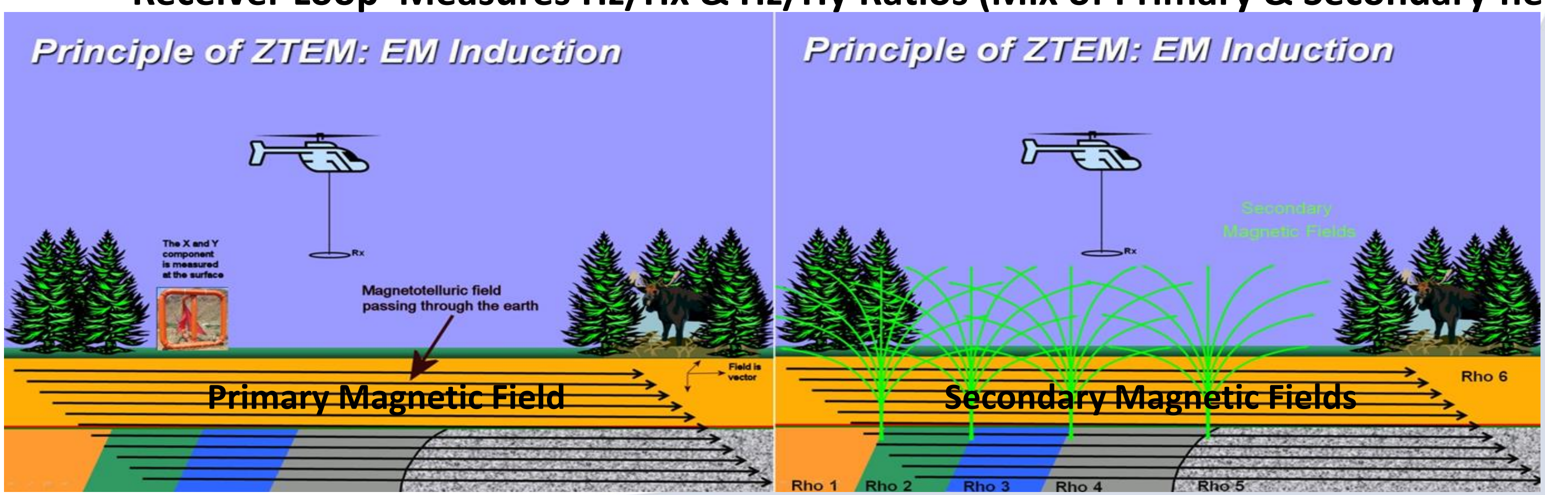
ZTEM BASIC PRINCIPLESOF OPERATION – How it's Similar Yet Different From HTEM

HTEM : Primary EM Field Comes from Transmitter Current-Loop (Fields Mainly Vertical – Up)
Receiver Loops Measure Secondary Hz & Hx +/- Hy Fields in Off Time



(After Witherly, PDAC 2011)

ZTEM : Primary EM Field Comes from World-Wide Thunderstorms (Fields Horizontal – Lateral)
Receiver Loop Measures Hz/Hx & Hz/Hy Ratios (Mix of Primary & Secondary fields)

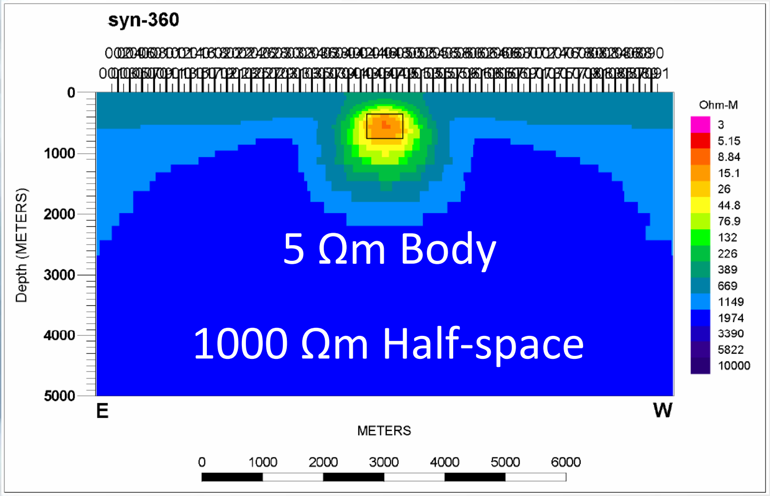


(after Witherly, PDAC 2011)

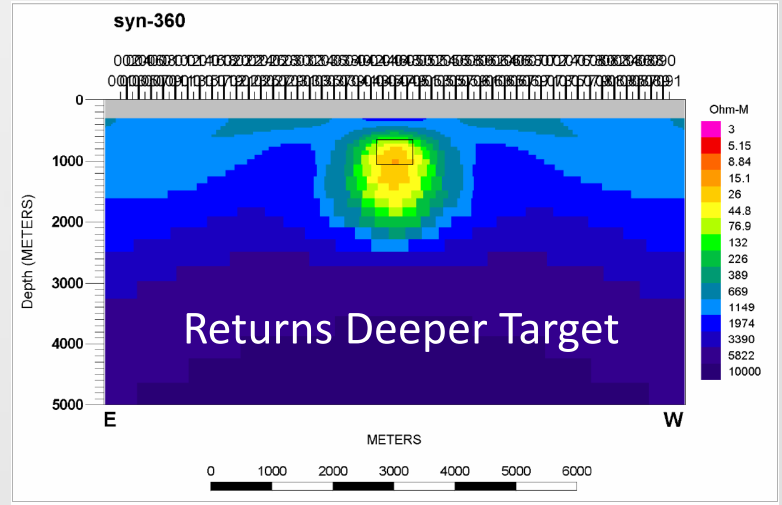
ZTEM Basic Principles

2D Synthetic Inversion Modeling

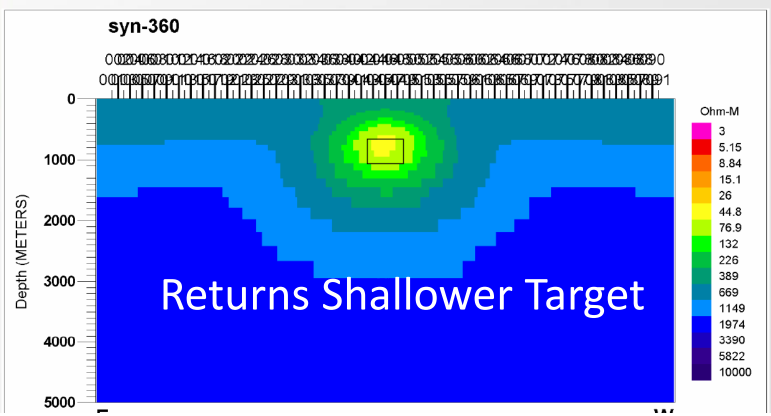
Inversion for ZTEM profile along ground surface over brick.



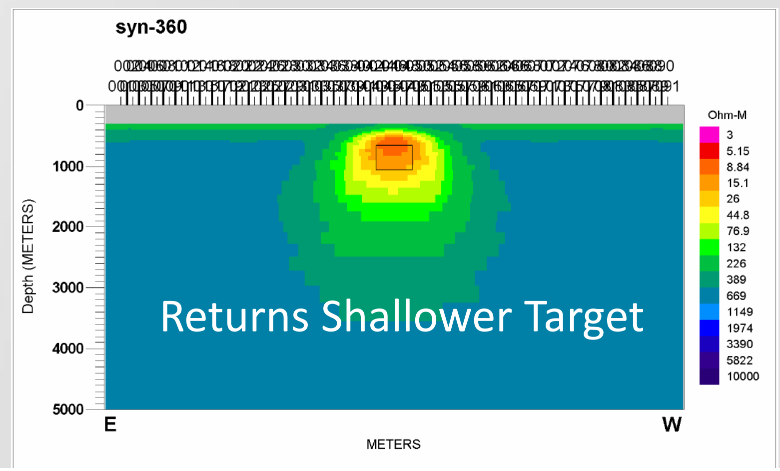
Inversion with 3200 ohm-m Apriori.



Inversion with Air Layer Ignored



Inversion with 320 ohm-m Apriori

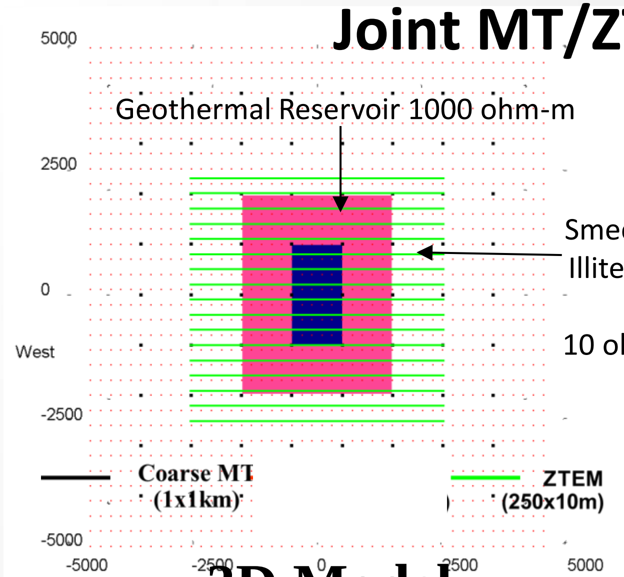


Examples of ZTEM 2D Inversion and Effects of Apriori Parameters on Model Accuracy

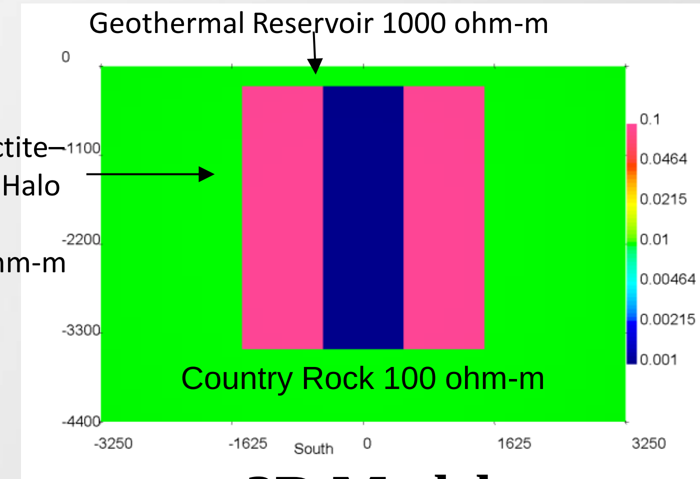
(*after Wannamaker, PDAC 2009*)

ZTEM Basic Principles

Joint MT/ZTEM 3D Inversion

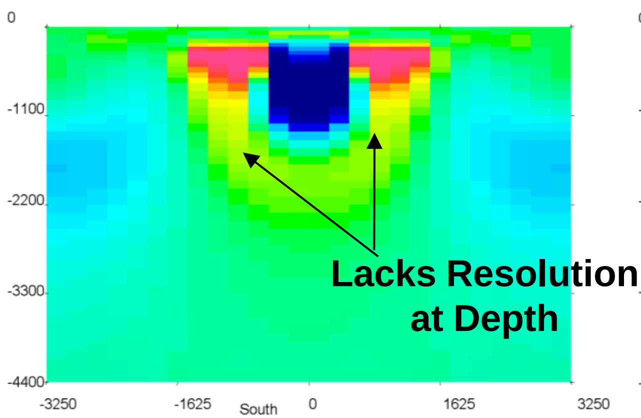


3D Model
(Plan-View)

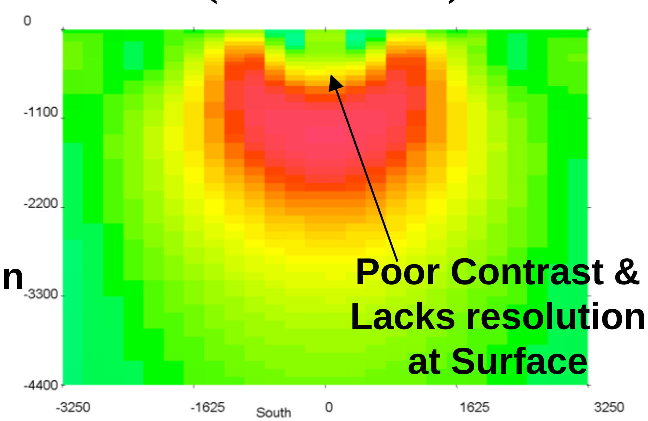


3D Model
(Cross-Section)

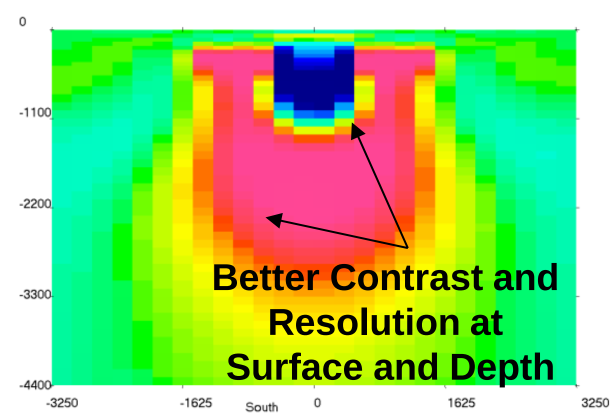
ZTEM 3D
(10x250m)



Coarse MT 3D
(1km x 1km)



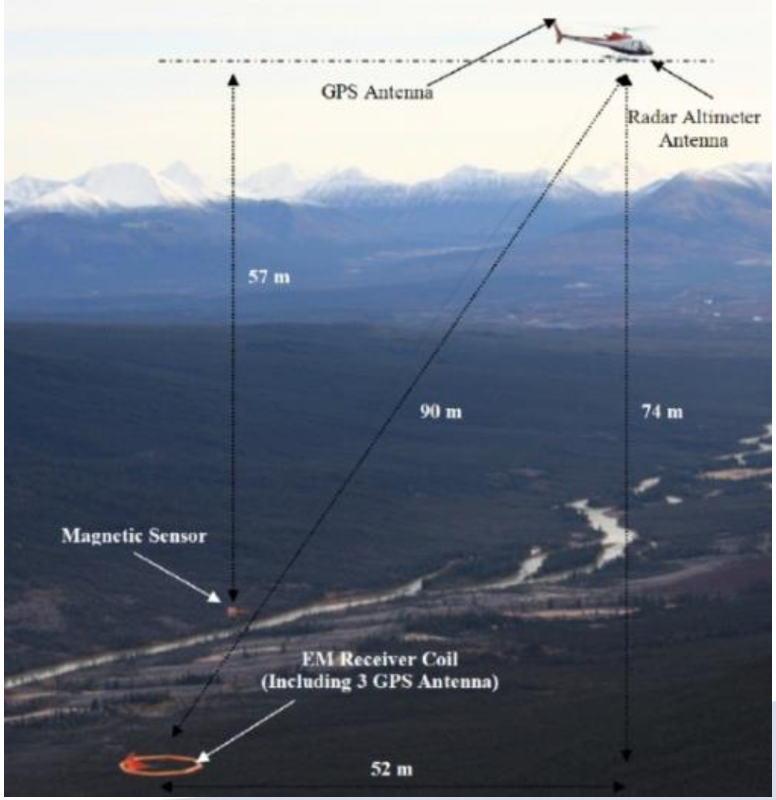
Joint 3D
MT-ZTEM

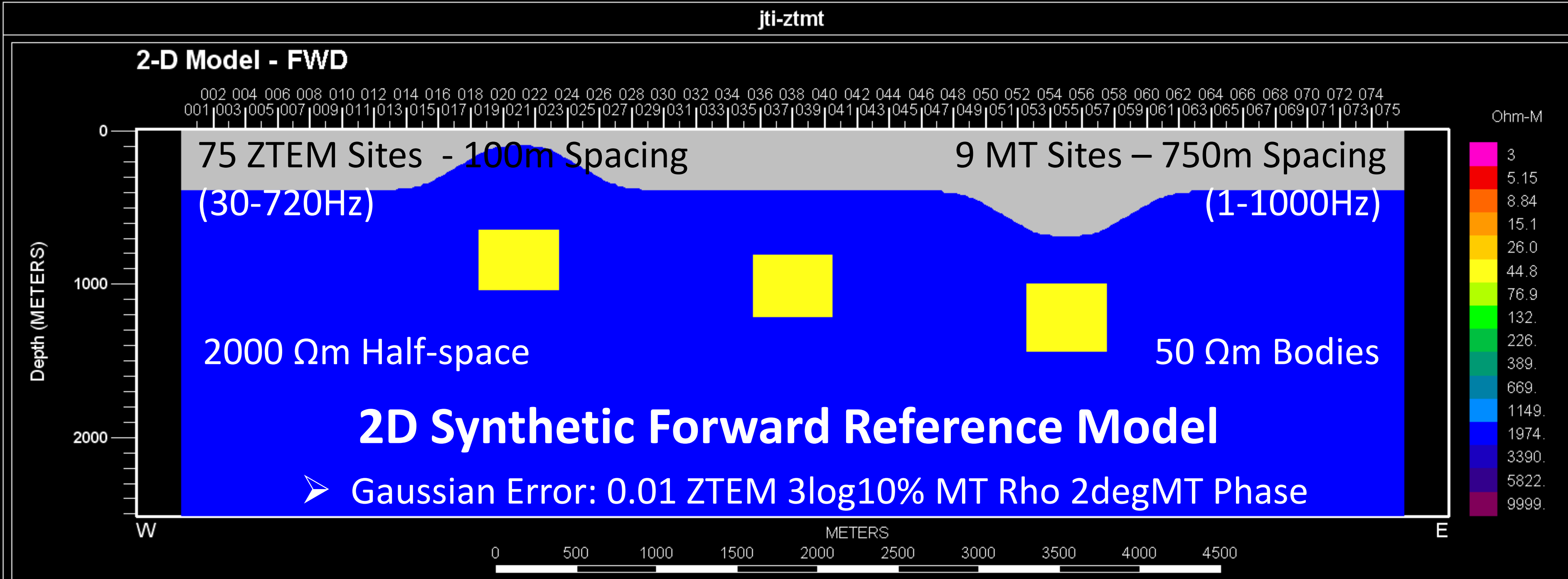


Joint MT-ZTEM Inversion shows marked improvement over stand-alone models

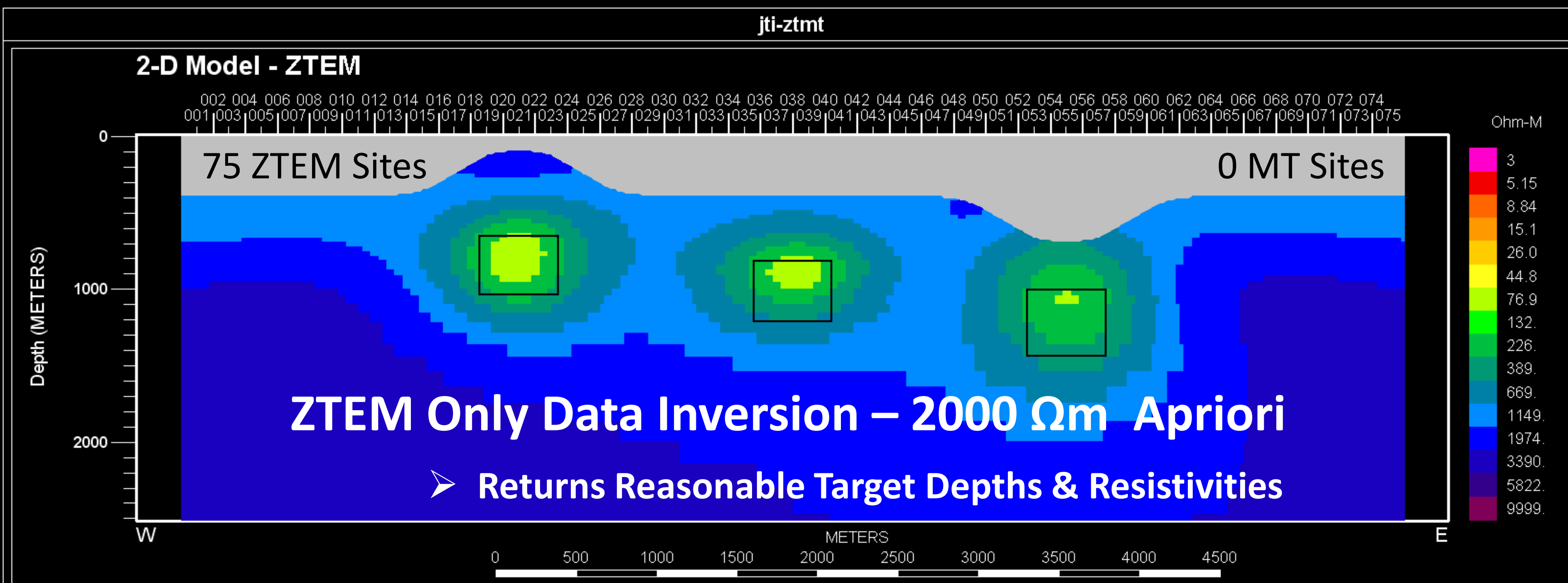
(after Holtham and Oldenburg, 2010)

Joint MT-ZTEM 2D Model Study

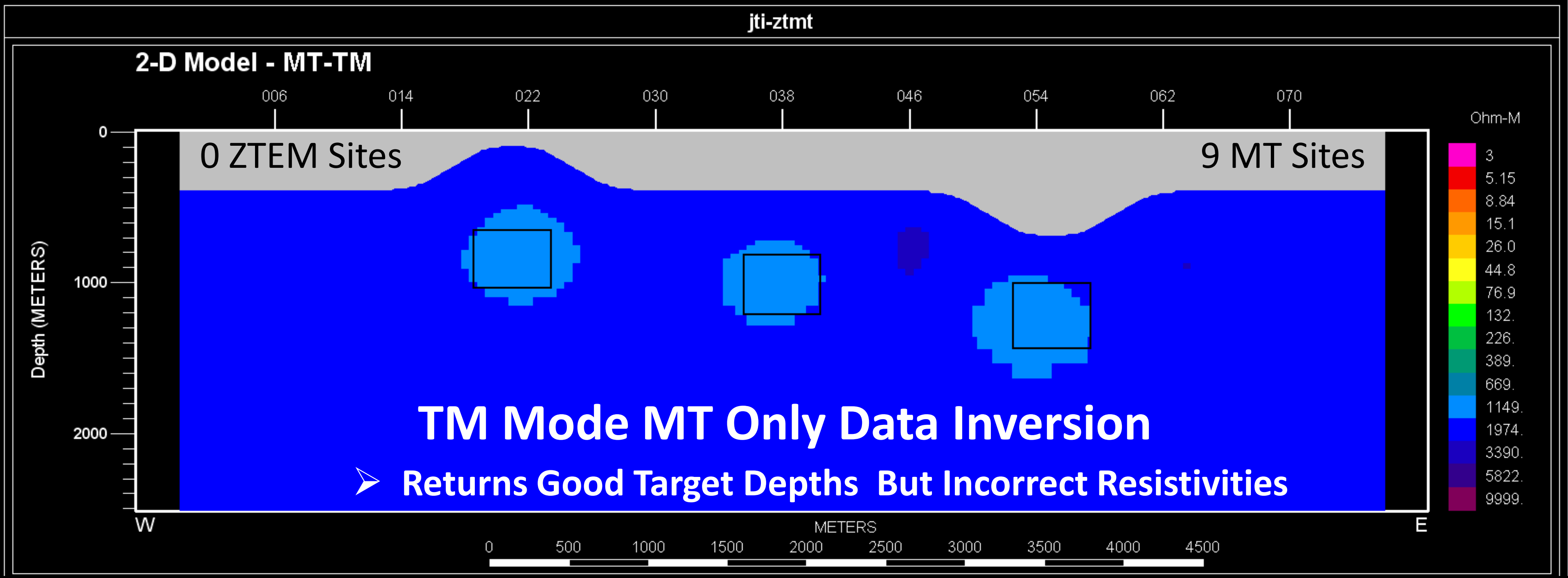




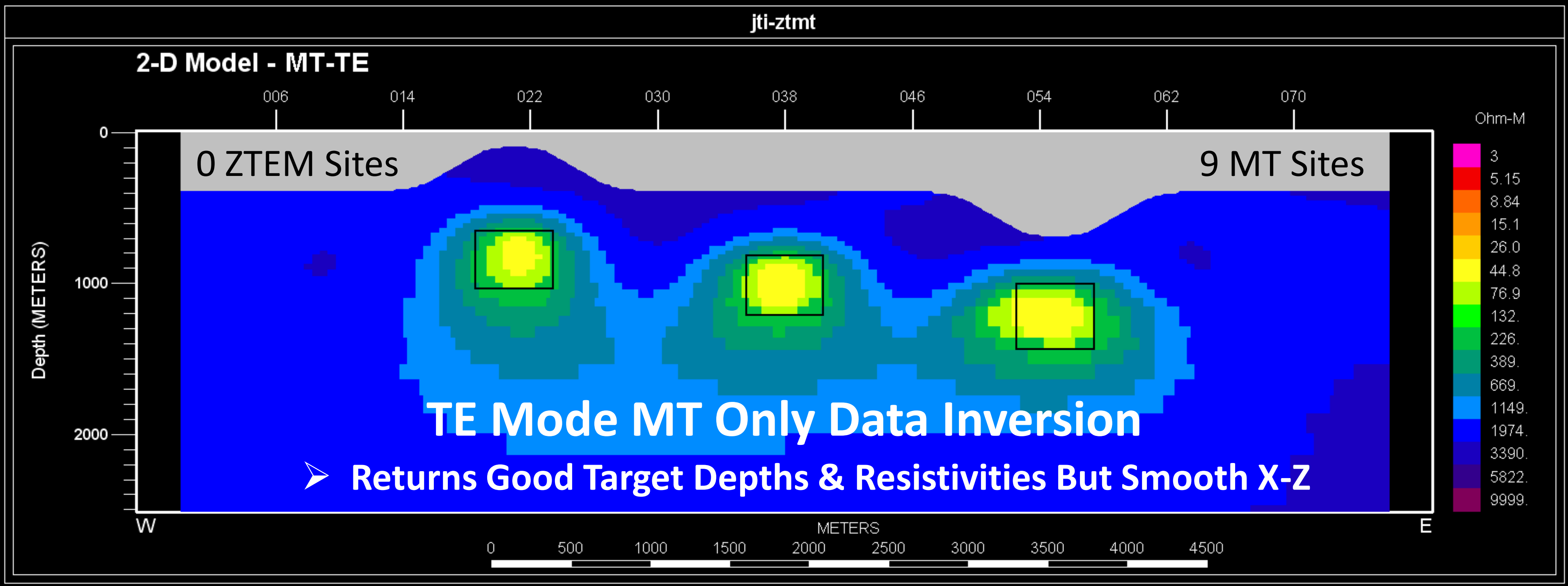
jti-ztmt
2-D Model - FWD
002 004 006 008 010 012 014 016 018 020 022 024 026 028 030 032 034 036 038 040 042 044 046 048 050 052 054 056 058 060 062 064 066 068 070 072 074
001 003 005 007 009 011 013 015 017 019 021 023 025 027 029 031 033 035 037 039 041 043 045 047 049 051 053 055 057 059 061 063 065 067 069 071 073 075
Ohm-M
3
5.15
8.84
15.1
26.0
44.8
76.9
132.
226.
389.
669.
1149.
1974.
3390.
5822.
9999.
0
1000
2000
Depth (METERS)
75 ZTEM Sites - 100m Spacing
(30-720Hz)
9 MT Sites – 750m Spacing
(1-1000Hz)
2000 Ωm Half-space
50 Ωm Bodies
2D Synthetic Forward Reference Model
➢ Gaussian Error: 0.01 ZTEM 3log10% MT Rho 2degMT Phase
W
E
METERS
0 500 1000 1500 2000 2500 3000 3500 4000 4500



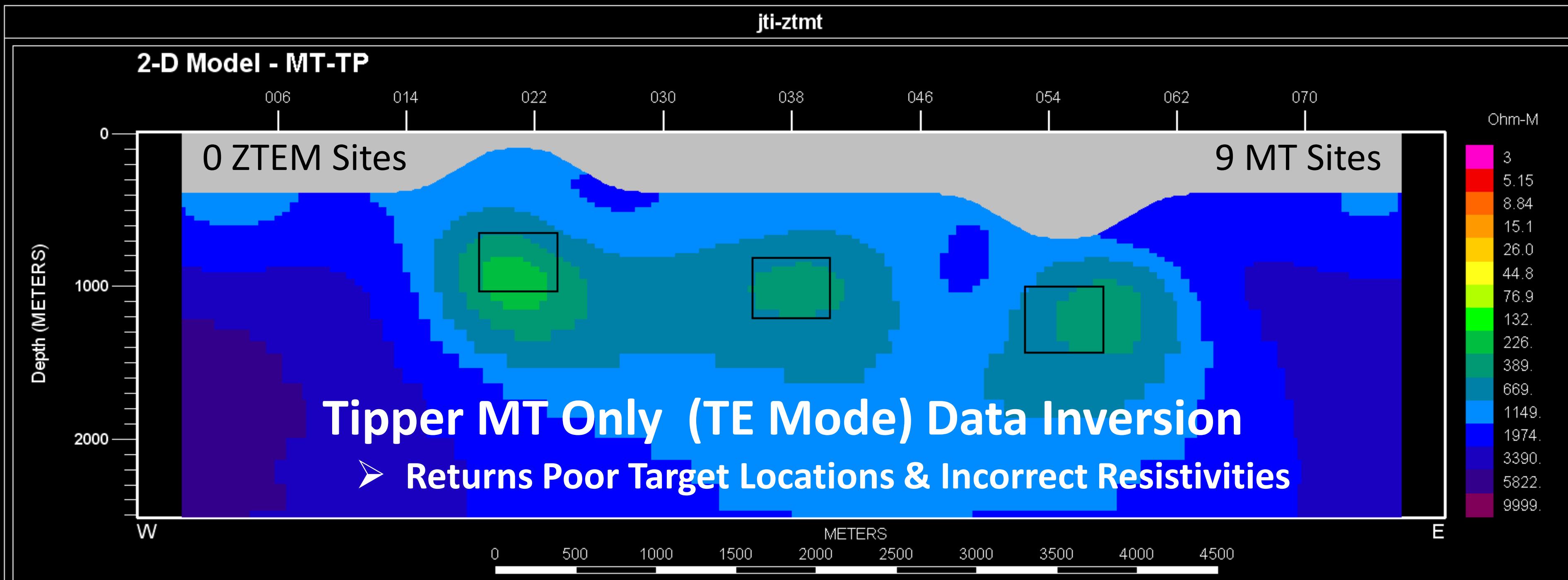
jti-ztmt
2-D Model - ZTEM
002 004 006 008 010 012 014 016 018 020 022 024 026 028 030 032 034 036 038 040 042 044 046 048 050 052 054 056 058 060 062 064 066 068 070 072 074
001 003 005 007 009 011 013 015 017 019 021 023 025 027 029 031 033 035 037 039 041 043 045 047 049 051 053 055 057 059 061 063 065 067 069 071 073 075
Ohm-M
3
5.15
8.84
15.1
26.0
44.8
76.9
132.
226.
389.
669.
1149.
1974.
3390.
5822.
9999.
0
1000
2000
Depth (METERS)
75 ZTEM Sites
0 MT Sites
ZTEM Only Data Inversion – 2000 Ωm Apriori
➢ Returns Reasonable Target Depths & Resistivities
W
E
METERS
0 500 1000 1500 2000 2500 3000 3500 4000 4500

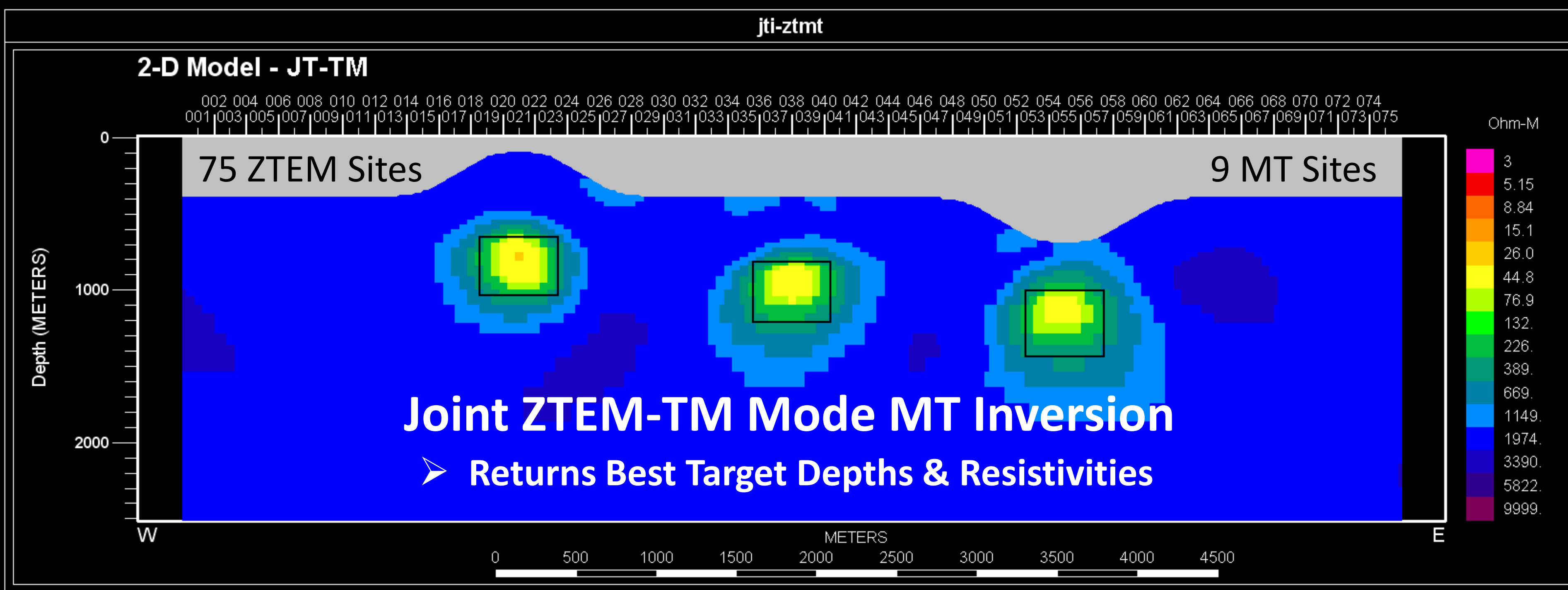


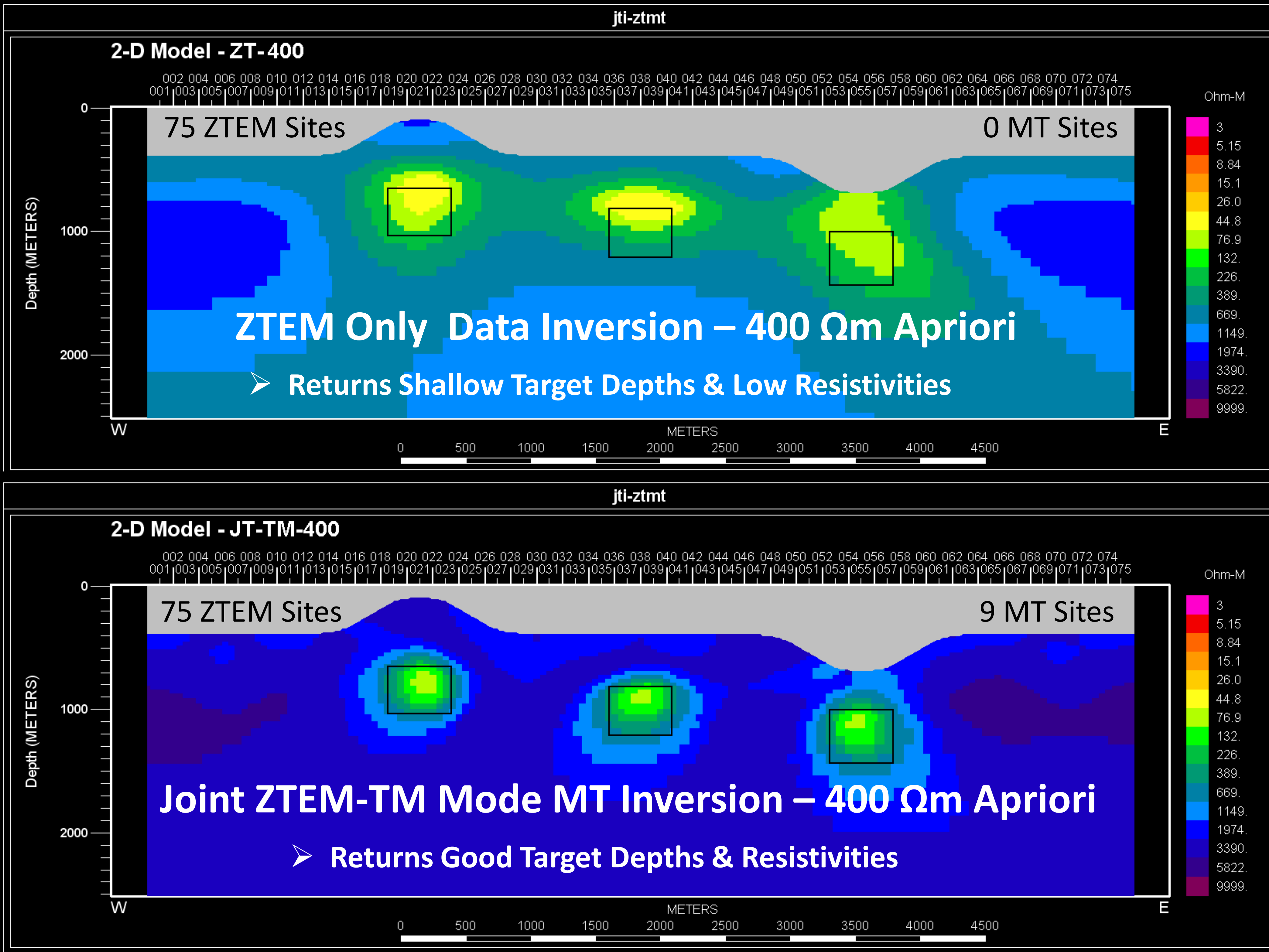
jti-ztmt
2-D Model - MT-TM
006
014
022
030
038
046
054
062
070
0 ZTEM Sites
9 MT Sites
TM Mode MT Only Data Inversion
Returns Good Target Depths But Incorrect Resistivities
Depth (METERS)
0
1000
2000
W
E
METERS
0 500 1000 1500 2000 2500 3000 3500 4000 4500
Ohm-M
3
5.15
8.84
15.1
26.0
44.8
76.9
132.
226.
389.
669.
1149.
1974.
3390.
5822.
9999.



jti-ztmt
2-D Model - MT-TE
006
014
022
030
038
046
054
062
070
0 ZTEM Sites
9 MT Sites
TE Mode MT Only Data Inversion
Returns Good Target Depths & Resistivities But Smooth X-Z
Depth (METERS)
0
1000
2000
W
E
METERS
0 500 1000 1500 2000 2500 3000 3500 4000 4500
Ohm-M
3
5.15
8.84
15.1
26.0
44.8
76.9
132.
226.
389.
669.
1149.
1974.
3390.
5822.
9999.


jti-ztmt
2-D Model - MT-TP
006 014 022 030 038 046 054 062 070
0 ZTEM Sites
9 MT Sites
Ohm-M
3
5.15
8.84
15.1
26.0
44.8
76.9
132.
226.
389.
669.
1149.
1974.
3390.
5822.
9999.
0
1000
2000
Depth (METERS)
Tipper MT Only (TE Mode) Data Inversion
➢ Returns Poor Target Locations & Incorrect Resistivities
W
E
METERS
0 500 1000 1500 2000 2500 3000 3500 4000 4500


jti-ztmt
2-D Model - JT-TM
002 004 006 008 010 012 014 016 018 020 022 024 026 028 030 032 034 036 038 040 042 044 046 048 050 052 054 056 058 060 062 064 066 068 070 072 074
001 003 005 007 009 011 013 015 017 019 021 023 025 027 029 031 033 035 037 039 041 043 045 047 049 051 053 055 057 059 061 063 065 067 069 071 073 075
75 ZTEM Sites
9 MT Sites
Ohm-M
3
5.15
8.84
15.1
26.0
44.8
76.9
132.
226.
389.
669.
1149.
1974.
3390.
5822.
9999.
0
1000
2000
Depth (METERS)
Joint ZTEM-TM Mode MT Inversion
➢ Returns Best Target Depths & Resistivities
W
E
METERS
0 500 1000 1500 2000 2500 3000 3500 4000 4500


jti-ztmt
2-D Model - ZT-400
002 004 006 008 010 012 014 016 018 020 022 024 026 028 030 032 034 036 038 040 042 044 046 048 050 052 054 056 058 060 062 064 066 068 070 072 074
001 003 005 007 009 011 013 015 017 019 021 023 025 027 029 031 033 035 037 039 041 043 045 047 049 051 053 055 057 059 061 063 065 067 069 071 073 075
75 ZTEM Sites
0 MT Sites
ZTEM Only Data Inversion – 400 Ωm Apriori
➢ Returns Shallow Target Depths & Low Resistivities
Depth (METERS)
0
1000
2000
W
E
METERS
0 500 1000 1500 2000 2500 3000 3500 4000 4500
Ohm-M
3
5.15
8.84
15.1
26.0
44.8
76.9
132.
226.
389.
669.
1149.
1974.
3390.
5822.
9999.
jti-ztmt
2-D Model - JT-TM-400
002 004 006 008 010 012 014 016 018 020 022 024 026 028 030 032 034 036 038 040 042 044 046 048 050 052 054 056 058 060 062 064 066 068 070 072 074
001 003 005 007 009 011 013 015 017 019 021 023 025 027 029 031 033 035 037 039 041 043 045 047 049 051 053 055 057 059 061 063 065 067 069 071 073 075
75 ZTEM Sites
9 MT Sites
Joint ZTEM-TM Mode MT Inversion – 400 Ωm Apriori
➢ Returns Good Target Depths & Resistivities
Depth (METERS)
0
1000
2000
W
E
METERS
0 500 1000 1500 2000 2500 3000 3500 4000 4500
Ohm-M
3
5.15
8.84
15.1
26.0
44.8
76.9
132.
226.
389.
669.
1149.
1974.
3390.
5822.
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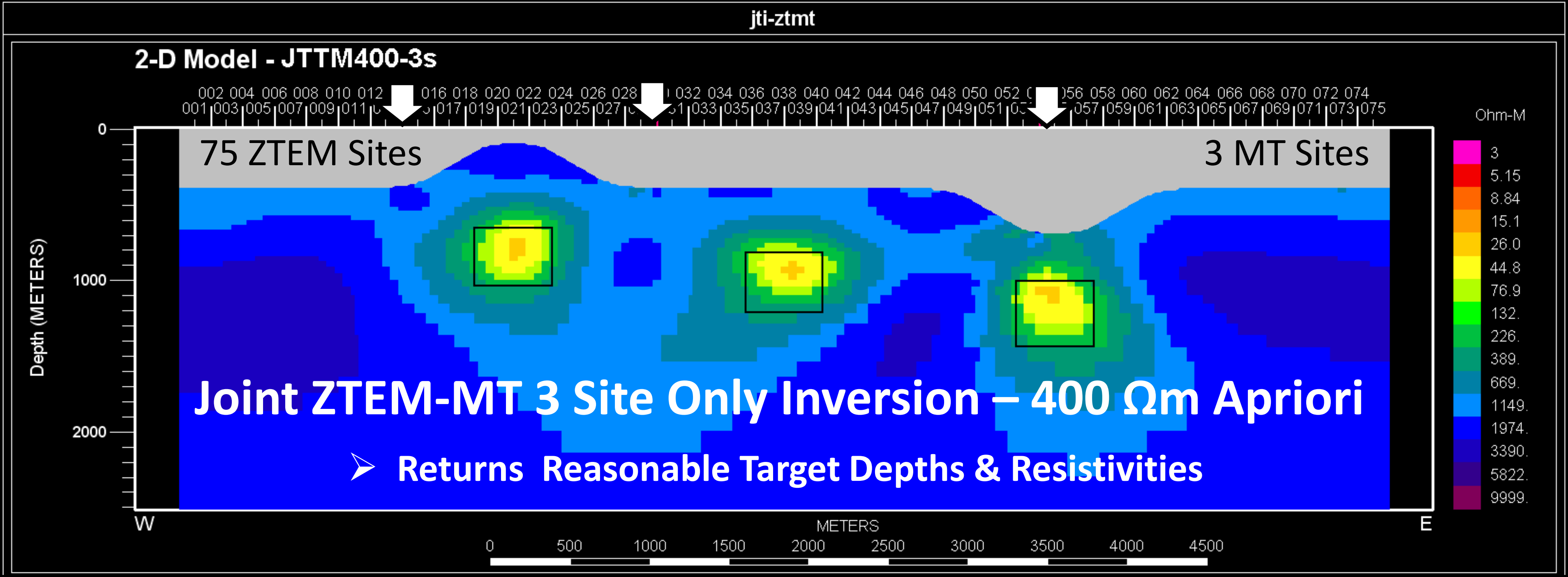
jti-ztmt
2-D Model - JTTM400-3s
75 ZTEM Sites
3 MT Sites
Depth (METERS)
0
1000
2000
Joint ZTEM-MT 3 Site Only Inversion – 400 Ωm Apriori
➢ Returns Reasonable Target Depths & Resistivities
W
E
METERS
0 500 1000 1500 2000 2500 3000 3500 4000 4500
Ohm-M
3
5.15
8.84
15.1
26.0
44.8
76.9
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226.
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1149.
1974.
3390.
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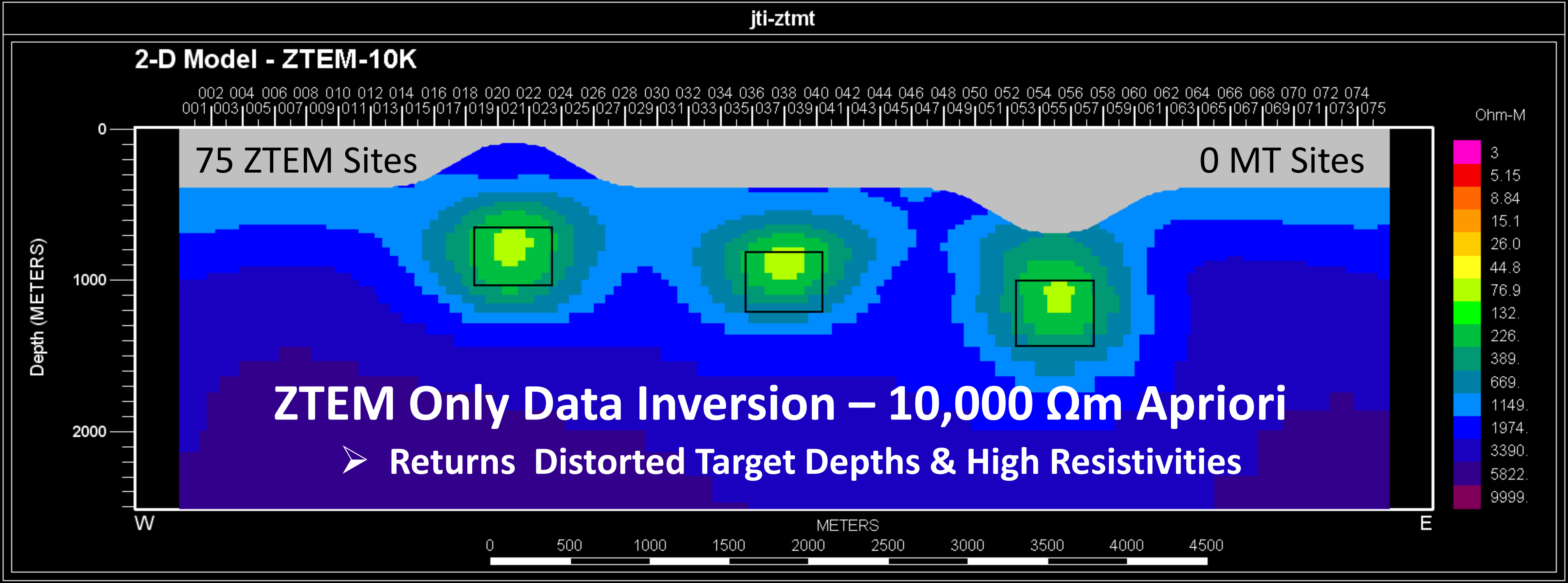
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2-D Model - ZTEM-10K
002 004 006 008 010 012 014 016 018 020 022 024 026 028 030 032 034 036 038 040 042 044 046 048 050 052 054 056 058 060 062 064 066 068 070 072 074
001 003 005 007 009 011 013 015 017 019 021 023 025 027 029 031 033 035 037 039 041 043 045 047 049 051 053 055 057 059 061 063 065 067 069 071 073 075
75 ZTEM Sites
0 MT Sites
Depth (METERS)
0
1000
2000
ZTEM Only Data Inversion – 10,000 Ωm Apriori
➢ Returns Distorted Target Depths & High Resistivities
W
E
METERS
0 500 1000 1500 2000 2500 3000 3500 4000 4500
Ohm-M
3
5.15
8.84
15.1
26.0
44.8
76.9
132.
226.
389.
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1149.
1974.
3390.
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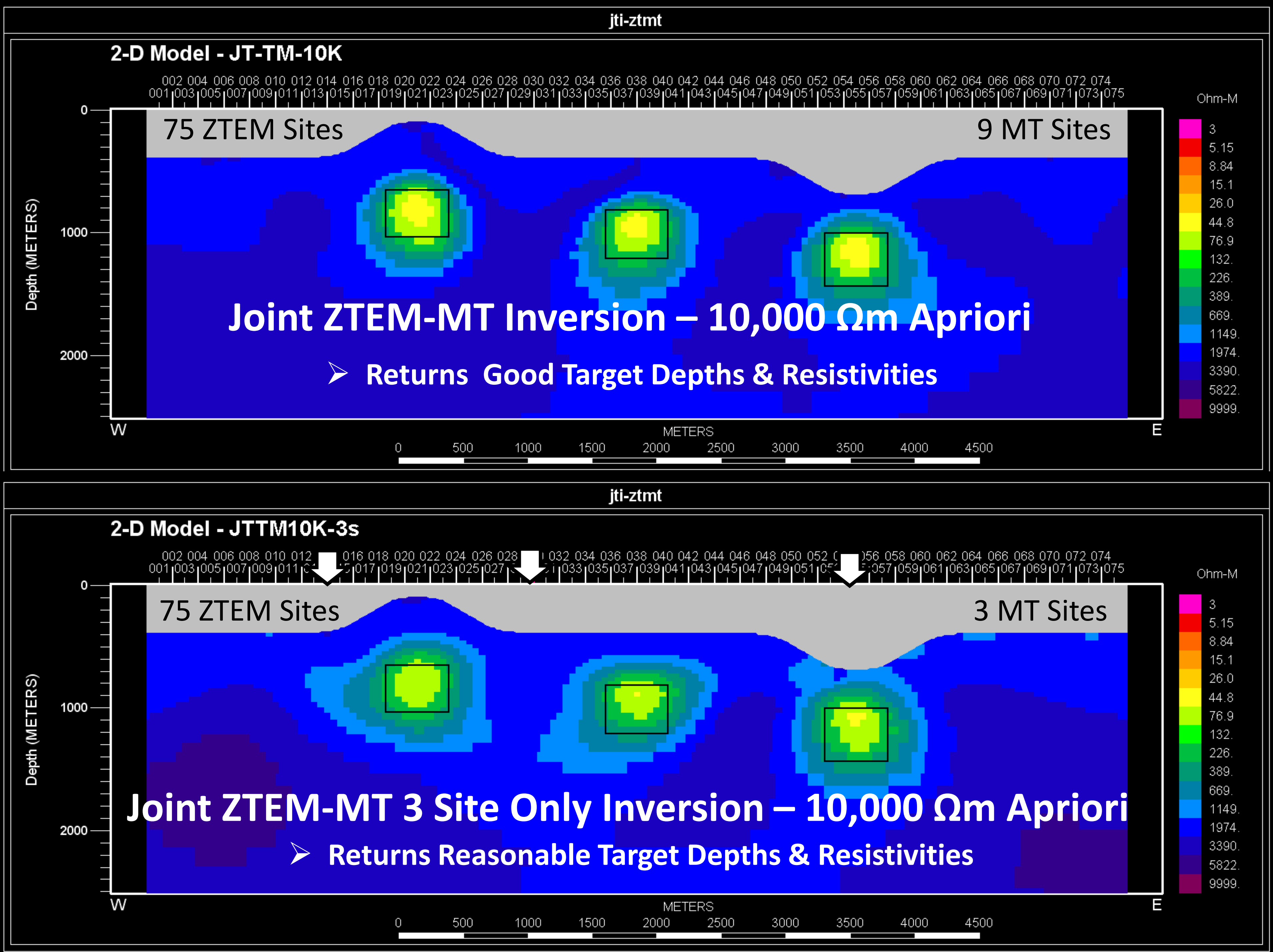
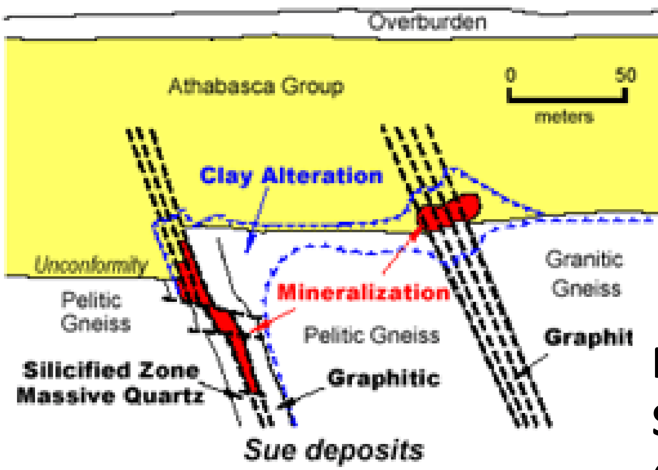
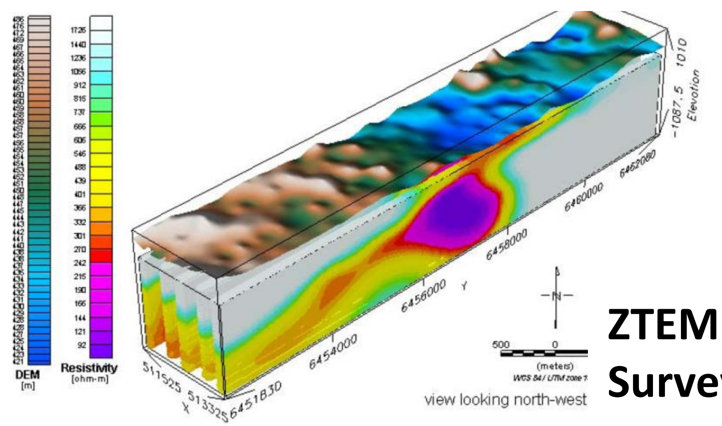

jti-ztmt
2-D Model - JT-TM-10K
002 004 006 008 010 012 014 016 018 020 022 024 026 028 030 032 034 036 038 040 042 044 046 048 050 052 054 056 058 060 062 064 066 068 070 072 074
001 003 005 007 009 011 013 015 017 019 021 023 025 027 029 031 033 035 037 039 041 043 045 047 049 051 053 055 057 059 061 063 065 067 069 071 073 075
Depth (METERS)
0
1000
2000
75 ZTEM Sites
9 MT Sites
Joint ZTEM-MT Inversion – 10,000 Ωm Apriori
Returns Good Target Depths & Resistivities
W
E
METERS
0 500 1000 1500 2000 2500 3000 3500 4000 4500
Ohm-M
3
5.15
8.84
15.1
26.0
44.8
76.9
132.
226.
389.
669.
1149.
1974.
3390.
5822.
9999.
jti-ztmt
2-D Model - JTTM10K-3s
Depth (METERS)
0
1000
2000
75 ZTEM Sites
3 MT Sites
Joint ZTEM-MT 3 Site Only Inversion – 10,000 Ωm Apriori
Returns Reasonable Target Depths & Resistivities
W
E
METERS
0 500 1000 1500 2000 2500 3000 3500 4000 4500
Ohm-M
3
5.15
8.84
15.1
26.0
44.8
76.9
132.
226.
389.
669.
1149.
1974.
3390.
5822.
9999.

Athabasca Type Unconformity Uranium Deposit Style

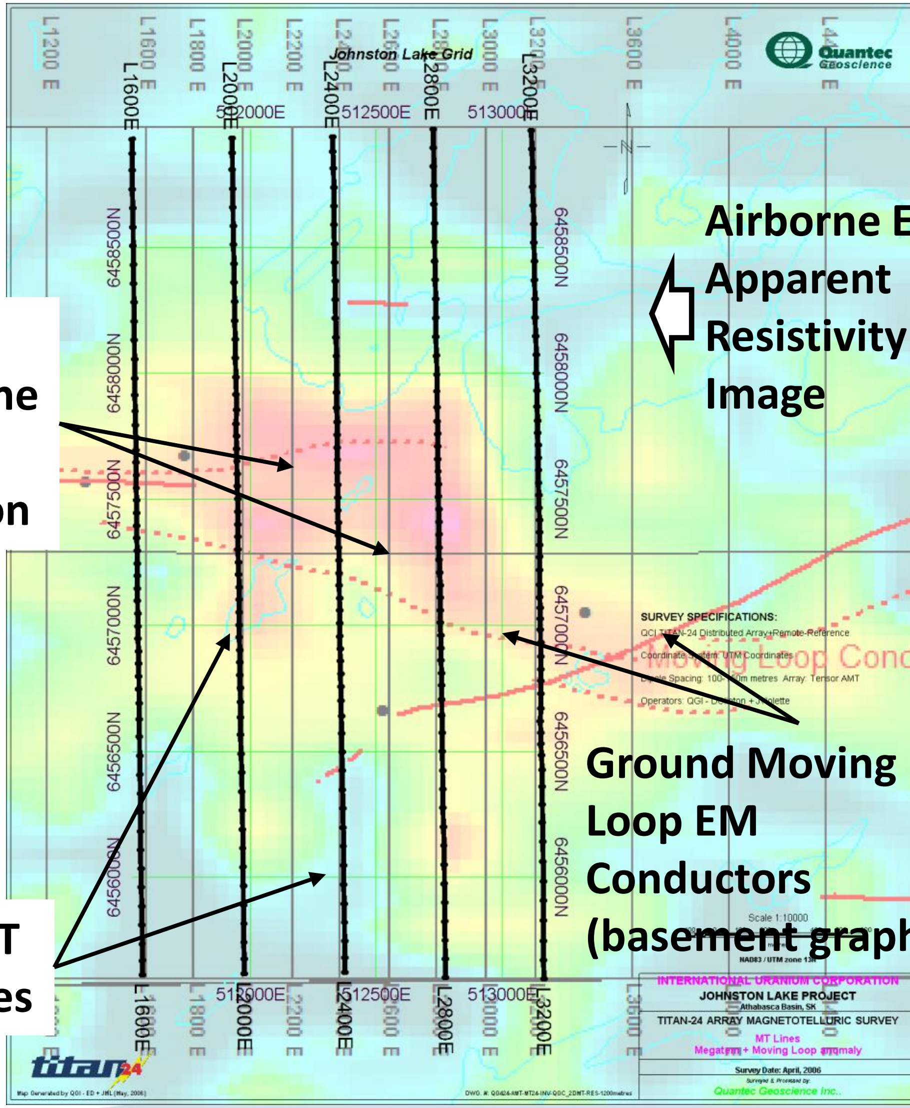
Unconformity Uranium ZTEM-MT Case Study – East Athabasca Basin



ZTEM 2D Resistivity Model



ZTEM & MT Profile Site Map



Airborne EM Apparent Resistivity Image

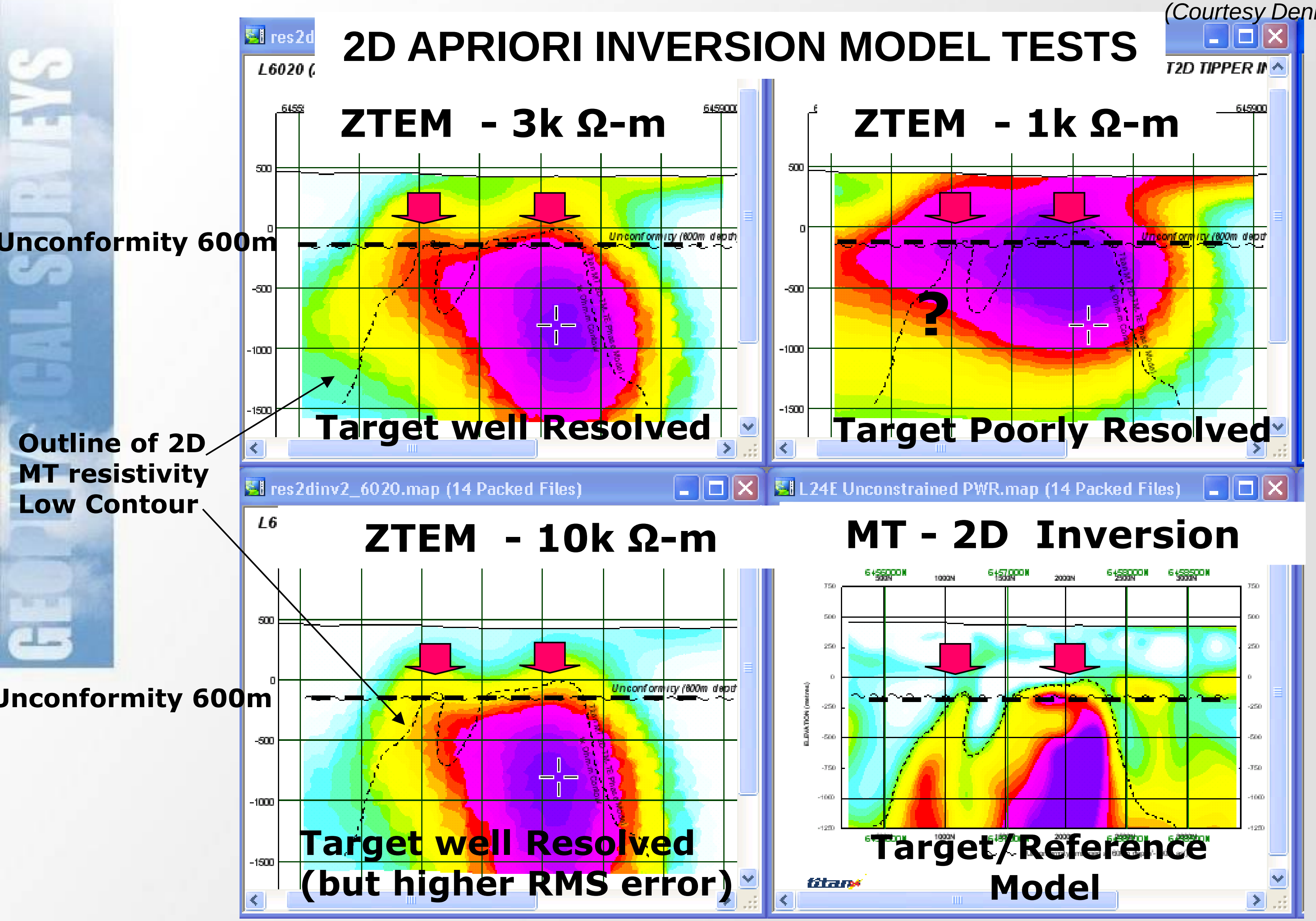
Possible Sandstone Clay Alteration

Ground Moving Loop EM Conductors (basement graphites)

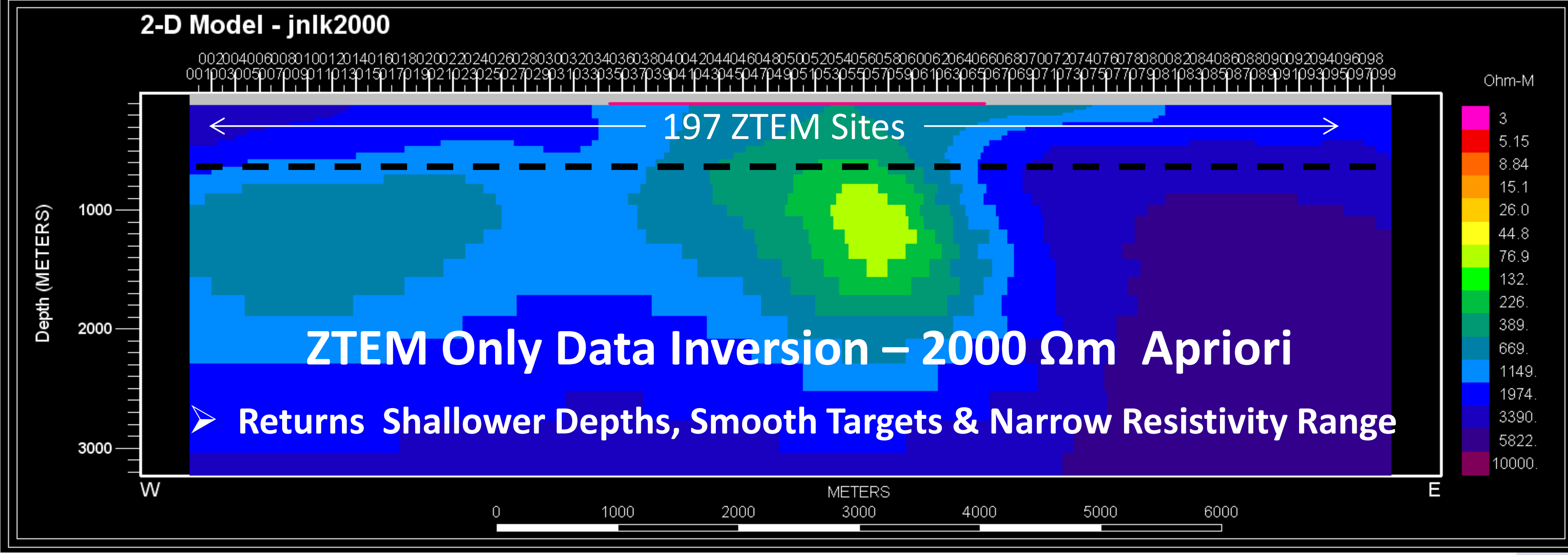
ZTEM & MT Survey Lines

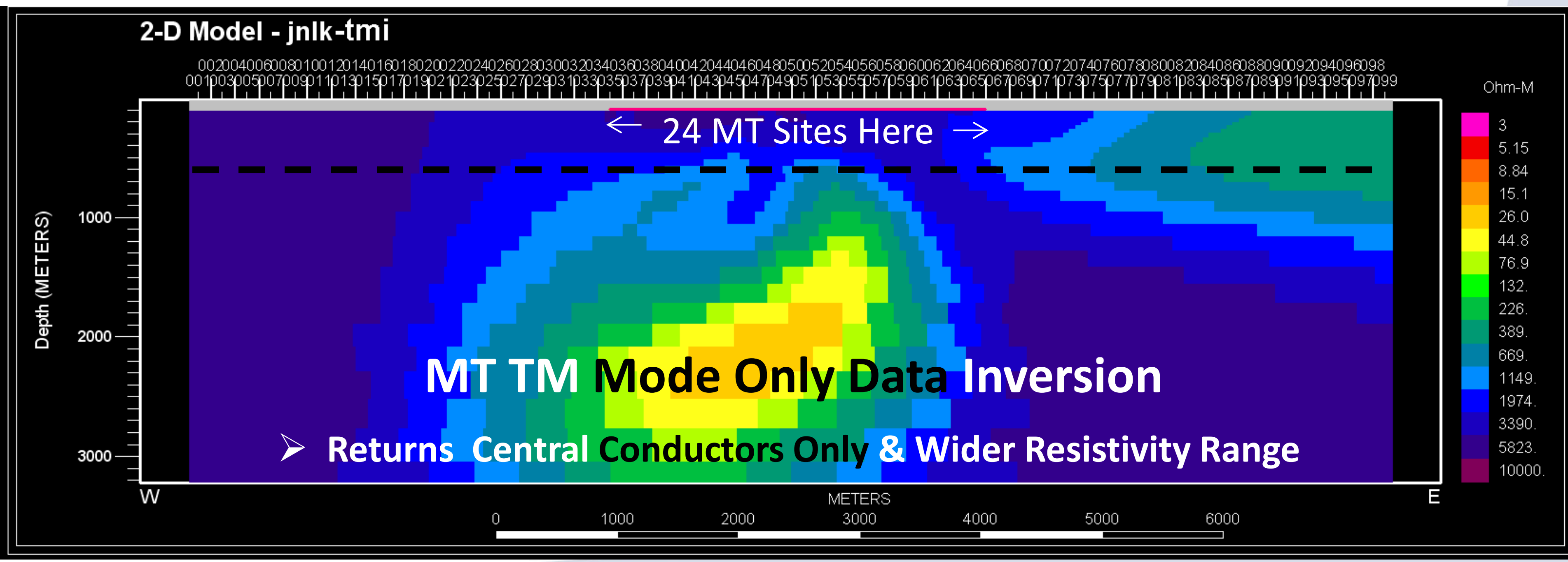
Unconformity Uranium ZTEM-MT Case Study – East Athabasca Basin

(Courtesy Denison Mines, 2009)



Showing effect of Half-space Start model on target depth in 2D Inversions (2009)


2-D Model - jnlk2000
Ohm-M
3
5.15
8.84
15.1
26.0
44.8
76.9
132.
226.
389.
669.
1149.
1974.
3390.
5822.
10000.
197 ZTEM Sites
ZTEM Only Data Inversion – 2000 Ωm Apriori
Returns Shallower Depths, Smooth Targets & Narrow Resistivity Range
Depth (METERS)
1000
2000
3000
W
E
METERS
0
1000
2000
3000
4000
5000
6000


2-D Model - jnlk-tmi
Ohm-M
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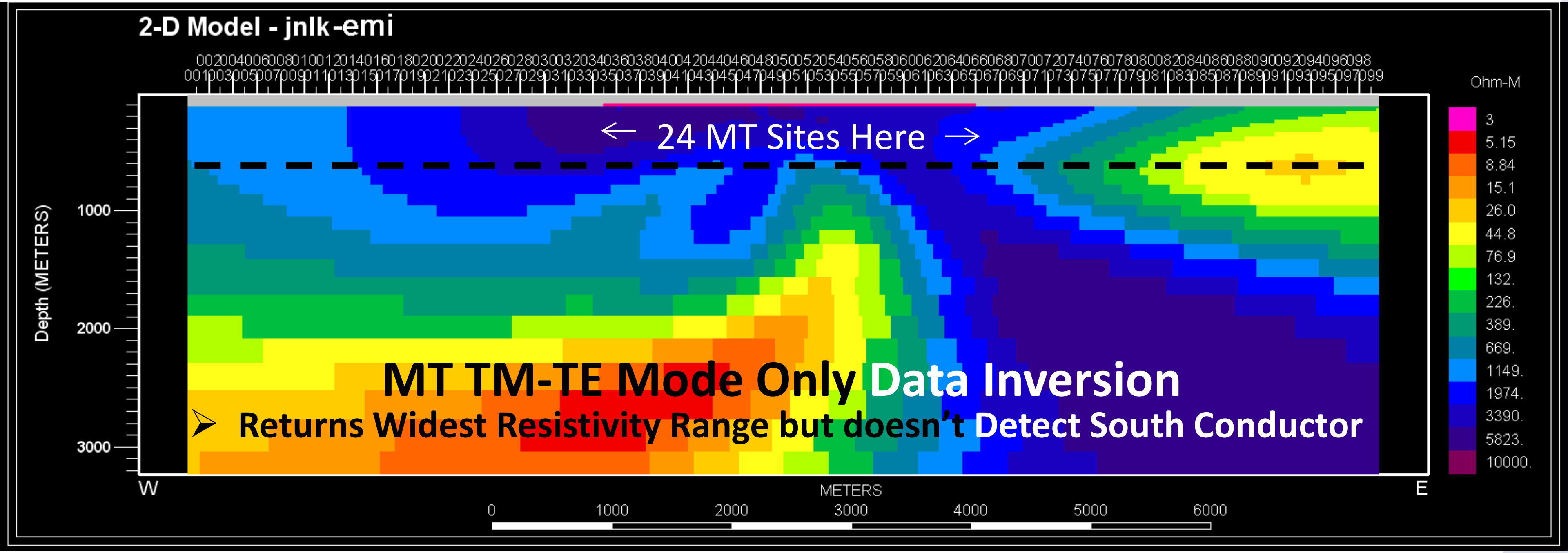
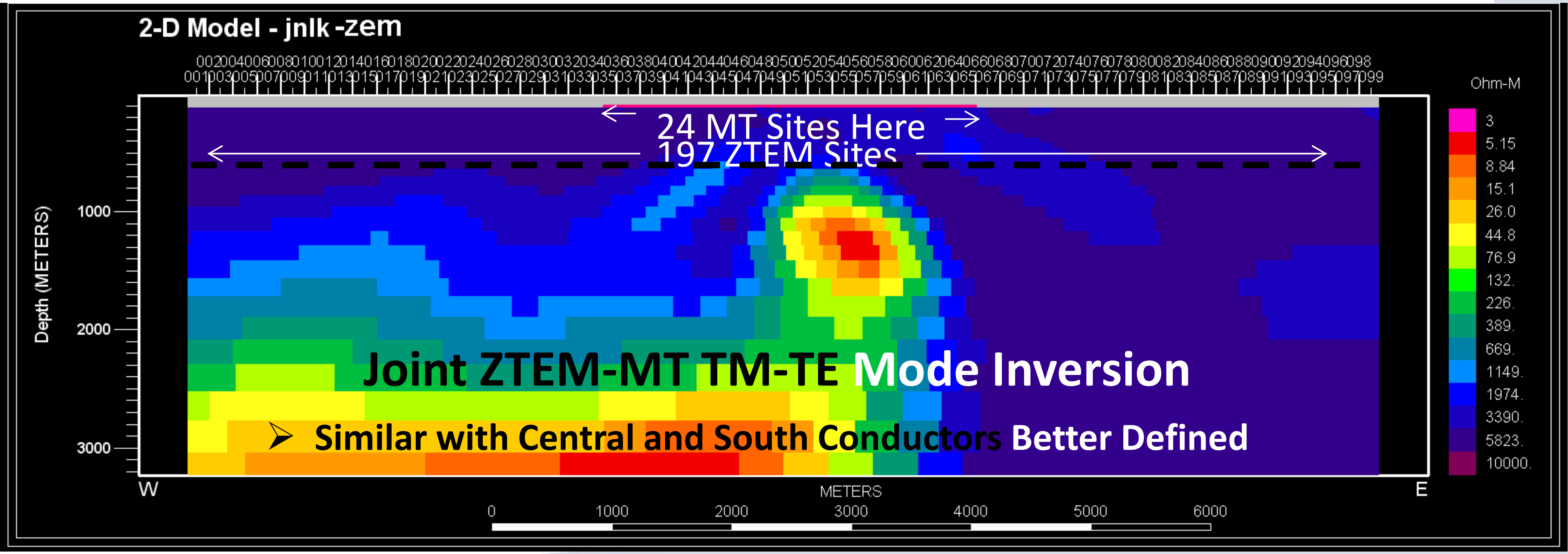
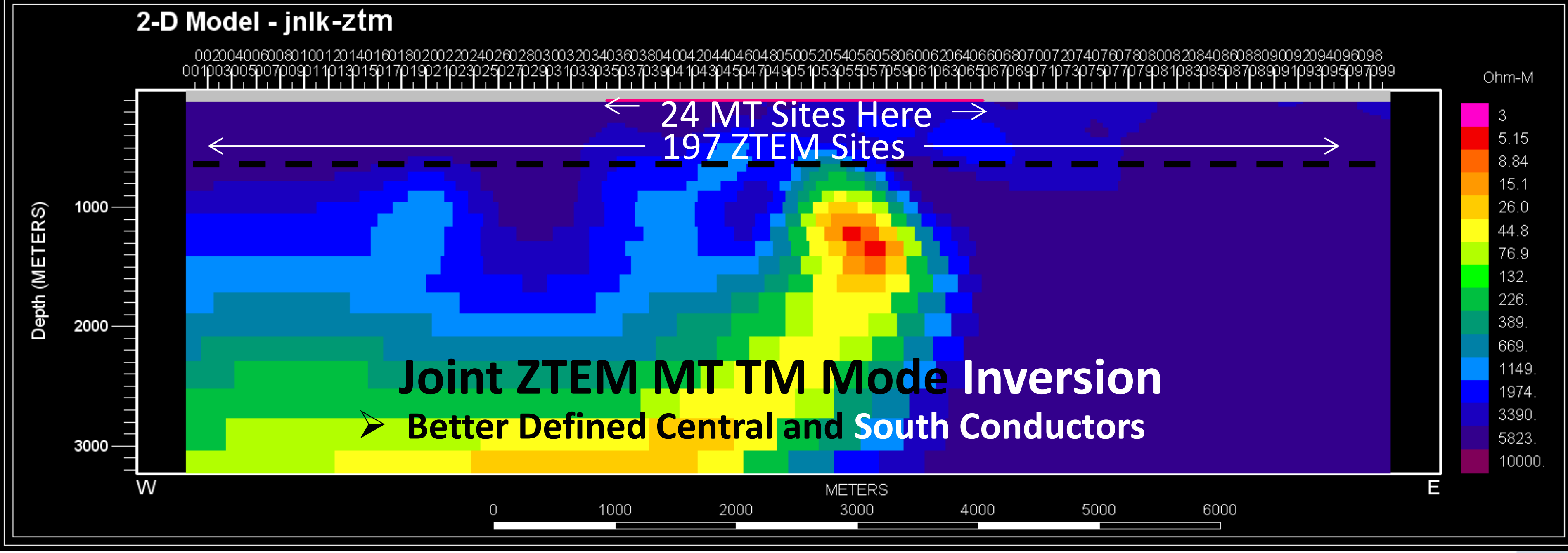
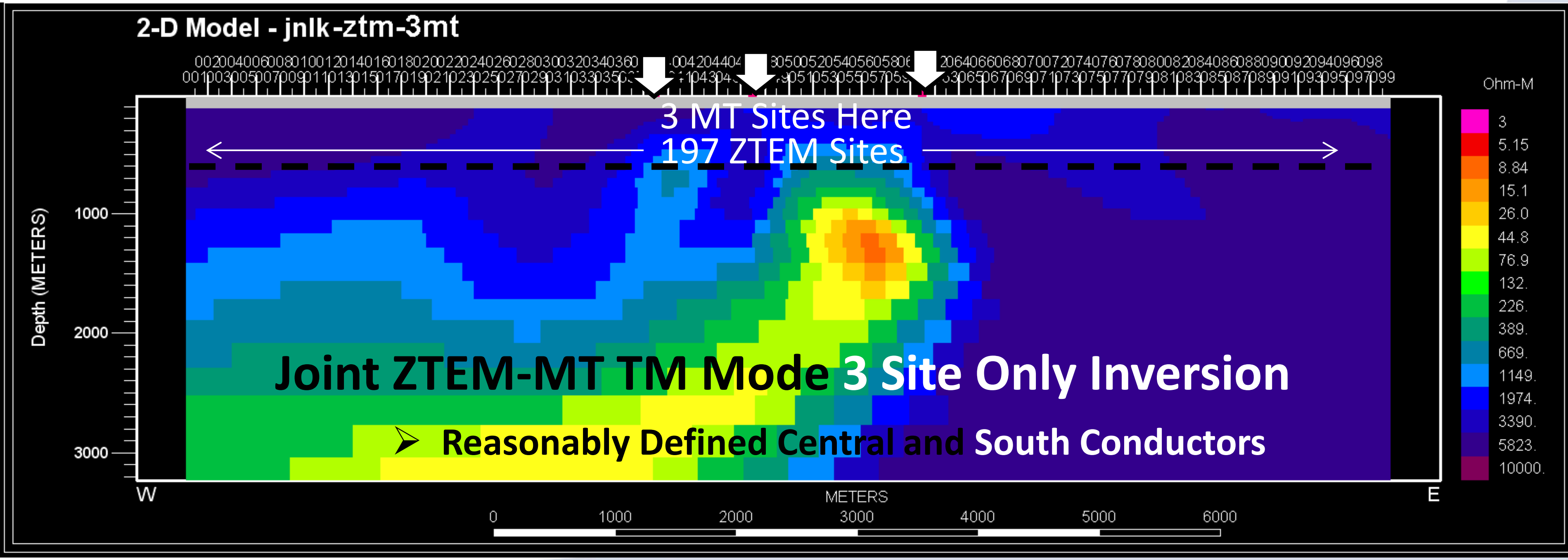
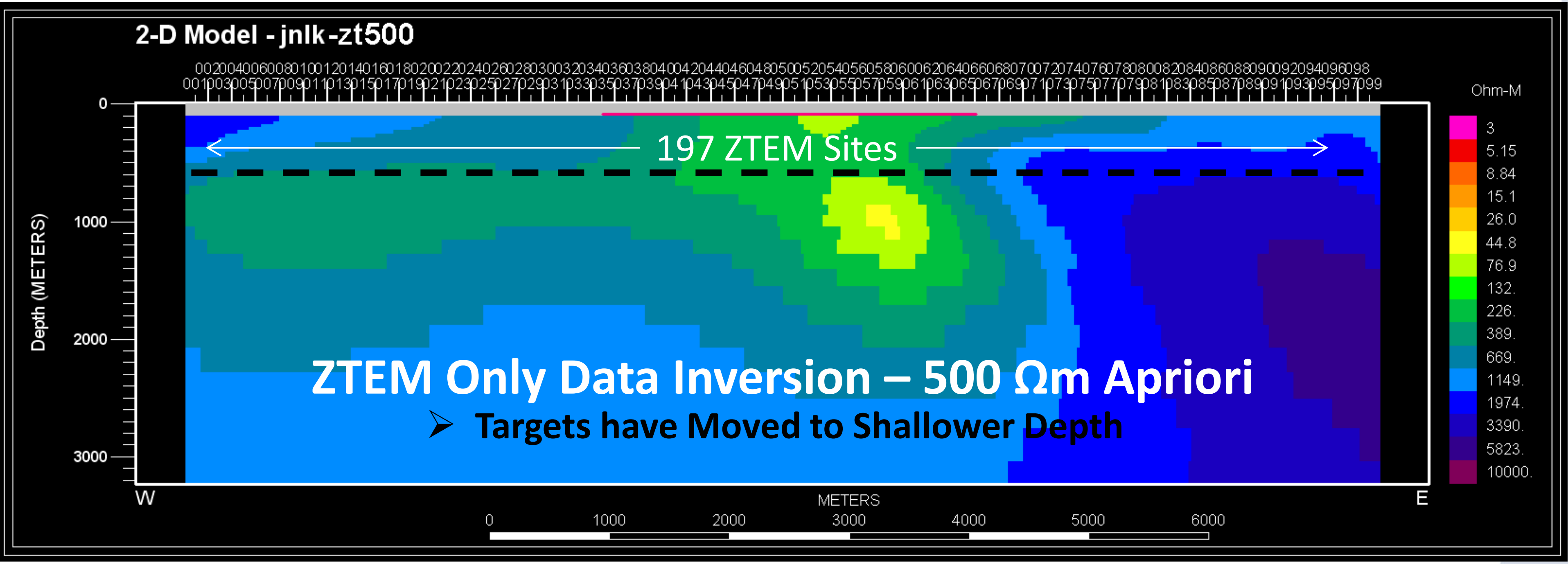
5.15
8.84
15.1
26.0
44.8
76.9
132.
226.
389.
669.
1149.
1974.
3390.
5823.
10000.
24 MT Sites Here
MT TM Mode Only Data Inversion
Returns Central Conductors Only & Wider Resistivity Range
Depth (METERS)
1000
2000
3000
W
E
METERS
0
1000
2000
3000
4000
5000
6000

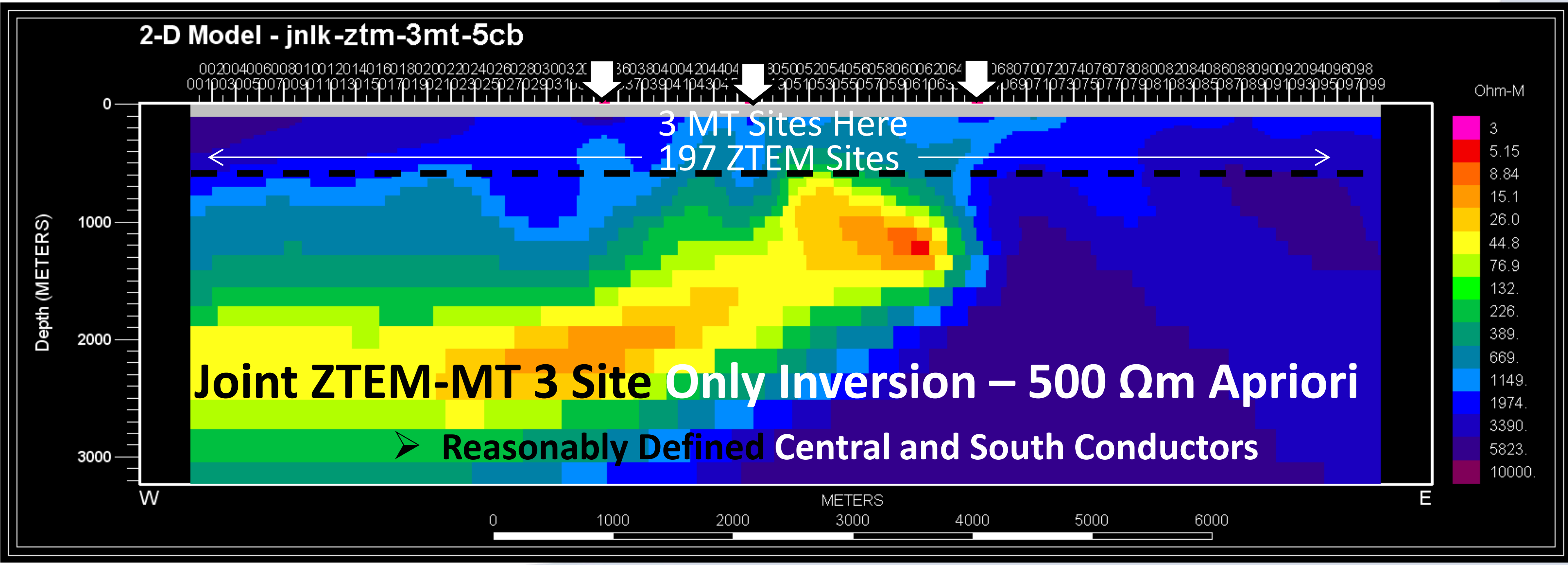

2-D Model - jnlk-emi
24 MT Sites Here
MT TM-TE Mode Only Data Inversion
Returns Widest Resistivity Range but doesn't Detect South Conductor
Depth (METERS)
1000
2000
3000
W
E
METERS
0
1000
2000
3000
4000
5000
6000
Ohm-M
3
5.15
8.84
15.1
26.0
44.8
76.9
132.
226.
389.
669.
1149.
1974.
3390.
5823.
10000.


2-D Model - jnlk-zem
24 MT Sites Here
197 ZTEM Sites
Joint ZTEM-MT TM-TE Mode Inversion
Similar with Central and South Conductors Better Defined
Depth (METERS)
1000
2000
3000
W
E
METERS
0
1000
2000
3000
4000
5000
6000
Ohm-M
3
5.15
8.84
15.1
26.0
44.8
76.9
132.
226.
389.
669.
1149.
1974.
3390.
5823.
10000.


2-D Model - jnlk-ztm
24 MT Sites Here
197 ZTEM Sites
Joint ZTEM MT TM Mode Inversion
Better Defined Central and South Conductors
Depth (METERS)
1000
2000
3000
W
E
METERS
0
1000
2000
3000
4000
5000
6000
Ohm-M
3
5.15
8.84
15.1
26.0
44.8
76.9
132.
226.
389.
669.
1149.
1974.
3390.
5823.
10000.


2-D Model - jnlk-ztm-3mt
3 MT Sites Here
197 ZTEM Sites
Joint ZTEM-MT TM Mode 3 Site Only Inversion
Reasonably Defined Central and South Conductors
Depth (METERS)
1000
2000
3000
W
E
METERS
0
1000
2000
3000
4000
5000
6000
Ohm-M
3
5.15
8.84
15.1
26.0
44.8
76.9
132.
226.
389.
669.
1149.
1974.
3390.
5823.
10000.


2-D Model - jnlk-zt500
Ohm-M
3
5.15
8.84
15.1
26.0
44.8
76.9
132.
226.
389.
669.
1149.
1974.
3390.
5823.
10000.
Depth (METERS)
0
1000
2000
3000
197 ZTEM Sites
ZTEM Only Data Inversion – 500 Ωm Apriori
➢ Targets have Moved to Shallower Depth
W
E
METERS
0
1000
2000
3000
4000
5000
6000


2-D Model - jnlk-ztm-3mt-5cb
Ohm-M
3
5.15
8.84
15.1
26.0
44.8
76.9
132.
226.
389.
669.
1149.
1974.
3390.
5823.
10000.
Depth (METERS)
0
1000
2000
3000
3 MT Sites Here
197 ZTEM Sites
Joint ZTEM-MT 3 Site Only Inversion – 500 Ωm Apriori
➢ Reasonably Defined Central and South Conductors
W
E
METERS
0
1000
2000
3000
4000
5000
6000

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Conclusion

- Algorithm ZTMT2DIV can compute accurate 2D inversion images through separate or joint inversion of ZTEM and MT including ‘smooth’ topography.
- Joint inversion is mutually beneficial for each data type:
  - Inclusion of MT data should constrain resistivity baseline values to improve resolution of ZTEM structure (depth, ρ).
  - Detailed lateral resolution of contrasts by ZTEM data should provide control between possibly sparser MT stations.
- Some consideration must be given to relative placement of ZTEM and MT sites in the finite element mesh (Best if MT Sites Widely Distributed across Survey Extents)

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