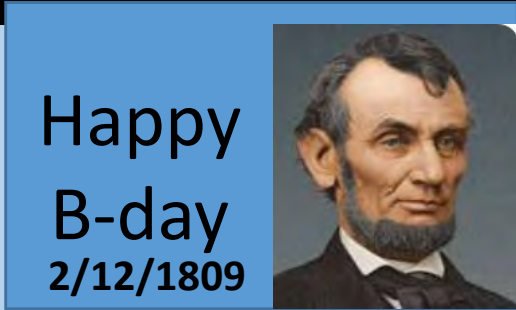
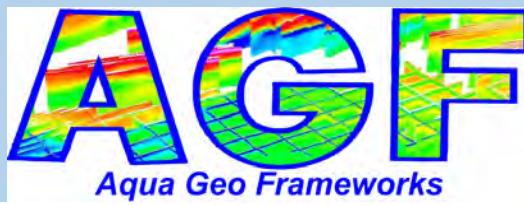
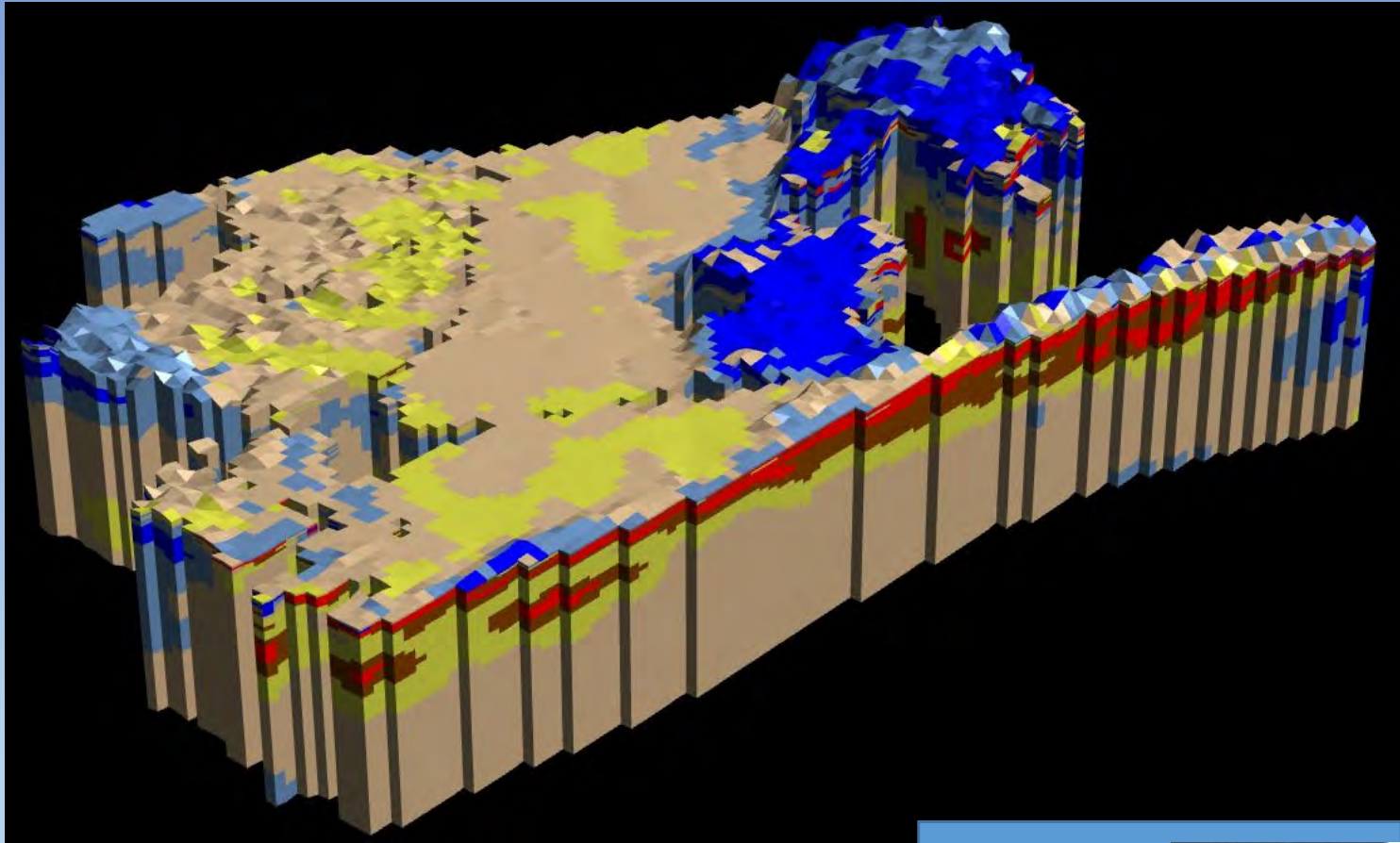


Airborne Geophysical Investigations of Saltwater Intrusion Along Coastal California

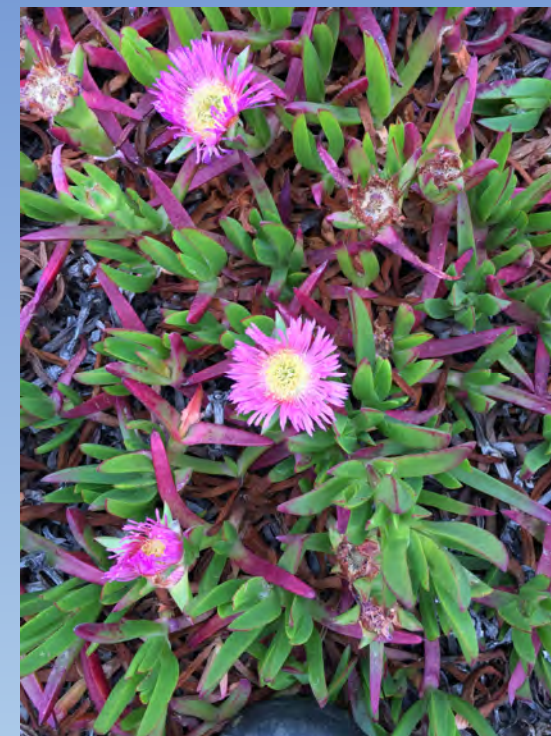
Theodore Asch, Ph.D., PGp
Jared Abraham, and James Cannia
Aqua Geo Frameworks, LLC

February 12, 2019



Presentation Outline

- Hydrostratigraphy & Investigation Objectives
- AEM Data Acquisition, Processing & Inversion
- Interpretation – Chloride Concentrations
- Forward/Inverse Modelling



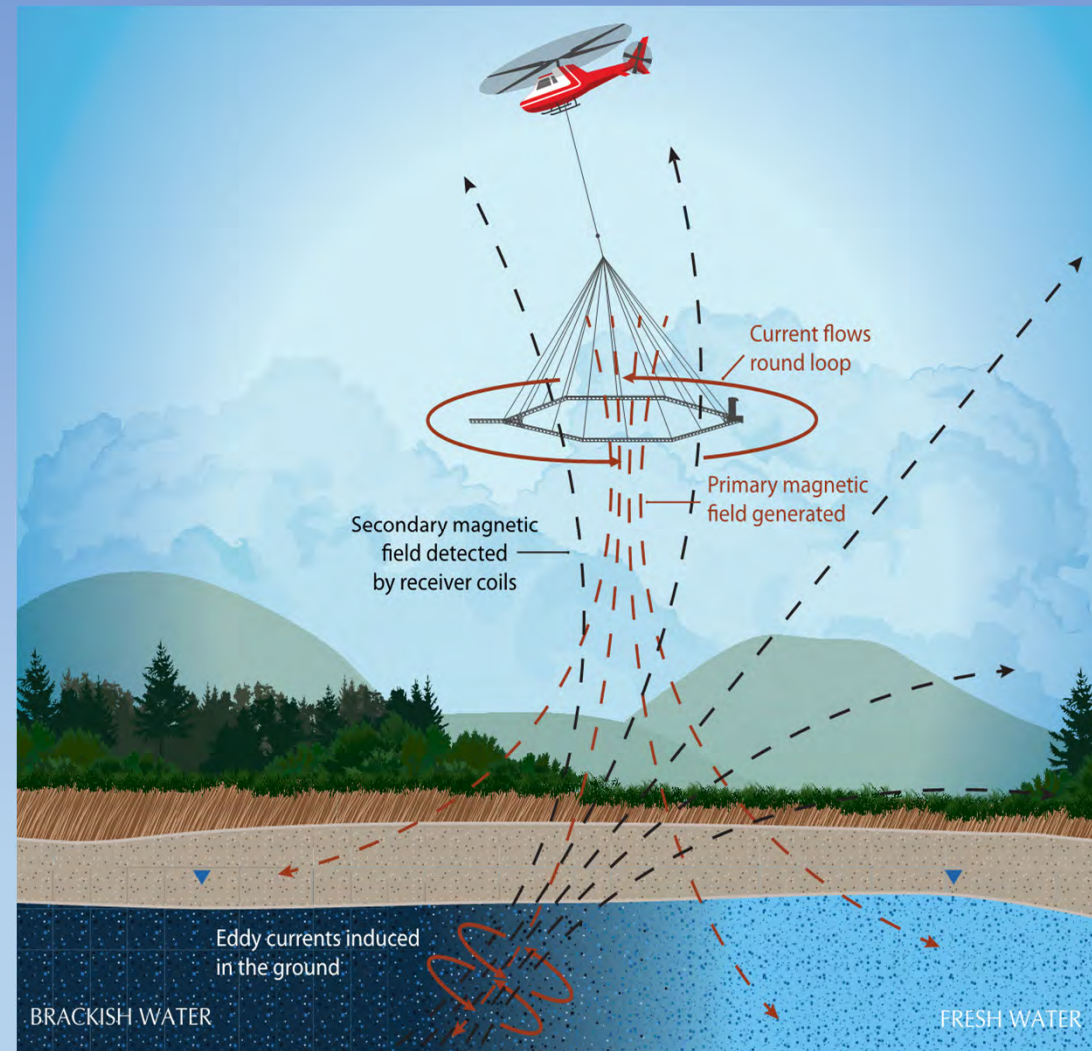
Typical AEM Investigation Objectives

- 1) Map subsurface geology; Ground truth with Boreholes
- 2) Develop a 3D hydrogeological framework to assist in water resources management.
- 3) Produce maps of aquifer materials
- 4) Locate potential Managed Aquifer Recharge (MAR) areas
- 5) Identify optimal drilling locations for production, monitoring, and test wells
- 6) Identify zones of various chloride concentrations (in areas of saltwater intrusion)

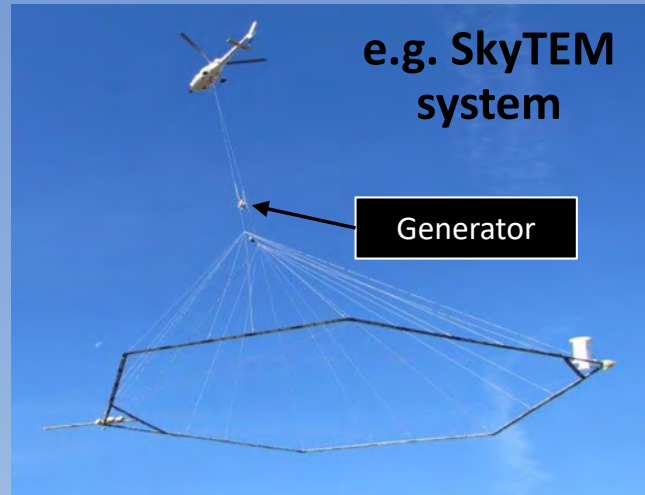
How an AEM System Works

**Maxwell's 2nd Equation:
Faraday's Law**

$$\nabla \times E = -\frac{\partial B}{\partial t}$$



Modified from E. Auken, Univ. Aarhus, Denmark

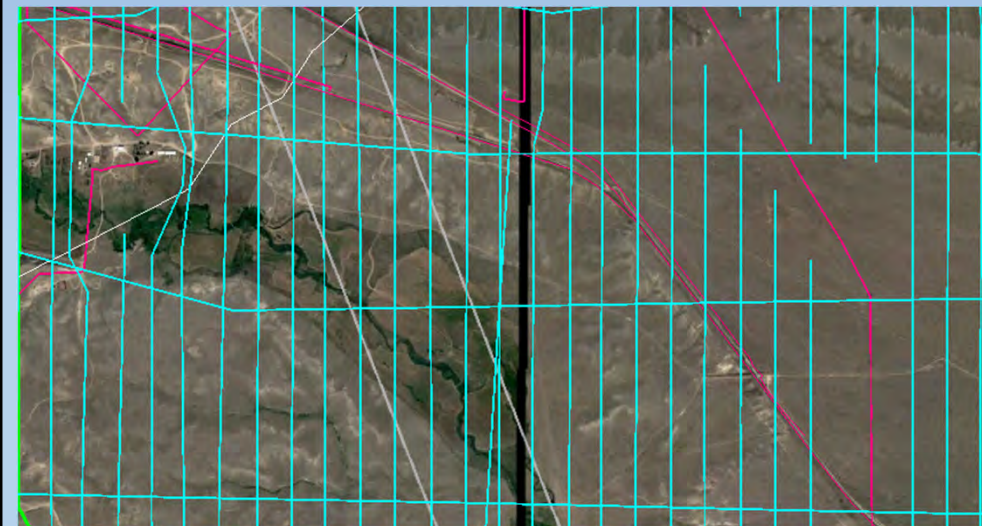


*Usually 2-3 Flights/day
 Totaling about 180-250 line-miles/day
 Approx. 100' – 150' above ground
 Along-Line Data Density
 Approximately Every ~ 10 ft*



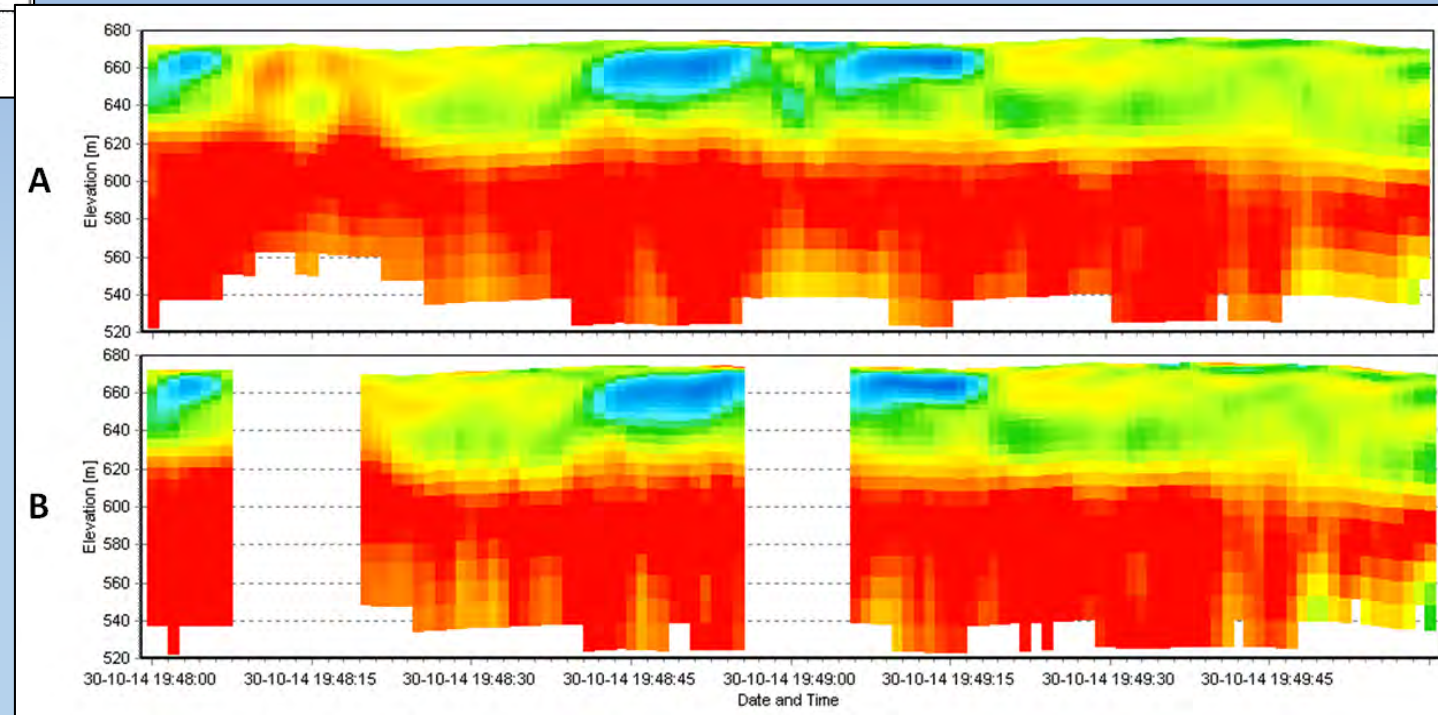
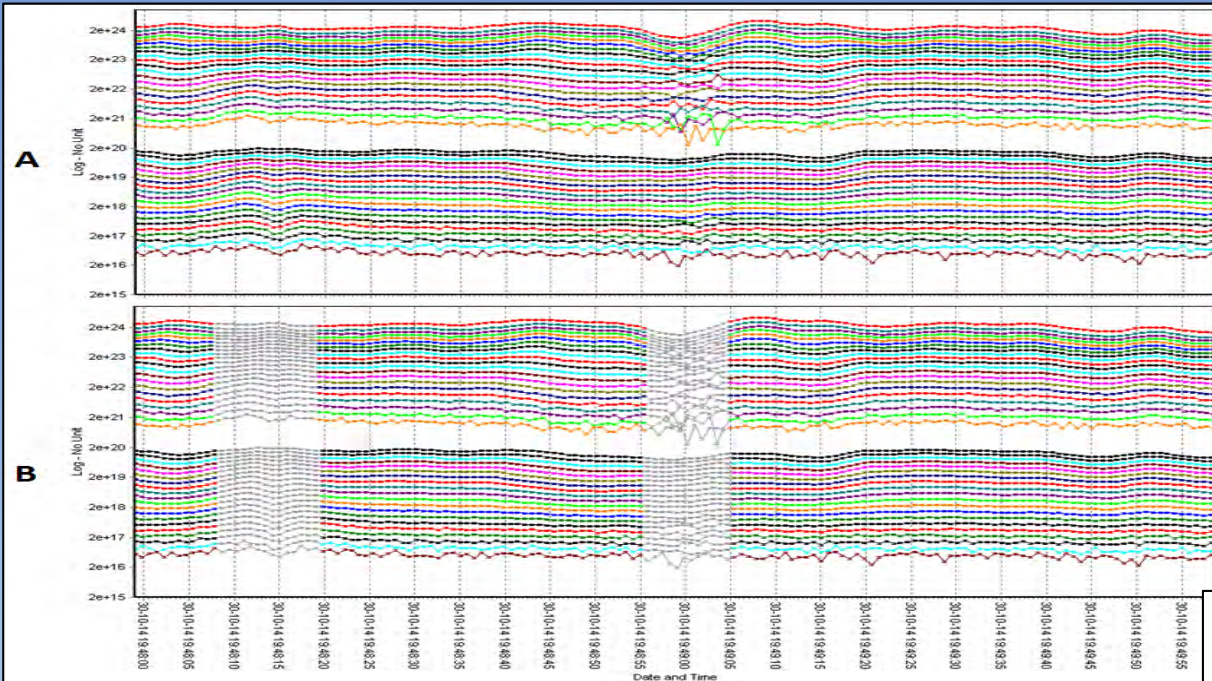
Need Careful Flight Line Planning for Each Project

- Maps of electrical lines along AEM flight lines
- Maps of pipelines and other infrastructure along the AEM flight lines
- Inspection of Google Earth coverages along each flight line for buildings, roads, and other possible no fly objects
- Provide detailed flight lines to pilot for navigation. *Pilot has final say on safety.*



Within 24 hours:

- Check EM response (early, late times)
- Check GPS, Altitude, Tilt
- Check for powerline coupling effects
- Edit & Numerically Invert Data

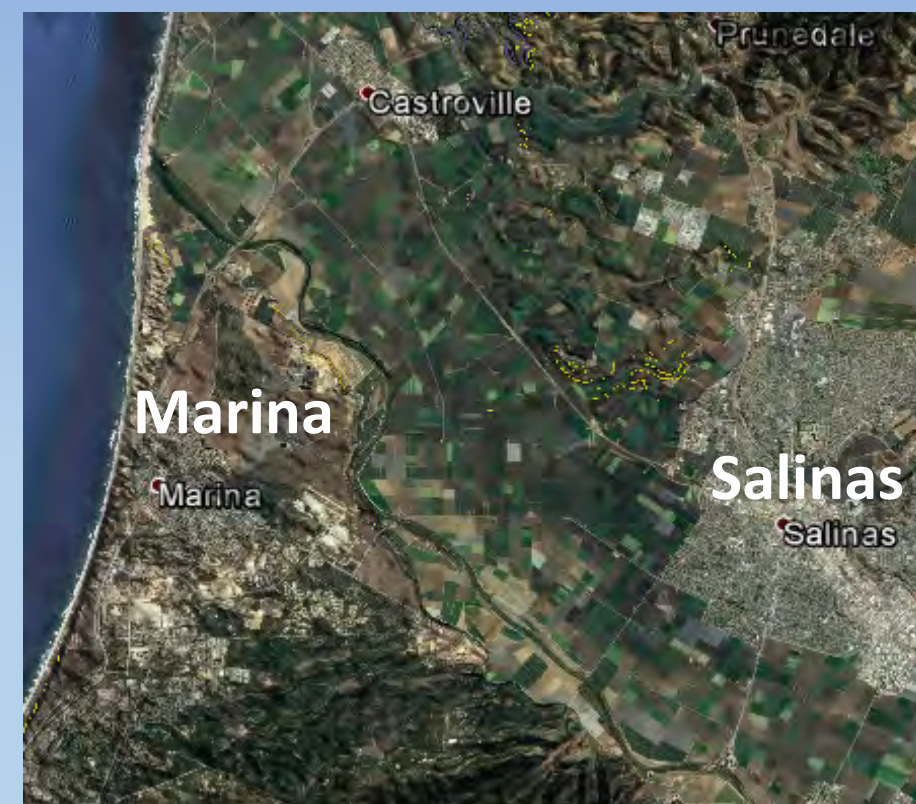


Abraham et al., 2016

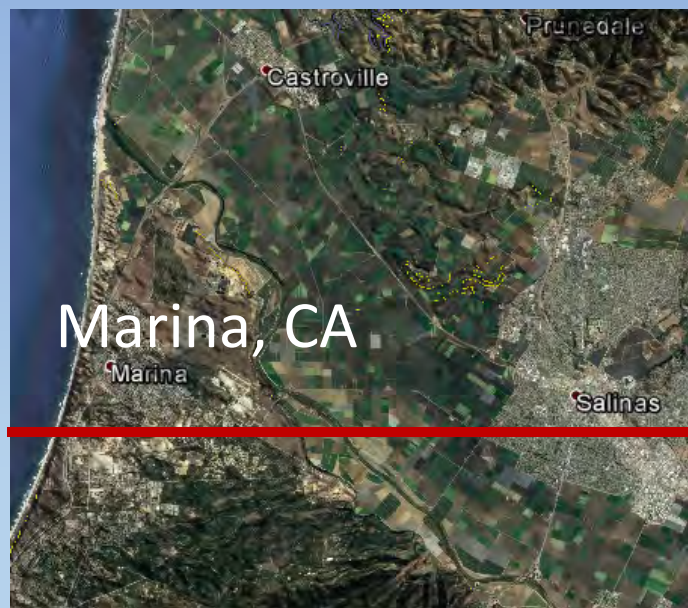
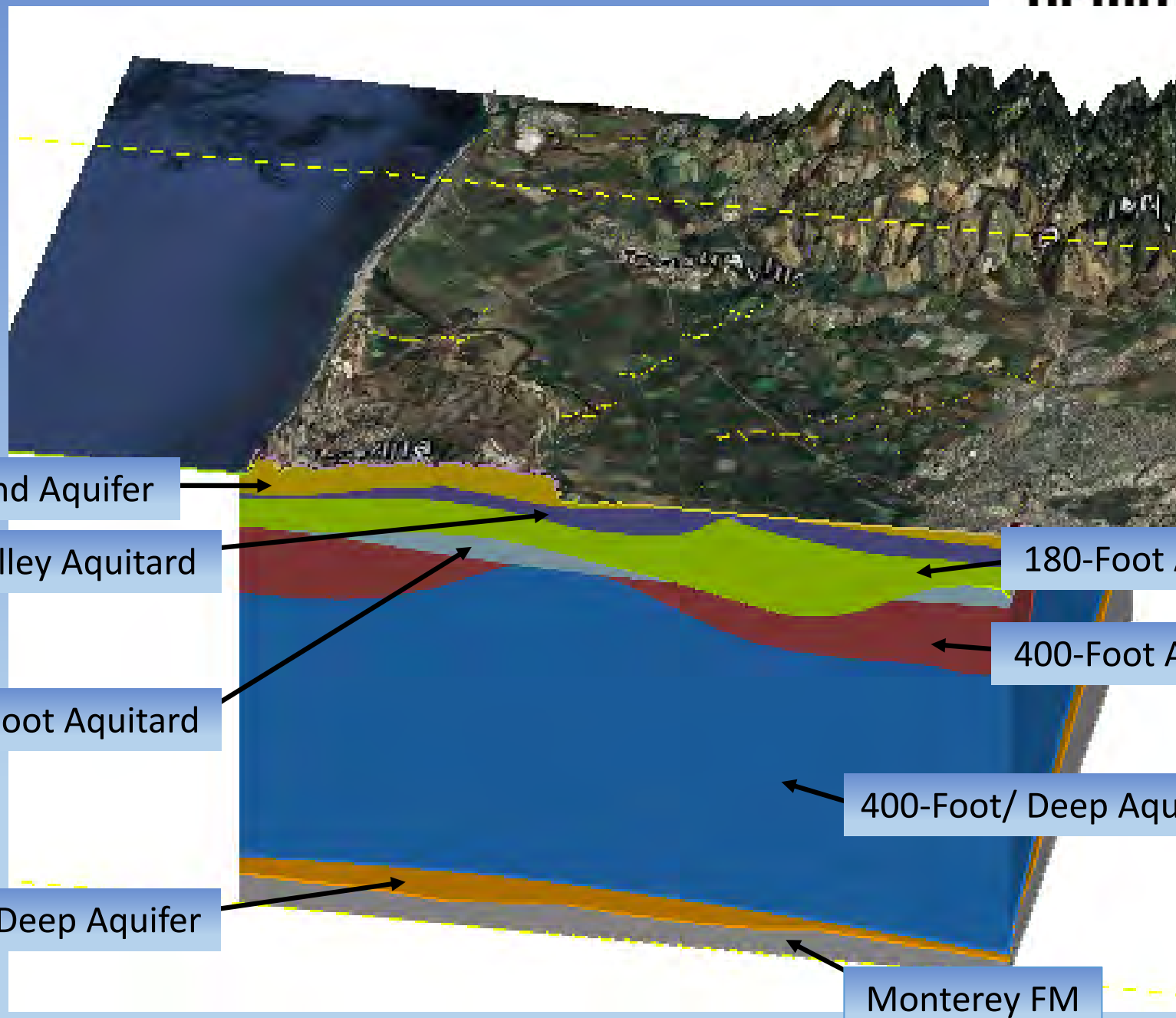
Hydrostratigraphic Setting

Basic Hydrostratigraphy of the northern Salinas Valley near the Monterey Bay coast in the Marina Coast Water District (MCWD)

- **Surficial Aquifers** - Dune Sand Aquifer (near the coast) / Perched Dune Sand Aquifer (slightly inland from coast) / Shallow Perched “A” Aquifer (away from coast)
- **Salinas Valley Aquitard (SVA)**
- **180-Foot Aquifer**
- **180/400-Foot Aquitard**
- **400-Foot Aquifer**
- **400-Foot/Deep Aquitard**
- **Deep Aquifer**
- **Monterey Formation**



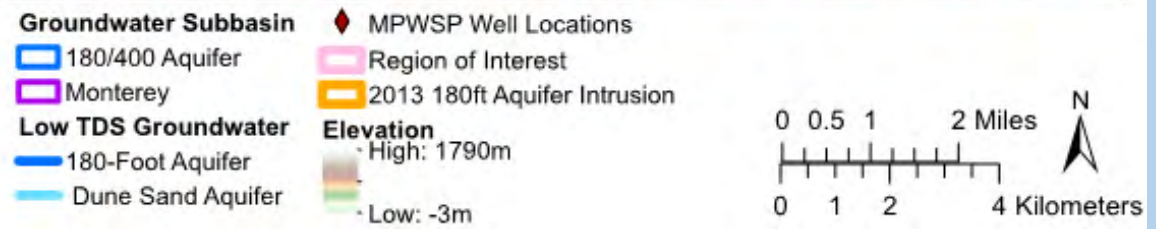
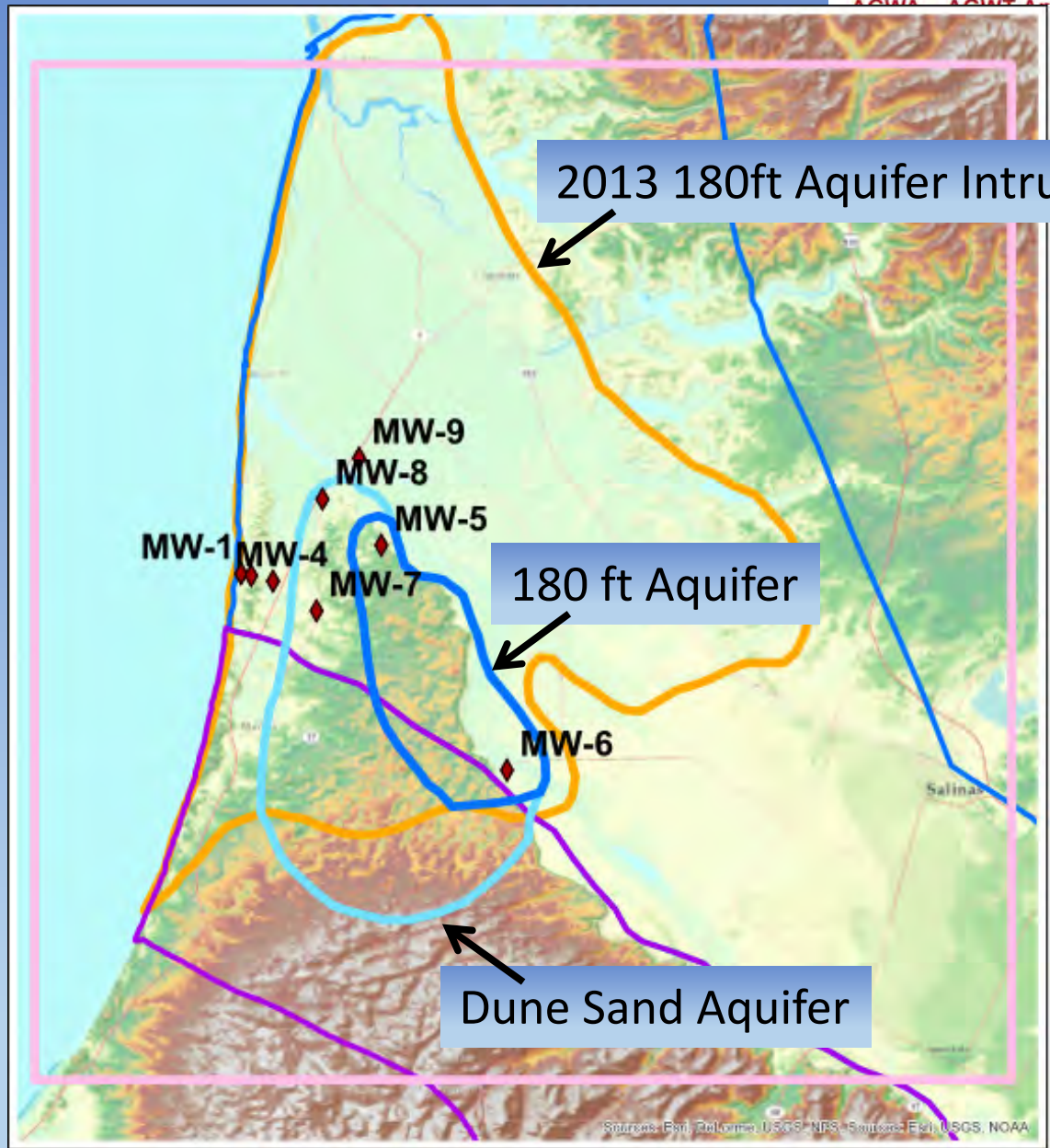
Hydrostratigraphic Setting



Cross-section location

AEM Investigation Objectives

- 1) Distribution of water quality (Where is the saltwater? Where is the fresh water?)
- 2) Understanding of hydrostratigraphy needed to evaluate the current state of groundwater resources
- 3) Identify “gaps” in the 180 ft/400 ft Aquitard near the Coast
- 4) Demonstrate Confidence in Resolution

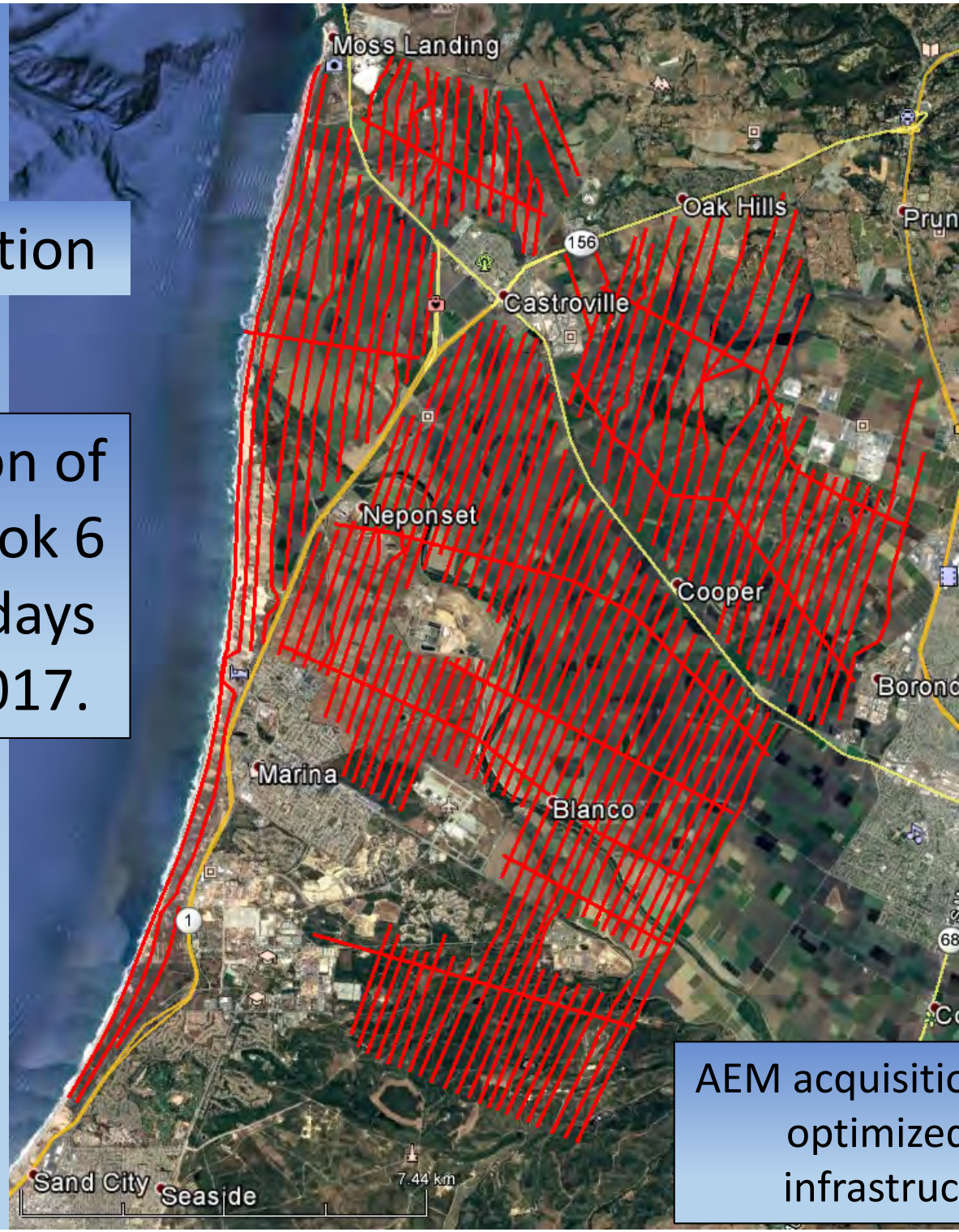


AEM Investigation

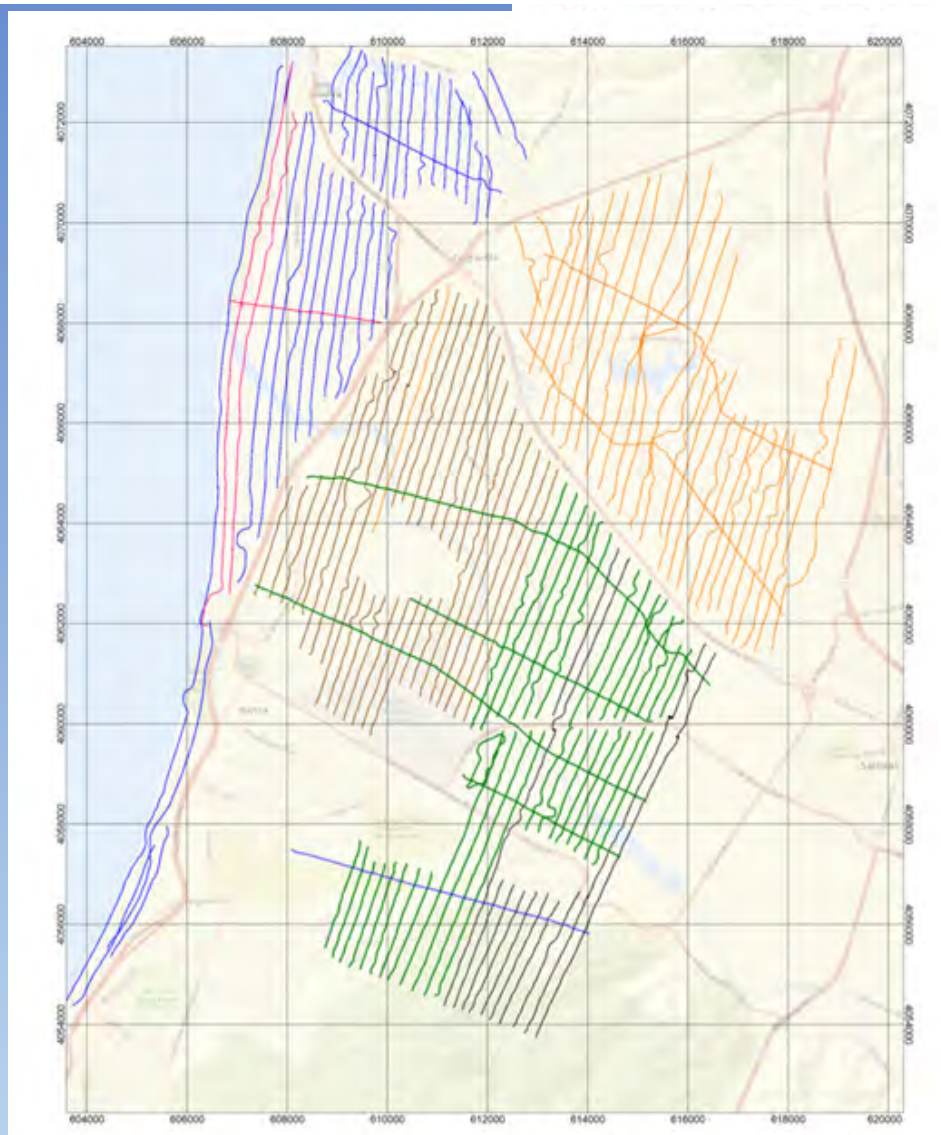
AEM acquisition of 635 line-km took 6 flights over 3 days in mid-May 2017.

SkyTEM 304M used for acquisition

12 February 2019



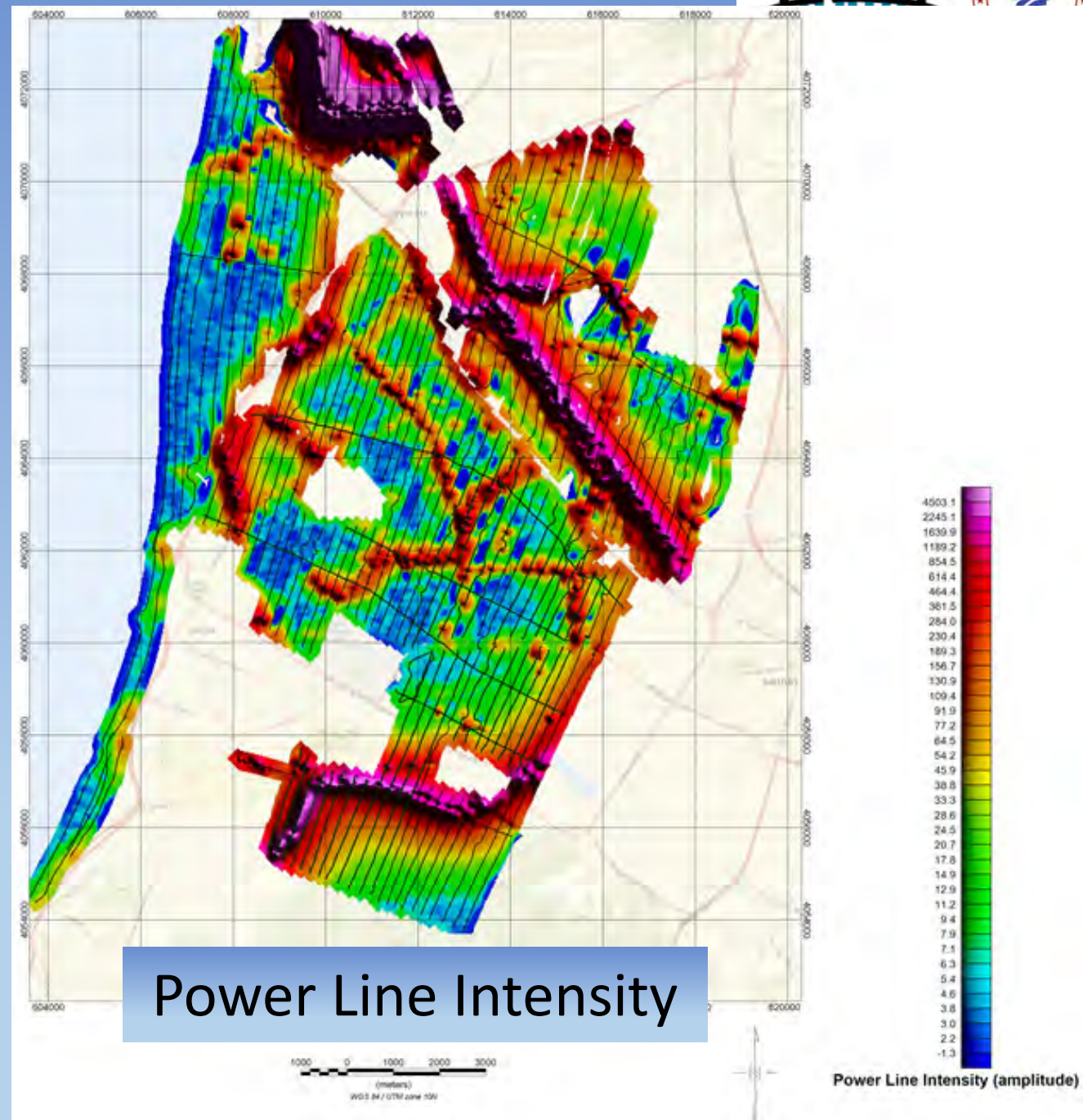
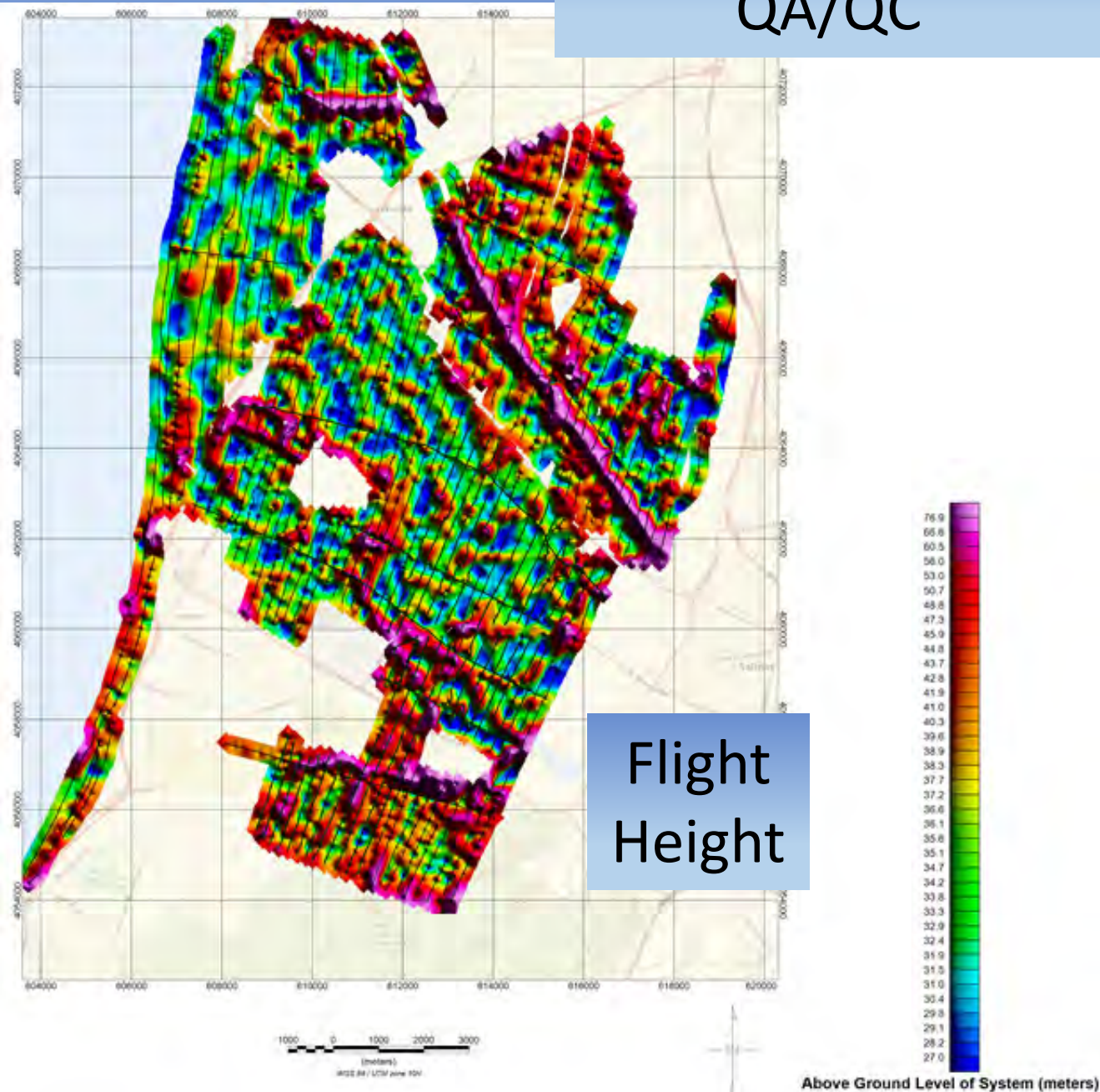
AEM acquisition design optimized for infrastructure



AEM Acquisition by Date

- Flight 051603 05-16-2017
- Flight 051602 05-18-2017
- Flight 051701 05-17-2017
- Flight 051702 05-17-2017
- Flight 051801 05-18-2017
- Flight 051802 05-18-2017

AEM Investigation QA/QC



AEM Investigation Processing

BLUE -
Retained for
Inversion

RED -
Decoupled
(Cut Out)

12 February 2019



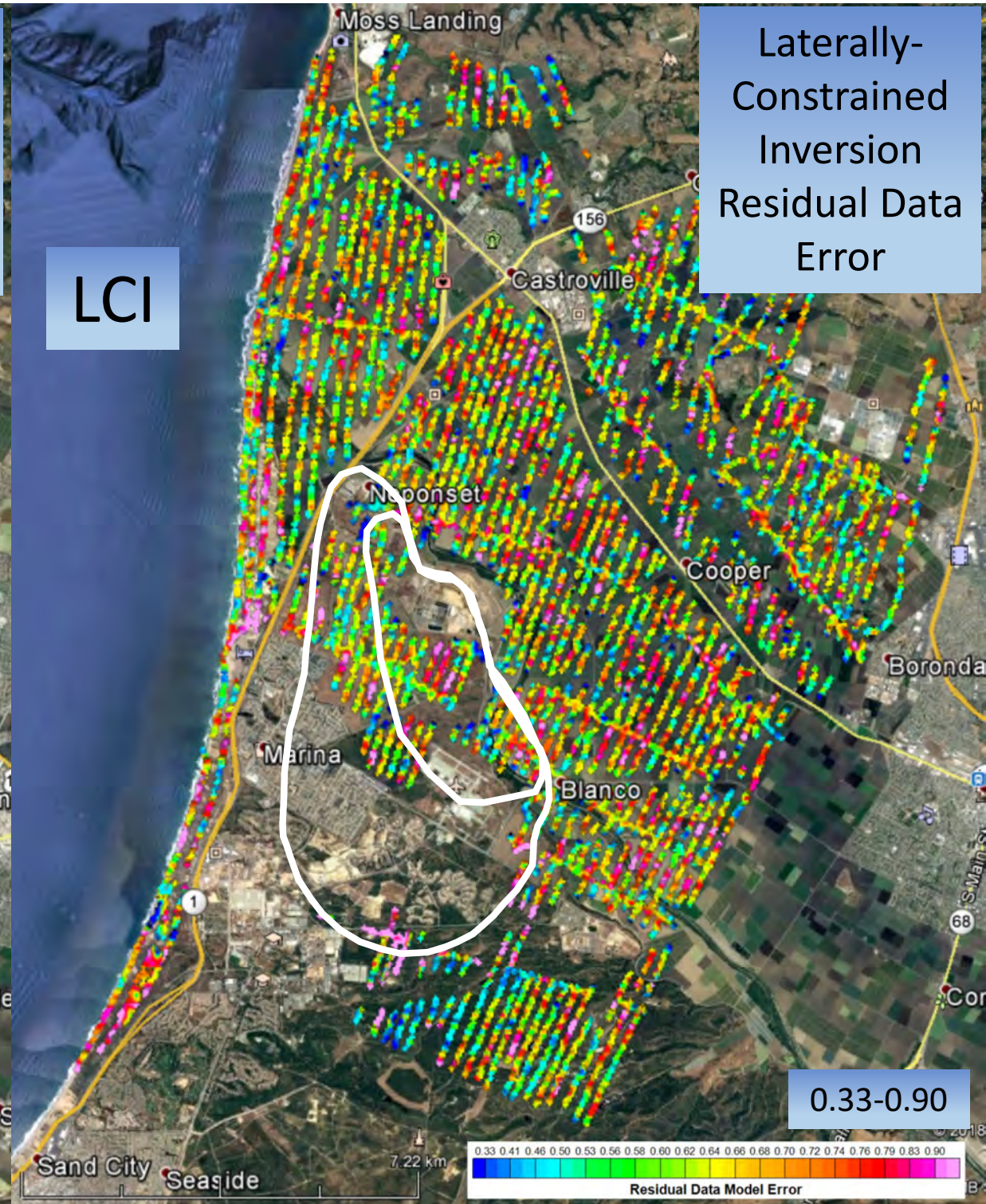
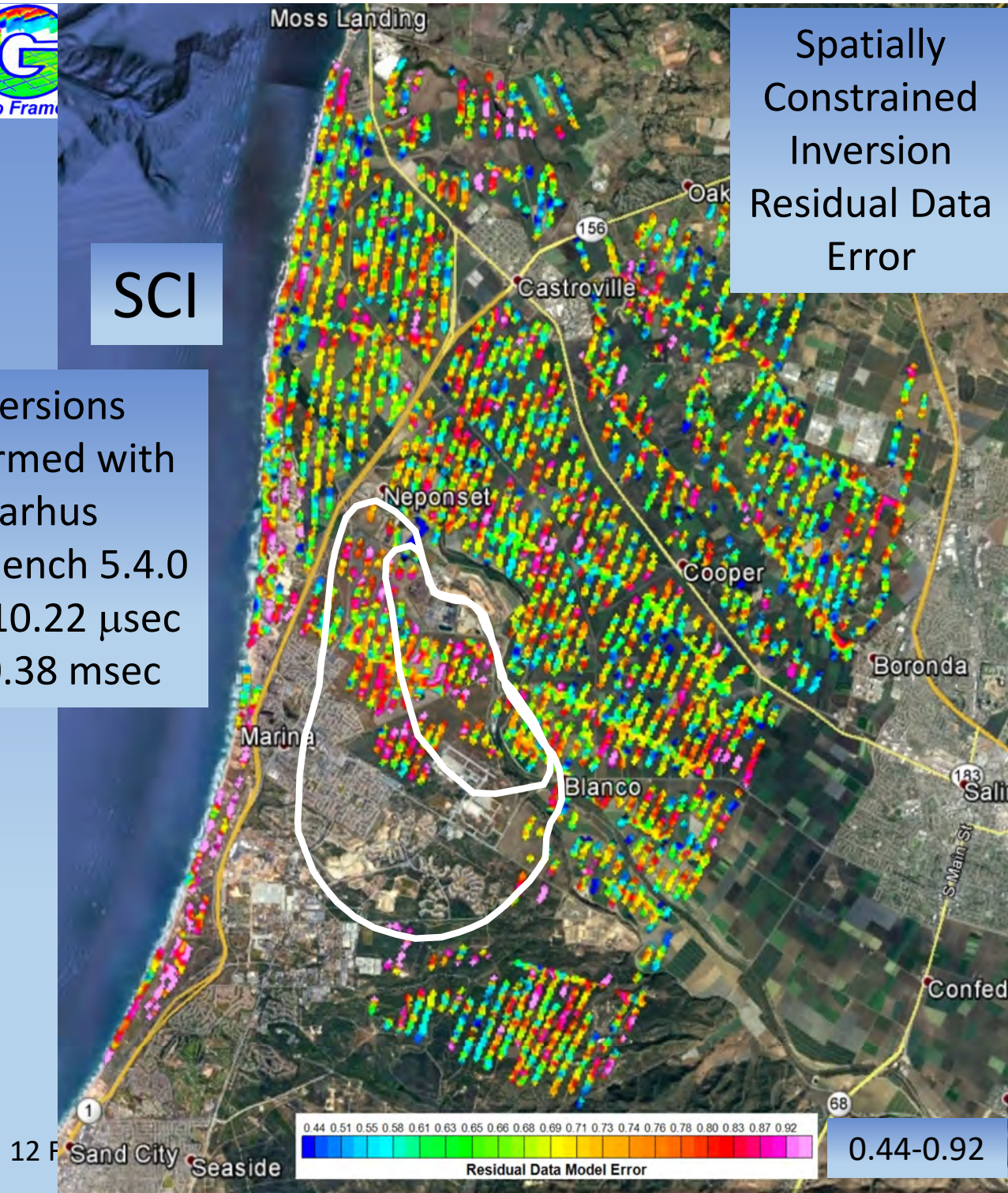
SCI

Spatially
Constrained
Inversion
Residual Data
Error

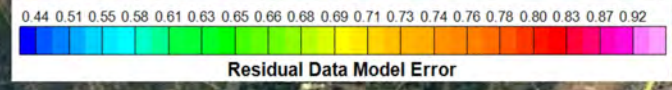
LCI

Laterally-
Constrained
Inversion
Residual Data
Error

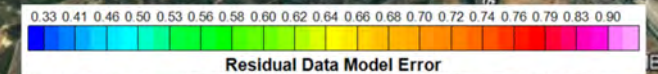
Inversions
Performed with
Aarhus
Workbench 5.4.0
from 10.22 μ sec
to 10.38 msec



12 F Sand City Seaside



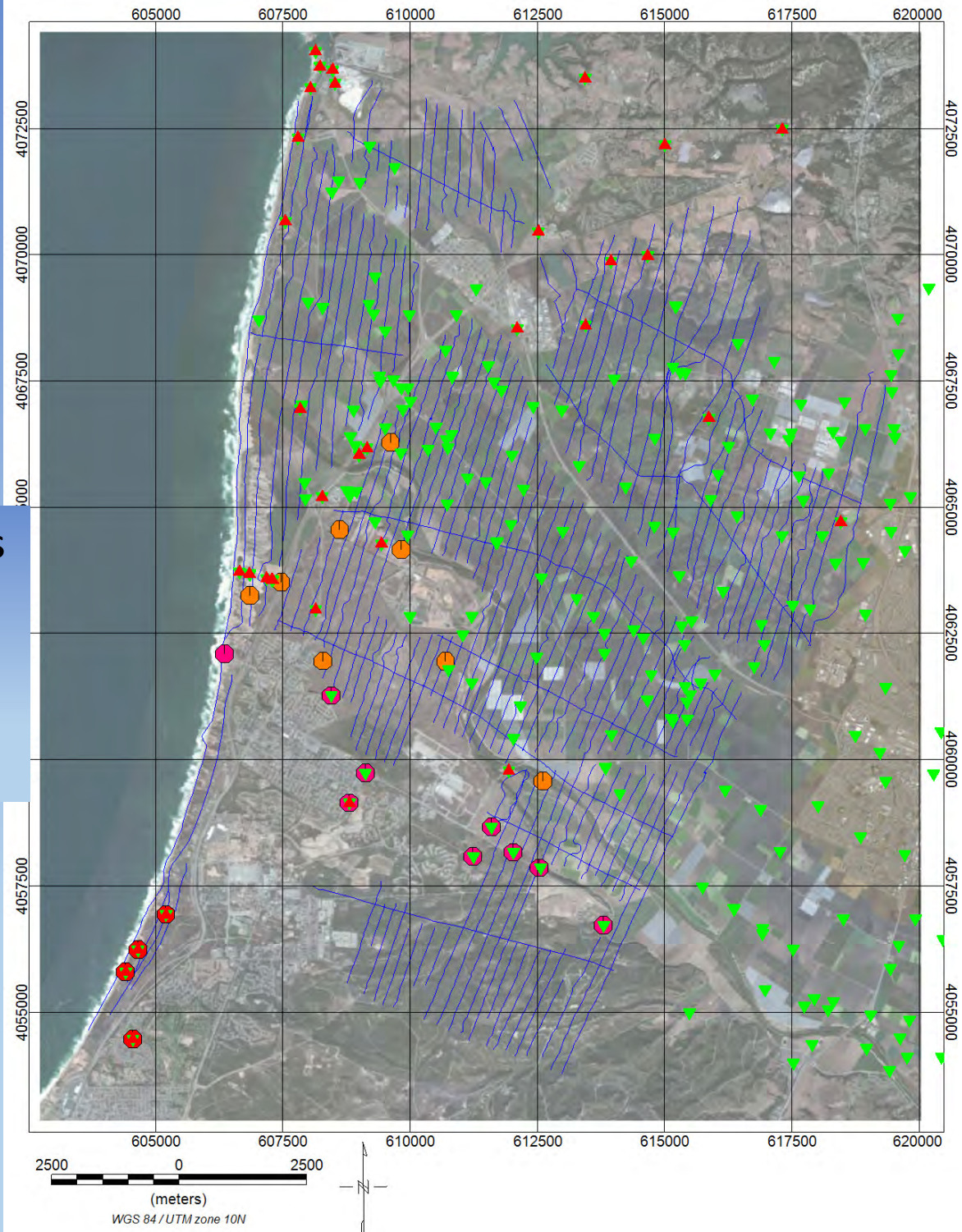
0.44-0.92



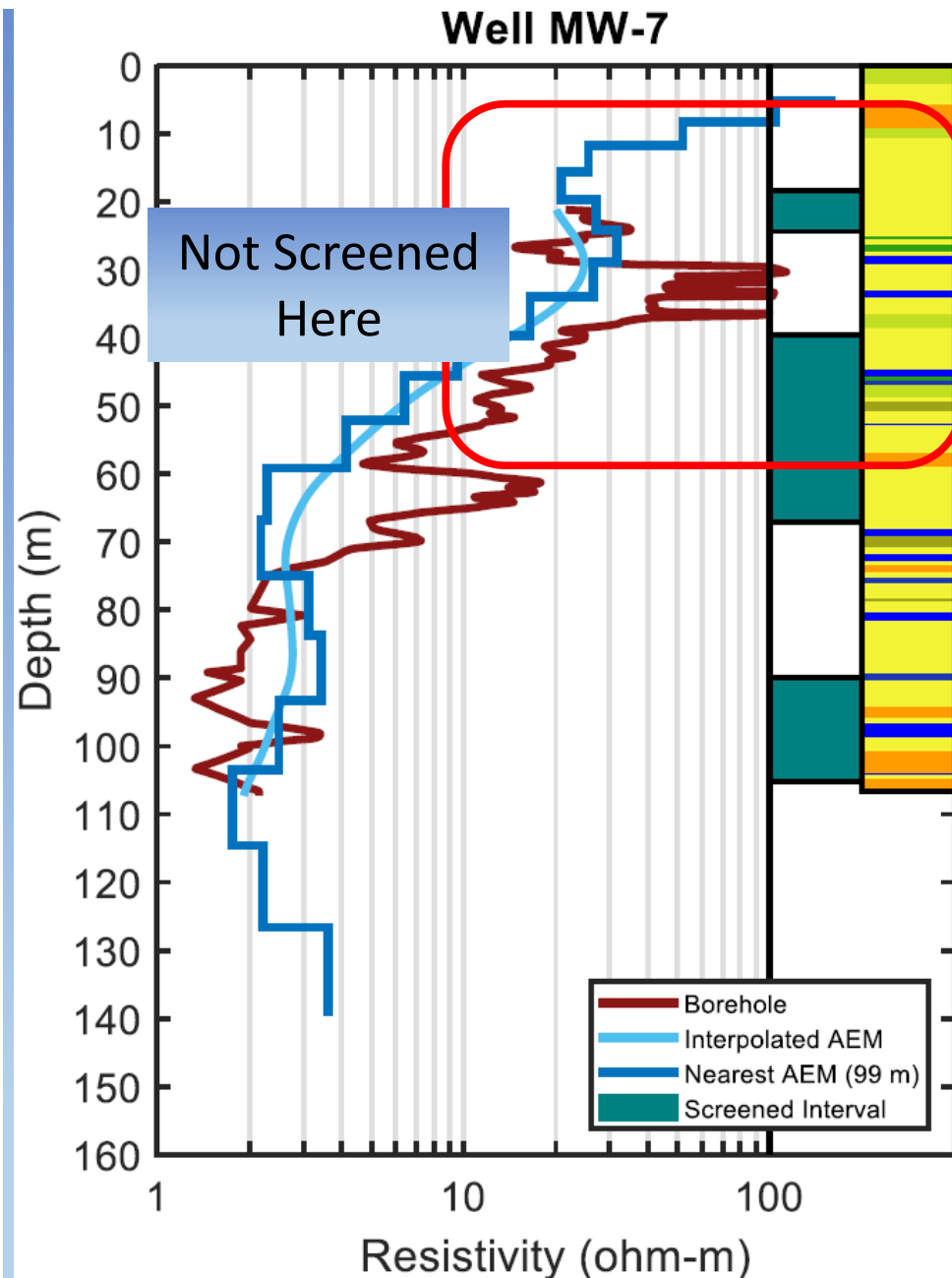
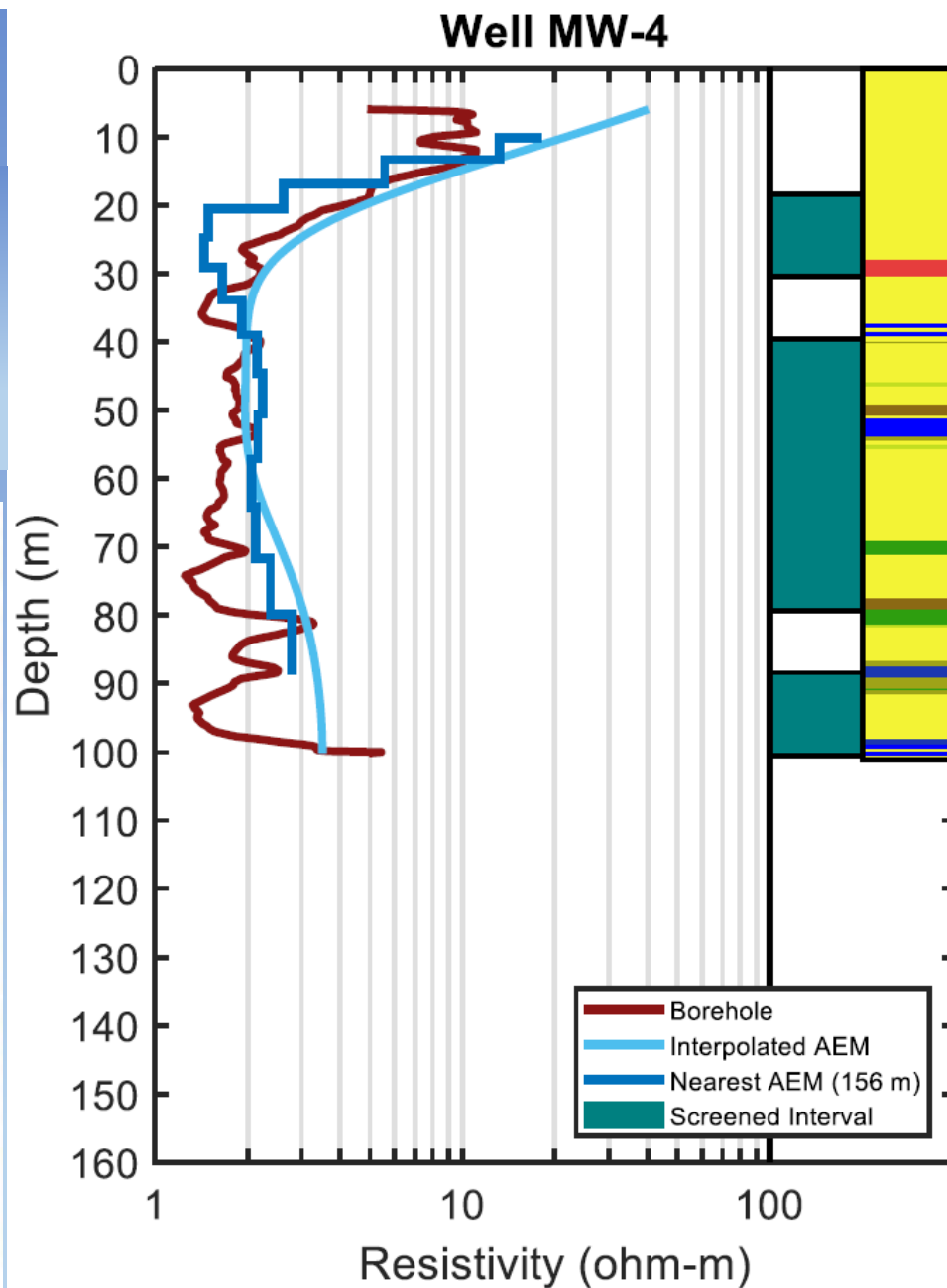
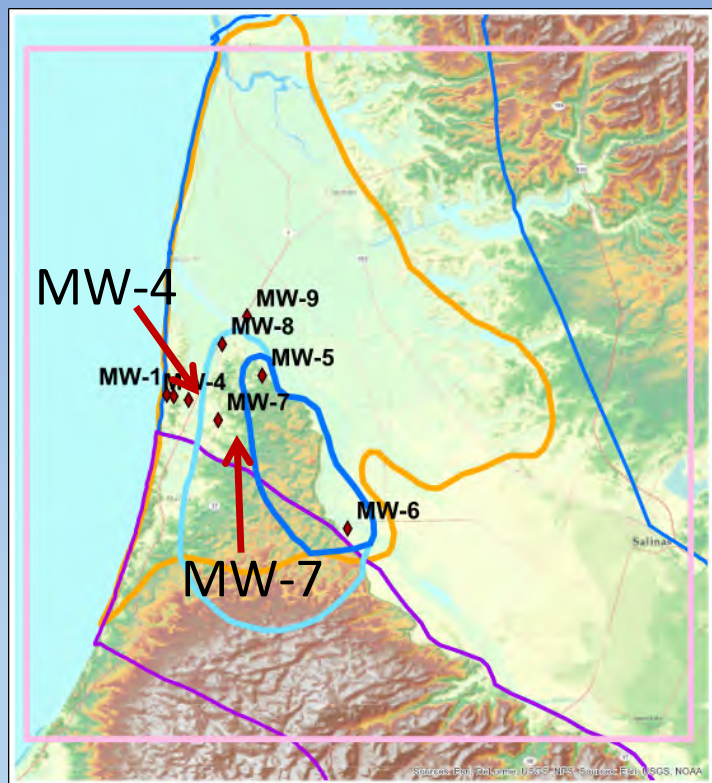
0.33-0.90

AEM Interpretation Borehole Control

Seaside Sentinel Monitoring wells – red circles
Monitoring wells – orange circles
Production wells – pink circles
Geophysical logs – red triangles
Lithology logs – inverted green triangles.



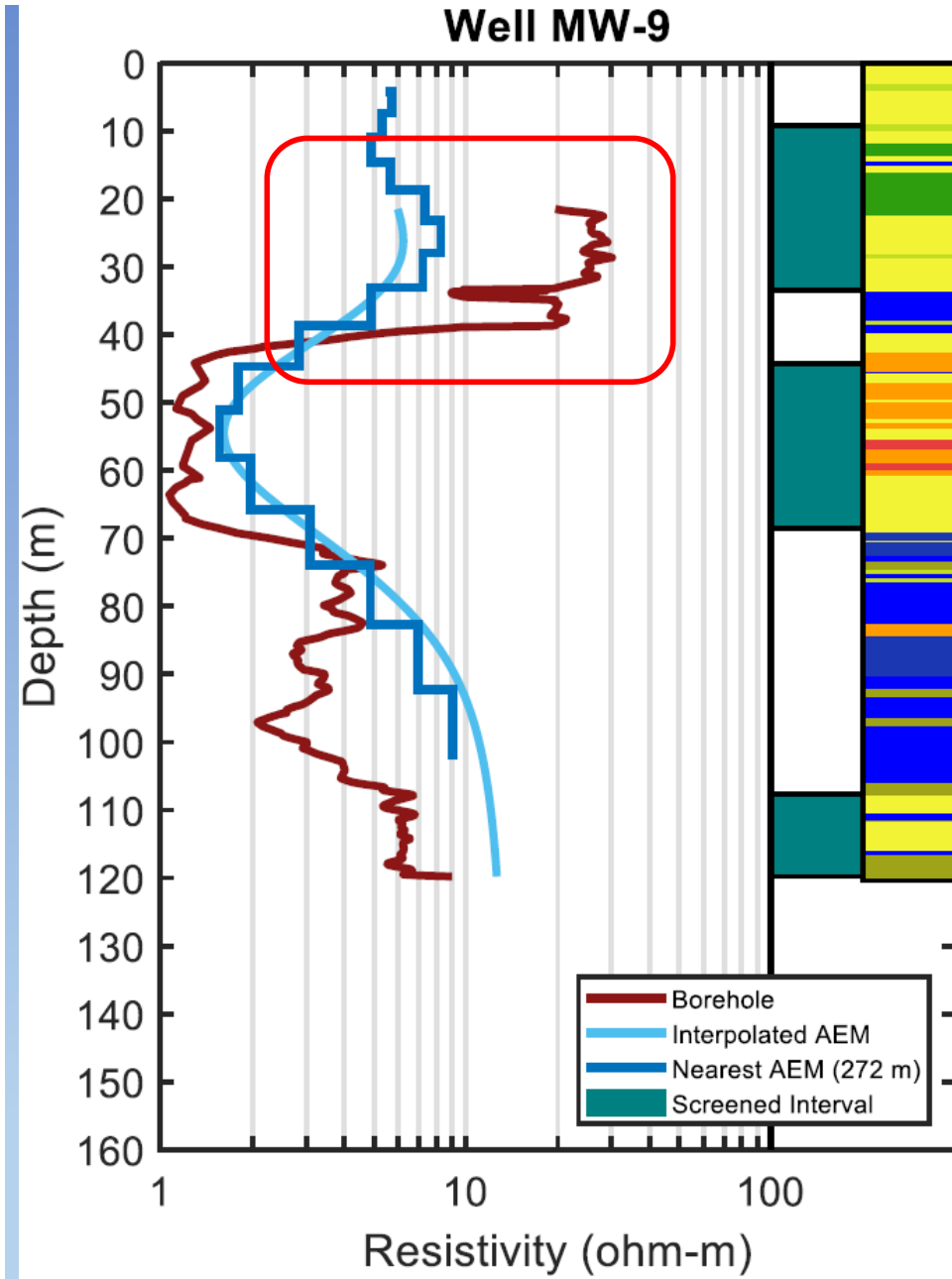
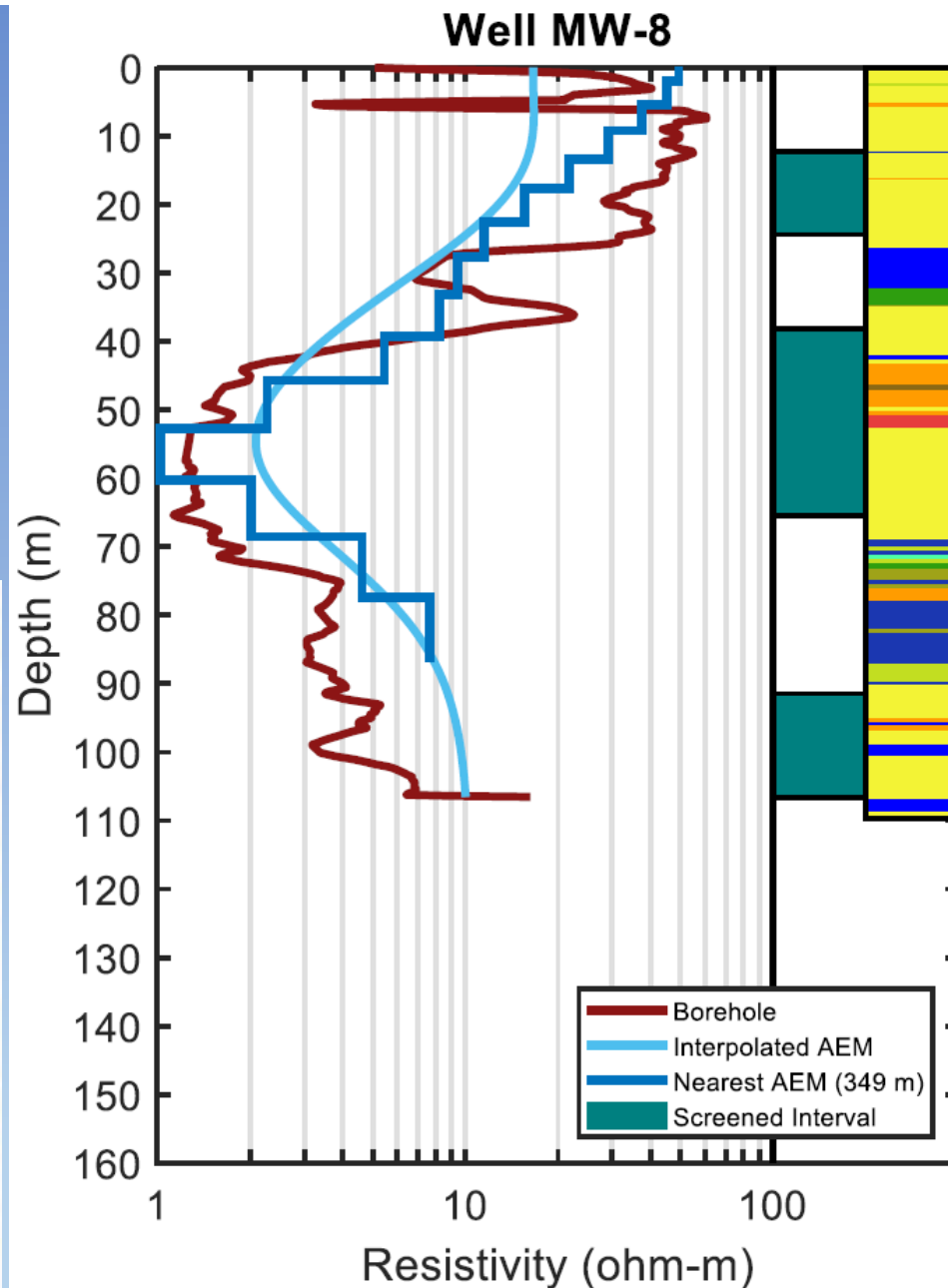
Comparison of AEM Inversion Results to Borehole Geophysics



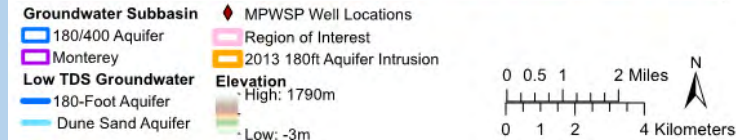
Lithology

- | | | | | |
|---------------|-----------------|------------|-----------------|------------|
| Clay | Clayey Sand | Silt/Loess | Sand and Gravel | Silty Clay |
| Clayey Gravel | Gravel/Boulders | Sand | Sandy Clay | Silty Sand |

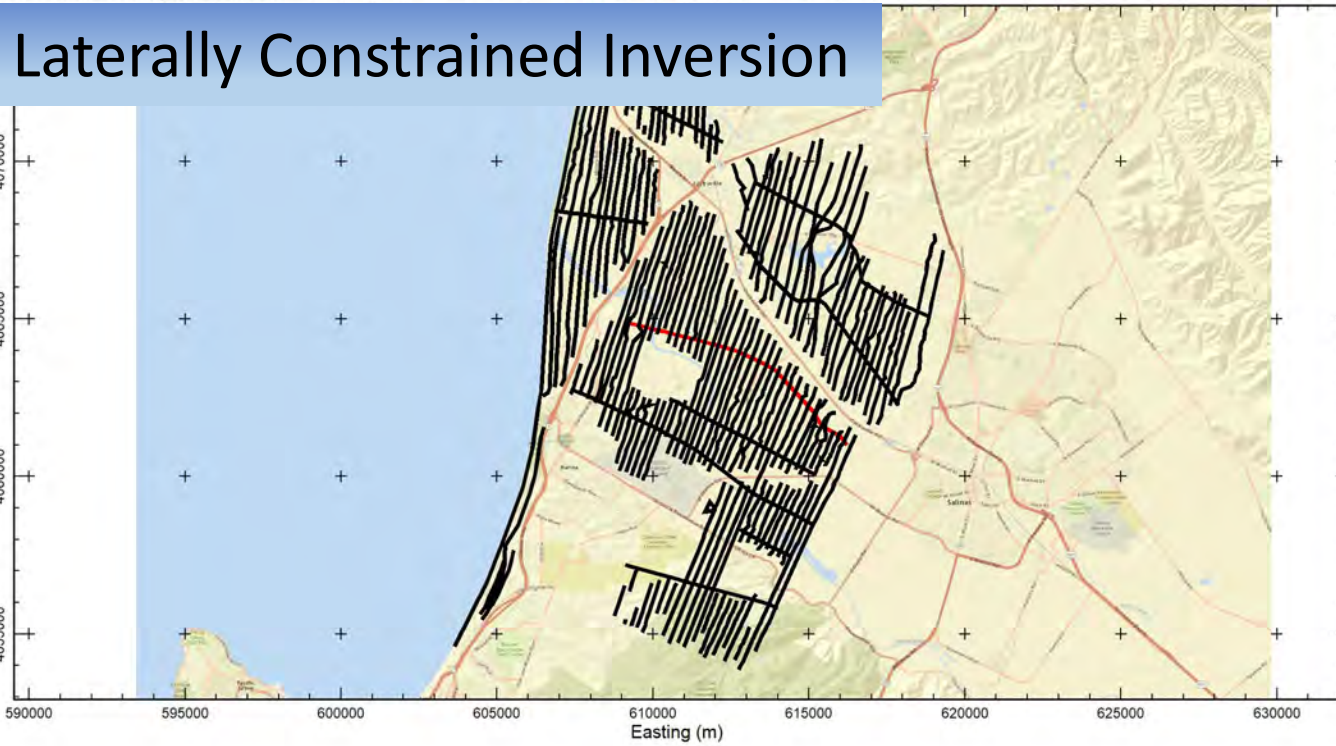
AEM Evidence of Saltwater Intrusion Since Installation of Monitoring Wells



Lithology



Laterally Constrained Inversion



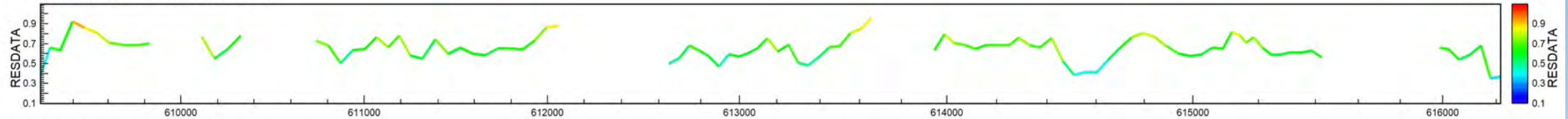
Results of the final inversion of Airborne Electromagnetic (AEM) data collected along flight lines within the Marina Coast Water District on May 16-18, 2017. The inversions shown are Spatially-Constrained using the Aarhus Geo Software Workbench versions 5.4.0.0. Prepared for the Marina Coast Water District by Aqua Geo Frameworks, LLC.

Red line indicates current displayed profile. White gaps in profile are due to removed EM coupling. Gray dashed lines on the AEM Inversion Profile are Depth of Investigation (DOI) approximations (Christiansen and Auken, 2012).

Datum: WGS84, UTM Zone 10 North (meters), NAVD88 (meters)

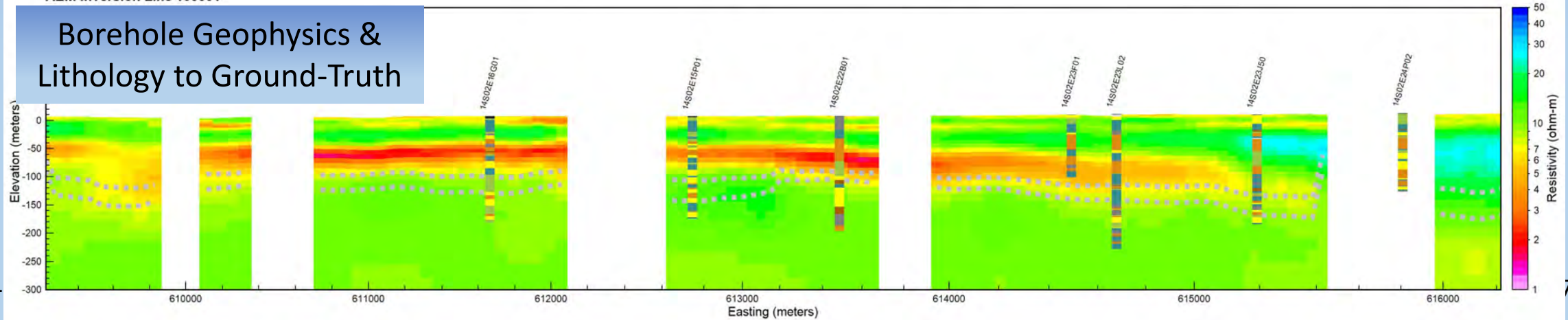


Inversion Data Residual Line 100501

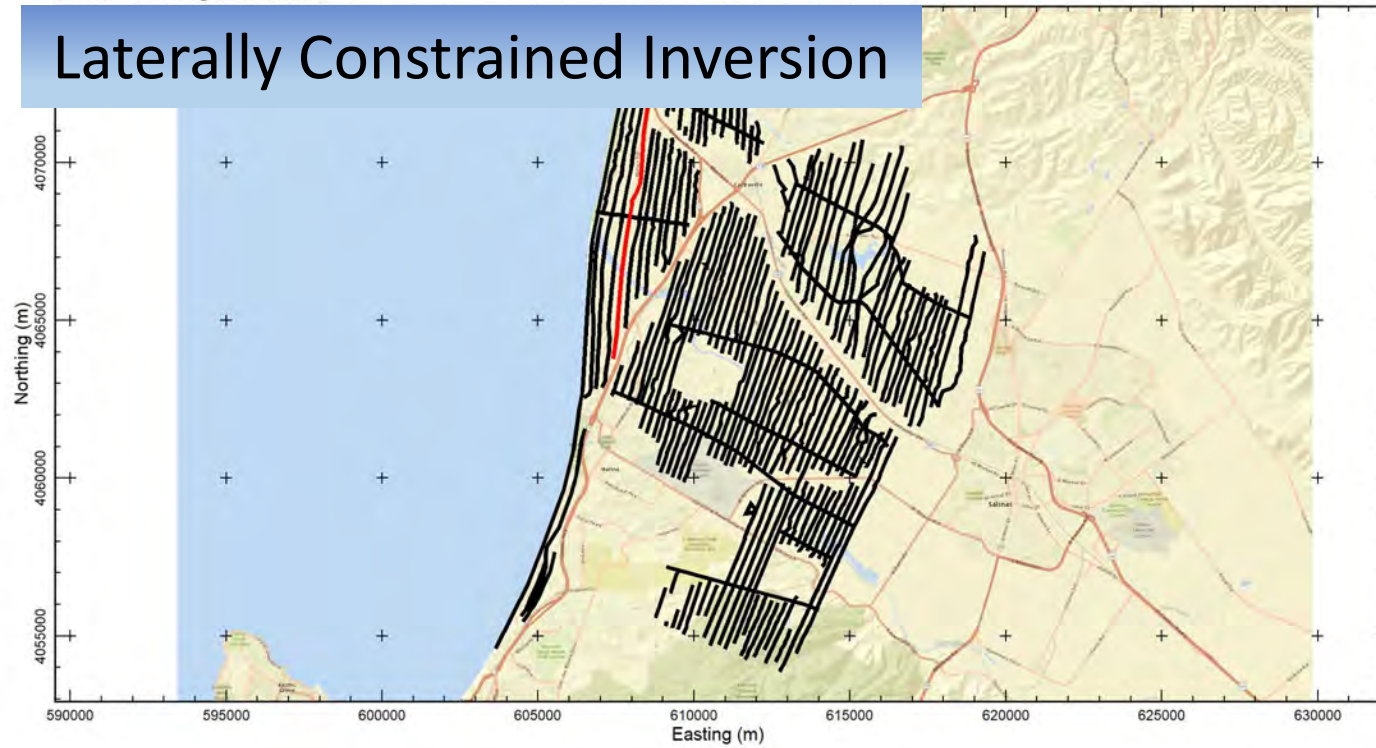


AEM Inversion Line 100501

Borehole Geophysics & Lithology to Ground-Truth



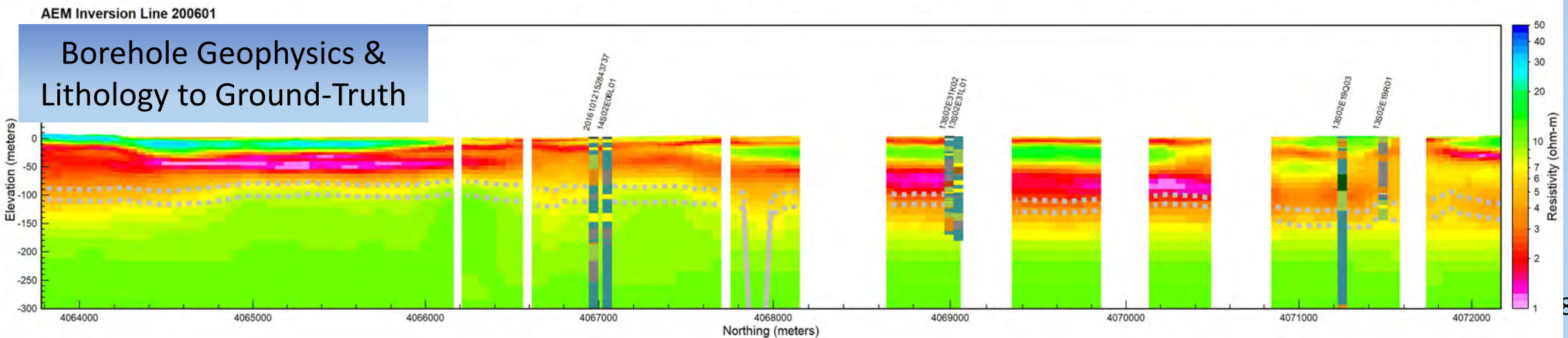
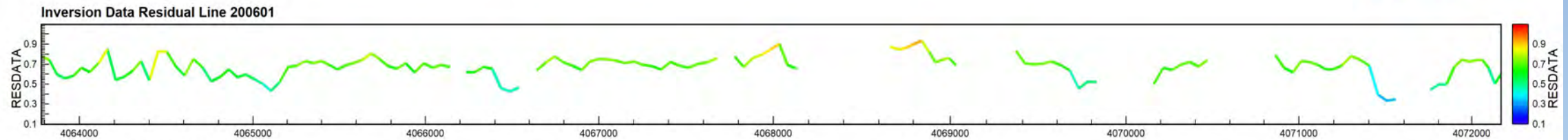
Laterally Constrained Inversion



Results of the final inversion of Airborne Electromagnetic (AEM) data collected along flight lines within the Marina Coast Water District on May 16-18, 2017. The inversions shown are Spatially-Constrained using the Aarhus Geo Software Workbench versions 5.4.0.0. Prepared for the Marina Coast Water District by Aqua Geo Frameworks, LLC.

Red line indicates current displayed profile. White gaps in profile are due to removed EM coupling. Gray dashed lines on the AEM Inversion Profile are Depth of Investigation (DOI) approximations (Christiansen and Auken, 2012).

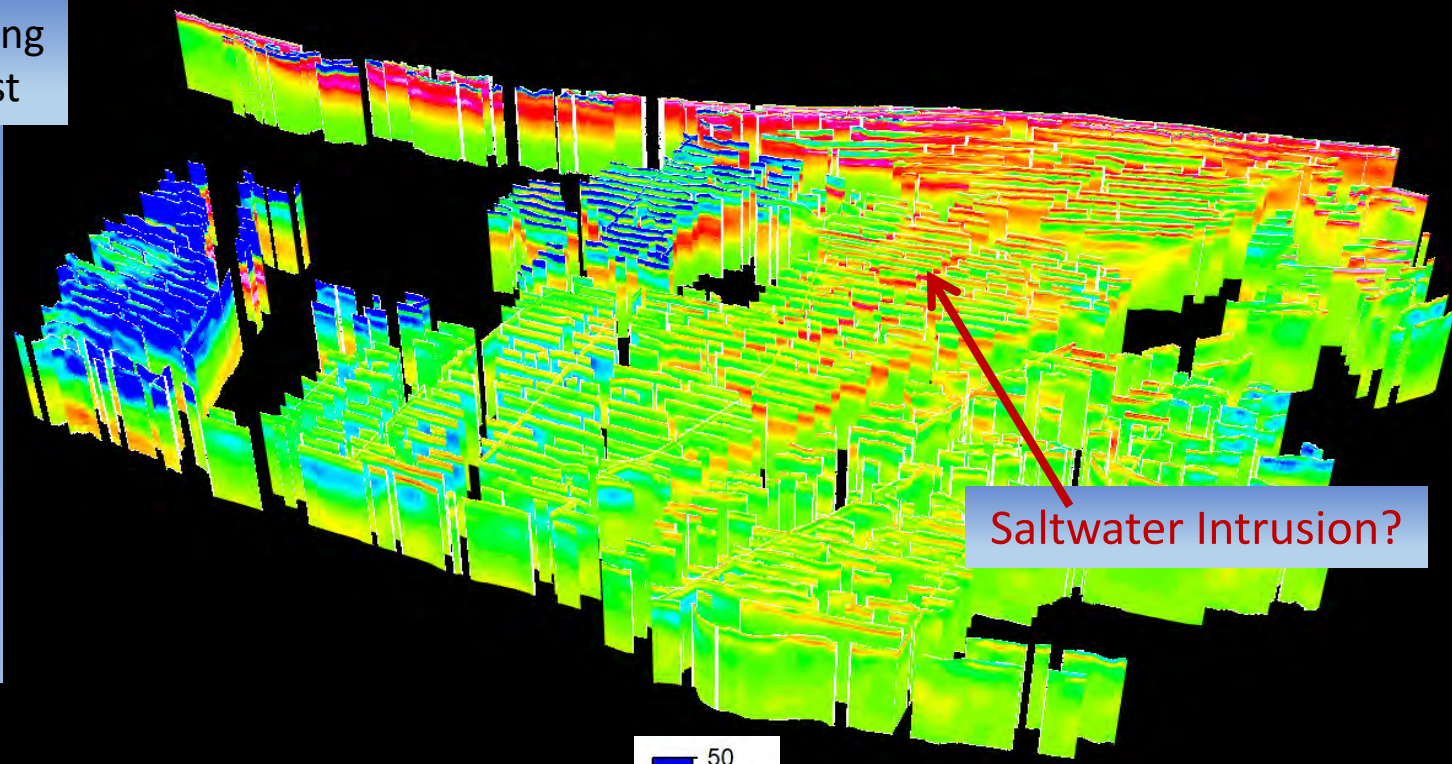
Datum: WGS84, UTM Zone 10 North (meters), NAVD88 (meters)



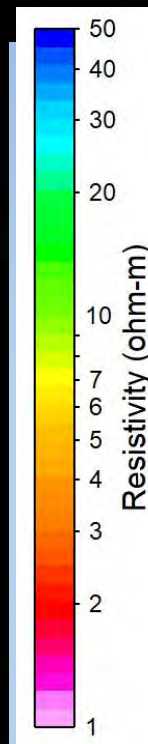
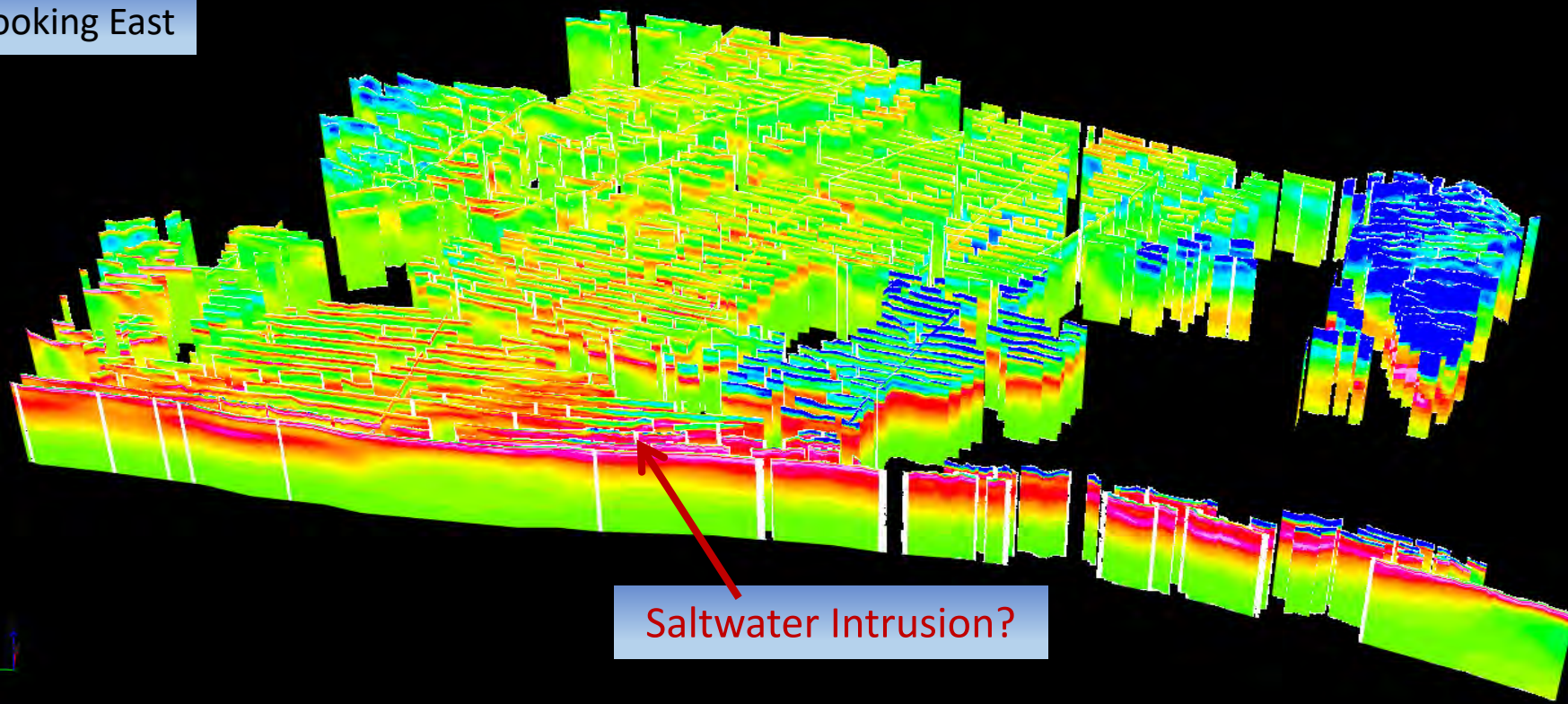
Borehole Geophysics & Lithology to Ground-Truth

AEM Inversion Results: 3D Fence Diagram

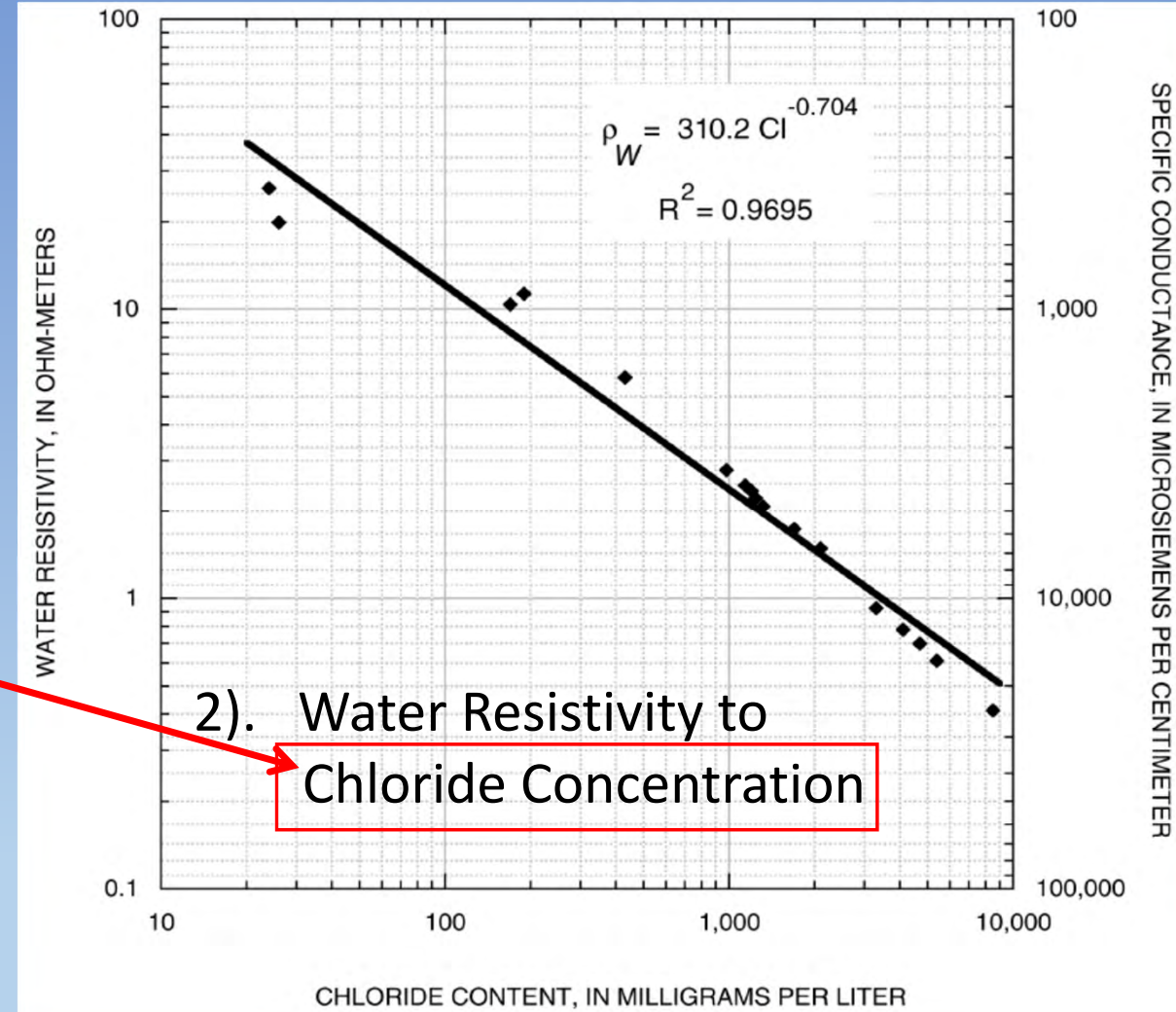
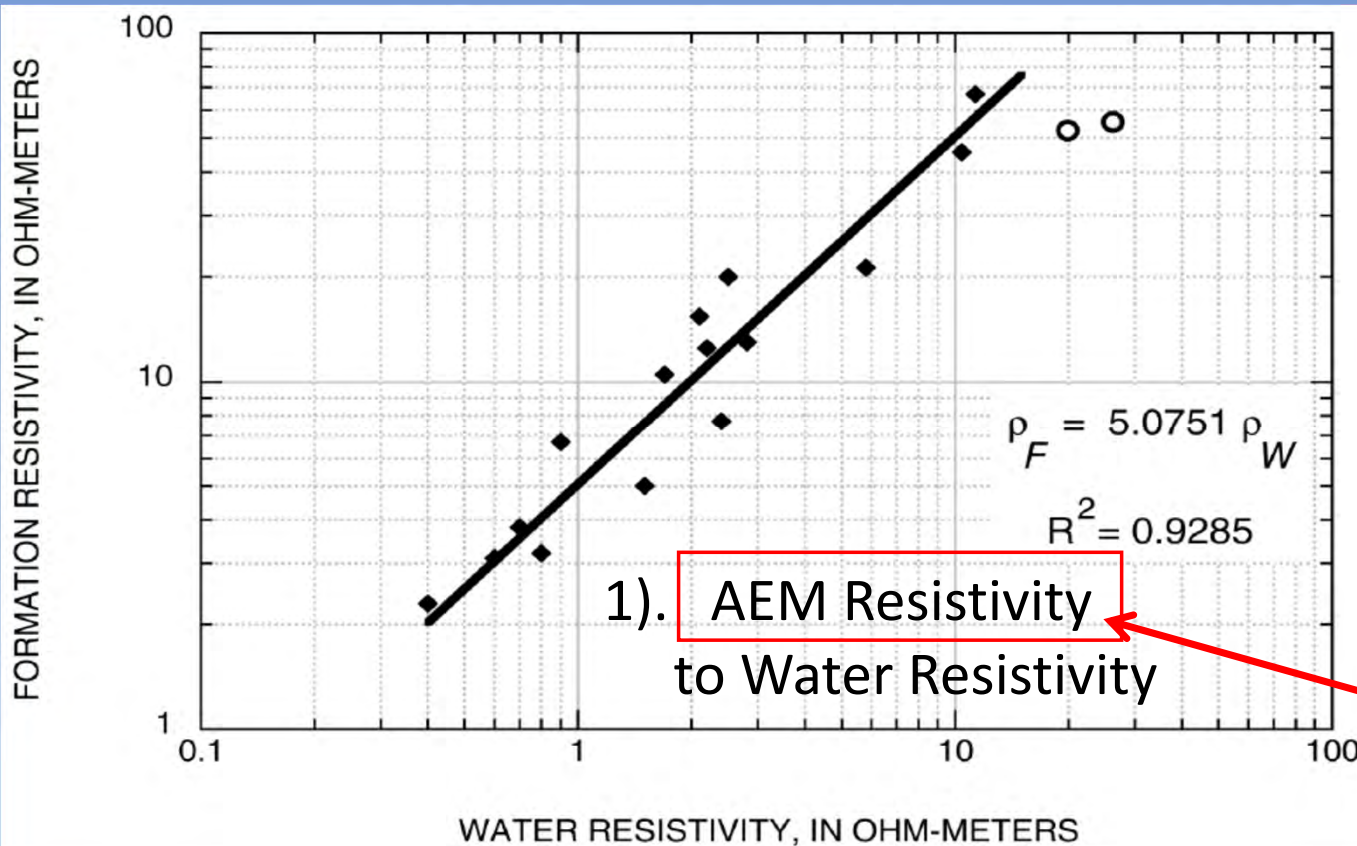
Looking
West



Looking East



AEM Bulk Resistivity to Chloride Concentration Regression Relationship



Fitterman, D.V., and Prinos, S.T., 2011, Results of time-domain electromagnetic soundings in Miami-Dade and southern Broward Counties, Florida: U.S. Geological Survey Open-File Report 2011-1299, 289p.

AEM Bulk Resistivity to Chloride Concentration Regression Relationship

Question: How reliable is using data from Florida to predict Monterey Bay saltwater intrusion chloride concentrations?

Available Measured Local Data (from well MW-7S, mid-May 2017):

Groundwater electrical conductivity: 2,200 $\mu\text{S}/\text{cm}$

TDS data: 1,470 mg/L

Analysis of the AEM data using Fitterman and Prinos (2011) (102 m from MW-7):

AEM inversion bulk resistivity: 21 ohm-m \rightarrow Groundwater resistivity: 4.14 ohm-m

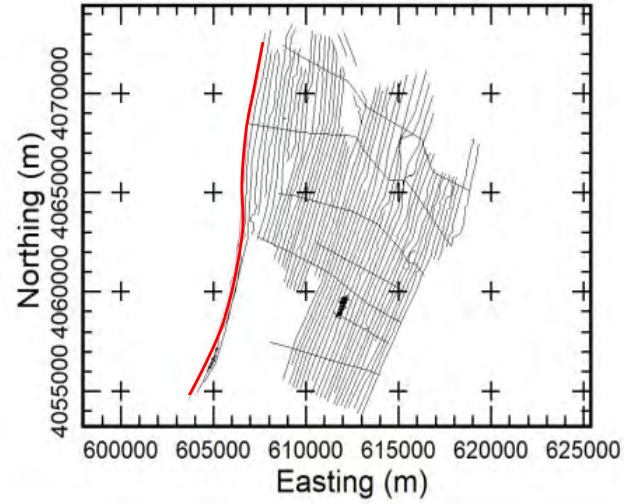
\rightarrow Groundwater conductivity: 2415 $\mu\text{S}/\text{cm}$ \rightarrow Chloride Concentration 1,453 mg/L

Other locations
checked out as well

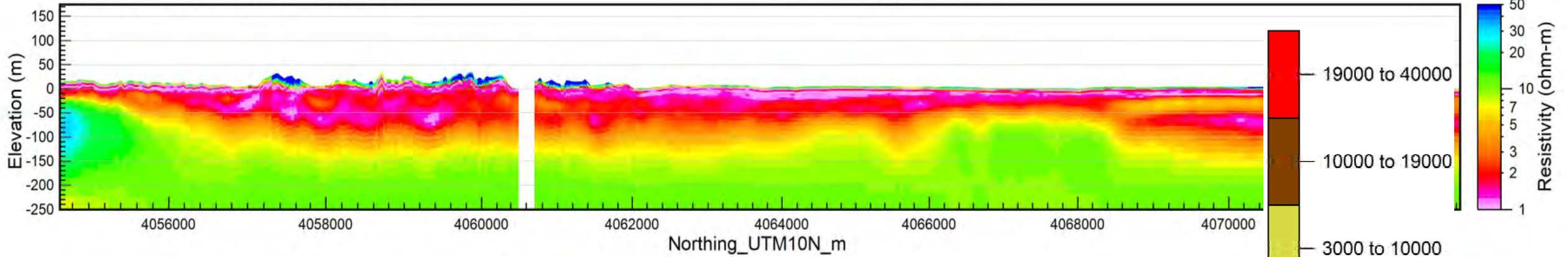
Answer: The Fitterman and Prinos (2011) Chloride Concentration Conversion Relations are Reliable.

AEM Bulk Resistivity to Chloride Concentration

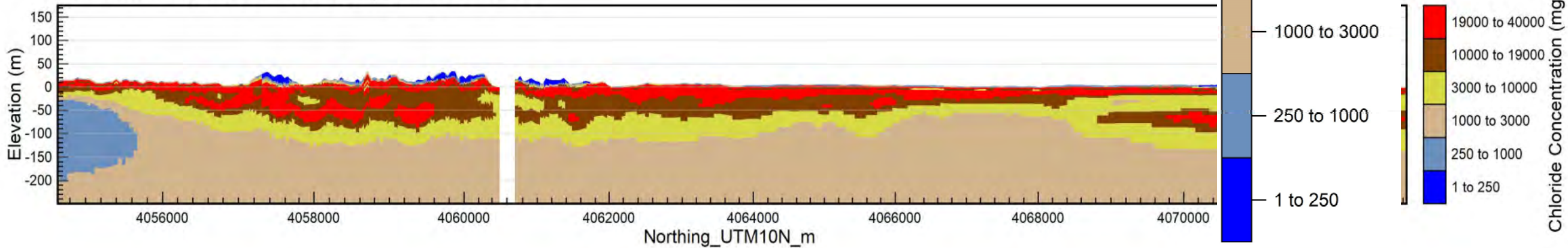
Flight Path MCWD May 2017



Profile 1 - Resistivity, Line 200101 <<<

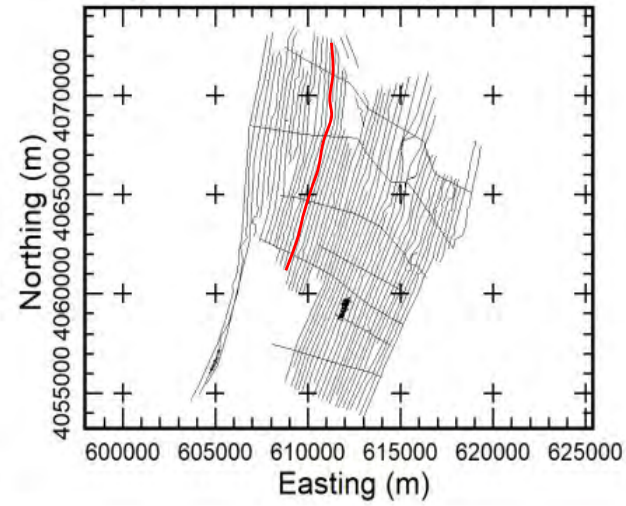


Profile 2 - Chloride Concentration, Line 200101 <<<

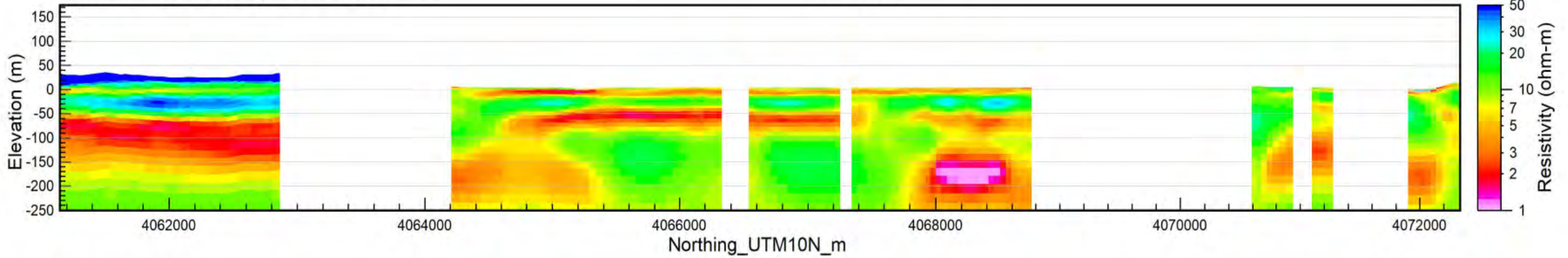


AEM Bulk Resistivity to Chloride Concentration

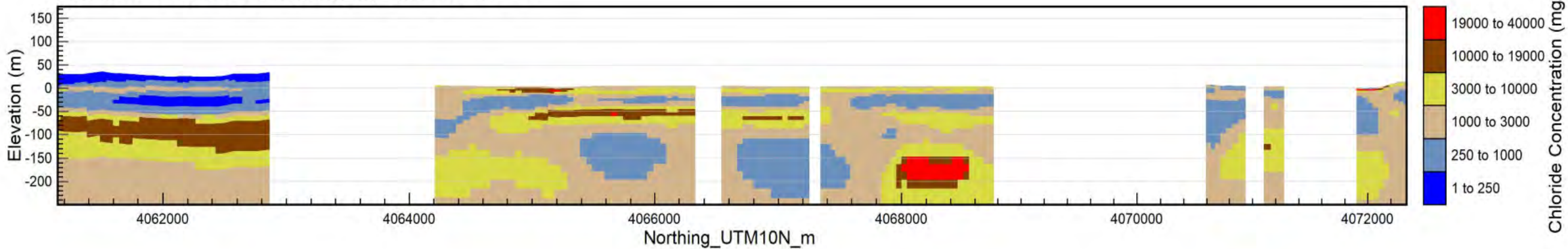
Flight Path MCWD May 2017



Profile 1 - Resistivity, Line 203401 >>>

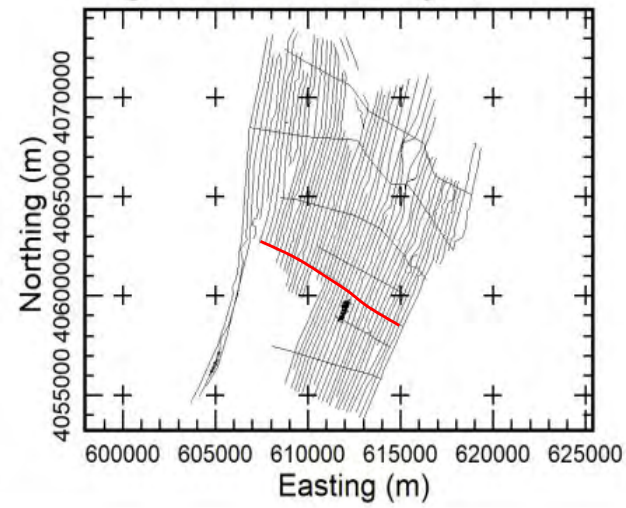


Profile 2 - Chloride Concentration, Line 203401 >>>

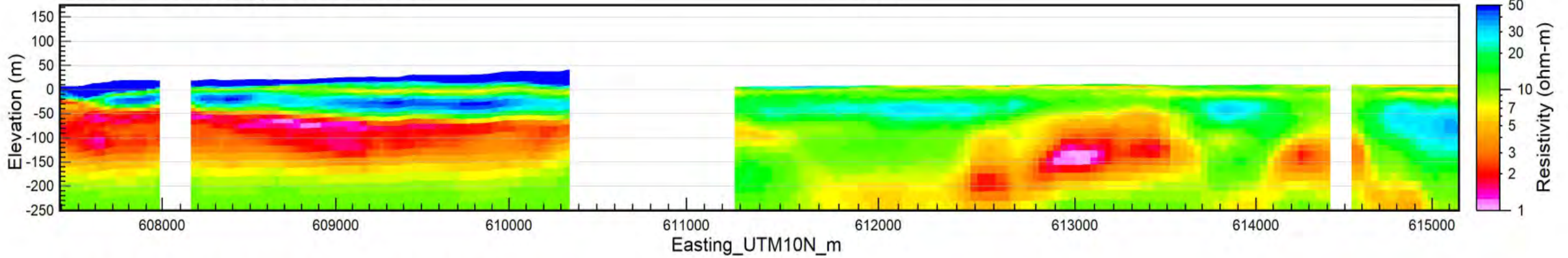


AEM Bulk Resistivity to Chloride Concentration

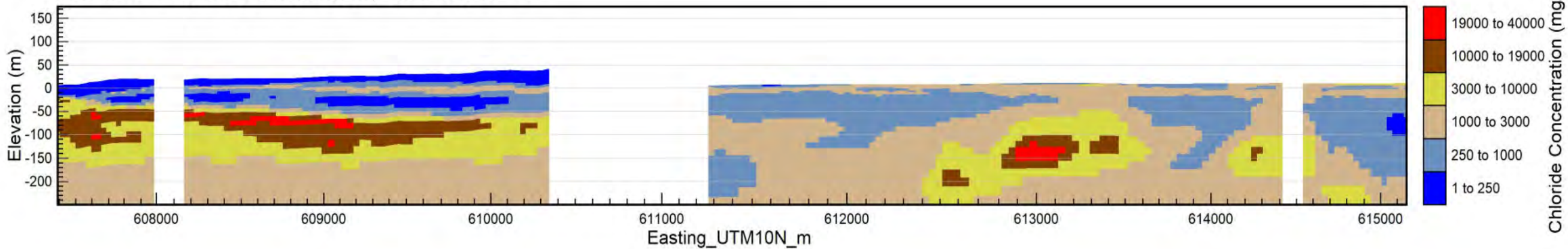
Flight Path MCWD May 2017



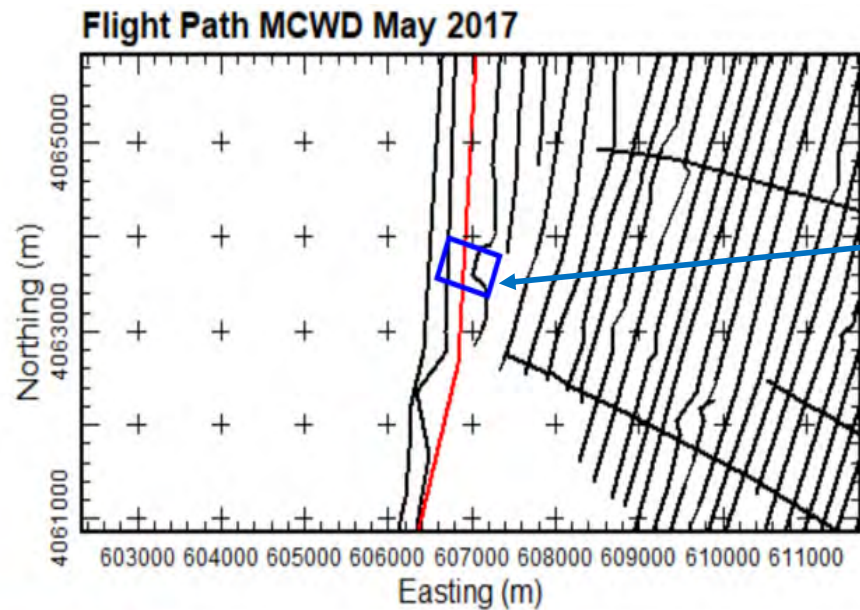
Profile 1 - Resistivity, Line 100701 <<<



Profile 2 - Chloride Concentration, Line 100701 <<<

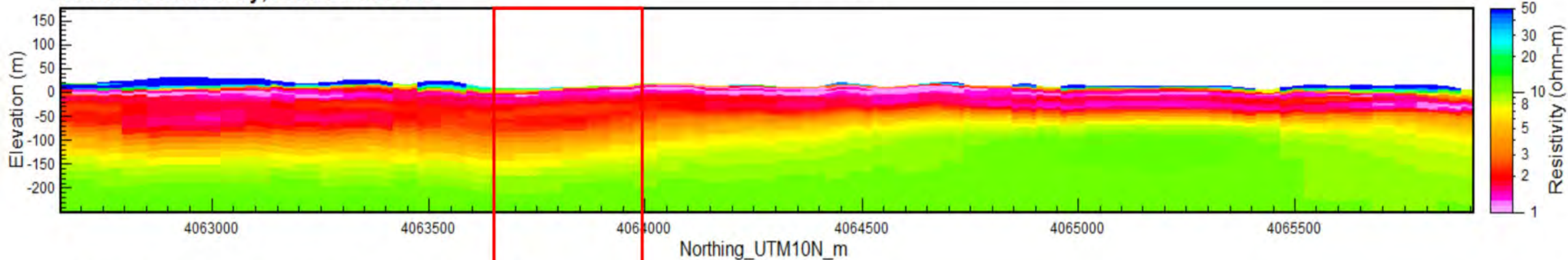


AEM Bulk Resistivity to Chloride Concentration

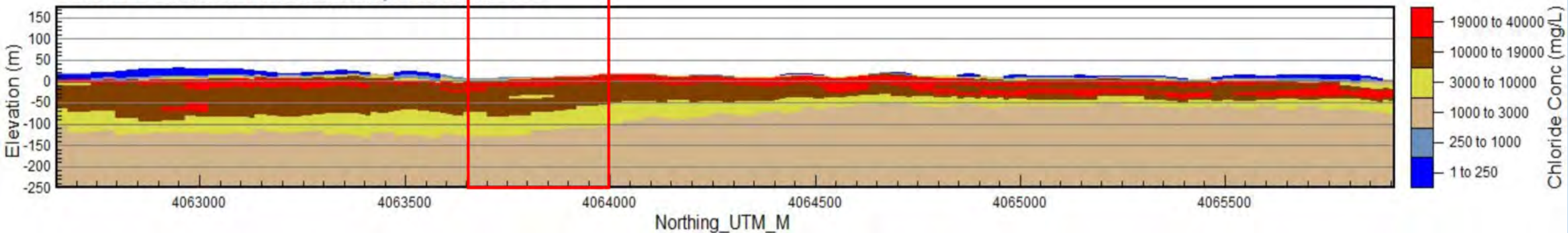


AEM Bulk Resistivity to Chloride Concentration Used to Study Nature of Aquitard in the Area of the Blue Box

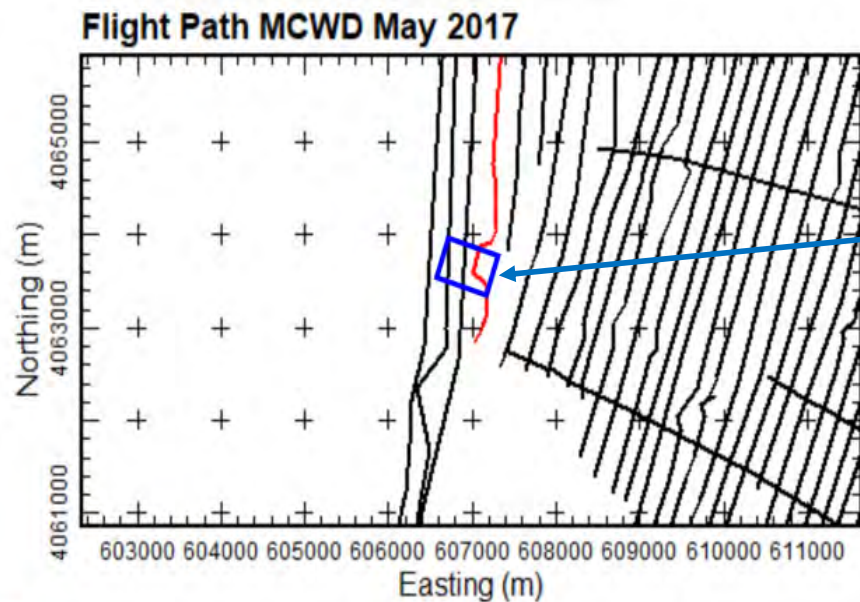
Profile 1 - Resistivity, Line 200301 <<<



Profile 2 - Chloride Concentration, Line 200301 <<<

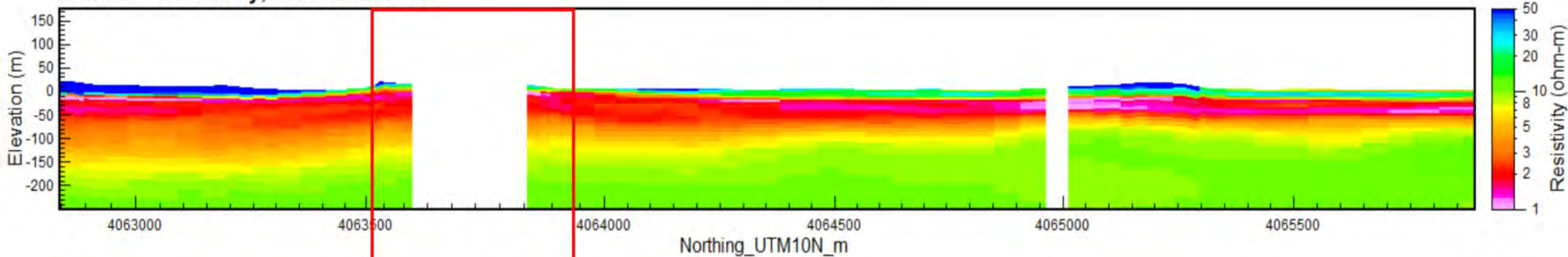


AEM Bulk Resistivity to Chloride Concentration

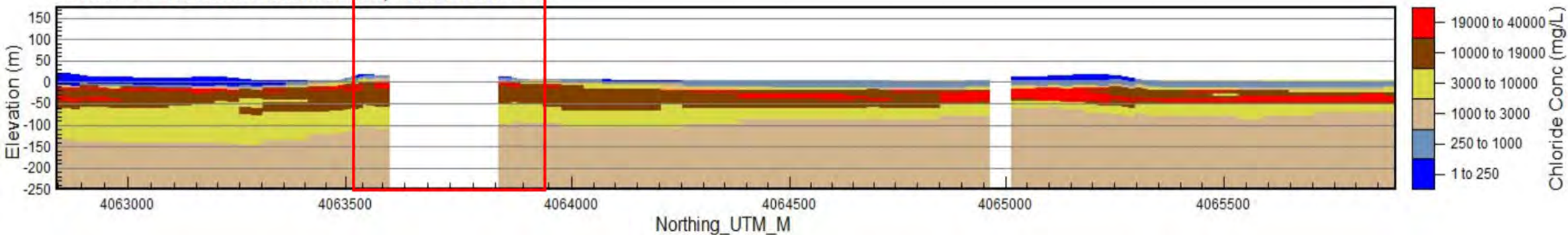


AEM Bulk Resistivity to Chloride Concentration Used to Study Nature of Aquitard in the Area of the Blue Box

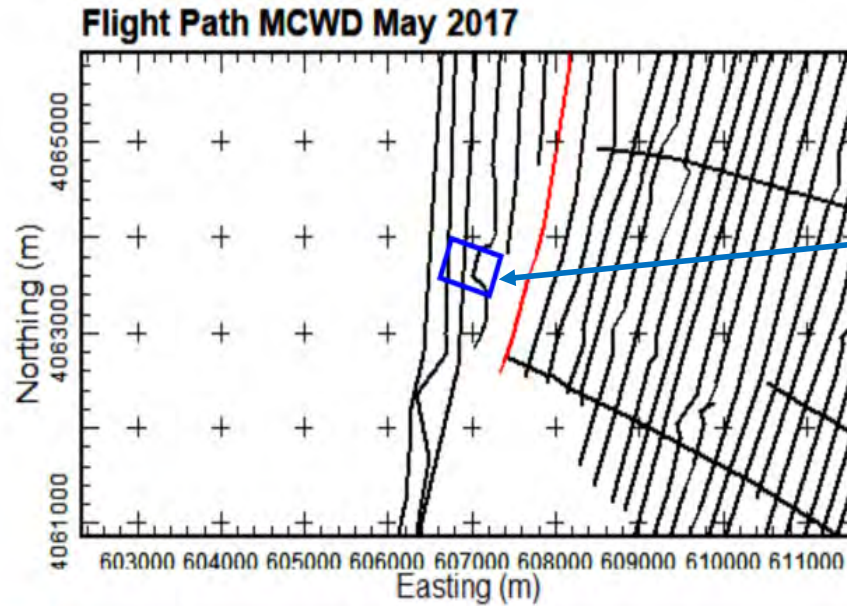
Profile 1 - Resistivity, Line 200501 >>>



Profile 2 - Chloride Concentration, Line 200501 >>>

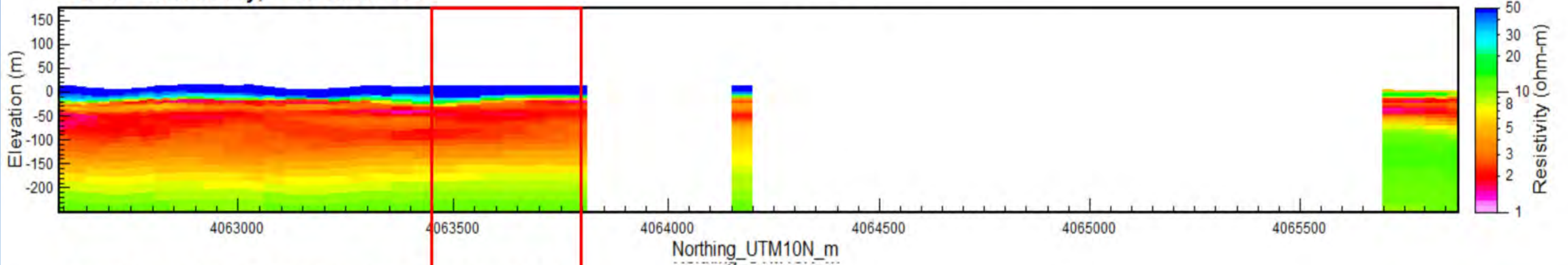


AEM Bulk Resistivity to Chloride Concentration

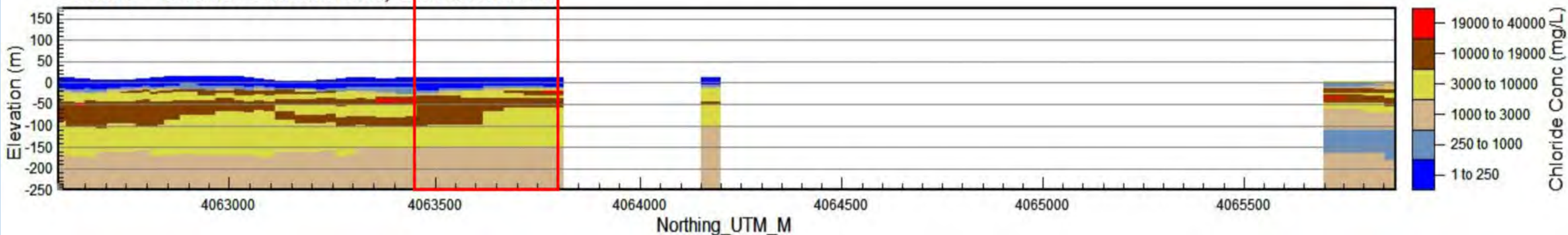


AEM Bulk Resistivity to Chloride Concentration Used to Study Nature of Aquitard in the Area of the Blue Box

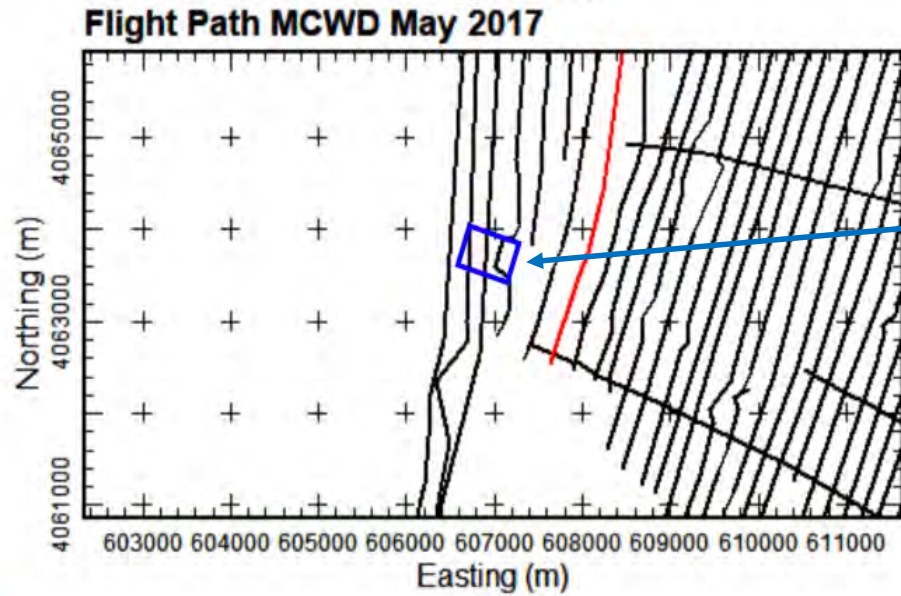
Profile 1 - Resistivity, Line 200901 >>>



Profile 2 - Chloride Concentration, Line 200901 >>>

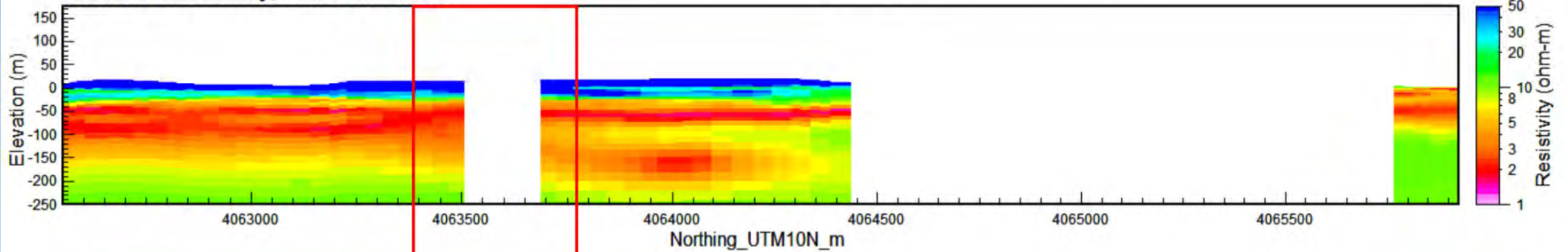


AEM Bulk Resistivity to Chloride Concentration

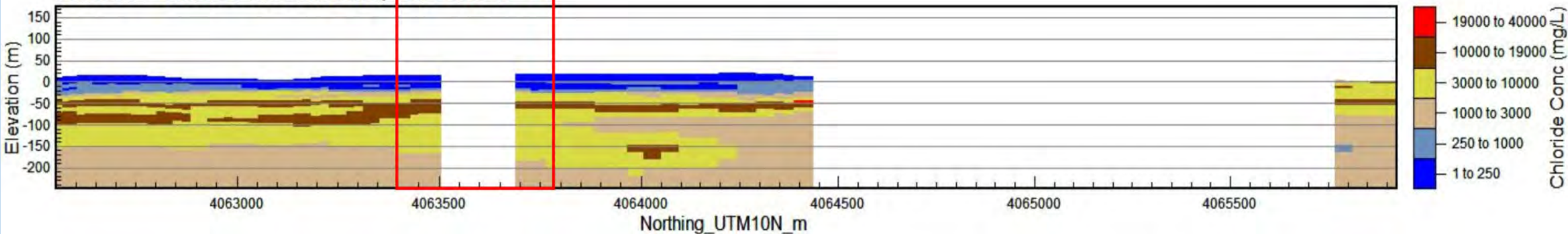


AEM Bulk Resistivity to Chloride Concentration Used to Study Nature of Aquitard in the Area of the Blue Box

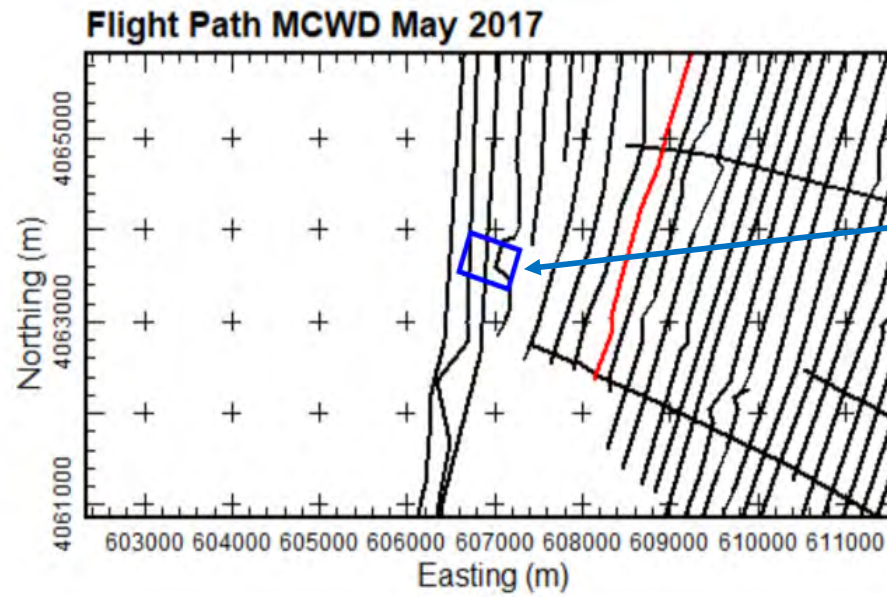
Profile 1 - Resistivity, Line 201201 >>>



Profile 2 - Chloride Concentration, Line 201201 >>>

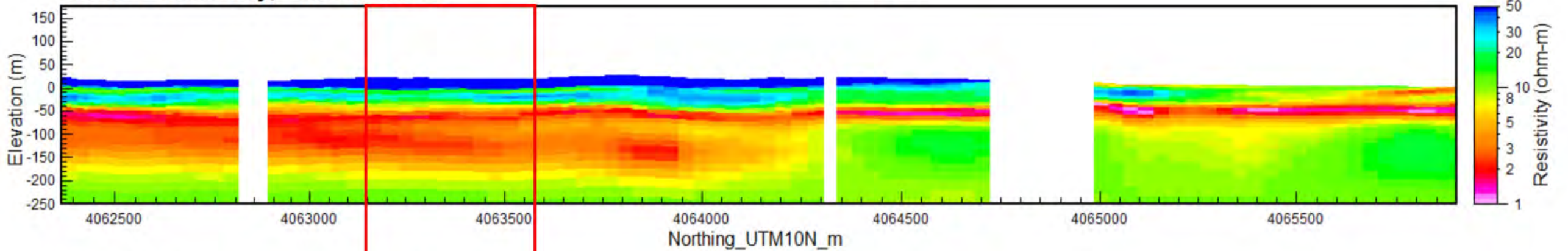


AEM Bulk Resistivity to Chloride Concentration

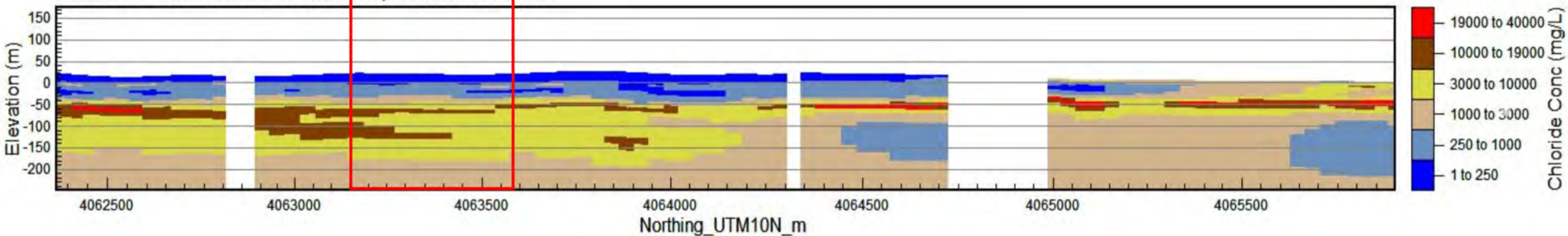


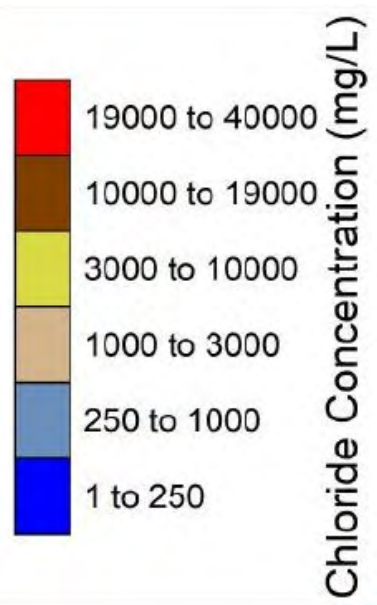
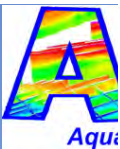
AEM Bulk Resistivity to Chloride Concentration Used to Study Nature of Aquitard in the Area of the Blue Box

Profile 1 - Resistivity, Line 202201 >>>

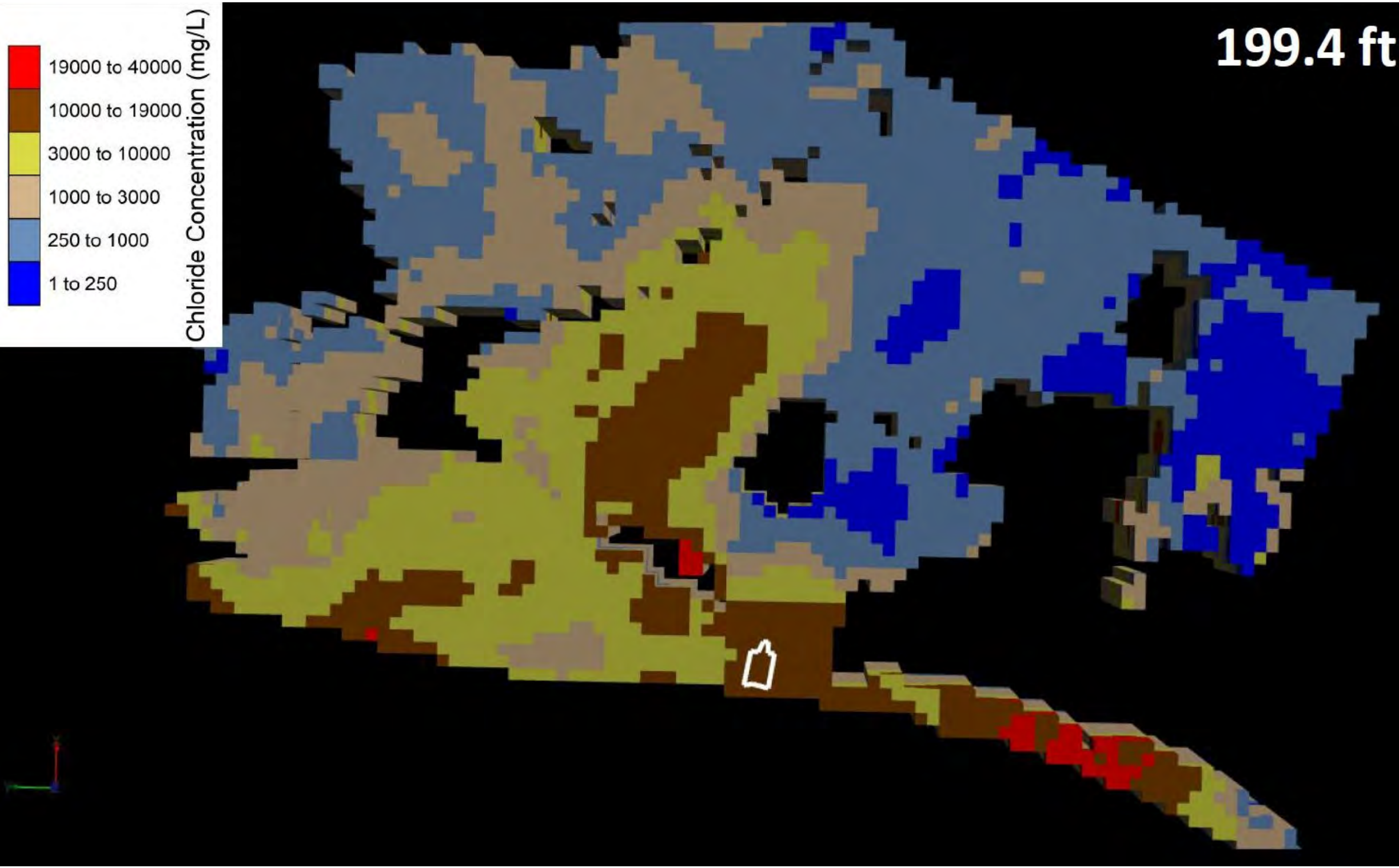


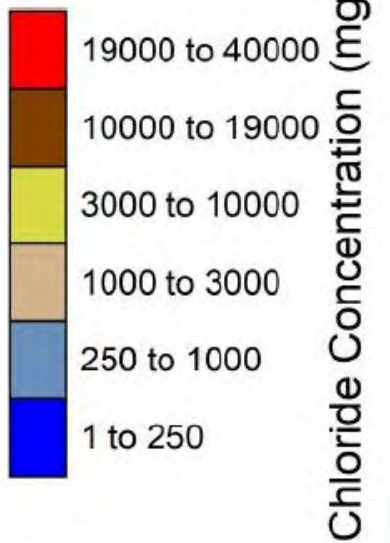
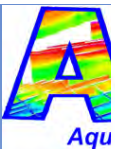
Profile 2 - Chloride Concentration, Line 202201 >>>



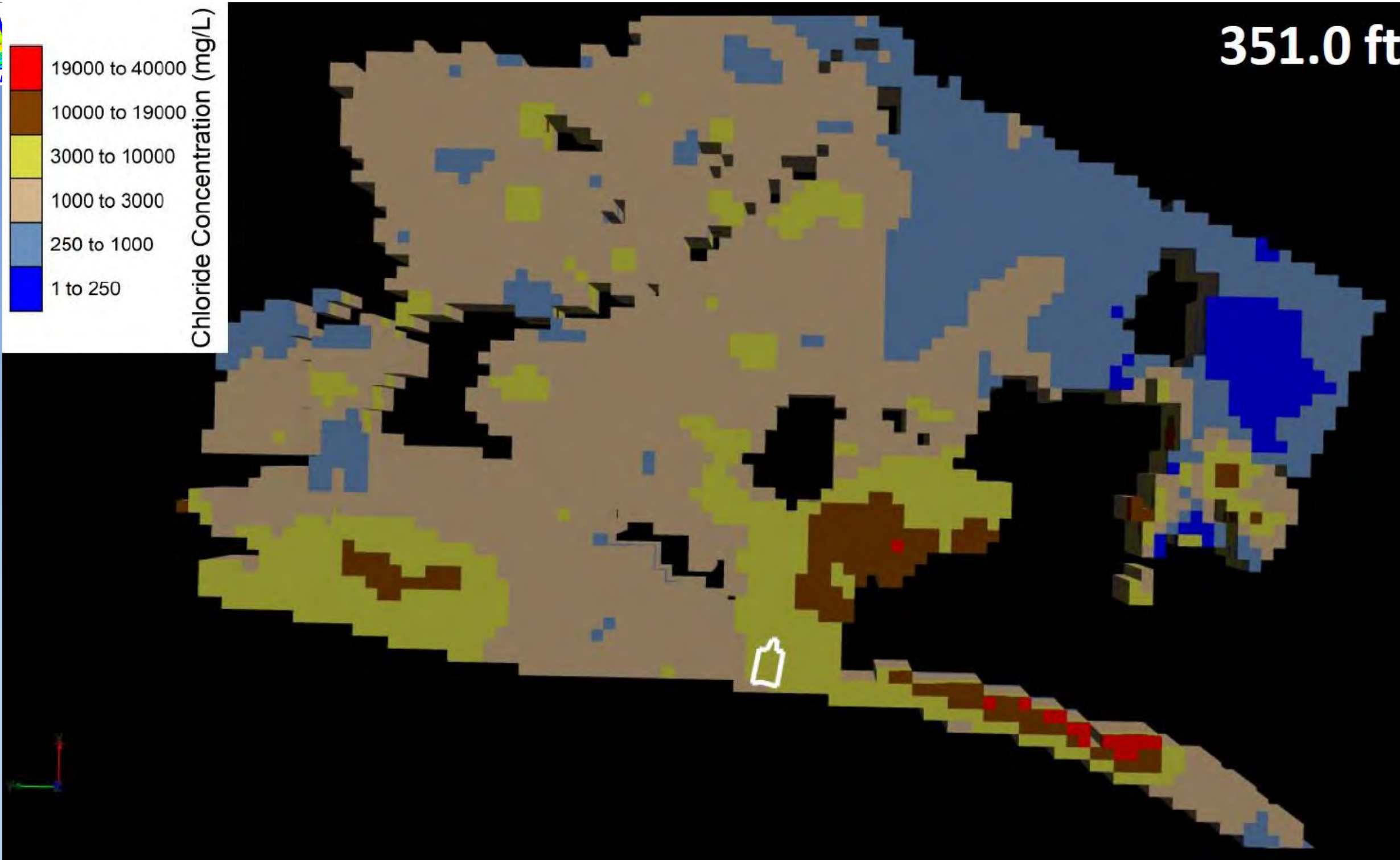


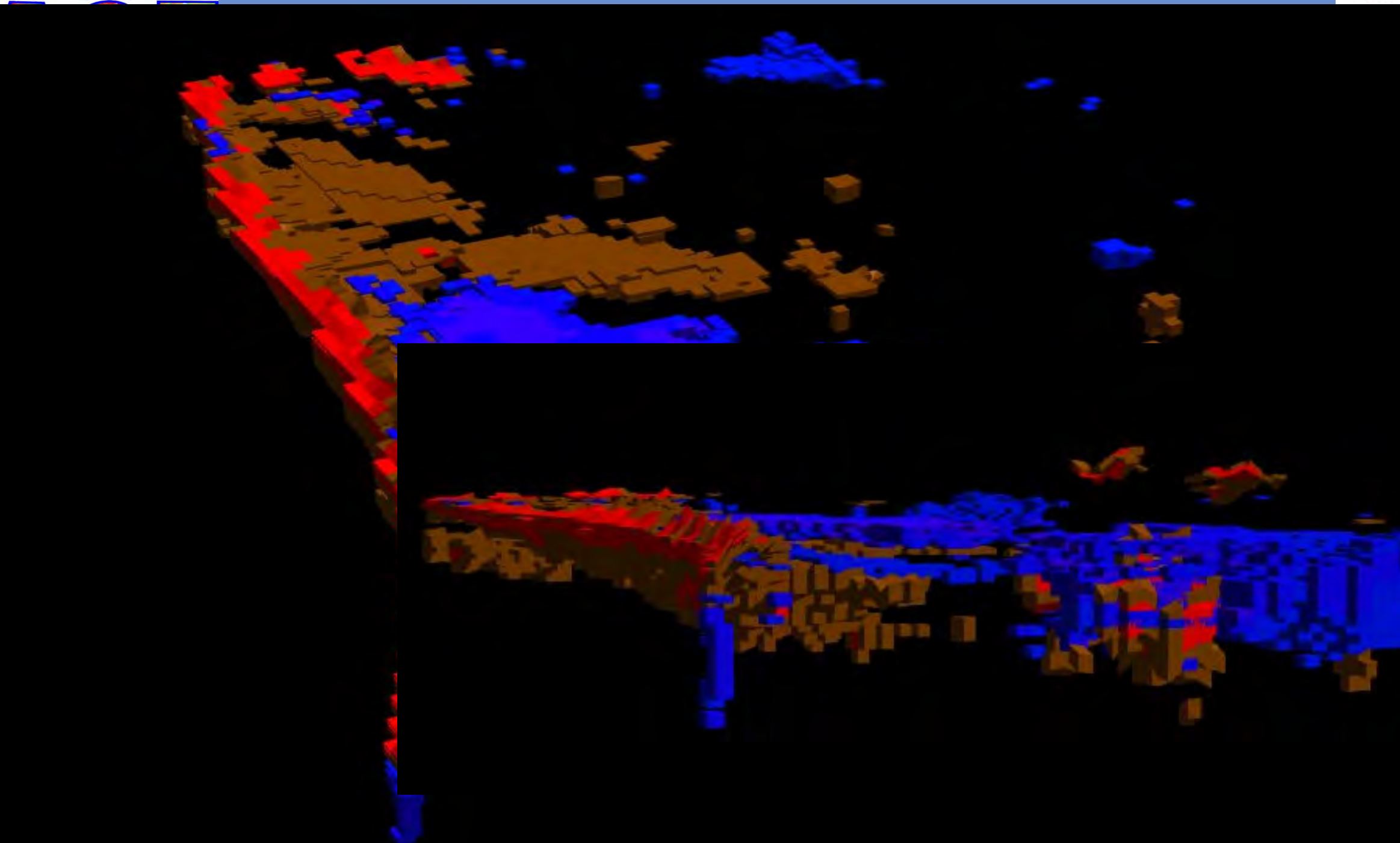
199.4 ft














351.0 ft



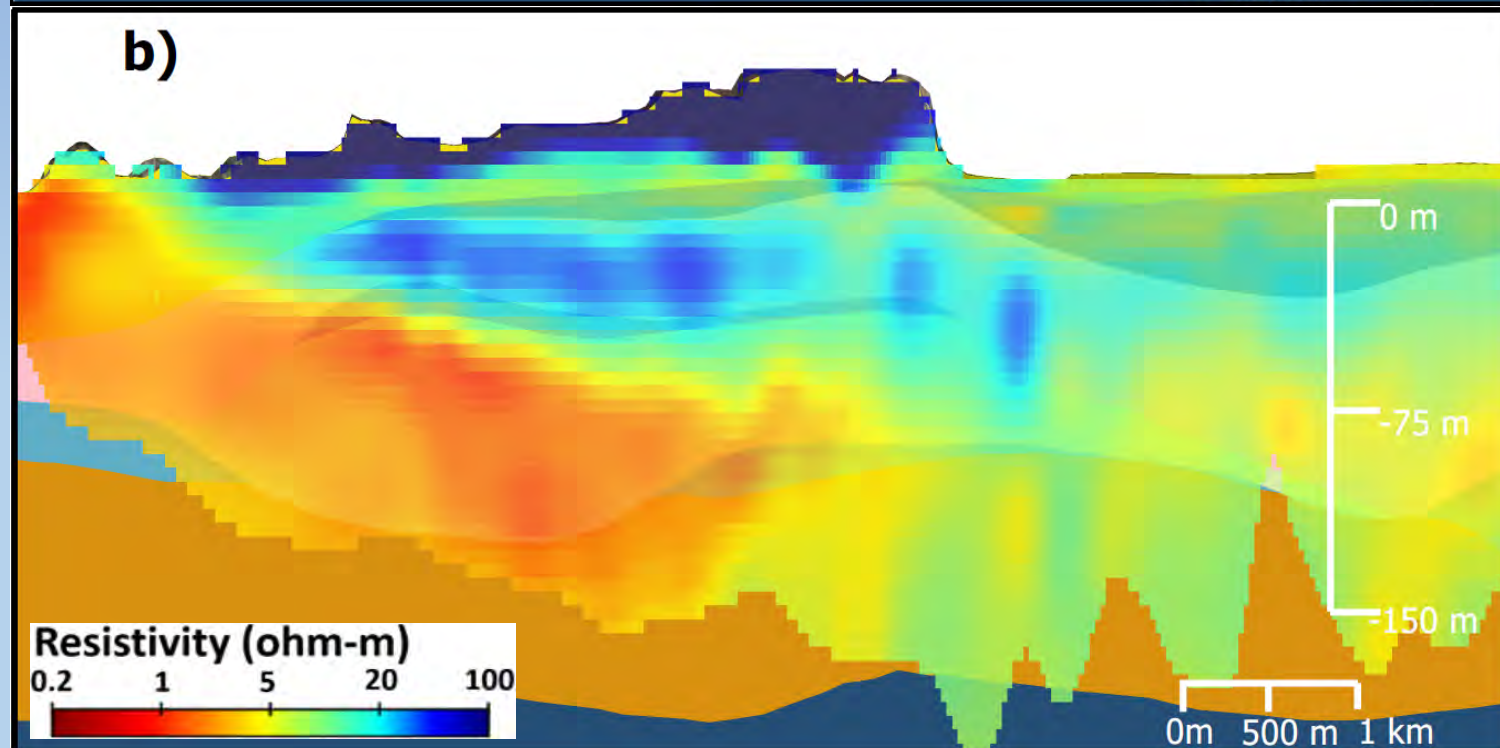
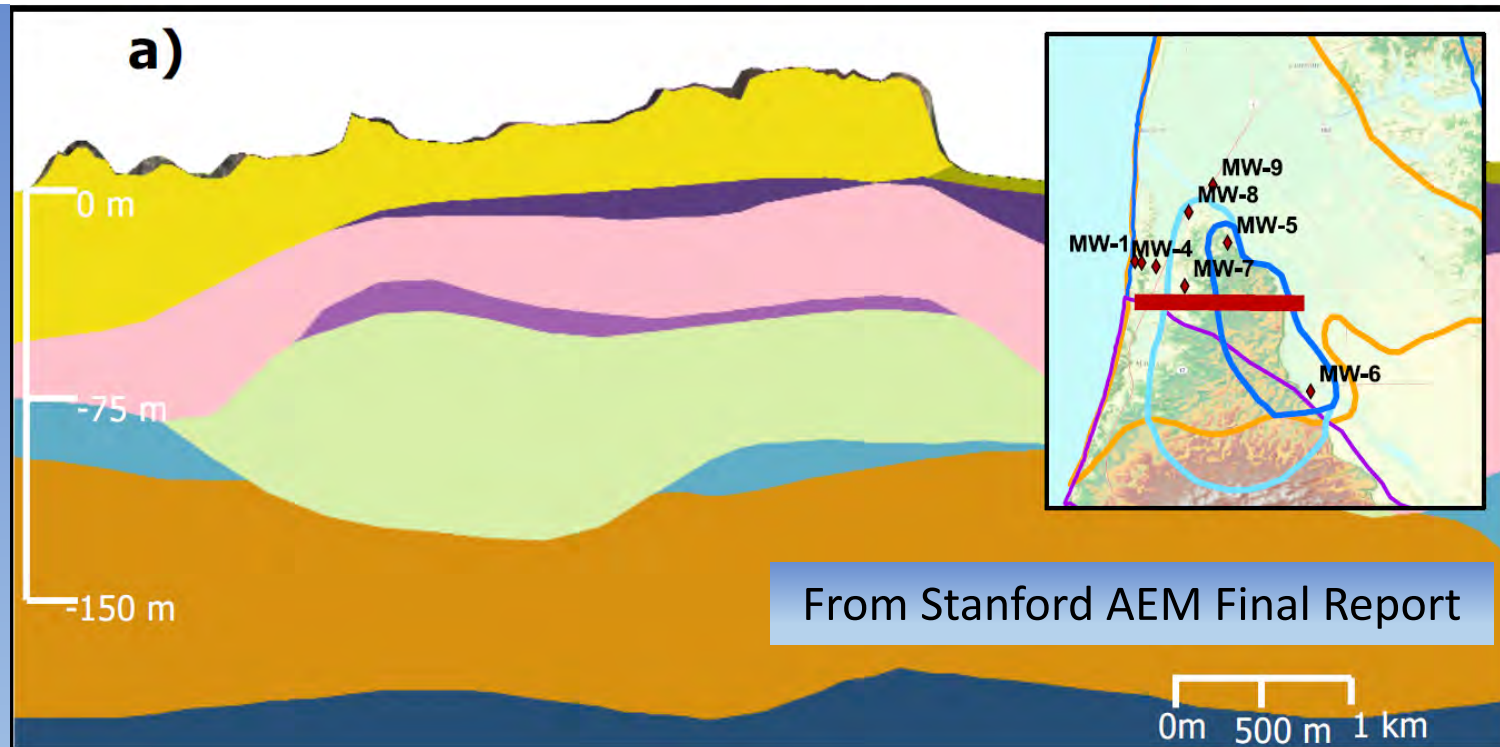


AEM Interpretation Example

Hydrostratigraphic Unit

-  Perched "A" Aquifer
-  Dune Sand Aquifer
-  Salinas Valley Aquitard
-  Upper 180-Foot Aquifer
-  Int. 180-Foot Aquitard
-  Lower 180-Foot Aquifer
-  180/400-Foot Aquitard
-  400-Foot Aquifer
-  400/Deep Aquitard

12 February 2019



AEM Modeling: Sensitivity of the AEM to Chloride Content

Question: What is the sensitivity of the AEM method to *small* variations in chloride concentration in the subsurface?

Reason: We have certain regulatory chloride concentration zone boundaries. We need to be able to monitor those zone boundaries. Can you do that with AEM?

In other words, “You run the inversion and get a result. Is it an *accurate* result? Or at least close? How close?”

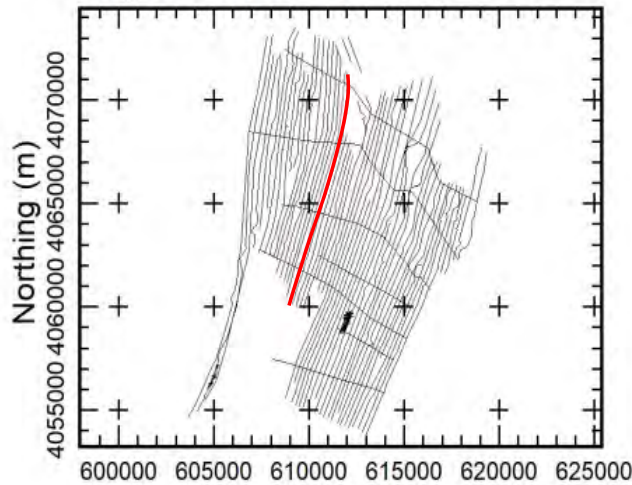
Process
To Check

1. Pick Sounding
2. Forward/Inverse Model Original to Check
3. Modify Certain Layers; Forward/Inverse
4. Check Result

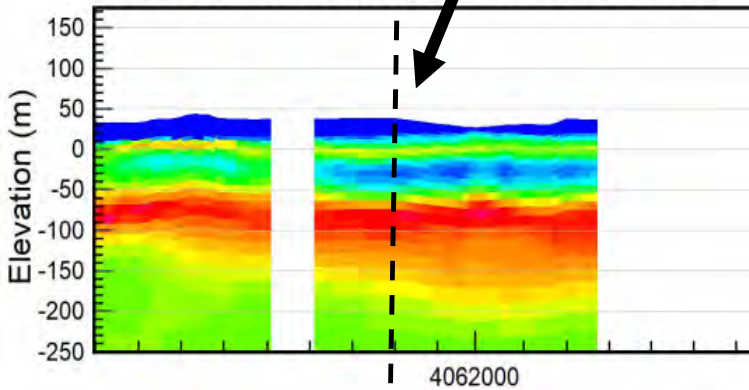
AEM Modeling: Sensitivity of the AEM to Chloride Content

Sounding Location Under Study

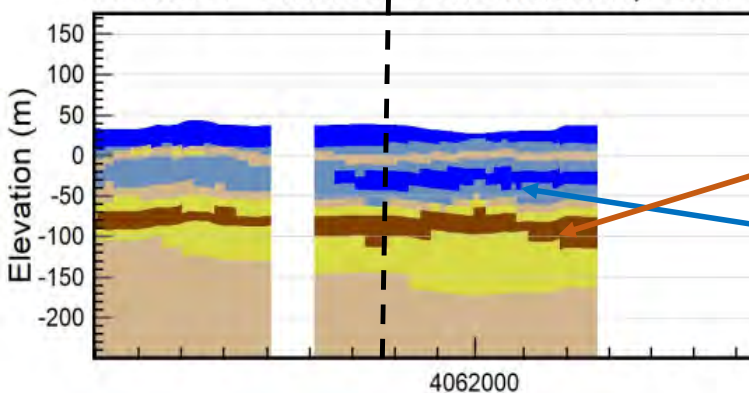
Flight Path MCWD May 2017



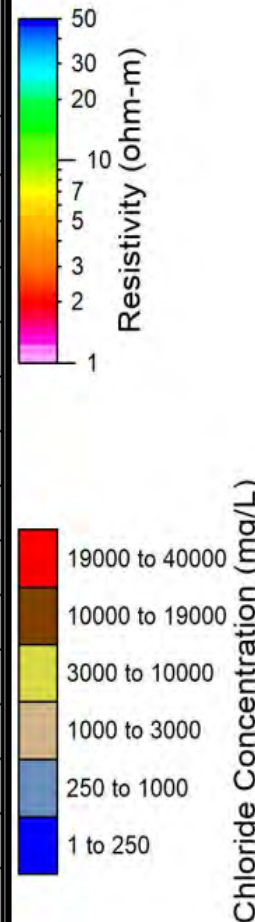
Profile 1 - Resistivity, Line 204001 >>>



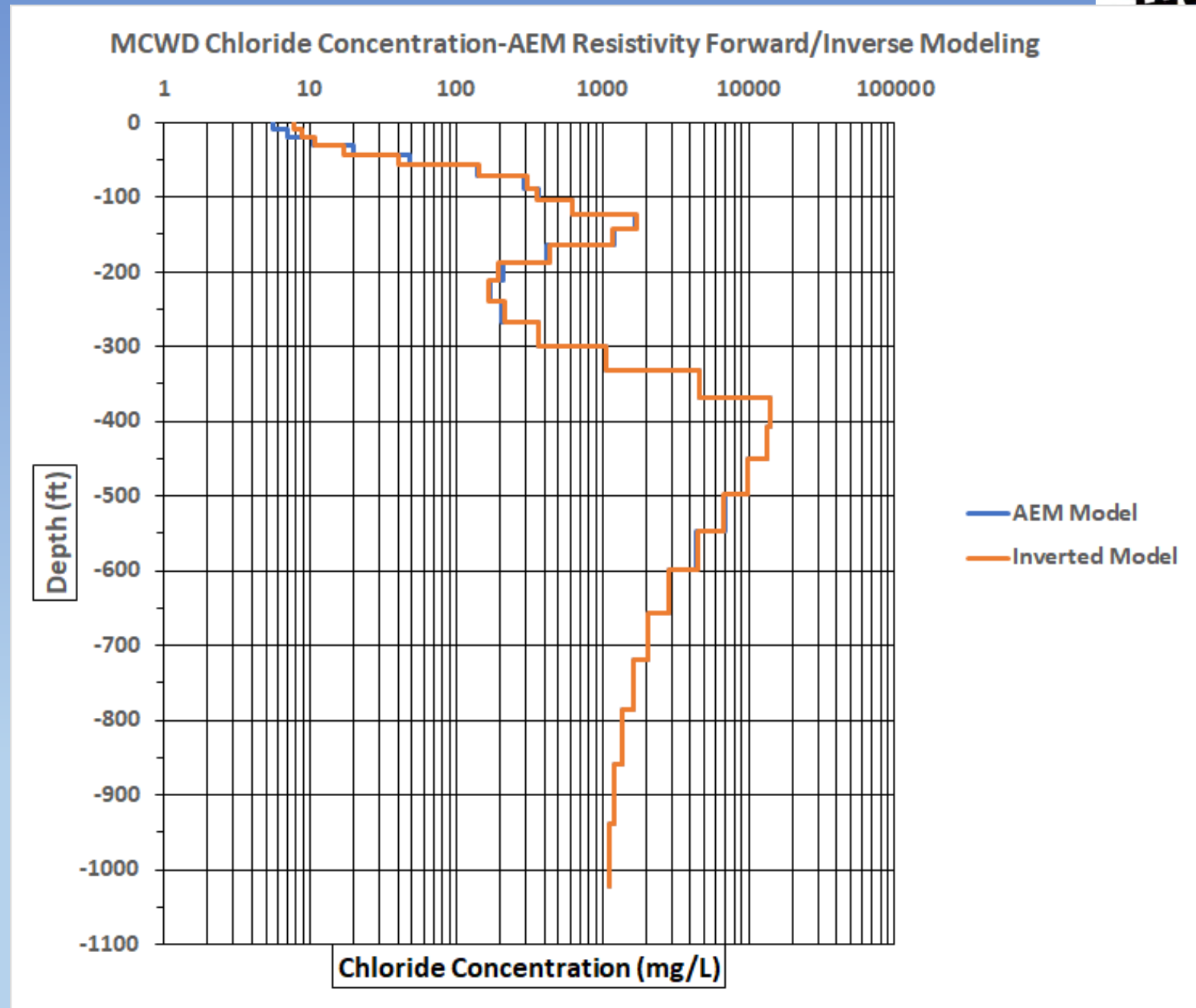
Profile 2 - Chloride Concentration, Line 204001 >>>



Layer	Depth (ft)	Resistivity (ohm-m)	Chloride Concentration (mg/L)	Layer	Depth (ft)	Resistivity (ohm-m)	Chloride Concentration (mg/L)
1	9.8	470	6	16	298.8	24.53	369
2	20.3	399.9	7	17	332.6	11.74	1052
3	31.8	300.1	11	18	369.0	4.14	4623
4	44.3	193.1	20	19	408.4	1.879	14198
5	57.7	102.8	48	20	450.7	1.964	13333
6	72.2	48.45	140	21	496.6	2.422	9900
7	87.9	28.89	293	22	546.1	3.143	6837
8	104.6	24.87	362	23	599.6	4.3	4380
9	123.0	16.98	623	24	657.3	5.784	2875
10	142.7	8.425	1685	25	719.6	7.328	2054
11	164.0	10.63	1211	26	786.9	8.693	1612
12	187.0	22.68	413	27	859.7	9.781	1363
13	211.9	36.52	210	28	938.4	10.63	1211
14	238.8	42.27	170	29	1023.4	11.28	1113
15	267.6	37	206				



Forward/Inverse
Original Model
Sounding





Forward/Inverse
Original Model
Sounding

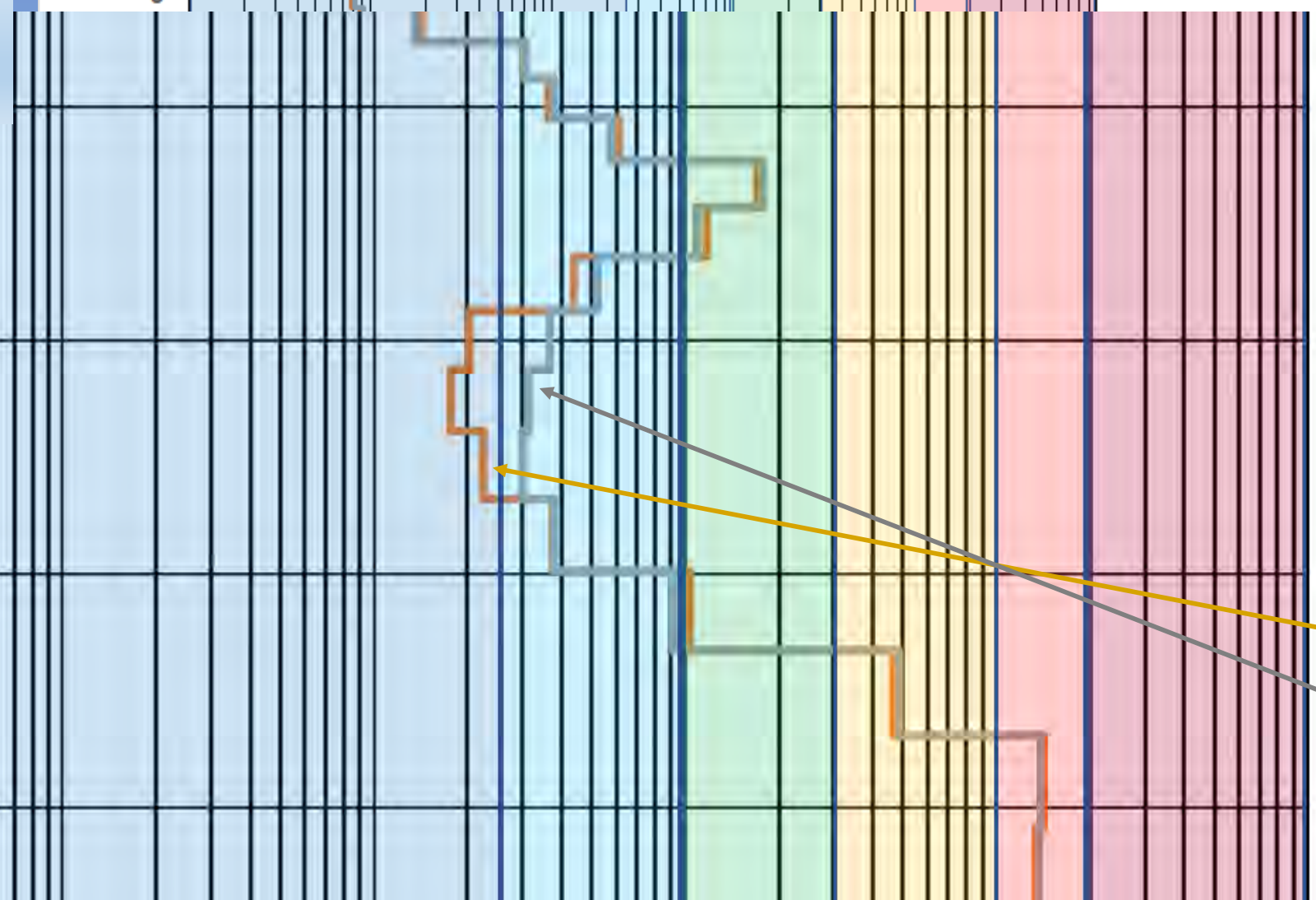
MCWD Chloride Concentration AEM Resistivity Forward/Inverse Modeling

1 10 100 1000 10000 100000

Modeling:
200 mg/L
400 mg/L

Depth (ft)

-300
-400
-700



200 mg/L
400 mg/L

Chloride Concentration (mg/L)

10,000-15,000
19,000+



Forward/Inverse
Original Model
Sounding

MCWD Chloride Concentration AEM Resistivity Forward/Inverse Modeling

1 10 100 1000 10000 100000

Modeling:
800 mg/L
1,000 mg/L
1,200 mg/L

Depth (ft)

-400

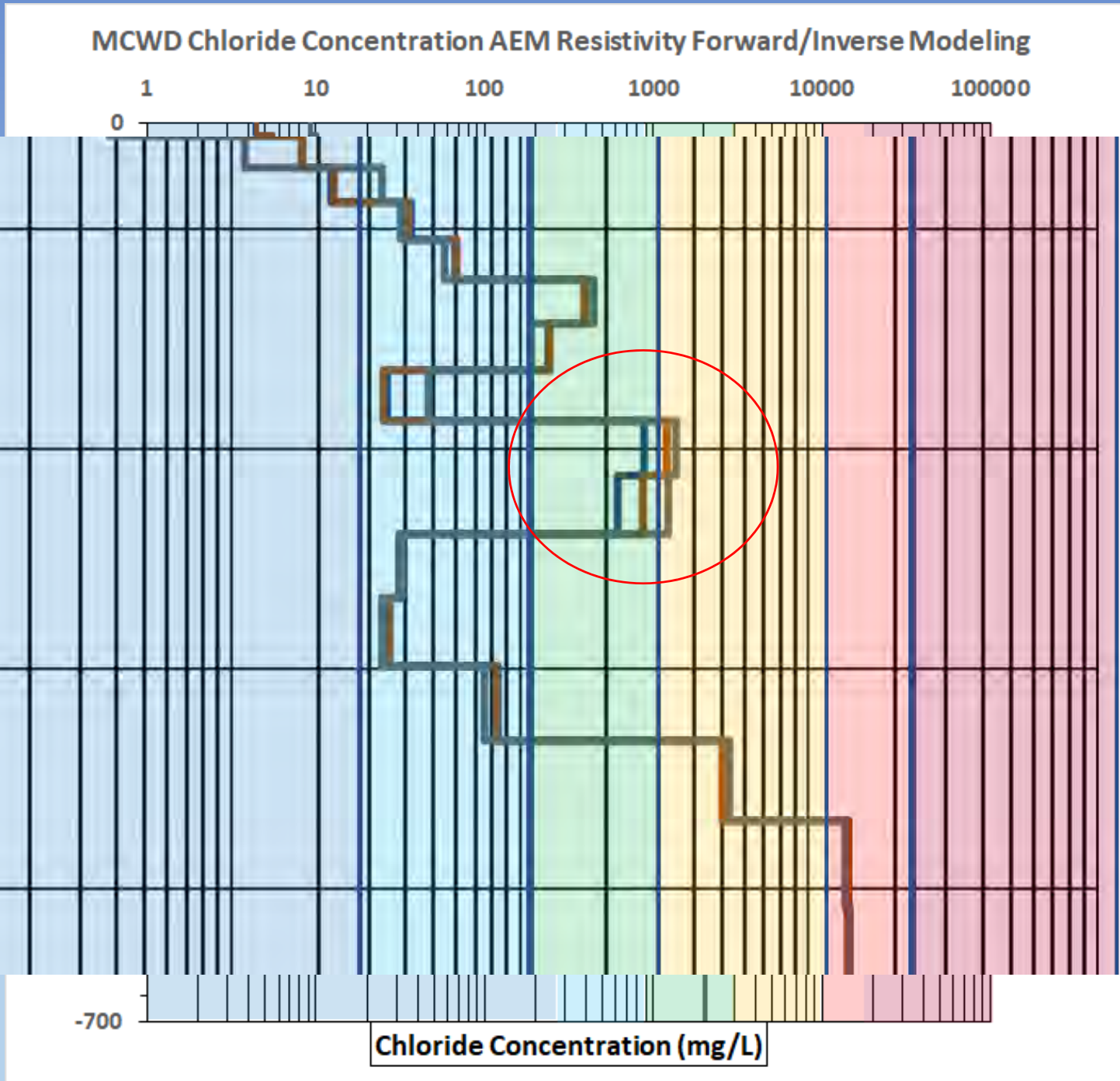
-700

Chloride Concentration (mg/L)

- 800 mg/L
- 1000 mg/L
- 1200 mg/L



Forward/Inverse
Original Model
Sounding



Modeling:
2,500 mg/L
3,000 mg/L
3,500 mg/L

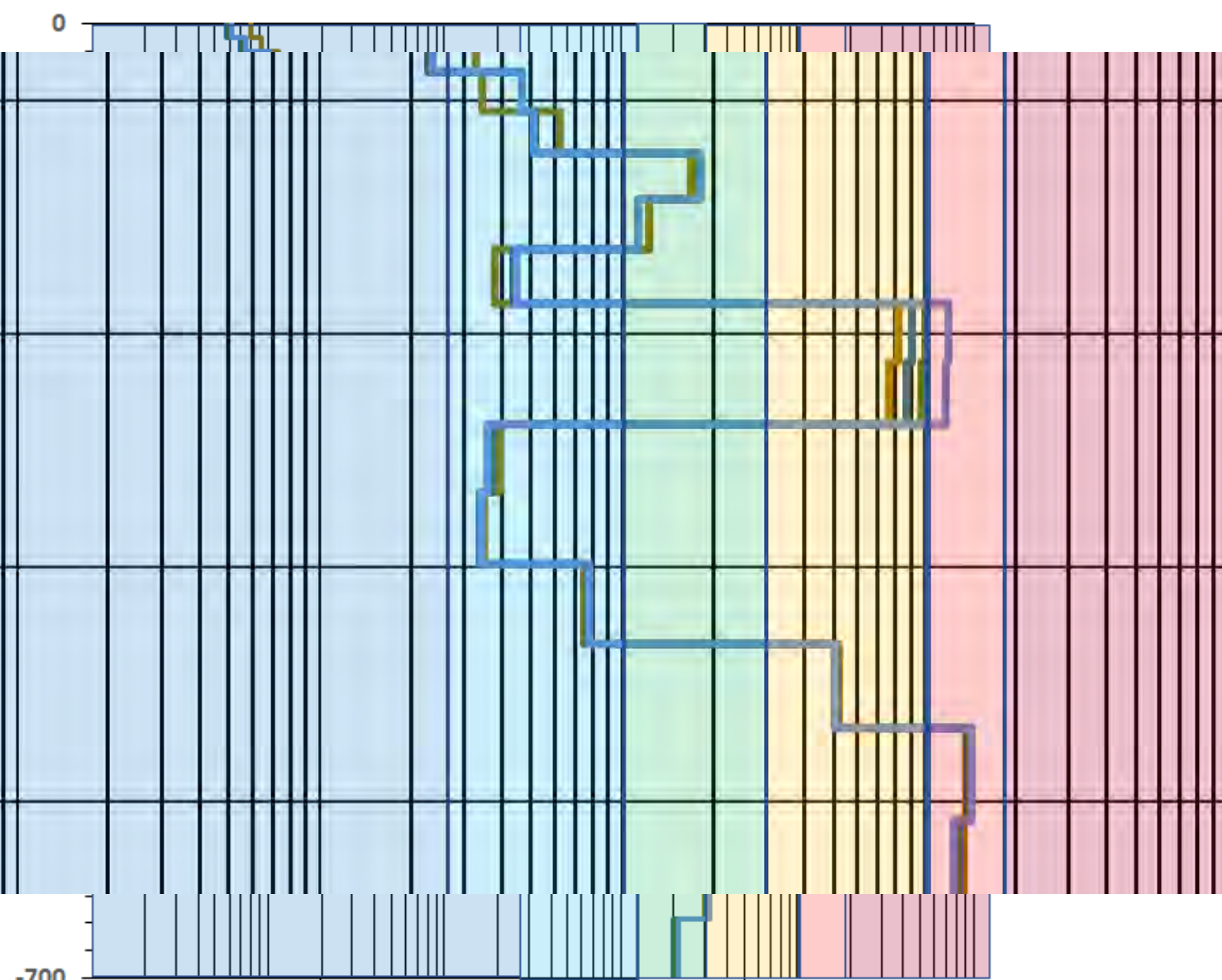
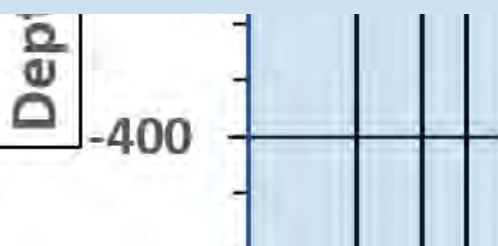


Forward/Inverse Original Model Sounding

MCWD Chloride Concentration AEM Resistivity Forward/Inverse Modeling

1 10 100 1000 10000 100000

Modeling:
8000 mg/L
9,000 mg/L
10,000 mg/L
12,000 mg/L



-700

Chloride Concentration (mg/L)

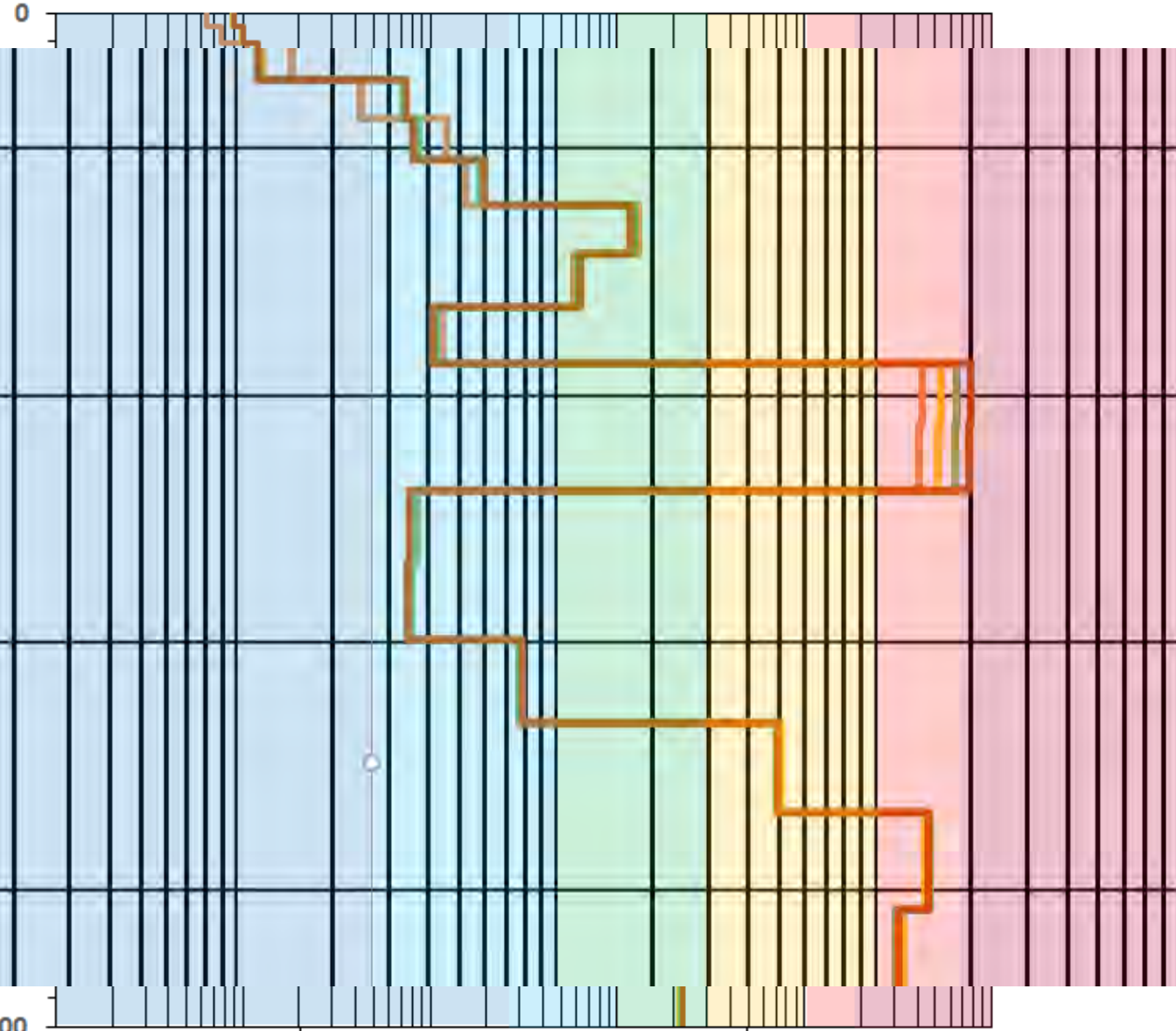
- 8000 mg/L
- 9000 mg/L
- 10000 mg/L
- 12000 mg/L



Forward/Inverse
Original Model
Sounding

MCWD Chloride Concentration AEM Resistivity Forward/Inverse Modeling

1 10 100 1000 10000 100000



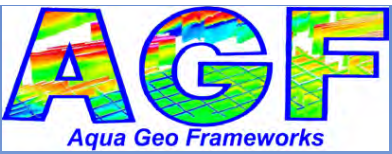
Modeling:
14,000 mg/L
16,000 mg/L
18,000 mg/L
20,000 mg/L

- 14000 mg/L
- 16000 mg/L
- 18000 mg/L
- 20000 mg/L

Depth
-400

-700

Chloride Concentration (mg/L)



Summary

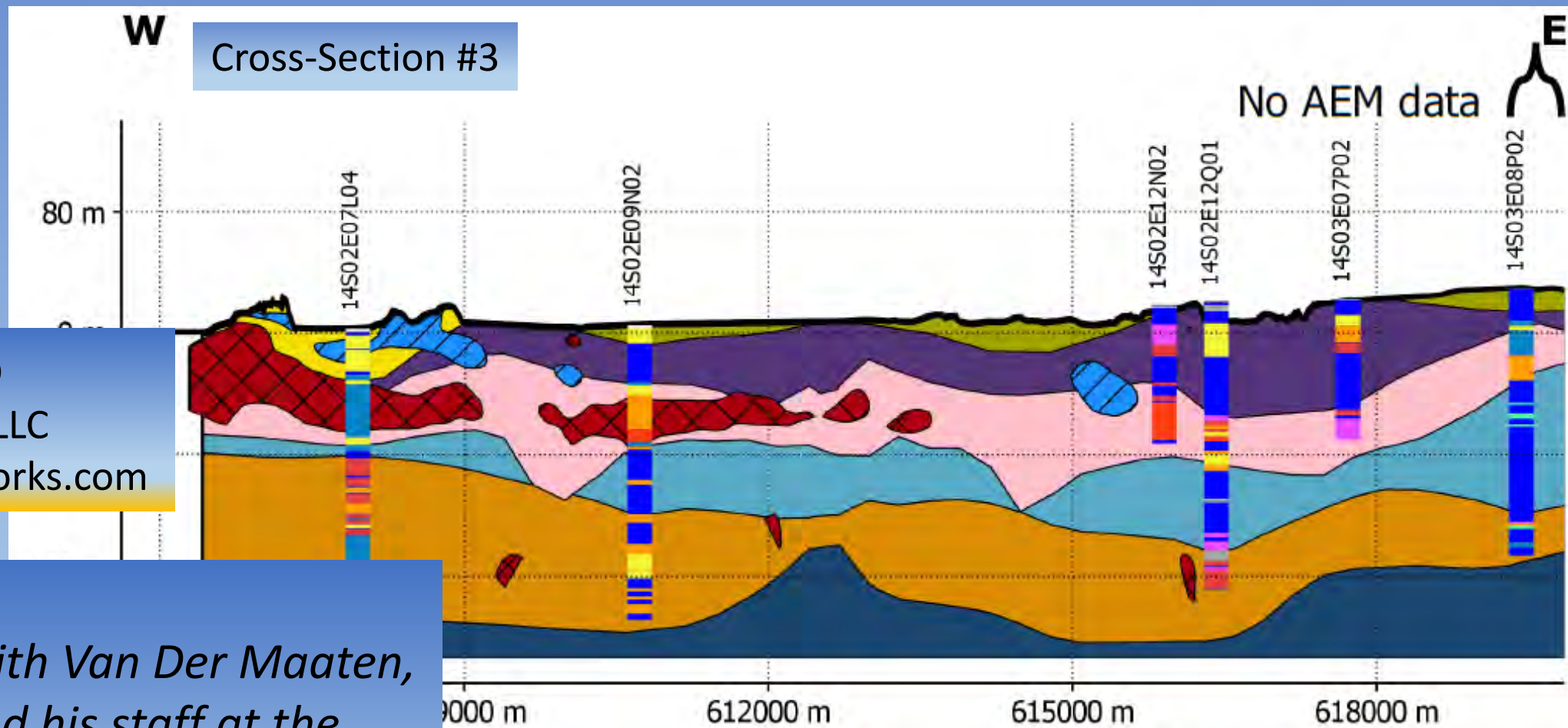
1. 635 line-kilometers of airborne time-domain acquired in the heavy-infrastructure environment of the MCWD.
2. The AEM data were processed, edited, and inverted with LCI and SCI inversions and the results were examined and studied as 2D and 3D profile sections, fence diagrams, and voxels.
3. Correlation was made between the AEM-inverted resistivity and local lithology based on inversion results, known local geology, and borehole logs.
4. Correlation was also made between AEM-inverted resistivities and chloride concentrations
5. The investigation objectives of mapping the hydrostratigraphy of the investigation area, determining locations of gaps in the 180/400-Foot Aquitard, and identifying zones of drinking water and saltwater intrusion have been achieved.
6. Forward/Inverse modeling demonstrates resolution of the AEM technique for mapping zones of various chloride concentrations.

Questions?
Comments?

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Marina Coast
Water District

