The Perfect Conductor (PerC)
Some fundamental issues

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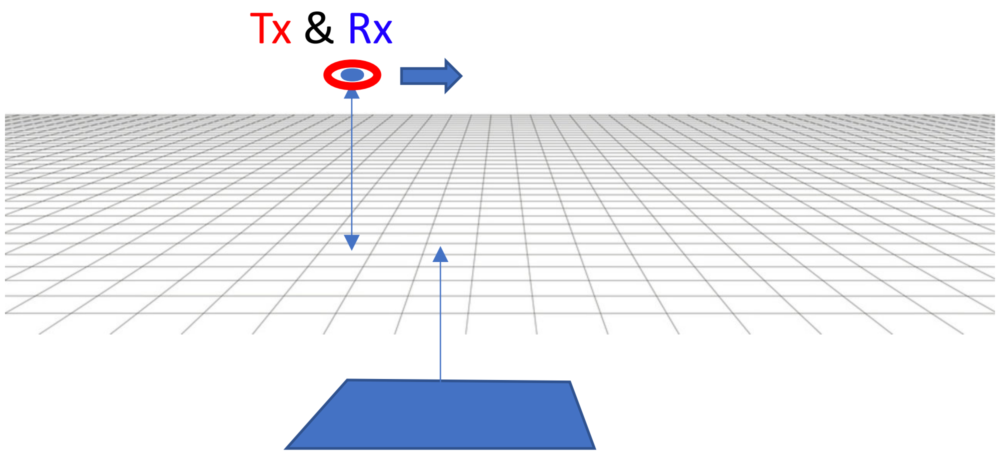
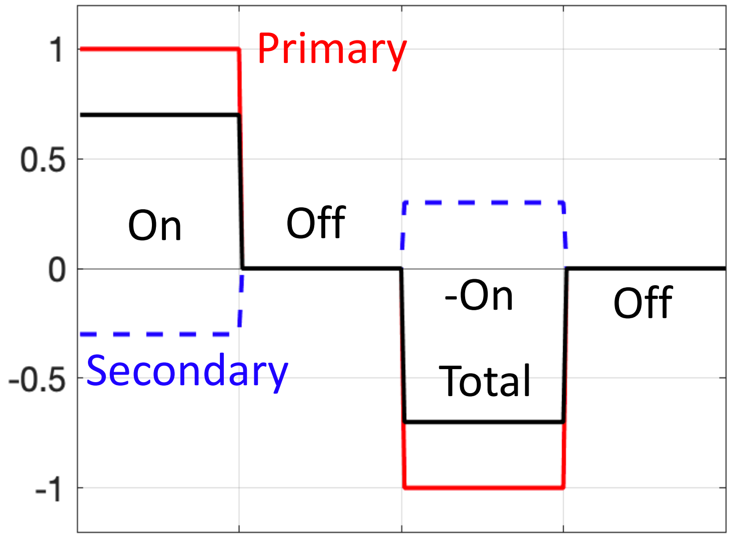
RMIT UNIVERSITY

Method 1: Use “on-time” to detect Perfect Conductor (PerC)

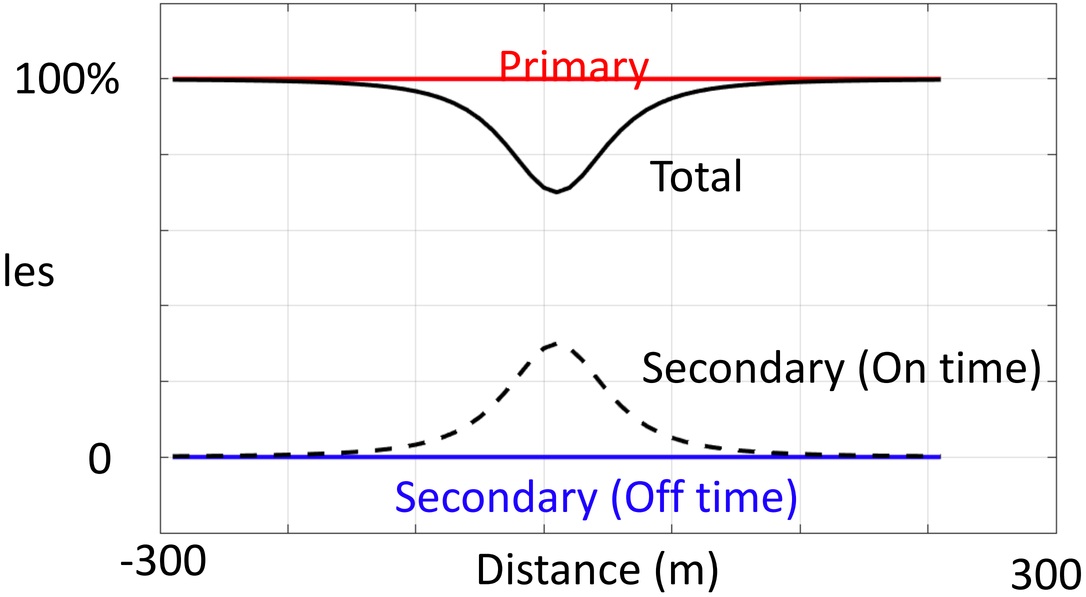




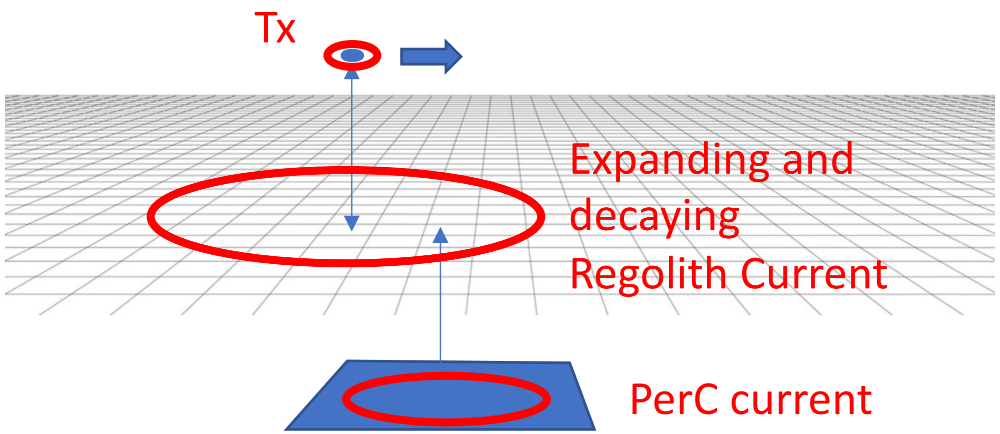
Waveform

PerC sees primary of Tx
Current induced in PerC with exactly same waveform as primary
Rx sees currents in PerC in on-time only

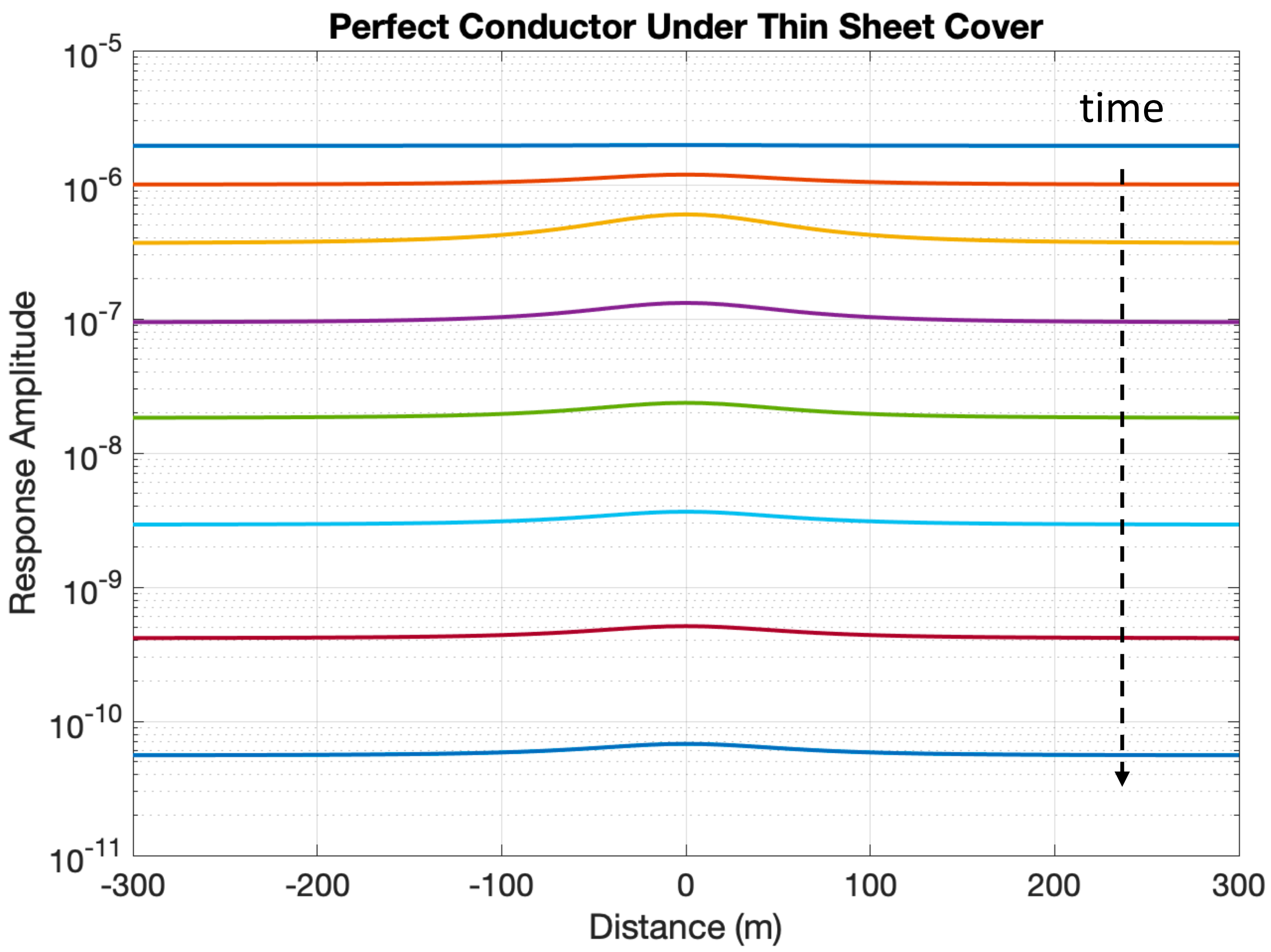
Profiles



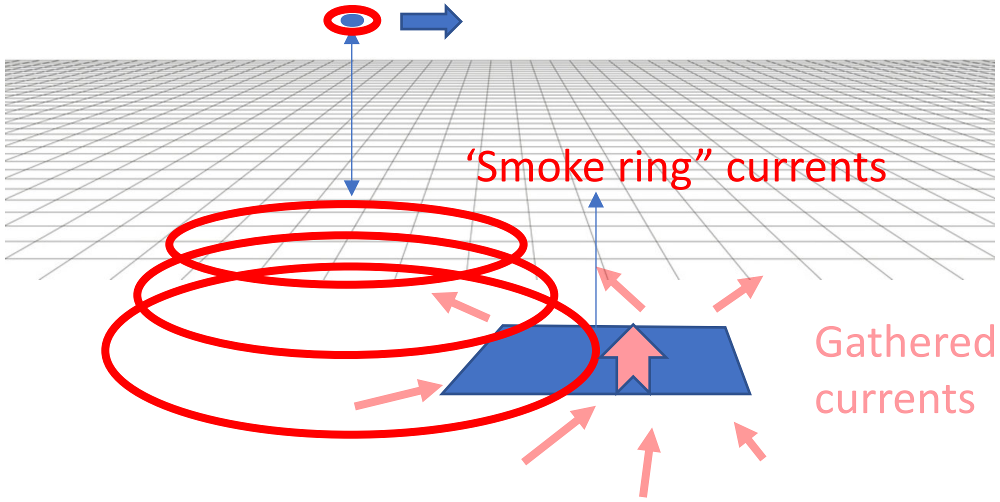
Method 2 (on or off-time): Hide PerC under conductive overburden (alas not discriminatory)



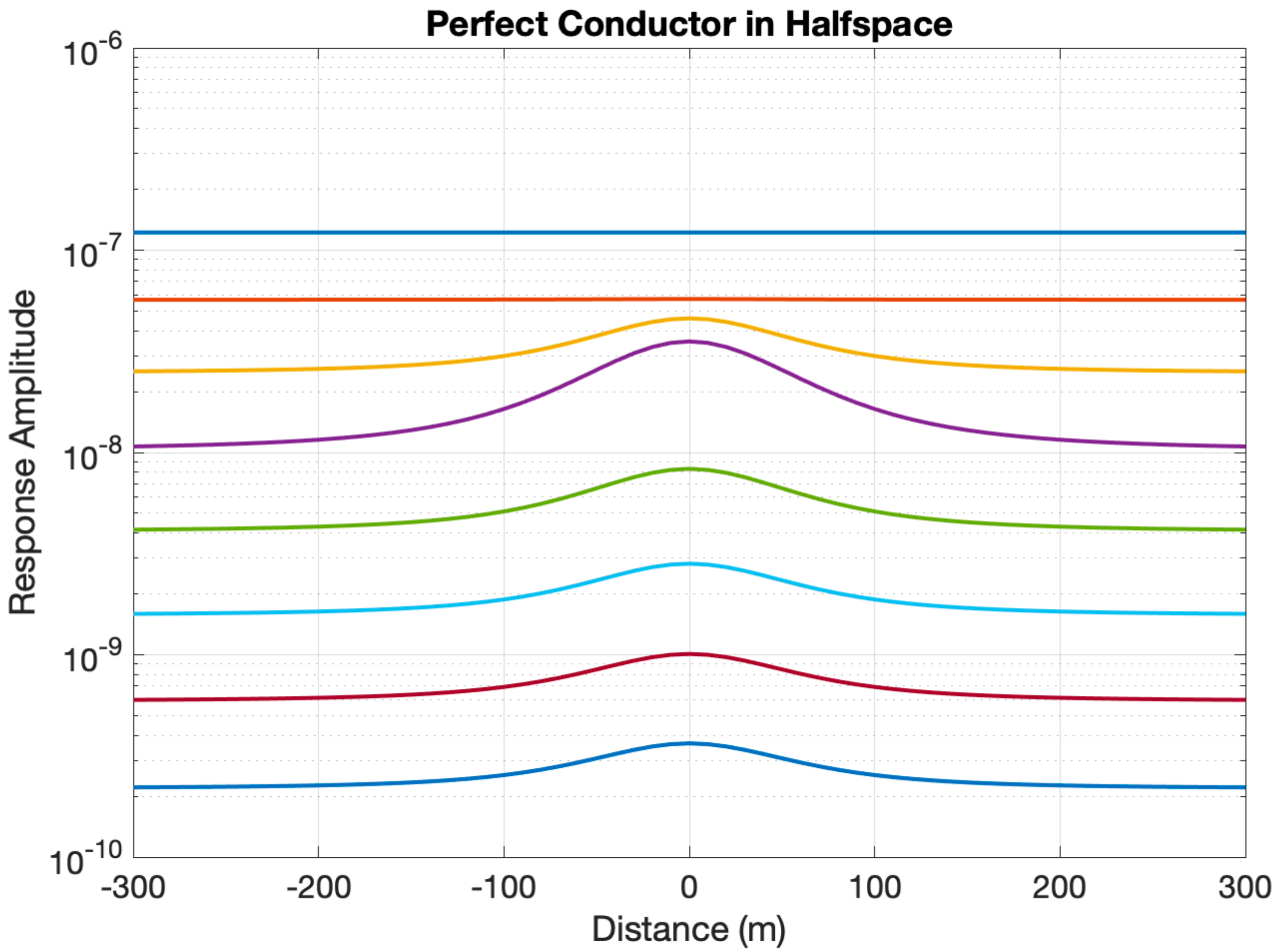
PerC sees delayed primary of Tx under conductive overburden
Current induced in PerC with “background response” waveform
Rx sees overburden plus field of the (further delayed) currents in PerC



Method 3 (on or off-time) : Bury PerC in a conductive horizon. Get current gathering (still not discriminatory)



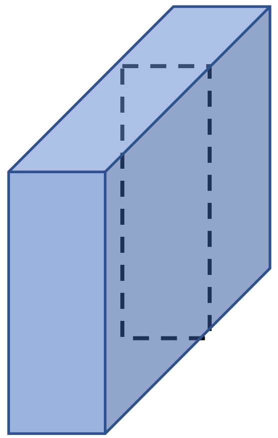
PerC sees delayed primary of Tx
Current gathered into PerC with background response waveform
Rx sees background plus (time-delayed) field of gathered currents in PerC
Bigger response than in method 2.

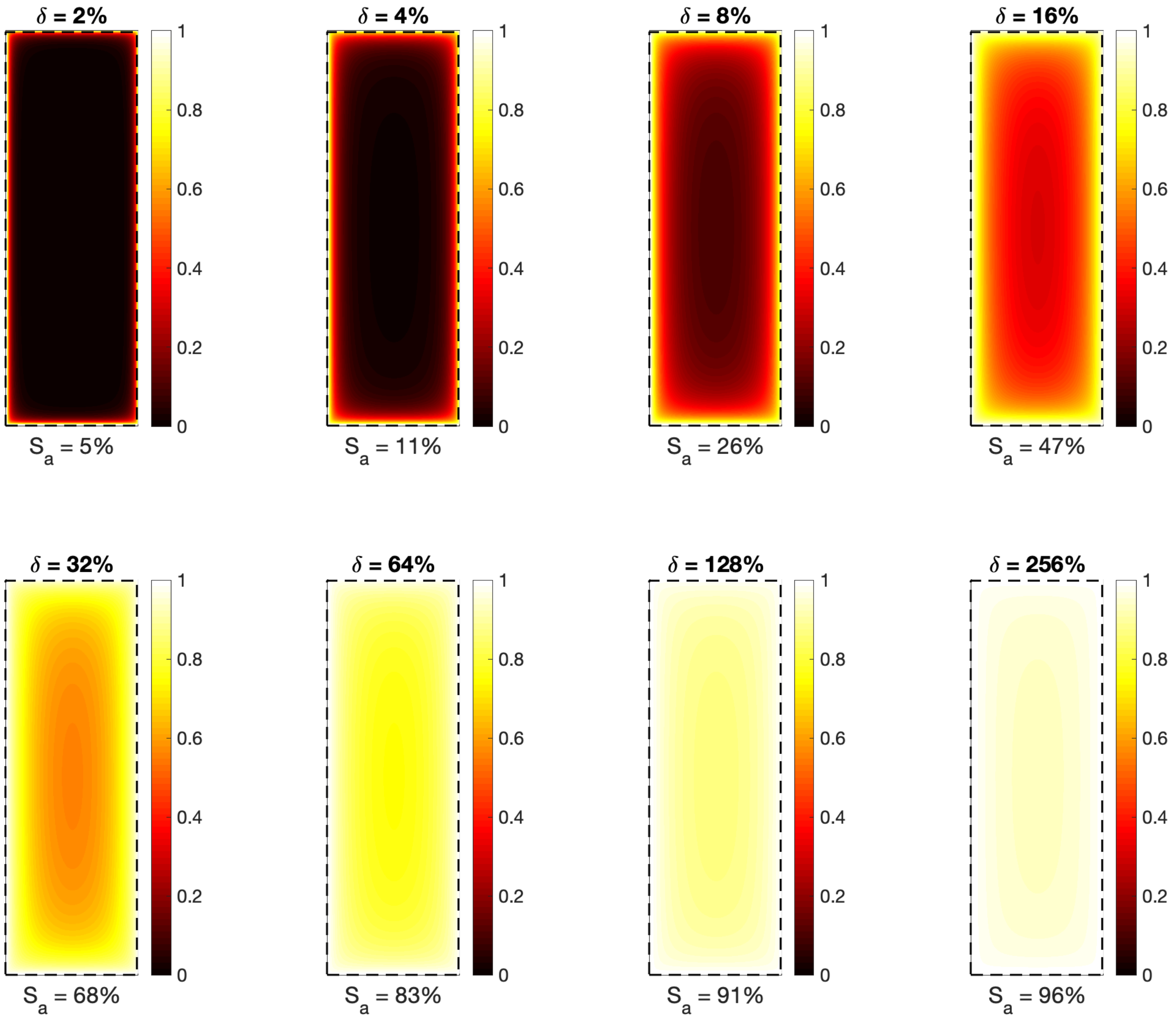


Method 4: Use “Inductive Thickness” for almost PerC

- Other than inside SQUID sensors, there are no perfect conductors in the field.
- Often use Conductance S to describe conductors S = product of conductivity and thickness for targets
- Any geological conductor has finite conductivity
  - Seawater, 5 S/m, Conductance at Marianas trench is 50,000 S
    - **Geometrically thick** since 10 km “thick” (deep) >> survey dimensions
    - **Inductively thick** since skin depth << sea depth at typical survey frequencies
  - 0.5 m wide seam of Pyrrhotite of 100,000 S/m also has conductance 50,000 S.
    - **Geometrically thin** since width << survey dimensions
    - **Inductively thick** since skin depth << width at typical survey frequencies

Skin depth $\boldsymbol{\delta} = \sqrt{(2/\sigma\mu\omega)}$ = 1.6 cm at 10 kHz, 16 cm at 100 Hz and 1.6 m at 1 Hz





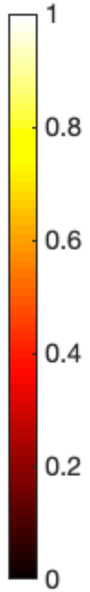
100000 S/m
F = 1 Hz, δ = 1.6 m

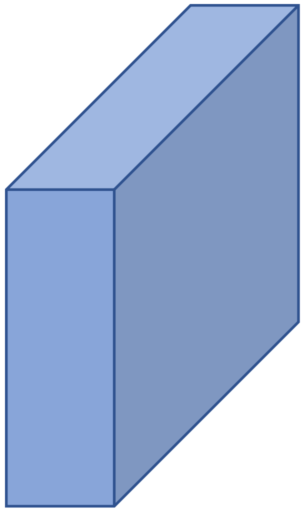
If 10 m wide. Then estimated conductance <50% of true value

Penetration of field into tabular conductor as a function of skin-depth δ shown as a percentage of the conductor width

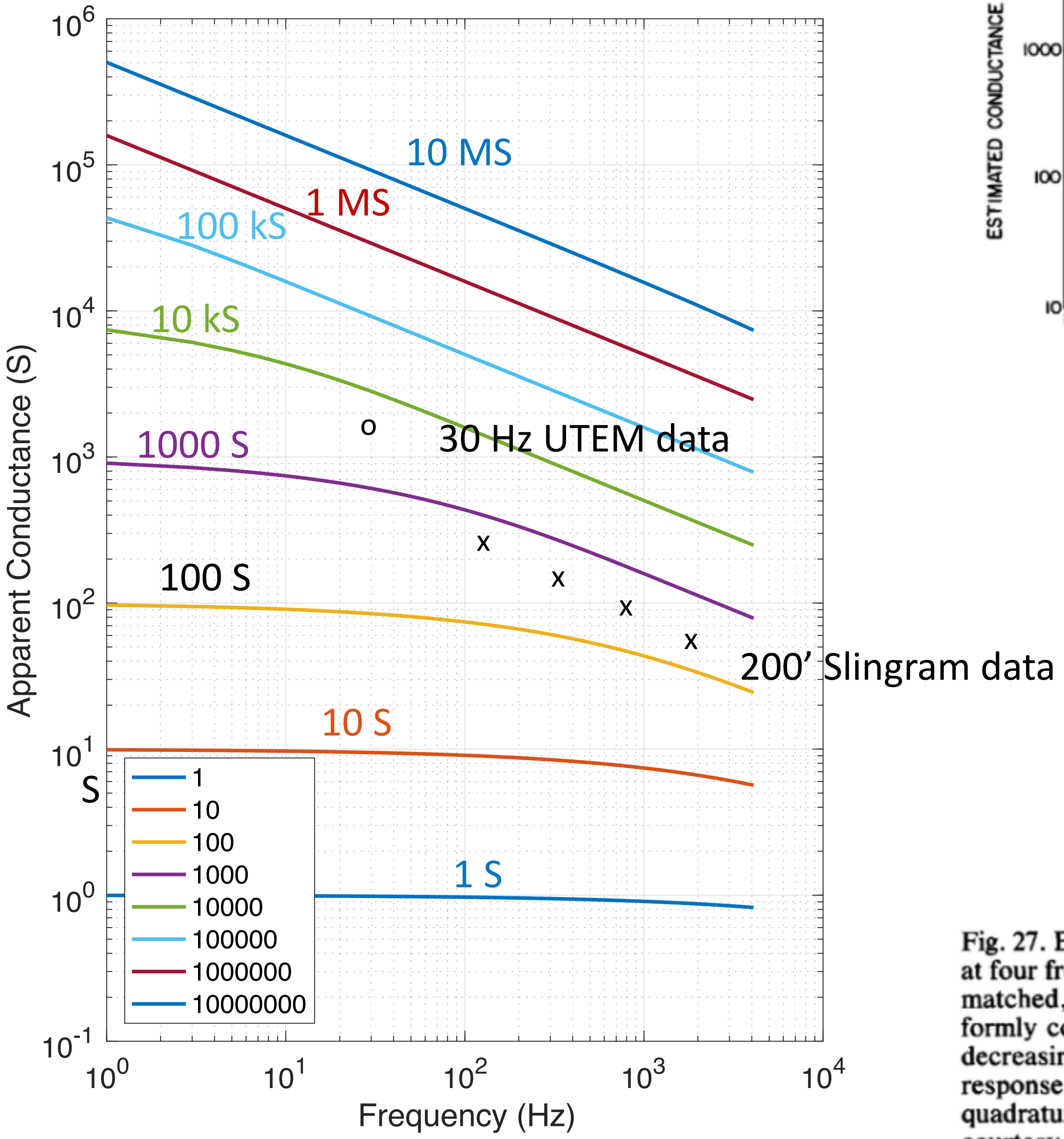
Effective conductance S_a as percentage of true conductance

Amplitude Fraction

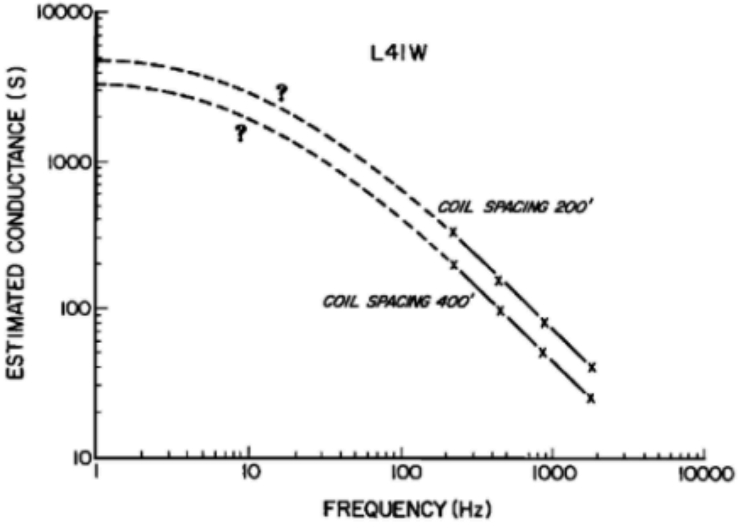




Frequency domain apparent conductance S_a



$S_a = \alpha/(\mu\omega\ell)$



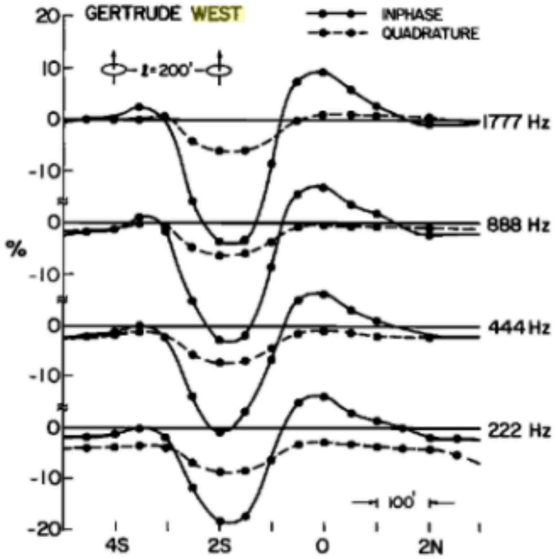
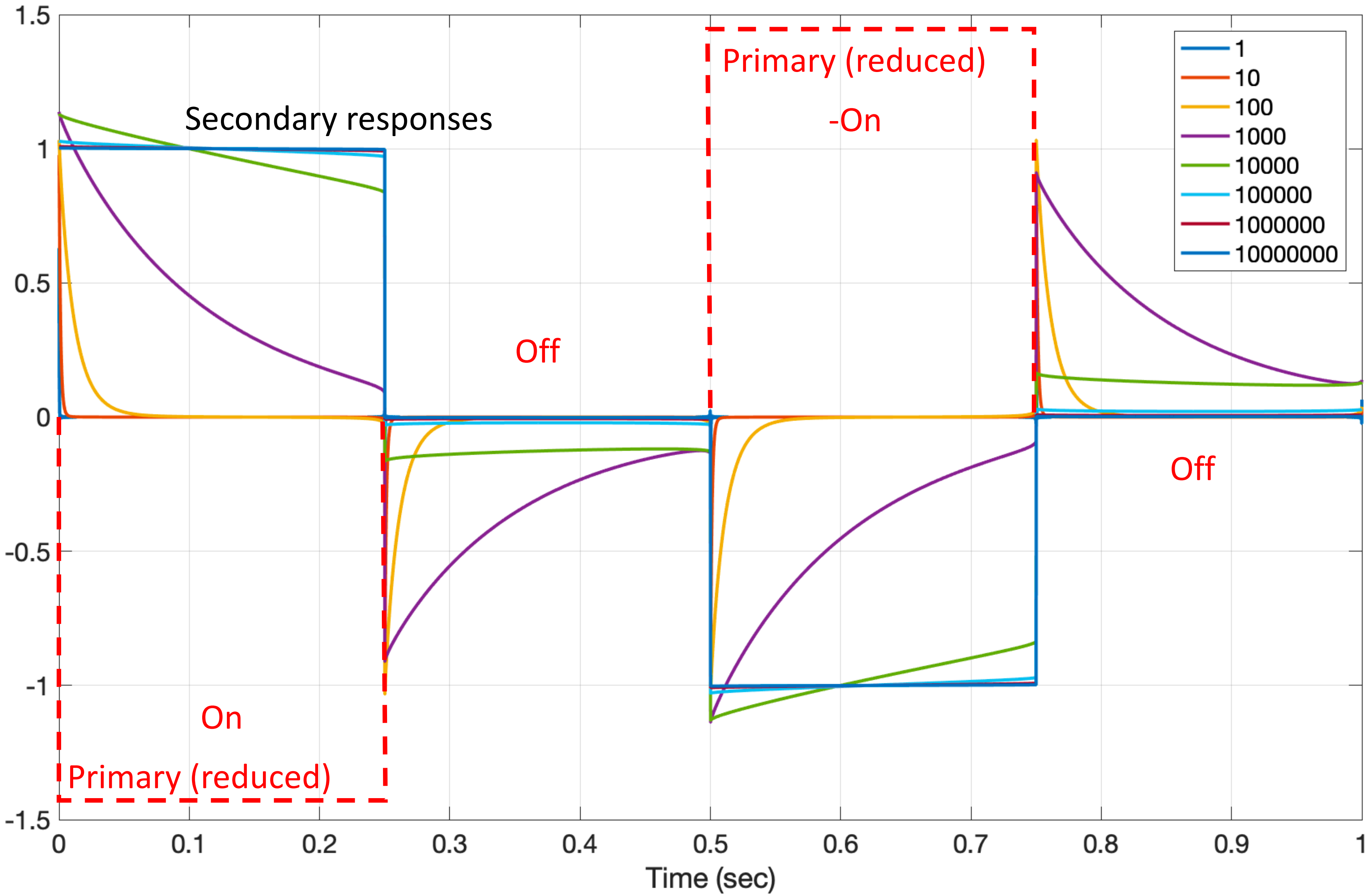


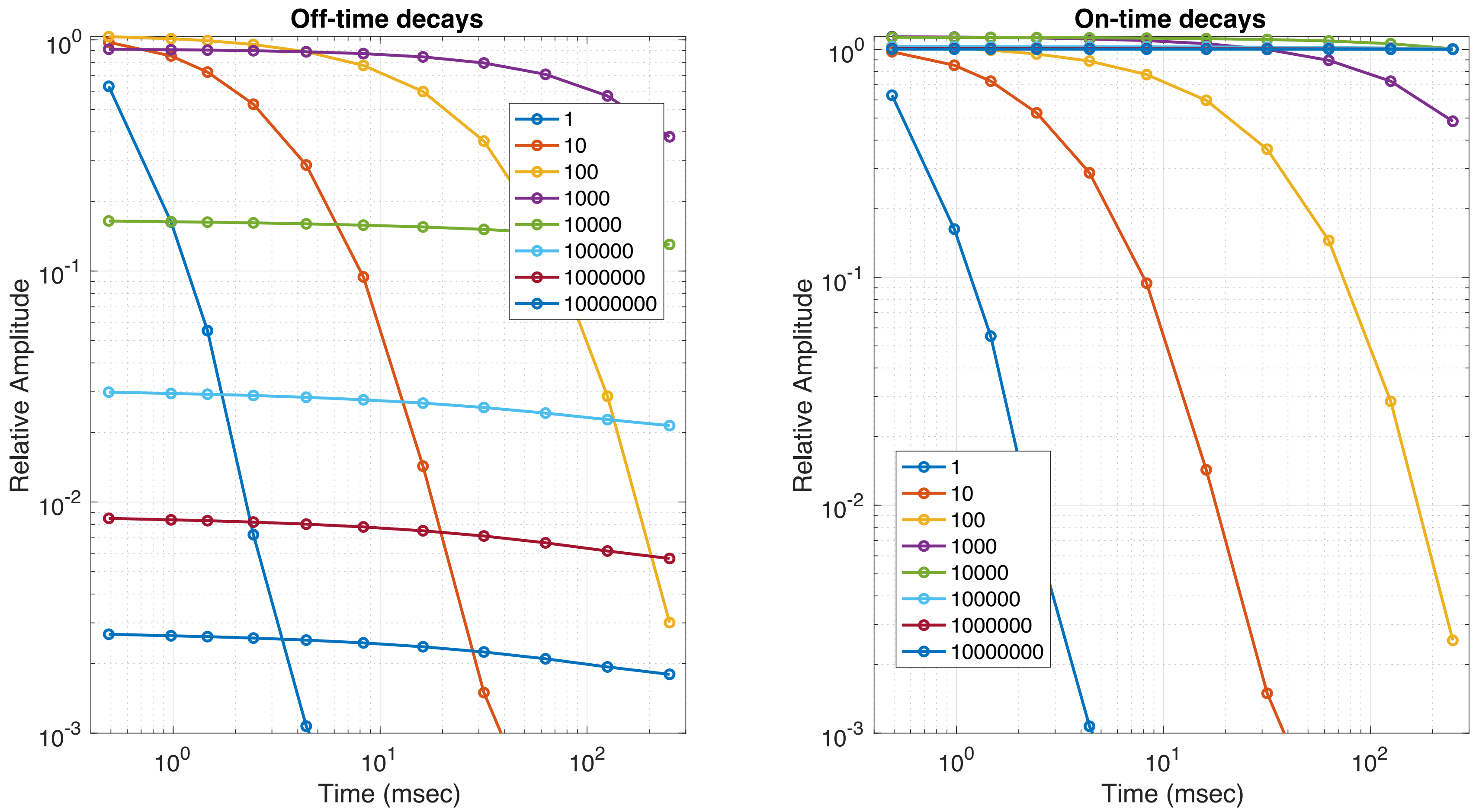
Fig. 27. EM response observed over a massive sulphide zone at four frequencies. When the observed spectral response is matched, frequency by frequency, with any simple uniformly conductive model, the fitted conductivity rises with decreasing frequency. The effect is large unless the induced response is in the resistive limit, i.e., the ratio of in-phase to quadrature response is well below one (HLEM data by courtesy of J. Betz and INCO Limited).

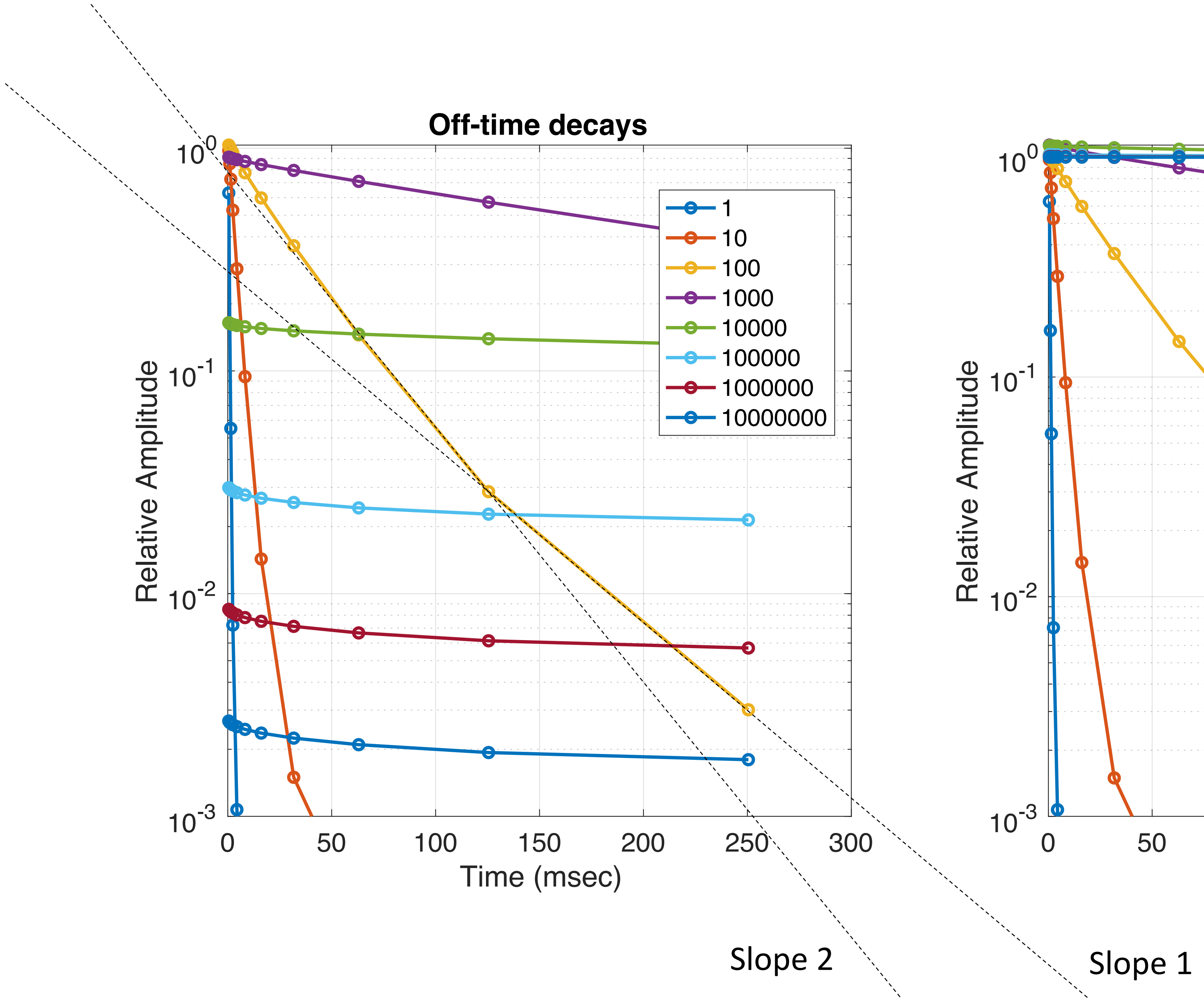
1 Hz 50% duty cycle plane wave, B field

Variable Thin Sheet Conductance (S)



Secondary field decays; Inductively thick target in free space, 1 Hz system





Off-time decays
Relative Amplitude
Time (msec)
1
10
100
1000
10000
100000
1000000
10000000
On-time decays
Relative Amplitude
Time (msec)
1
10
100
1000
10000
100000
1000000
10000000
Slope 2
Slope 1

Summary, 10 m wide conductor, 100 m characteristic system geometry, 1 Hz

Conductor	Predicted S Off-time	True S	Predicted S On-time	Conductor
Weak	1	1	1	Weak
Medium	7	10	7	Medium
Good	55	100	55	Good
Excellent	307	1 000	307	Excellent
Perfect	1 820	10 000	2 444	Superb
Perfect	2 097	100 000	13 803	Amazing
Perfect	1 674	1 000 000	49 535	Astounding
Perfect	1 695	10 000 000	156 250	Astonishing

The UNDERESTIMATE of Conductance S was predicted from the last 2 channels above (numerical) noise

Inductive Thickness Symptoms (B field) to detect almost PerC's in free space

- Longest tau estimated from data similar to base period (e.g. 1 sec at 1 Hz)
- Estimated tau increases with delay time (double delay time, empirically increase tau by 1.4 to 2), better in on-time (if Tx stable enough or monitored)
- Double Base frequency… estimate 0.5 to 0.7 of the tau value (or 0.5 to 0.7 of the conductance in frequency domain)
- There is a limit on how conductive PerC's appear to be using off-time data.
- On-time MUCH better than off-time even if geometry uncertain, available from streaming receivers but need current monitor

Effect of cover / conductive host on PerC detection

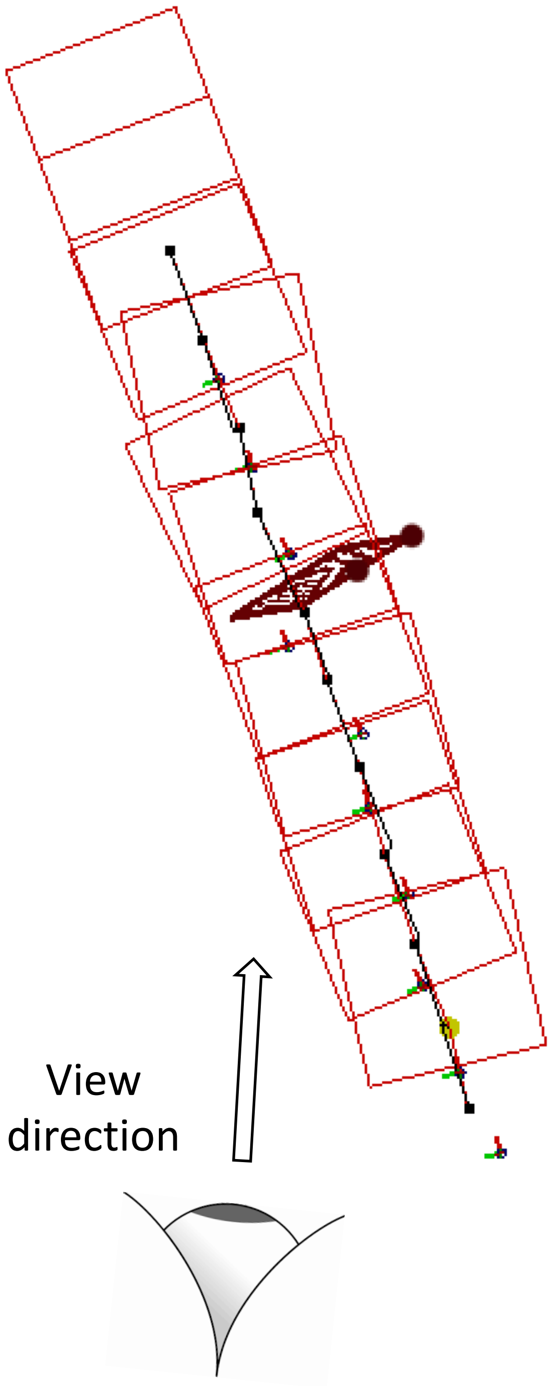
- No time to discuss, example to follow
- Need to minimise deleterious effects in survey design (e.g. use small Tx loops when conductive overburden present)

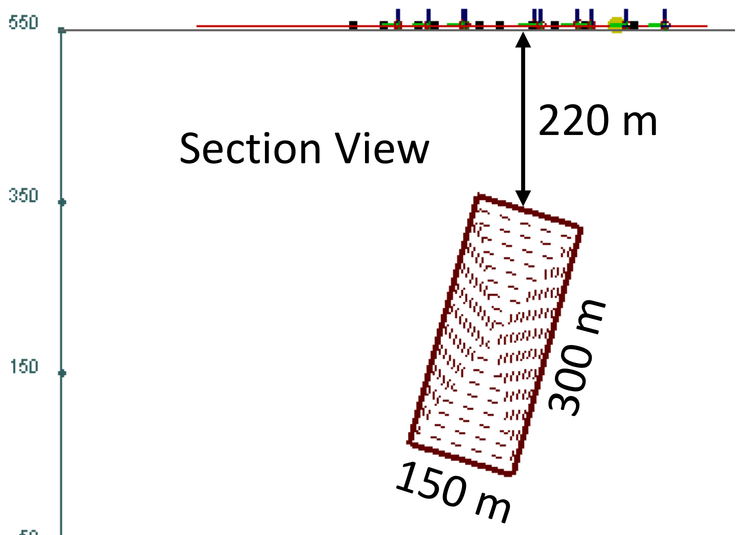
Can we use dB/dt???

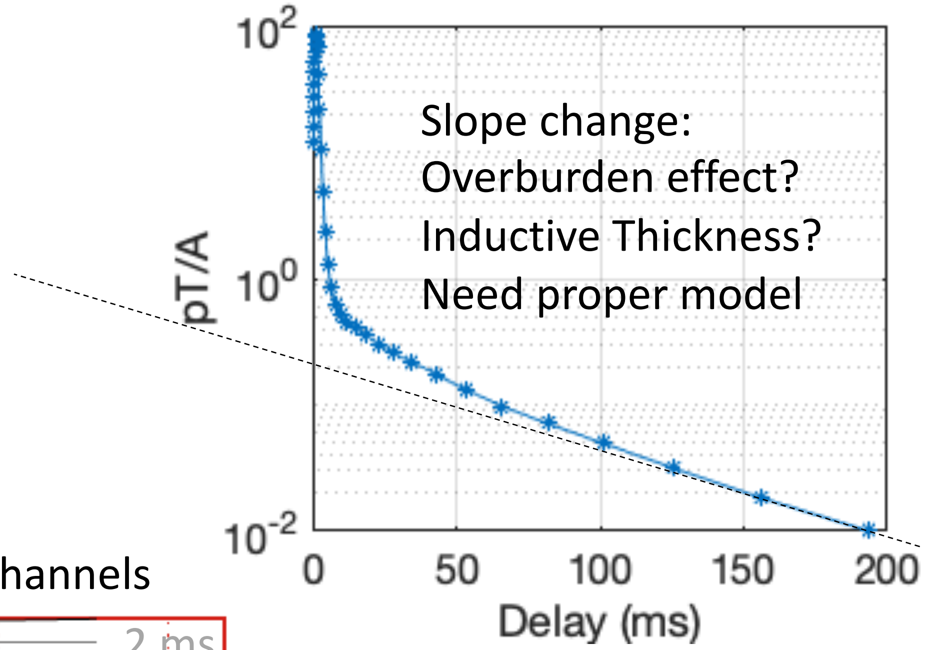
- dB/dt on time can be used with streaming receiver, but not nearly as good as B
- Off time basically forget it… inductive thickness and/or other conductors in vicinity energise non-discriminatory response
- Best case: May detect associated halo sulphides / alteration nearby??

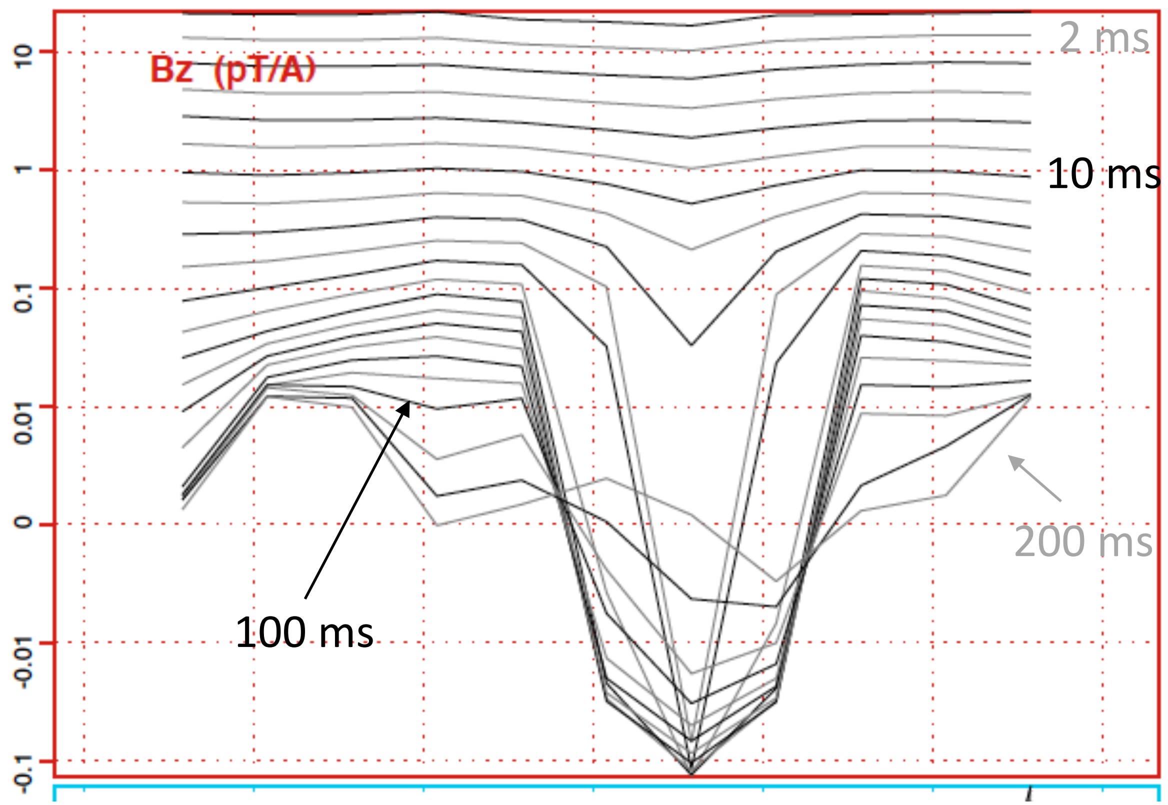
ARMIT field example

Courtesy of Newexco and Sandfire









NEWEXCO
GEOLOGY GEOPHYSICS DISCOVERY

ARMIT v4 sensor
1.04 Hz Base Frequency
150 A current into
300 by 300 m loops
300 m Slingram geometry
Predicted S = 2000 S
220 m deep pyrrhotite
target confirmed by
drilling & DHEM

Acknowledgements

Nick Ebner
BCGS / EMinar

NEWEXCO
GEOLOGY GEOPHYSICS DISCOVERY

Data

SANDFIRE RESOURCES NL

RMIT UNIVERSITY

ABITIBI GEOPHYSICS

ARMIT development

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TDEM

Hits and Misses

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Hits and Misses

1 Physical Properties

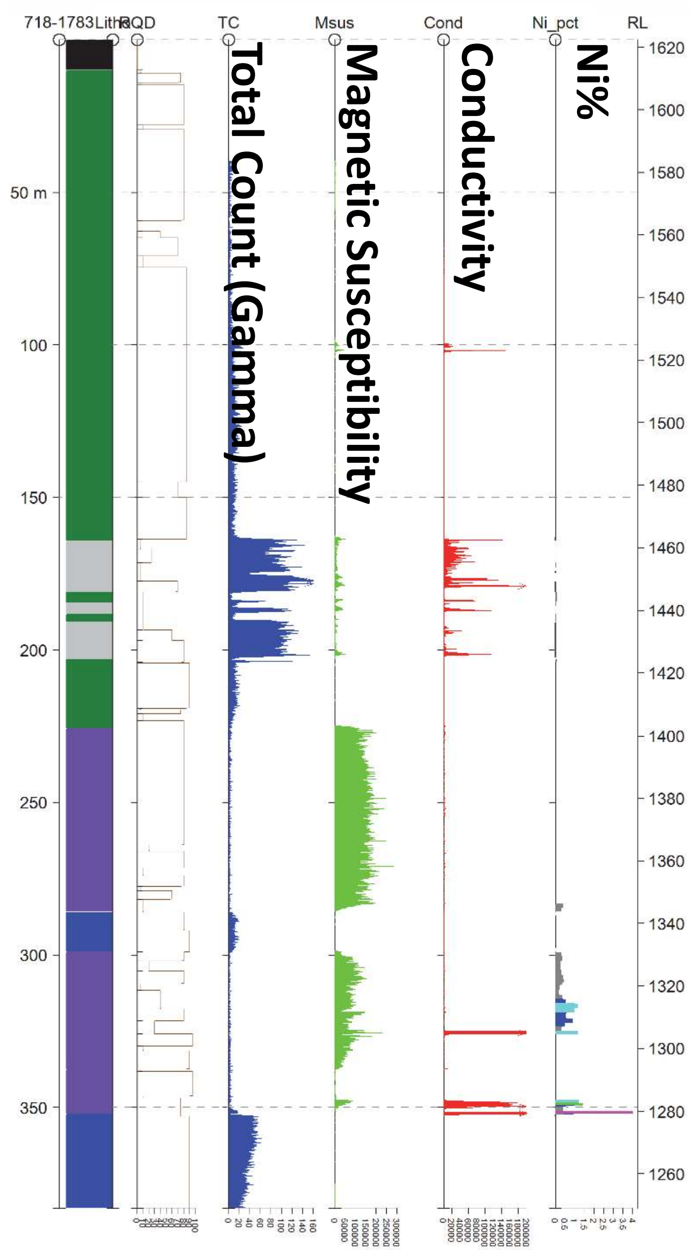
2 Airborne Surveys

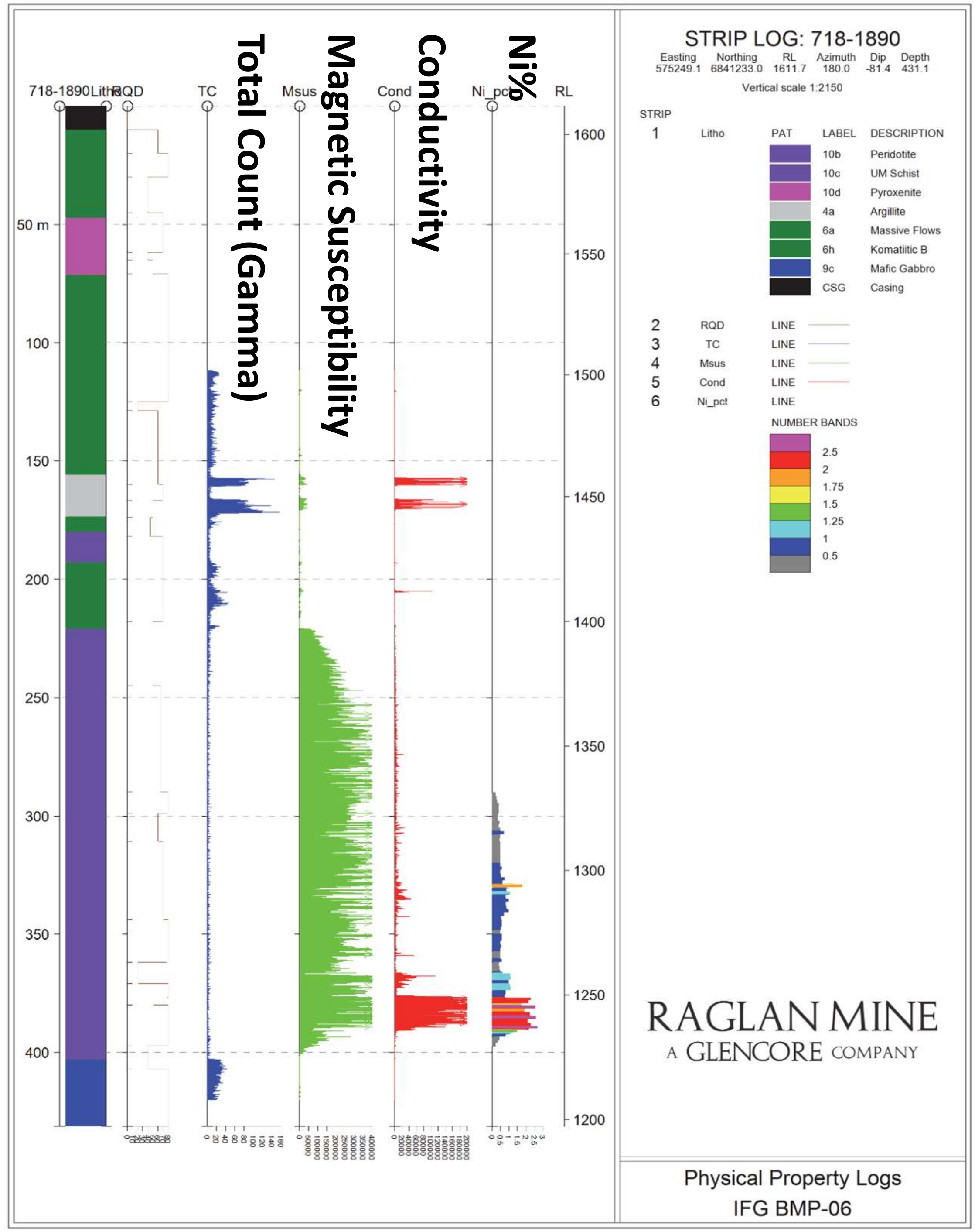
3 Ground Surveys

4 Boreholes Surveys

5 Conclusions

1 Physical Properties





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KT-10 Magnetic Susceptibility and Conductivity Meters

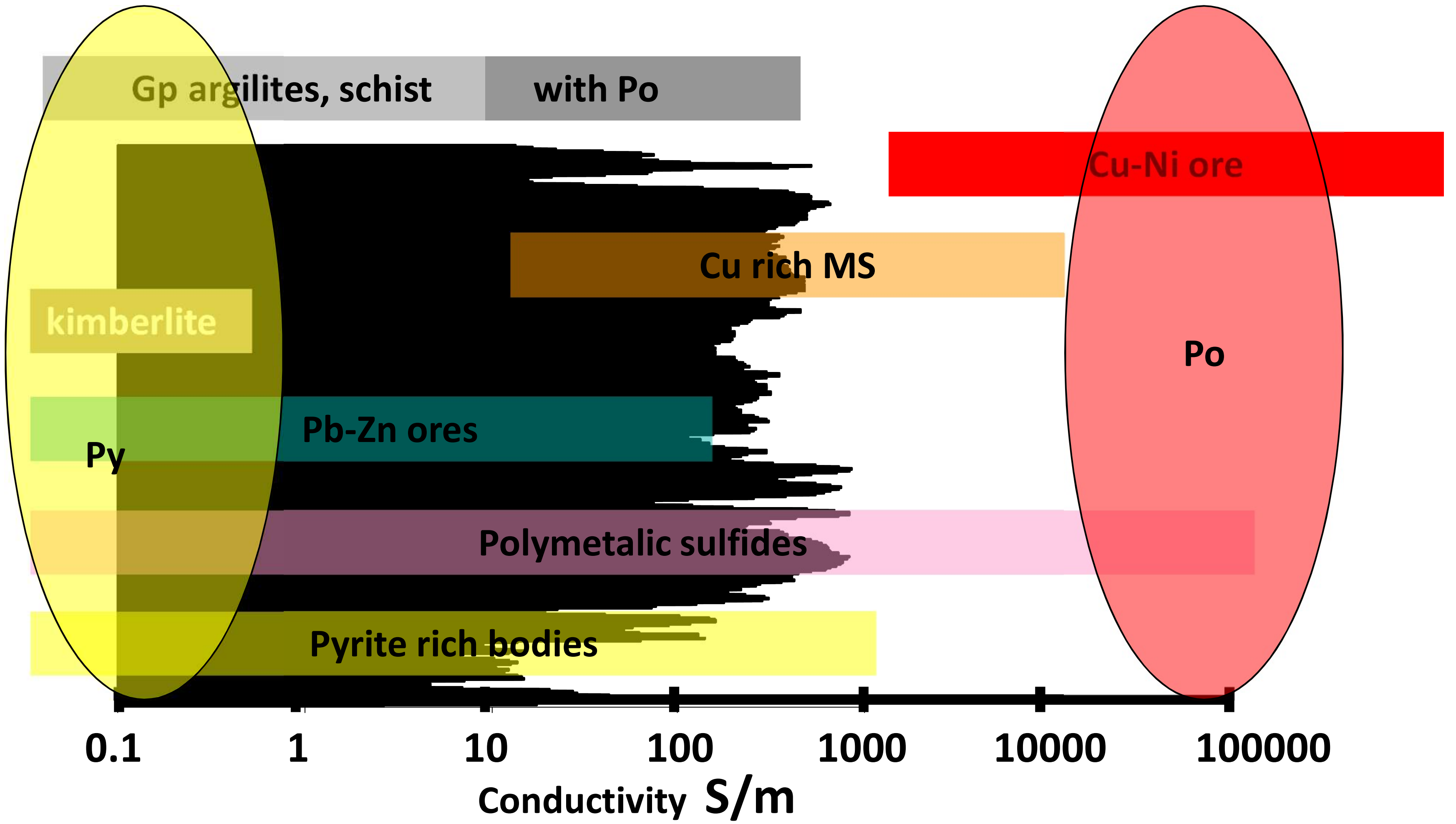
Magnetic Susceptibility Meters · Conductivity Meters · Combined Magnetic Susceptibility/Conductivity Meters

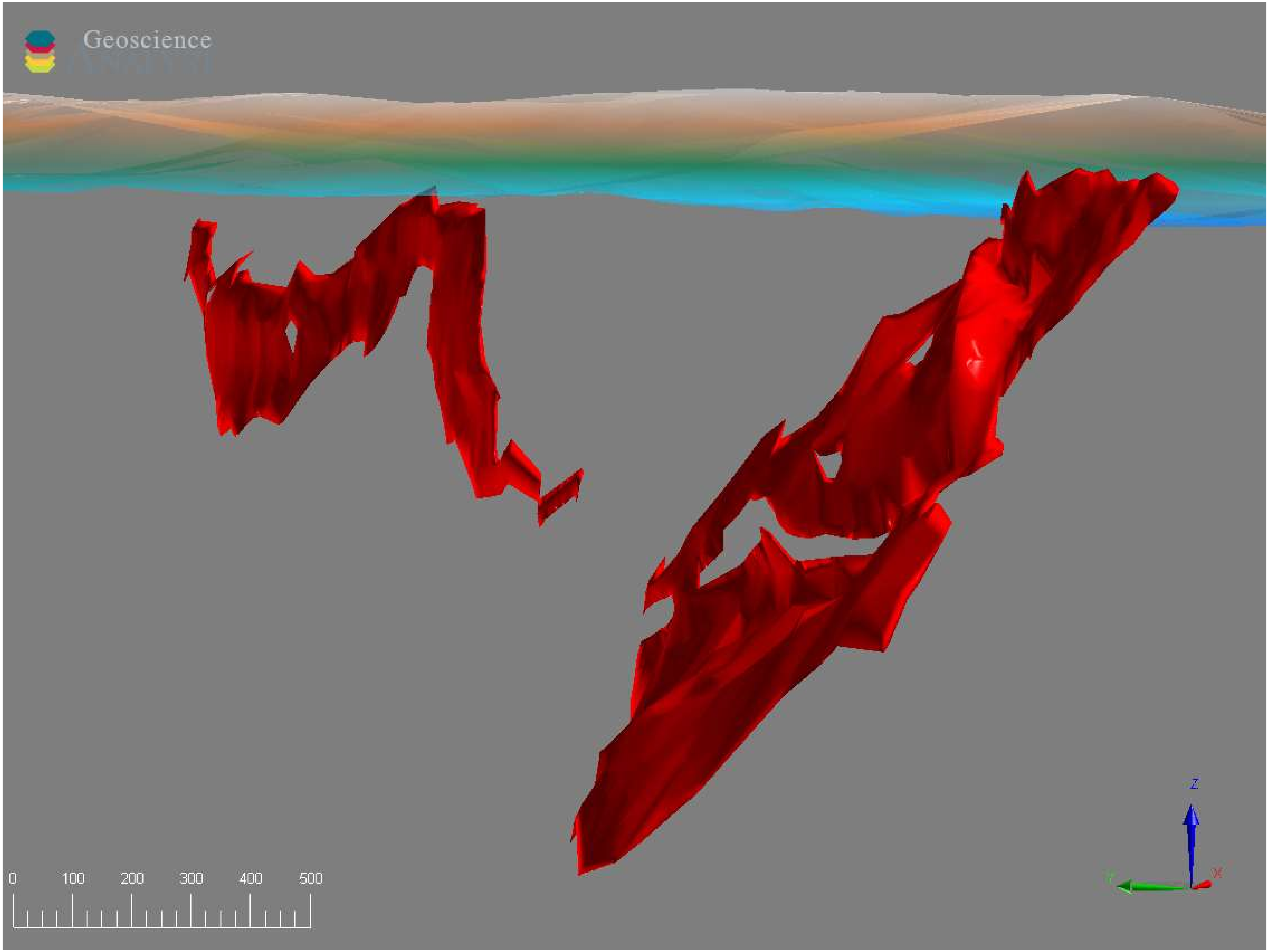
The KT-10 meters are a line of handheld instruments that measure the magnetic susceptibility and/or conductivity of a geological sample or core. The meters are available in circular and rectangular coil designs to measure large or small sized samples, respectively. The KT-10 meters produce repeatable results, and include features such as corrections for split and full cores, the ability to input information to correlate measurements to their appropriate depths, a built-in microphone to record voice notes, and the GeoView data management/visualization software. With its compact and rugged design, the KT-10 meters are ideal instruments for use in the field, core shack, or lab.

KT-10 v2 Magnetic Susceptibility Meter (Circular Coil)

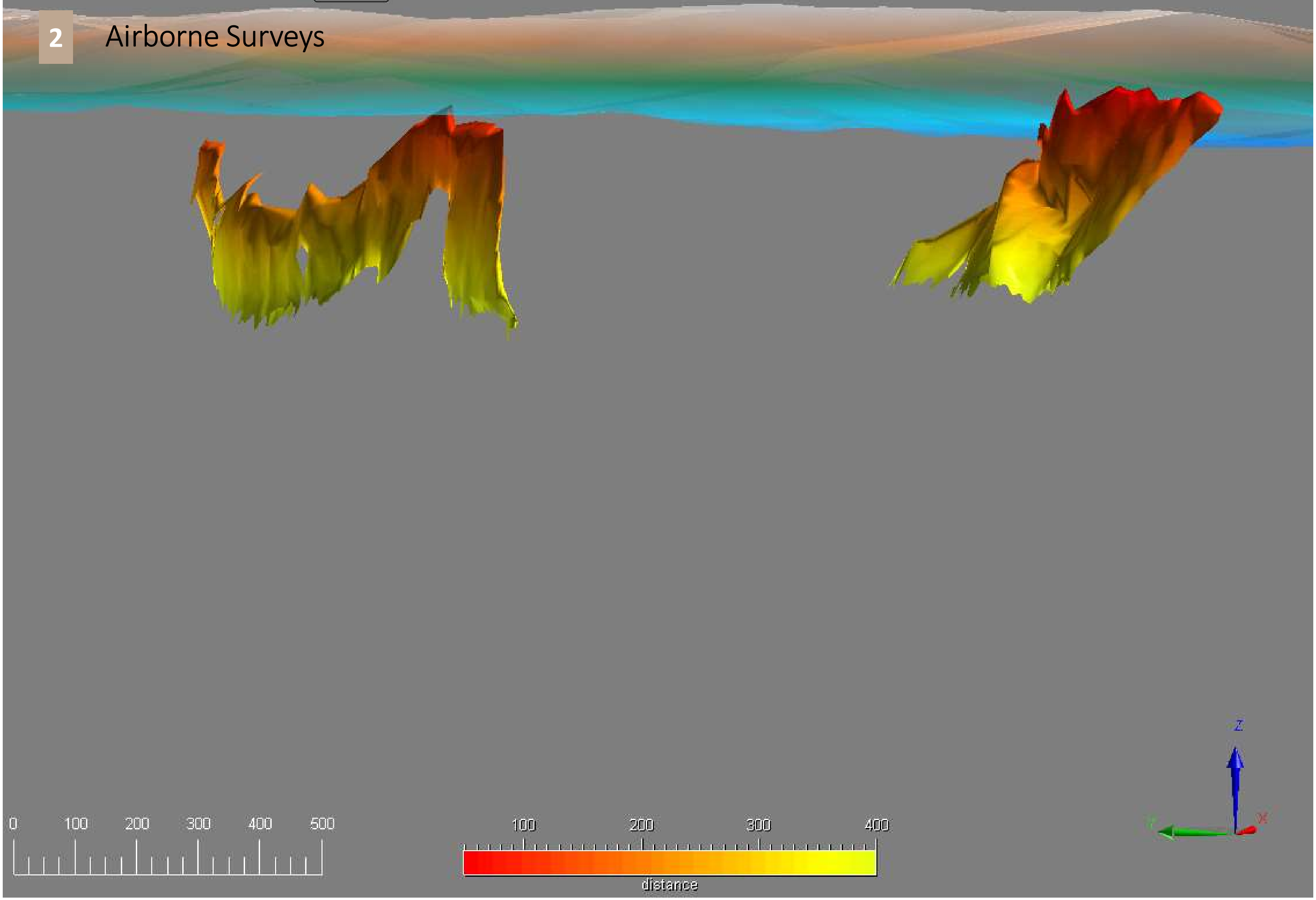
Conductivity measurement range 1 to 100,000S/m

Magnetic susceptibility range 0.001 x 10^{-3} to 1999.99 x 10^{-3} SI units

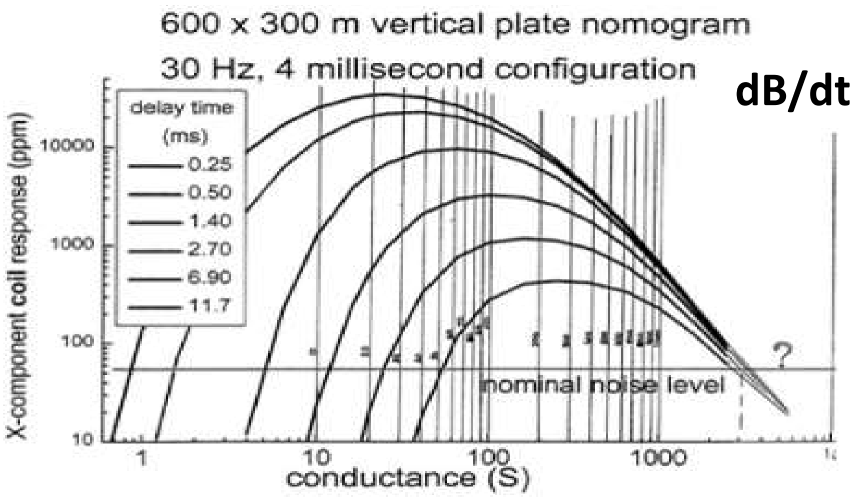

Gp argilites, schist
with Po
Cu-Ni ore
Cu rich MS
kimberlite
Po
Pb-Zn ores
Py
Polymetalic sulfides
Pyrite rich bodies
0.1
1
10
100
1000
10000
100000
Conductivity S/m

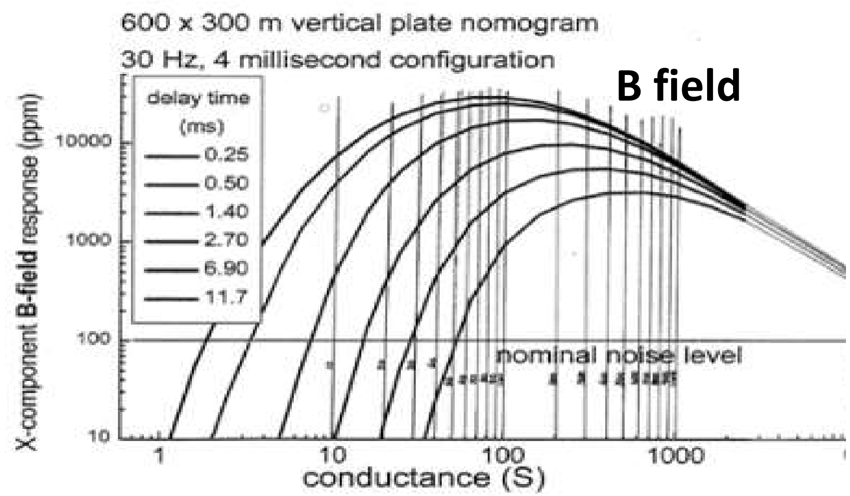

Geoscience
0
100
200
300
400
500
Z
X

2 Airborne Surveys



2 Airborne Surveys


600 x 300 m vertical plate nomogram
30 Hz, 4 millisecond configuration
dB/dt
delay time (ms)
0.25
0.50
1.40
2.70
6.90
11.7
X-component coil response (ppm)
10000
1000
100
10
nominal noise level
?
1
10
100
1000
conductance (S)


600 x 300 m vertical plate nomogram
30 Hz, 4 millisecond configuration
B field
delay time (ms)
0.25
0.50
1.40
2.70
6.90
11.7
X-component B-field response (ppm)
10000
1000
100
10
nominal noise level
1
10
100
1000
conductance (S)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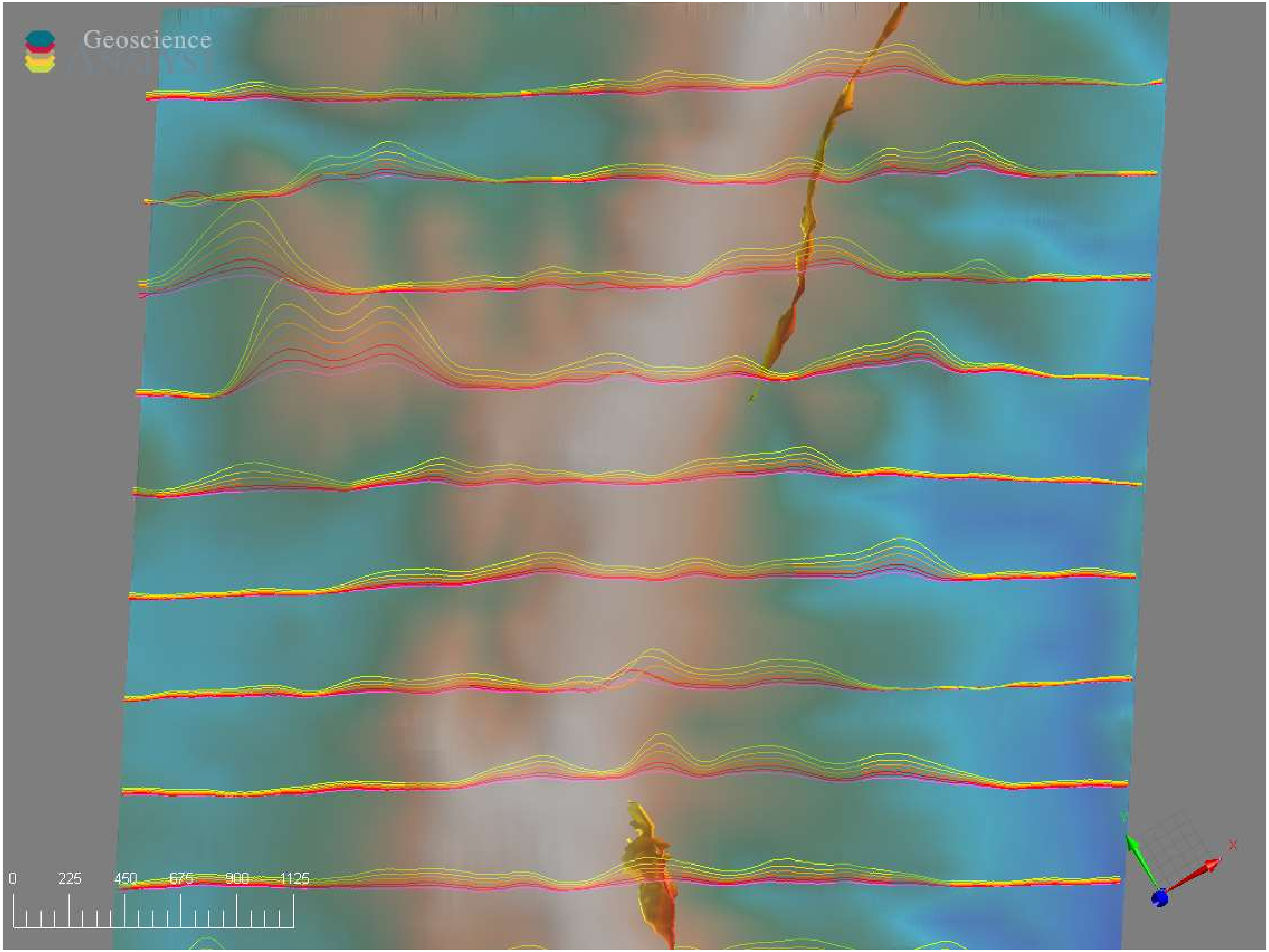
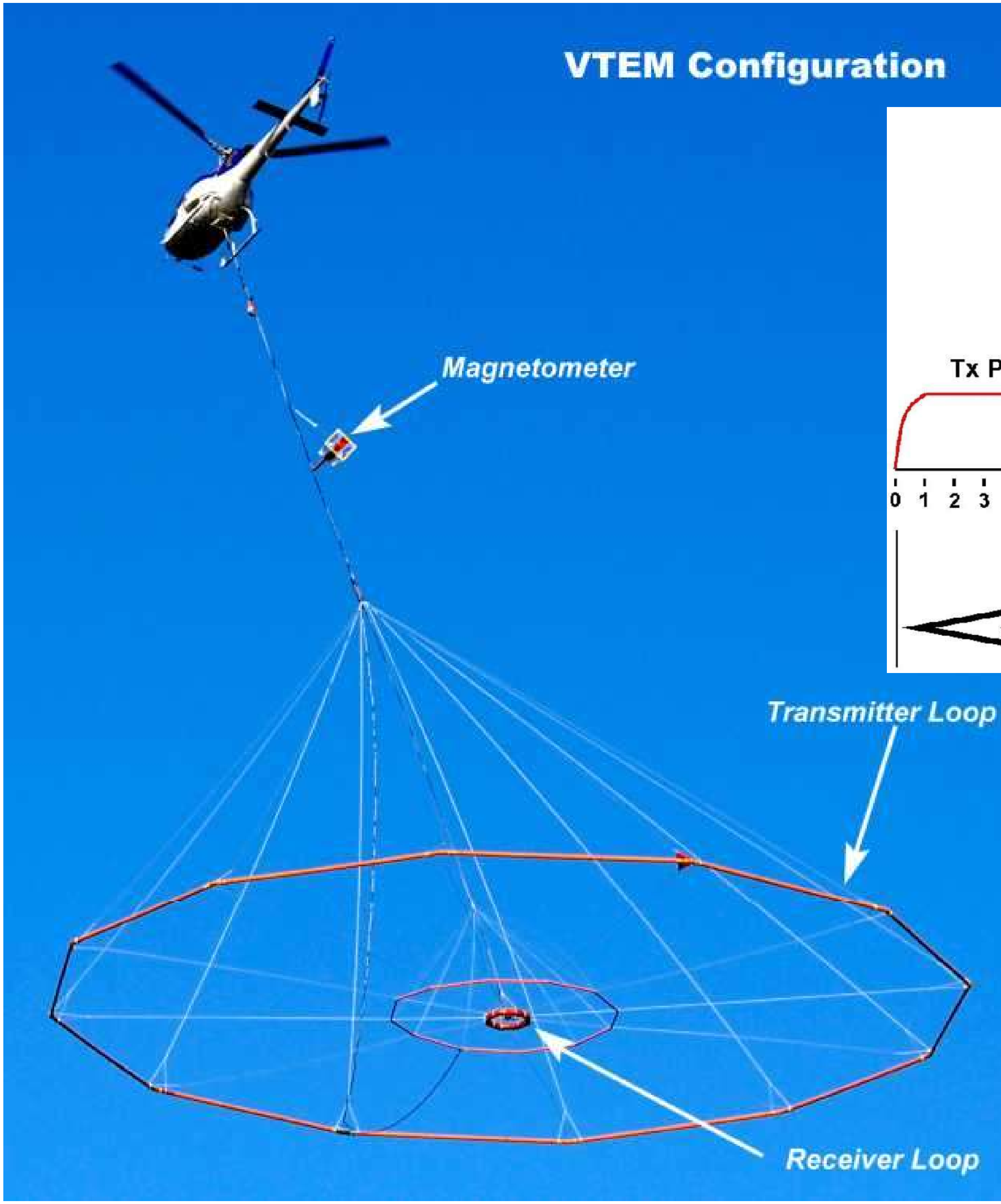
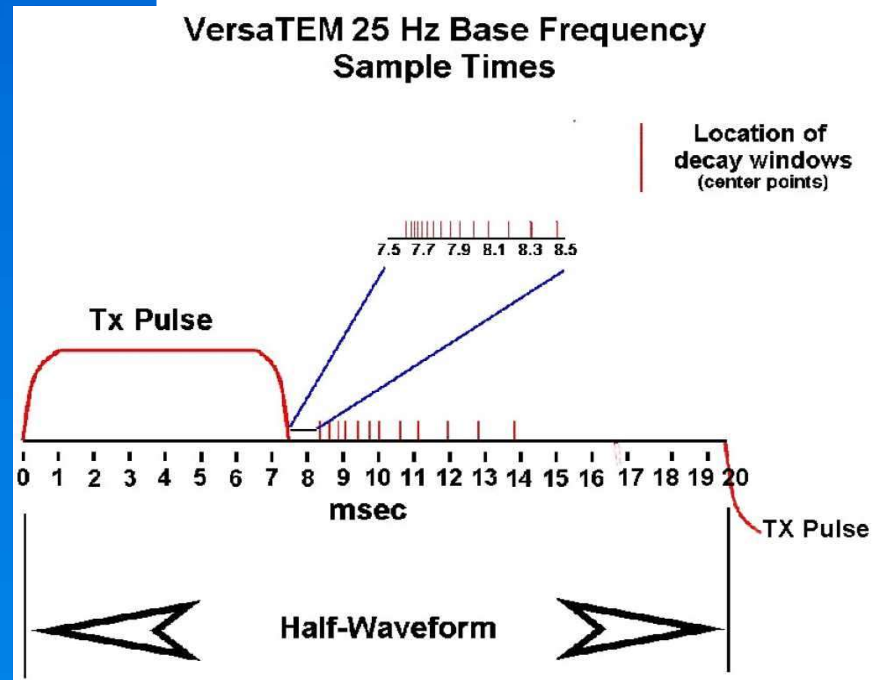

Geoscience
0
225
450
675
900
1125
X


VTEM Configuration
Magnetometer
Transmitter Loop
Receiver Loop


VersaTEM 25 Hz Base Frequency
Sample Times
Location of
decay windows
(center points)
7.5 7.7 7.9 8.1 8.3 8.5
Tx Pulse
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
msec
TX Pulse
Half-Waveform

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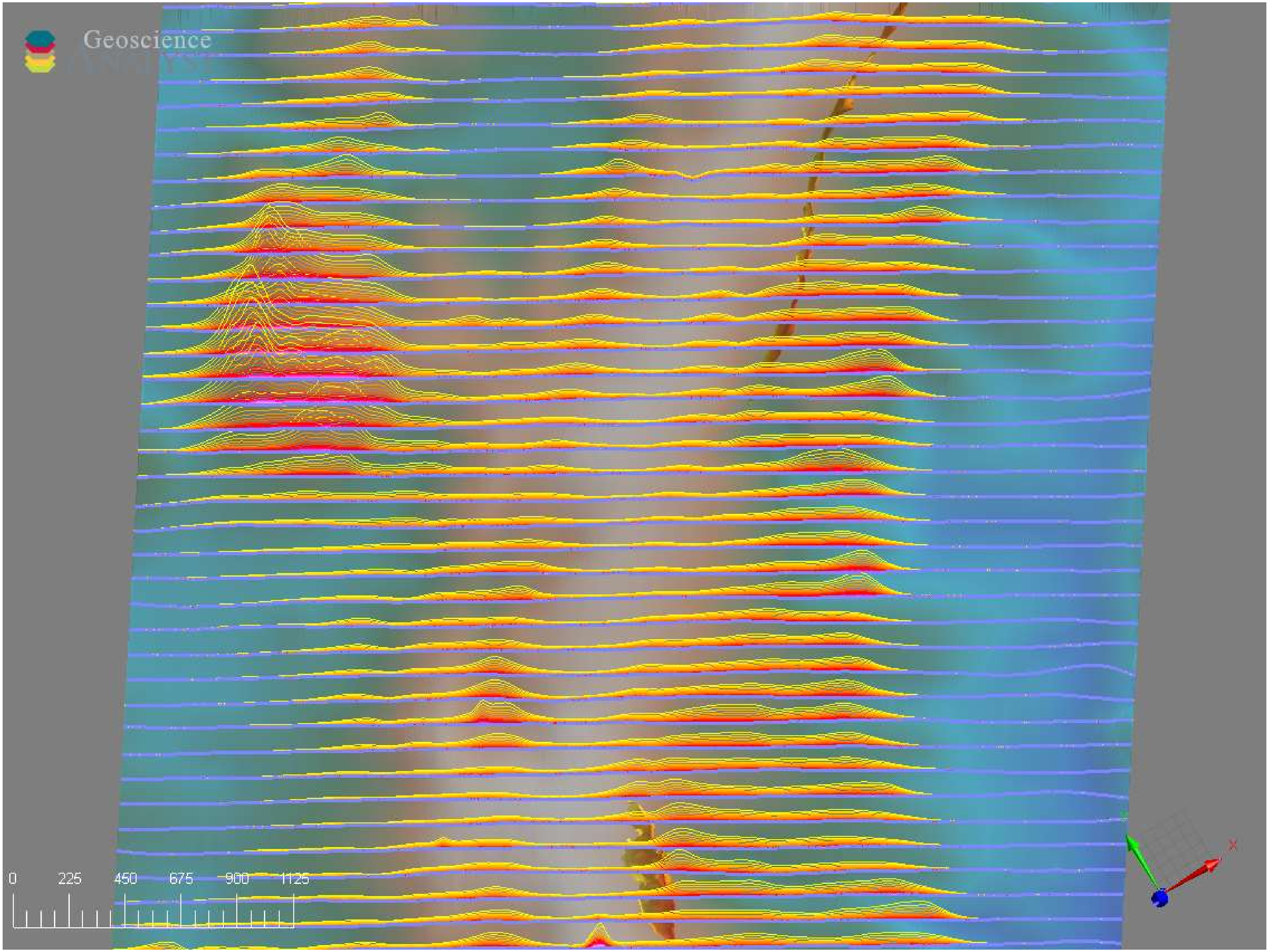
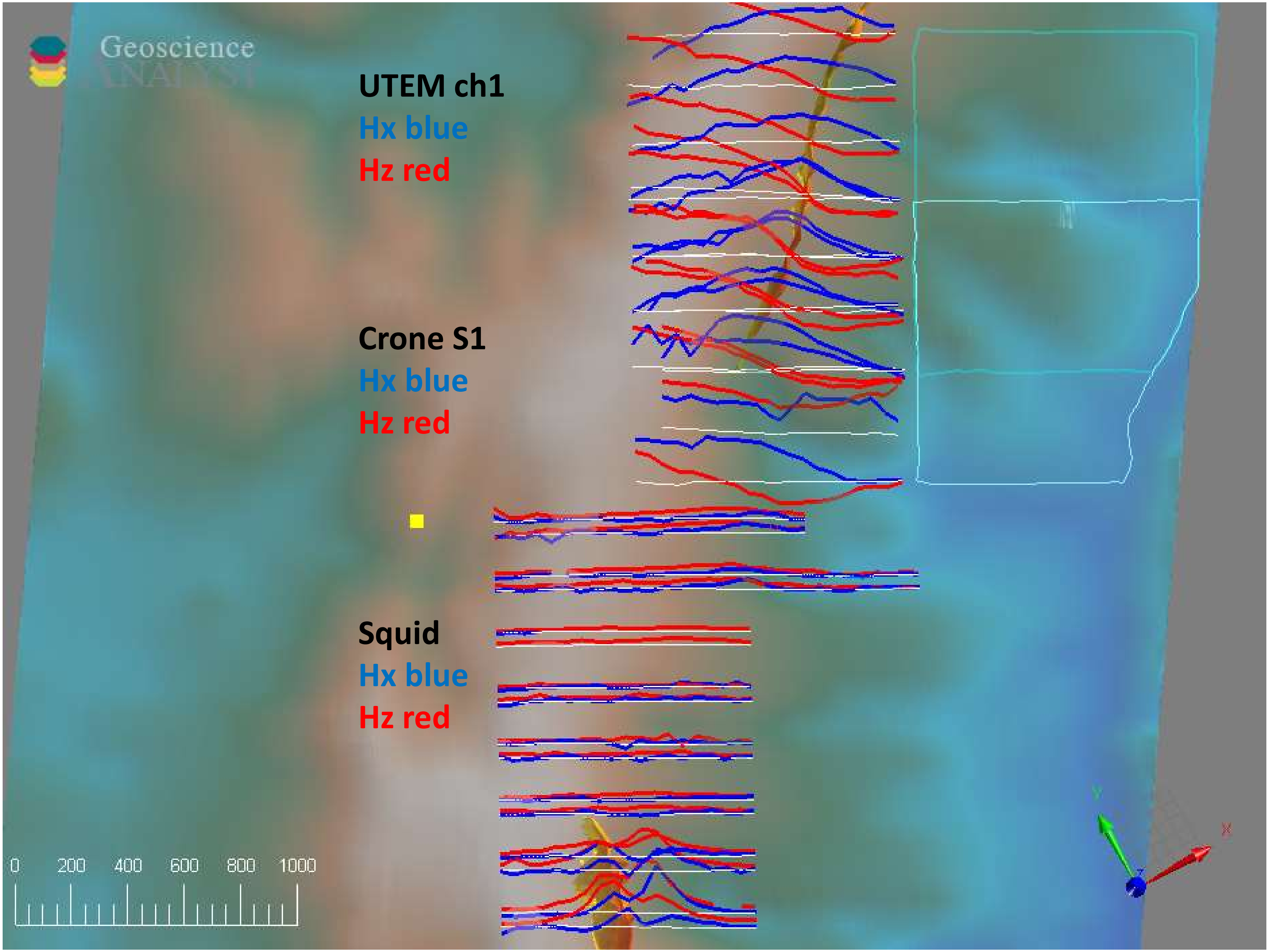
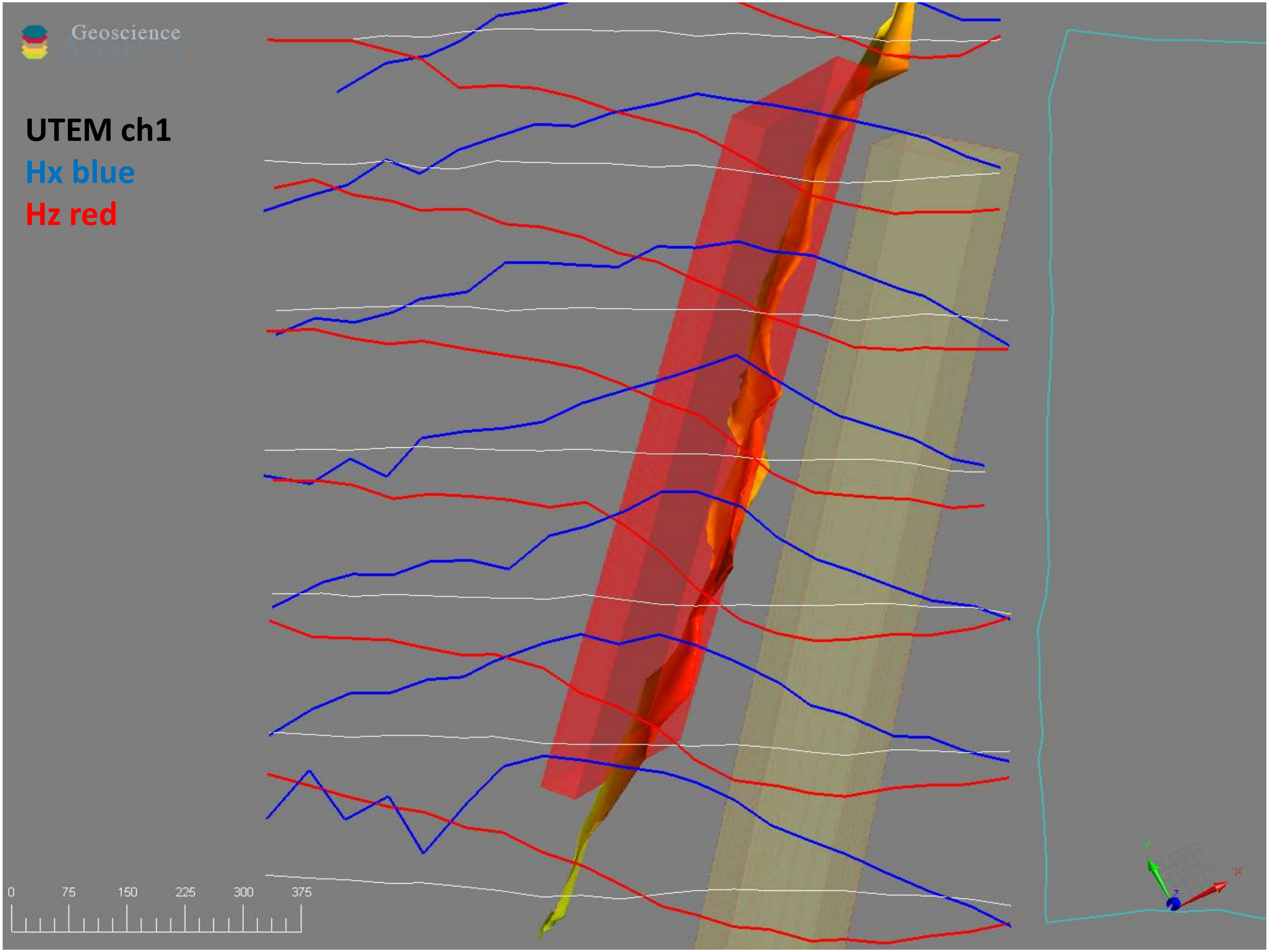
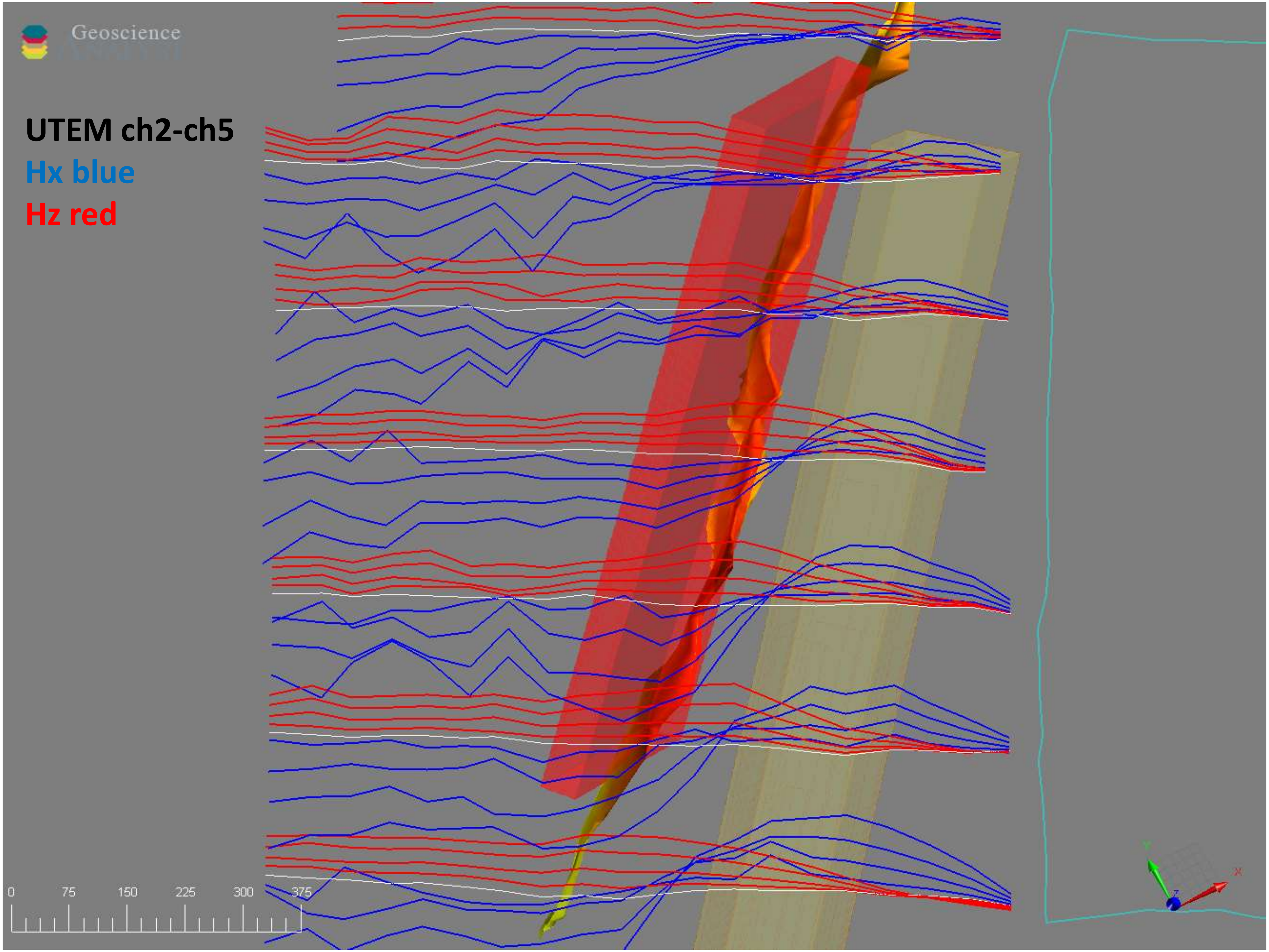
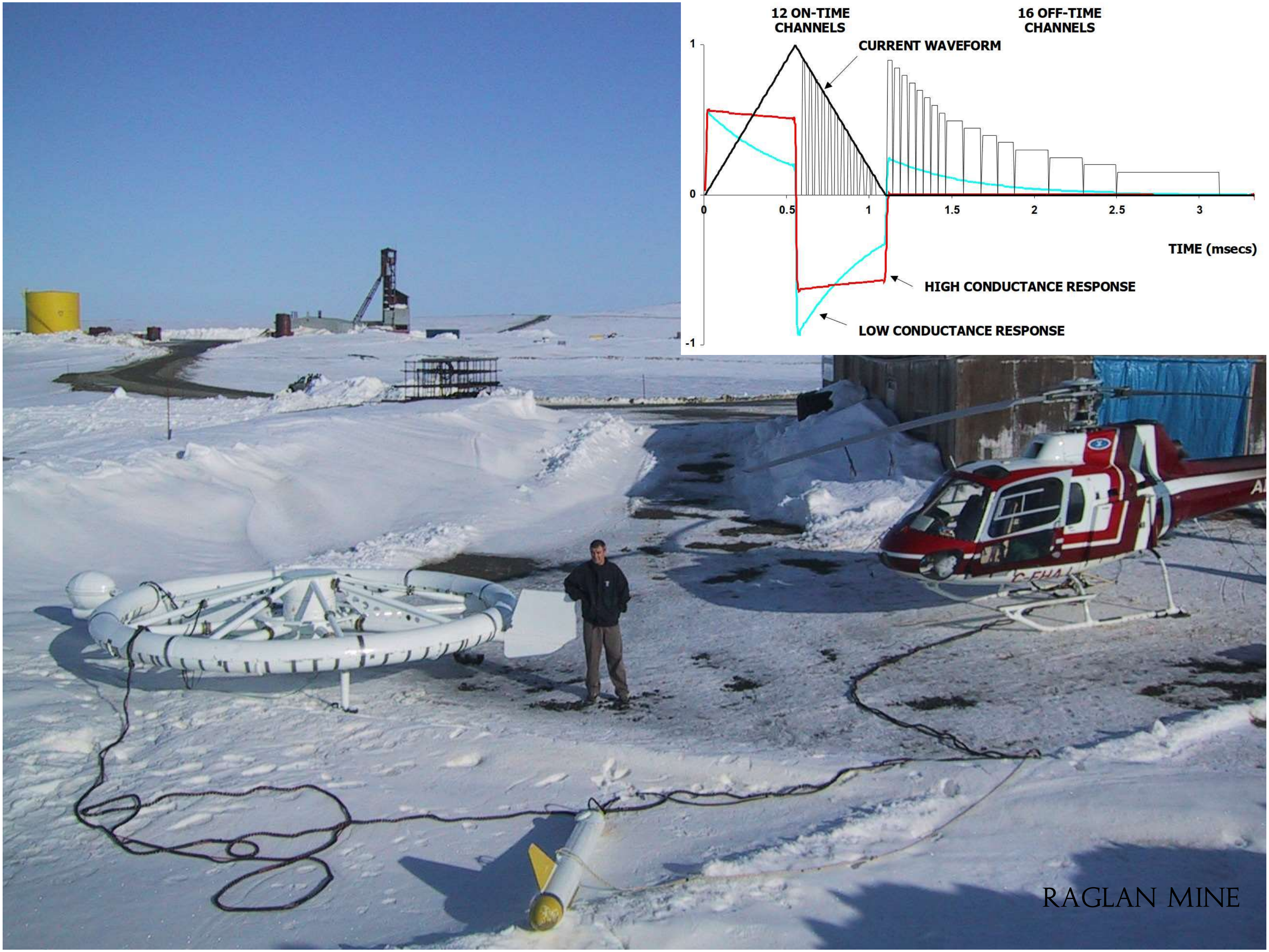

Geoscience
0
225
450
675
900
1125
X

3 Ground Surveys


Geoscience ANALYST
UTEM ch1
Hx blue
Hz red
Crone S1
Hx blue
Hz red
Squid
Hx blue
Hz red
0 200 400 600 800 1000
Y
X


Geoscience
UTEM ch1
Hx blue
Hz red
0
75
150
225
300
375
y
x
z


Geoscience
UTEM ch2-ch5
Hx blue
Hz red
0
75
150
225
300
375


12 ON-TIME CHANNELS
16 OFF-TIME CHANNELS
CURRENT WAVEFORM
1
0
-1
0
0.5
1
1.5
2
2.5
3
TIME (msecs)
HIGH CONDUCTANCE RESPONSE
LOW CONDUCTANCE RESPONSE
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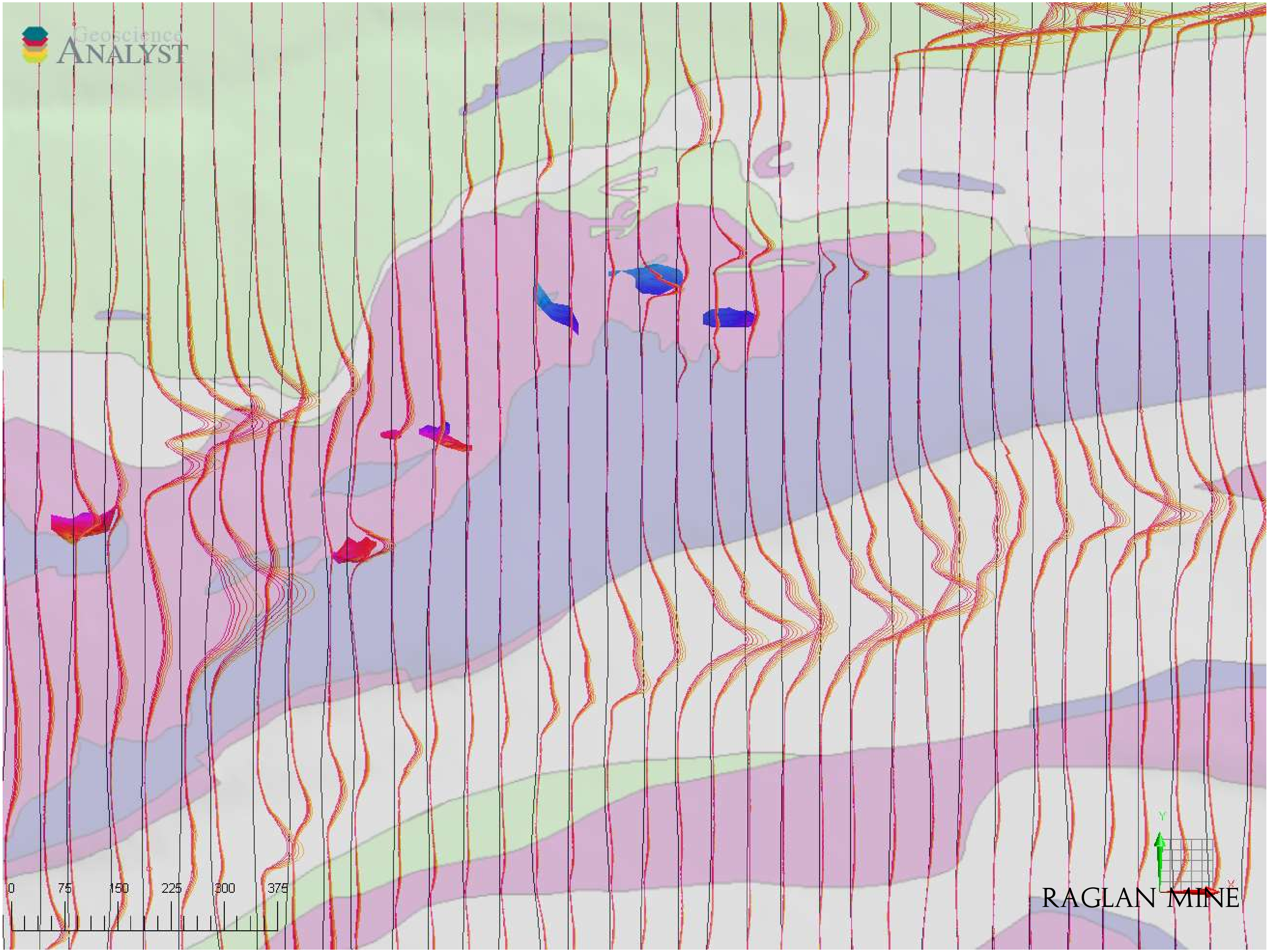
Geoscience ANALYST
0 75 150 225 300 375
Y
X
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4 Boreholes Surveys

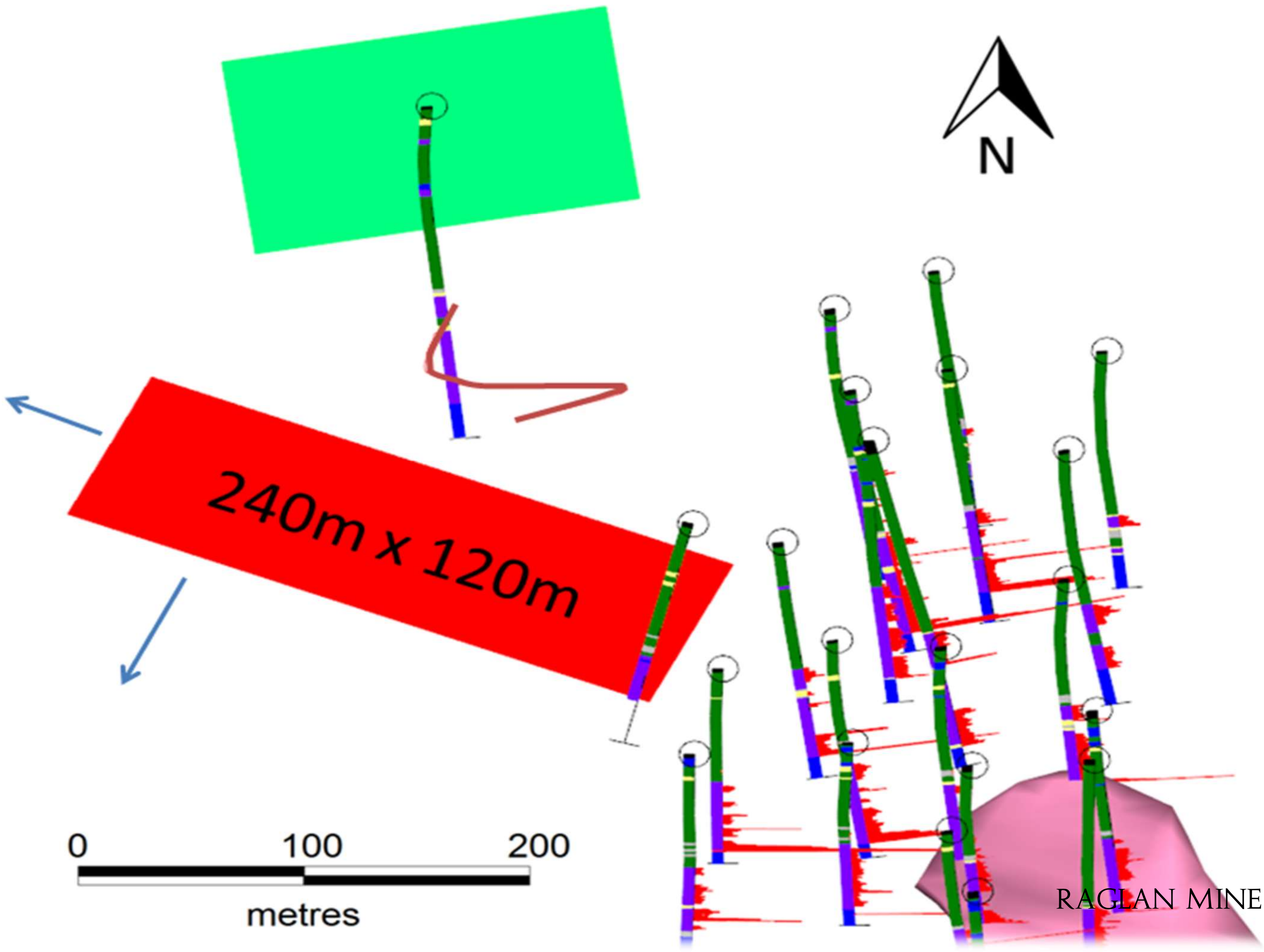
Lamontagne BH UTEM4

SJ Geohysics Volterra

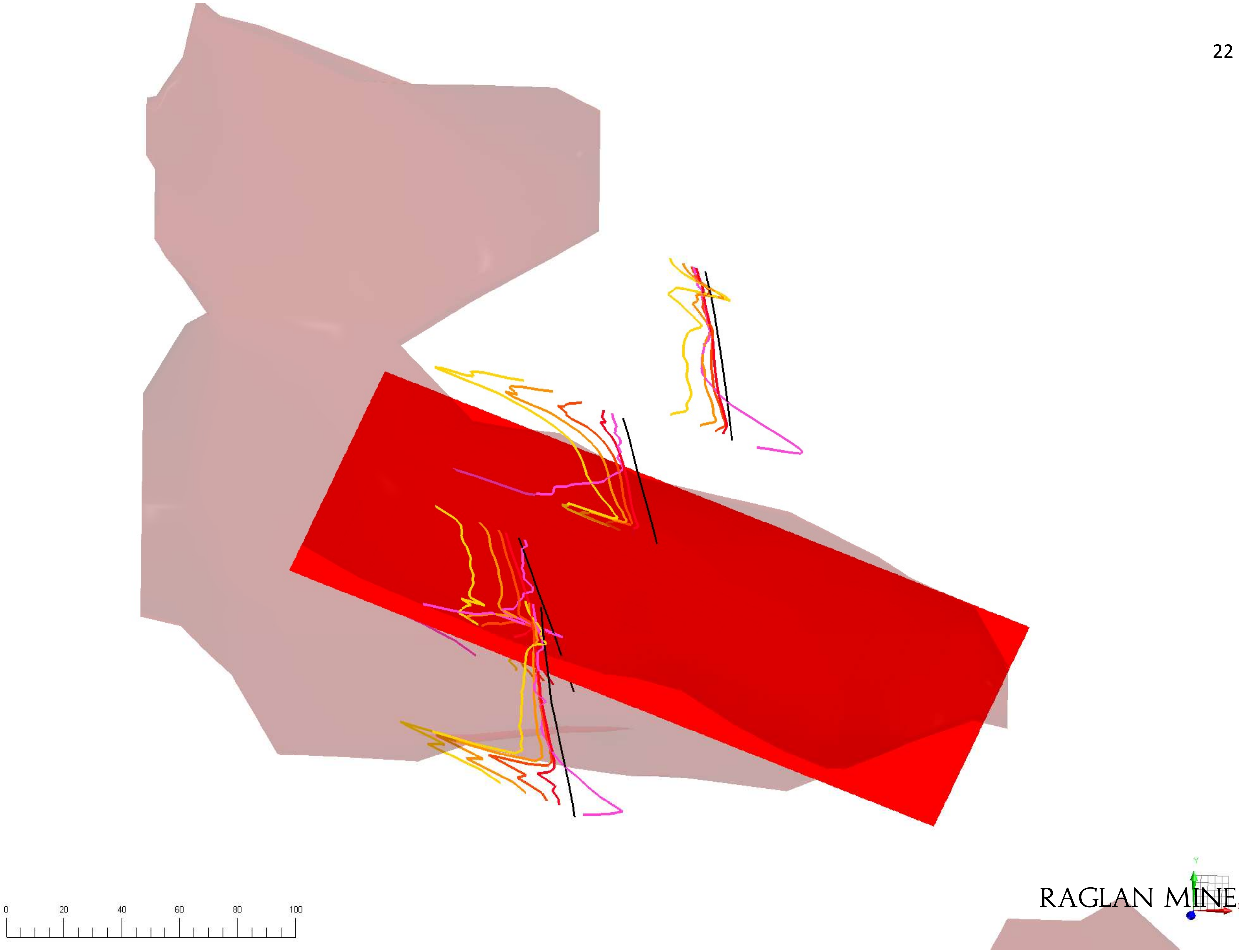
Crone Fluxgate

A quote from a 2002 era report

It appears that the mineralization here is exceptionally conductive, giving rise to unconventional DHEM responses that are difficult to model with conventional plate modeling software … investigated the effectiveness of analyzing the "ramp-response" in this environment, but concluded that more information is present in the "off-time" data than the "ramp-time".



N
240m x 120m
0
100
200
metres
RAGLAN MINE


0
20
40
60
80
100
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- **Know and understand your physical properties**
- **Perform a test survey over a known target (if possible)**
- **Use a survey method appropriate for the target**
- **Beware of conductive sedimentary sulphides**


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Discussion on …Time-Domain EM for Highly-Conductive Targets

Andrew Duncan,

Electromagnetic Imaging Technology Pty Ltd

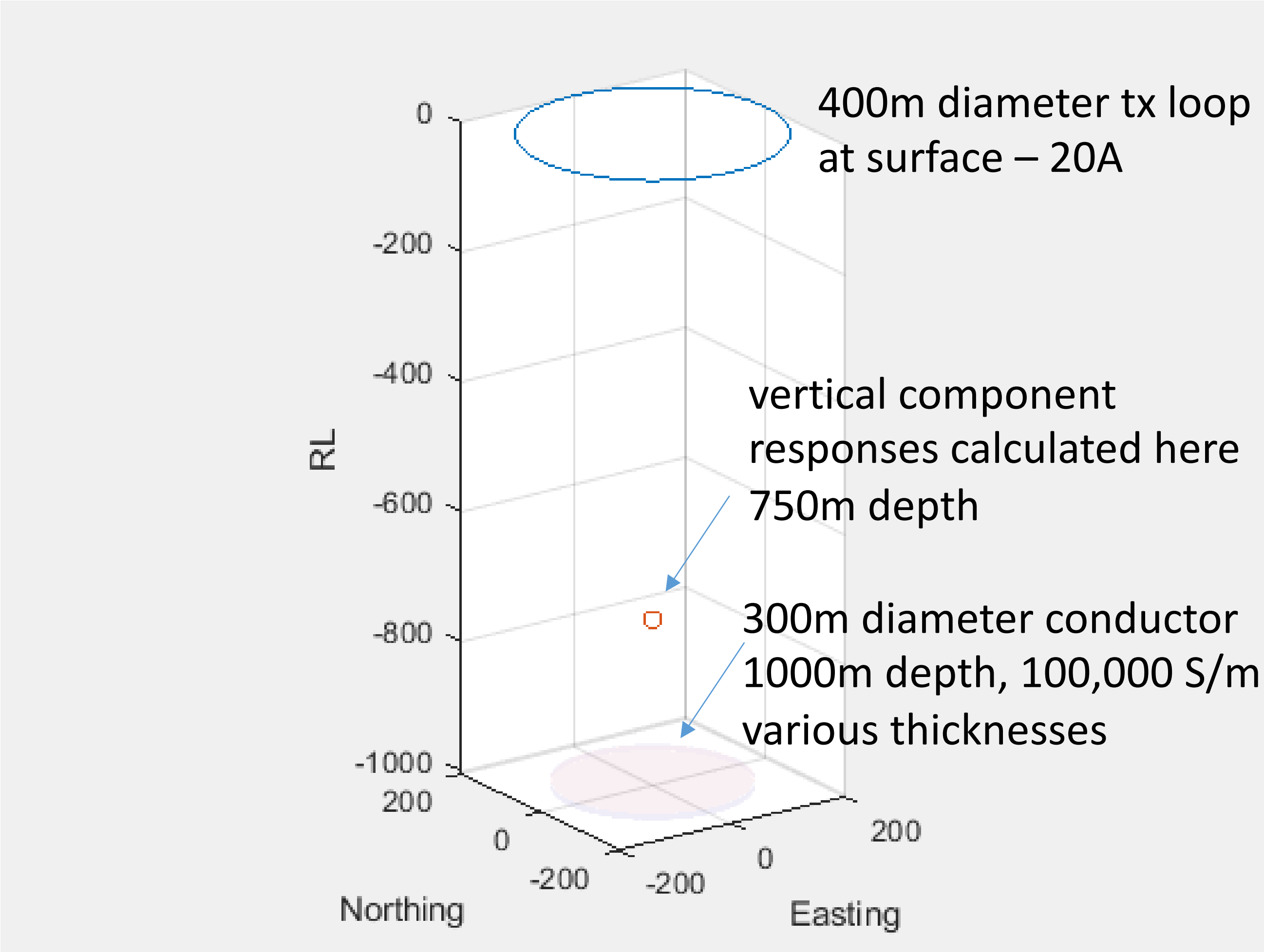
Introduction

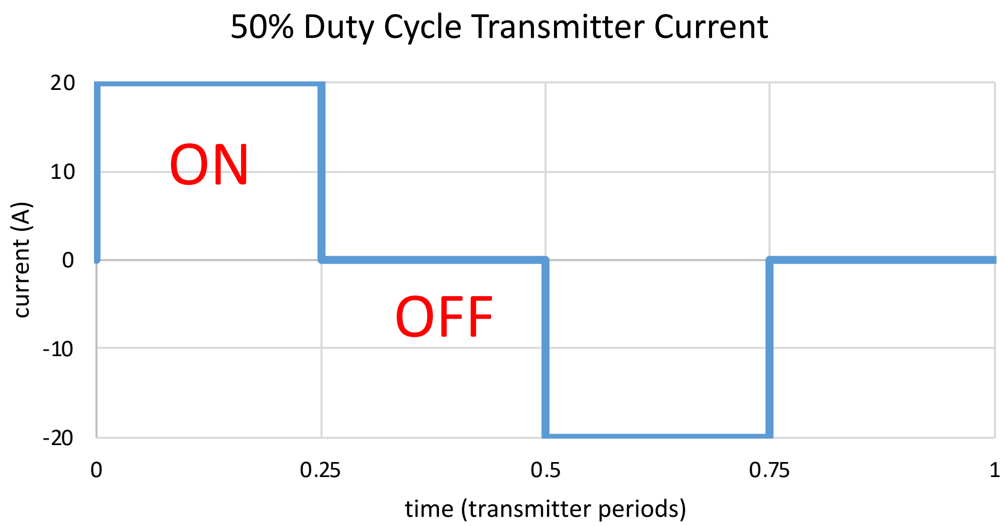
- In my Exploration ’17 paper I gave some examples of TEM responses from highly-conductive 3-D models and comparisons of responses for 50% duty cycle (on- and off-time), 100% duty cycle and late-time normalised 100% duty cycle. In an extension to that work, models will be updated here and we’ll discuss a bit more about signal/noise.
- The key issues in this topic are: detection and discrimination. Detection of a highly-conductive target and discrimination from weaker conductors.

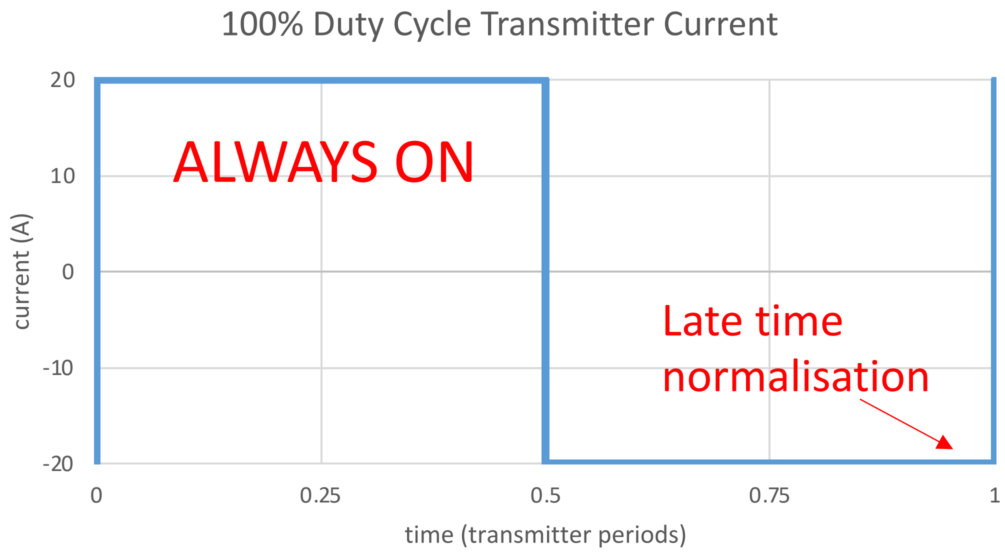
Highly Conductive

- Here we are talking about end-member targets. Massive pyrrhotite, NiS, CuS. And big, which makes them harder to see in the off-time, because bigger, more conductive targets have TEM responses in-phase with primary field
- Conductivity of the models I use is 100,000 S/m – this is end-member conductivity, with conductive halo absent
- For simplicity I am using a fairly arbitrary cylindrically-symmetric model, the aim is to demonstrate what happens when you make different types of measurements on the same target and vary its conductivity without varying any geometry
- I am going to calculate B responses for 0.1 Hz and 1 Hz transmitter waveforms (at 50% and 100% duty cycle) with 20 logarithmically-spaced time windows

(Arbitrary) Model with 100,000 S/m Targets

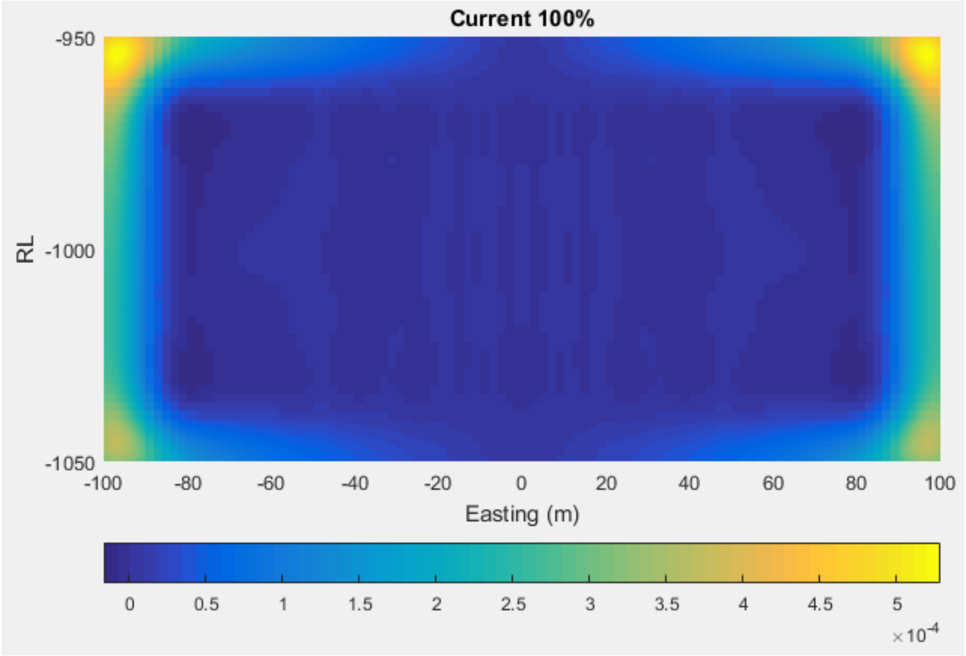






TEM Current Flow

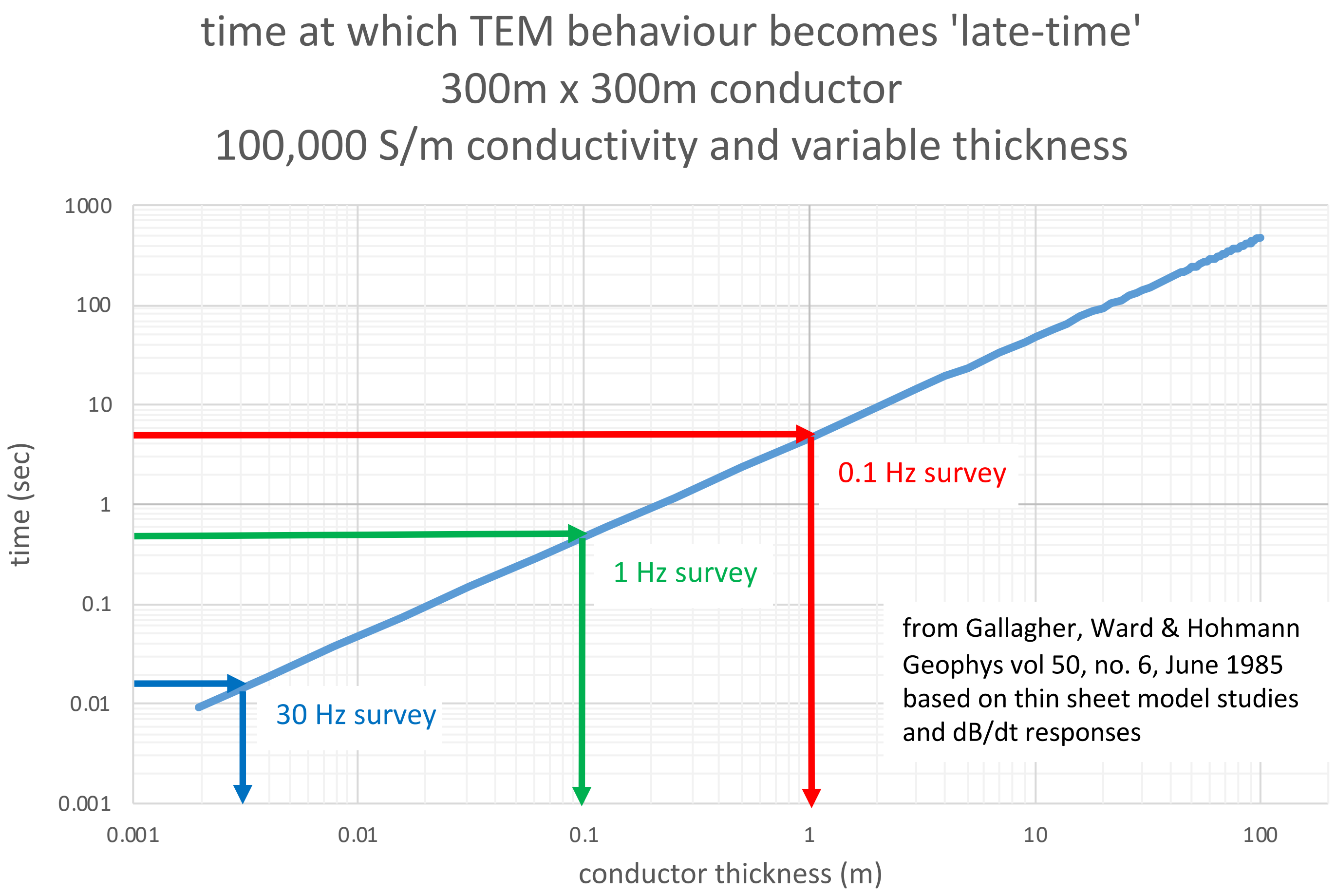
- Current Flow looks like this in a TEM survey at 0.1 Hz in The Ovoid
- Current flows in the skin of these targets and a simple view of these targets based on their overall conductance is entirely invalid



10,000,000S conductor
Illustrating currents flowing in a slice through Ovoid model, at the latest time, 0.1 Hz, 100% duty cycle survey

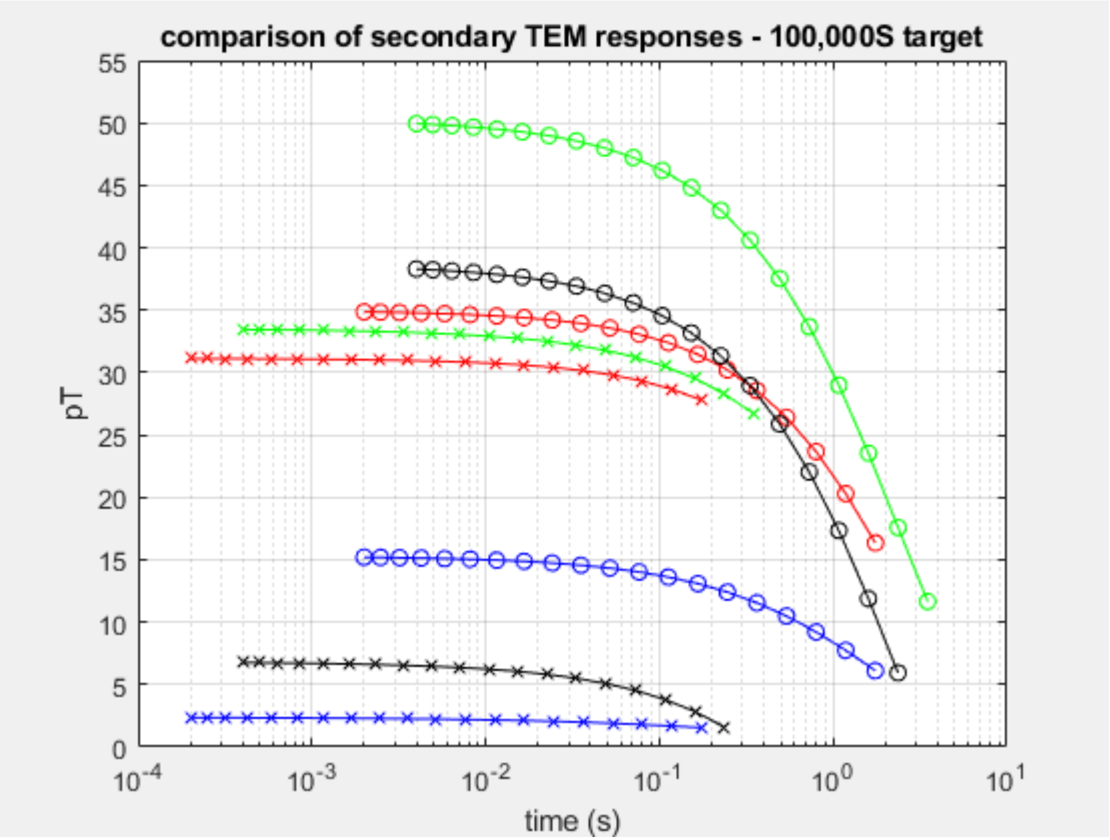
When does late-time behaviour start?

- We never get close to late-time TEM behaviour for an economic 100,000 S/m target
- We never see the slow decays that you might estimate from conductance
- Currents are moving inwards from the skin of the target when we make our measurements
- We do still have the ability to discriminate thickness



3-D Model Response

- 100,000S target
- 1m thick x 100,000 S/m
- 300m diameter horizontal disc conductor at 1000m depth
- Vertical component response measured at 750m depth
- 300m diameter transmitter loop at surface with 20A
- Demonstrates considerable increase in signal size by dropping transmitter frequency

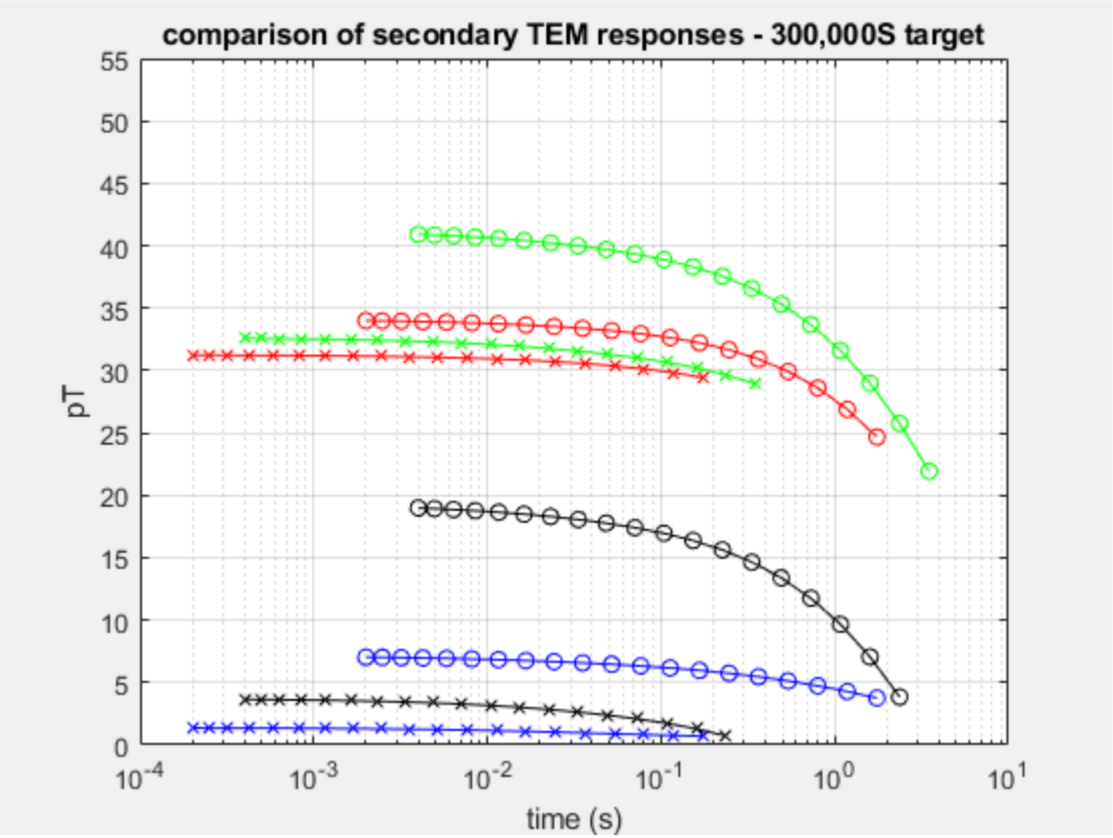


100% Late Time Normalized 100% 50% On 50% Off

O = 0.1 Hz X = 1 Hz

3-D Model Response

- 300,000S target
- 3m thick x 100,000 S/m
- 300m diameter horizontal disc conductor at 1000m depth
- Vertical component response measured at 750m depth
- 300m diameter transmitter loop at surface with 20A

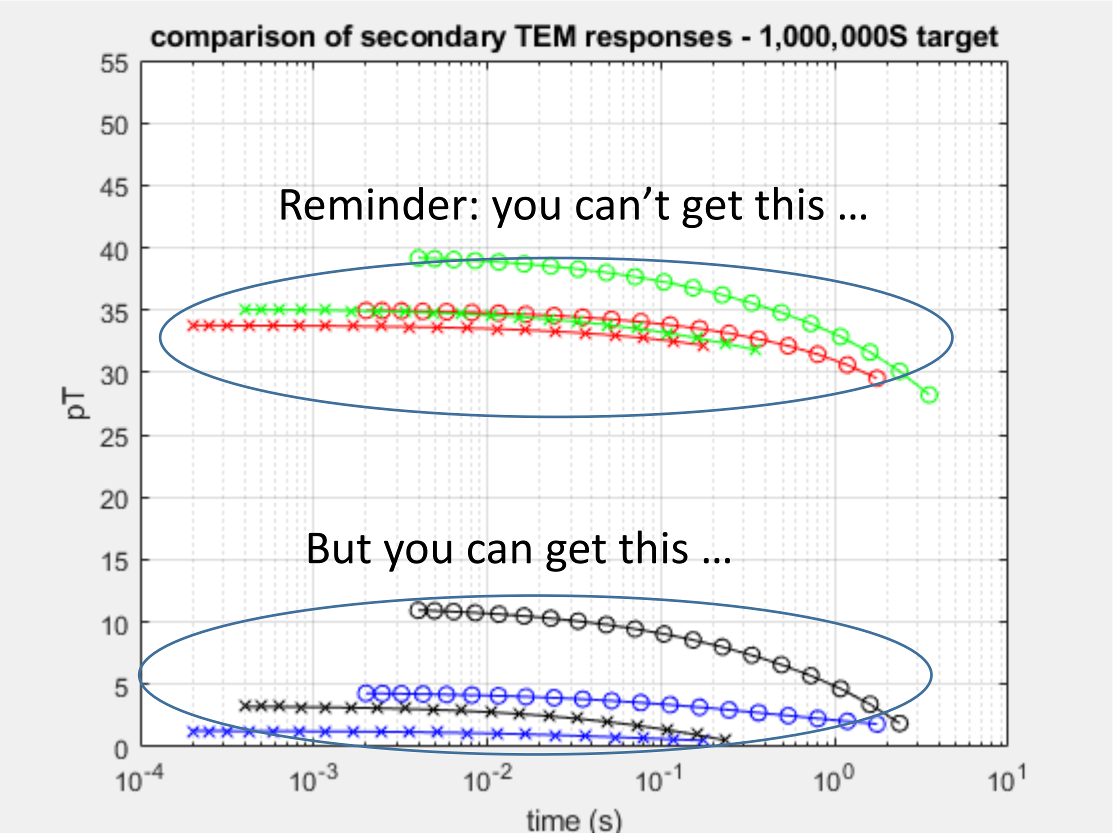


100% Late Time Normalized 100% 50% On 50% Off

O = 0.1 Hz X = 1 Hz

3-D Model Response

- 1,000,000S target
- 10m thick x 100,000 S/m
- 300m diameter horizontal disc conductor at 1000m depth
- Vertical component response measured at 750m depth
- 300m diameter transmitter loop at surface with 20A
- Bigger distinction between on-time and off-time / normalised responses

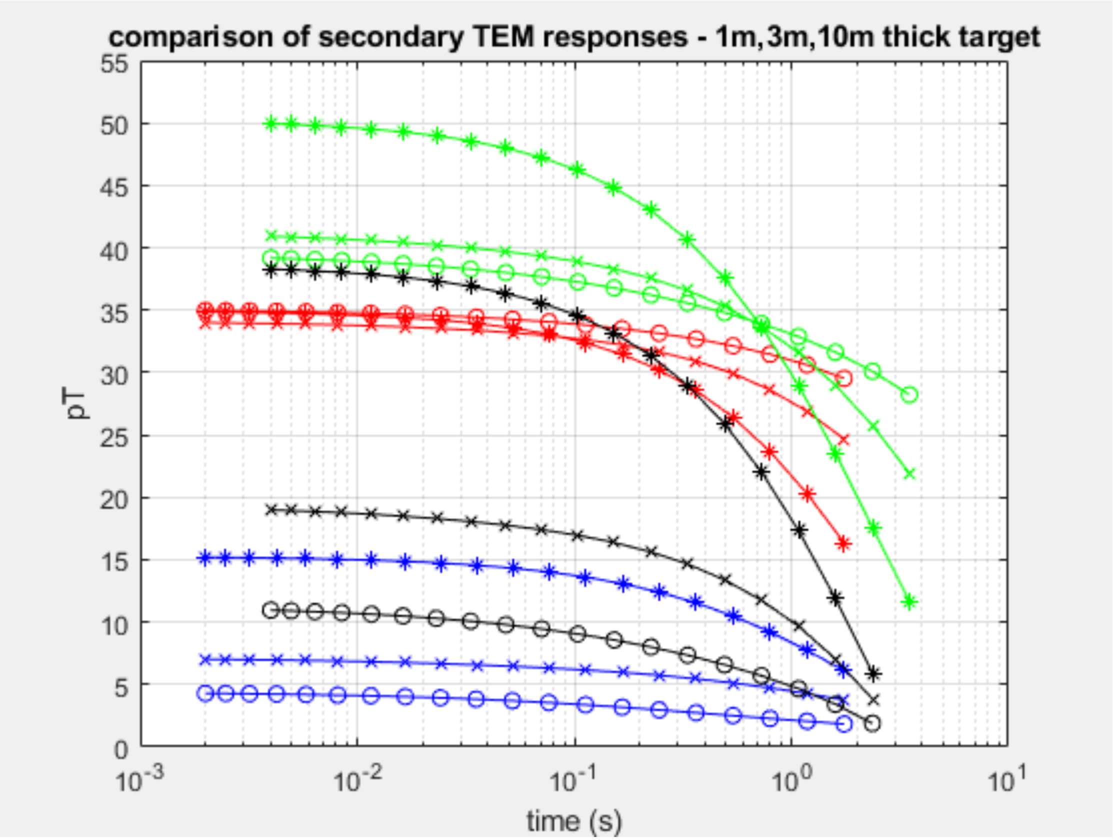


100% Late Time Normalized 100% 50% On 50% Off

O = 0.1 Hz X = 1 Hz

3-D Model Response

- 0.1 Hz only – 1, 3m and 10m thickness x 100,000 S/m
- Comparison of responses of different conductances
- 0.1 Hz TEM theoretically has the ability to discriminate target conductance at 1,000,000S
- The best technique for discrimination depends on the S/N of the measurement techniques

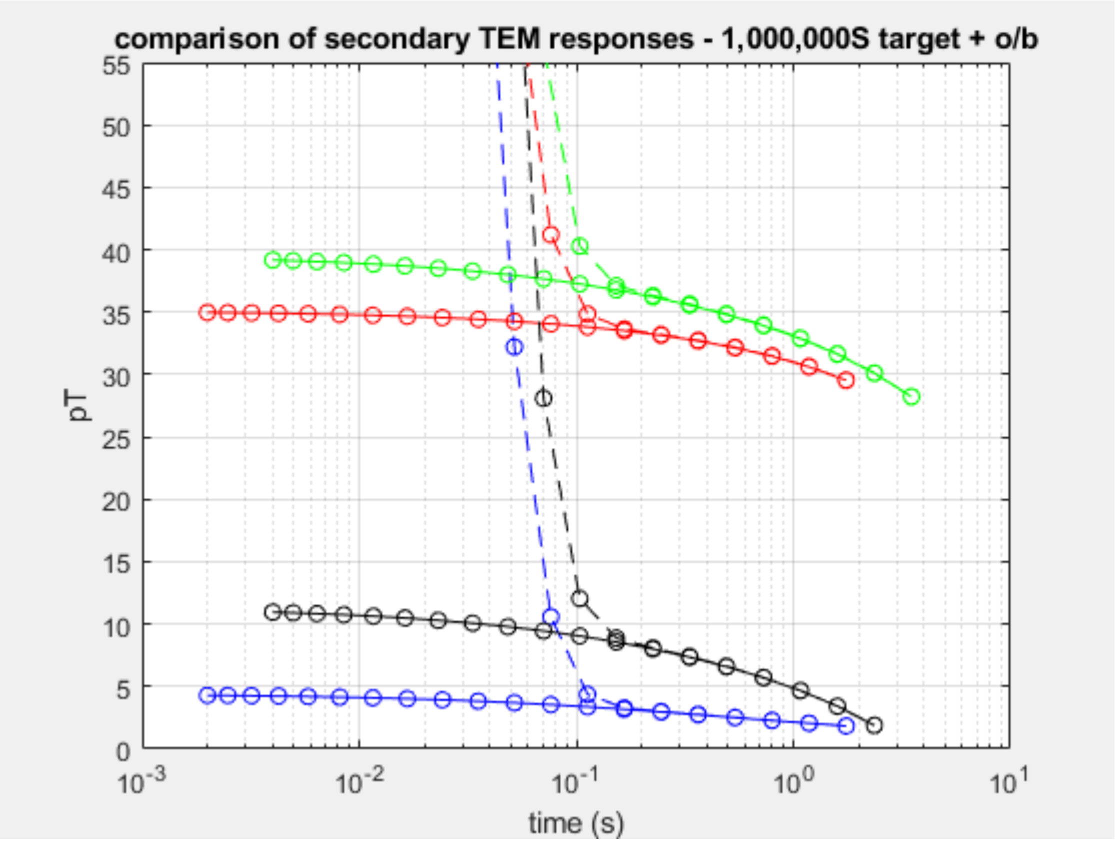


100% Late Time Normalized 100% 50% On 50% Off

* = 1m thick X = 3m thick O = 10m thick

3-D Model Response

- 0.1 Hz only
- 1,000,000S conductor
- 100S overburden, 100m thick x 1 S/m at surface (0m to 100m depth)
- Overburden model is a 2000m diameter disc, centred on transmitter loop
- Asymptote to target response occurs at similar time (about 200 msec) regardless of the type of field calculation
- A conductive host may affect late-time responses, but not in this case of a thick overburden well above the target



100% Late Time Normalized 100% 50% On 50% Off

O = 0.1 Hz

Model Responses Discussion

- TEM signals in the on-time are larger than in the off-time (assuming same transmitter current) by an amount that depends on the target and the transmitter frequency
- As you go to lower transmitter frequency, like 0.1 Hz, on-time and off-time responses become fairly close for all but the most conductive, large targets [these are the nice ones to find]
- Late-time-normalised 100% duty cycle responses are around the same as 50% off-time responses at late time – this is important.
- For an extremely good conductor like the ones presented here … there is not much difference between the on-time response from a 50% duty cycle waveform and a 100% duty cycle waveform

That was Signal, how about the other half of the S/N equation: Noise?

- The considerations of noise are very different for on and off-time surveys. This seems to be ignored in many discussions
- Generally, the noise in an off-time measurement is a result of either the sensor noise floor OR external noise factors. Interestingly, these issues can both be addressed by increasing transmitter power.
- In an on-time survey, the biggest source of noise is generally the primary field, the secondary field rides on top of it. If you are measuring a long distance from the transmitter loop, then this may not be the case. The primary field (which is large) needs to be estimated somehow (eg. by measuring the geometry of the survey) or dealt with somehow (eg. by late-time-normalization). Increasing transmitter power doesn't help. This source of noise is absent in off-time surveys and secondary fields that are a very small fraction of the primary field can be measured in an off-time survey
- In an on-time survey, if variations in current (either by design or not) are significant then they need to be measured and corrected for, otherwise they are another source of noise in general.

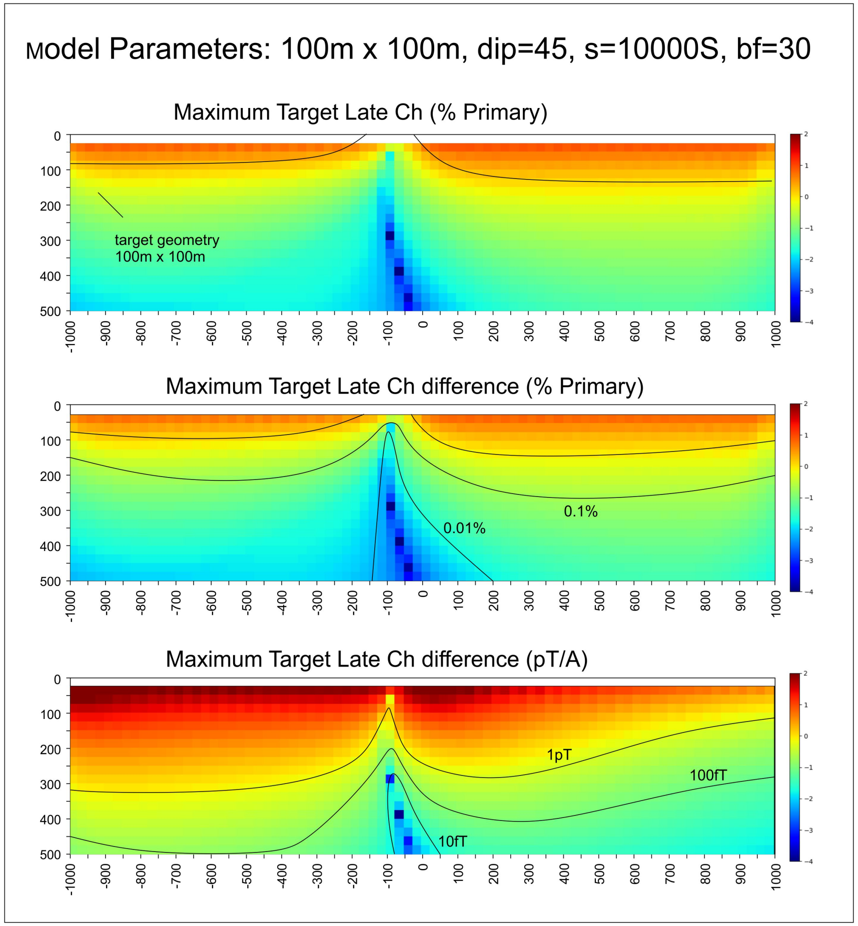
Summary

- I’ve been talking about end-member conductors. Less conductive or thinner or smaller targets are relatively easier to see in off-time TEM, assuming same transmitter frequency etc
- Without full 3-D modelling of highly-conductive targets, the wrong conclusions are easily drawn about signal size
- A consideration of noise must be made in any analysis of detectability. Calculate the primary field
- Low noise magnetometers and low frequency surveys have changed the way that discoveries of highly-conductive targets are made everywhere
- Model or estimate a survey S/N – this is important. Review the noise of different survey style in the same units

Acknowledgements

- BCGS
- MTNet
- James, Ben and Daryl
- DMEC (material pulled from Exploration '17 paper)

Tools and Concepts for Prediction of EM System Performance for Detection of Long Time-Constant Targets



Thanks to Glenn McDowell and Vale for allowing me to use the field data featured in this work

Ben Polzer
December 10, 2020

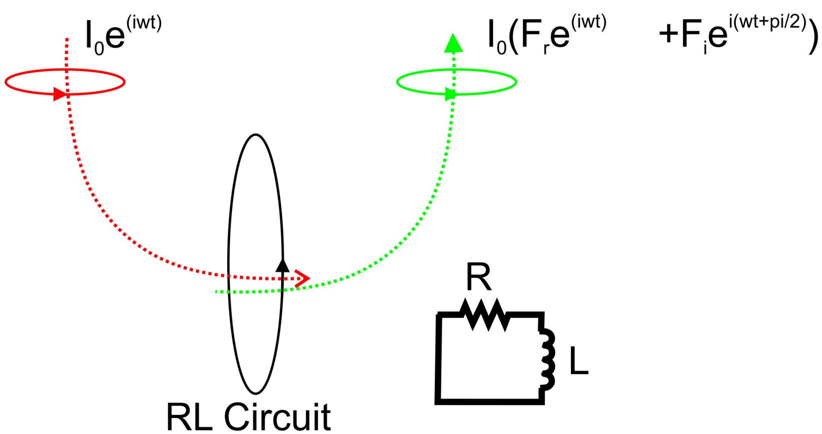
Signal and Noise

- On-time and Off-time approaches have different sensitivities (signal strengths) with respect to target parameters, especially for high conductance targets.
- The detectability of a target depends on the S/N ratio not just the signal strength.
- On-time systems can be more vulnerable to systematic noise sources
- Off-time approaches become more vulnerable to vibration noise in the quest to coax out a decay
- If we are going to study the S/N it is useful to use very simple models and noise estimation techniques to predict system performance

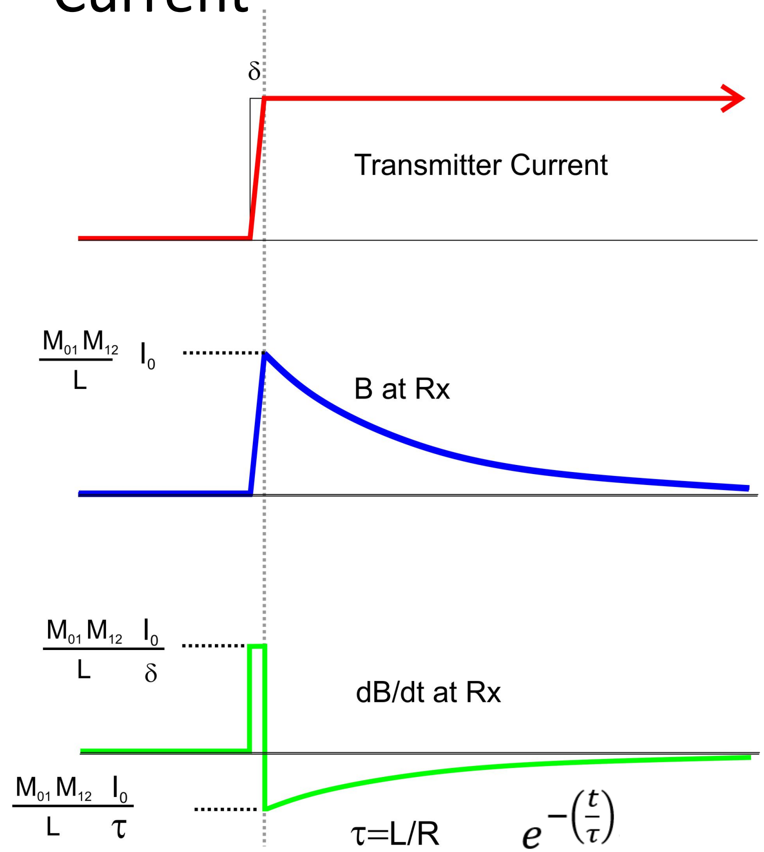
RL Circuit Model For Target

- After Grant and West (1965)

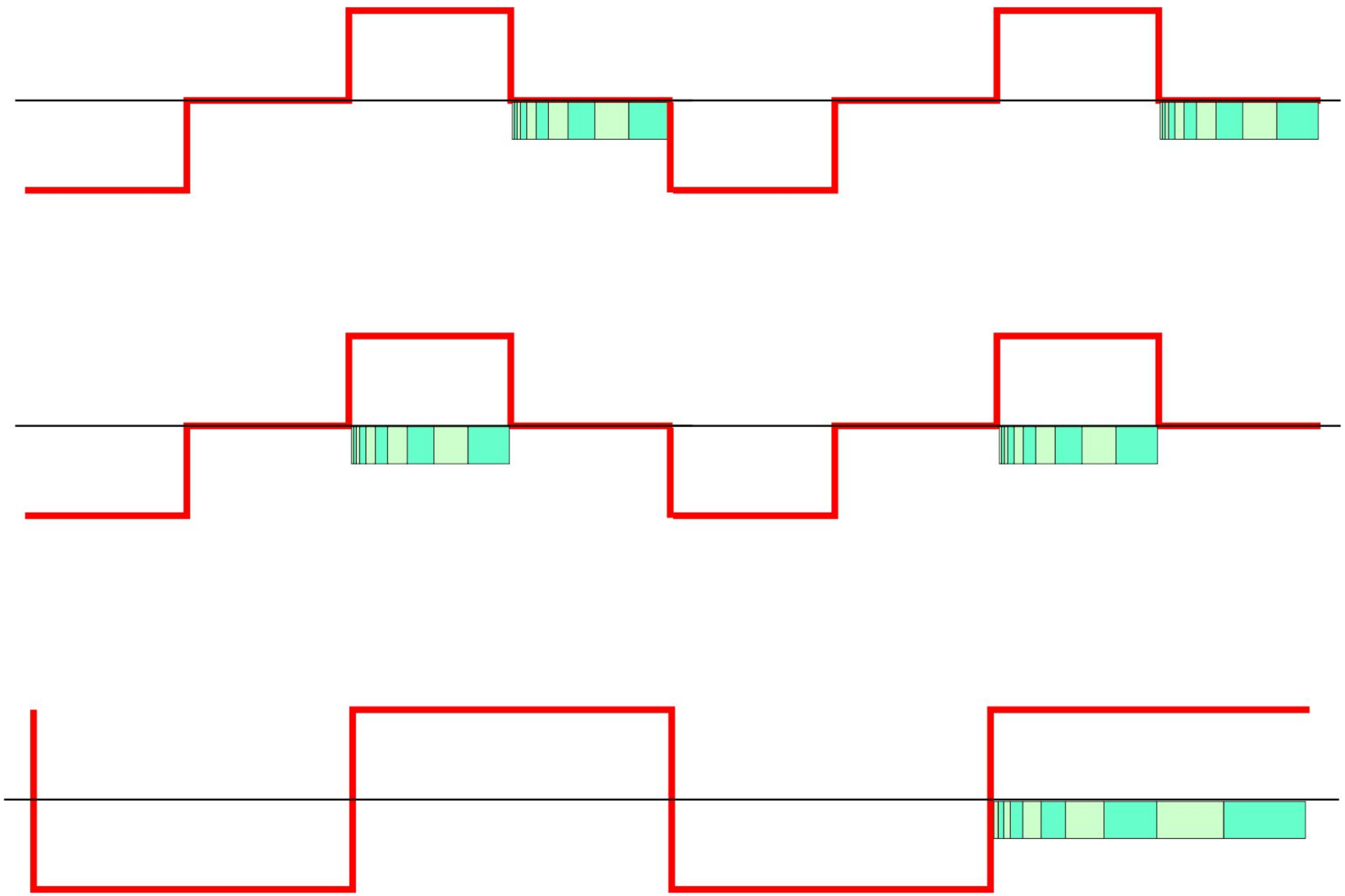
RL Circuit Model



Response to Step Tx Current

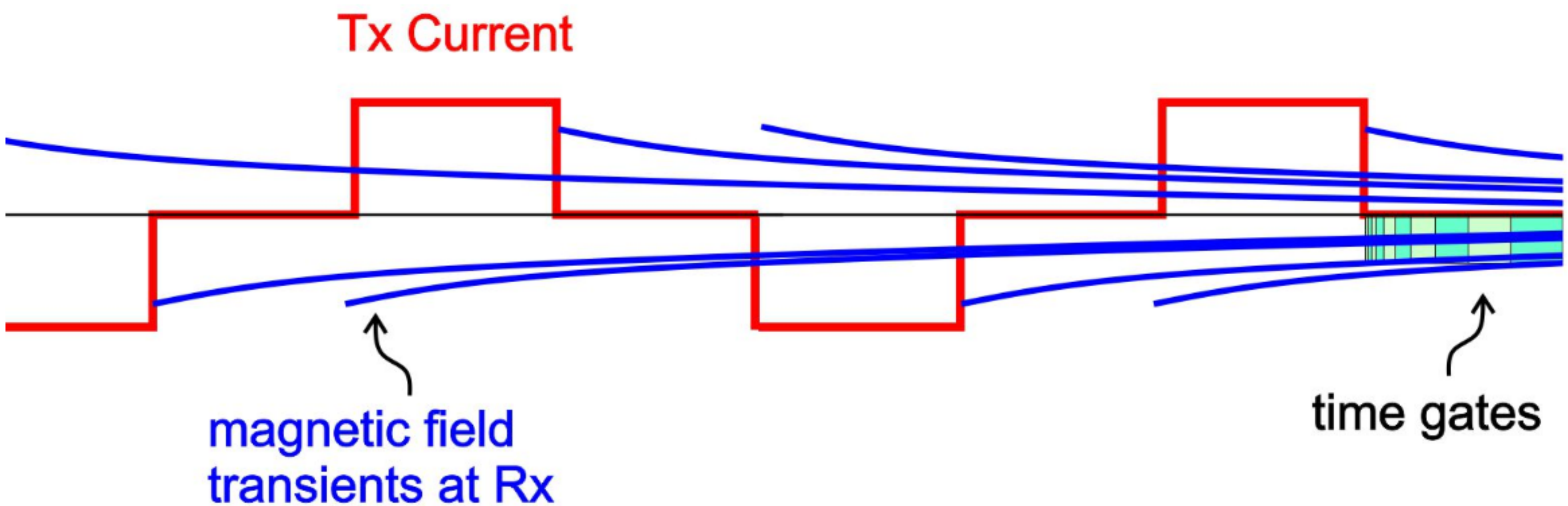


Waveforms and Sampling



Periodic Transient Effect

- EM systems drive a periodic signal with a base frequency.
- Transients from previous half cycles overlap and the effect becomes more significant as the ttime constant of the target gets longer.



Periodicity Factors

- The infinite series of exponential transients can be summed analytically to yield the original transient modified by a Periodicity Factor which is dependent on the tau to base period ratio.

$$e^{-\left(\frac{t}{\tau}\right)} - e^{-\left(\frac{t}{\tau}+\frac{P}{4}\right)} + e^{-\left(\frac{t}{\tau}+\frac{P}{2}\right)} - e^{-\left(\frac{t}{\tau}+\frac{3P}{4}\right)} + e^{-\left(\frac{t}{\tau}+P\right)} - \ldots$$

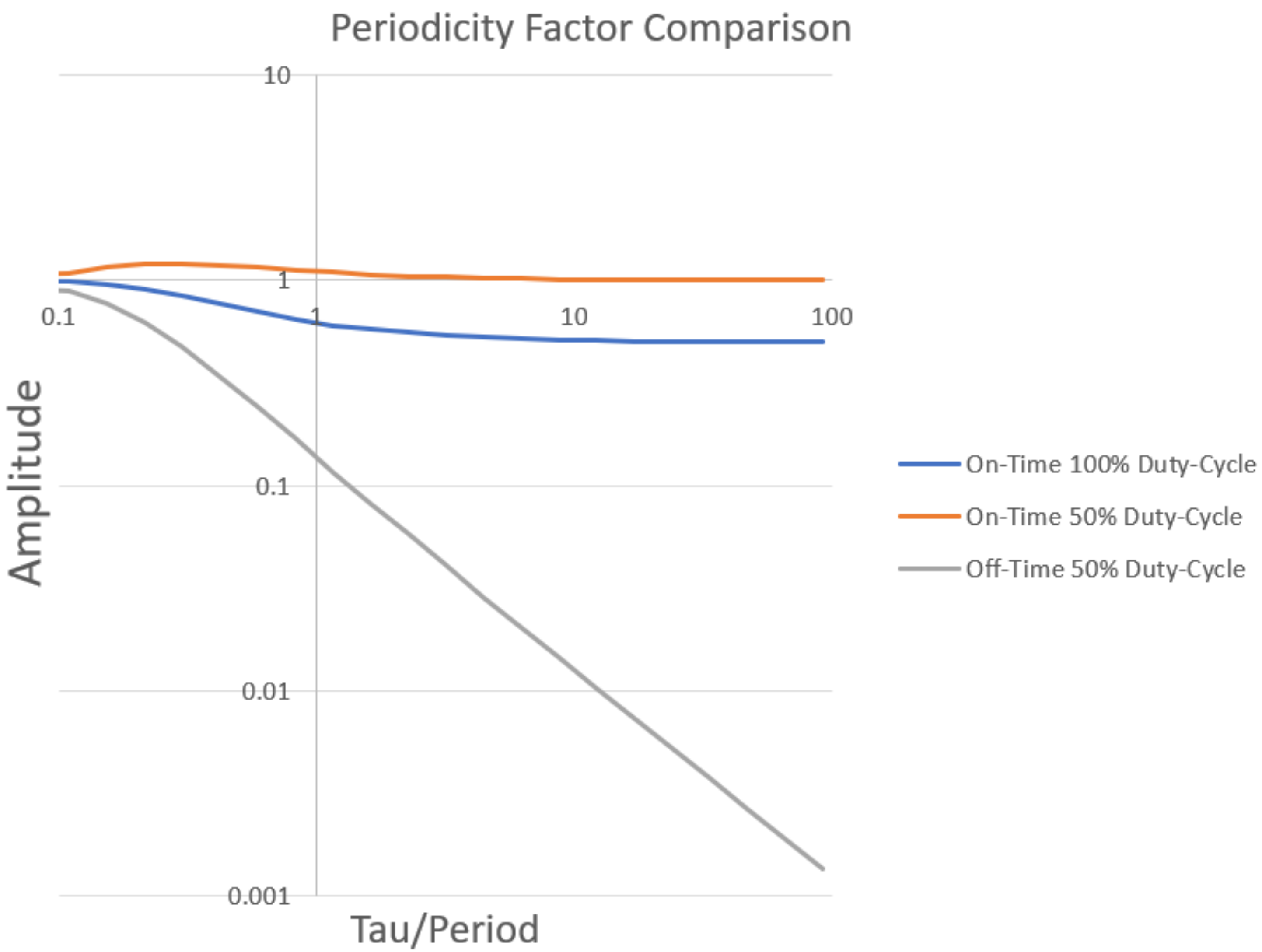
$$= e^{-\left(\frac{t}{\tau}\right)}[1 - X + X^2 - X^3 + X^4 - X^5 + \cdots]$$

$$= e^{-\left(\frac{t}{\tau}\right)}[1 + X]/[1+X^2]$$

original transient | Periodicity Factor

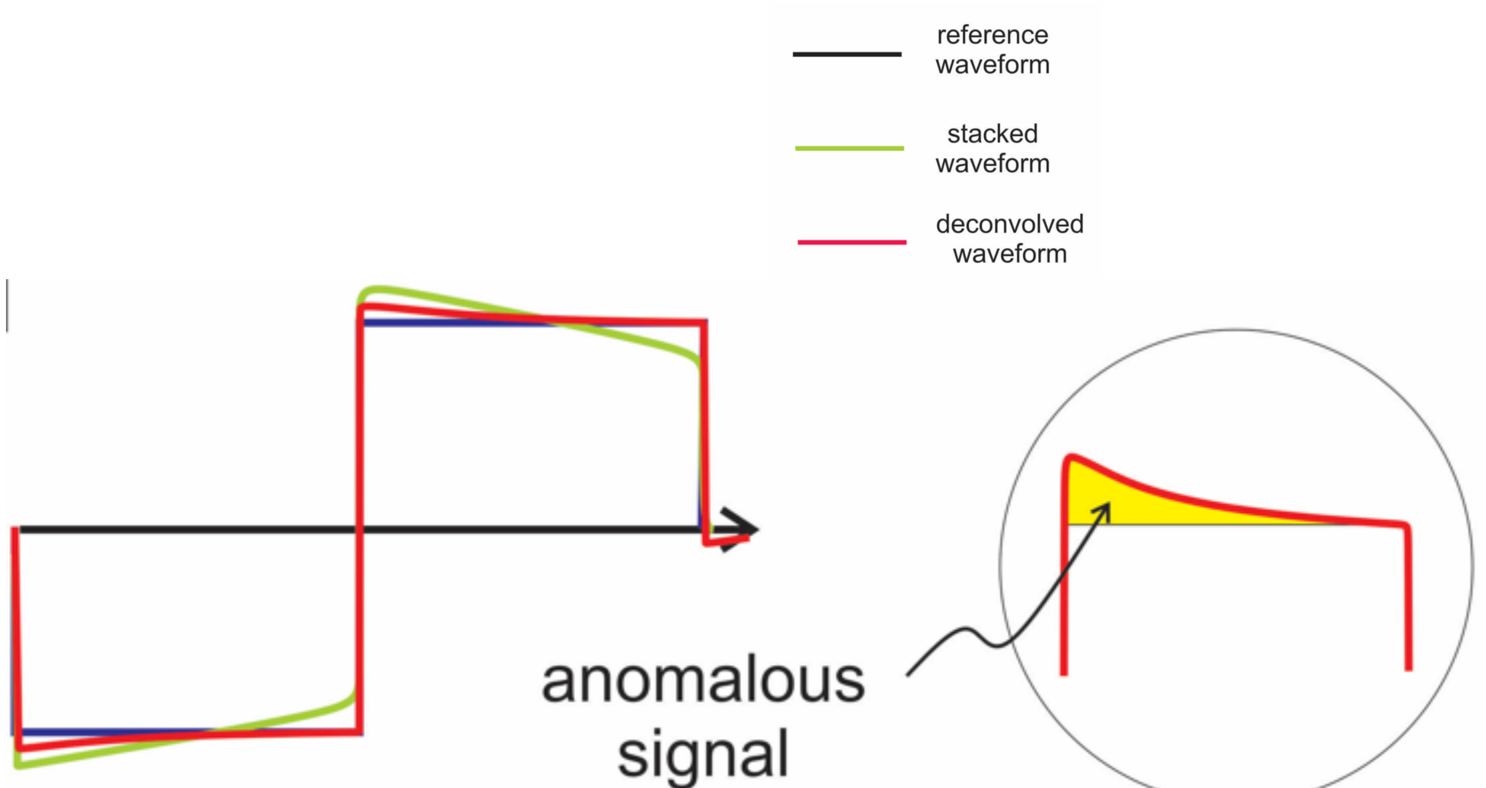
where X= $e^{-\left(\frac{P}{4}\right)}$ and P= $\frac{Period}{\tau}$

Periodicity Factors



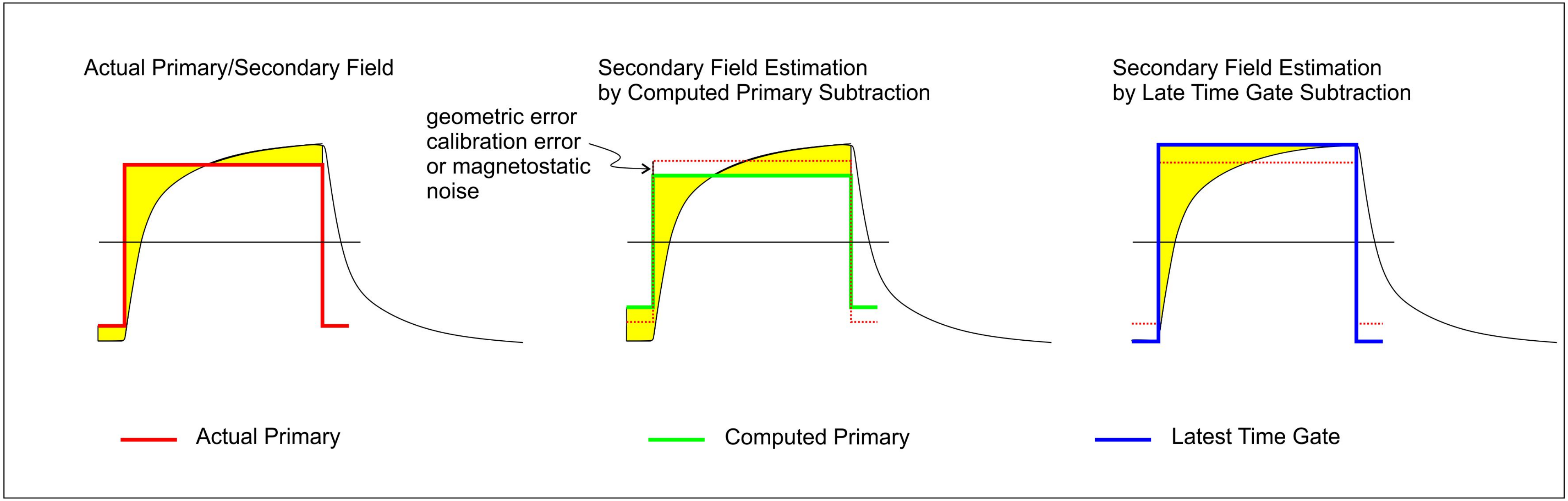
How Are On-Time measurements Done?

- For on-time measurements the anomalous response is deviation of the signal from an expected response curve.
- the response can be deconvolved in post processing to a perfect square wave response



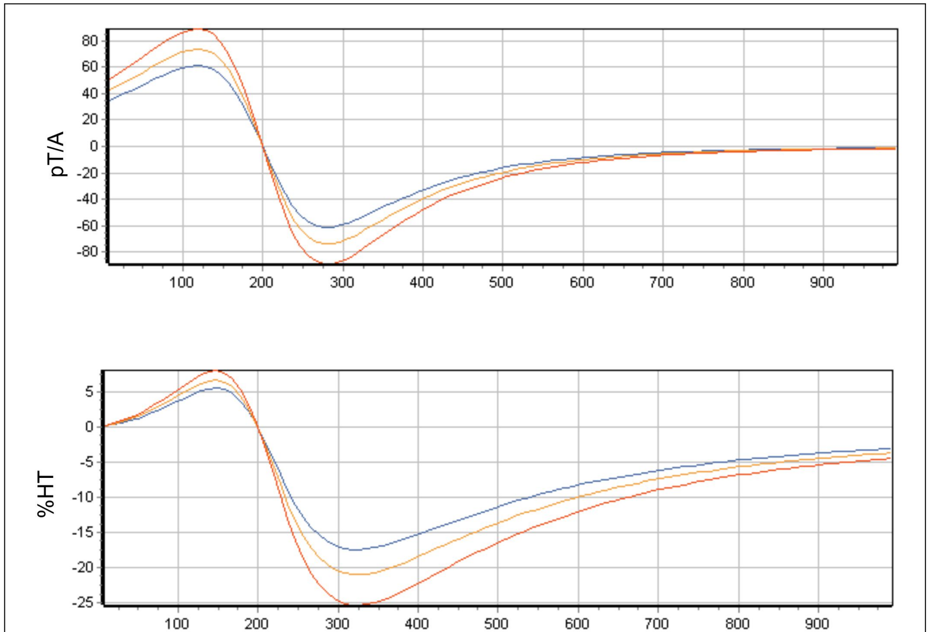
Primary Field Removal

- For off-time system primary field removal is automatic
- For on-time systems removal of primary field requires
  - Subtraction of the computed field
  - Subtracting the late transient as a reference.
  - Usually the late time is referenced to primary field (eg UTEM ch1)
  - Usually the transient is characterized using the late time reference



Filament Model Responses

- Filament modelling useful for analysis of signal for different stacking and averaging schemes and plate parameters
- Generate primary field reference channel and late time referenced transients



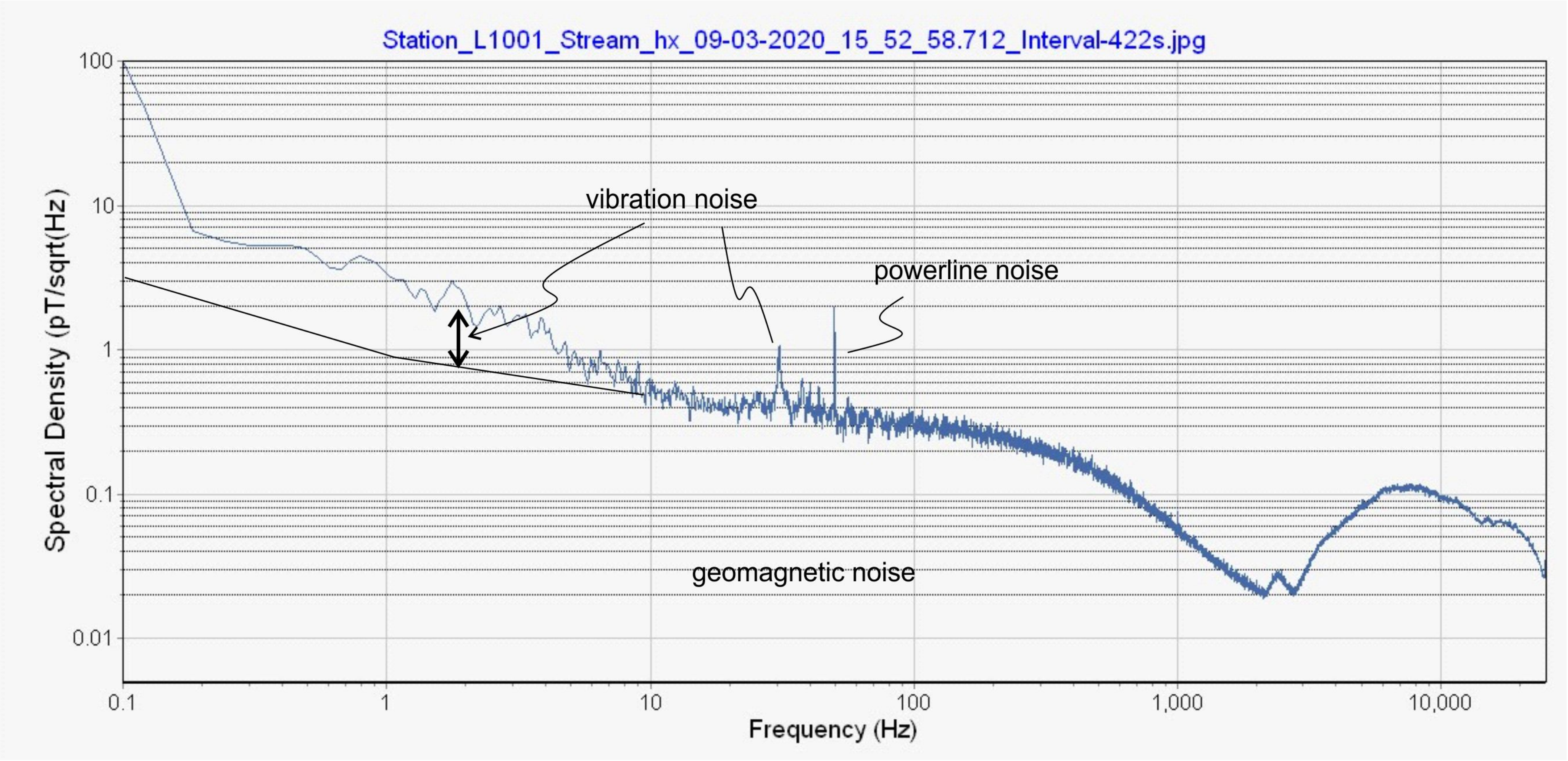
Sources of Noise

- While on-time data are much more sensitive to long tau decays they are also subject to more systematic "noise"
  - Fidelity of the waveform, calibration and deconvolution process
    - 0.1% easy to do
    - 0.01 % hard
    - 0.001% ???
  - Magnetostatics "Noise"
    - Very dependent on geological environment (0.1%-20%) of primary field
  - Geometry errors
    - ~1% at best
    - Very different for Hx a

- Stochastic noise common to both approaches
    - Sensor and system noise
    - Vibration noise

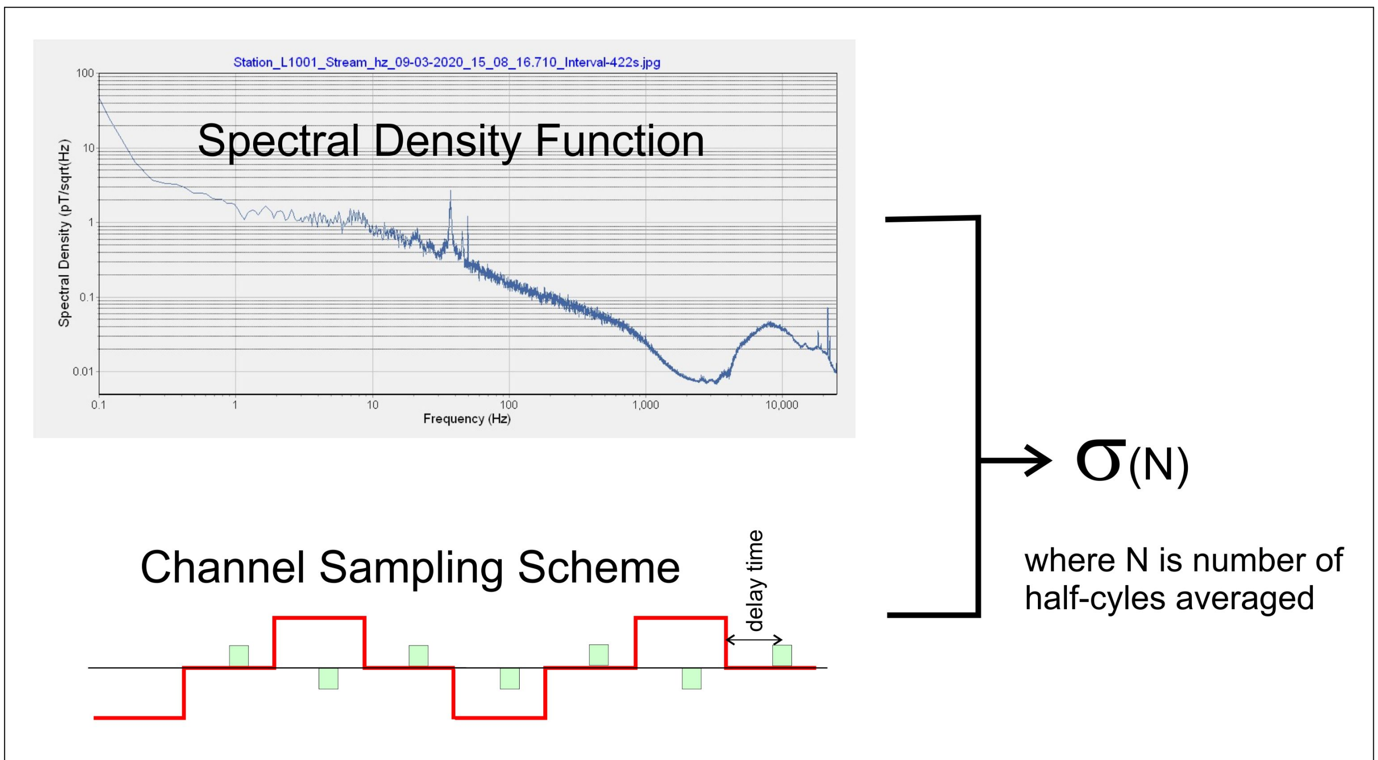
Sources of Stochastic Noise

- Sferics, Powerlines, Sensor vibration
- Time series recording provides a valuable tool for analyzing noise and optimizing survey parameters



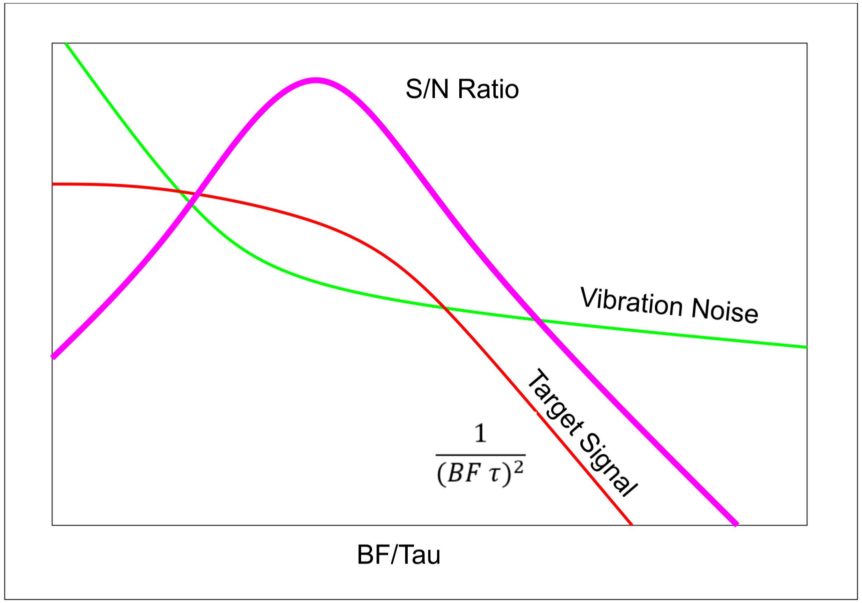
TDEM Gated Channel Noise from Spectral Density Estimates

- Time series recording are potentially useful for determining expected noise in stacked data for different base frequencies and stacking schemes
- Eg Macnae, Noise processing techniques for time-domain EM systems, **GEOPHYSICS, VOL. 49, NO. 7 (JULY 1984);**



Proposed optimization of off-time detection

- Most important parameter is the base frequency
- Based on previous experience in the environment need to estimate channel std deviation as a function of base frequency. Easy to do from time series with or without the loop running.
- For any target plot the expected S/N versus BF based on the noise estimate and the target parameters.



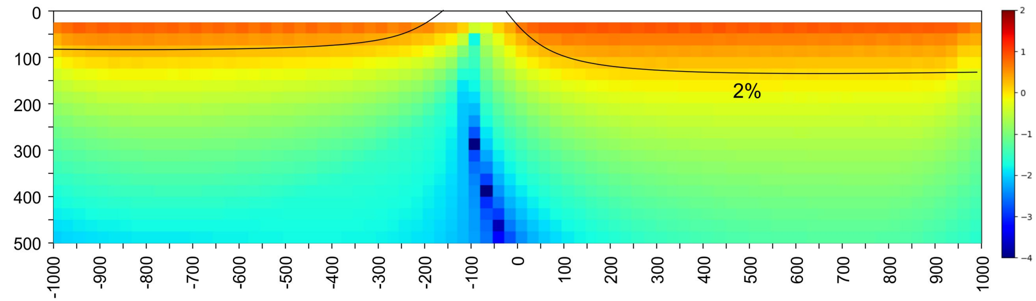
S/N Analysis

- Use the filament model to compute signal as
  - In on time as a late time channel (e.g. UTEM ch1)
    - Expressed as pT/A
    - Expressed as %HT
  - In on time as a late time channel difference (e.g. UTEM ch2-ch1)
    - Expressed as pT/A
    - Expressed as %HT
  - In off time expressed as pT/A
- For any given model: strike length, dip extent, dip, sigma-t, base frequency
  - Compute the responses over an entire grid for each of an ensemble of plate locations, for instance on a vertical plane
  - Plot the maximum (absolute) response observed on the entire grid at position of each plate (centre of top edge referenced).
  - Use the contours of these images at the specified noise limits for the systematic and stochastic noise for the system in question.

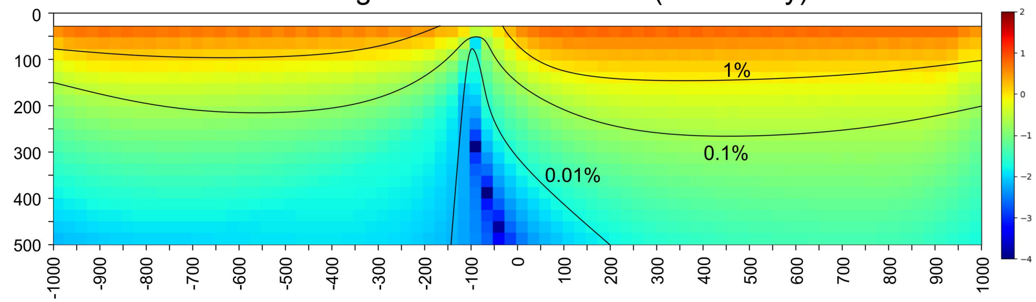
S/N Analysis
Locii of Detectability

Model Parameters: 100m x 100m, dip=45, s=10000S, bf=30

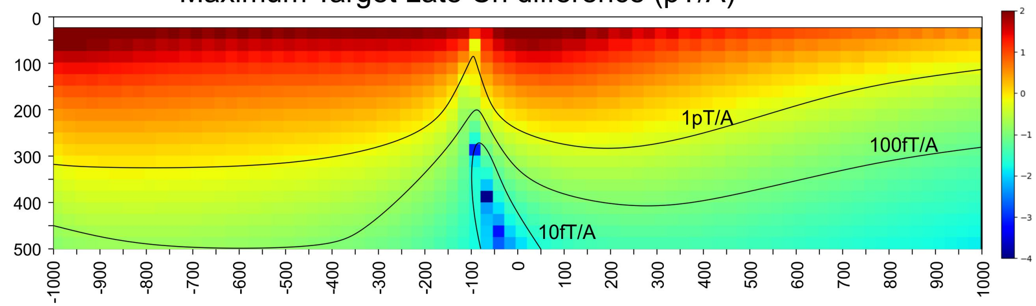
Maximum Target Late Ch (% Primary)



Maximum Target Late Ch difference (% Primary)



Maximum Target Late Ch difference (pT/A)



Conclusions

Nova
Mining Exploration Solutions

- It is possible to use simple models for induction that recreate the sensitivity of a system response to conductance and base frequency.
- All sources of noise should be characterized for any given system
- The two can be combined to form S/N ratio that can be used to predict system effectiveness for a particular exploration target.

Appeals

Nova
Mining Exploration Solutions

- To off-time EM practitioners
  - Pay heed to base frequencies that are too low to be useful given vibration noise
  - Get some add-on on-time recording into your systems. Because of the limits of magnetostatic noise and positioning and pointing errors the on-time recording does not have to be very precise to reduce the risk of missing a VB Ovoid at shallow depth.
- To both species
  - Time series data are extremely useful for understanding noise sources and optimizing S/N