

# The Future of AEM

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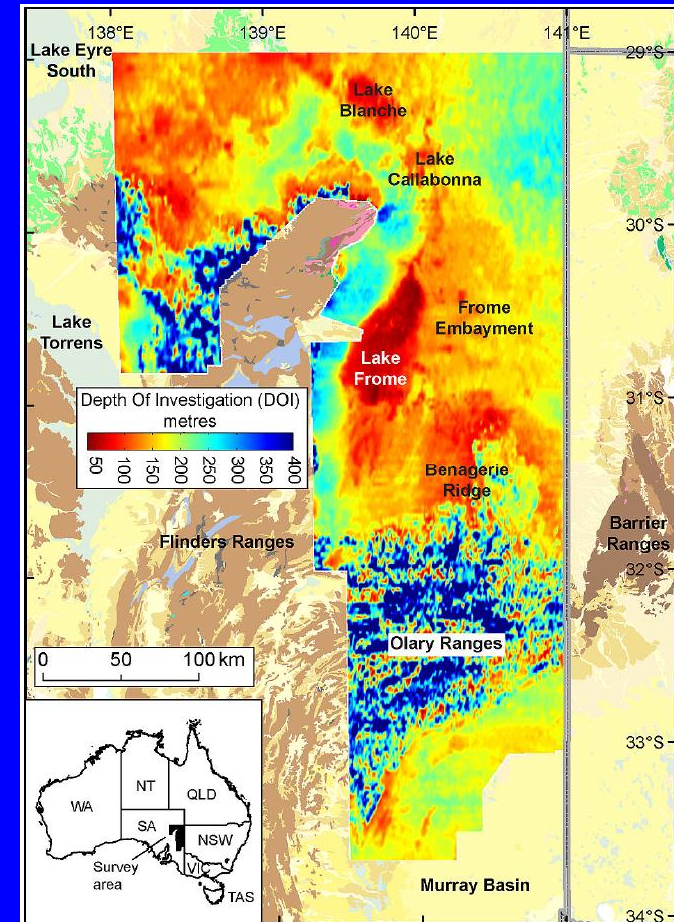


(Stettler, 2009)

# Acknowledgements

## Contributors

- Anglo American Exploration
- Niels Christensen (Aarhus University)
- Andrew Duncan (EMIT)
- Geological Survey of Queensland
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- Peter Kowalczyk (OFG / Mira Geoscience)
- Jean Legault (Geotech)
- Jim Macnae & Terry Kratzer (RMIT University)
- Tim Munday (CSIRO)
- Louis Polome (Spectrem Air)
- James Reid (Groundprobe)
- Richard Smith (Laurentian University)
- Chris Wijns (First Quantum)
- Ken Witherly (Condor Consulting)



Frome Tempest survey (Roach, 2012)

All mistakes are mine!

# Apologies

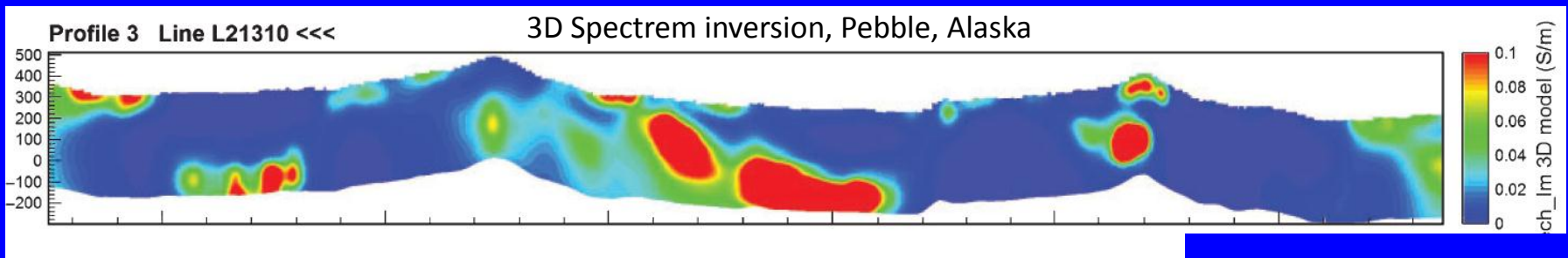
- I can't cover all relevant material in 25 minutes
- I certainly can't cut into beer drinking time

# Disclosure

- Fullagar Geophysics sells EmaxAIR and VPem1D software, and is developing VPem3D, for AEM
- I am Technical Director of Mira Geoscience Advanced Geophysical Interpretation Centre, which is actively engaged in interpretation (including 3D inversion) of AEM. Mira is developing an EM workflow interfaced to Gocad.

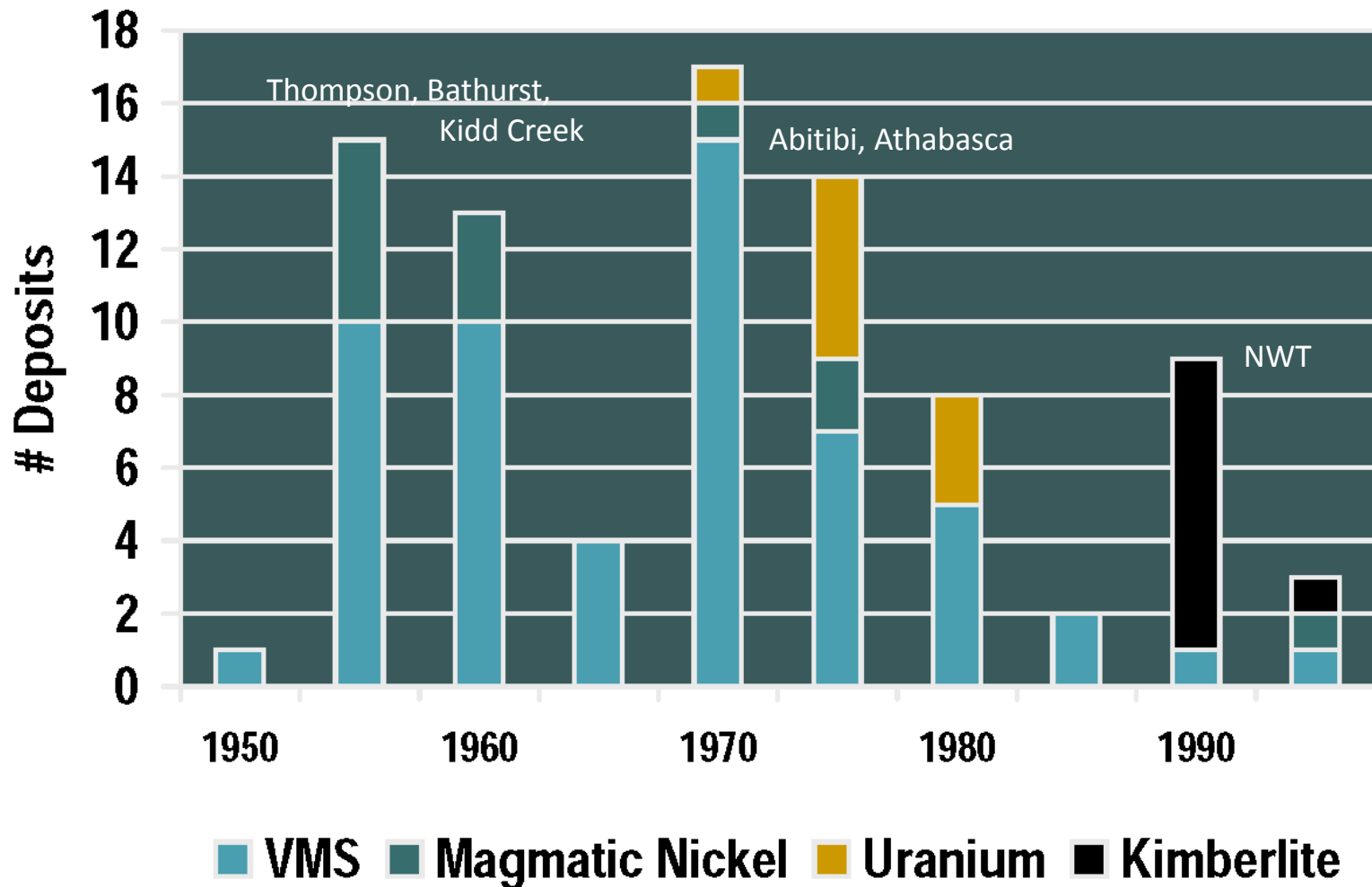
# Outline

1. Introduction
2. New Developments: Acquisition & Interpretation
3. Effectiveness of AEM in Mineral Exploration
4. Improving Effectiveness:
  - Calibration
  - Integrated interpretation
5. Conclusions



(Pare et al, 2011)

# In the beginning ...



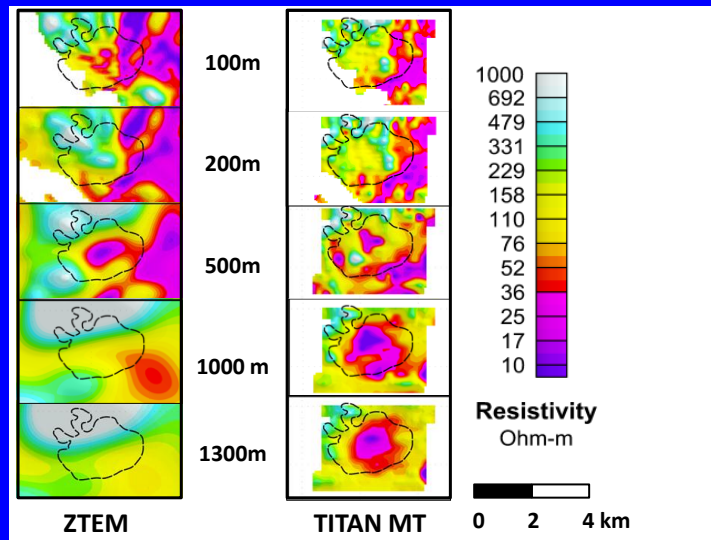
**Canadian AEM discoveries by deposit style**

# 1. Introduction

- Overall, AEM has been extremely successful in both mineral exploration and hydrogeological mapping
- Three key developments during past 10 years:
  - Helicopter TEM, e.g. Hoistem, VTEM, SkyTEM, XTEM, HeliTEM
  - Passive AEM, e.g. ZTEM, AirMT
  - 3D EM inversion, e.g. CEMI/TechnoImaging, UBC/Mira Geoscience

## ZTEM and ground MT comparison

Silver Queen, BC, Canada  
(Smith, 2012;  
after Mira Geoscience)



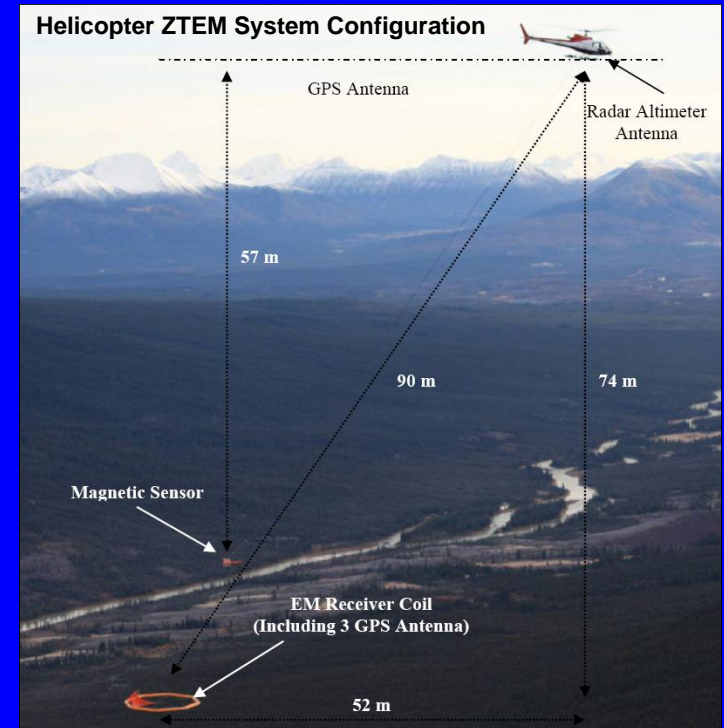
# Airborne EM pros & cons

- **Advantages**

- Speed
- Mobility
- Flexibility

- **Limitations**

- Speed, hence stacking time;
- Weight, hence power;
- Safety, hence height & weather;
- Tx & Rx motion & flexure, hence noise & uncertainty;
- All the above (in conjunction with EM attenuation) conspire to restrict depth of penetration



# Targeting Application

## Targeting of discrete conductors (sometimes deeply buried)

- High power
- Low frequency
- High conductivity (often)
- Preferably B-field
- Arbitrary geology
- Calibration not usually critical

### Principal Markets:

Mineral exploration

Government: UXO detection

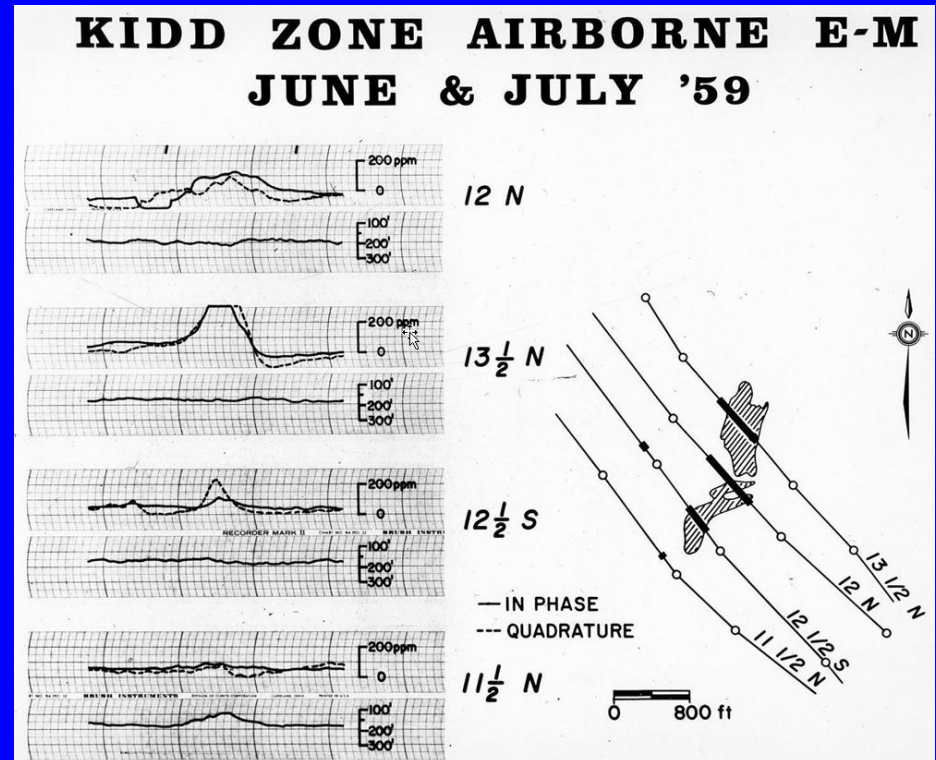
Environmental

...

volts



conductivity  
&  
geometry



(per favour K. Witherly)

# Mapping Application

## Mapping of laterally extensive geological features (often shallow)

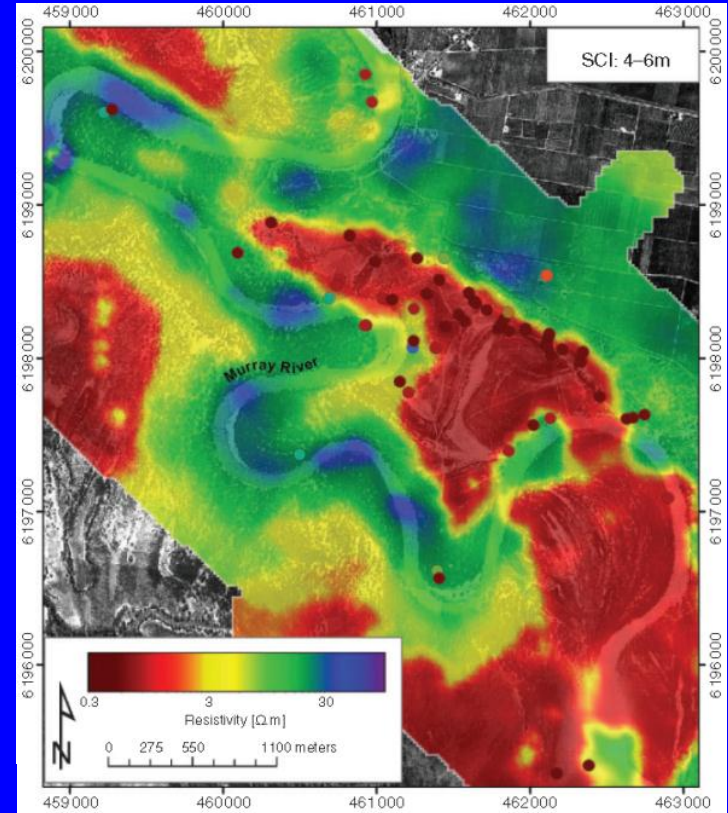
- Moderate power
- Higher frequency
- Moderate conductivity
- Preferably dB/dt
- Layered “1D” geology
- Calibration often critical

### Principal Markets:

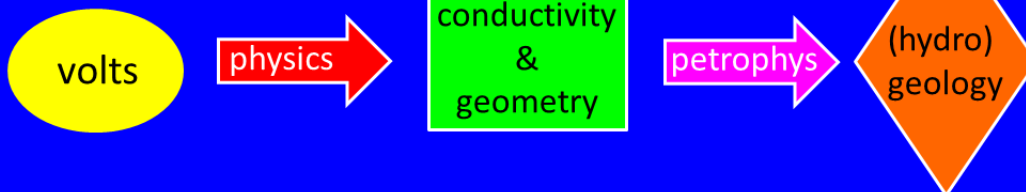
Government: Hydrology  
Bathymetry

...

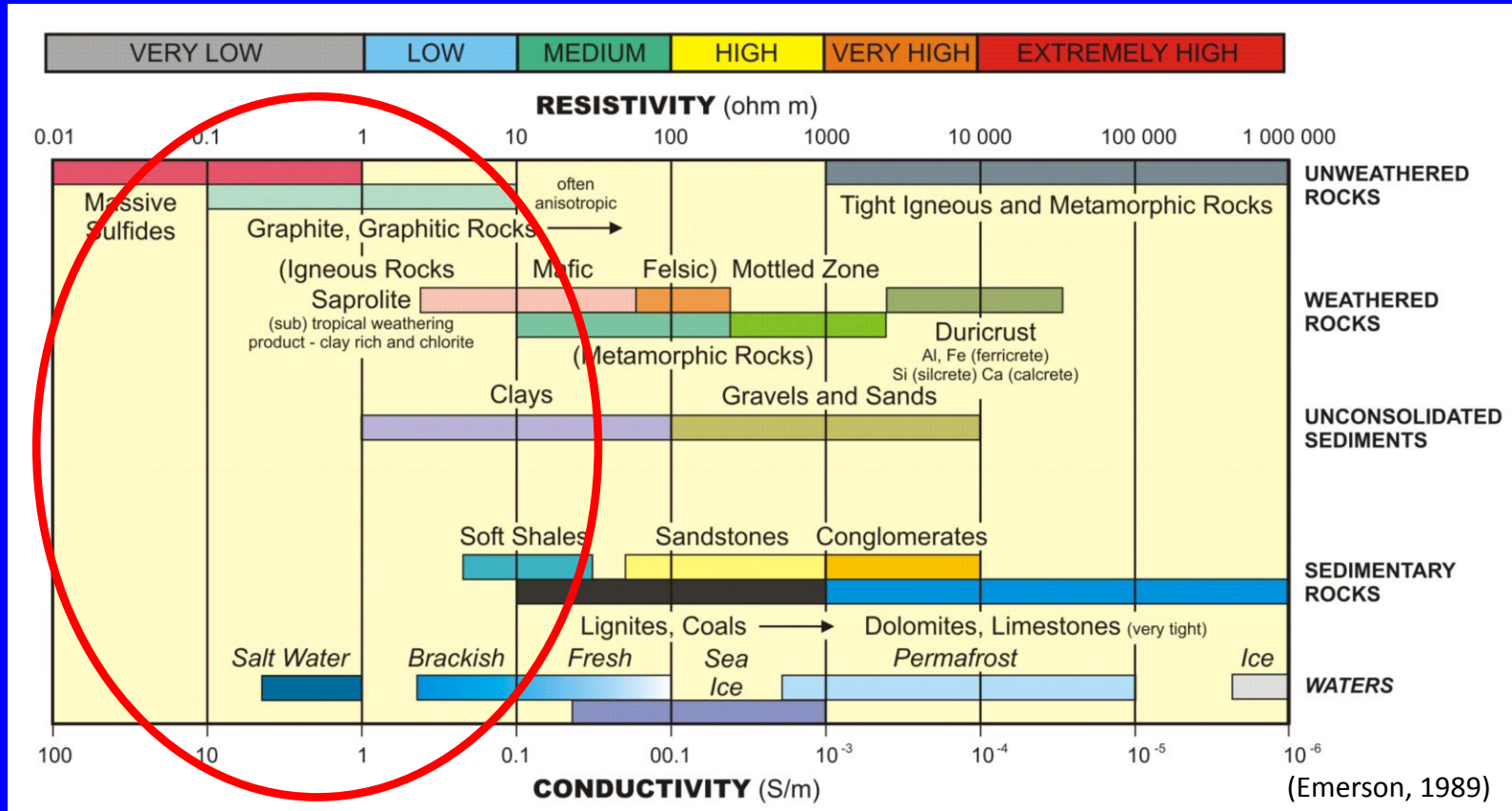
Mineral exploration



(Viezzoli et al, 2009)



# Electrical conductivity



AEM is sensitive to moderate–high conductivity

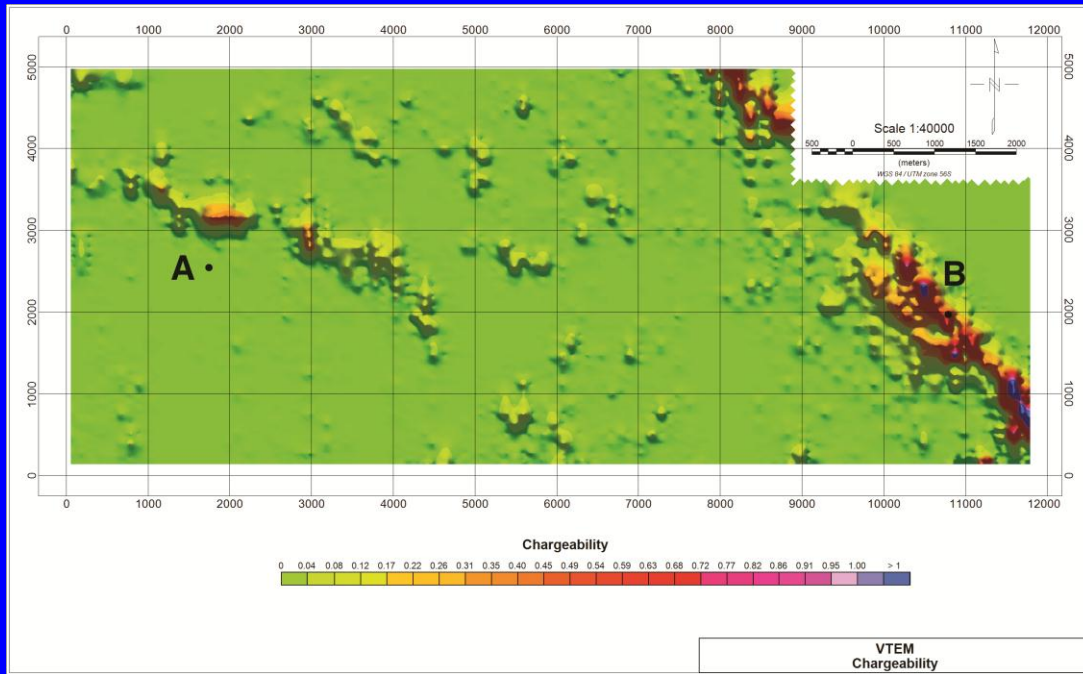
Also influenced by magnetic permeability, SPM, chargeability, and dielectric constant

# 2. New developments

## 2.1 Acquisition

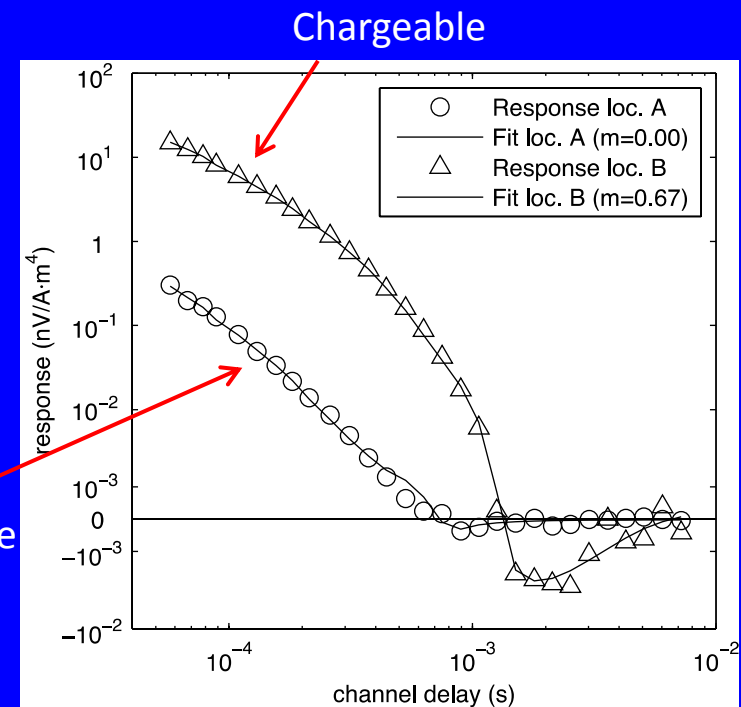
- **Lower TEM base frequency:** e.g. SkyTEM 12.5 Hz trial
  - Increased depth of penetration
  - Improved recognition of SPM effects ( $\sim 1/t$  decays) in central loop helicopter TEM data.
  - Aid detection of “perfect” conductors
  - Inductive IP?
- **Improved calibration**
- **Full waveform recording,** e.g. SkyTEM, VTEM<sup>FullWaveform</sup>
- **More powerful transmitters,** e.g. MegaTEM, VTEM<sup>Max</sup>, Spectrem
- **Very early time acquisition**
  - Higher resolution at shallow depth
- **Direct measurement of B-field:** e.g. total field (HeliSAM), ARMIT sensor, SQUIDs?
- **Airborne E-field measurements (airborne IP):** current AMIRA project.
- **UAVs (drones or airships) for hybrid (ground/air) surveys**
- **Gradient data,** e.g. VTEM<sup>HGRAD</sup>
- **Multiple transmitter configurations,** e.g. as deployed in some UXO systems.
- **Multiple receiver configurations**

# Inductive (M)IP

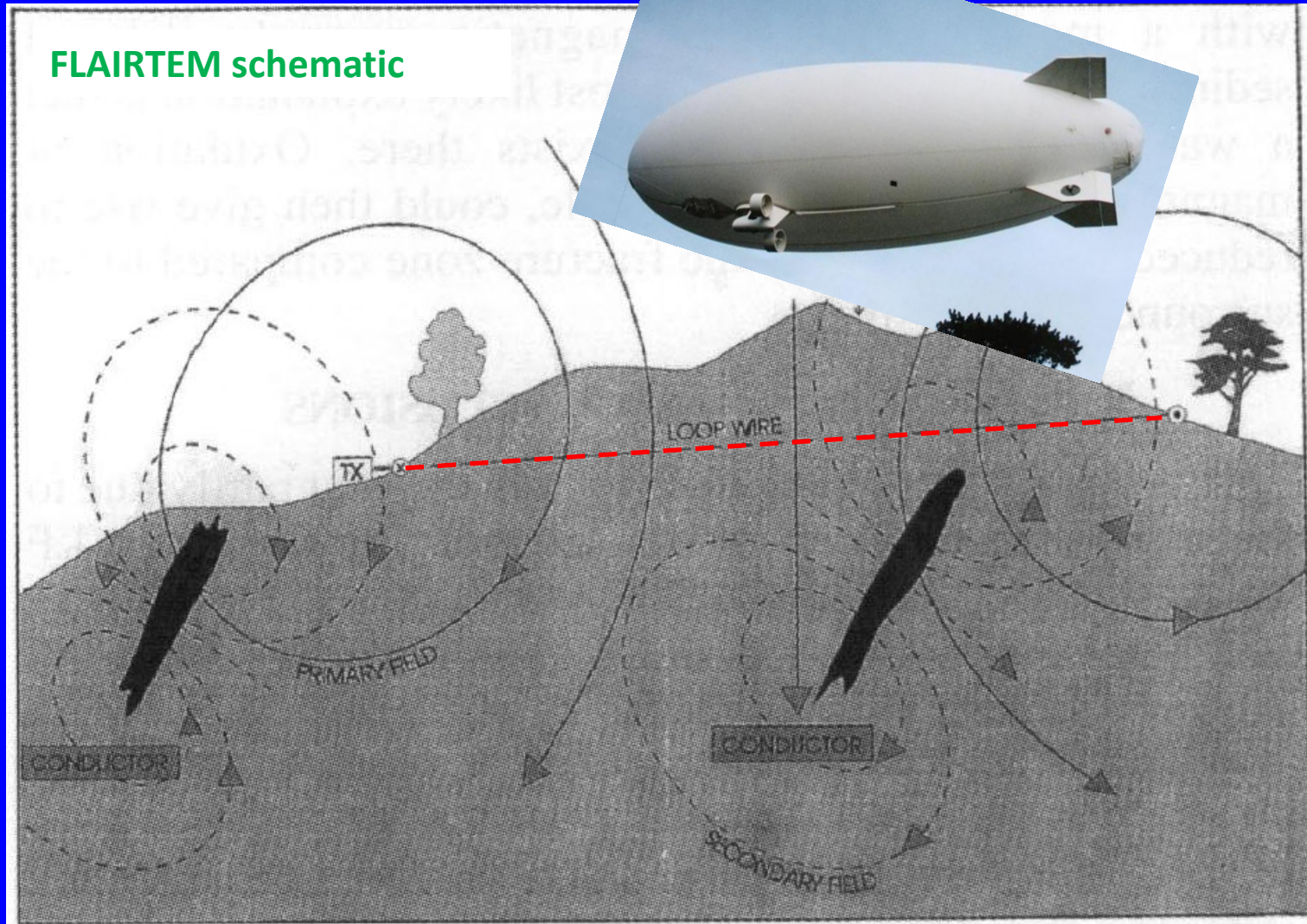


VTEM survey – apparent chargeability

(Kratzer & Macnae, 2012)



# Drones or airships for low noise hybrid AEM



(Elliott, 1998)

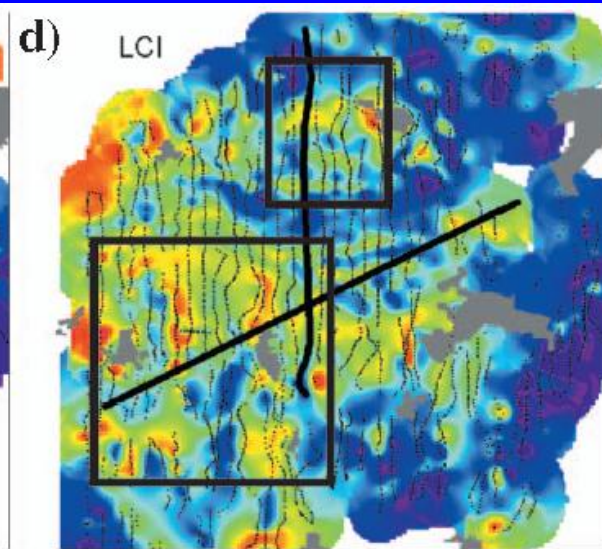
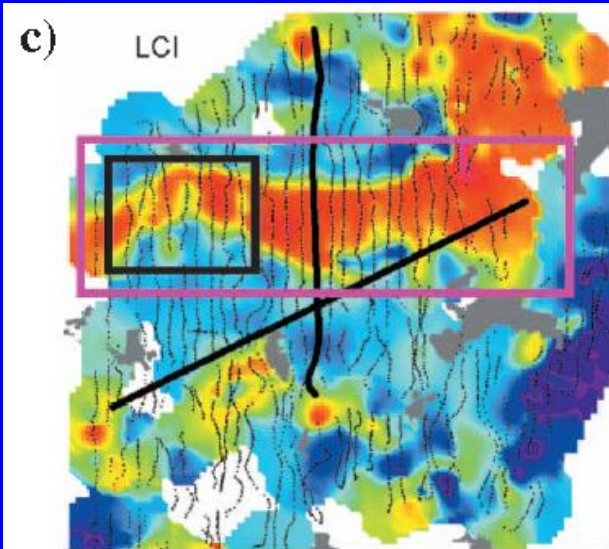
# New developments

## 2.2 Interpretation

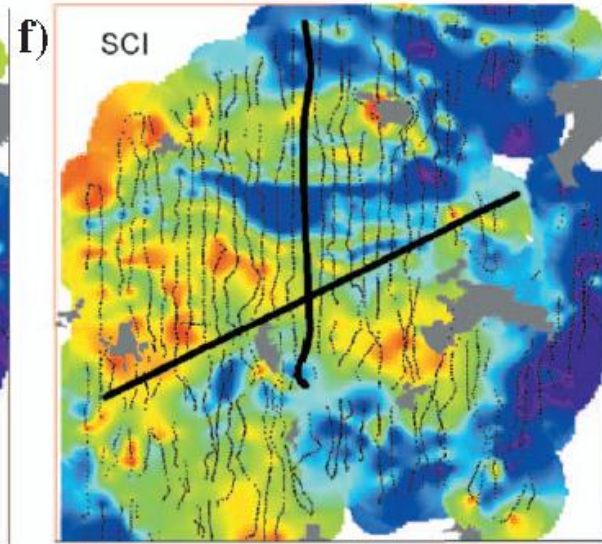
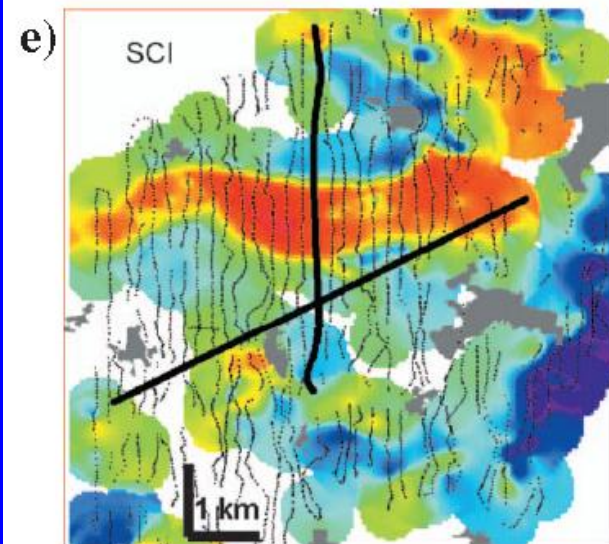
- **Expanded range of 3D inversion options:**
  - Full 3D inversion, e.g. TechnoImaging, UBC;
  - Fast approximate inversion, e.g. VPem3D;
  - Anomaly selection/discrimination, and localised 3D inversion
- **Hybrid 1D/3D inversion**, e.g. holistic, LCI/SCI, VPem1D
- **Data fusion**, e.g. SOM (Hodgkinson et al, 2012)
- **Integrated interpretation**
  - Inversion based on geological or hydrogeological model, e.g. VPem1D, VPem3D
  - Lithology and/or hydrological parameters inferred from multiple geophysical data sets
  - Generation of exploration targets
- **Joint inversion**, e.g. active and passive AEM
- **Petrophysical data base**, e.g. Mira Geoscience RPDS
- **Bayesian inversion**, e.g. Minsley (2012), Brodie & Sambridge (2012)

# Laterally and spatially constrained 1D inversion

Mean resistivity  
-160  
to  
-140m  
elevation

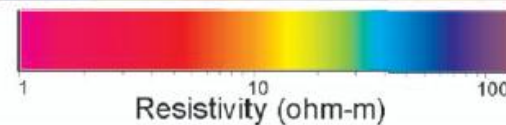


Mean resistivity  
-80  
to  
-60m  
elevation



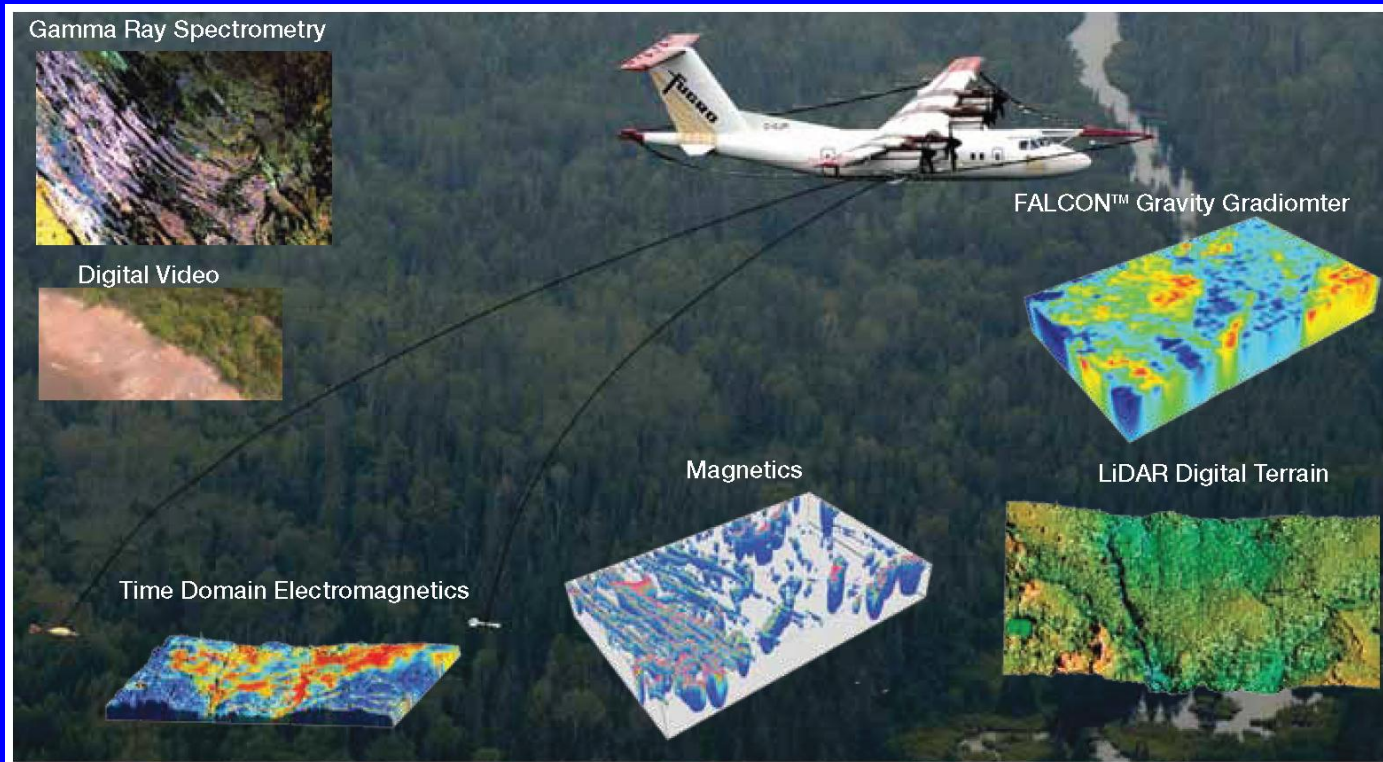
Stevnstrup,  
Denmark

(Viezzoli et al, 2008)



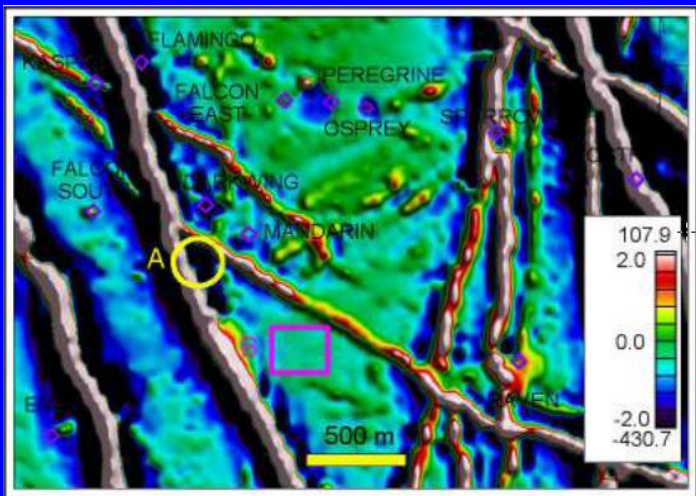
# Interpret multiple parameters

- EM in combination with other parameters more likely to discriminate targets
- Cooperative inversion

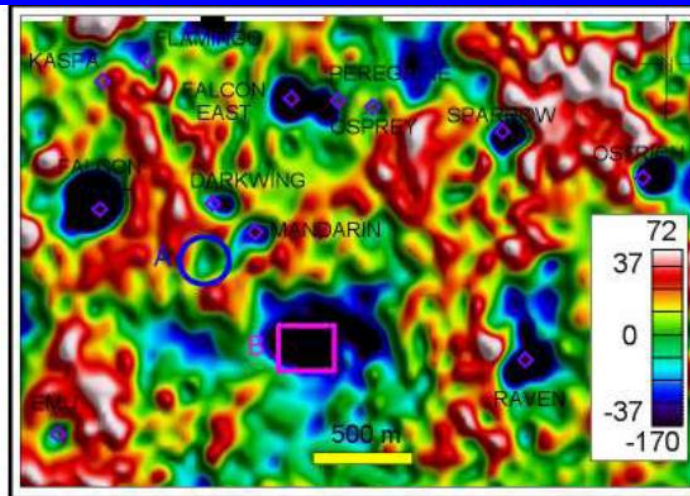


Fugro Gryphon system

# Data Fusion

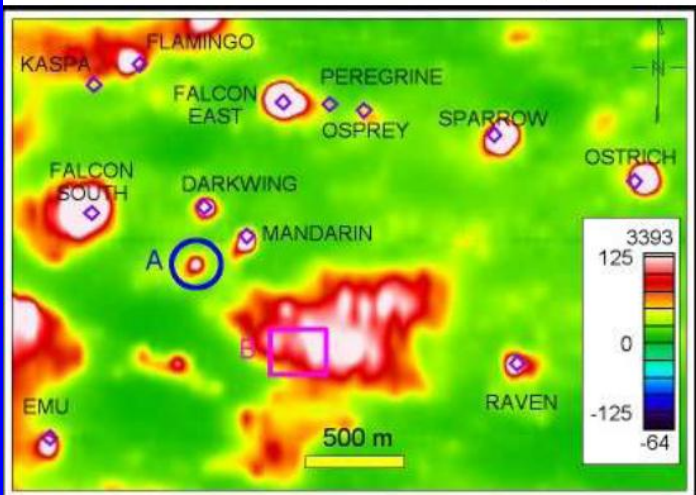


Magnetic map

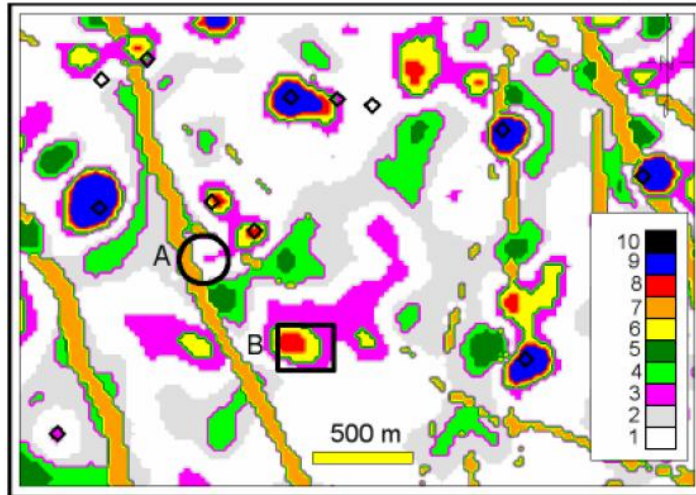


Vertical gravity gradient map

Quadrature EM map



RESULTING classification map



# 3. Effectiveness of AEM in mineral exploration

Significant improvements, especially in acquisition technology in 21<sup>st</sup> Century:

Higher power

GPS navigation

Lower frequency

New (Tempest) & improved (Spectrem 2000) B-field systems

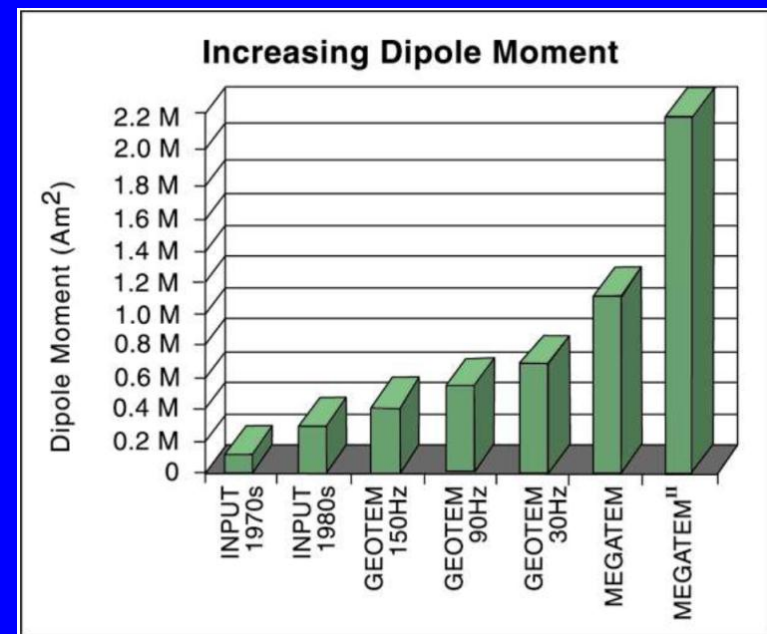
Helicopter TEM

Passive AEM

Fast 1D inversion

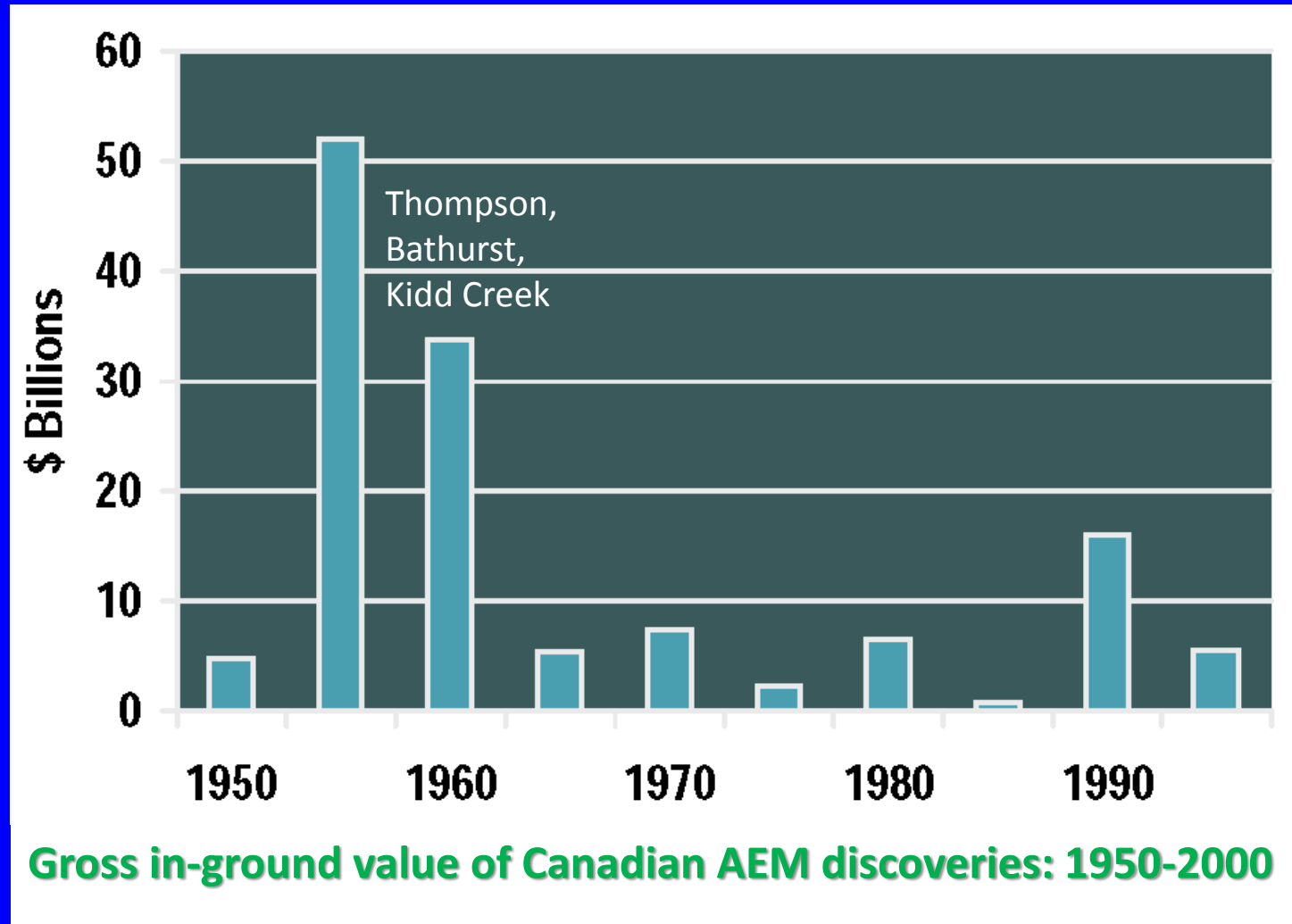
Advent of 3D inversion

However, ...



(Smith, 2012)

# Effectiveness of AEM in mineral exploration - 2

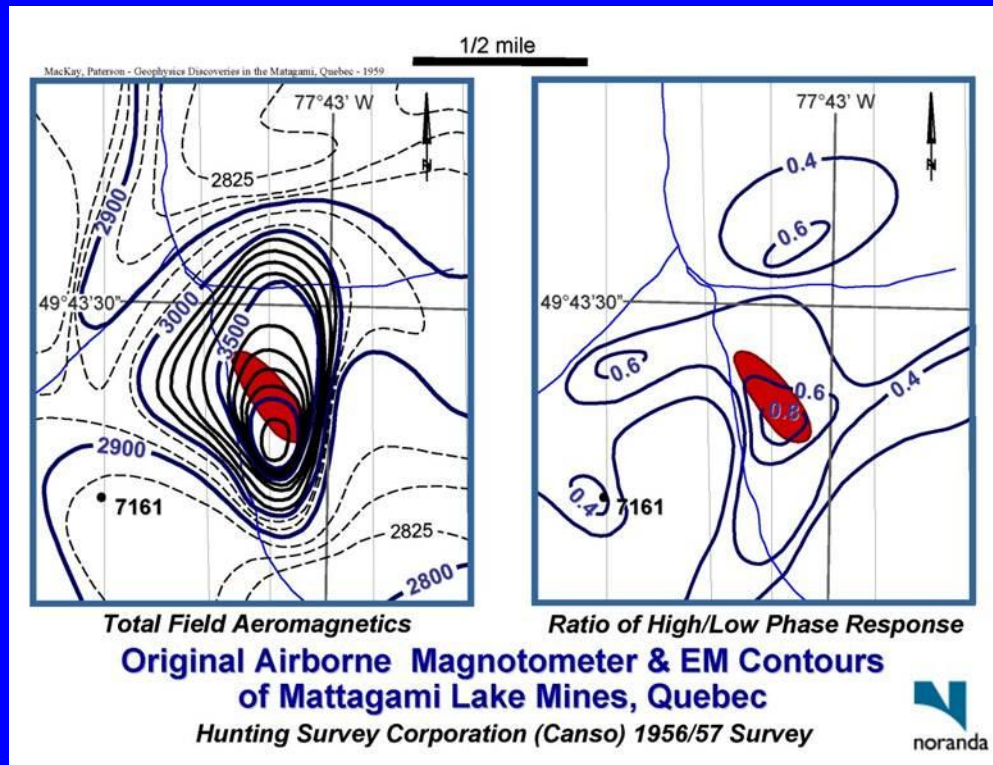


(Witherly, 2000)

# Effectiveness of AEM in mineral exploration - 3

... few major new AEM discoveries in recent years.

=> Extra incentive to improve effectiveness of AEM



# 4. Improving effectiveness of AEM

## What are the factors to examine?

1. All elephants already found?
2. Targets too deep?
3. Too many anomalies?
4. Poor area selection?
5. Not enough AEM flown?
6. Sub-optimal calibration?
7. Geologically-challenged interpretation?
8. ...

# 4.1 Improving effectiveness of AEM

**Strategies:**

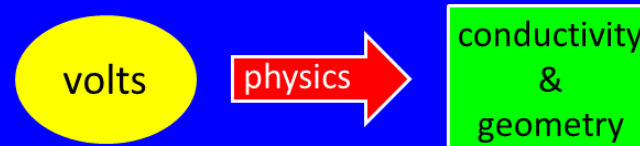
1. improved system calibration
2. integrated interpretation

## Tactics:

- 1.1 Renewed emphasis on system calibration
- 1.2 Re-visit system geometry specification
- 1.3 Disclosure of filter parameters
  
- 2.1 Invert (hydro)geological models
- 2.2 Interpret lithology from AEM + gravity + magnetics + ...
- 2.3 Incorporate geological targeting criteria

# System calibration

- Ensures correct relationship between AEM data and ground conductivity



- Always recognised as important
  - Underpins consistent quantitative interpretation
  - Essential for seamless national mapping
  - Improves detectability of subtle conductivity variations, e.g. alteration haloes
- Calibration entails verification of processing & modelling software as well as acquisition systems



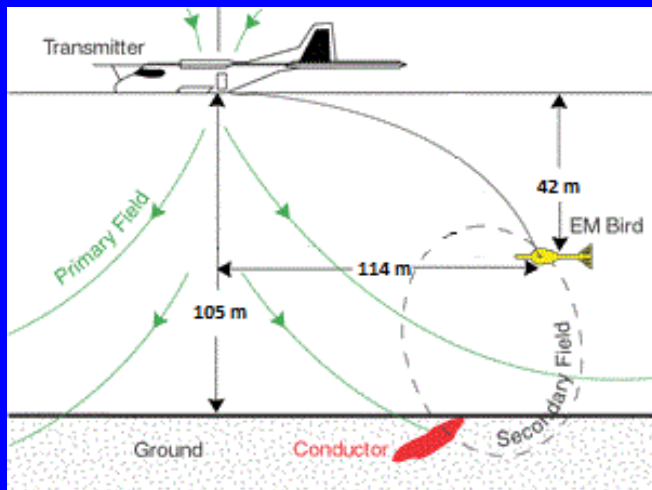
# System parameter specification

Position and attitude of transmitter and receiver: more difficult for fixed wing (towed bird)

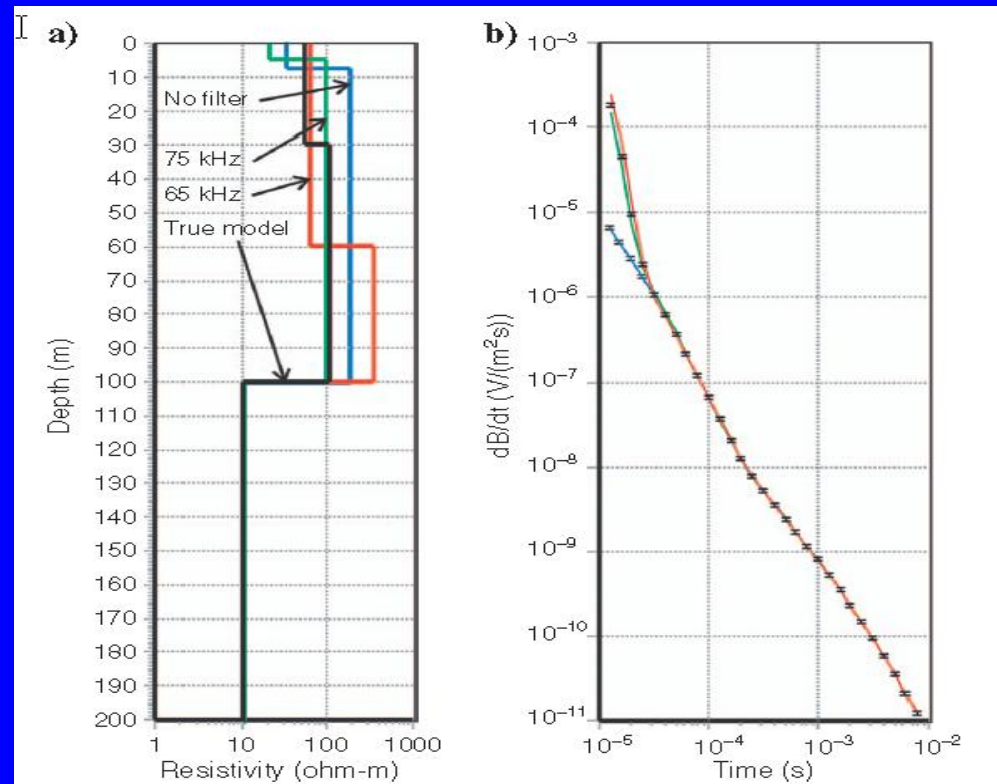
Require parameter settings for modelling/inversion of the data

Sometimes feasible to invert for system parameters, e.g. Brodie & Sambridge (2006)

## Effect of incorrect filter settings on inverted models



Errors in position or filter settings can seriously degrade AEM data



(Christiansen et al, 2011)

# System calibration

## Mechanics:

Ideally, establish cross-calibrated sites, nationally & internationally, and ...

... disseminate calibration site data freely.

## Several types of calibration site, including:

### 1. Layered (1D), e.g. Lyngby (Denmark)

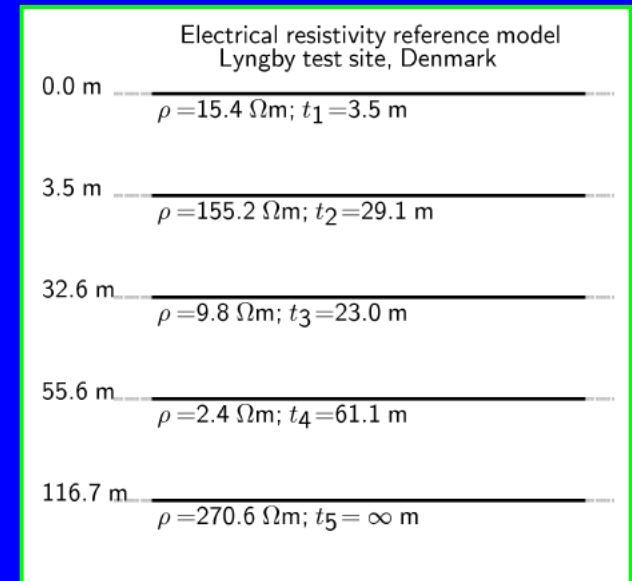
- Develop standard model
- Define standard response curves (for each system)
- Hover calibrates (for helicopter systems)
- Extendable to other sites, e.g. Davis et al (2010)

### 2. Conductive target(s), e.g. Reid-Mahaffy (Ontario)

Options in WA: Nepean, Forrestania, Kauring?

### 3. Highly resistive (for wire loop calibrate): Davis & Macnae (2007)

### 4. Marine: seawater conductivity; altitude calibration



## 4.2 Improving effectiveness of AEM

**Strategies:**

1. improved system calibration
2. integrated interpretation

### Tactics:

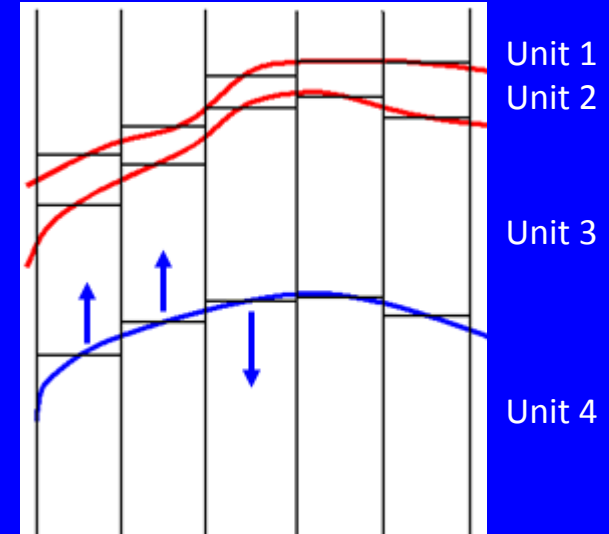
- 1.1 Renewed emphasis on system calibration
- 1.2 More accurate system geometry
- 1.3 Disclosure of filter parameters
  
- 2.1 Invert (hydro)geological models
- 2.2 Interpret lithology from AEM + gravity + magnetics + ...
- 2.3 Incorporate exploration targeting criteria

# Inversion of a geological model

Model cells

Rocktype classification & properties

category	mean	min	max	pdf
Severne sandstone	2.56	2.51	2.65	
Cambrian	2.72	2.69	2.82	
felsic sediment				
dolerite				
granite				
fault zone				
breccia				
massive mt				
disseminated mt				



Strong driver for integration if underlying model is geological

Permits additional inversion options, e.g. adjustment of geometry

“Natural” incorporation of geological constraints

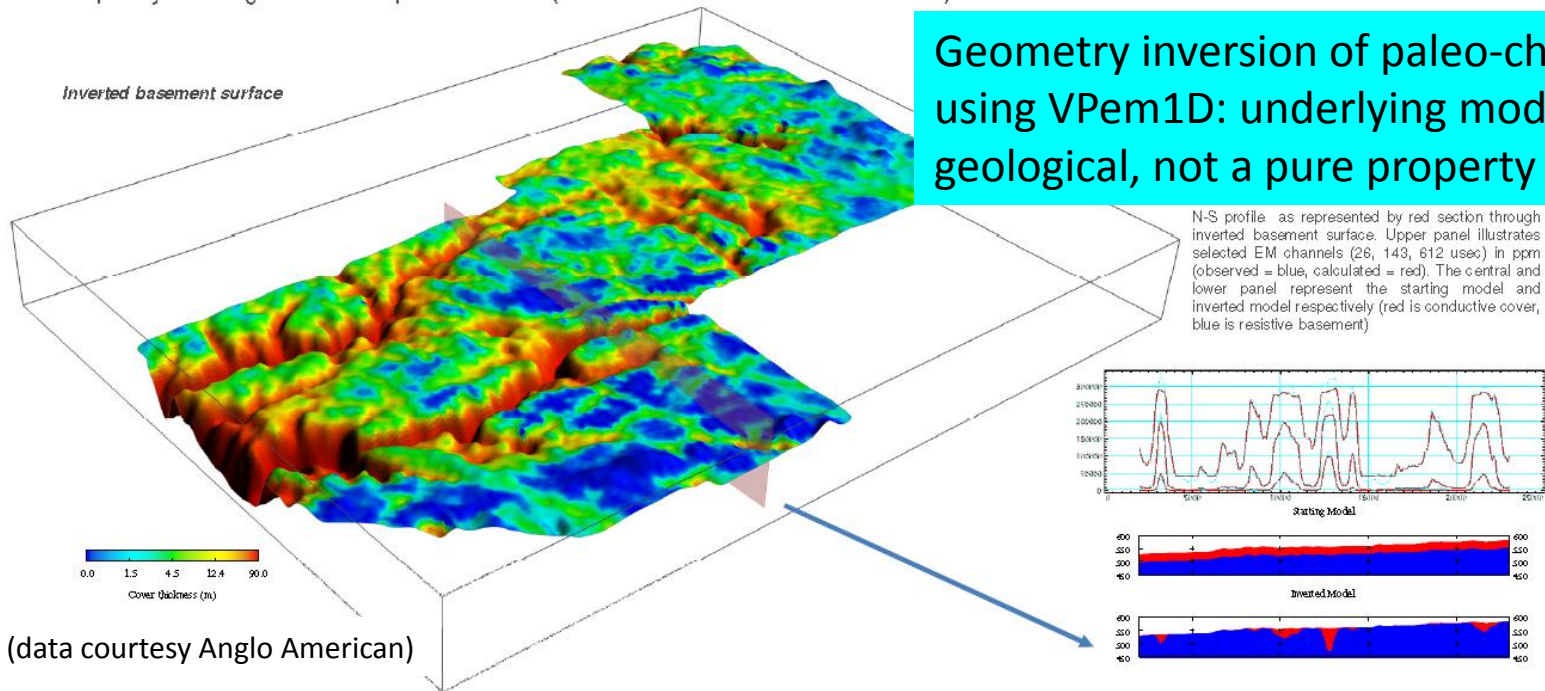
Apply same approach to hydrological models?

# Inversion of a geological model

## Spectrem Example:

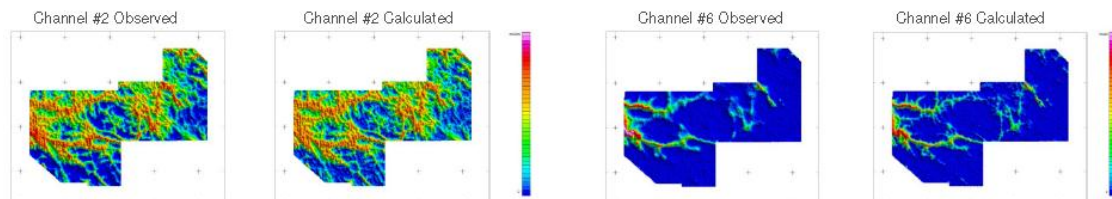
A simple two layer starting model was assumed comprising 30m of conductive (100mS/m) cover/paleochannel overlying resistive (1mS/m) basement. VPem1D geometry inversion adjusted the base of the upper conductive layer to produce a simple geological model explicitly defining the base of paleochannel (all EM time channels were inverted).

Geometry inversion of paleo-channel using VPem1D: underlying model is geological, not a pure property model



(data courtesy Anglo American)

Geometry inversion adjusted the base of the paleochannel reducing the chi-square data misfit from 8436 to 55 (assuming a 1% data uncertainty). Data misfit could be further reduced by then inverting for conductivity variations in the basement (or cover). Observed and calculated responses of selected EM time channels (#2 @65 usec and #6 @1237 usec) are shown in map view to the right.



(Mira Geoscience & Fullagar Geophysics)

# Interpret lithology from multiple data sets

AEM as one ingredient in a greater whole

Data sets for GSQ Mount Dore integrated interpretation

300m BHP Geotem data

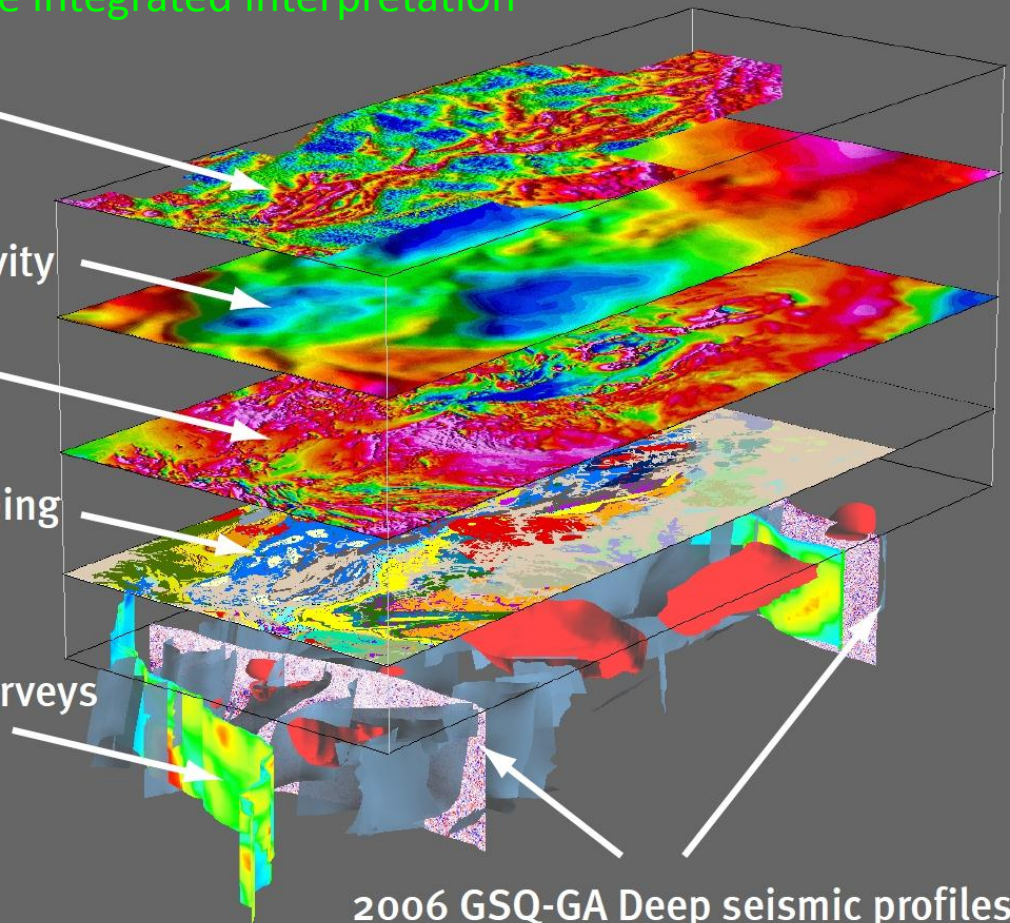
Company and GSQ (4km) Gravity

Company and government  
400m TMI Magnetics data

2006-9 GSQ Geological mapping

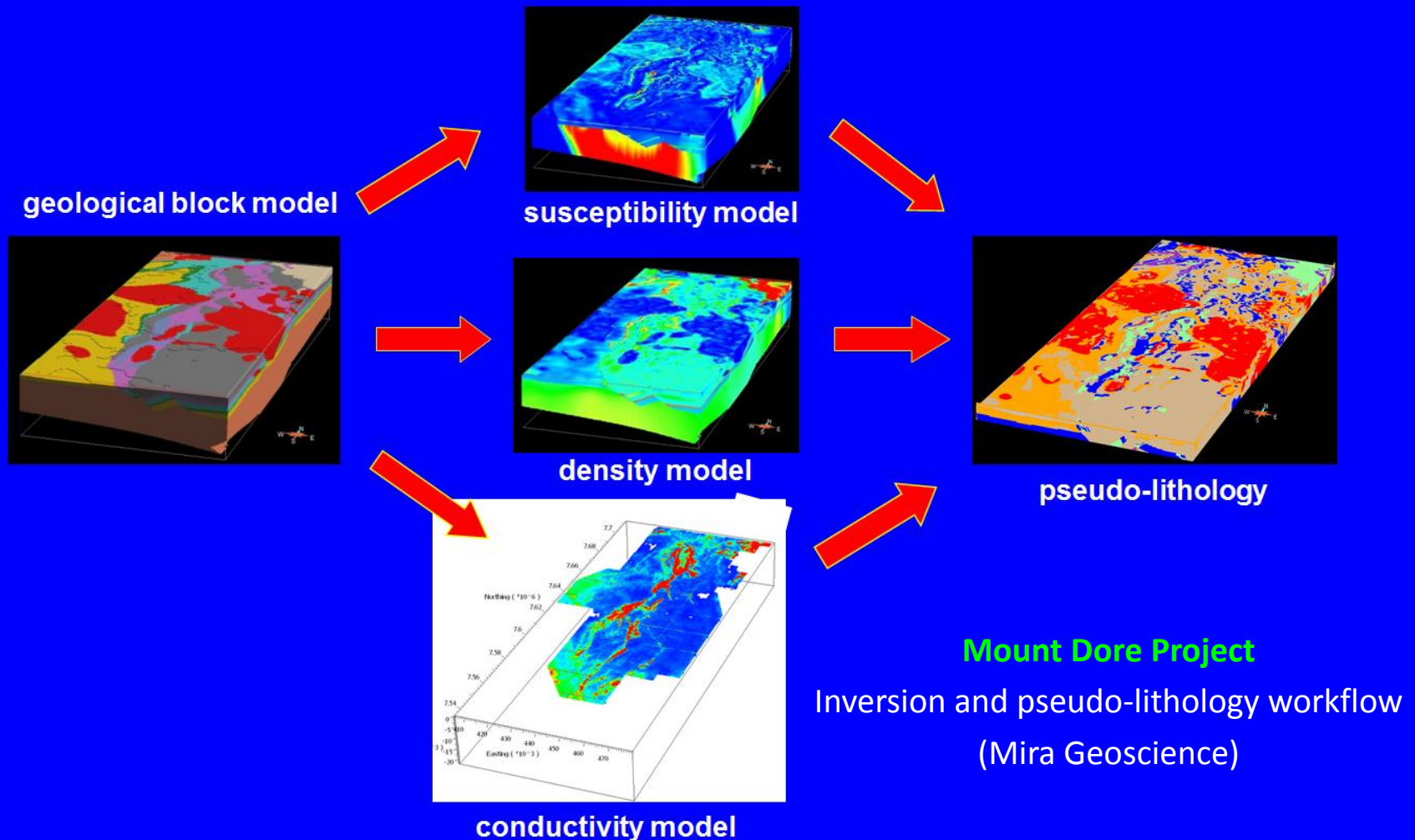
2009 GSQ Magnetotelluric surveys

2006 GSQ-GA Deep seismic profiles



# Interpret lithology from multiple data sets

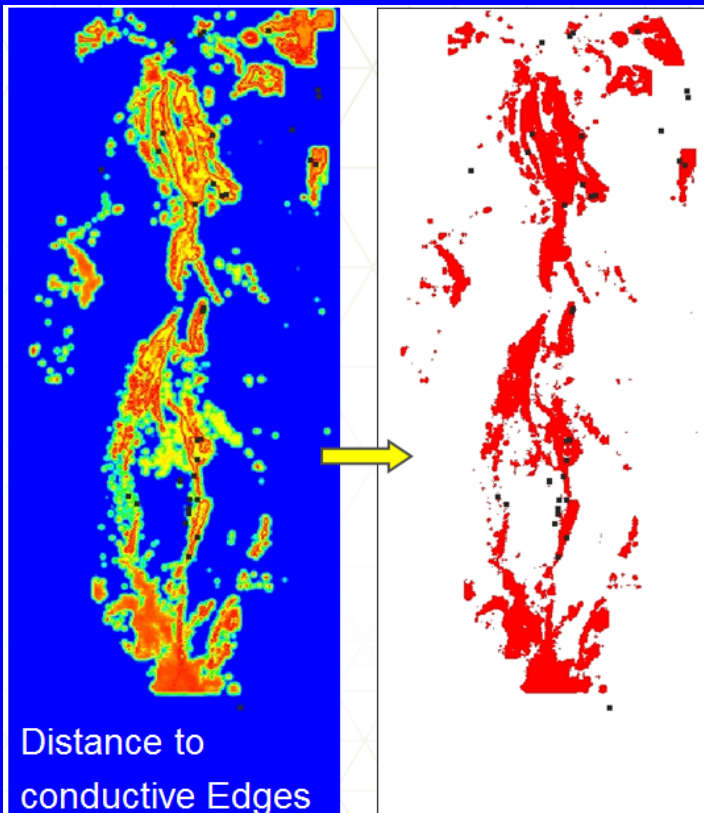
- Incorporate geological observations (constraints)
- Develop translators: geology  $\longleftrightarrow$  geophysics, e.g. LogTrans, SOM



# Incorporate exploration targeting criteria

Combine ...

- Current geological conceptual models
- Understanding of geophysical footprints (possibly subtle)



Exploration Criteria	Weight +	Weight -	Contrast	Stud. Contrast	Favourable Range - Start	Favourable Range - End
Coincident Gravity High-Magnetic High	2.29	-0.2	2.49	5.9	0.81	0.246
Distance C-Sharp Filter ISO <35	2.88	-0.91	3.79	11.09	0m	300m
Distance to Crustal faults	0.74	-0.32	1.06	3.12	0m	964m
Distance to faults intersecting mafics	1.12	-0.29	1.41	4	0m	921m
Fault Roughness	2.79	-0.17	2.96	6.63	0	0.00015
Geological Complexity	1.8	-0.35	2.15	6.09	0.107	0.0198
Normalised Susceptibility	3.25	-0.14	3.39	7.03	0.372	0.0884
Regional Density Model	3	-0.08	3.08	5.11	0.426	0.32
Uranium divided by Thorium	2.12	-0.58	2.7	8.1	1.289	0.274
Distance to Gold Anomaly <150	5.16	-0.29	5.45	14.15	0m	304m
Distance to Copper Anomaly <2000	5.72	-0.75	6.47	19.35	0m	250.7m

3D Weights of Evidence Targeting

# Conclusions

## General:

- Impressive technical developments in AEM delivered during the past decade.
- Mapping has supplanted direct targeting as the prime AEM application

## Future Developments driven by mineral exploration:

- Lower frequency TEM
- Higher power
- Expanded range of 3D inversion options

## Future developments driven by hydrological mapping:

- Very early time recording
- Bayesian inversion

# Conclusions - 2

## Generic future developments (needs and wants) for both exploration & hydrology:

- Calibration
- Full waveform recording
- Hybrid 1D/3D inversion
- Integrated interpretation
- Petrophysical data base

## Last word:

- Need greater engagement with geologists and hydrologists, to maximise end-user benefit
- This workshop is a good start!

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