Deep Exploration Technologies Cooperative Research Centre

WA-ASEG-Inversion Workshop
Perth WA - September 2014

Brett Harris[1,2], Andrew Pethick[1,2], Eric Takam[1,2],
[1,] *Department of Exploration Geophysics - Curtin University*
[2] *Deep Exploration Technologies Cooperative Research Centre*

2 September 2014

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SEEK WISDOM

OUTLINE

1. MT and Seismic (Conductivity vs Velocity)

2. ***A distraction***: Seismic to electromagnetic coupling (and visa versa). (Is it real)

3. ***Cooperative Inversion:*** What are we trying to achieve – (could gradients be the key).

4. Properties that can be measured and ***sub-domains***.

5. Seismic – ***Reflectivity → Spatial Attributes***

6. Seismic - ***Attributes General*** (Dip Attributes, Streamlines, Direction of change, automatic conditioning of MT inversion)

7. Conclusion

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Inputs → Output

Input

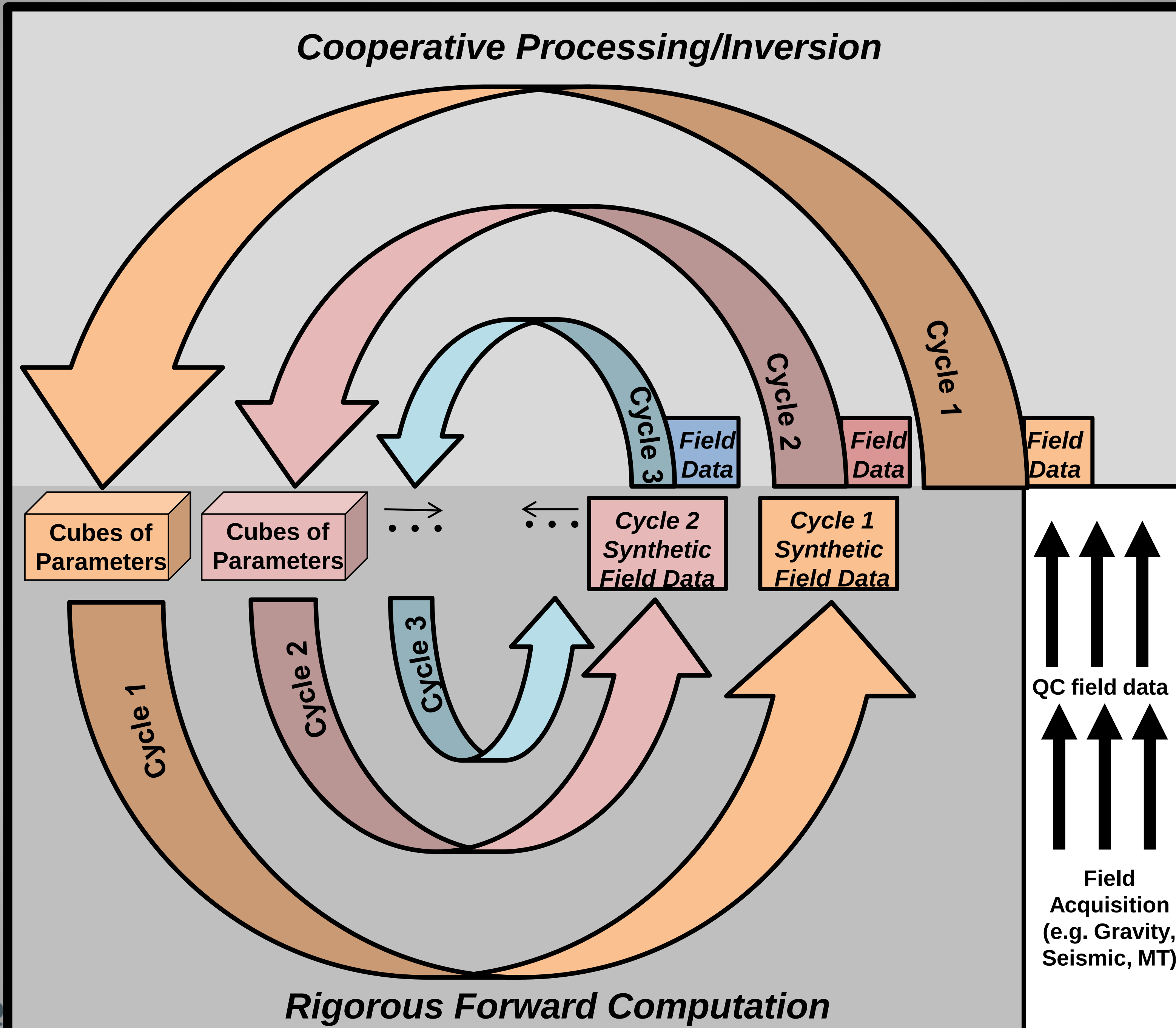
- MT → QC + Prepossessing absolutely critical.
- Seismic → Wide band acquisition + QC + True amplitude processing

Output

- Conductivity distribution,
- Acoustic impedance distribution,
- Derived parameters distribution (e.g. an attribute)

The output from cooperative inversion may be the *inputs* for:

1. ***Full waveform seismic inversion***
2. Validation by ***rigorous MT / Seismic Forward Modelling***
3. Or they may a ***constraint on migrations*** etc


Cooperative Processing/Inversion
Cycle 1
Cycle 2
Cycle 3
Field Data
Field Data
Field Data
Cubes of Parameters
Cubes of Parameters
Cycle 2 Synthetic Field Data
Cycle 1 Synthetic Field Data
QC field data
Field Acquisition (e.g. Gravity, Seismic, MT)
Cycle 1
Cycle 2
Cycle 3
Rigorous Forward Computation

1. Basics EM and Seismic

1. Review Basics → EM and Seismic (conductivity?? and velocity??)
    1. EM - Basic equation and parameters
    2. Electrical conductivity from logging
    3. P-wave velocity from logging
    4. Acoustic impedance

The complete description

$$\nabla \times E = -\frac{dB}{dt}$$

$$\nabla \times H = J + \frac{dD}{dt}$$

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Medium dependent parameters

$$B = \mu H$$

$$J = \sigma E$$

$$D = \varepsilon E$$

The generic start point solution (Harris 2002)

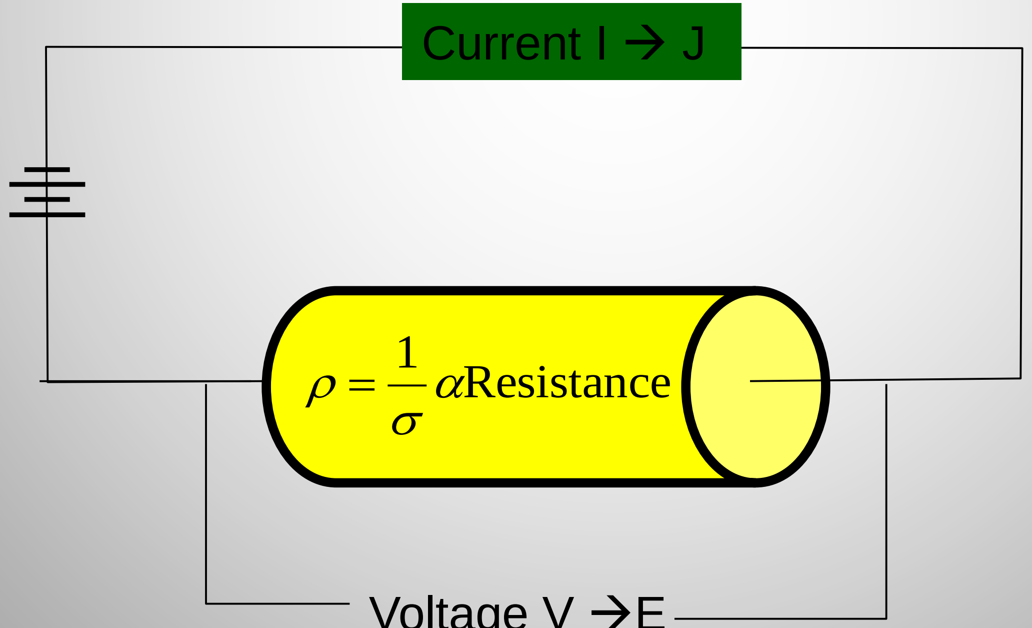
$$(\nabla^2 + k^2)\Pi^{em} = -\delta(i)\delta(x)\delta(y)\delta(z)\,\mathbf{s}^{\mathbf{em}}$$

$$k^2 = \mu\varepsilon\varpi^2 - i\mu\sigma\varpi$$

Electrical Conductivity

medium dependent parameter

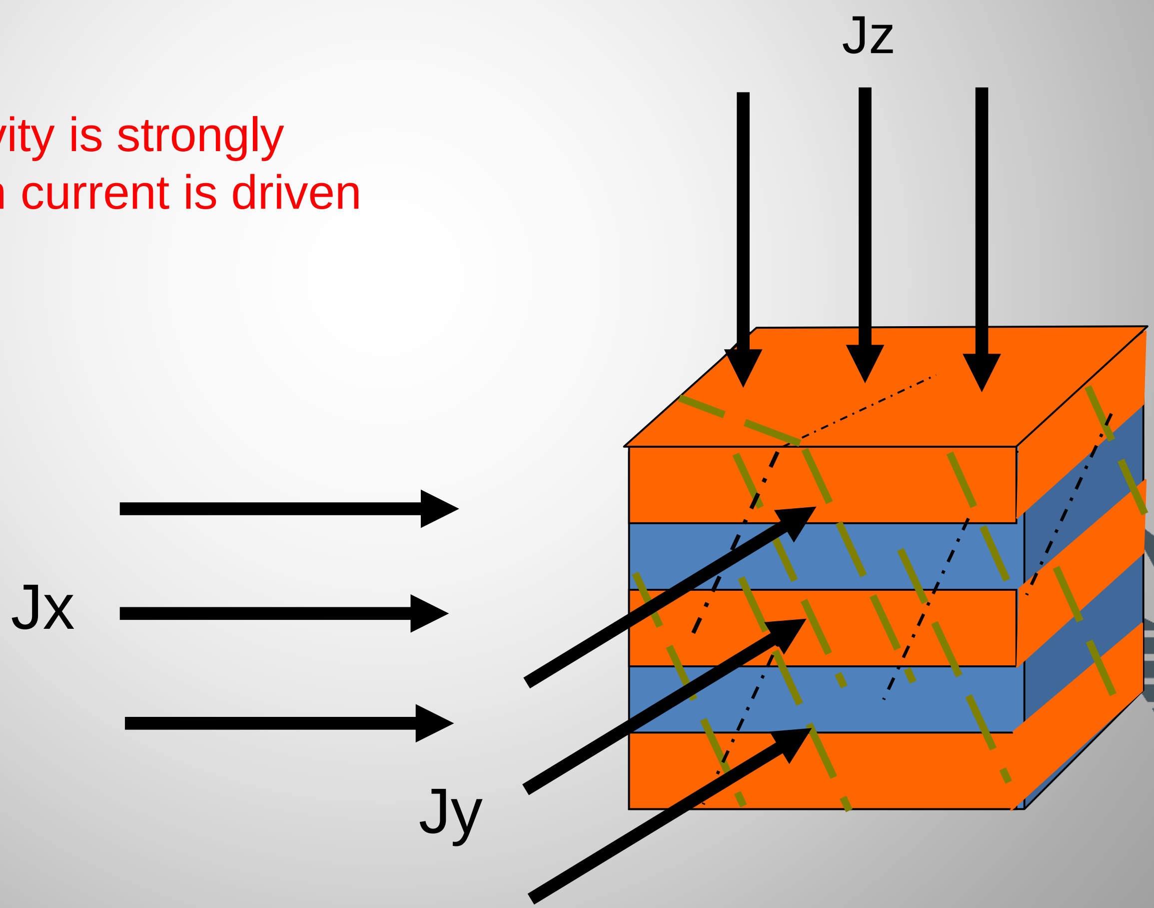
$$J = \sigma E \qquad I = \frac{V}{R}$$



Tensor Conductivity

- **J** = σ **E** (σ = 1/ρ)

What we call conductivity is strongly dependent on direction current is driven through the rock.



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Seismic Basics

- Acoustic Impedance

$$Z = V\rho$$

- Reflection Coefficient

$$R = \frac{V_2\rho_2 - V_1\rho_1}{V_2\rho_2 + V_1\rho_1}$$

Seismic

The Seismic Acquisitions challenge is to push frequency below 1 Hz
Why?

Surface Seismic
10 200

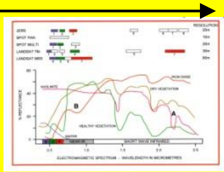
Sonic logging

Ultrasonic (Lab)

1.0E-05 1.0E-04 1.0E-03 1.0E-02 1.0E-01 1.0E+00 1.0E+01 1.0E+02 1.0E+03 1.0E+04 1.0E+05 1.0E+06 1.0E+07 1.0E+08

Frequency

EM



SeaBed EM

Induction Logging

LWD (EM/Radar range)

Measure for Years

EM

AMT

MT

Radar

1.0E-05 1.0E-04 1.0E-03 1.0E-02 1.0E-01 1.0E+00 1.0E+01 1.0E+02 1.0E+03 1.0E+04 1.0E+05 1.0E+06 1.0E+07 1.0E+08

Frequency

2. Seismic to EM coupling

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 114, B10306, doi:10.1029/2008JB005939, 2009

Anatomy of a seismoelectric conversion: Measurements and conceptual modeling in boreholes penetrating a sandy aquifer

J. C. Dupuis,[1,2] K. E. Butler,[1] A. W. Kepic,[2] and B. D. Harris[2]

Received 17 July 2008; revised 25 June 2009; accepted 13 July 2009; published 3 October 2009.

[1] Conversions of compressional seismic waves to electric fields have been measured in two boreholes drilled in an unconfined sandy aquifer on the Gnangara Mound near Perth, Australia. The seismoelectric conversions at both field sites occurred in the vicinity of the water table at 13-m depth and yielded maximum amplitudes of 1 μV/m using a sledgehammer source on surface. Partially cemented layers, inferred from geological and geophysical logs, straddle the water table and may play a role in generating the conversion and influencing its amplitude distribution. The dense vertical sampling used in these borehole experiments reveals spatial and temporal polarity reversals of the interfacial signal which provide new evidence in support of the conceptual model for seismoelectric conversions at interfaces. We demonstrate that the growth rate of the source zone and its maximum vertical extent below the water table are encoded in the polarity of the interfacial signal. These experiments confirm that vertical seismoelectric profiling can be used to gain further insight into seismoelectric conversions and characteristics of interfaces that makes them amenable to detection.

An Interesting distraction

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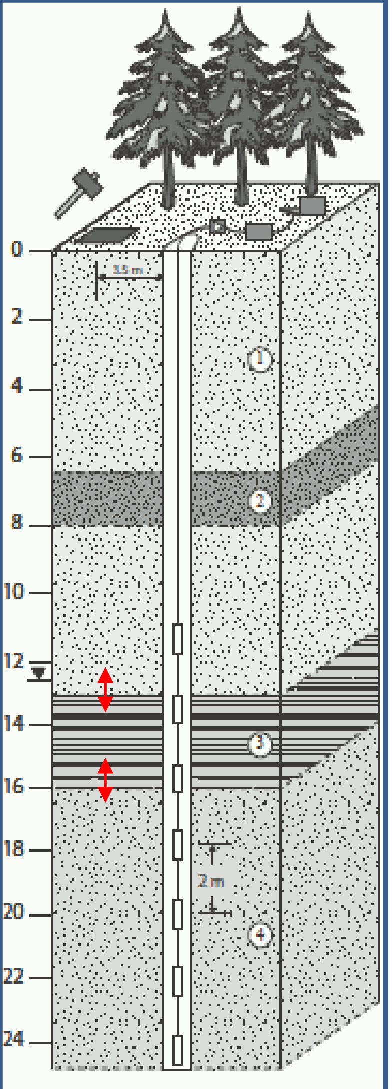
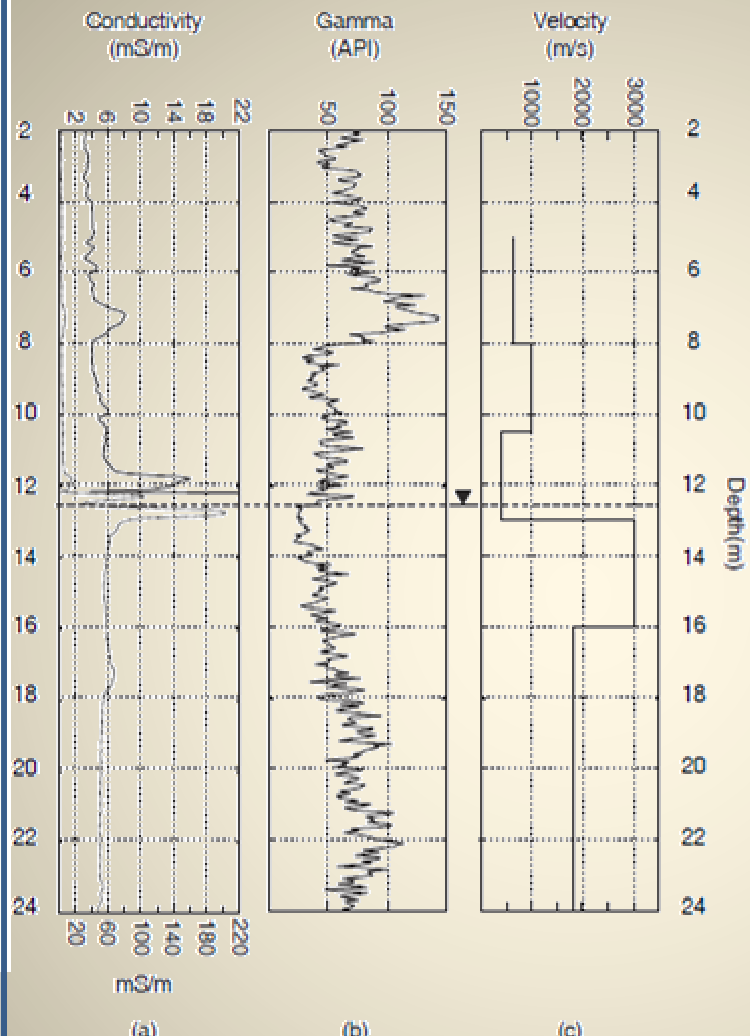
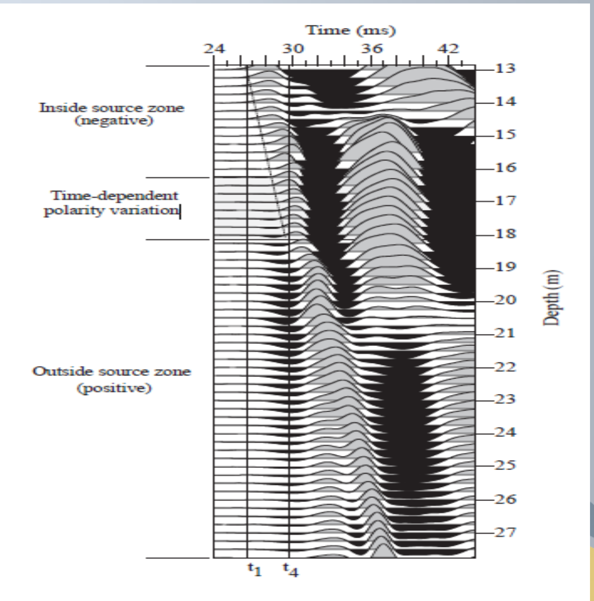


Wire line logs



Do Seismic Wavefields Create EM wavefields Why ??

An Interesting distraction



Figures adapted from Dupuis, Butler, Kepic and Harris 2009 (JGR Vol 114 – B10306)

2. Of Course they do

But: How can we compute the EM Field ???
How big are they ??

An Interesting distraction

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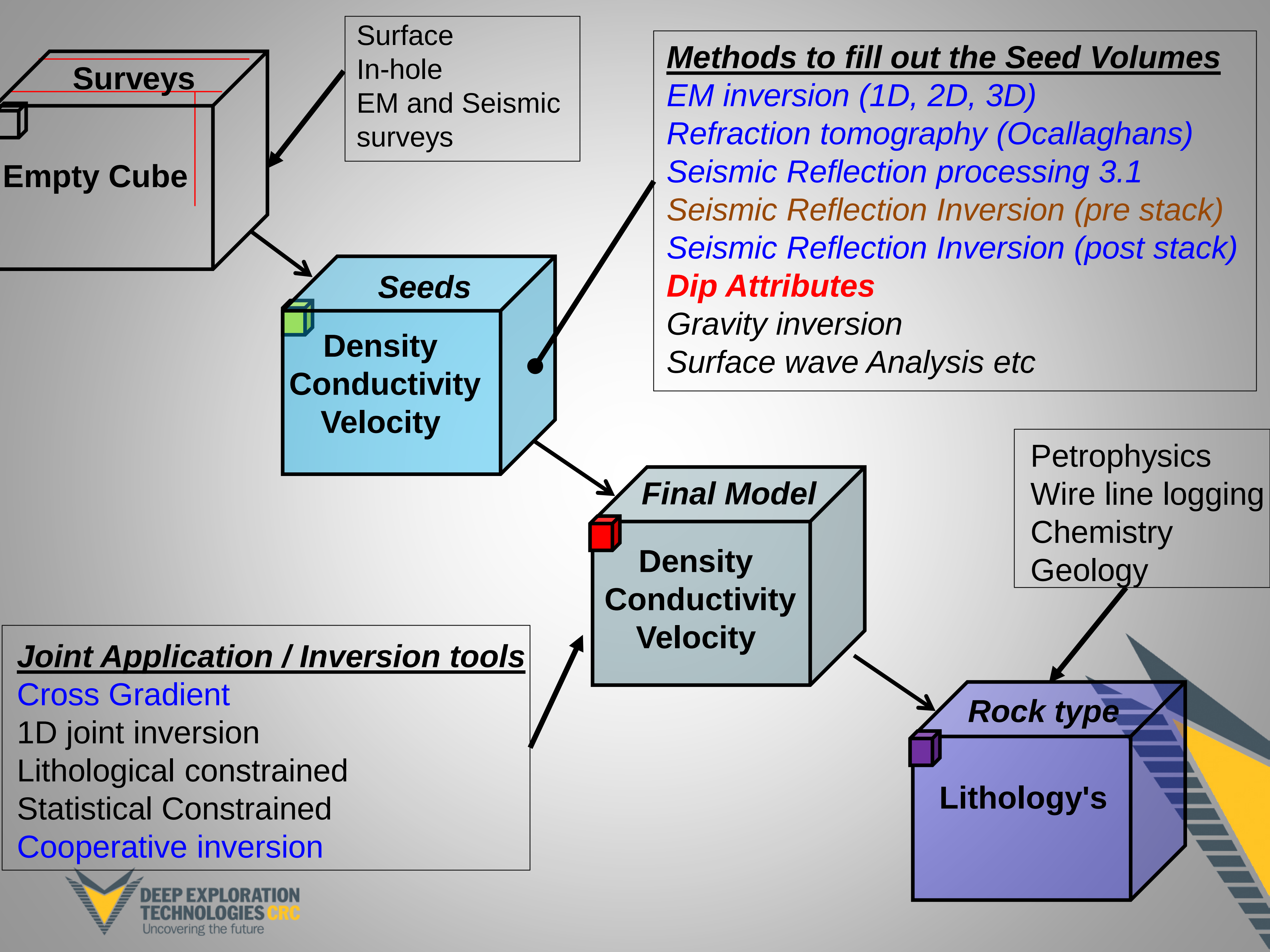
Surveys
Empty Cube
Surface
In-hole
EM and Seismic
surveys
Methods to fill out the Seed Volumes
EM inversion (1D, 2D, 3D)
Refraction tomography (Ocallaghans)
Seismic Reflection processing 3.1
Seismic Reflection Inversion (pre stack)
Seismic Reflection Inversion (post stack)
Dip Attributes
Gravity inversion
Surface wave Analysis etc
Seeds
Density
Conductivity
Velocity
Final Model
Density
Conductivity
Velocity
Petrophysics
Wire line logging
Chemistry
Geology
Rock type
Lithology's
Joint Application / Inversion tools
Cross Gradient
1D joint inversion
Lithological constrained
Statistical Constrained
Cooperative inversion
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Some Tools

- ***Building/Perturbing Seed Models or conditioning inversion*** (cube of conductivities, velocity and density).
  - EM derived conductivities (1D, 2D, 3D)
  - MT inversion (Graham)
  - LMO Cube
  - Refraction techniques
  - Full waveform tomography
  - Virtual source imaging (evolving quickly)
  - Surface wave analysis
  - Seismic Reflection Imaging (Milovan)
  - Diffraction Imaging (Roman)
  - Post and Pre-stack inversion (seismic)
  - **Attribute analysis**

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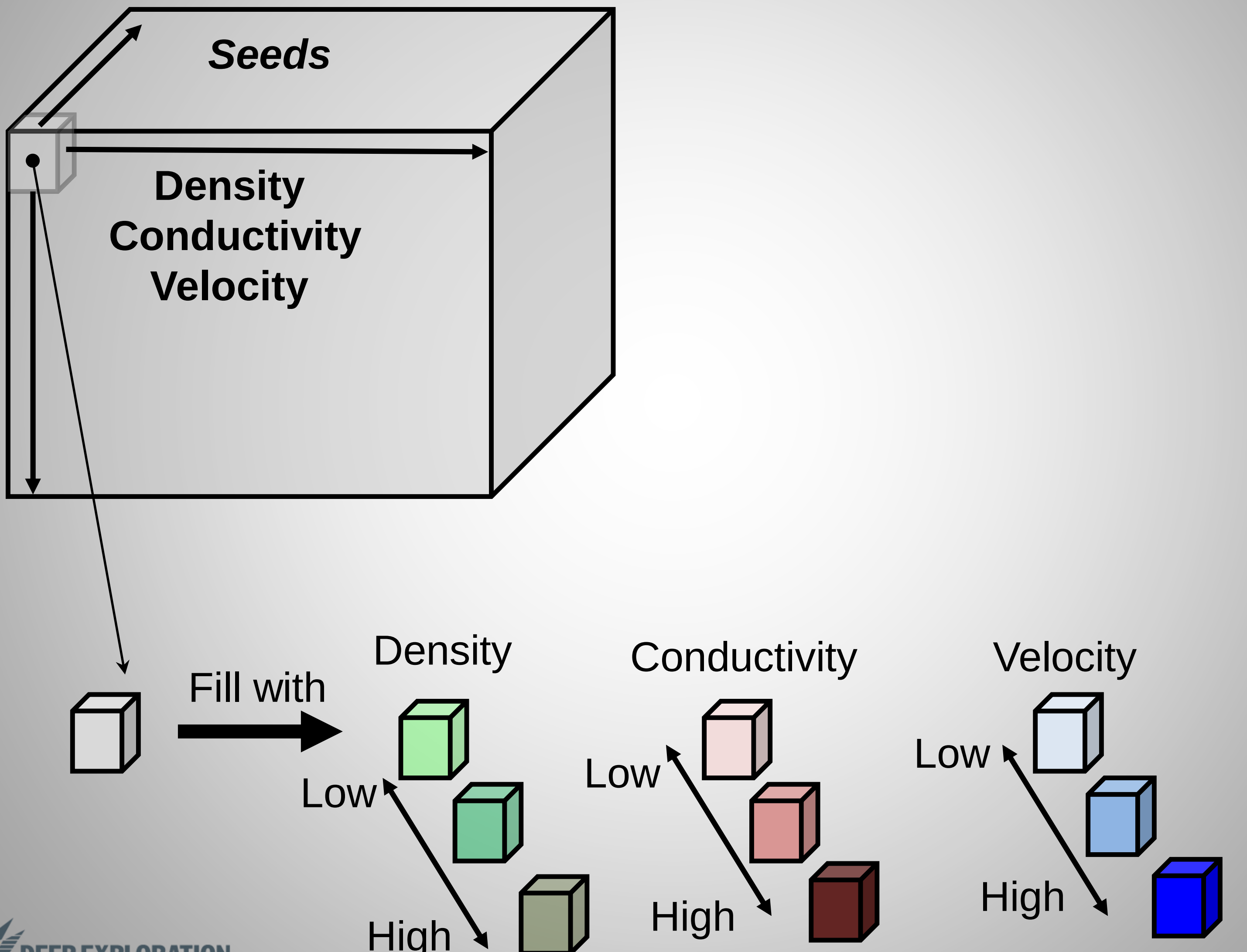
Sub-domains

- Strategies for each sub-domain are different but interdependent.

1. Cover,
2. Weathering,
3. Host,
4. Mineralization.

We want the range of reasonable densities, conductivities and Velocities

For each sub-domain.



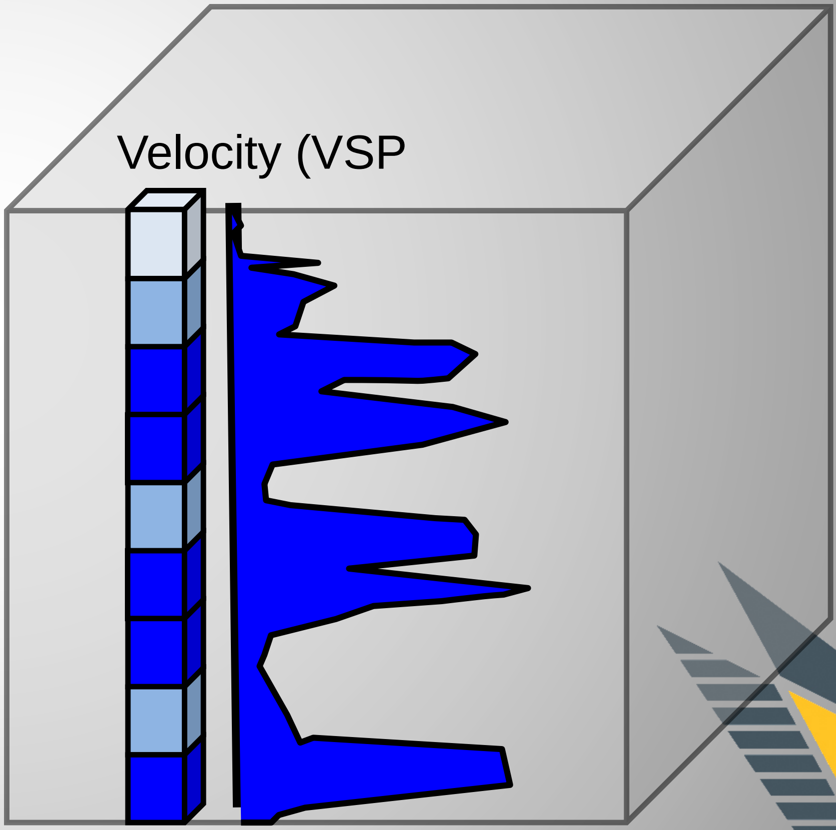
Either know the value or at least know the range

Neither the value nor the confidence in each value are uniform throughout the volume

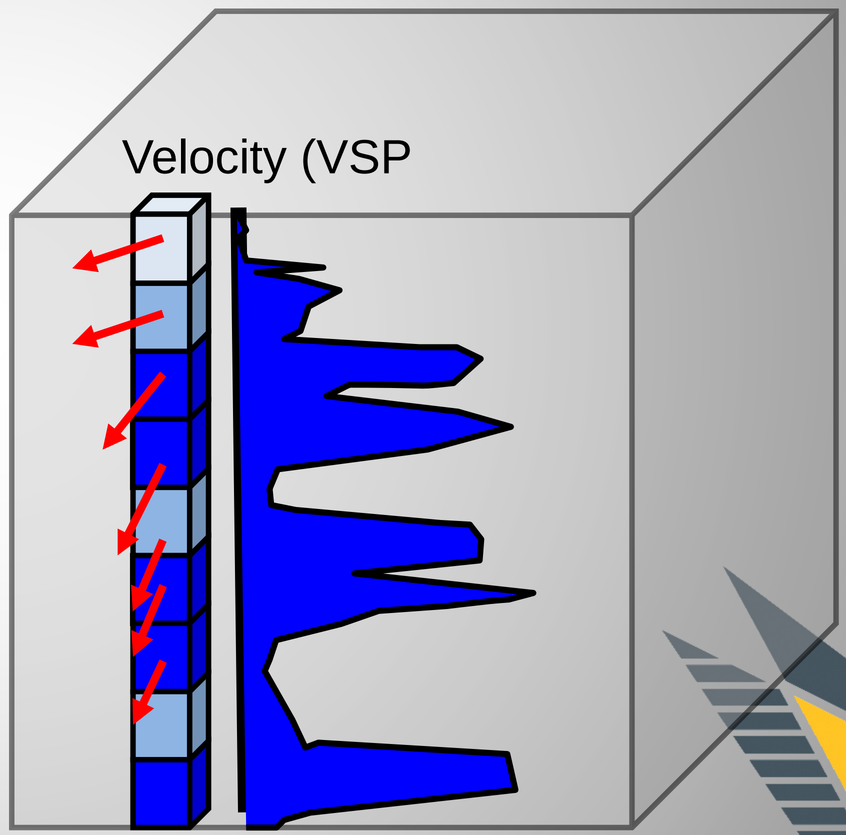
Example:

VSP velocity **→ High certainty low coverage tight constraint around the bore hoel**

Surface EM **– Low resolution high coverage**



Each Cell Need a parameter and direction of change



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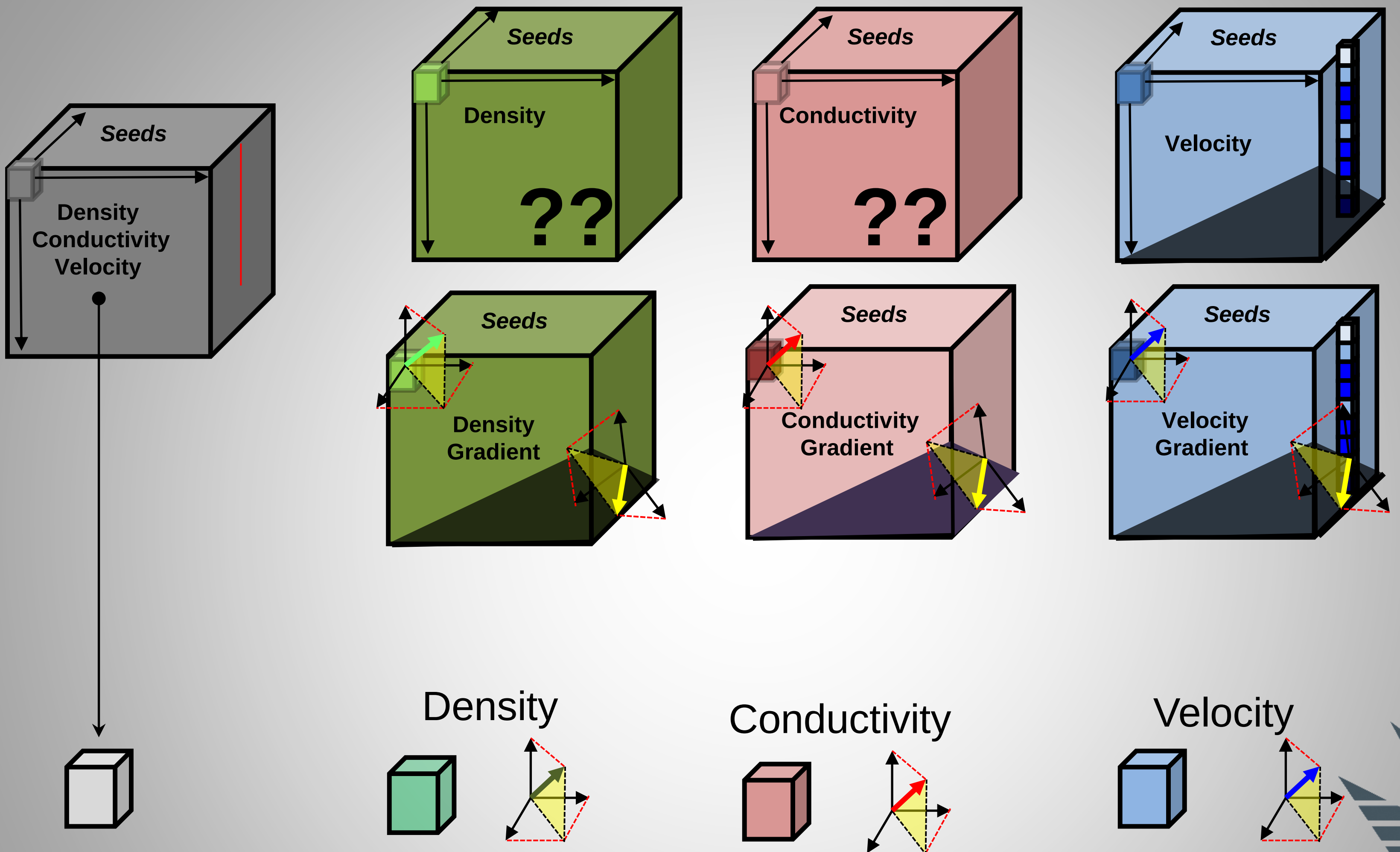


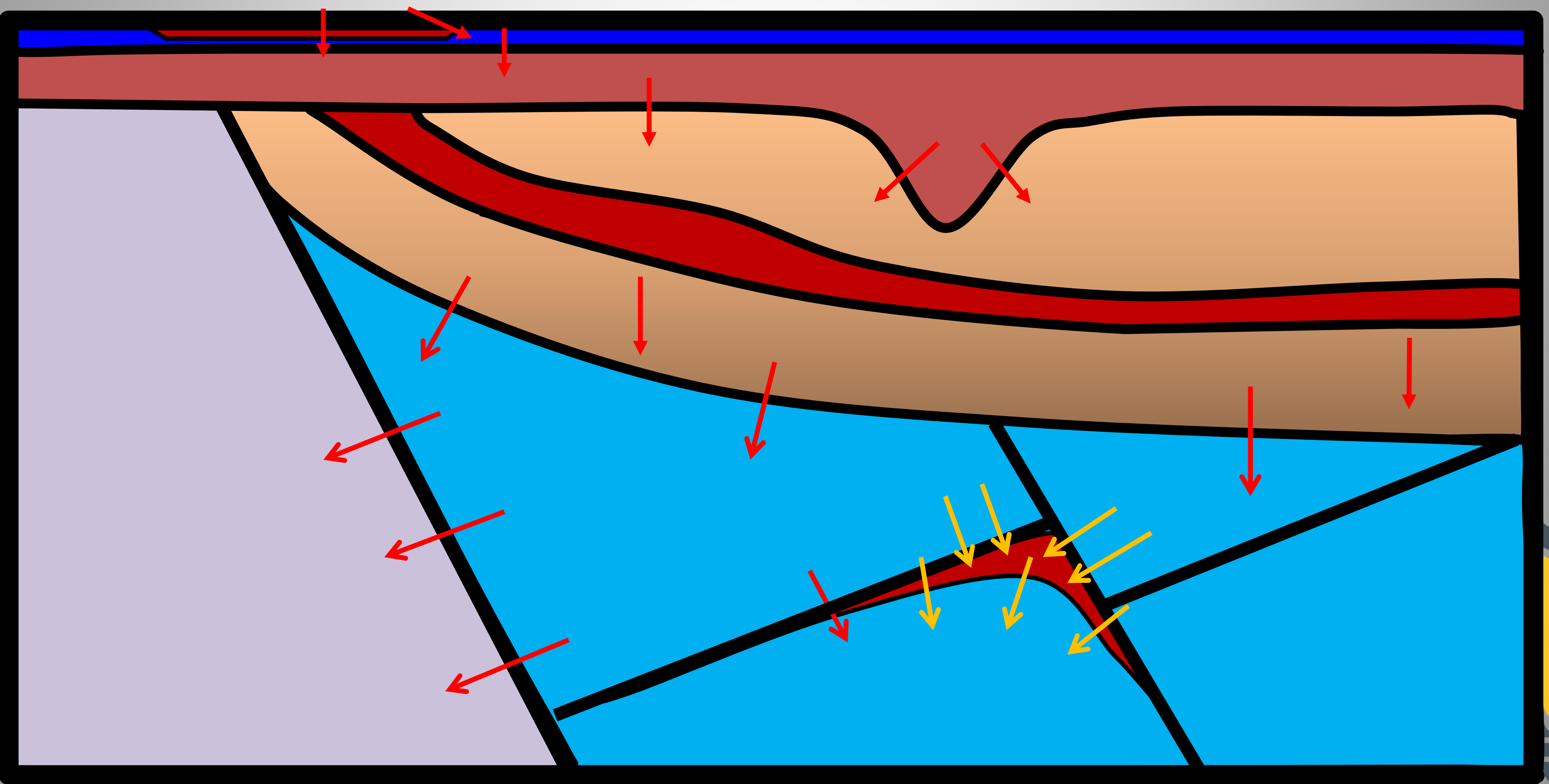
Often the gradient is known for all parameter
However the contrast may not be know

Large Data Set (Barrick Gold) Reflectivity Vs Acoustic Impedance

How to deal with Gradients through

(i) How do vectors change at Boundaries
(ii) How do vectors change in Sub-volumes

1. **Velocity**
2. **Density**
3. **Acoustic Impedance**
4. **Conductivity**
5. **Lithology**
6. **Geochemistry**
7. **Hydrogeology**



Directional Attributes

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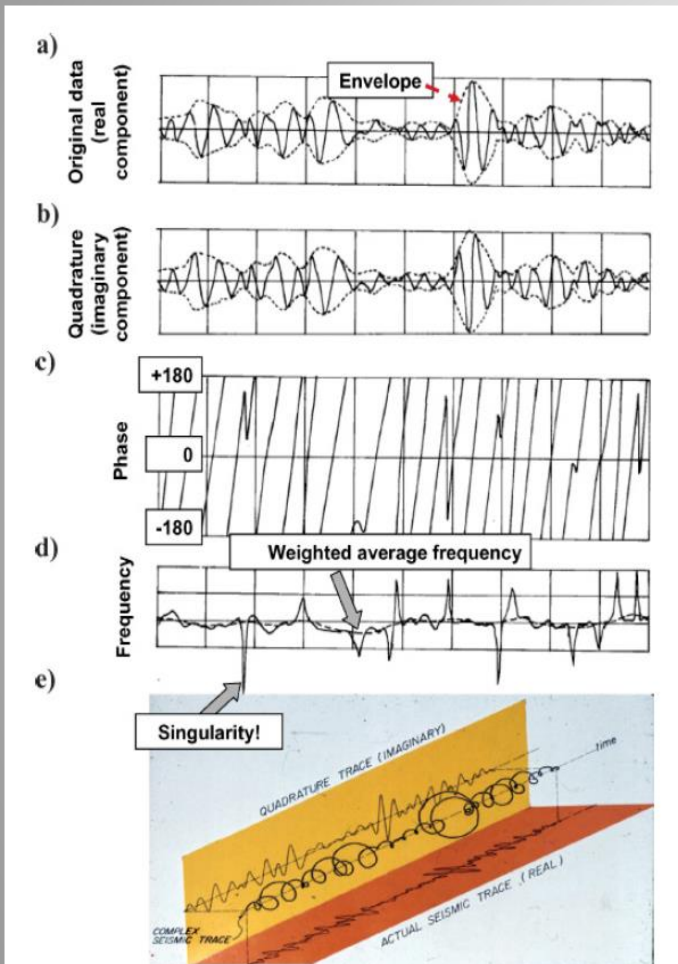
5. Seismic – Reflectivity → Amplitude and Spatial Attributes



Conductivity

Reflectivity?

Azimuth

Cosine Phase

Polar Dip

Acoustic Impedance

Energy

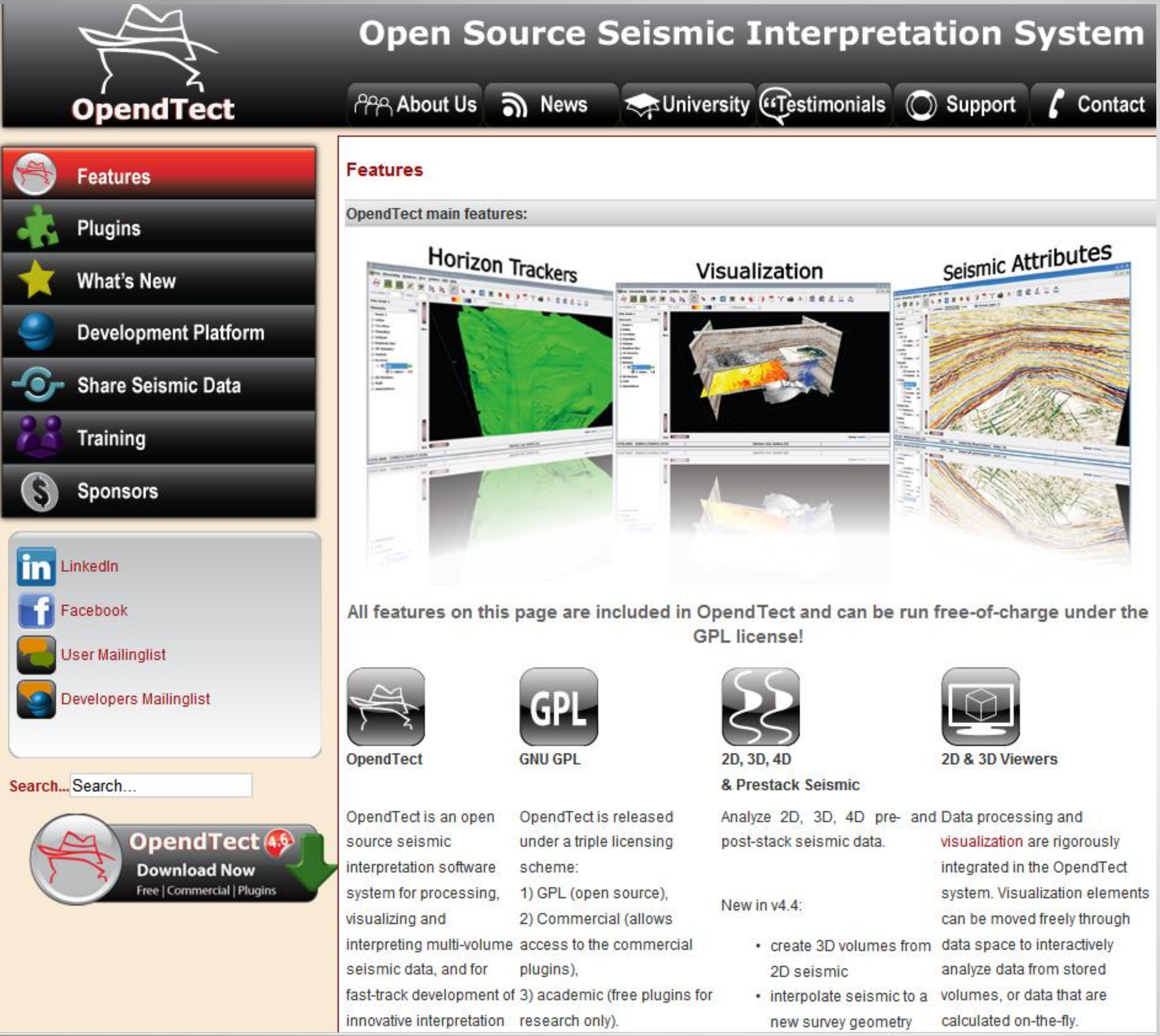
Max. pos. curvature

Density

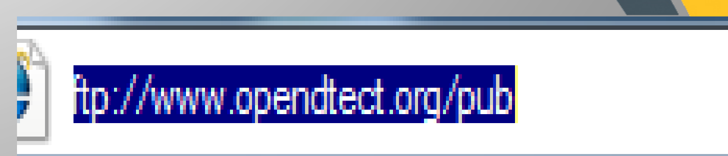
Adapted from Chopra and Marfurt 2005

GEOPHYSICS, VOL. 70, NO. 5 (SEPTEMBER-OCTOBER 2005); P. 3SO–28SO, 32 FIGS. 10.1190/1.2098670

6. Seismic - Attributes General



From http://www.opendtect.org/pub



More interactive INTERACTIVE EM SOFTWARE
See Andrew’s MCSEM web site

ELSEVIER
Computers & Geosciences
Volume 60, October 2013, Pages 1–10

Interpreting marine controlled source electromagnetic field behaviour with streamlines

A.M. Pethick, B.D. Harris
Department of Exploration Geophysics, Curtin University, GPO Box U1987, Perth, Western Australia 6845, Australia

MCSEM.com

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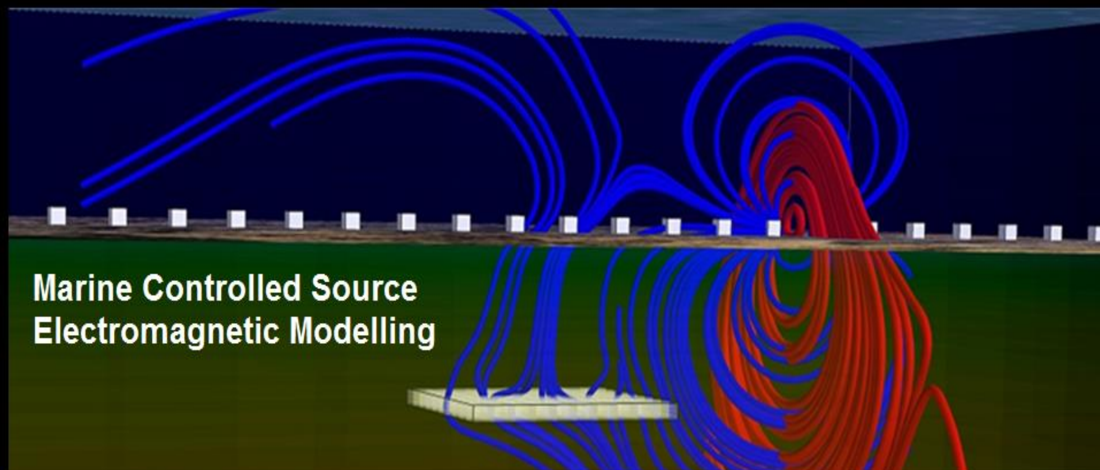

DEVELOPED BY ANDREW PETHICK

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GALLERY
View the MCSEM.com gallery of program screenshots and pretty 3D visualisation done over my PhD and Honours Thesis

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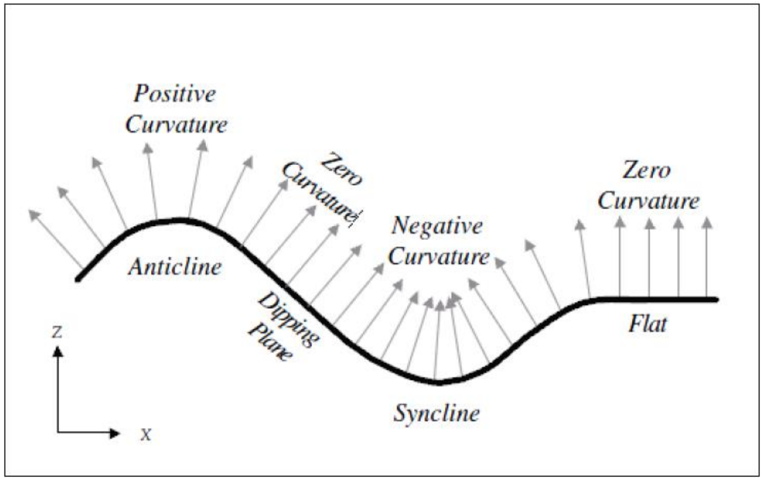
Read more about what is happening in our world.

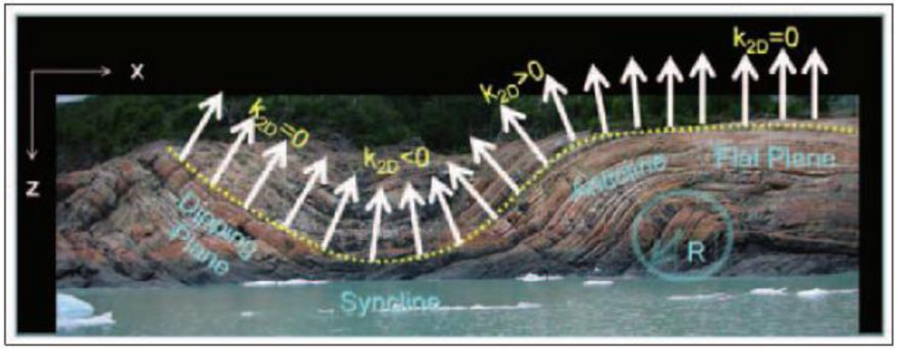
LEARN ABOUT MCSEM
View a short video and an overview about the marine controlled source electromagnetic method

Examples of positive and negative curvature

•Chopra, S. and K.J. Marfurt, 2010. Integration of coherence and curvature images: The Leading Edge, v. 29, p. 1092-1107
•Roberts, A., 2001, Curvature attributes and their application to 3D interpreted horizons: First Break, 19, 85–99.

Positive and Negative Curvature

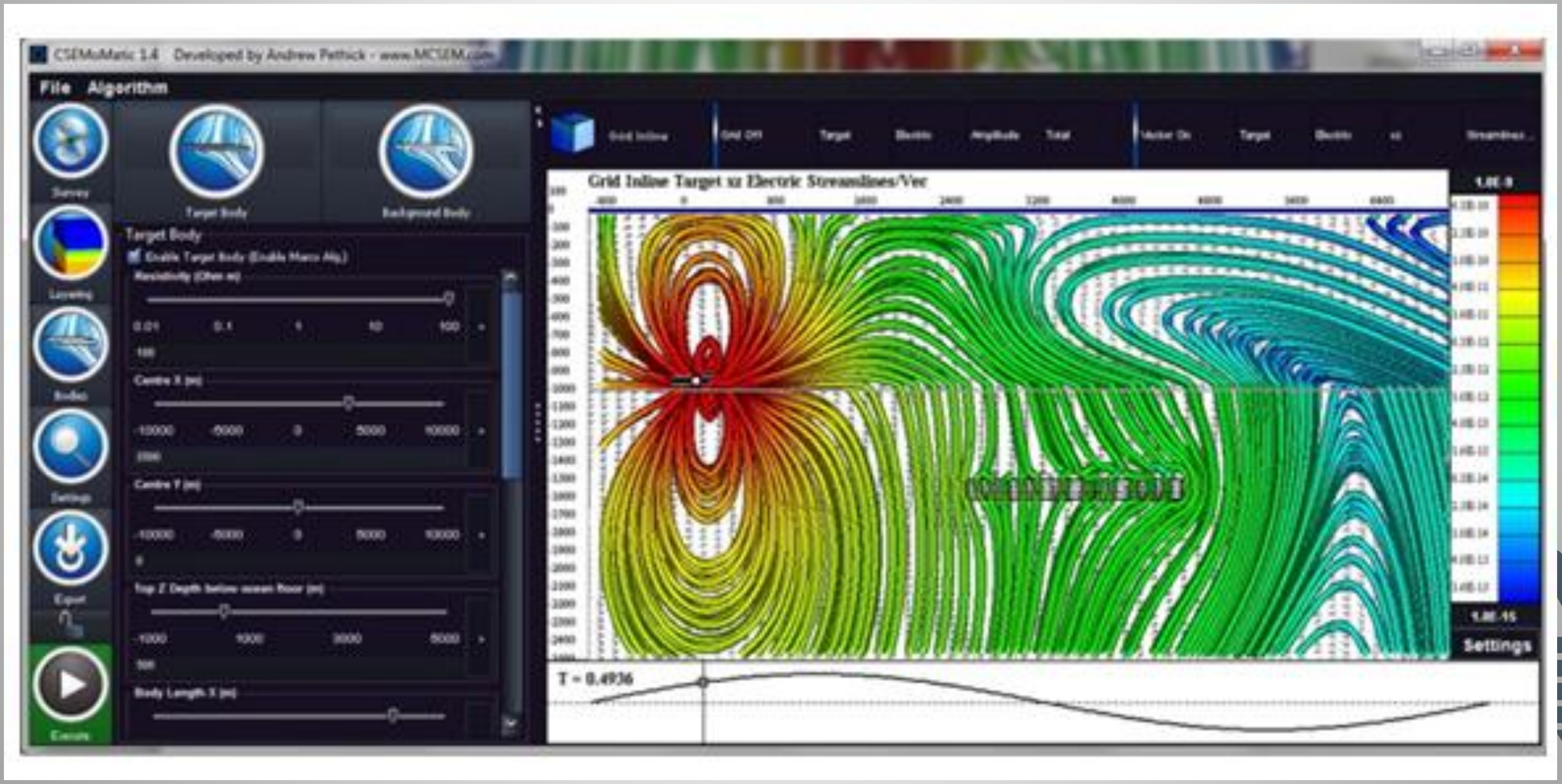




Roberts et al. 2001; Chopra et al. 2010

Streamline – EM fields

1. EM fields - Streamlines (Pethick and Harris 2013)



Conclusions / Three key outcomes

1. ***Computations of streamlines*** representing direction of change of conductivity and direction perpendicular to horizons with strong reflection cooeficient.

2. ***MT constrained post stack inversion***. Here the MT inversion can help constrain the large scale Acoustic impedance model. The outcome must be viewed as a new type of MT constrained impedance attribute rather than explicit or accurate recovery of acoustic impedance.

3. ***Automatic extraction of seismic structural constrains for MT inversion***

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Importance of parallel computing for cooperative inversion workflow

Andrew Pethick, Curtin University

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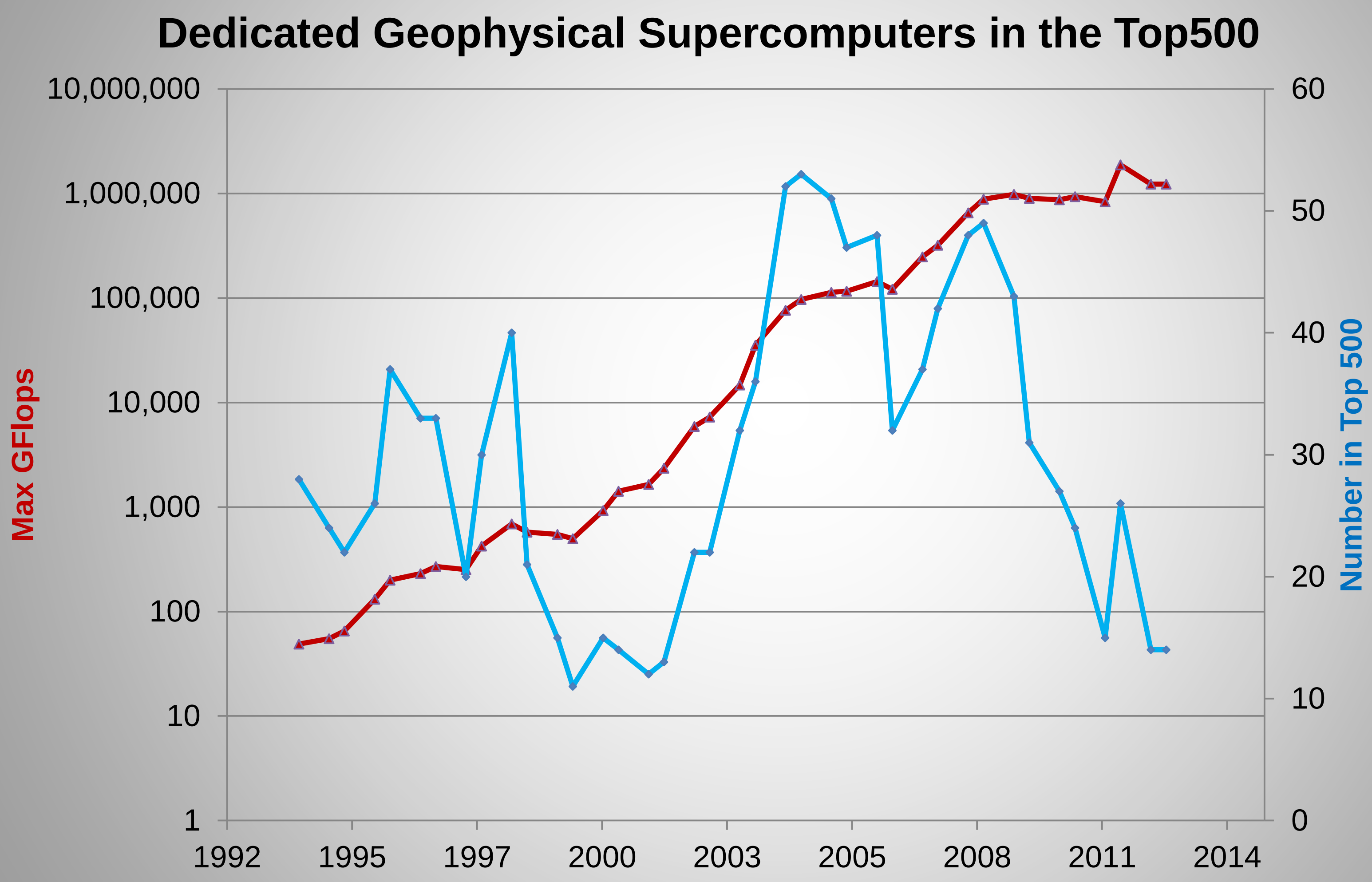
A Declining Industry?



Overview

What is parallelisation

Overview parallelisation methods

Electromagnetic parallelisation case studies

Potential methods for parallelisation of joint inversion workflows

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What is Parallelisation?

What is Parallelisation

"Parallelisation is the ability to perform two or more calculations simultaneously"

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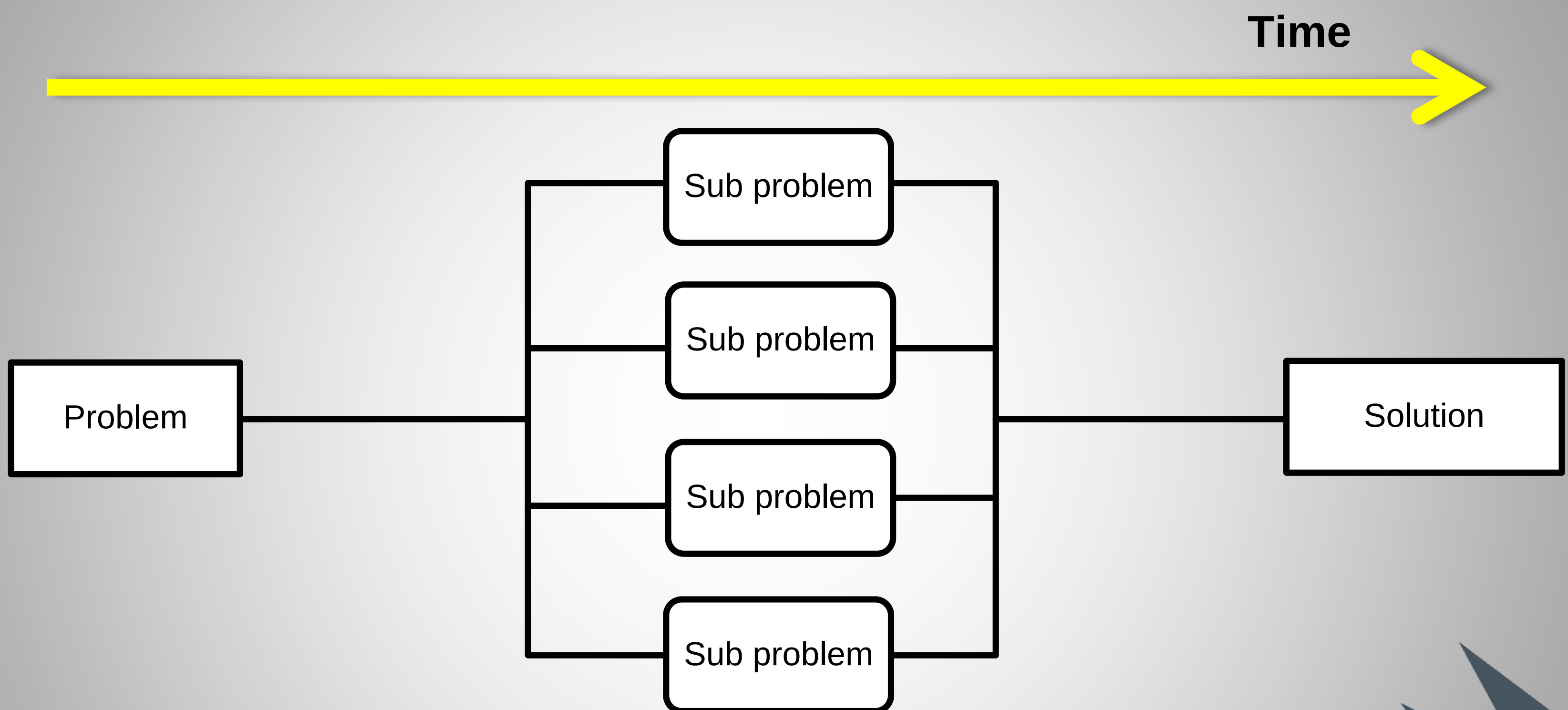
What is Parallelisation



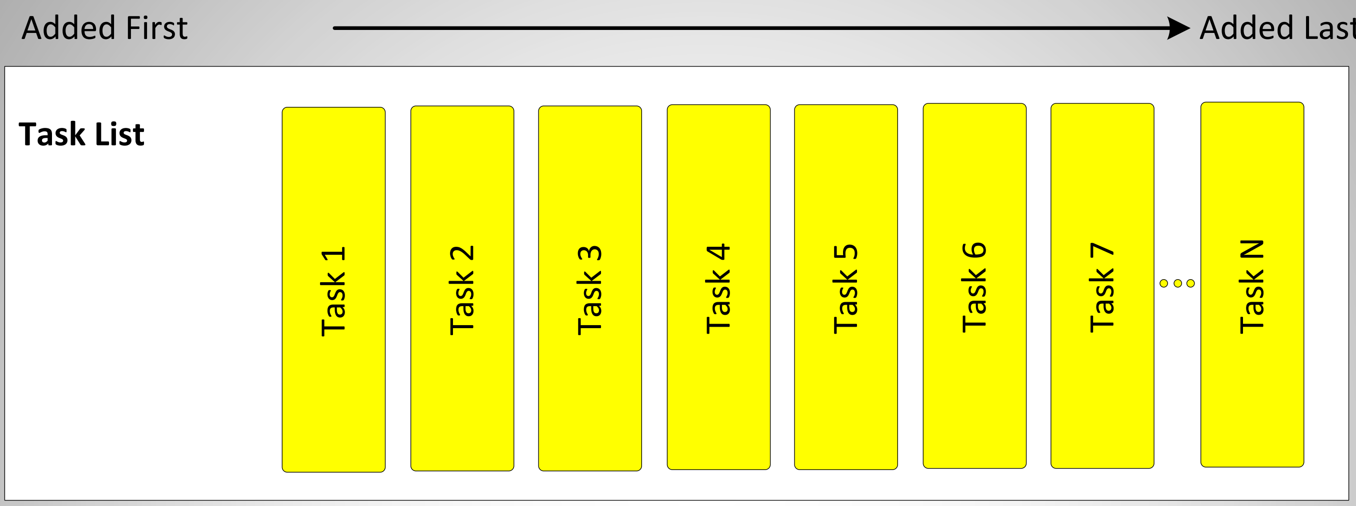
Each sub problem is solved concurrently.

Parallelisation: Multi-threading

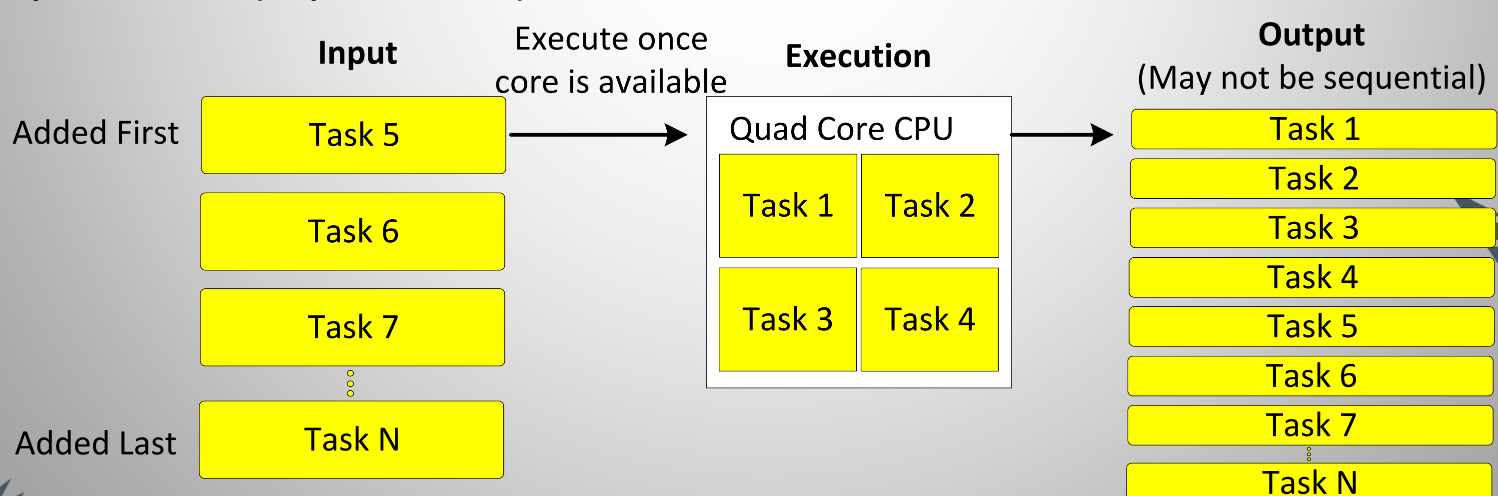
- A thread is a single piece of executable code scheduled to run on a processor
- Multi-threading is the ability to concurrently execute multiple pieces of code

Multi-threading produces faster execution speeds and enables true multi-tasking

Parallelisation: Multi-threading (Sequential batch)



Dynamic Queue (Sequential Batch)

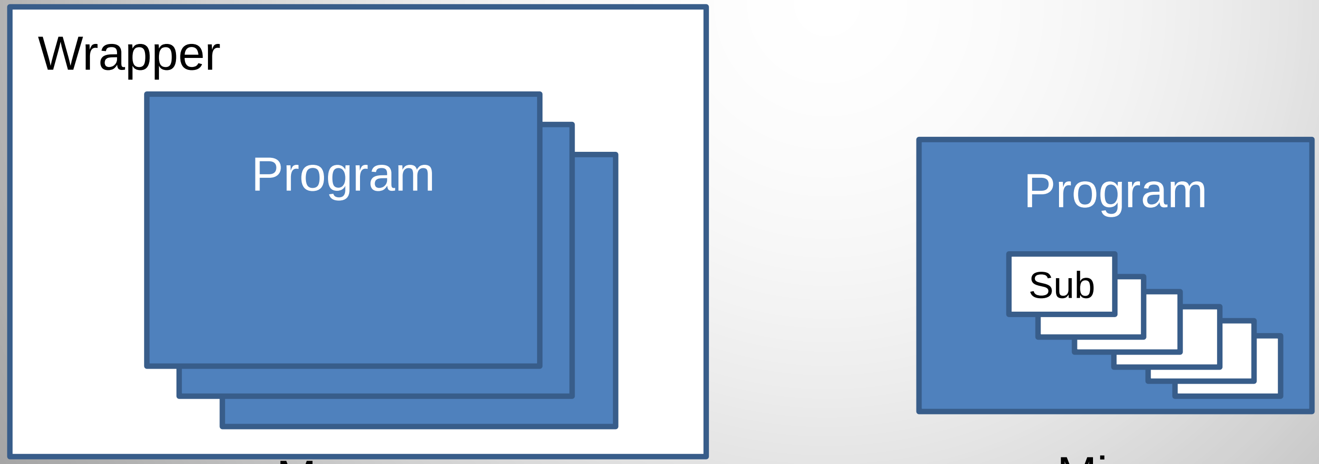


Parallelisation

- Parallelisation can be integrated at two levels,
  - ‘Macro’ – On top of the compiled executable
  - ‘Micro’ – Within the code

Requires compiled code

Requires source code



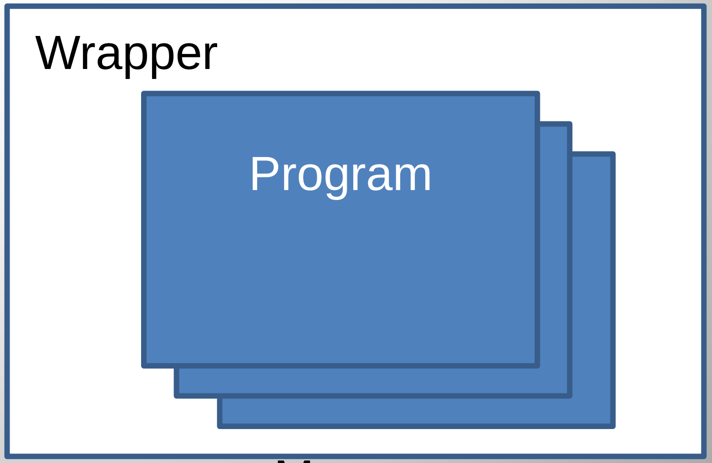
Macro
(Wrapper)

Micro
(Internal)

Parallelisation

- Macro Parallelisation
  - Useful when only a compiled executable exists
  - Modernizing legacy code
    - Poorly documented
    - overly complex
    - Unknown language
  - Simpler than using MPI

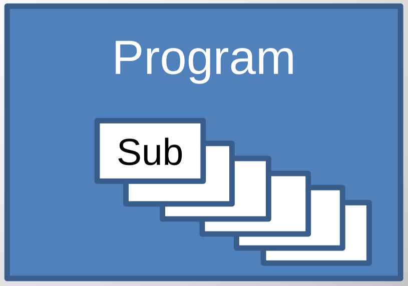
Requires compiled code



Macro
(Wrapper)

Parallelisation

- Micro Parallelisation
  - Requires source code and knowledge of code function
  - Good for when there are known computational dependencies
  - Difficult to implement effectively but more compatible with and better at scaling on supercomputers



Micro
(Internal)

Methods of Measuring Parallelization Effectiveness

- **CPU Time**
  - The total time each thread actively runs on the CPU core
- **Wall Time**
  - The total time taken from the start of the execution to the termination of the last thread.
- **Speedup**
  - The percentage increase in speed by parallelization
- **Efficiency**
  - How effective is the algorithm is distributing across multiple cores (i.e., does it scale well?)

Case Study 1
Marine Controlled Source EM

MCSEM: Computing The Fields

- Solving the Integral Equation method for computing EM Fields (Taken from Raiche, 1974)

Starting with Maxwell's Equations

$$\nabla \times E = -i\omega\mu H$$
$$\nabla \times H = (\hat{\sigma} + i\omega\varepsilon) + J_0) = \sigma E + J_0$$

Solving for a geo-electrical conductivity distribution

$$\sigma = \sigma_p + \sigma_p$$

MCSEM: Computing The Fields

The Integral equation method expresses each inhomogeneous cell by an equivalent scattered source.

MCSEM: Computing The Fields

- Solving the wave equation:

Inserting Faraday's Law into

$$\nabla \times H = \sigma_p E + (\sigma - \sigma_p)E + J_0 = \sigma_p E + J_S + J_0$$

Yields

$$\nabla \times \nabla E + i\omega\mu\sigma_p E = i\omega\mu(J_S + J_0)$$
$$\nabla^2 E - i\omega\mu\sigma_p E = i\omega\mu(J_S + J_0) + \nabla(\nabla \cdot E)$$
$$\nabla^2 E - k_p^2 E = i\omega\mu(J_S + J_0) + \nabla(\nabla \cdot E)$$
$$k_p^2 = -i\omega\mu\sigma_p = -i\omega\mu\hat{\sigma}_p + \omega^2\mu\varepsilon_p$$

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MCSEM: Computing The Fields

Taking the divergence gives

$$\nabla \cdot (\nabla \times H) = 0 = \nabla \cdot \left(\sigma_p E + J_S + J_0\right)$$

$$\nabla \cdot \left(\sigma_p E\right) = -(J_S + J_0)$$

$$\nabla \sigma_p \cdot E + \sigma_p \nabla \cdot E = -\nabla \cdot (J_S + J_0)$$

$$\nabla \cdot E = -\frac{\nabla \sigma_p}{\sigma_p} \cdot E - \frac{\nabla \cdot (J_S + J_0)}{\sigma_p}$$

Plugging that back into wave eq. solution

$$\nabla^2 E + k_p^2 E = i\omega\mu(J_S + J_0) - \nabla\left(\frac{\nabla \sigma_p}{\sigma_p} \cdot E\right) + \frac{\nabla \cdot (J_S + J_0)}{\sigma_p}$$

$$\nabla^2 E + k_p^2 E + \nabla\left(\frac{\nabla \sigma_p}{\sigma_p} \cdot E\right) = i\omega\mu(J_S + J_0) - \nabla \frac{\nabla \cdot (J_S + J_0)}{\sigma_p}$$

MCSEM: Computing The Fields

(Finally, the tensor Green's Function.)

- The tensor Green's Function G is a kernel function which solves inhomogeneous partial differential equations

$$E(r) = E_P(r) + \int_v G^E(r, r') \cdot \sigma_a(r') E(r') dv'$$

$G^E(r, r')$ relates the electric field at a radial position r In layer 1 to a source element (scatterer) at r' in layer j

MCSEM: Computing The Fields

- Notice that the IE solution needs to be computed independently for each
  - Source Location
  - Transmission Frequency
  - Conductivity distribution

$$E(r) = E_P(r) + \int_v G^E(r, r') \cdot \sigma_a(r') E(r') dv'$$

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MCSEM: Computing The Fields

- So how does this all fit in to parallelization?

- If a survey consisted of
  - 128 Source locations
  - 8 Transmission frequencies
  - 25 Receivers
- Then the tensor Green's function would have to independently be solved 1024 times (128 sources x 8 frequencies)
- IE Fields computed with Marco (CSIRO's P223 Project) (Xiong, 1992)

This means we can parallelize over source or transmission frequency but not receiver location!

MCSEM: Parallelisation

A ‘macro’ parallelisation method and software was developed to rapidly forward model electromagnetic fields generated during a MCSEM survey

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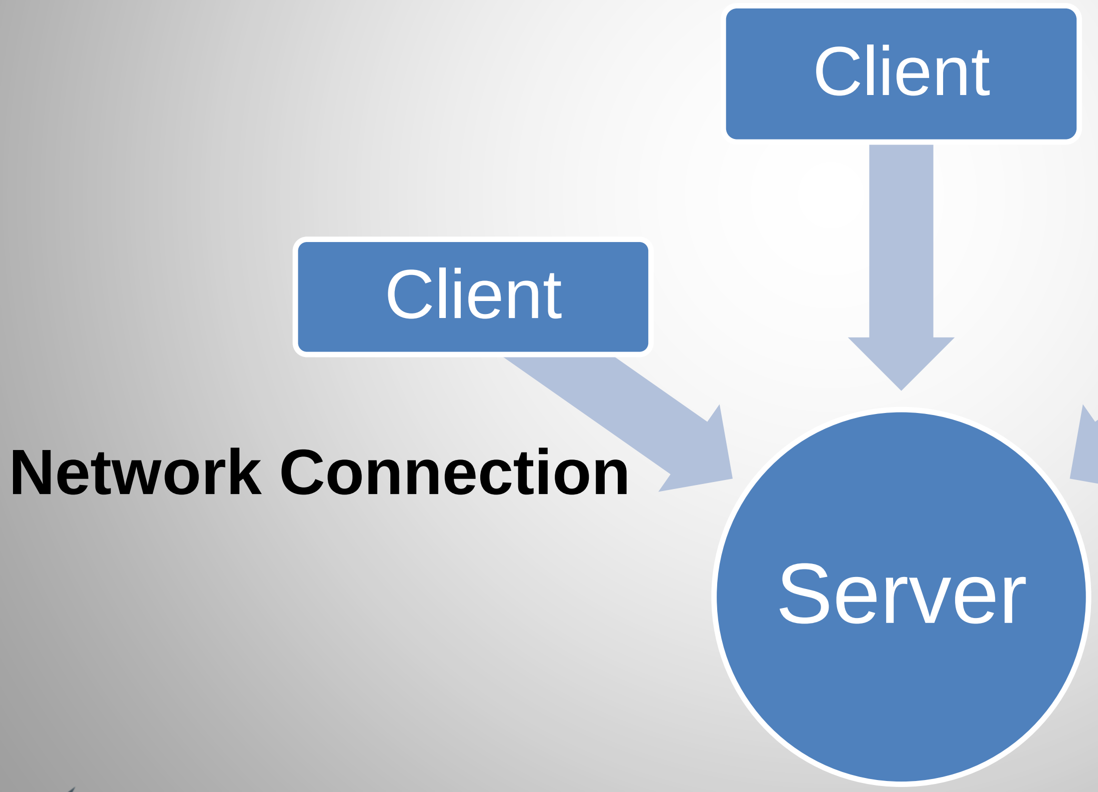
MCSEM: Our Approach

- A grid computing based approach



MCSEM: Parallelising by Transmitter vs Freq.

Removed

$$Speedup = \frac{t_{ws}}{t_{wn}}$$

$$Efficiency = \frac{Speedup}{N}$$

Where,
t_{ws}-Wall Time on a single CPU
t_{wn}-Wall Time on a N CPU's
N-The total number of CPU's utilised

MCSEM: Parallelising by Transmitter vs Freq.

Parallelisation reduces a 12hr task to a 3.2hrs on a single multi-core CPU!

A 375% Speedup

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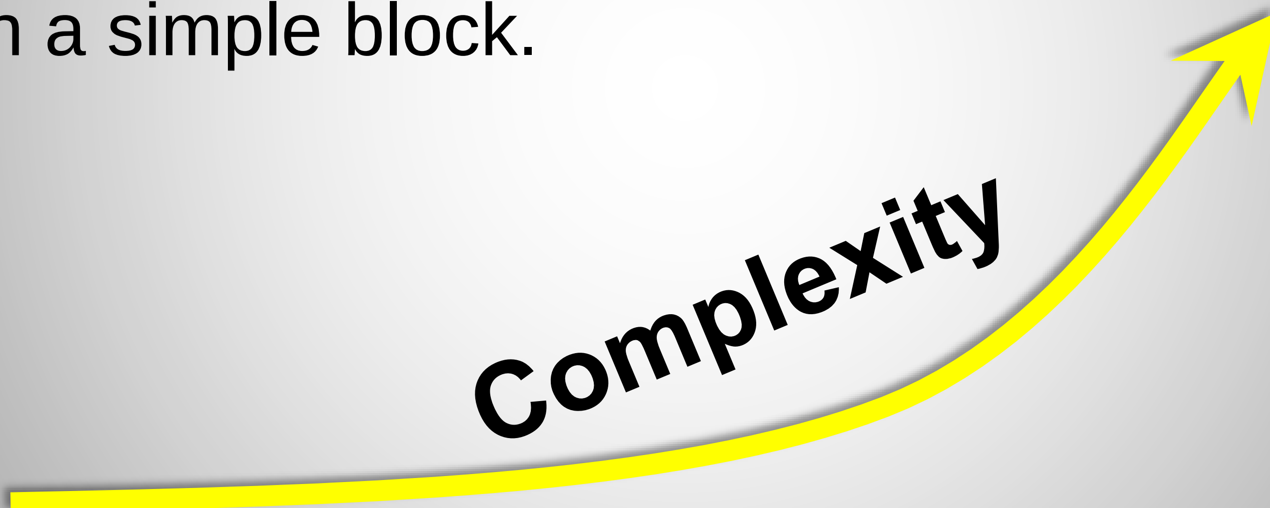
MCSEM: Scaling the Problem

- Real surveys can be composed of thousands of transmitters, hundreds of receiver locations in geo-electrical environments much more complex than a simple block.



Survey Complexity=nTrans. x nFreq.

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MCSEM: Testing a Scaling Problem

- Utilising an empty computer lab with 16 intel core2 quad machines
  - Modelling performed using 64 cores
  - Surveys of increasing complexity were forward modelled
  - 16 computers running at 100% CPU for 24 hours creates a fair bit of heat and electricity.
  - ~57kW was used to run these 'small' experiments (@150W/hr per PC = 24x150x16=57600W or $17)

  …the equivalent of running a 2400 Watt heater

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MCSEM: Parallelising by Transmitter vs Freq.

MCSEM: Parallelisation, the bigger picture

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Case Study 2
Airborne EM

AEM: Introduction

- An AEM survey was performed in Allanooka, North Perth Basin
- Consists of 93819 Source locations

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AEM: The Experiment

- Using the same ‘macro parallelisation’ method described in case study 1
- Integrating the Airbeo 1D inversion routine (Chen and Raiche, 1998)
- Using a grid of 16 quad-code hyper-threaded Intel Core i7 computers
  - Despite only have 4 cores hyper-threading enables two threads to be executed on the same core
  - Hyper-threading is ~30% faster on a 4 core CPU

AEM: Testing the Parallelisation Method

AEM: Scaling the Problem

AEM: Resulting Inversion

Parallelisation integration into joint inversion workflows

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Joint Inversion

- MT Inversion
  - ModEM (Egbert and Kelbert, 2000)
  - ModEM has a coarse grained parallelisation over source locations or geo-electrical models
- Seismic Inversion
  - 1D Model based post stack inversion within Hampson Russell

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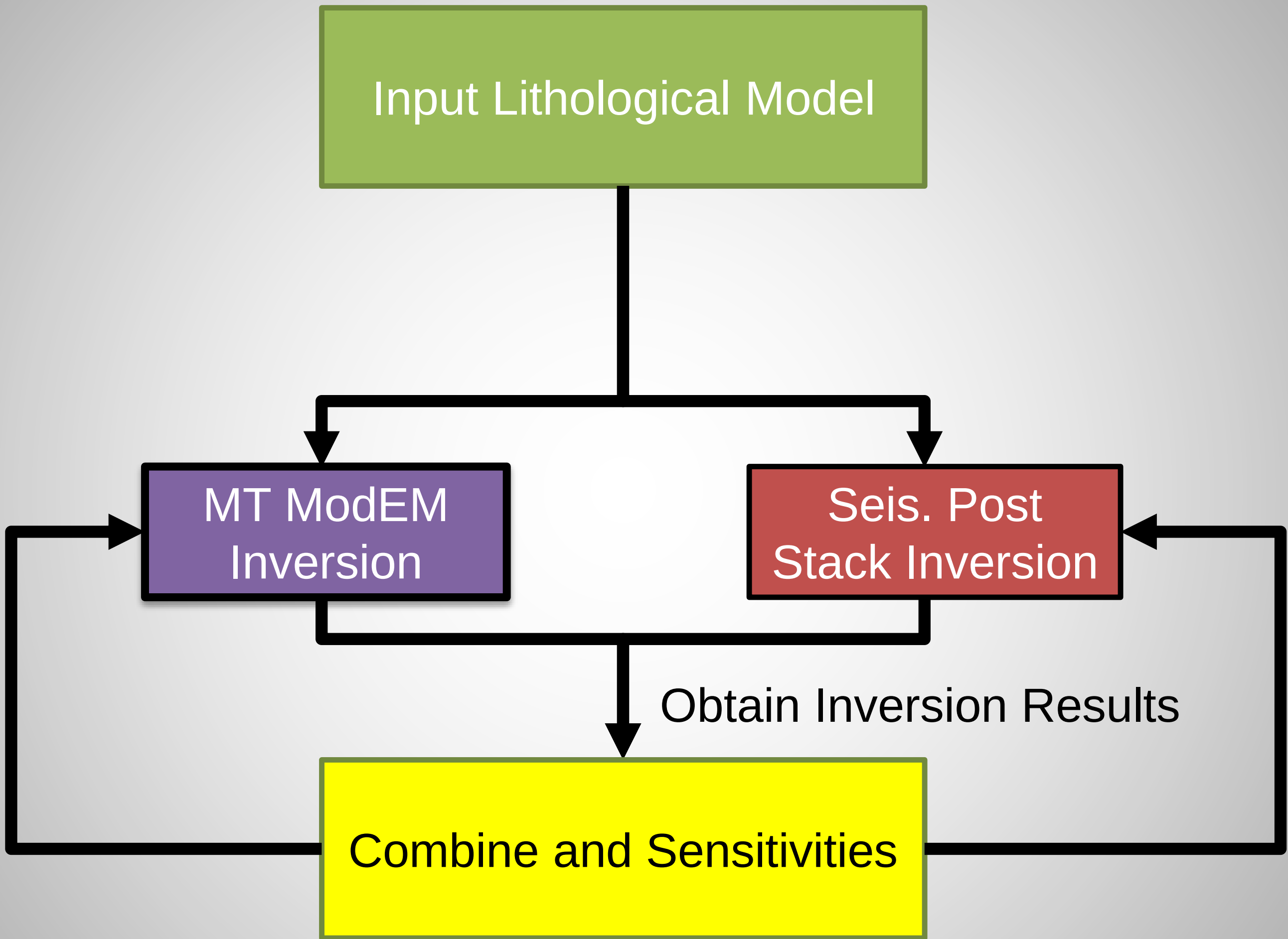
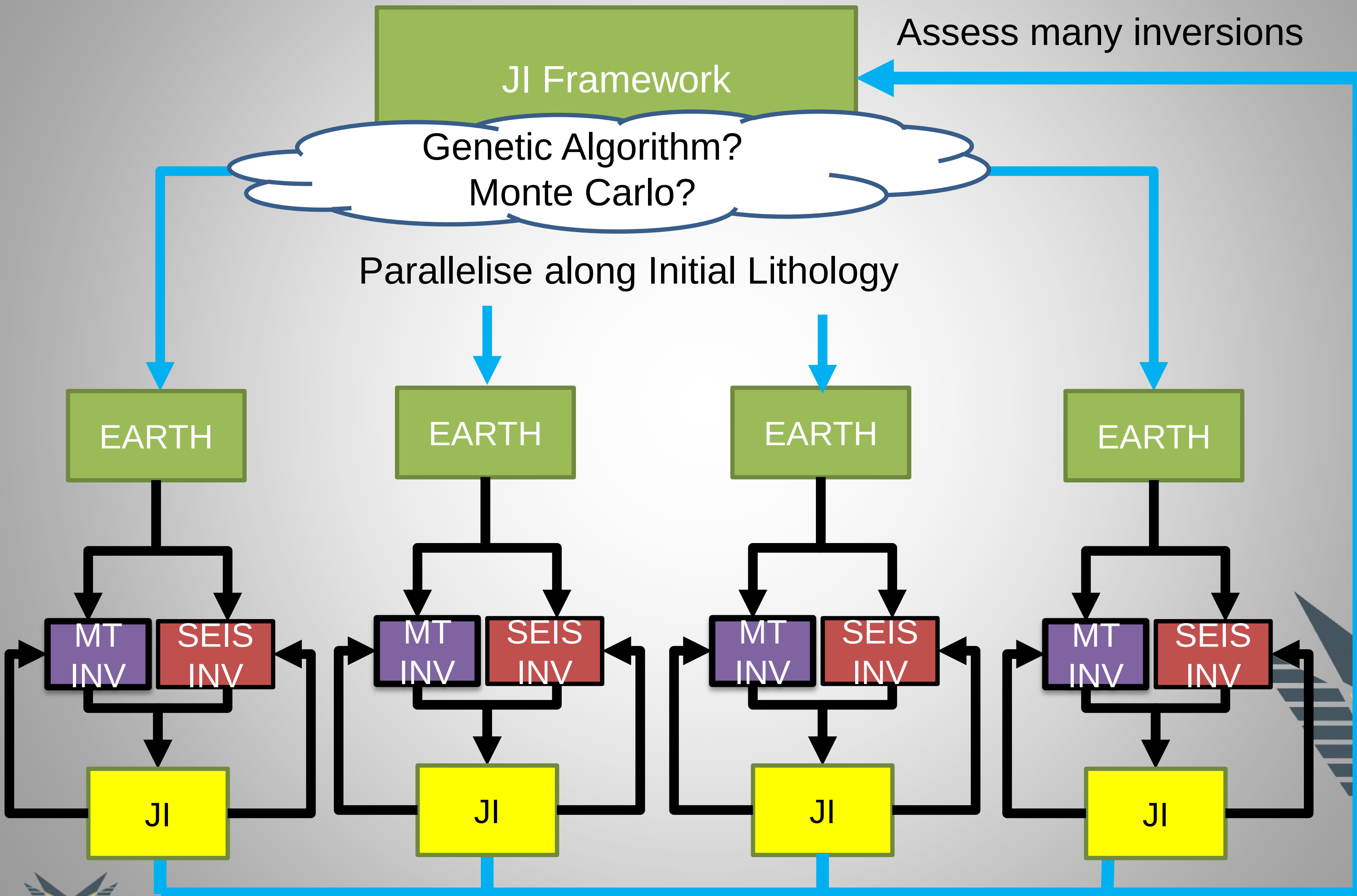
JI: Potential Workflow



Compare polar dip and conductivity gradient

JI: Implementing Macro-Parallelisation



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Conclusions

- Parallelisation can be used to dramatically improve computational speed
- Parallelisation can be applied at ‘macro’ and/or ‘micro’ scales
- Electromagnetic problems are generally parallelised by source excitation, frequency. conductivity distribution or seed model

Conclusions

- Using Parallelisation, we are working towards a rapid joint MT Seismic inversion workflow
  - Producing multi-seed model inversions
  - Within a simple and semi-automated software framework

Useful References

- Barney, B., Introduction to Parallel Computing, Lawrence Livermore National Laboratory, Accessed Nov 2013 from https://computing.llnl.gov/tutorials/parallel_comp/.
- Chen J., Raiche A. (1998) Inverting AEM data using a damped eigenparameter method. Exploration Geophysics 29 , 128–132.
- Egbert, G., Kelbert, A., 2000, Computational Recipes for Electromagnetic Inverse Problems, Geophys. J. Int., 142, 000-000.
- Marr, D., F. Binns, D. Hill, G. Hinton, D. Koufaty, A. Miller, and M. Upton, 2002, Hyper-threading technology architecture and microarchitecture: Intel Technology Journal, 6.
- Raiche, A. P., 1974, An integral equation approach to three-dimensional modelling: Geophysical Journal of the Royal Astronomical Society, 36, 363–376.
- Srivastava, U., and J. Widom, , Flexible time management in data stream systems: , ACM, 263–274.
- Top 500 Supercomputer Sites, Accessed Nov 2013 from http://www.top500.org/.
- Xiong, Z. (1992). Electromagnetic modeling of 3d structures by the method of system iteration using integral equations. Geophysics 57 (12), 1556–1561.
- AMIRA (2012). p223 - em modelling software. http://www.amirainternational.com/WEB/
- site.asp?section=news&page=projectpages/p223.
- Chopra, S. and K.J. Marfurt, 2010. Integration of coherence and curvature images: The Leading Edge, v. 29, p. 1092-1107
- Roberts, A., 2001, Curvature attributes and their application to 3D interpreted horizons: First Break, 19, 85–99.
- Chopra, S. and Marfurt, K. J. Siesmic Attributes – a historical perspective, GEOPHYSICS, VOL. 70, NO. 5 (SEPTEMBER-OCTOBER 2005); P. 3SO–28SO, 32 FIGS. 10.1190/1.2098670
- http://www.opendtect.org/pub
- Chen, Jinsong, G. Michael Hoversten, Donald Vasco, Yoram Rubin, and Zhangshuan Hou. 2007. "A Bayesian model for gas saturation estimation using marine seismic AVA and CSEM data." *Geophysics* no. 72 (2):WA85-WA95. doi: 10.1190/1.2435082.
- Chopra, Satinder, and Kurt J Marfurt. 2005. "75th Anniversary Seismic attributes—A historical perspective." *GEOPHYSICS* no. 70 (5).
- Colombo, D, and M De Stefano. 2007. "Geophysical modeling via simultaneous joint inversion of seismic, gravity, and electromagnetic data: Application to prestack depth imaging." *The Leading Edge* no. 26 (3):326-331.
- De Stefano, Michele, Federico Golfré Andreasi, Simone Re, Massimo Virgilio, and Fred F Snyder. 2011. "Multiple-domain, simultaneous joint inversion of geophysical data with application to subsalt imaging." *Geophysics* no. 76 (3):R69-R80.
- Fregoso, Emilia, and Luis A. Gallardo. 2009. "Cross-gradients joint 3D inversion with applications to gravity and magnetic data." *Geophysics* no. 74 (4):L31-L42. doi: 10.1190/1.3119263.
- Gallardo, Luis A., and Max A. Meju. 2007. "Joint two-dimensional cross-gradient imaging of magnetotelluric and seismic traveltime data for structural and lithological classification." *Geophysical Journal International* no. 169 (3):1261-1272. doi: 10.1111/j.1365-246X.2007.03366.x.
- Haber, E., and D. Oldenburg. 1997. "Joint inversion: a structural approach." *Inverse Problems* no. 13 (1):63.
- Hansen, Charles D, and Chris R Johnson. 2005. *The visualization handbook*: Academic Press.
- Kelbert, Anna, Naser Meqbel, Gary D. Egbert, and Kush Tandon. 2014. "ModEM: A Modular System for Inversion of Electromagnetic Geophysical Data." *Computers & Geosciences* (0). doi: http://dx.doi.org/10.1016/j.cageo.2014.01.010.
- Marfurt, Kurt J. 2006. "Robust estimates of 3D reflector dip and azimuth." *Geophysics* no. 71 (4):P29-P40.
- Ramachandran, Prabhu, and Gaël Varoquaux. 2011. "Mayavi: 3D visualization of scientific data." *Computing in Science & Engineering* no. 13 (2):40-51.
- Vozoff, K., and D. L. B. Jupp. 1975. "Joint Inversion of Geophysical Data." *Geophysical Journal of the Royal Astronomical Society* no. 42 (3):977-991. doi: 10.1111/j.1365-246X.1975.tb06462.x.
- Zhdanov, Michael S., Alexander Gribenko, and Glenn Wilson. 2012. "Generalized joint inversion of multimodal geophysical data using Gramian constraints." *Geophysical Research Letters* no. 39 (9):L09301. doi: 10.1029/2012GL051233.
- P and S waves -- ://en.wikipedia.org/wiki/File:Reflection_at_an_interface.png. Accessed 17/11/2013
- A.M. Pethick, B.D. Harris, Interpreting marine controlled source electromagnetic field behaviour with streamlines, Computers & Geosciences, Volume 60, October 2013, Pages 1-10, ISSN 0098-3004, http://dx.doi.org/10.1016/j.cageo.2013.04.017. (http://www.sciencedirect.com/science/article/pii/S0098300413001179)

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