The past, present and future of crustal structure modelling using potential field data.

Alan Aitken
with much help from many people

CCFS Workshop on Lithosphere Dynamics

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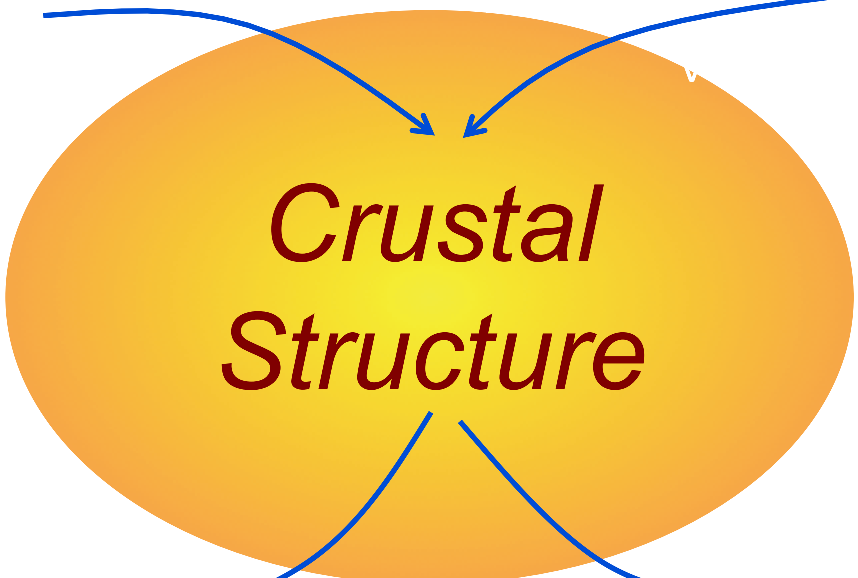
Gravity and magnetic modelling and the crust – what can they tell us?

1. Boundaries
- Basin thickness
- Moho
- Curie depth

2. Properties
- Crustal blocks,
- Underplates,
- Intrusive suites



3. Tectonics
- Crustal thickening/thinning
- Basin evolution
- Magmatic event mapping

4. Dynamics?
- Steady-state processes

Gravity and magnetic modelling can be broadly separated into 4 philosophies

1. Deterministic
2. Probabilistic (stochastic)
3. Structural-Tectonic
4. Process-Oriented

None is inherently better than the others, but in any circumstance the results will differ.

The choices made at this stage will very much determine the results achieved

Here I will go through the past and present of these philosophies, and speculate on their future

Gravity and magnetic modelling can be broadly separated into 4 philosophies

1. Deterministic

The solution to the problem is contained within the potential field data itself

Other data exist to modulate this solution

Dr Wikipedia says:

A **deterministic system** is a system in which no randomness is involved in the development of future states of the system.[1] A deterministic model will thus always produce the same output from a given starting condition or initial state.

The Deep Past…………

Semi-theoretical parameter estimation

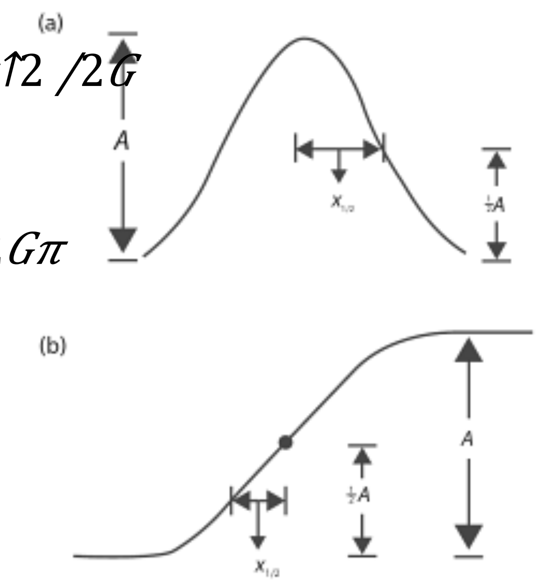
Given anomaly X, with wavelength Y and amplitude Z, the approximate depth and mass excess/magnetisation of the object can be estimated for certain shapes….

Sphere: $z = \frac{4}{3} x_{1/2}$ $M = g_{max} * z^2 / G$

Horizontal cylinder: $z = x_{1/2}$ $M/l = g_{max} * z^2 / 2G$

Semi-infinite thin sheet: $z = x_{1/2}$ $\rho t / l = g_{max} / 2G\pi$

No computer needed!



The Past…………

Layer Geometry Inversion (Parker-Oldenburg)

- Parker (1972) recognised that an undulating “contact” – e.g. base of a basin - could be modelled through FFT.

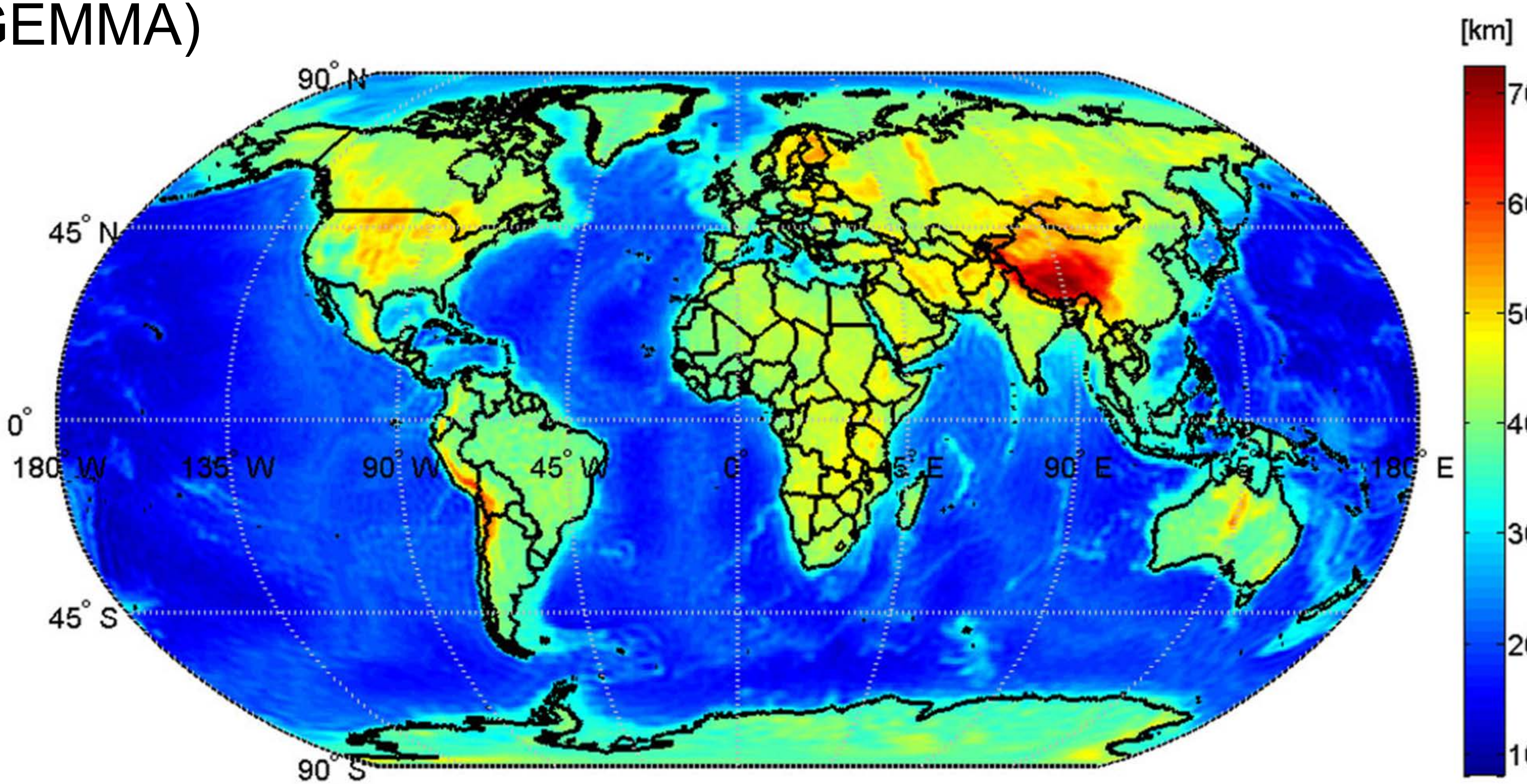
$$F[g_z] = -2\pi G \exp(-|k| z_0) \sum_{n=1}^{\infty} \frac{|k|^{n-1}}{n!} F[h^n(r)]$$

- Also he noted that the inversion was analytically unique
- Oldenburg (1974) implemented this inversion,
- Moritz (1990) extended it to geodetic coordinates

The Past…………

Layer Geometry Inversion (Parker-Oldenburg)

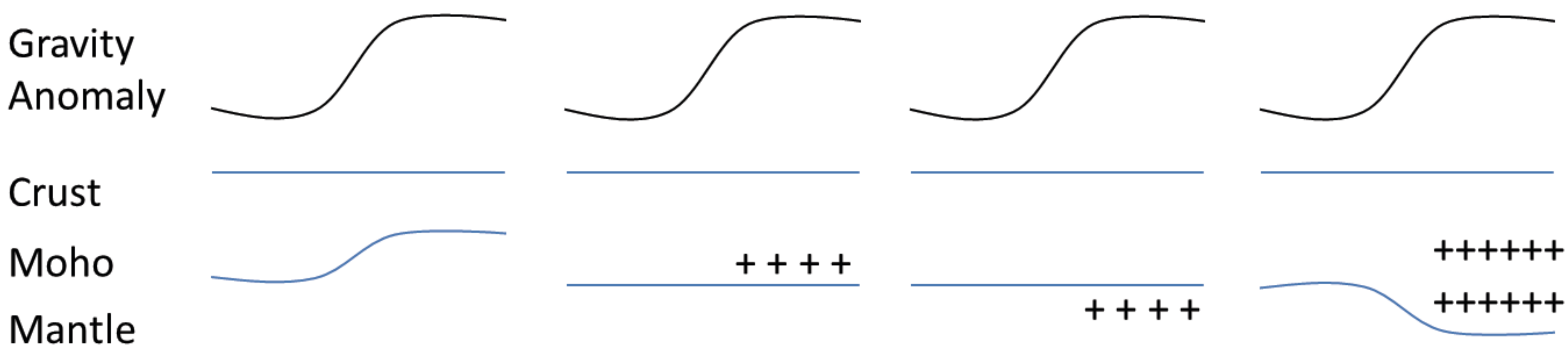
- Still in use today, e.g. for large-scale modelling of the Moho (GEMMA)



The Past………….

Layer Geometry Inversion (Parker-Oldenburg)

- This method is highly problematic:
  - Assumes ALL signal (after processing) is sourced from the contact



  - Also assumes constant source-sensor separation

The Past…………

Voxel Property Inversion (e.g. UBC-GIF)

- Uses the known gravity response of *m* cuboids each at some distance and depth to compute g_z at *n* data points

$$d = G\rho$$

- Once G is defined, this problem can be inverted
- However, the problem is highly underdetermined as $m >> n$
- So we need to add strong regularization
- This is where things get difficult…..

The Past…………

Voxel Property Inversion (e.g. UBC-GIF)

- Maximum Smoothness.
  - Minimise property gradients in x y and z
  - L^2 Norm ---- NB unstable for large misfits
- Depth and spatial weightings
  - Standard linear depth weighting
  - Arbitrary spatial weighting possible
- Reference Models
  - Can specify reference model

The Present…………

Some recent innovations have focused on how we approach inversions:

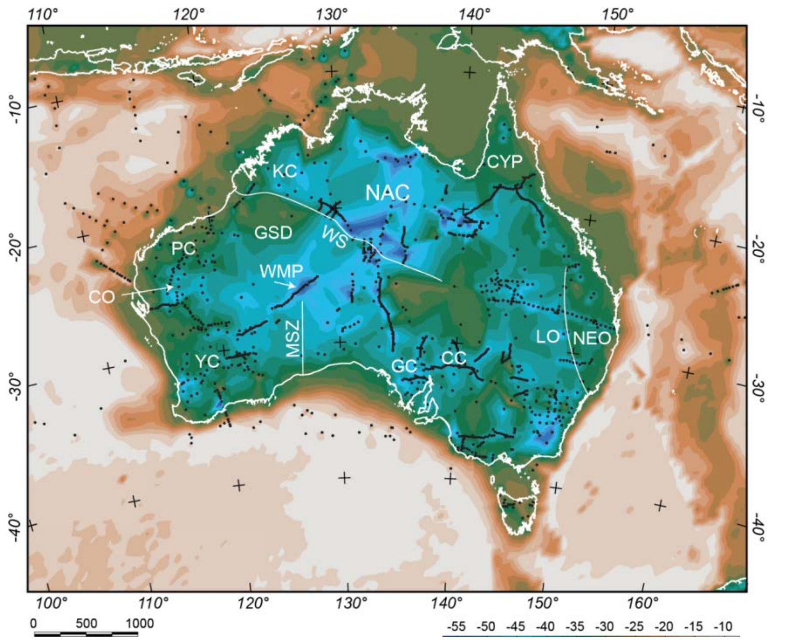
- Combined layer/property inversions (e.g. VPmg)
  - A mix of layers and voxets
- Lithologically-constrained modelling
- Lithological units are defined and tracked through inversion
- This provides flexibility……but also an extra degree of freedom to be controlled
- In the “voxet-based” world, developments have focused on numerical and computational advances…….

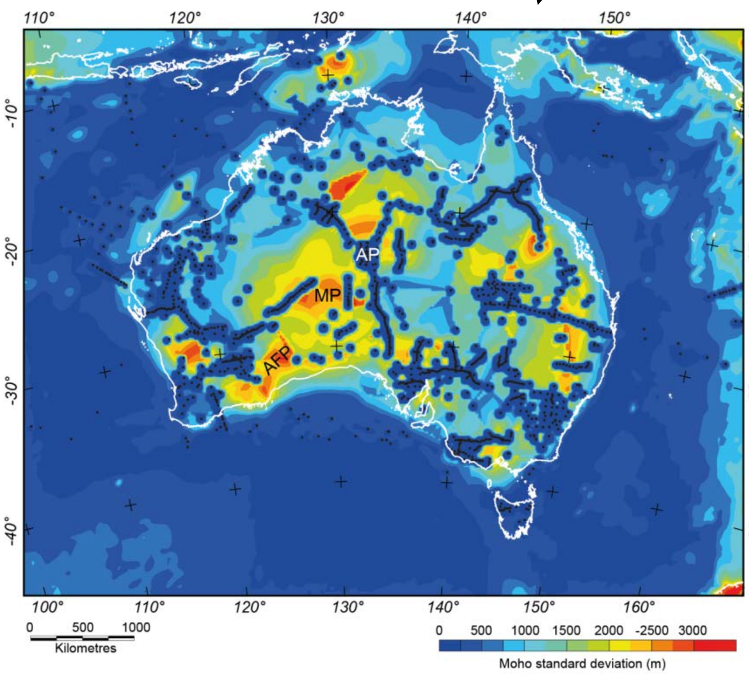
The "Present"…………

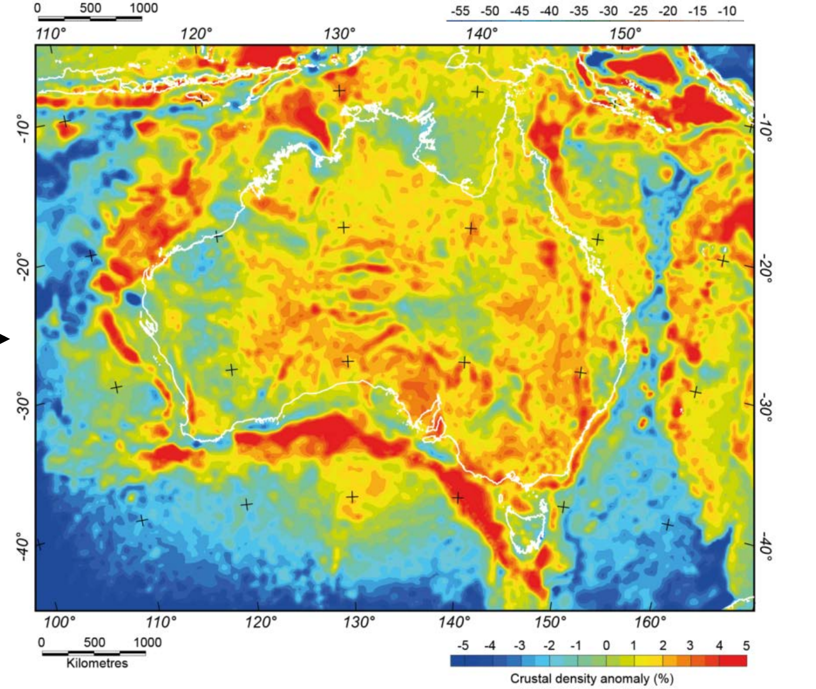
SOME VPmg models:

Australia's Moho (Aitken et al, in press)

- Simultaneous Moho geometry and crustal density
- Error (well, variability) analysis





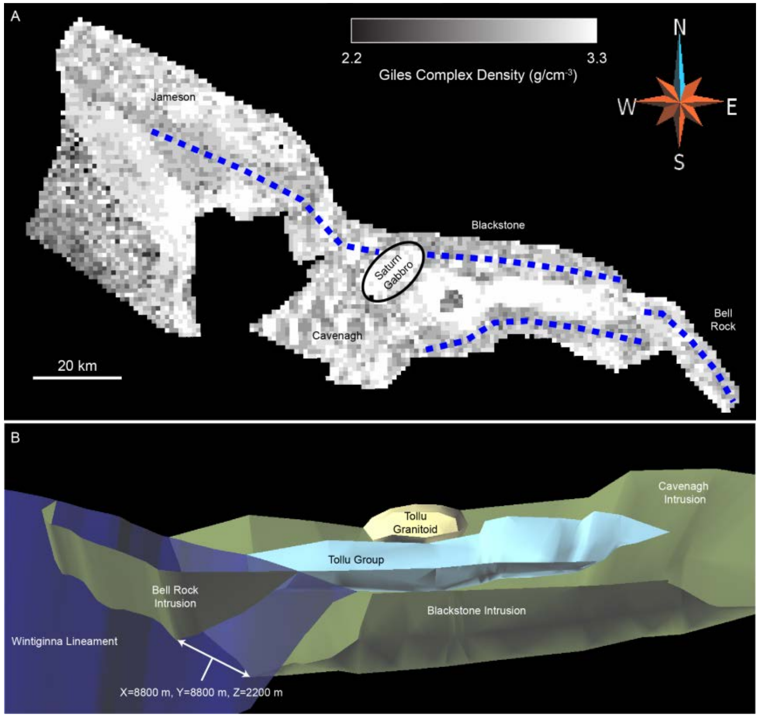


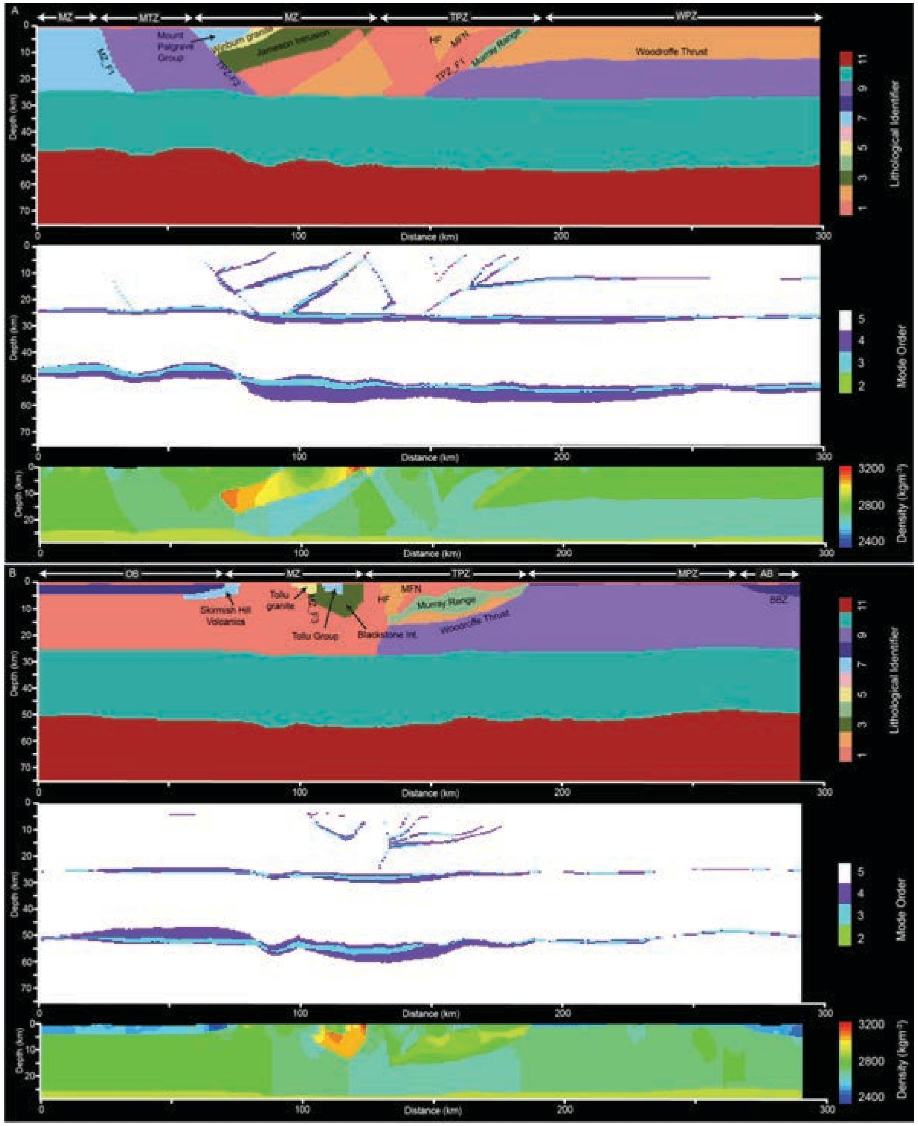
The "Present"............

SOME VPmg models:

The West Musgrave Province (Aitken et al, 2013)

- Simultaneous geometry and density
- Variability analysis

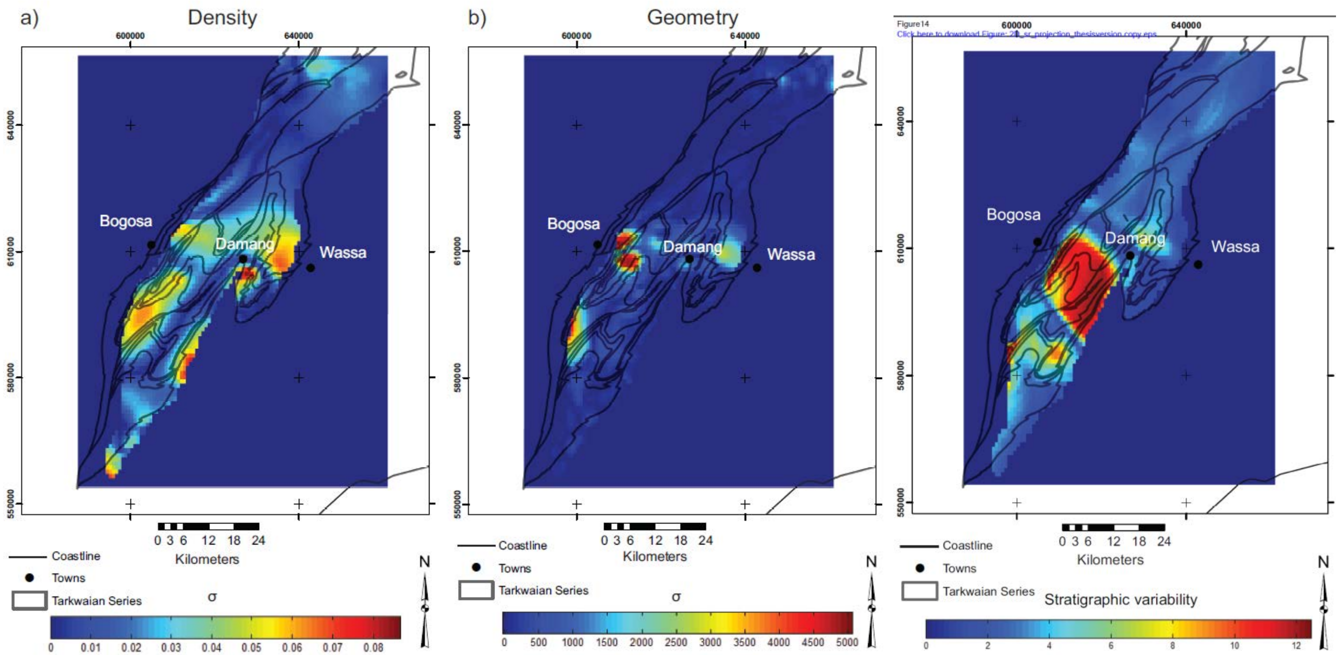




The "Present"………….

SOME VPmg models: Ashanti Belt (Lindsay et al, 2014)

Variability of the modeled contact and the density above/beneath is intimately related to the stratigraphic uncertainty of the initial model



Correlation coefficients:
Density variations vs stratigraphic uncertainty: 0.77
Geometry variations vs stratigraphic uncertainty: 0.67

The (near) Future?…………

Massively parallel codes - i.e. model size is becoming a non-issue:

escript (Gross et al, 2007, 2013)

16 million cells in 32 mins on 128 cores, tested up to 64m cells and 1000 cores

mag, grav, mag & grav potentials, joint inversion

geodetic coordinates

You can get this today….. (https://launchpad.net/escript-finley)

Wavelet compression and GPU acceleration (Martin et al, 2013)

~54 million cells in 6 mins on 256 cores

gravity only (for now, and as far as I know)

The Future?…………

- Problem size is becoming a non-issue
- Imperfect data distributions are a limitation, e.g. high-res and low-res data regions in the same model.

  Adaptive discretisation and appropriate regularisation

  On-the-fly remeshing based on model changes?

- Joint inversion is available through several avenues……but there are many issues still

  Suitability of cross-gradient constraints with differing spectral contents – e.g. TMI and gravity?

  “Rule” based methods suffer greatly from poorly defined “rules”

The Future?…………

- Getting geology "into" and then "out of" the inversions is a remaining challenge
    - Massively parallel lithological inversion?
    - Dealing with lithological change
    - Fine-boundaries
- Uncertainty in results remains the greatest challenge in deterministic modelling
    - Quantification through automated ensemble inversion
    - Imposed "conceptual" mistakes are hard to rectify

Gravity and magnetic modelling can be broadly separated into 4 philosophies

2. Probabilistic

The solution to the problem is contained within our knowledge of rock properties.

Potential Field data exist to control the distributions

Dr Wikipedia says:
"a **stochastic process**, or sometimes **random process** (*widely used*) is a collection of random variables; this is often used to represent the evolution of some random value, or system, over time. This is the probabilistic counterpart to a deterministic process (or deterministic system)."

The Past…………

Fundamentally we seek to answer the following:

$$\sigma(m) = k\rho(m)L(m)$$

Where L(m) describes the likelihood function. This usually contains a data fit term (with uncertainty)

$\rho(m)$ describes the a-priori PDF

$\sigma(m)$ describes the a-posteriori PDF

k is a suitable constant – e.g. ½ = L^2, 1=L^1

We are, in this approach, much less susceptible to “local maxima” in the likelihood function than deterministic methods.

We are much more susceptible to our assumptions about geology (encapsulated in the a-priori PDF)

The Past…………

Monte-carlo sampling (Mosegaard & Tarantola (1995))

1. Generate initial random model, conforming to PDFs
2. Generate "neighbouring" model – one that is close in some way (e.g. create or destroy a single interface in the model, change the density of a layer)
3. Compute likelihood function L(m)
4. if $L(m_i) \geq L(m_j)$ Accept

   Otherwise, decide randomly to accept or reject with acceptance probability:

   $P = L(m_i)/L(m_j)$

The Present…………

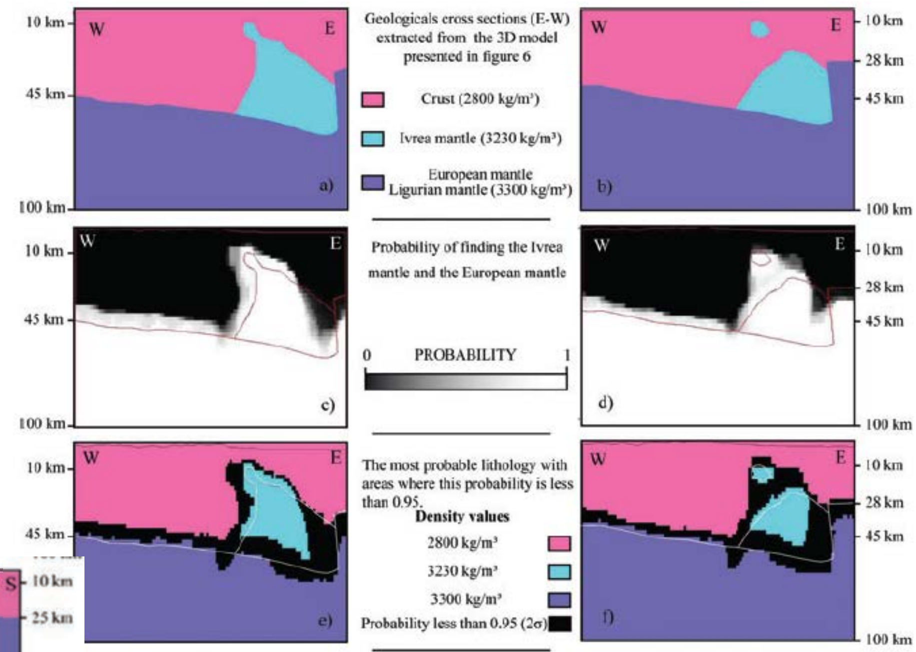
Monte-carlo probabilistic inversion with lithological constraint (e.g.Geomodeller, VPmg - sort of)

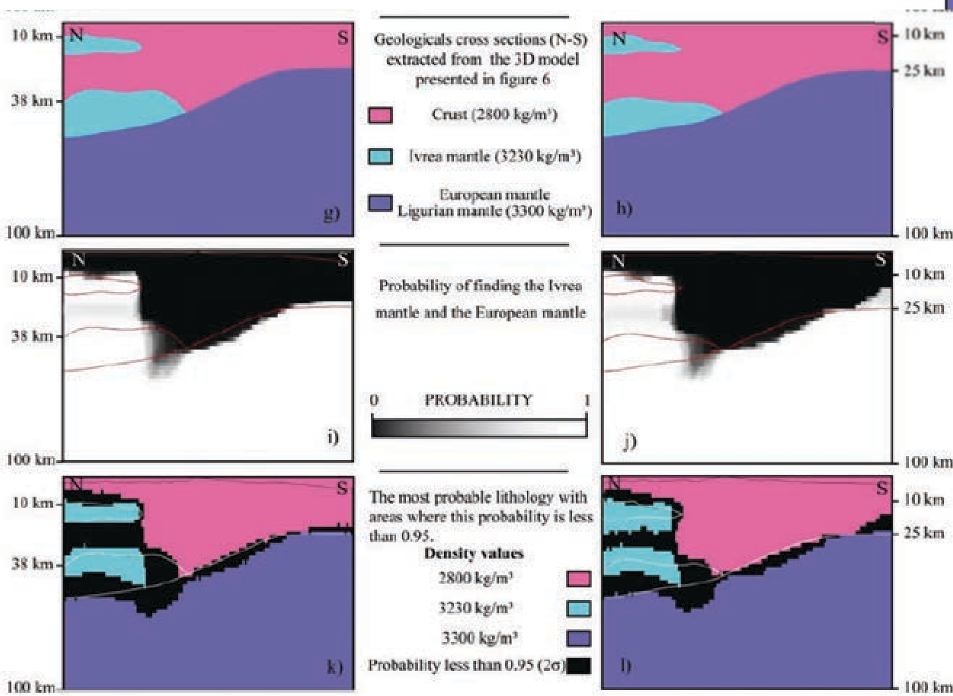
- An a-priori lithological model is provided with a PDF for property variation within each lithology
- In Geomodeller, the lithology of boundary cells can change randomly (primary parameter)
- Or the property can change randomly (secondary parameter)
- In Geomodeller, the model is permitted to run well past where the likelihood no longer increases --- equilibrium likelihood may be achieved
- This provides an estimate of uncertainty in the suite of valid models

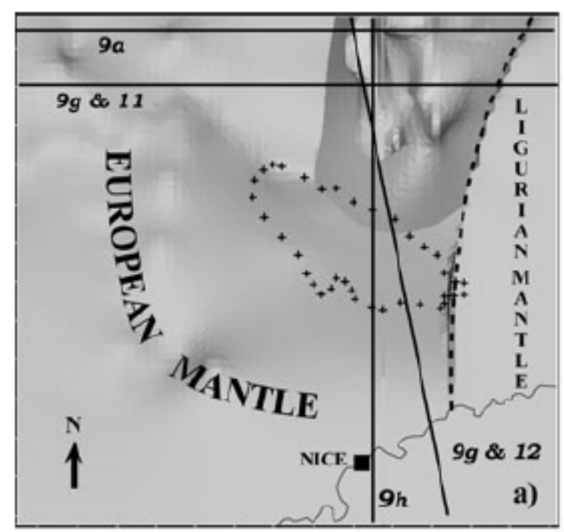
The Present…………

SOME Geomodeller models

3D bouguer graviy inversion of the Moho and Ivrea Zone in the SW alps (Schreiber et al (2010))







The Present…………

SOME Geomodeller models

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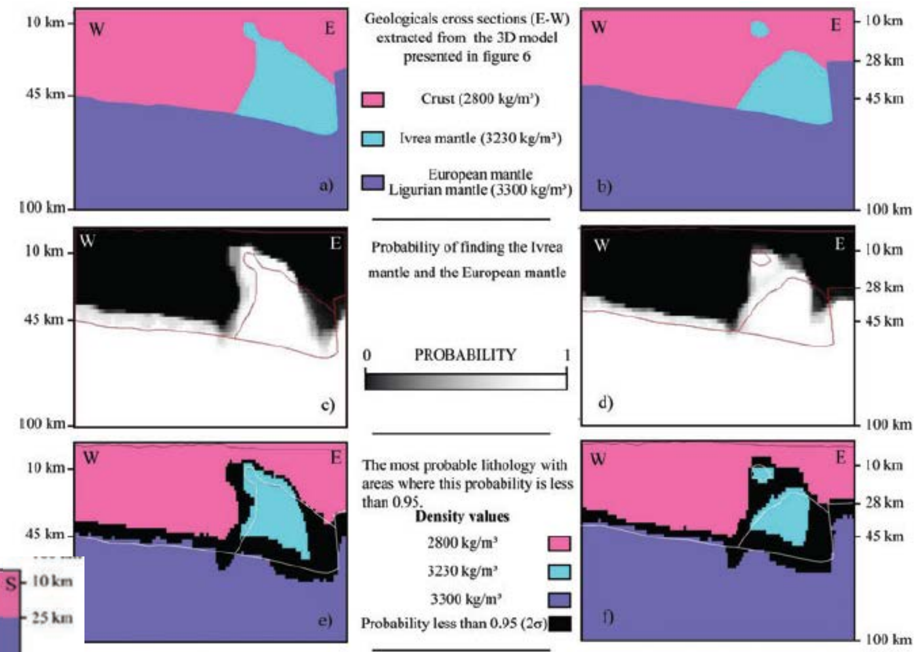
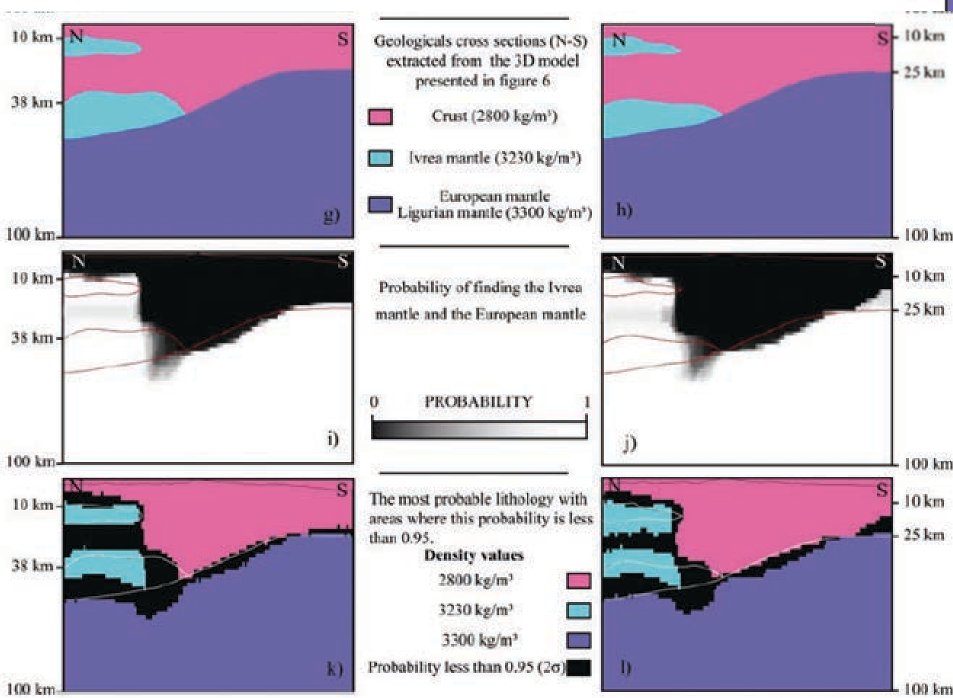
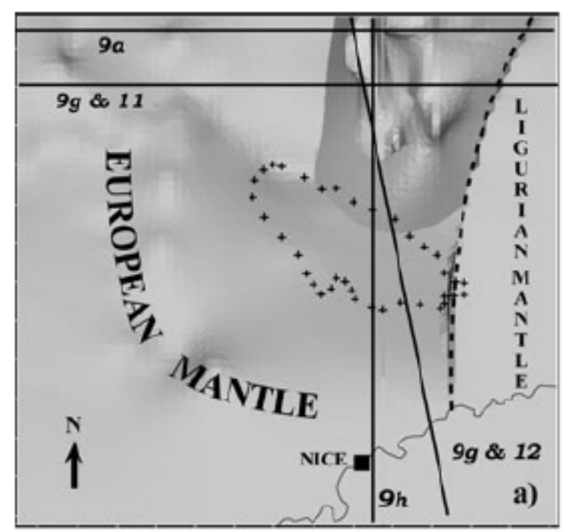
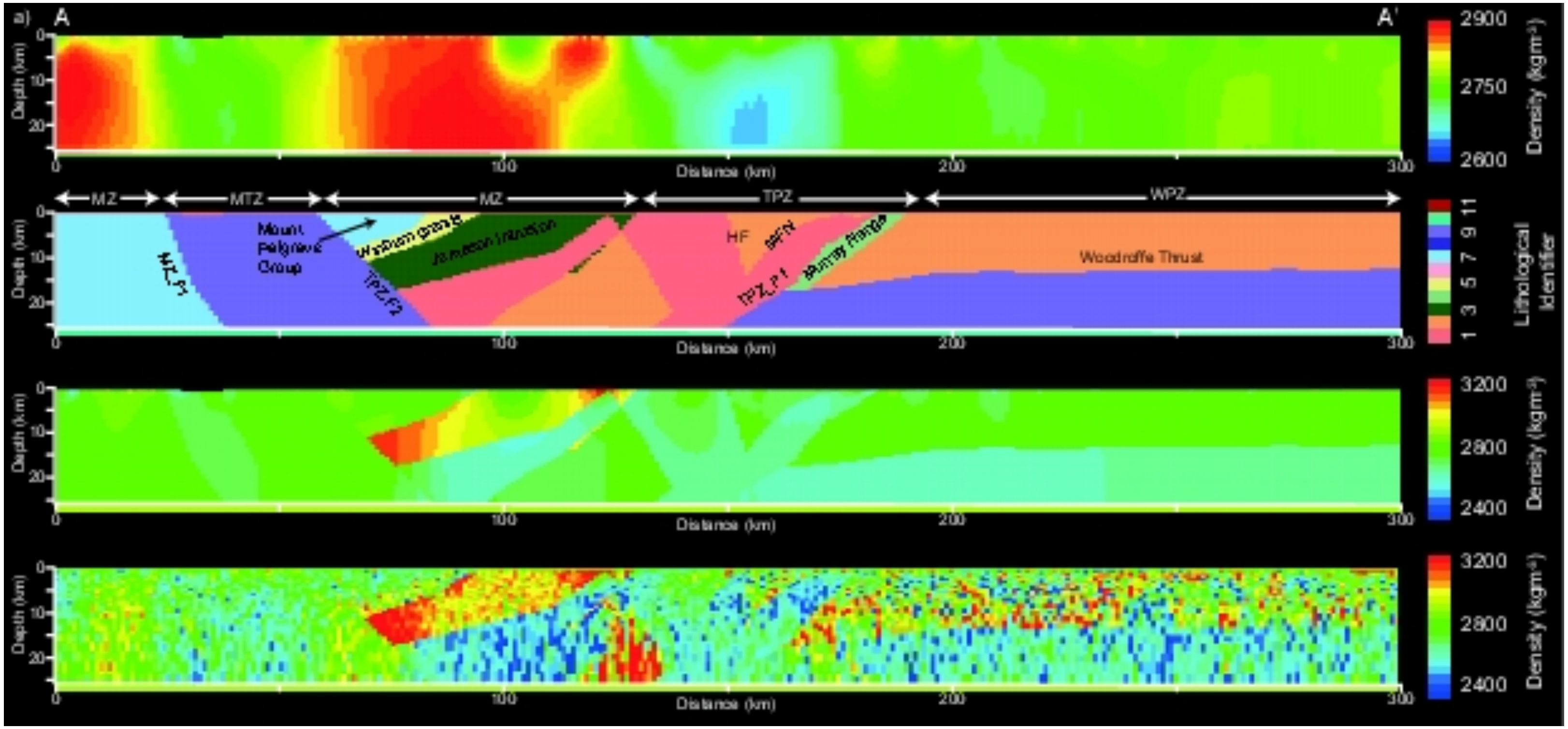






The Future?…………

- Areas of low-sensitivity can be populated with the more inconvenient parts of the density distribution



- So some method must be found to control the spatial probability

The Future?…………

- These methods are susceptible to the PDFs used. i.e. they must be well defined to get a solution that is close to reality

Solution A – Get a better knowledge of petrophysical data

Especially for the deep crust and uppermost mantle

Solution B – use multiple data types to constrain solutions

The Future?…………

Probabilistic mineralogical inversion (LitMod3D) (Afonso et al, 2013 a,b)

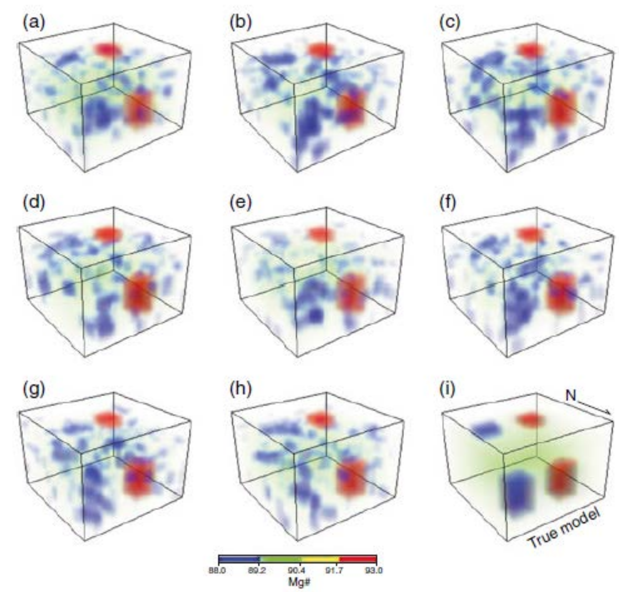
JOURNAL OF GEOPHYSICAL RESEARCH: SOLID EARTH, VOL. 118, 2586–2617, doi:10.1002/jgrb.501

3-D multiobservable probabilistic inversion for the compositional and thermal structure of the lithosphere and upper mantle. I: *a priori* petrological information and geophysical observables

J. C. Afonso,[1] J. Fullea,[2,3] W. L. Griffin,[1] Y. Yang,[1] A. G. Jones,[2] J. A. D. Connolly,[4] and S. Y. O'Reilly[1]

Received 14 June 2012; revised 4 February 2013; accepted 6 February 2013; published 30 May 2013.

[1] Traditional inversion techniques applied to the problem of characterizing the thermal and compositional structure of the upper mantle are not well suited to deal with the nonlinearity of the problem, the trade-off between temperature and compositional effects on wave velocities, the nonuniqueness of the compositional space, and the dissimilar



Recovered bulk mg# from a test inversion

I will not try to explain this, as JC and several co-authors are here.

Gravity and magnetic modelling can be broadly separated into 4 philosophies

3. Structural-Tectonic

The solution to the problem is contained within our knowledge of geological structure.

Potential Field data exist to control property distributions within known elements and modify known structure

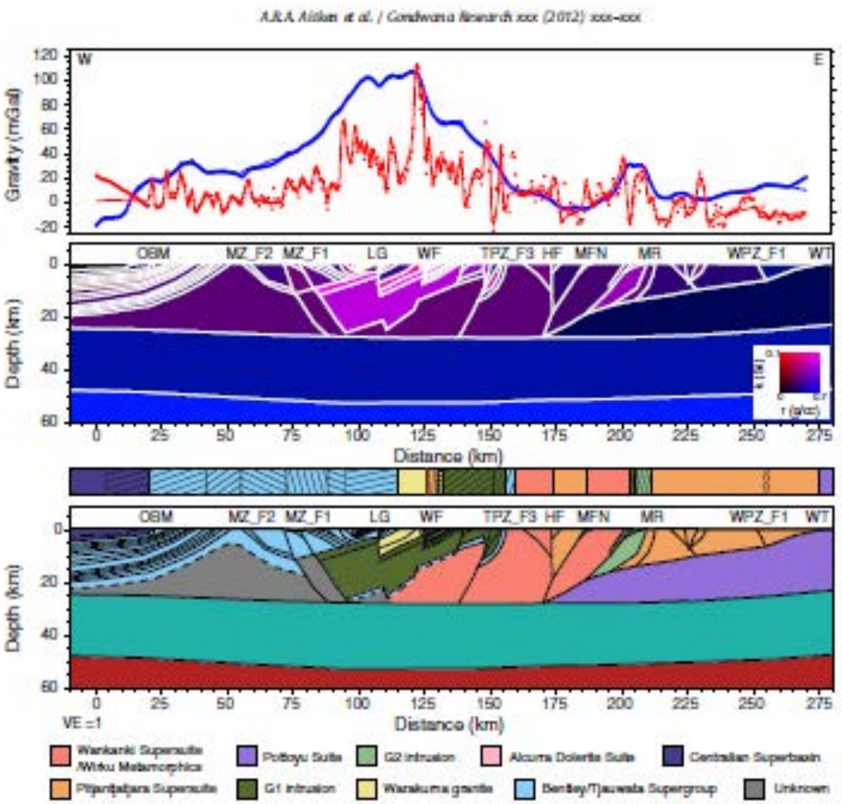
The Past…………

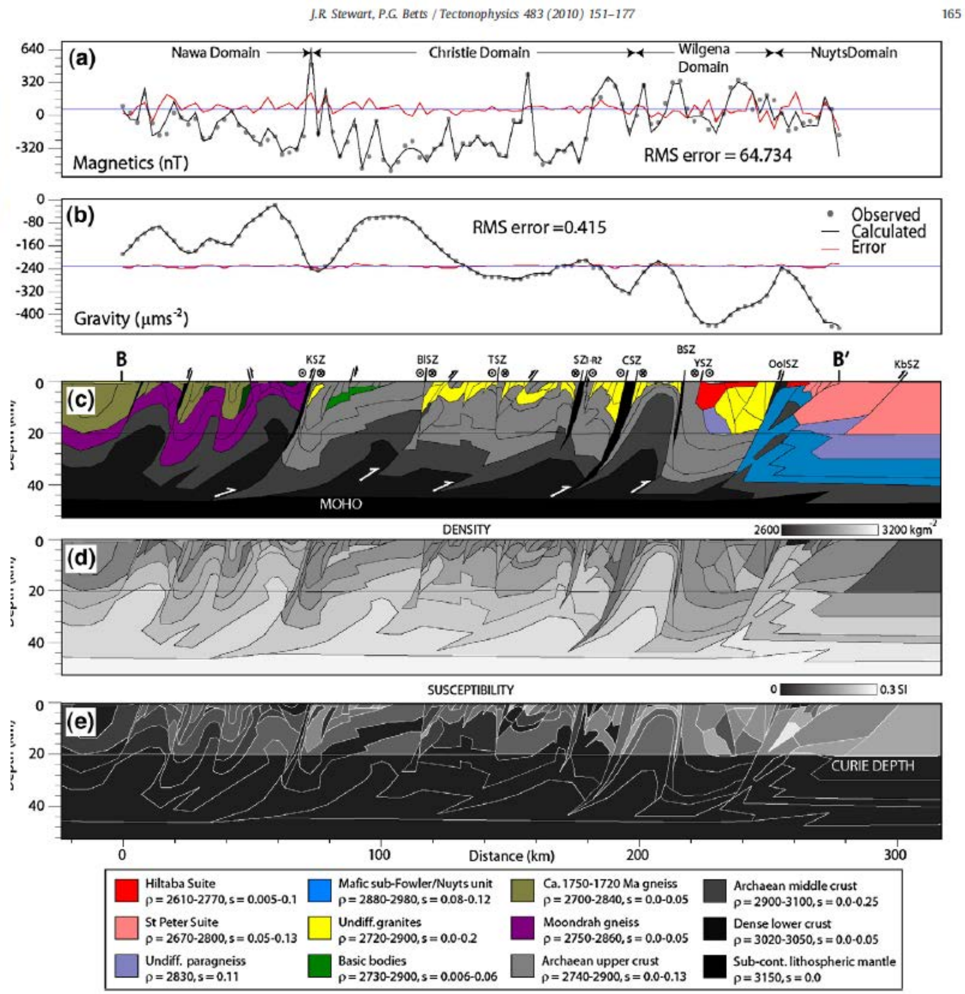
Talwani-style 2D forward modelling

- For an arbitrary prism, the gravity (or magnetic) field is easily calculated from the line-integral of an n-sided polygon (Talwani, 1959)
- So if you can draw the shape……you can model the gravity
- This has been extended to 3D (e.g. IGMAS)
- Using this approach it is easy to turn a geological cross section or tectonic model into a geophysical model….
- And it is easy to get it to fit the data…..(usually)

The Past…………

Talwani-style 2D forward modelling



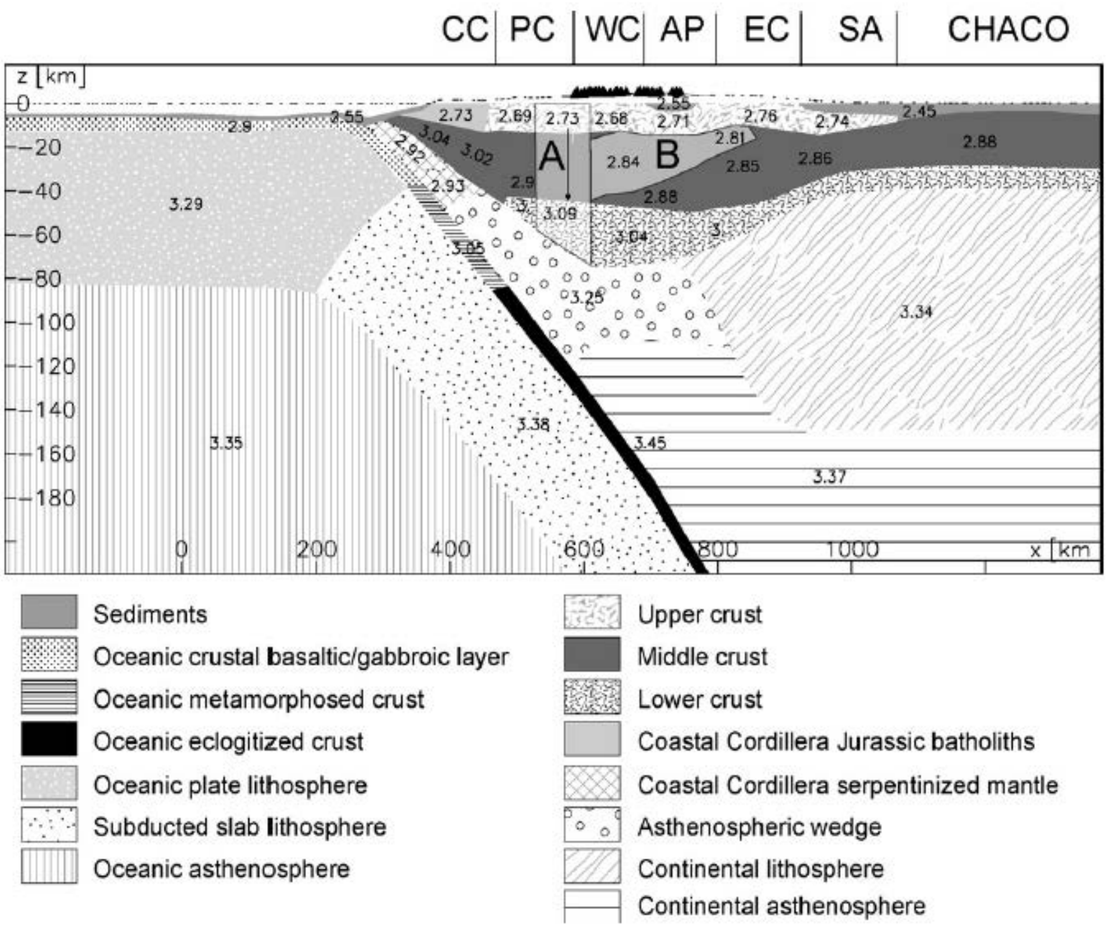


Examples where geological cross sections have been 'verified' by modelling

The Past…………

A 3D example in IGMAS forward modelling – the central Andes

C.B. Prezzi et al. / Physics of the Earth and Planetary Interiors 177 (2009) 217–234



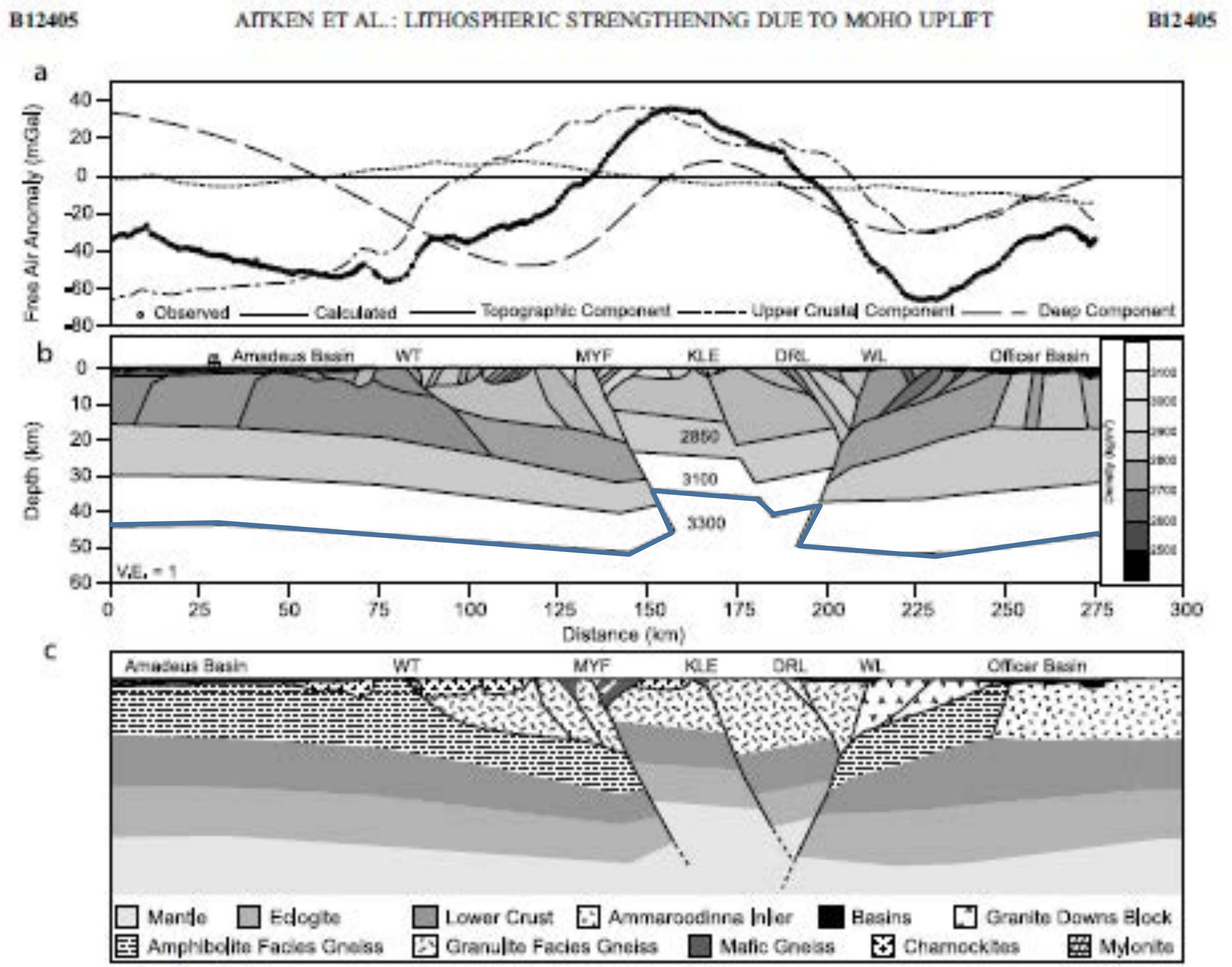
The Past…………

Talwani-style 2D forward modelling

- And it is easy to get a model to fit the data…..(usually)
- The hard part is verifying that those changes made are necessary and justifiable
  - Sensitivity studies
  - Minimum structure models
- Nonetheless, some good results can be achieved……

--------with luck and care

The Past…


B12405
AITKEN ET AL.: LITHOSPHERIC STRENGTHENING DUE TO MOHO UPLIFT
B12405
a
Free Air Anomaly (mGal)
Observed
Calculated
Topographic Component
Upper Crustal Component
Deep Component
b
Depth (km)
Amadeus Basin
WT
MYF
KLE
DRL
WL
Officer Basin
2850
3100
3300
V.E. = 1
Distance (km)
c
Amadeus Basin
WT
MYF
KLE
DRL
WL
Officer Basin
Mantle
Eclogite
Lower Crust
Ammaroodinna Inlier
Basins
Granite Downs Block
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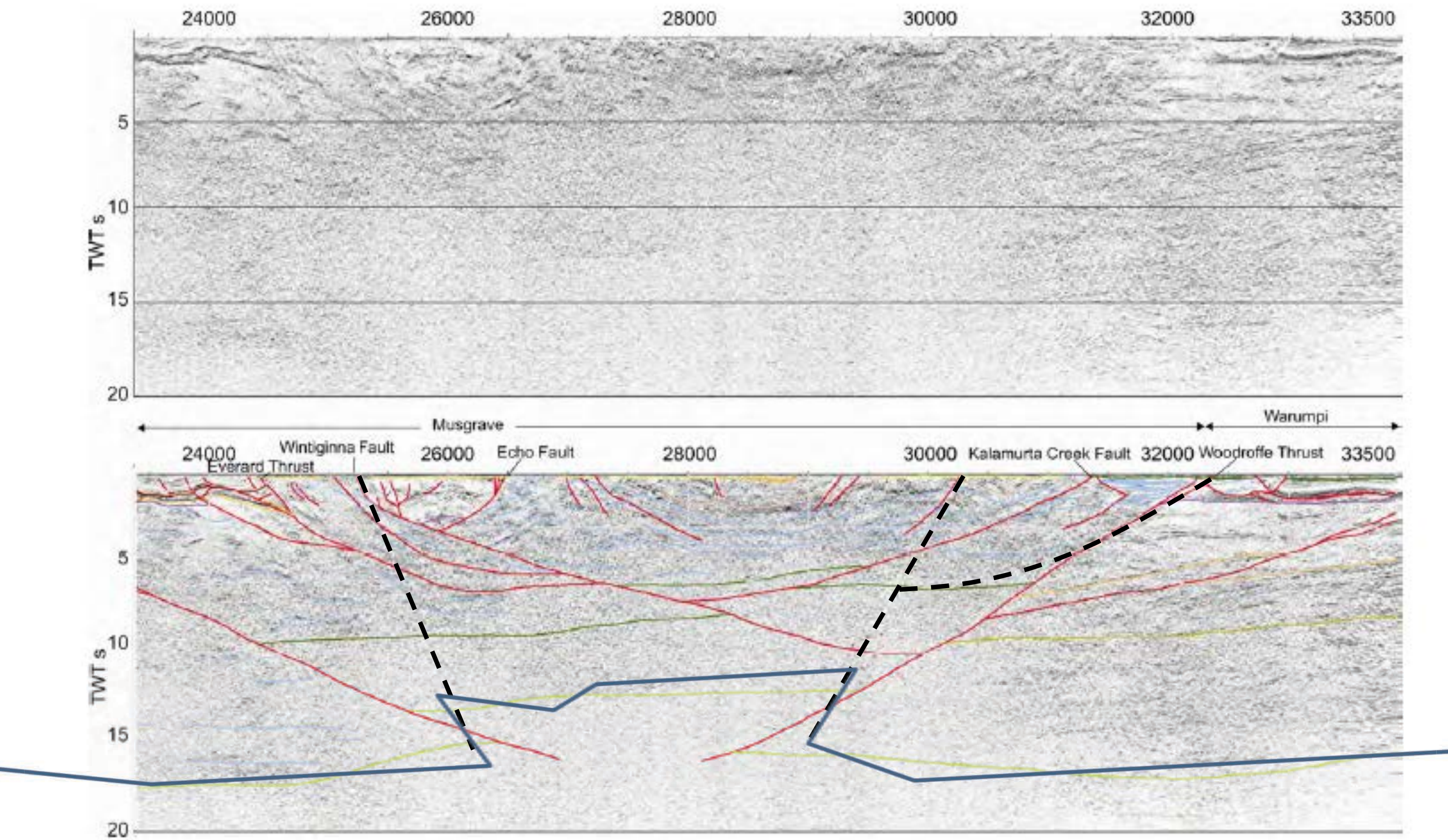
Granulite Facies Gneiss
Mafic Gneiss
Charnockites
Mylonite

The Past……


24000
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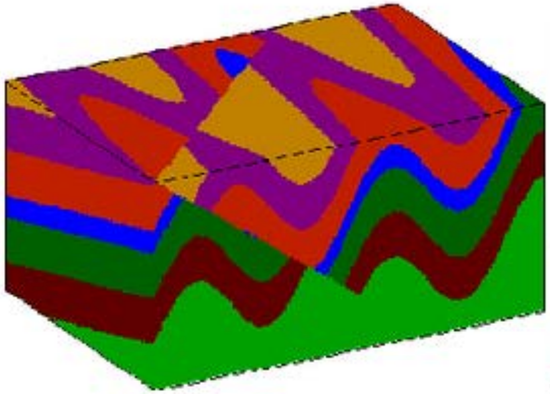
Musgrave
Warumpi
Wintiginna Fault
Everard Thrust
Echo Fault
Kalamurta Creek Fault
Woodroffe Thrust

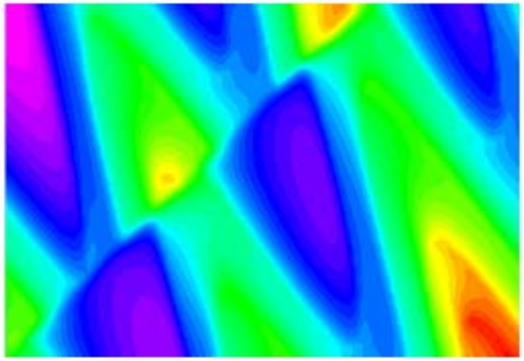
The Past……

Noddy modelling

IF you have a structural history, AND a reasonable idea of initial structure AND rock properties, you can use a Noddy model (Jessel and Valenta, 1996, Jessell et al)

One would hope this gives
At least an approximate fit
to your data



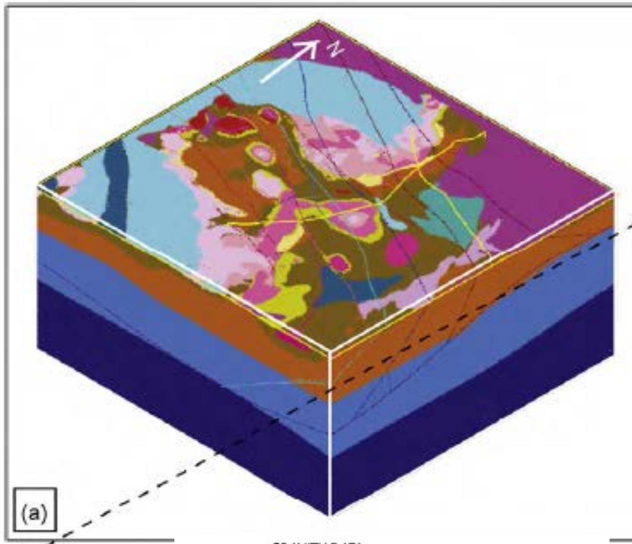


The Present…………

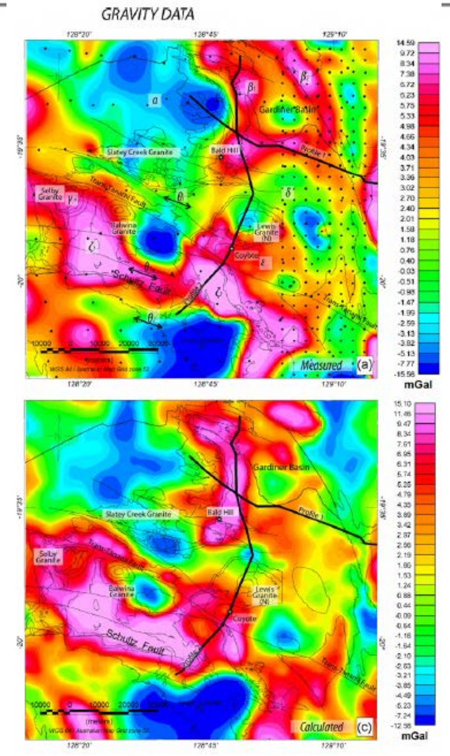
3D Structural modelling and coupled forward modelling and inversion (Geomodeller)

3D model is built through interpolating observed geological data (contacts and orientation data.)

- This can then be forward modelled
- Or inverted retaining the lithological information
- But not, at present, the orientation data



Joly et al, (2010)



The Future?…………

Arguably, this realm has seen the least recent development

- Geological concepts are quite static
  - Although easier semi-automated implementation would help
- Forward modelling is straightforward, if not easy, especially in 3D
- Inversion schemes are currently too crude to really conform to the data
- A supercomputer doesn’t help much

Gravity and magnetic modelling can be broadly separated into 4 philosophies

4. Process Oriented

The solution to the problem is contained within a known and model-able geological process.

Potential field data exist to control/select process parameters

The Deep Past…………

Isostatic and flexural modelling (Vening Meinesz – 1939 - 1959)

Uses gravity data to determine flexure of the crust

Honolulu is the perfect example

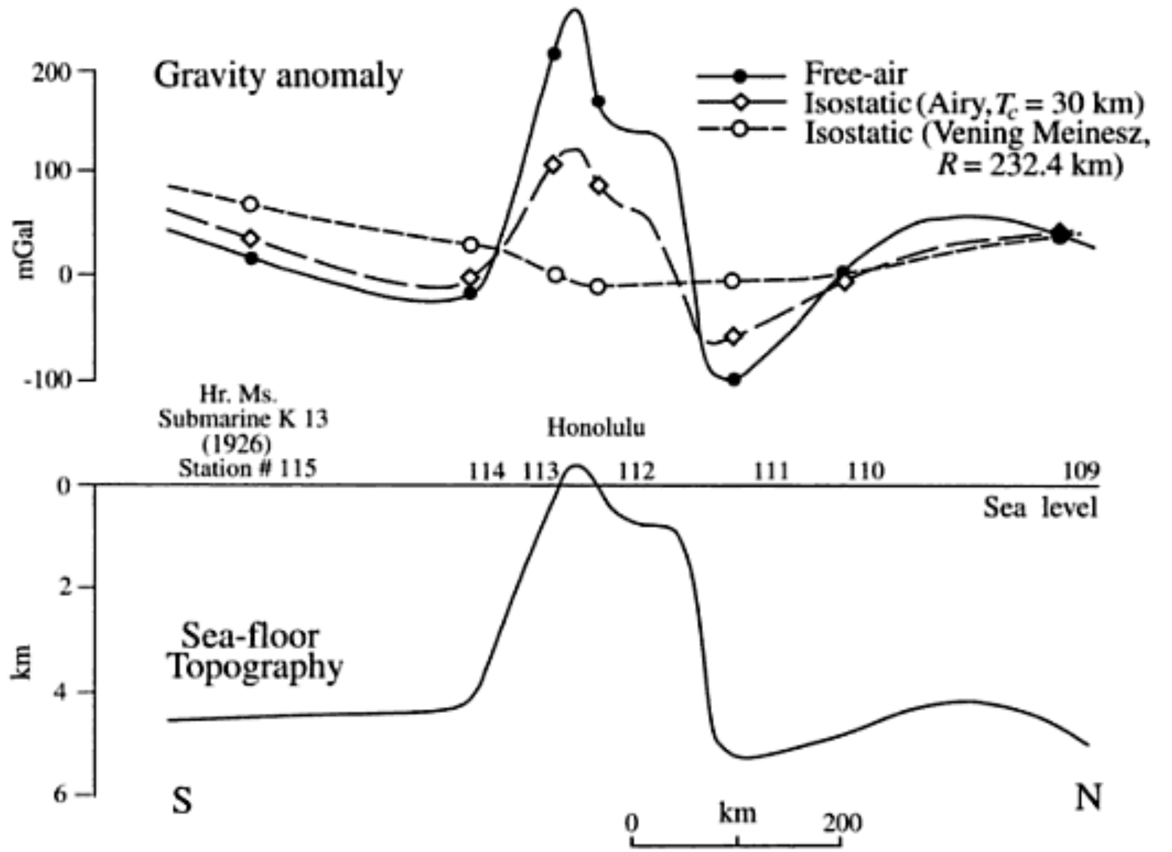
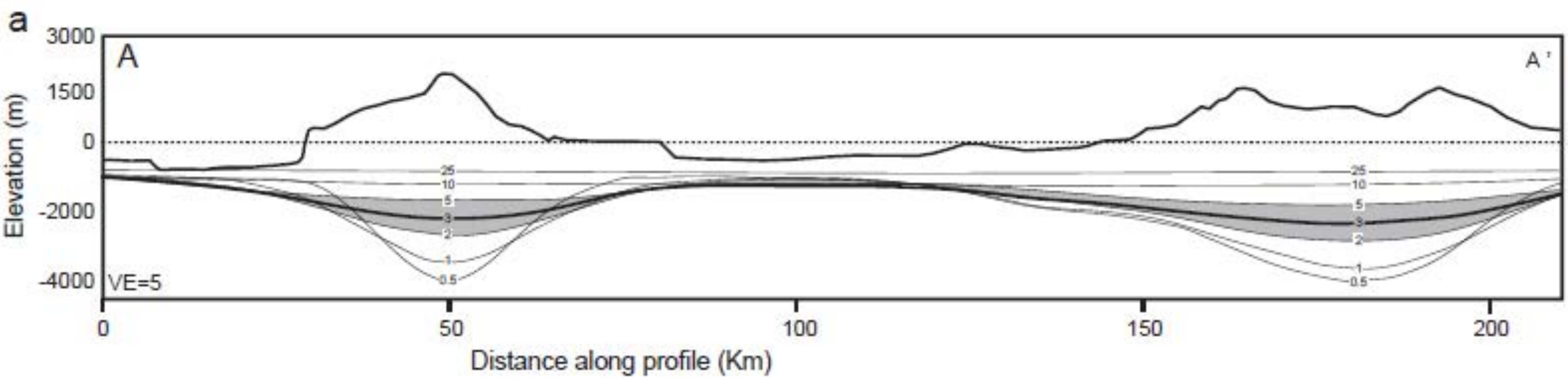


Fig. 2.14. Gravity anomaly and topography profiles of the Hawaiian Ridge in the region of Oahu. Based on measurements acquired by Vening Meinesz (1948) on board Submarine K13 of the Royal Netherlands Navy. The isostatic anomaly profiles are based on the Airy and Vening Meinesz models.

The Past…………

Flexural modelling (e.g. LithoFLEX)

- Point, line and arbitrary loads on elastic and viscoelastic plates
- Forward model flexure from gravitational loads
- Forward model gravity response and compare with observed
- Works well in foreland basins, around seamounts/volcanoes



Aitken et al, (2012)

The Present…………

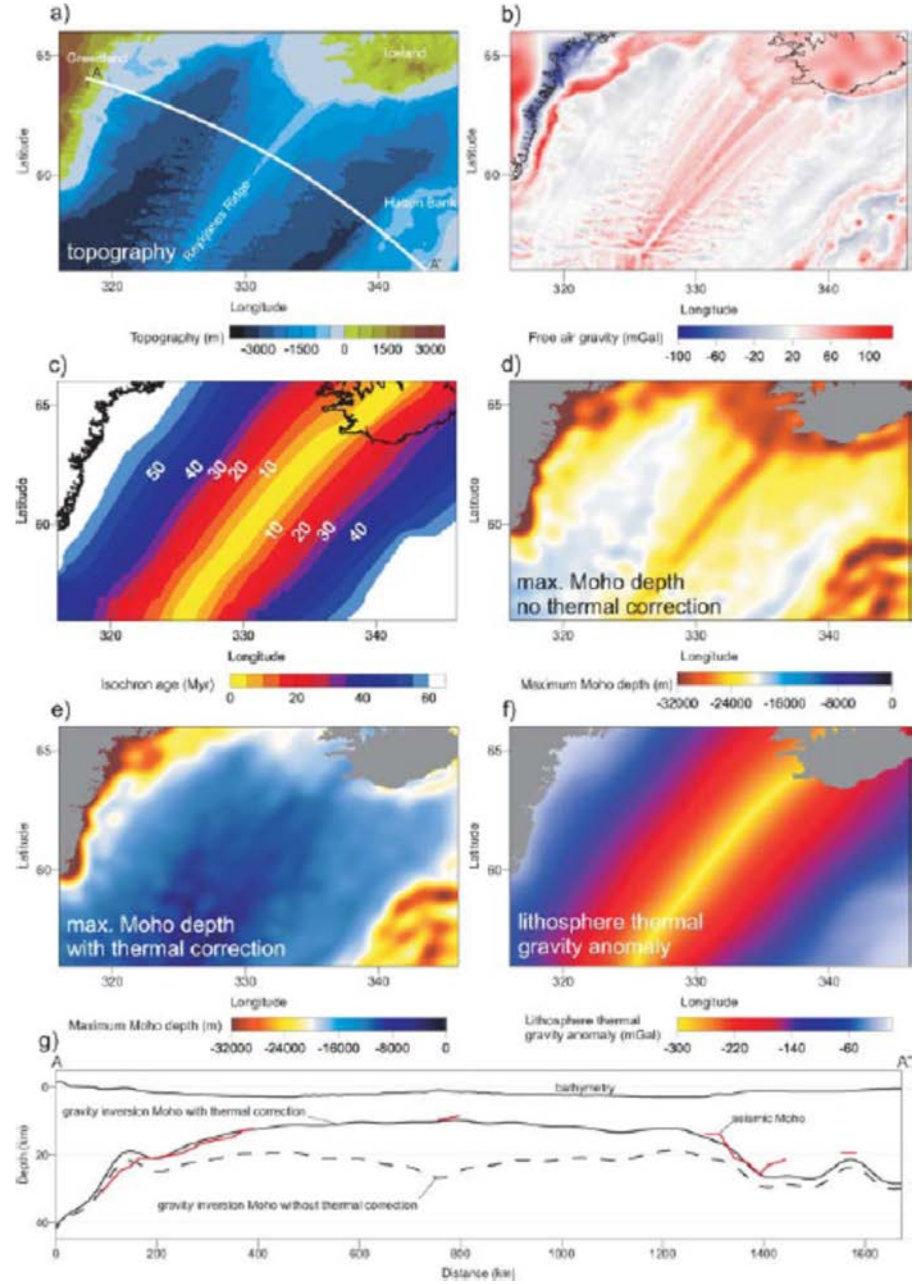
Coupled thermal and mechanical modelling…

For rifted continental and oceanic margins.

Iteratively inverts gravity for:

- ➢ Thermal model of the lithosphere
- ➢ Crustal thickness
- ➢ Crustal thinning factor

(Chappell and Kusznir, 2010)



The Present……

LitMod3D

Forward model the thermal, compositional, density, seismological, and rheological structure of the lithosphere (Fullea et al, 2009).

Properties (e.g. density) are functions of composition, pressure and temperature.

Can simultaneously fit multiple observed data sets

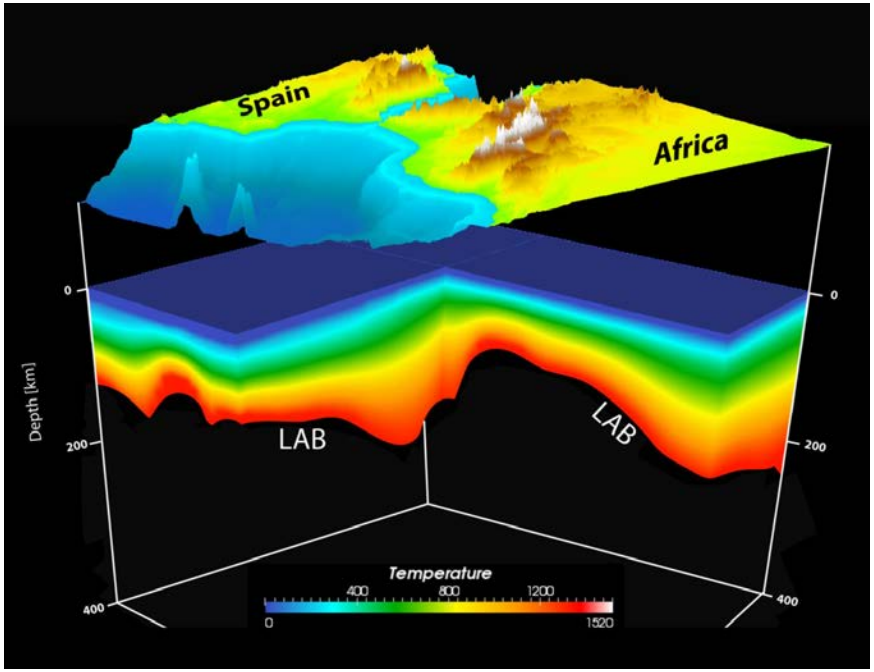


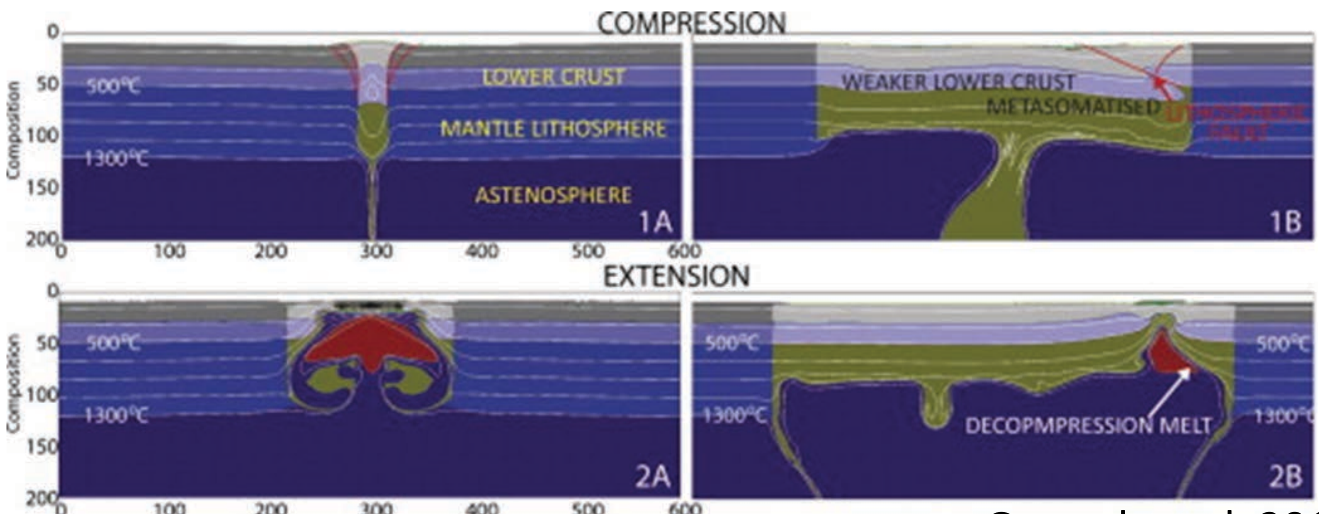
Image from Fullea et al, 2010. via JCs webpage.

The Future?…………

Massively parallel FEM environments

For solving the more complicated processes out there, or multi-process models

Fully-coupled geodynamic/geophysical modelling



Gorczyk et al, 2013

Can gravity and especially magnetic data be explicitly included in geodynamic modelling?

Summary…………

There is a broad range of gravity and magnetic approaches to crustal structure modelling – in four main categories

Each has developed to solve problems in specific circumstances…so different methods and/or hybrids work well in different circumstances

Future research directions MAY include

- Software and approaches for bigger higher resolution models
- Making robust joint inversion a reality
- Better use of structural knowledge and petrophysical data in inversion
- Better uncertainty characterisation and mitigation
- "Total Geophysics" – using these data as an active constraint on complex process modelling

Epilogue..use the tool for the problem

- Can it be described by a modelable physical process?

  Process oriented methods may work well

- Is the geology complex, but well understood?

  A structural-tectonic approach might work well

- Do I have good knowledge of the rock-property distributions?

  A probabilistic approach may work well, so long as the software can handle your PDF

- Do I have strong, well defined anomalies?

  A deterministic approach may work well