Gravity – Undercover
A tale of two competing objectives

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Intrepid Geophysics

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Two Objectives for Gravity Multi-scale

Regional Mapping

- Deep crustal elements mapping of Australia
- Basin studies for oil and geothermal
  - South Australia depth to basement studies

Mineral Prospecting

- Iron Ore in the Pilbara
- Mauritania exploration
- Gold in Carlin Trench
- IOCG in Carajas, Brazil

Coverage Averages

- Australian land area
  - 7,659,800 km^2
- 1.5 million stations
- 1 station every 5.1 km^2
- Average spacing 2250 m,
  - so useful wavelengths 4 km
- Required wavelengths for mineral exploration

  < 200m
- WA Goldfield 2.5km gravity data is soon to be released
- NSW, Ardlethan sheet, going from 11km to 2 km

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Conclusion 1

- The GADDS gravity database is very nice,
- Very important for regional mapping
- Not useful for detail mineral prospecting
- So
  - You have to fly FTG
- Or
  - Do detail gravity surveying yourself

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Outline

- Gravity Surveying
- Compilations of Gravity
- Depth methods
- Dip calculation strategies
- 3D fault network generation
- Case Studies

Publically Available National Gravity

AFGN Australian Fundamental Gravity network

ANGD Australian National Gravity Database

LaCoste Romberg Model G

Scintrex CG-5 AUTOGRAV

Land relative gravimeters

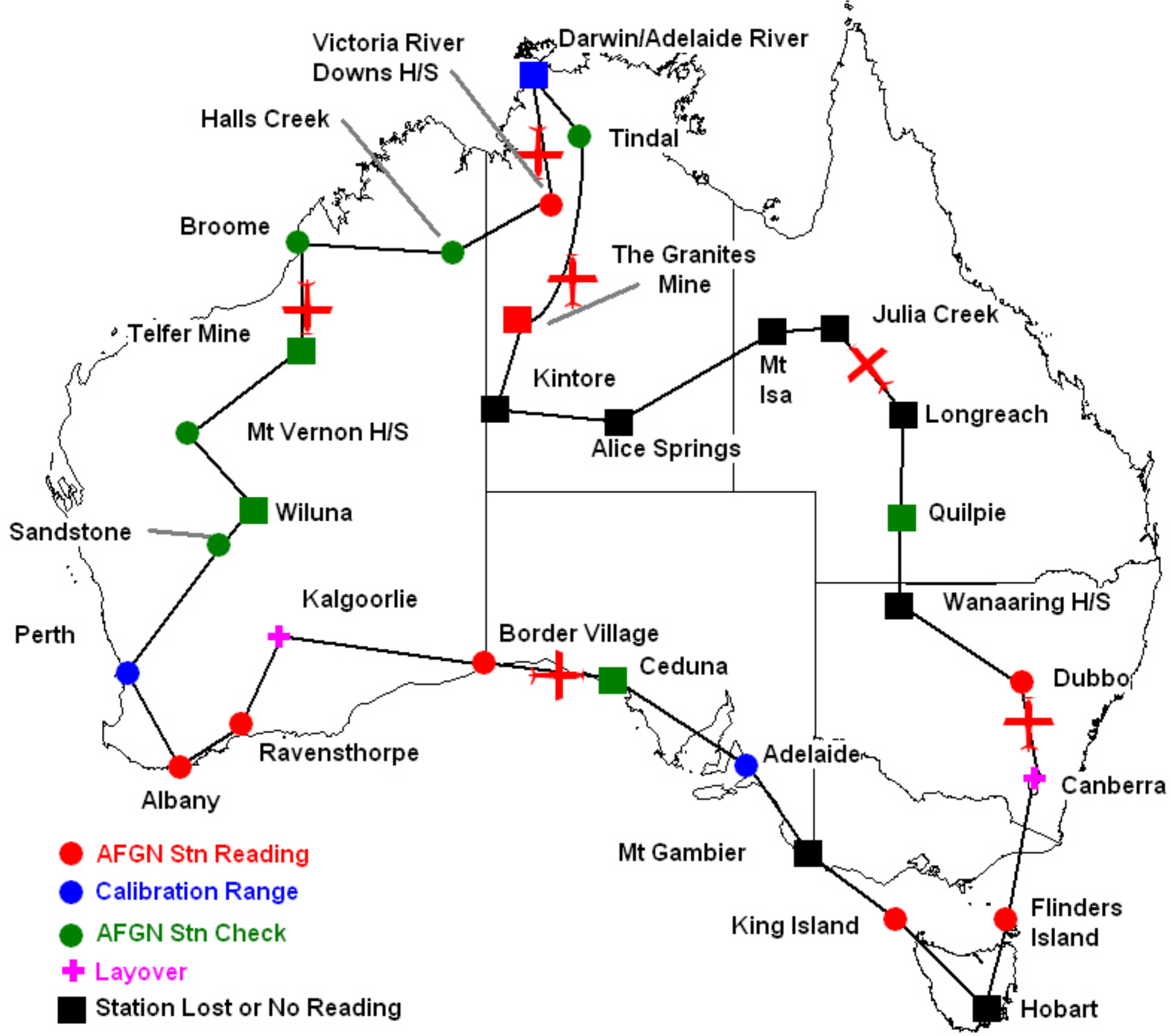
(Slide courtesy of Richard Lane - GA)

Micro-g LaCoste A10

(Photographs courtesy of Ray Tracey – ex-GA)

Land absolute gravimeter

AFGN absolute gravity observations



(Courtesy of Richard Lane,Ray Tracey, ex-GA)

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Sources of uncertainty values

1. Operations/Acquisition Report
2. Processing Report
3. Typical performance of reported method/ equipment used
4. Typical performance of assumed method/ equipment
5. Estimated from the date of the survey by reference to other surveys of a similar vintage
6. Analysis of the external network adjustment errors
7. Unknown source

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Airborne Gravity

(AG)

Regional Mapping Only

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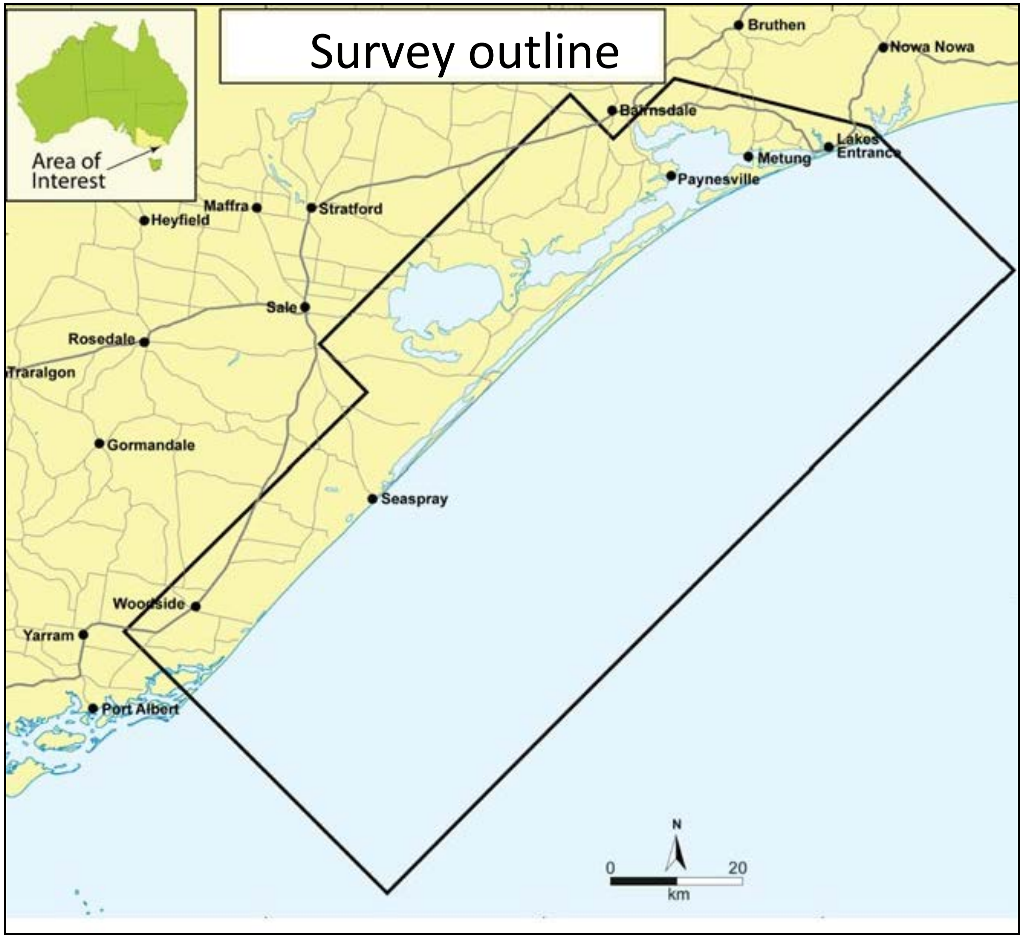
Gippsland Nearshore Airborne Gravity Survey
Victorian Department of Primary Industries (DPI)

- Consistent mapping of geological structure between onshore and offshore
- Sander AirGRAV
  - 120 x 70 km area
  - 10,500 km
  - 1 km spacing
  - RMS of 1.6 μms^{-2} for 3 km half wavelength
- Kauring Test Site in WA also flown



(http://www.dpi.vic.gov.au/energy/sustainable-energy/carbon-capture-and-storage/the-carbonnet-project/airborne-gravity-survey)

(Slide courtesy of Richard Lane - GA)

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Airborne Gravity Gradiometry

(AGG)

(FTG)

Prospect Scale mapping

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Status update on existing AGG systems

- ARKeX – FTG
  - Adding a GMA Gz sensor to an existing FTG system
  - Exclusive deal with LM for new system, still 12 months
- Bell Geospace – Air-FTG
  - Testing a combination of Air-FTG and ZTEM AEM (an ambient EM system – Geotech)
  - This has proven a failure so far
- Fugro – FALCON
  - Latest system (#5, “Cavendish”) delivered
  - HeliFALCON in commercial use since early 2011
  - Used in Brazil by Vale in 2012, $8m survey of Carajas
  - Successful test flight of FALCON and TEMPEST AEM systems

New AGG systems suitable for mineral exploration - 1 Eo per root Hz

- Rio Tinto – VK1
  - “Active period of airborne testing at the Kauring Test Site”
  - Seeking JV partners
- Lockheed Martin - Enhanced FTG
  - “initial test was in 2013 for NSA, Mexican border”
- ARKeX - EGG Exploration Gravity Gradiometer
  - “2 instruments built, ongoing flight trials”
  - Purchased the above Lockheed Martin system for 2015
- Gedex - High Definition Airborne Gravity Gradiometer HD-AGG™
  - “Upgrades are being implemented (following initial flight trials), and the flight testing will continue”

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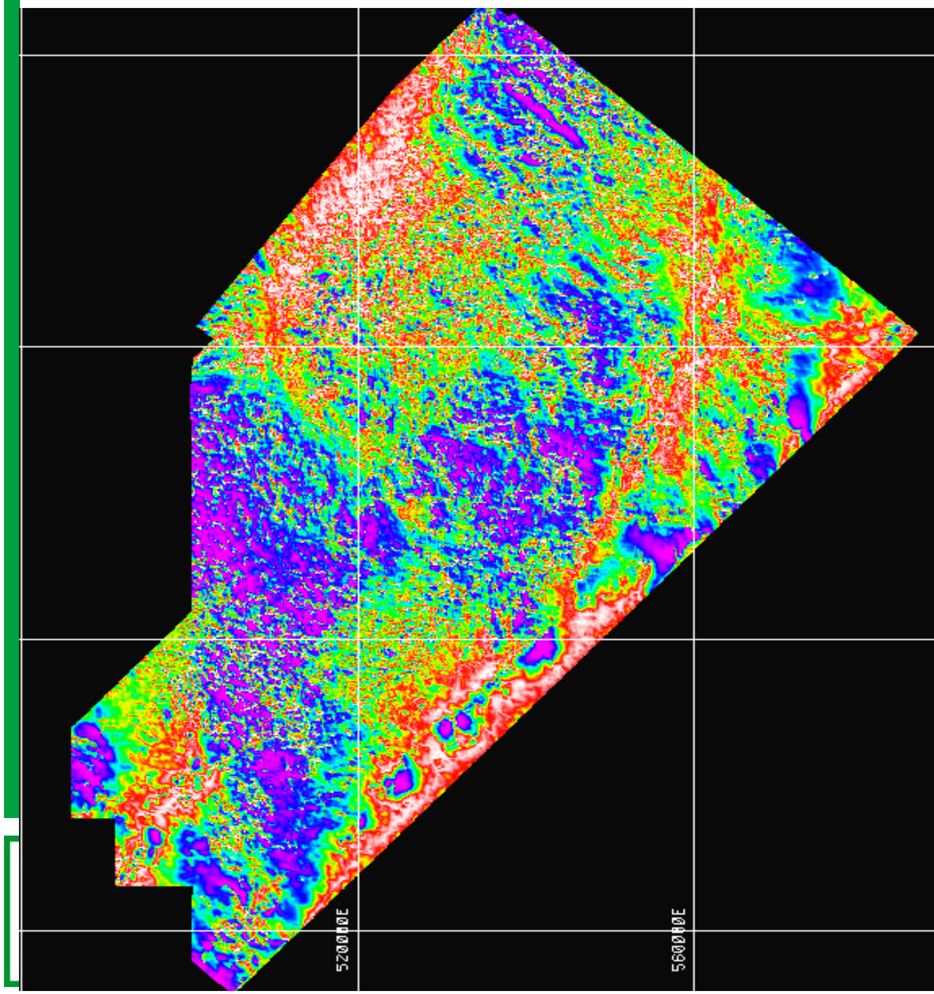
Australian FTG Example Bonaparte Gulf - Beach

AGC enhancement



Issues

- Still requires marine terrain correction
  - dunes
- Almost no geological interpretation done, as very few know how to extract value from the data
- Failed Devonian-Carboniferous rift

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Continental compilations

- This work is currently lagging
- The AFGN program is on hold
- The states contributions to ANGD continues, but no attempt to issue a new official, updated Australian Gravity grid since 2006
- The offshore-onshore silo, whilst now removed, needs pressure to get a new integrated product

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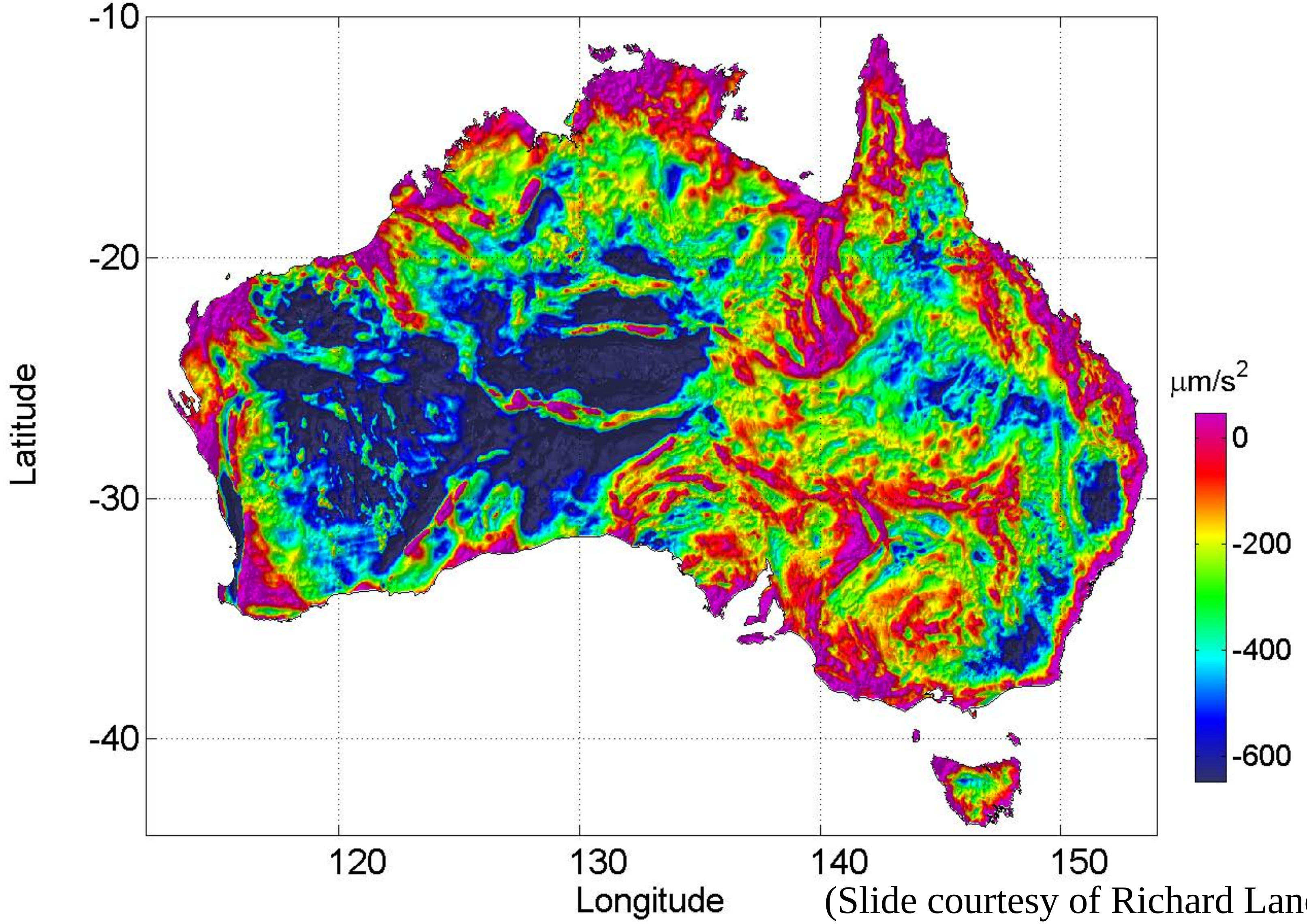
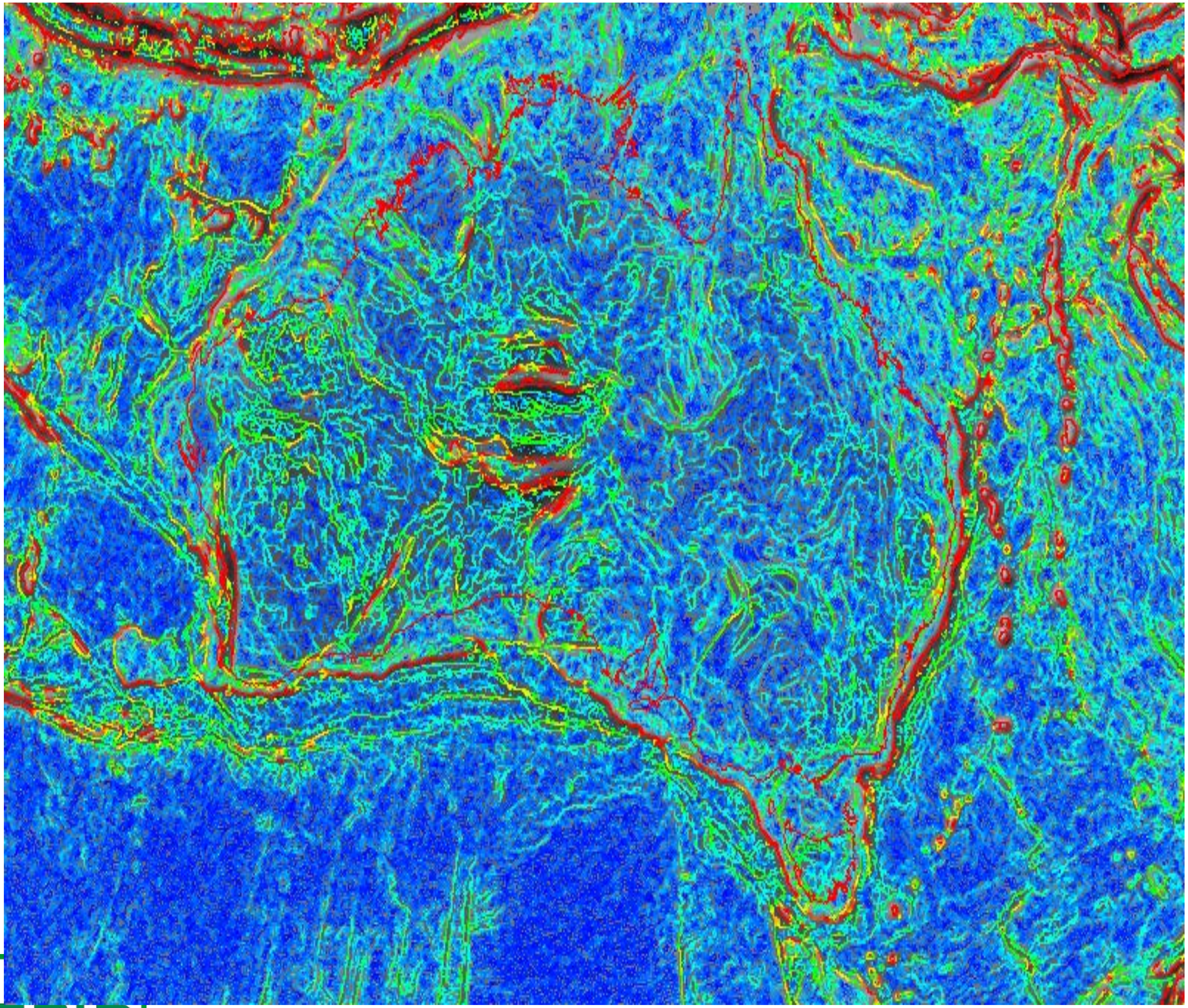
Simple Bouguer anomaly (SBA) (2.67 t/m^3)
Ellipsoid vertical datum Circa 2007



(Slide courtesy of Richard Lane - GA)

Australian gravity, upward continued 5 km, edge picked



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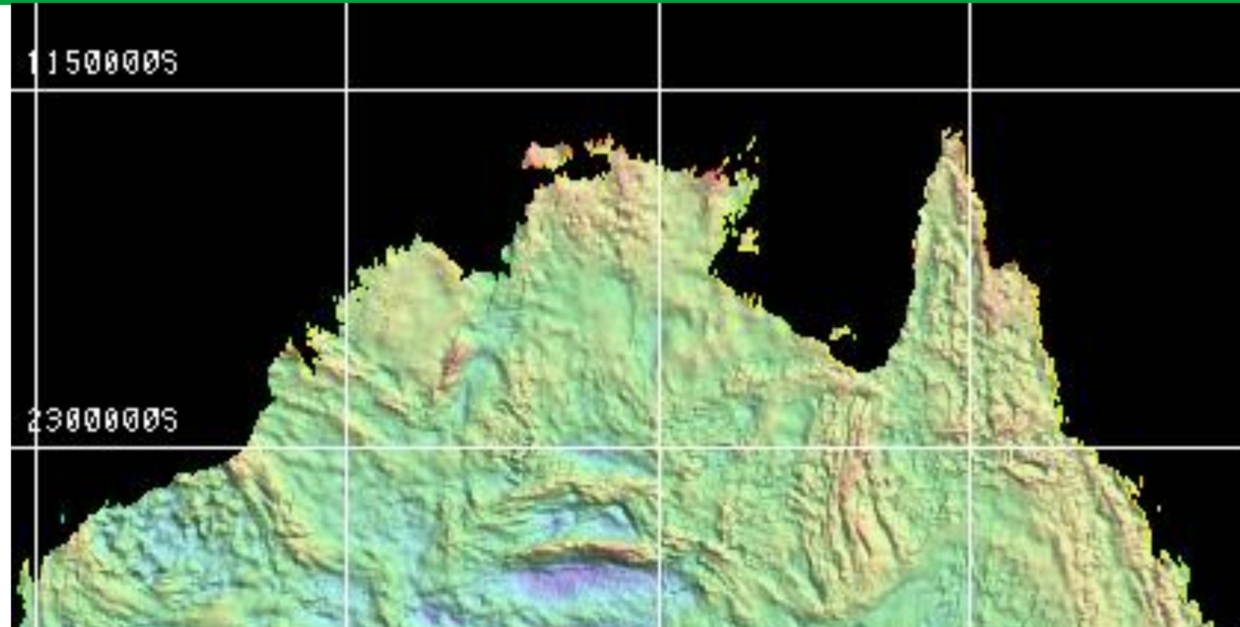
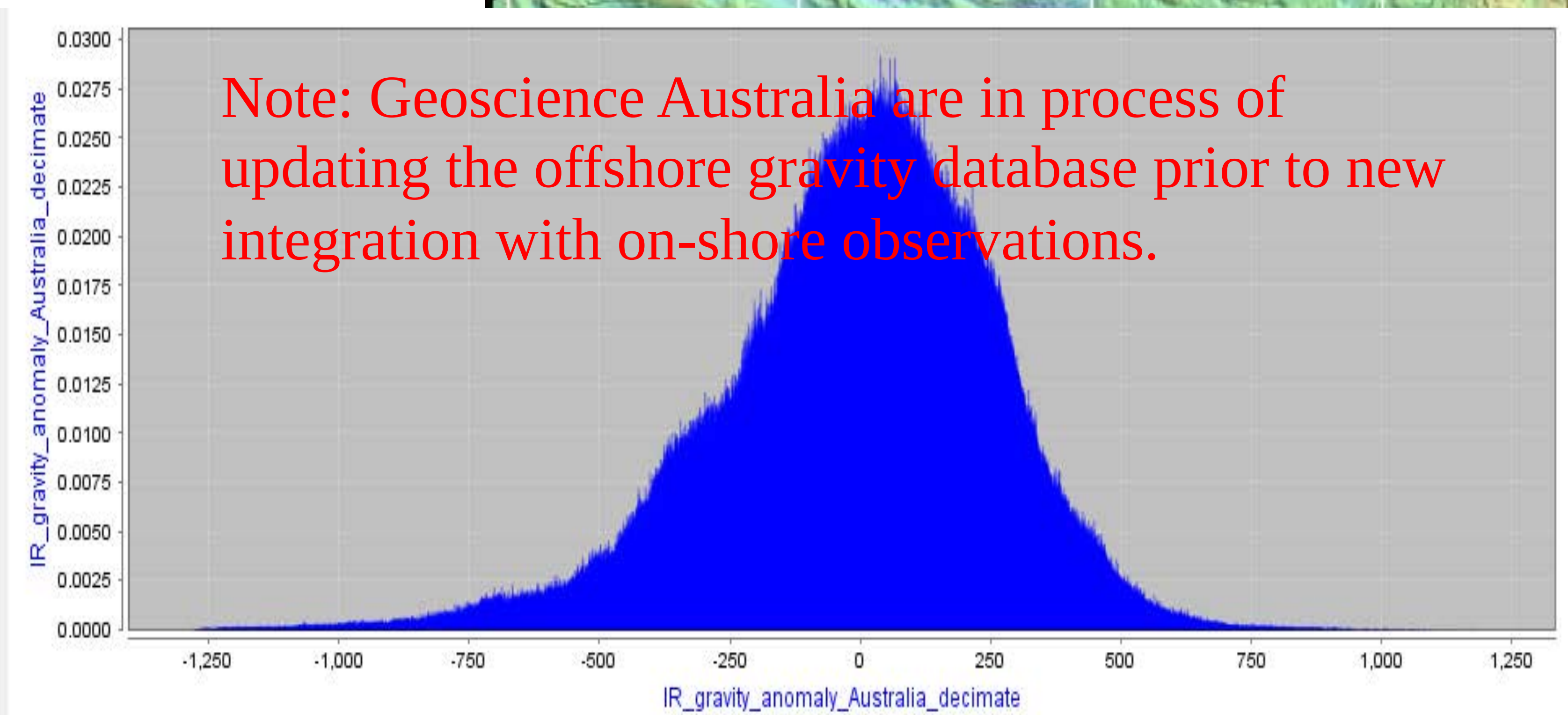
Australian Gravity Anomaly 2011



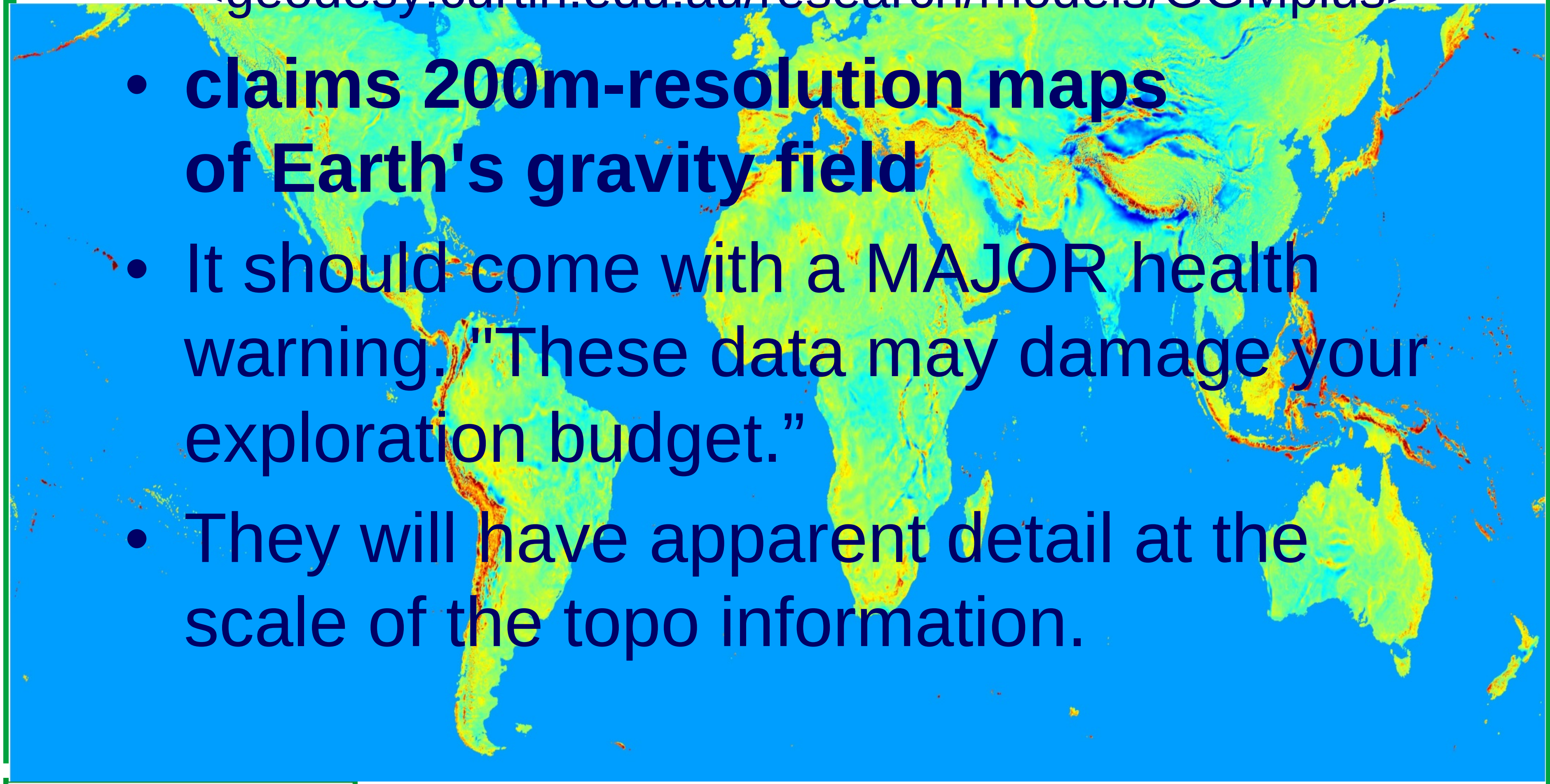
Is



Note: Geoscience Australia are in process of updating the offshore gravity database prior to new integration with on-shore observations.

GGMplus

- <geodesy.curtin.edu.au/research/models/GGMplus>
- **claims 200m-resolution maps of Earth's gravity field**
- It should come with a MAJOR health warning: "These data may damage your exploration budget."
- They will have apparent detail at the scale of the topo information.



GGMplus 1

- Since SRTM (0.001 degrees = 90m or better) is pretty much available for anywhere, this product will appear to have information at those sorts of scales.
- BUT that information is just a kind of “reverse terrain correction”.
- It is NOT reliable at scales better than the ground gravity incorporated in EGM2008. So in some cases it’ll only be as good as GOCE or GRACE (100 km at best). and in some cases quite a lot better if supported by the local ground gravity or other data available to the EGM08 academics.
- We have to peel over-keen geologists off this stuff.
  - One in particular had spent a lot of time and effort running with this pseudo-ball and was very reluctant to accept it was not what he thought.
  - It looks plausible, geologically, because topo correlates rather well with geology.
  - By all means use the topo for geological and exploration guidance. makes great sense.
  - But DO NOT disguise this as gravity and then assume its a new class of data.
  - It is not.

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Geology Content in Bouguer Gravity data for old contienents

- Isostatic balance, basins are compensated
- Dominated by edge effects
- Bulk mass effects minimized by the Bouguer correction
- Measured Curvature gradients much better again at revealing subtle detail
- Natural to then emphasize a 3D fault network proposal as a primary input for the geologist.

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What is wrong with using gravity in Mineral exploration in Australia?

- Dependent upon Government to provide data
  - Bad mistake
- Current public data can give
  - Depth of cover
  - Dips of major faults
- In other countries, becoming normal to acquire FTG for mining and basin studies

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Depth methods

- Traditional
  - Murty and Rao, Blakely
  - Euler deconvolution and gravity??
- Linear FFT inversion
  - Parker
- Stochastic joint inversion
  - Geomodeller & CGG Qatar

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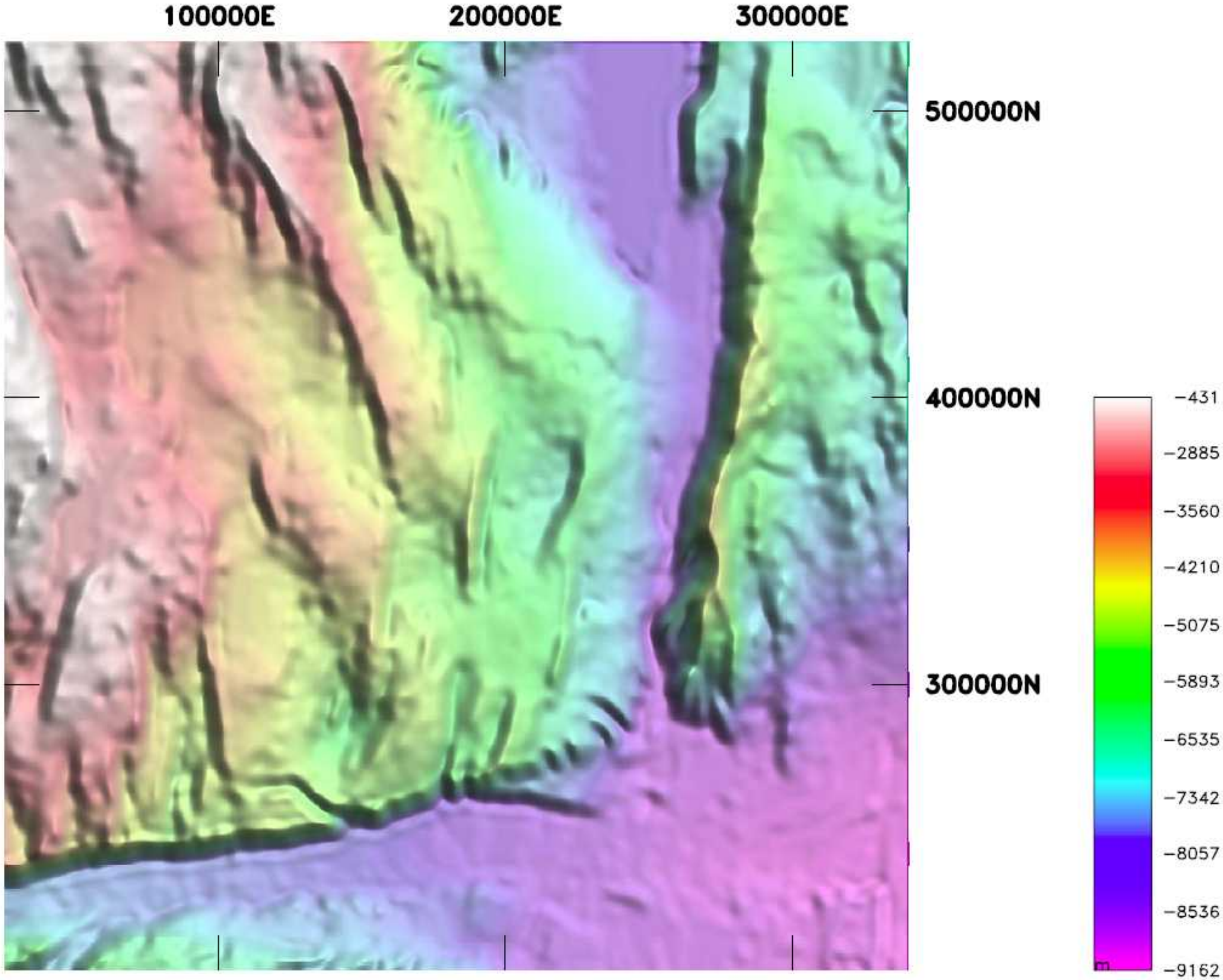
How do you test a basement depth method?

Construct a “Realistic model”

- Employ a real faulted topography for a basement surface
- Vary the basement densities with some contacts and intrusions
- Calculate a forward gravity model
- Use the tested method to estimate the basement depth and structure
- Compare interpretation and truth

Bishop model 4 – Basement depth – "Suprabasement"



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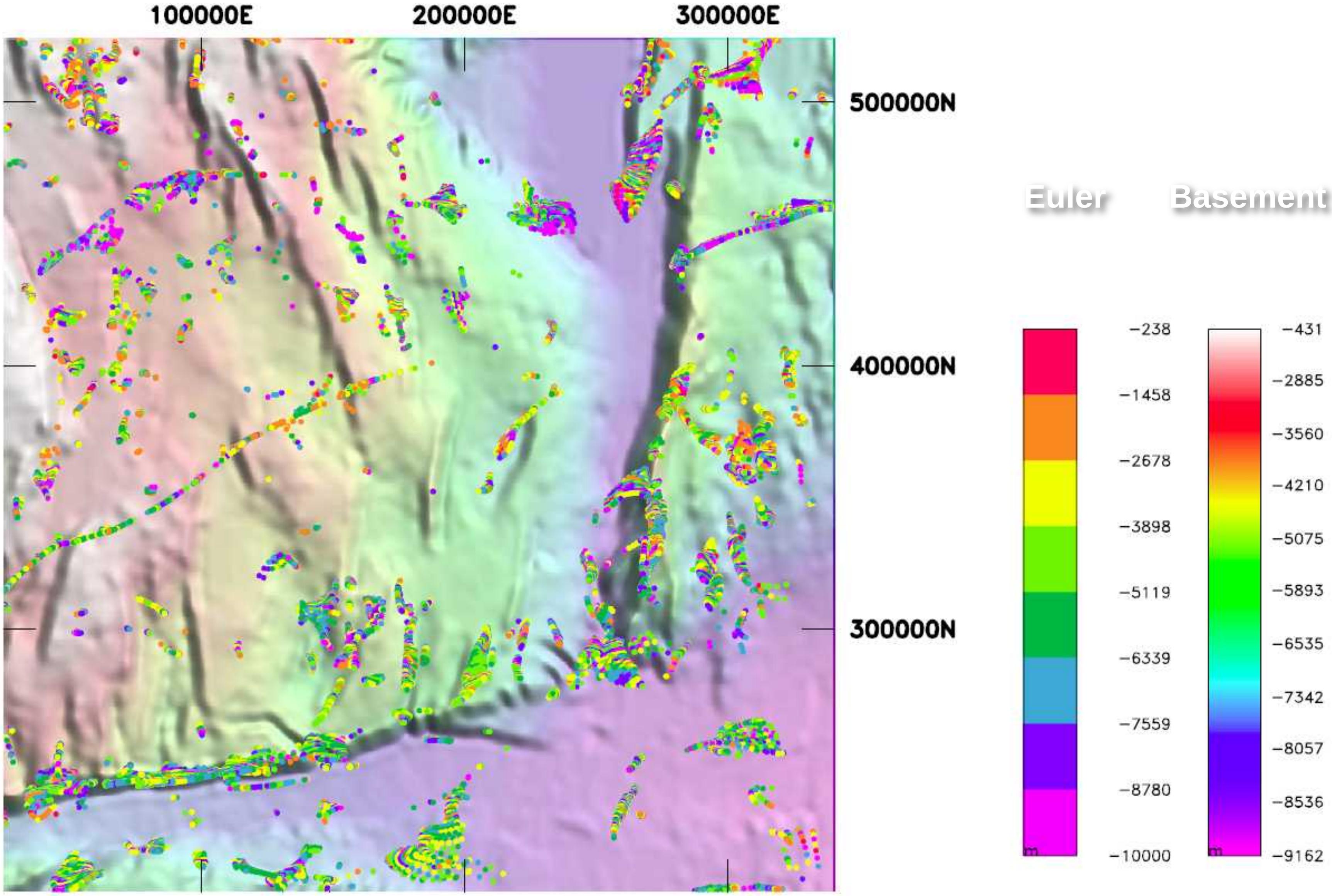
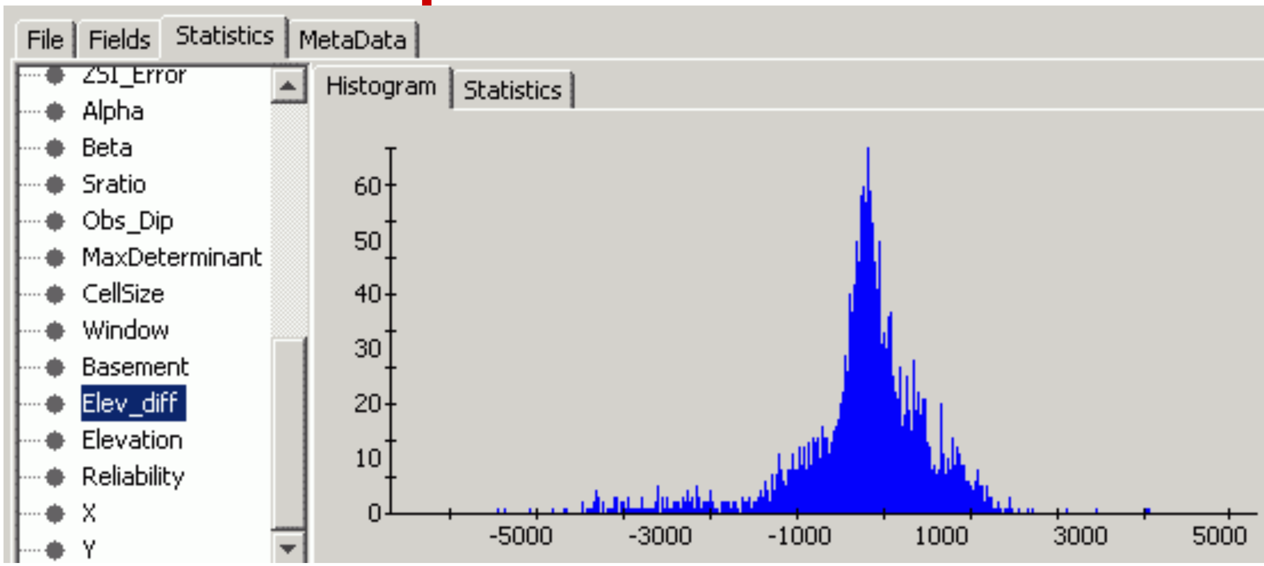
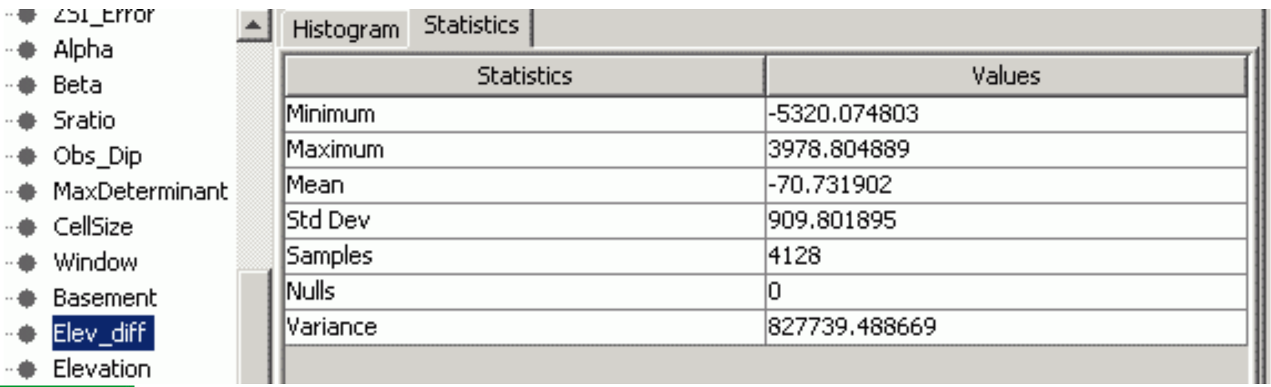
Bishop 4 – Basement and Hybrid Euler depths



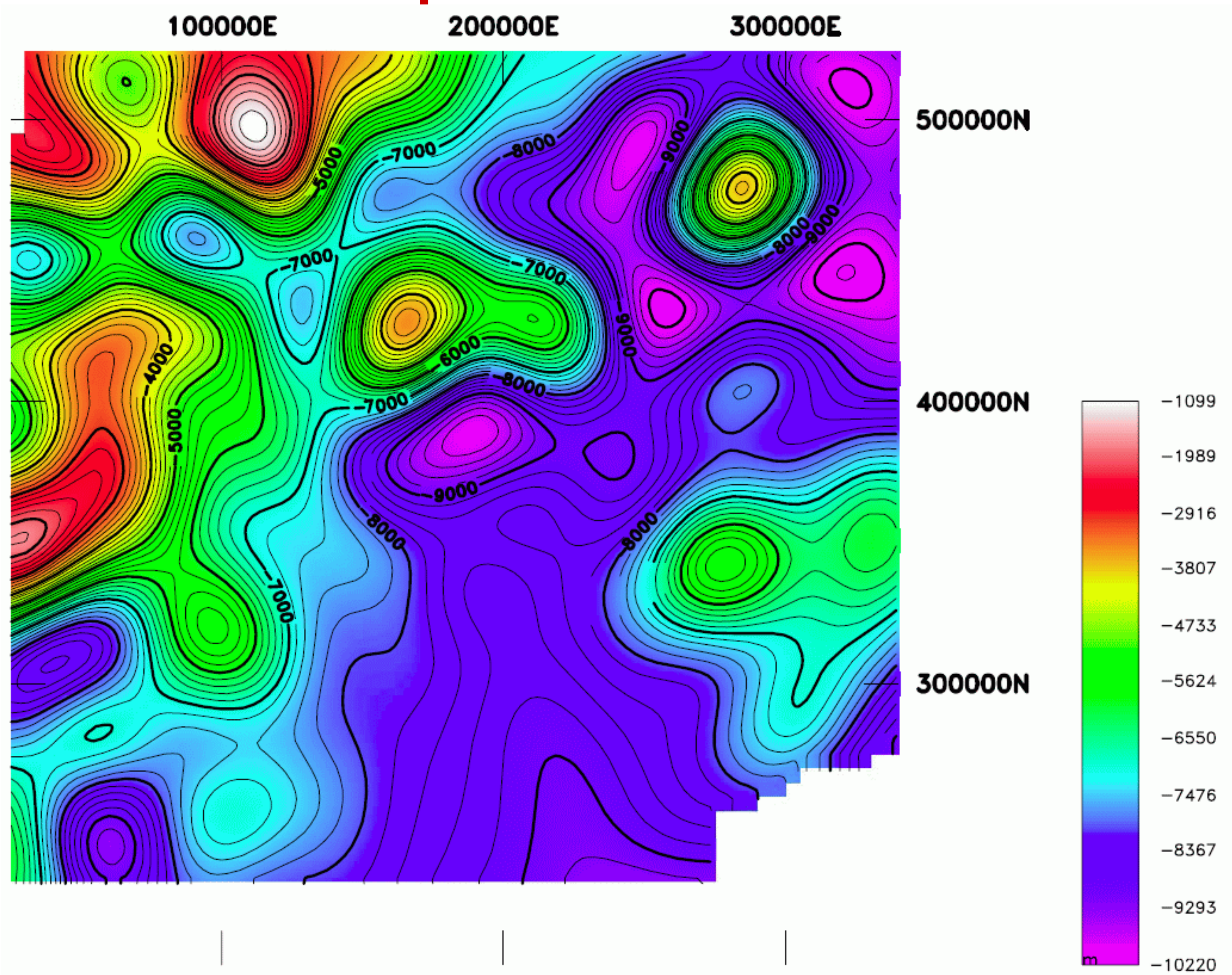
Bishop 4 – Real vs Hybrid Euler depth statistics





Statistics	Values
Minimum	-5320.074803
Maximum	3978.804889
Mean	-70.731902
Std Dev	909.801895
Samples	4128
Nulls	0
Variance	827739.488669

Bishop – Gridded Hybrid Euler depths



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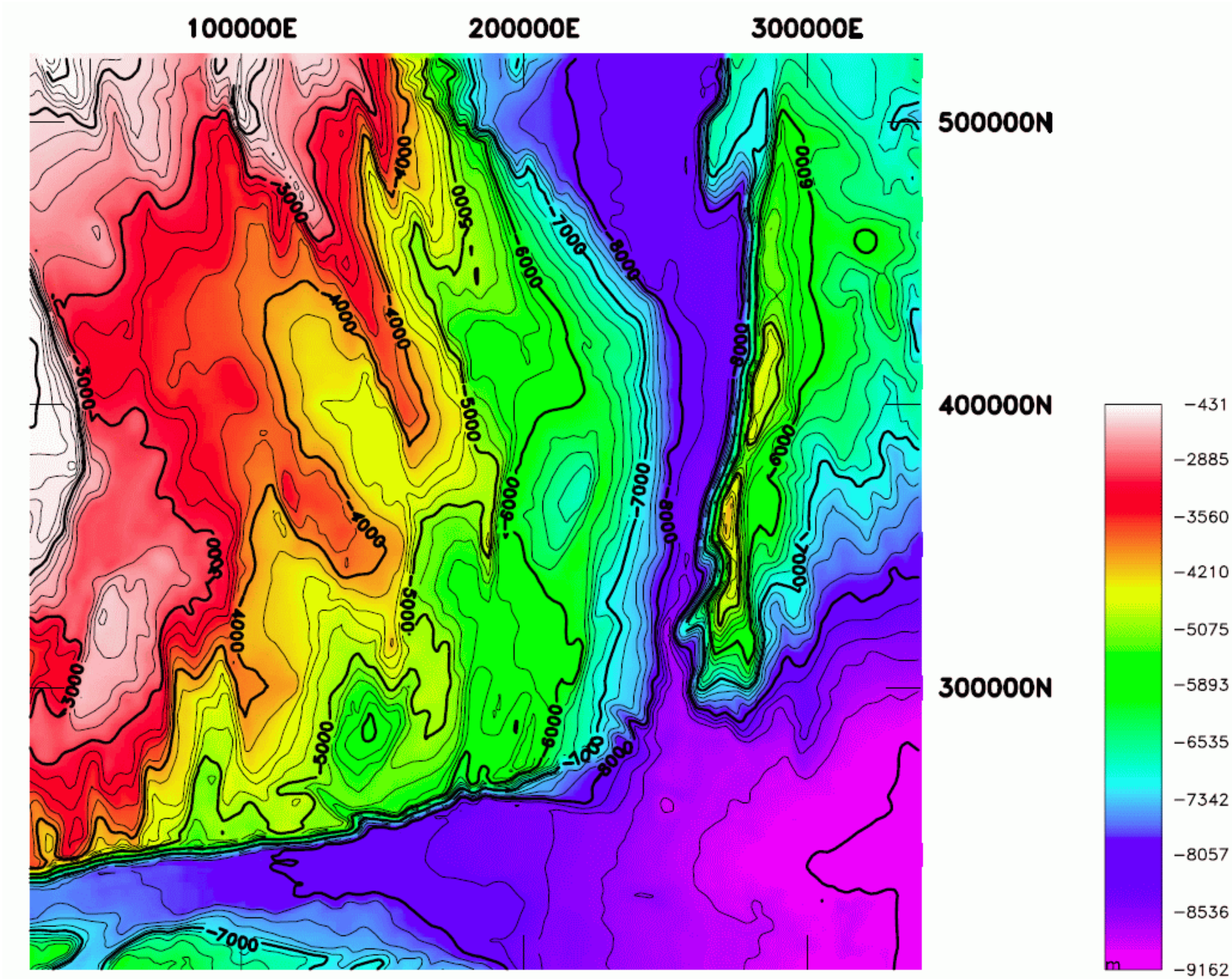
Bishop – Model depths



Pragmatic Depth to Basement Map

- Now that we have a way of optimizing what Euler can do
- What other data can be added to help?
  - Seismic
  - Drilling
  - Outcrop
- How to blend?

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Adopted Strategy for South Australia

- 4 sources of depth data
- Keep each dataset separate
- Combine the data dynamically at time of gridding, with a ranking
  - Outcrop
  - Drilling
  - Seismic
  - euler
- Use relatively coarse cell size

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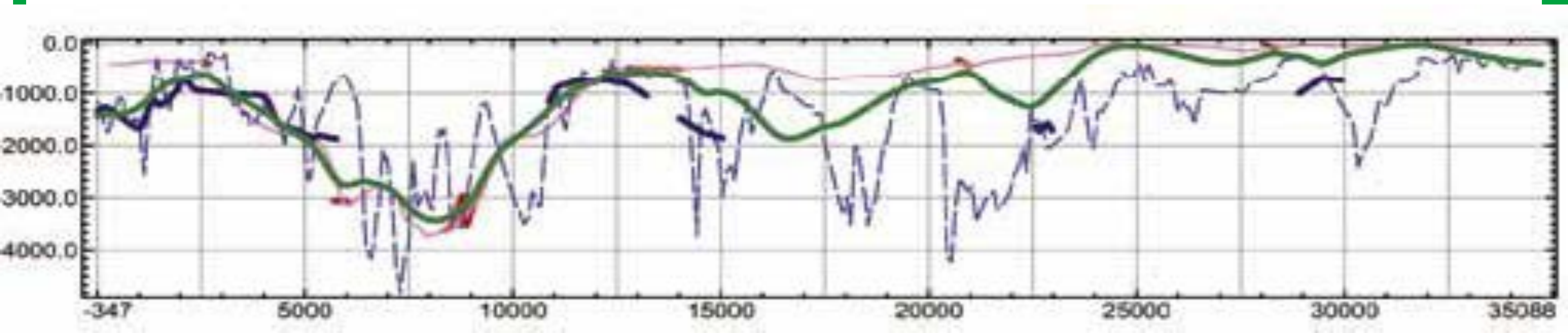
Validating Basment Depths

- Profile comparison of Euler Depth to magnetic source solutions with combined Euler solutions-drillhole-seismic depth grid and drillhole-seismic depth to basement grid (Burtt 2005)
- ___Combined Euler solution-drillhole-seismic depth
- ___Clustered Euler depth to magnetic source solutions
- _ _ Euler depth to magnetic source solutions
- ___ Drillhole-seismic DTB profile



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Dips

- How to establish the dip of a geological boundary?
  - e.g., fault or contact
- Usually limited area of surface outcrop.
  - Boundary is hidden beneath surficial materials.
- Often, the adjacent rock masses are of different density
  - the orientation and depth extent of the intervening boundary can be determined by analysing the associated gravity anomaly.

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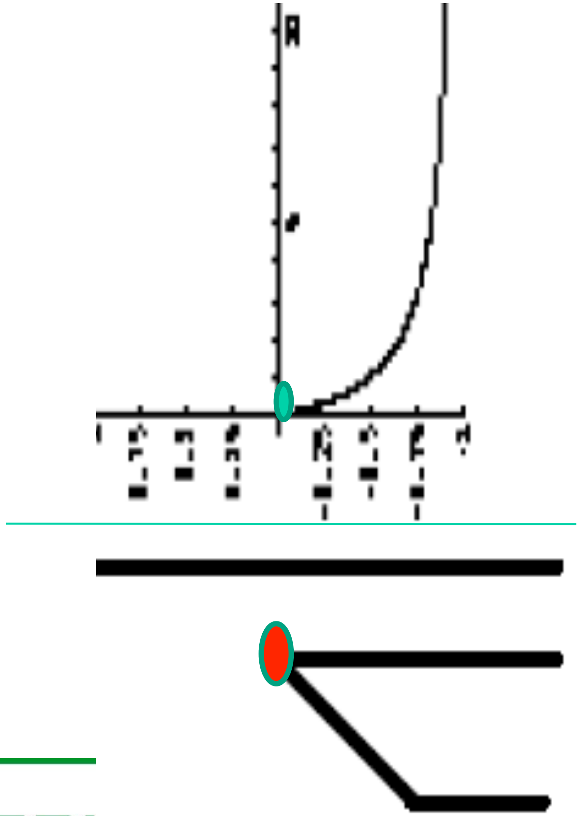
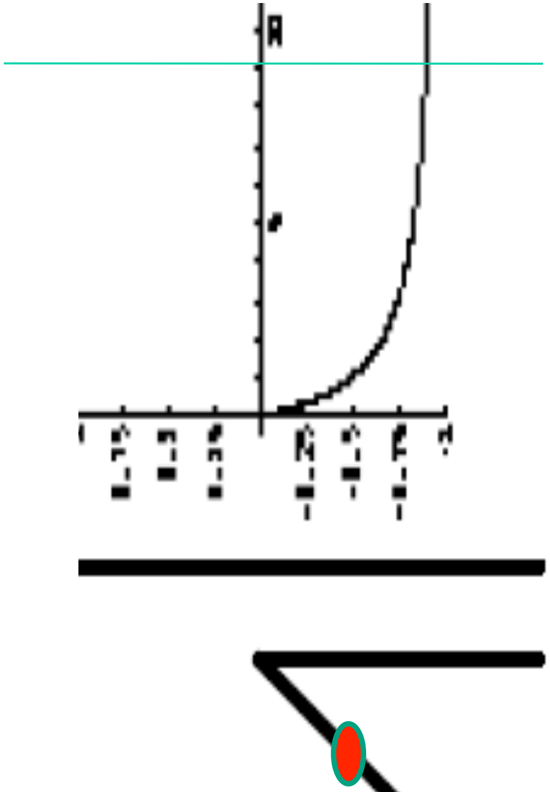
Quantative Method for dip

- SI from the non-homogenous Euler should be 1
- SI from the barycenter, or HOT_SPOT is 0





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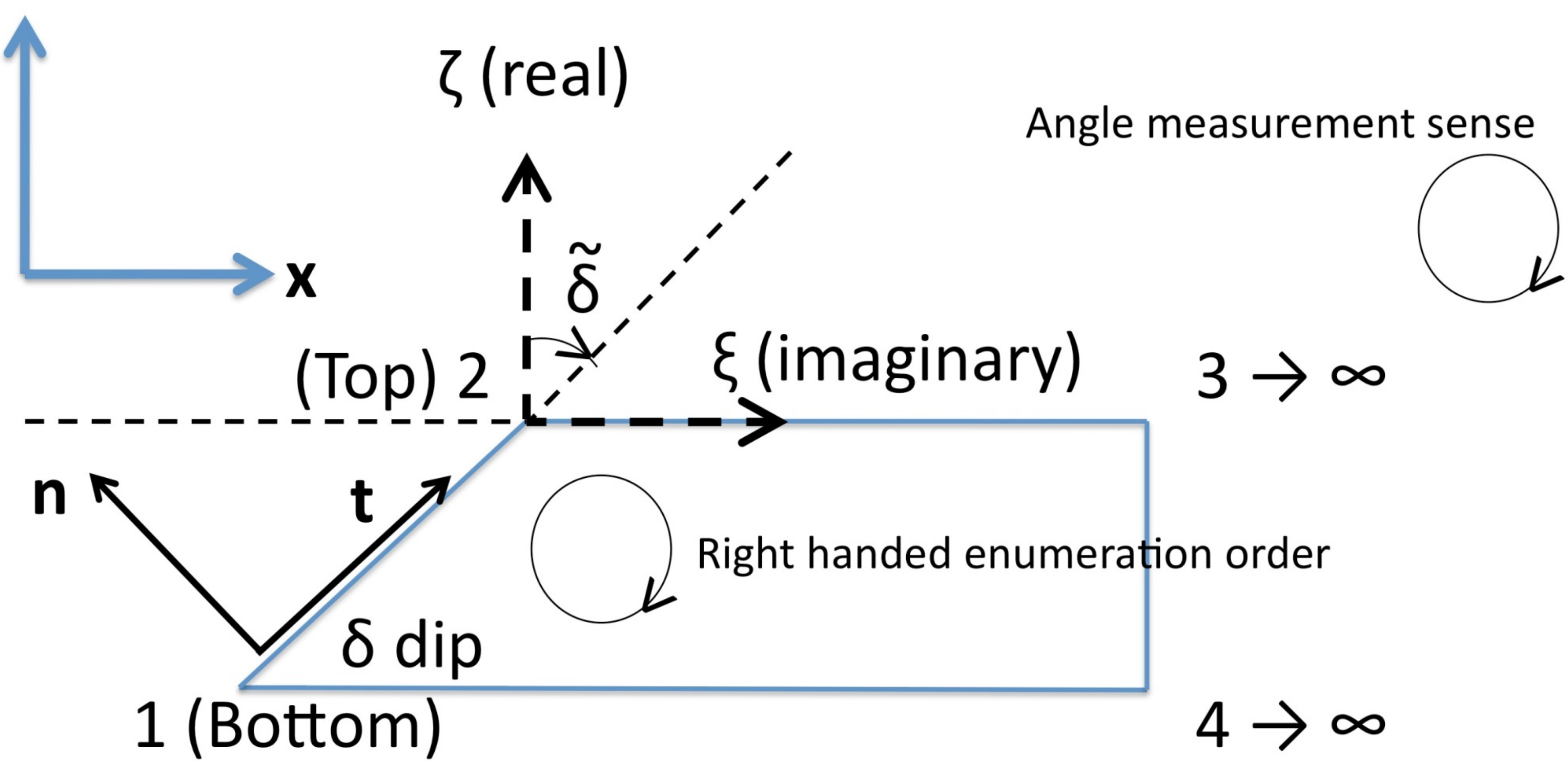
Coordinate system conventions

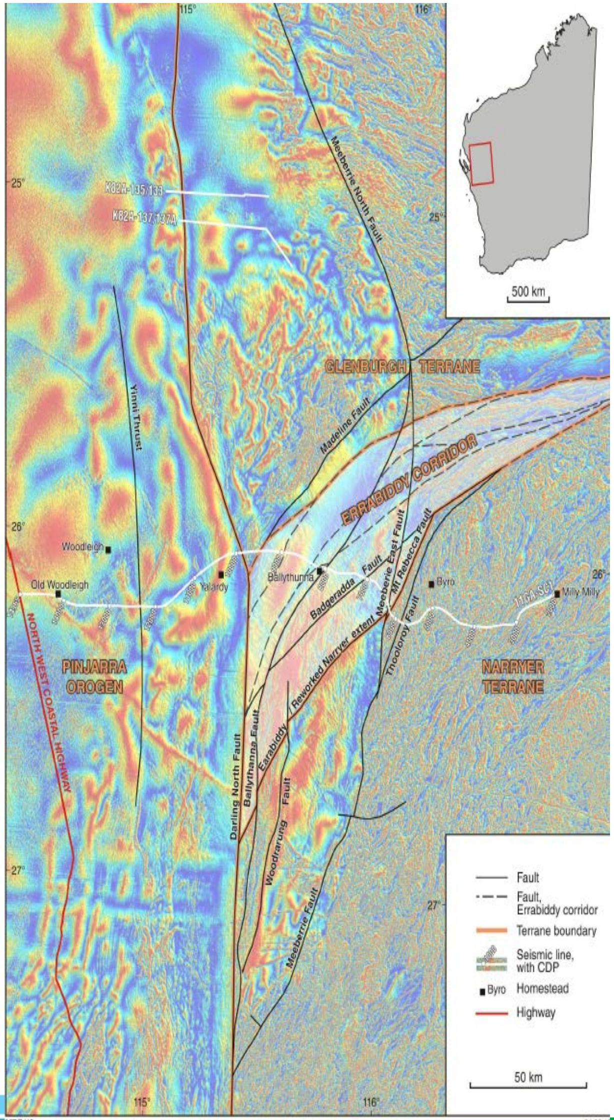


$\tilde{\delta}$ is the co-dip. The fault tangent is along exp($i\tilde{\delta}$)

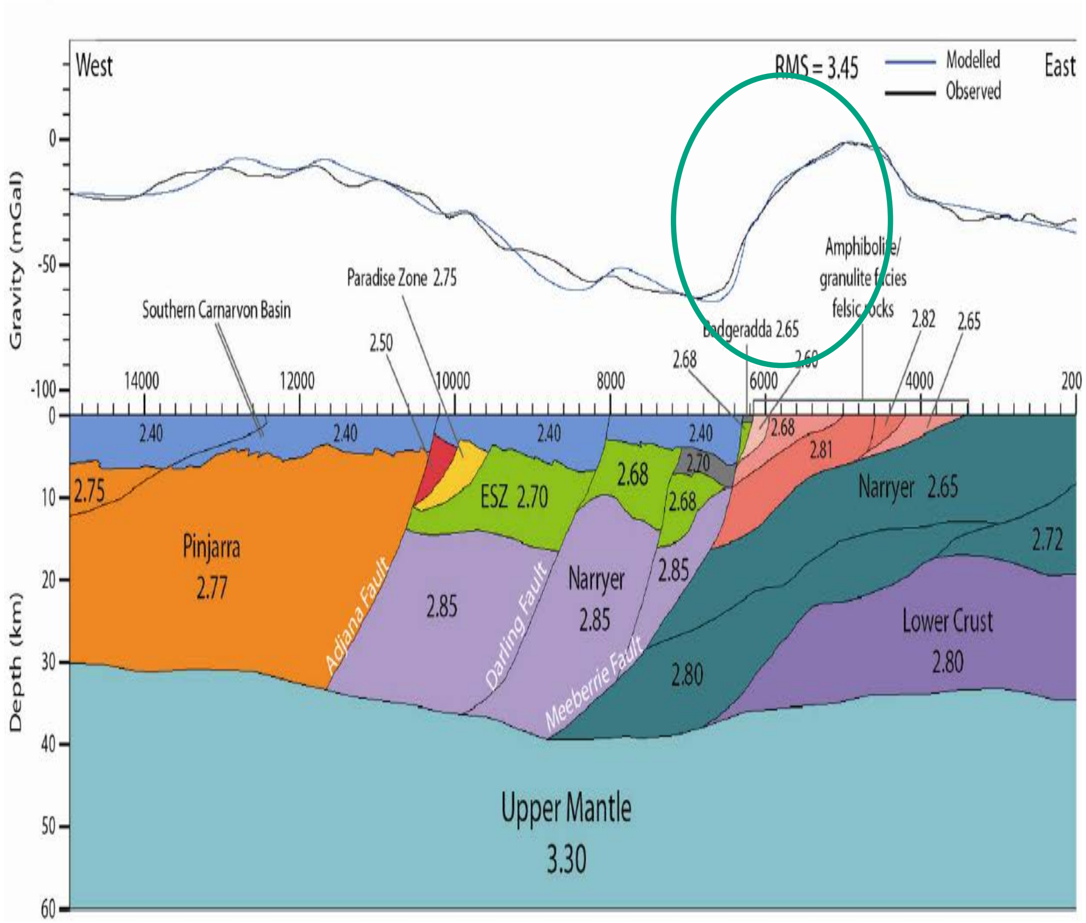
$$\hat{\mathbf{t}} = \hat{\mathbf{x}}\sin\tilde{\delta} + \hat{\mathbf{z}}\cos\tilde{\delta} \rightarrow \cos\tilde{\delta} + i\sin\tilde{\delta}$$

Southern Carnarvon Seismic Line

Aeromagnetic Location



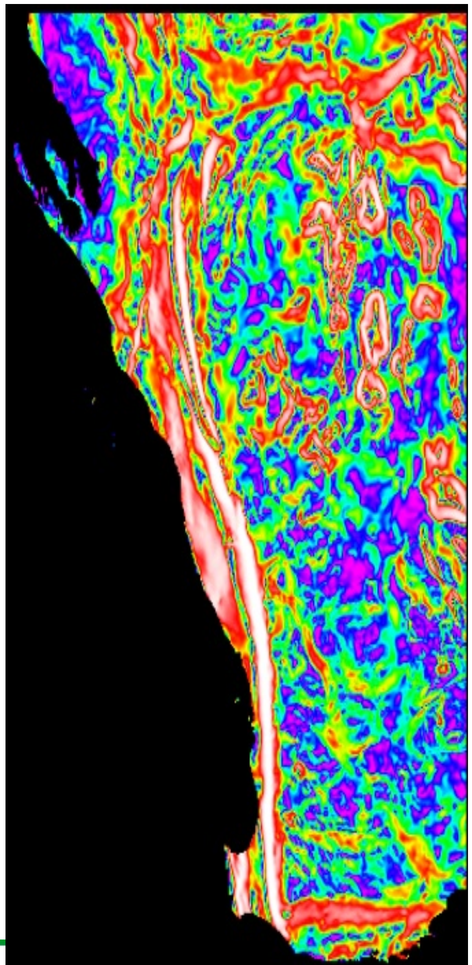
Meeberrie Fault – gravity model



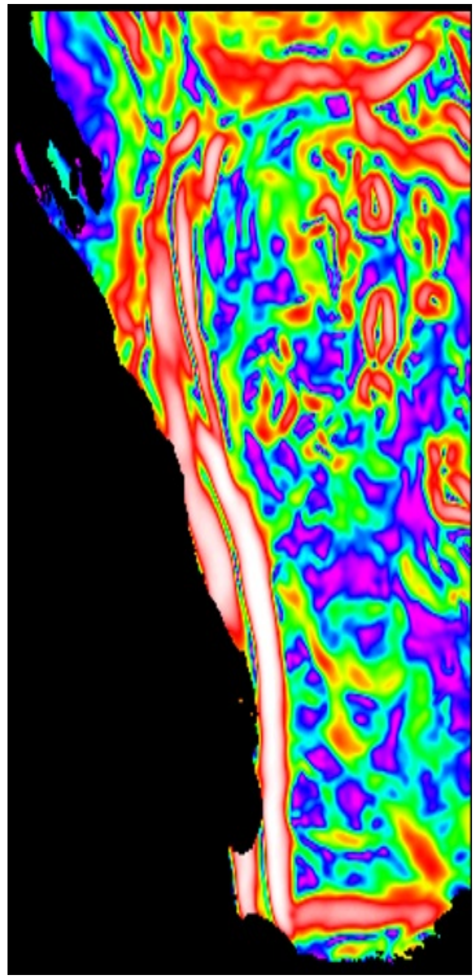
Darling Fault Total Horizontal Gradient

Upward continued

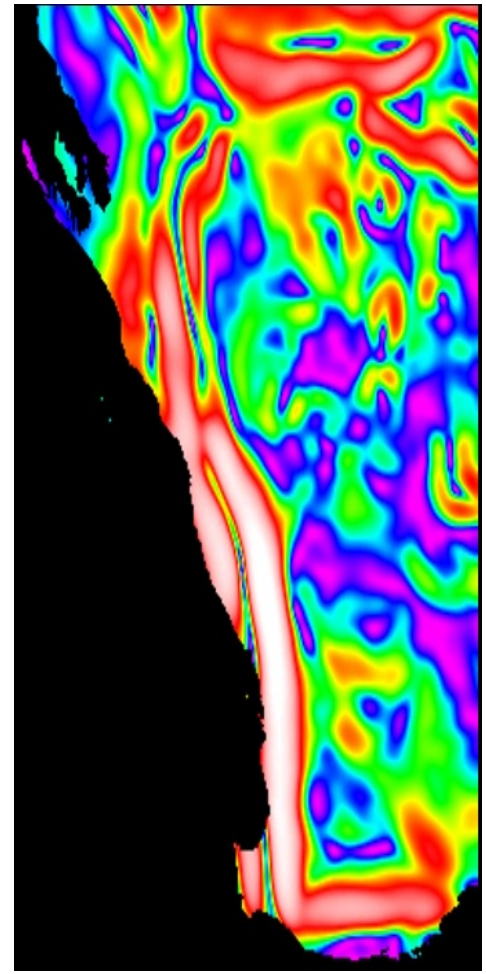
2,500 m



10,000 m



25,000 m



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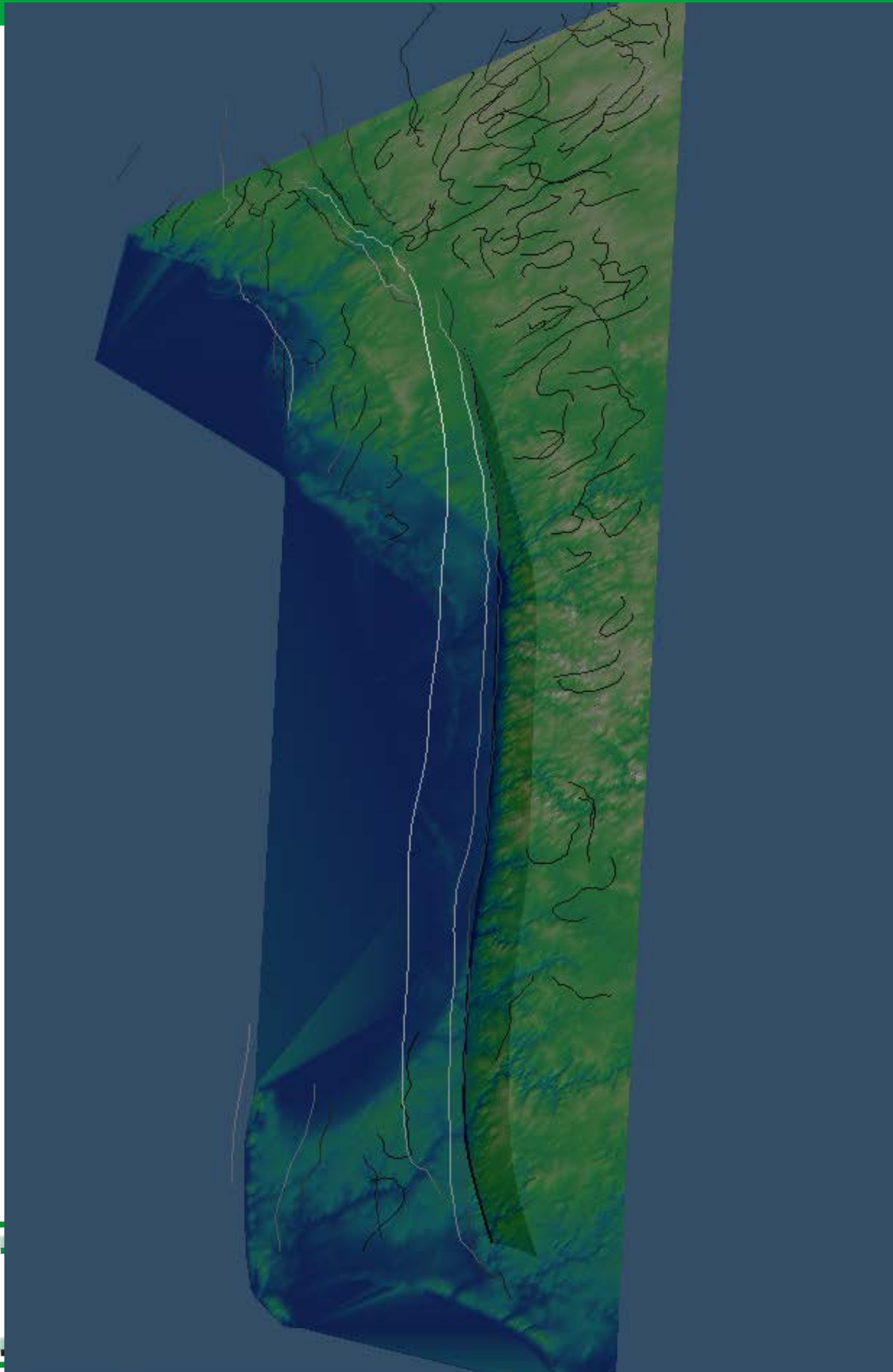
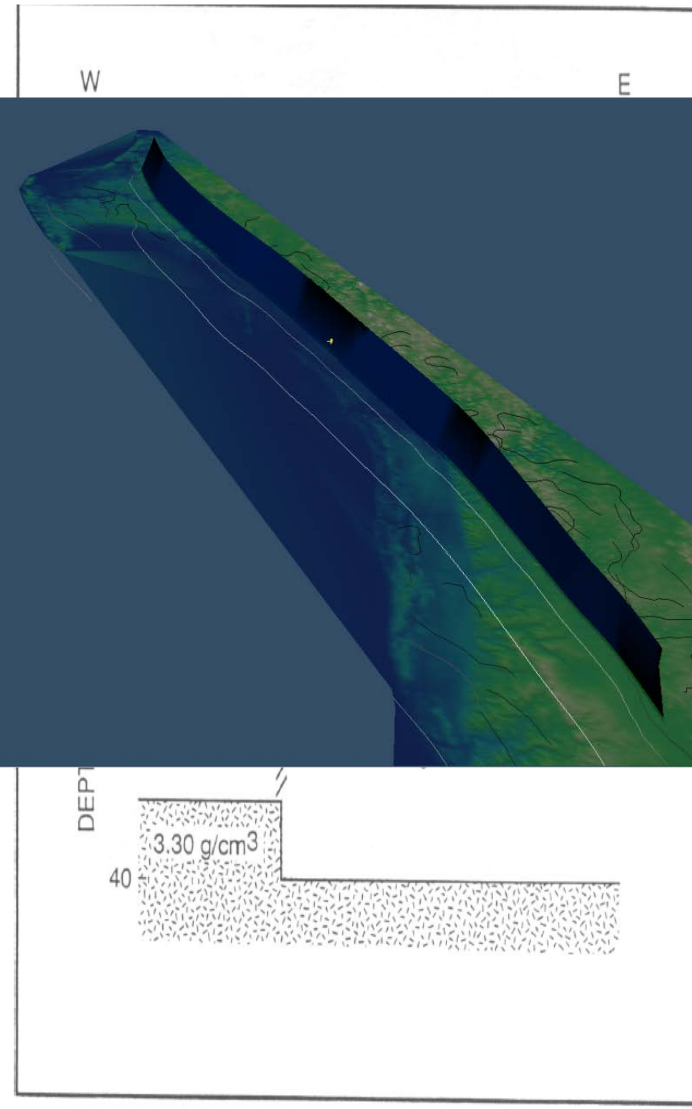
Calibration 2



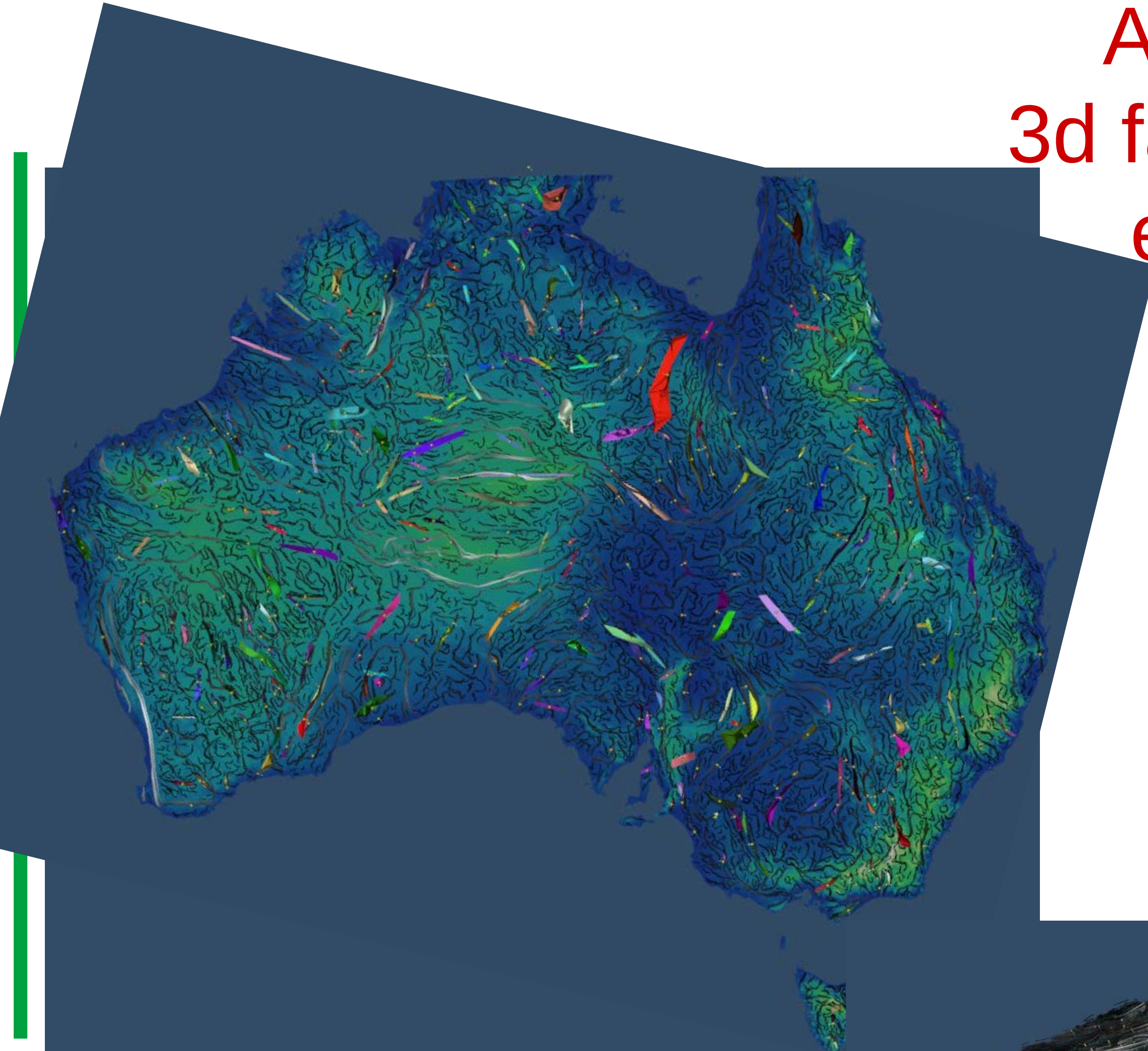
Original Gravity Model

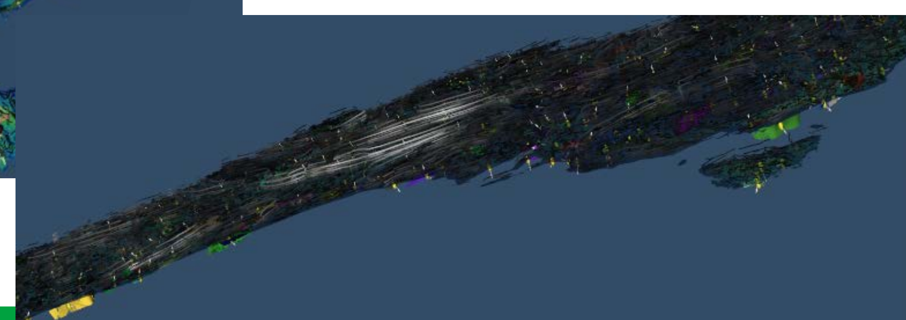


Mid - Darling Fault – 604 points

n	Ht	XnRel	Error	R	Thick	Offset	Origin	Dip	Density
0	17	56.355	-1439						
1	33	58.038	-131	0.937					
2	49	58.586	-103	1.480	127	2.54	56.04	84.8	-0.030
3	65	58.997	-61	1.385	232	2.375	56.62	86.7	-0.016
4	81	59.342	-34	1.281	258	2.622	56.72	87.0	-0.015
5	97	59.638	-18	1.171	174	3.465	56.17	85.7	-0.022
6	113	59.887	-10	1.069	68	6.706	53.18	75.7	-0.055
7	129	60.087	-5.9	0.972					
8	145	60.238	-3.5	0.869					

Australian 3d fault network example





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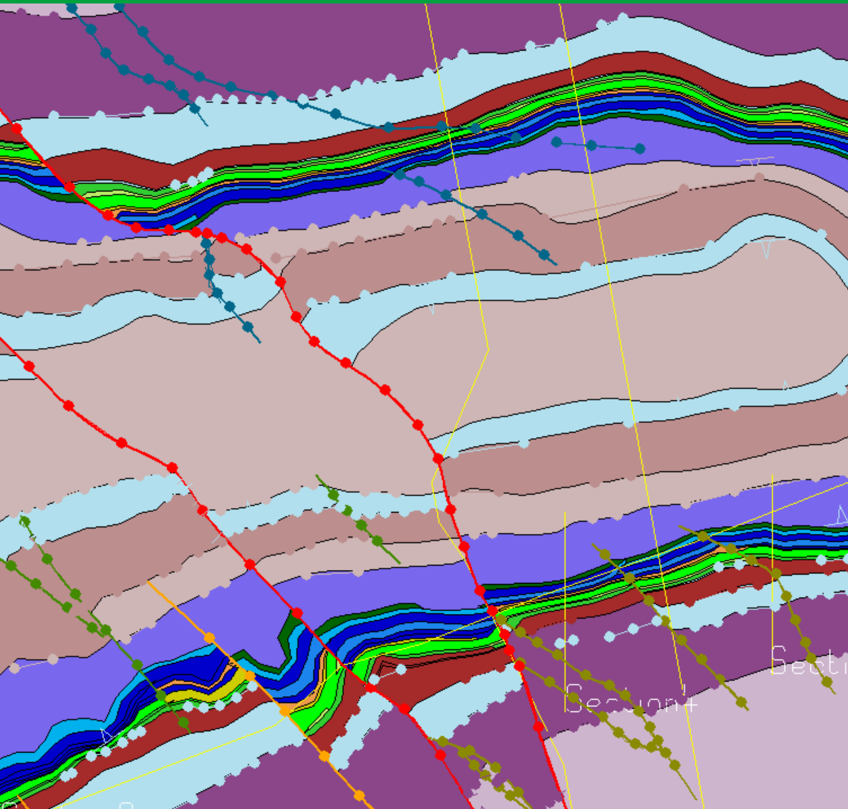
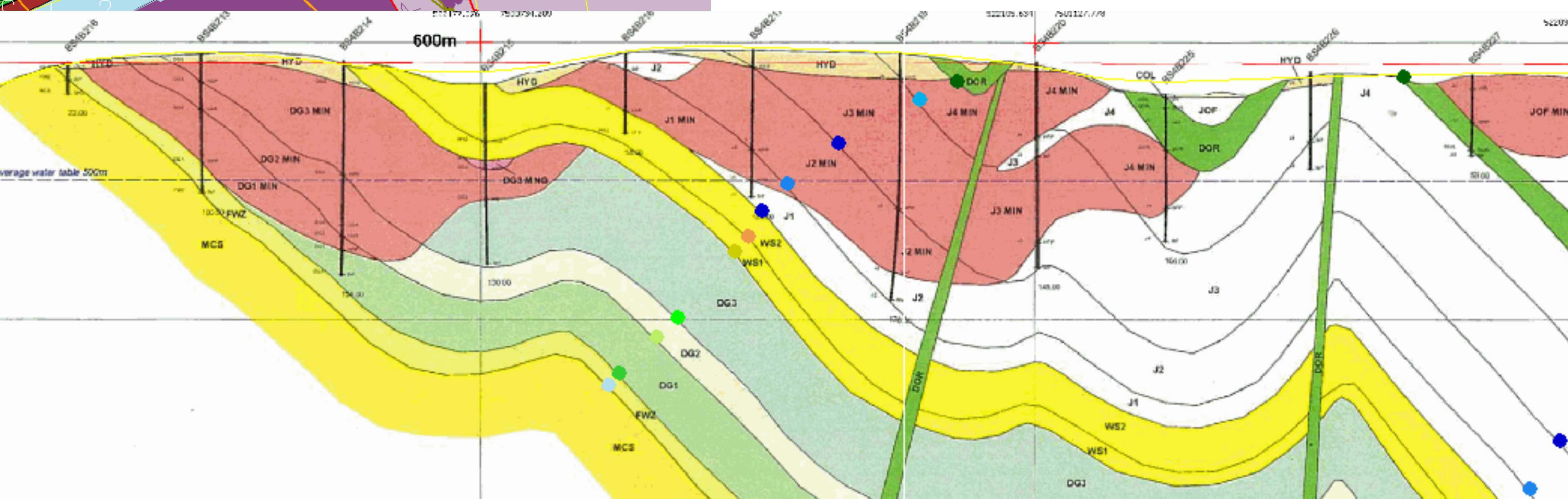


Pilbara Example

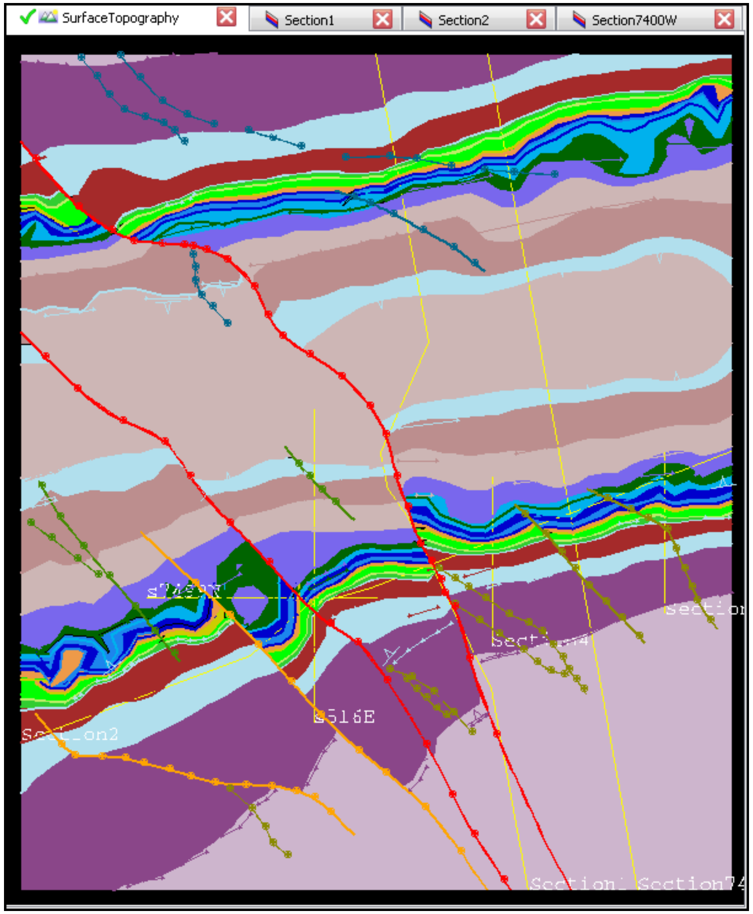
Surface of 3D model

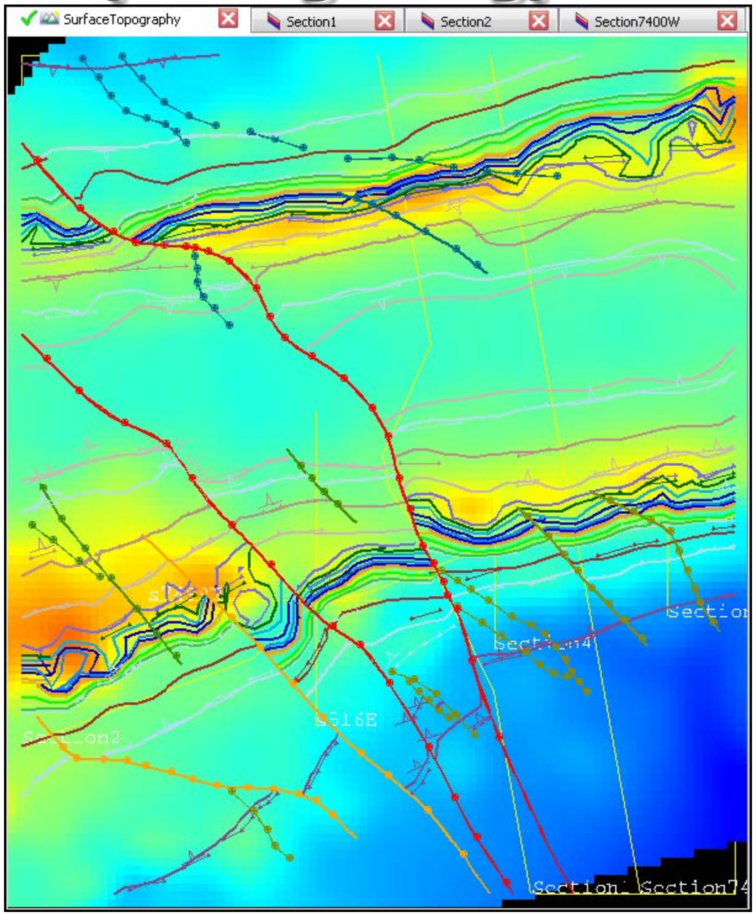
- Gravity and magnetics important
- Exploring under cover

Section 7400W detail



What else ? can I do with my 3D geology model





- ***Worming (multi-scale edge analysis – for auto structural analysis)***
- ***Forward & Inverse geophysics modelling: assessing uncertainty / multiple models***
- ***Use inversion outcomes to search for excess density***

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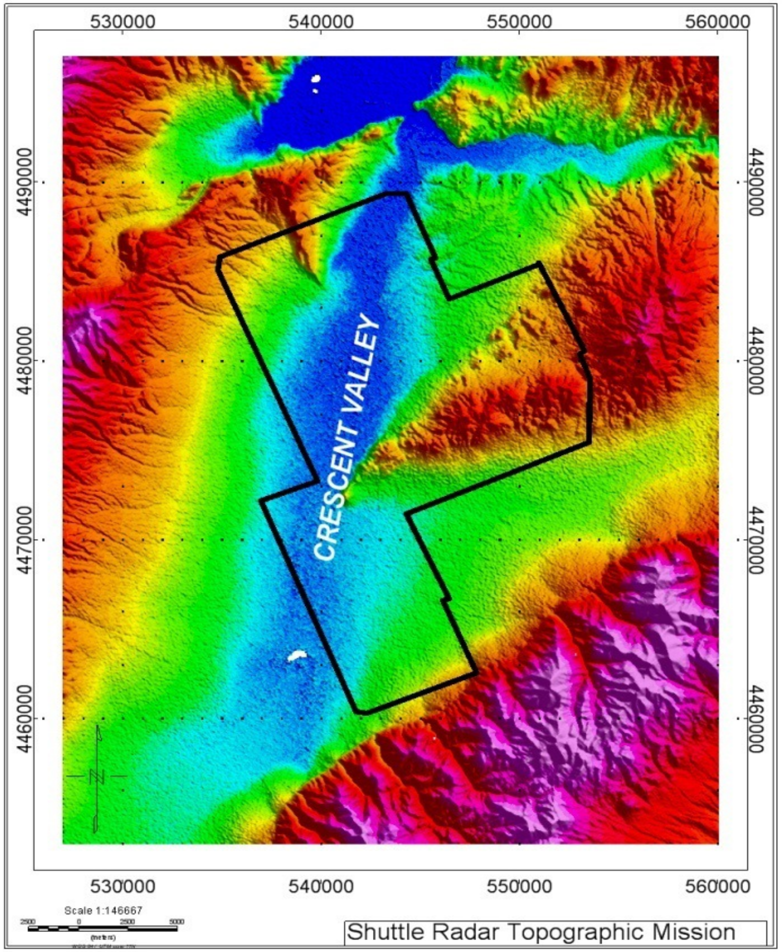
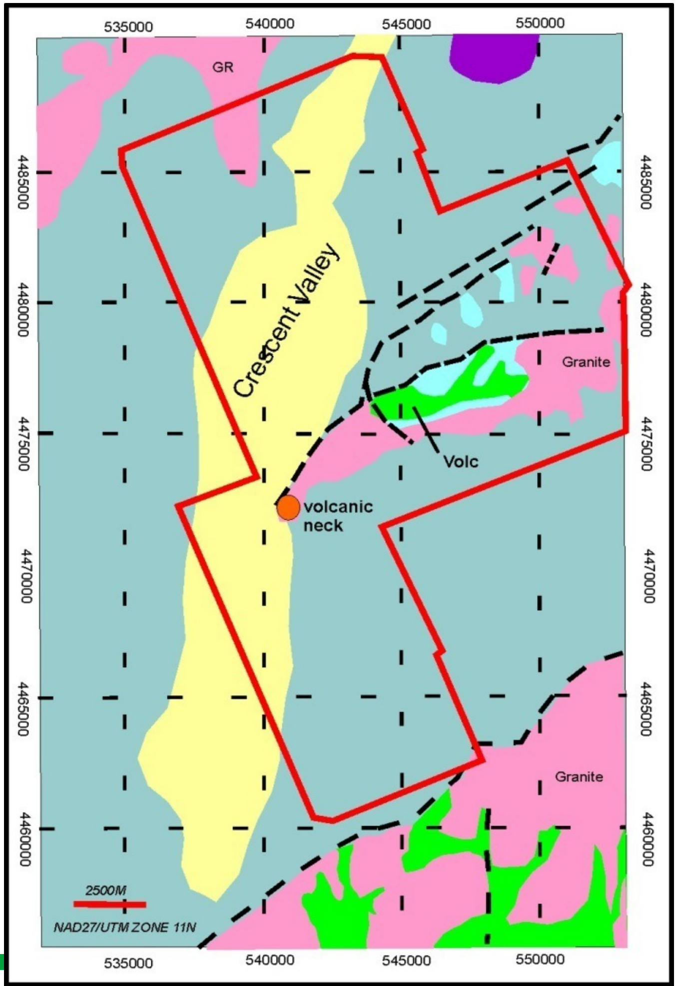
Brockman Syncline - BIF geology with free air gravity

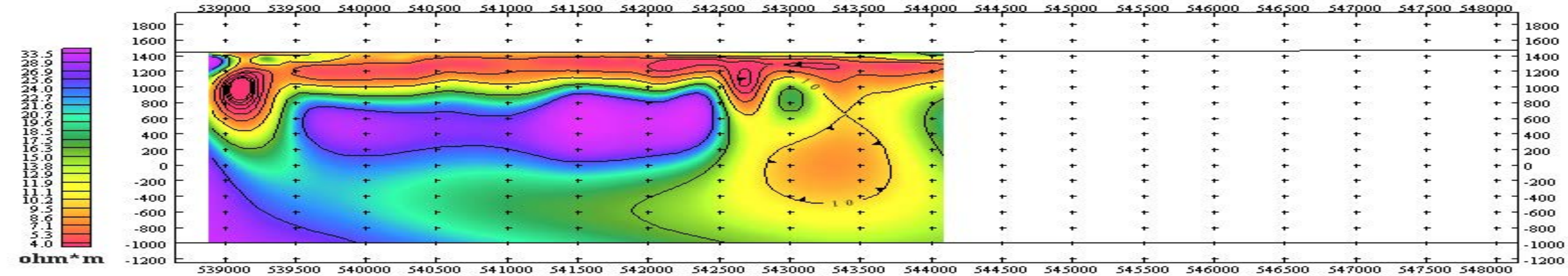
Montezuma-Vasquir, Nevada

Digital Terrain

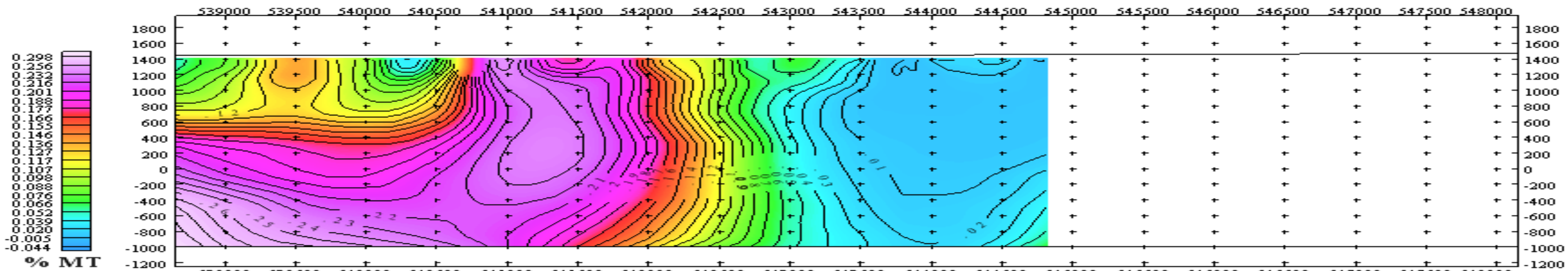


Geological Map

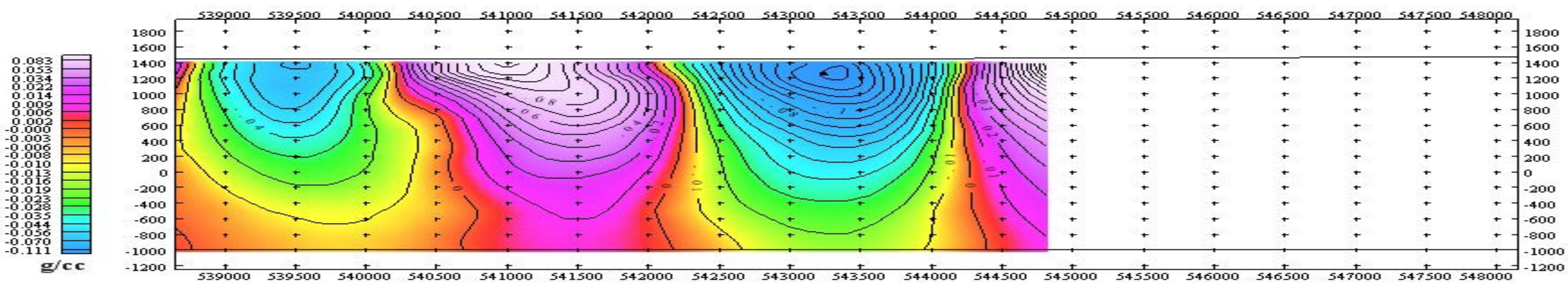




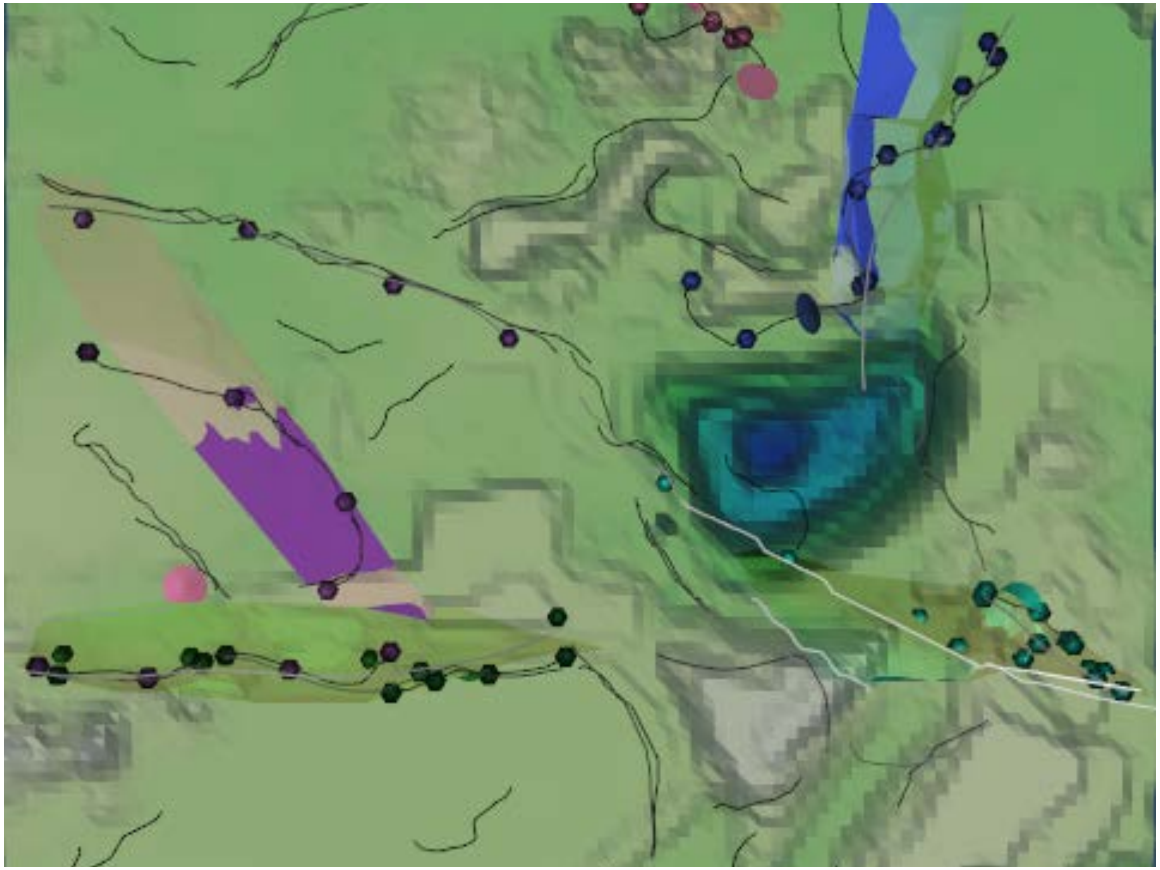
Montezuma-Vasquir Project, NV
Model: 2D AMT (Smooth)
Parameter: Resistivity (ohm*m)
Line: M1 (4469380 North)



Montezuma-Vasquir Project, NV
Model: MAG3D (Smooth)
Parameter: Susceptibility (Equivalent % Magnetite)
Line: M1 (4469380 North)



Montezuma-Vasquir Project, NV
Model: GRAV3D (Smooth)
Parameter: Density Contrast (g/cc)
Line: M1 (4469380 North)



IOCG prospect in Brazil

Gravity derived, 3D Fault controlled mineralization, intersecting the open-pit, in Northern Brazil. The construction points and foliation data are also shown.

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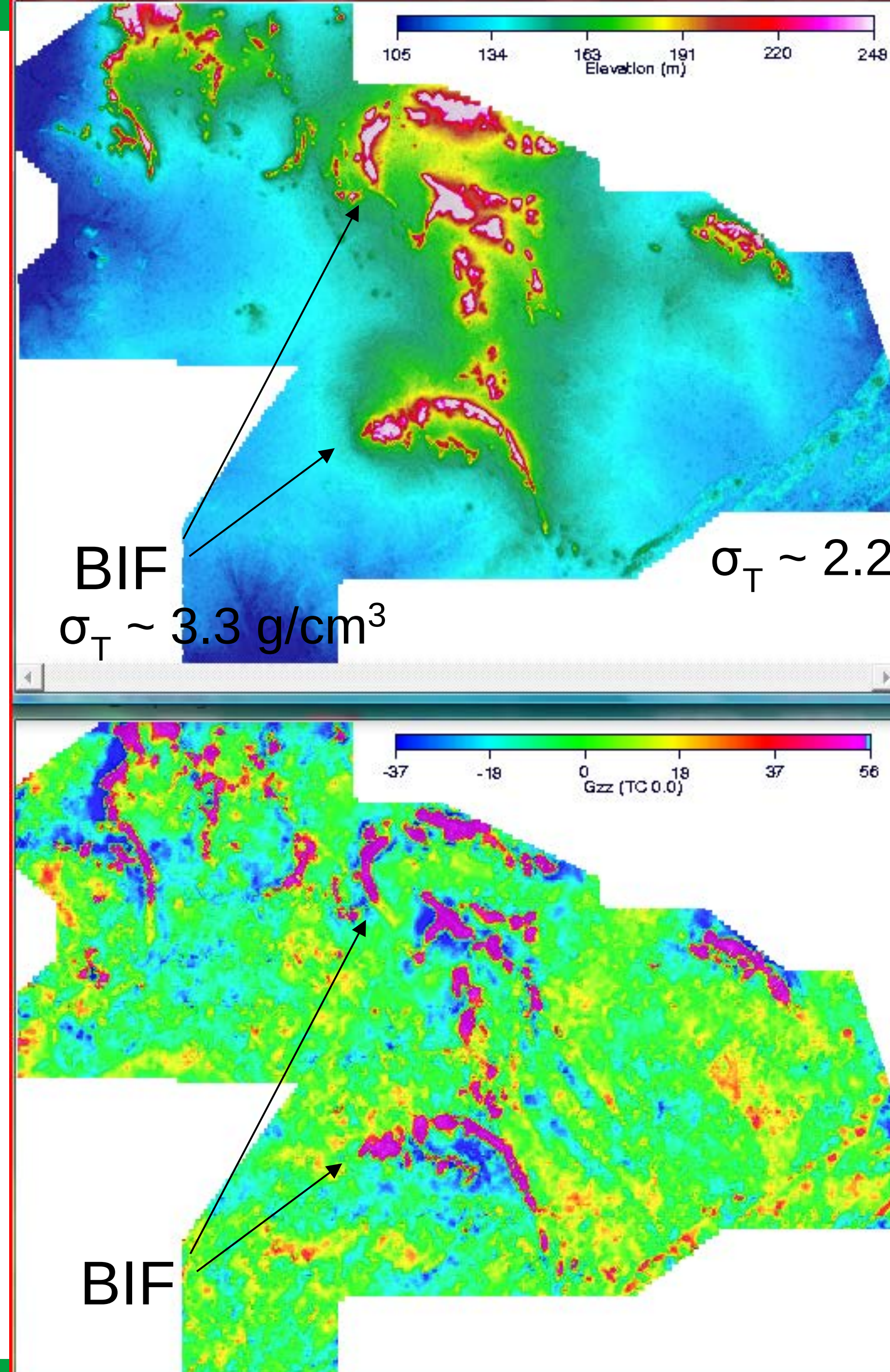
Example: FTG survey, Mauritania

DEM

First Quantum

Observed G_{zz} (no terrain correction)

$\sigma_T = 0.0$ g/cm^3



Sand dunes

$\sigma_T \sim 2.2$ g/cm^3

Sand dunes

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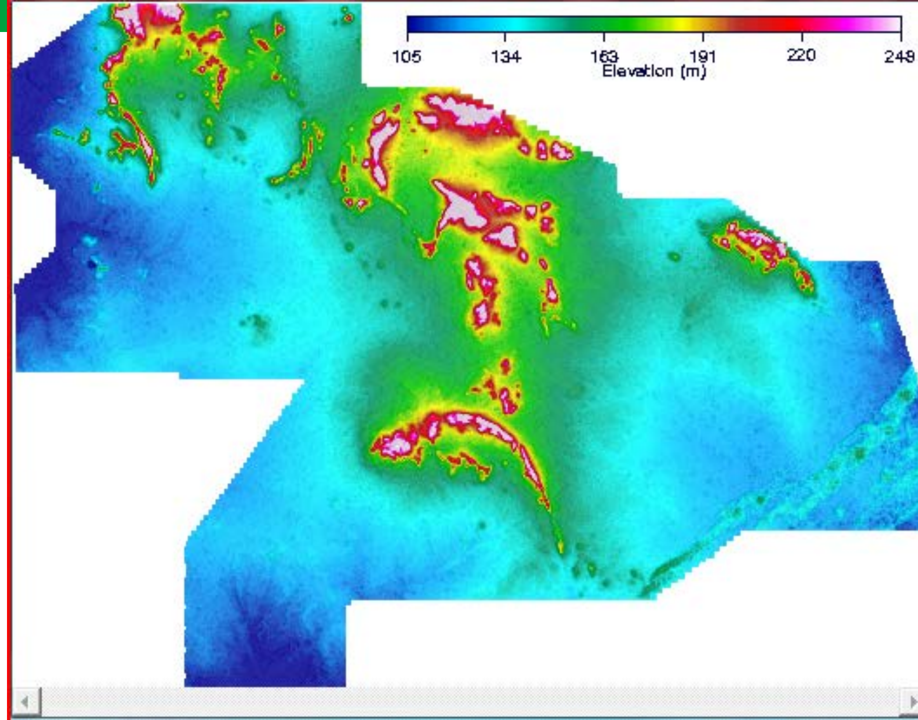
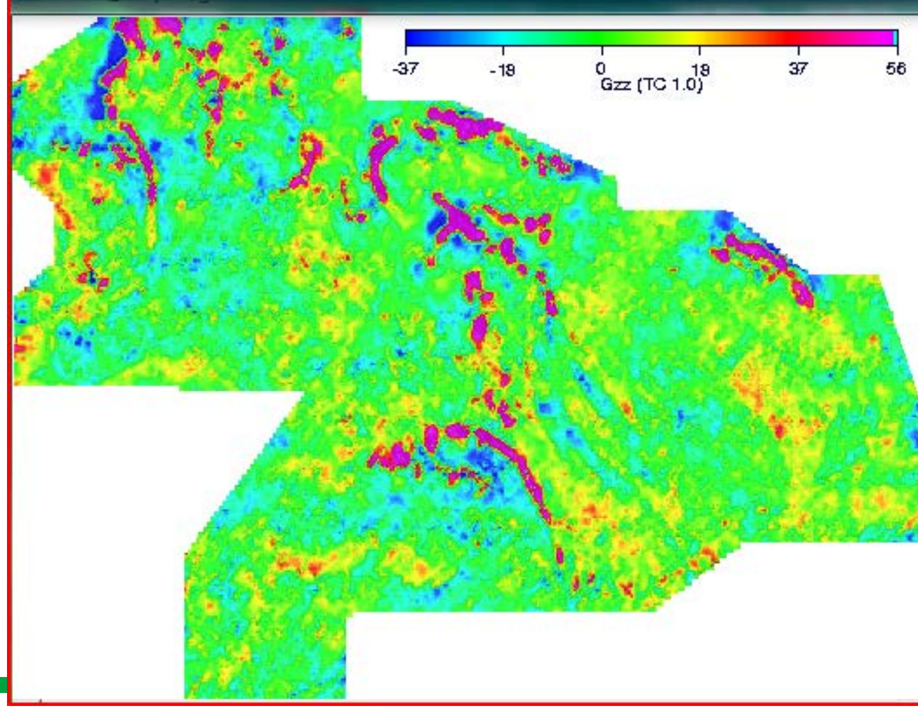
DEM



Terrain corrected G_{zz}

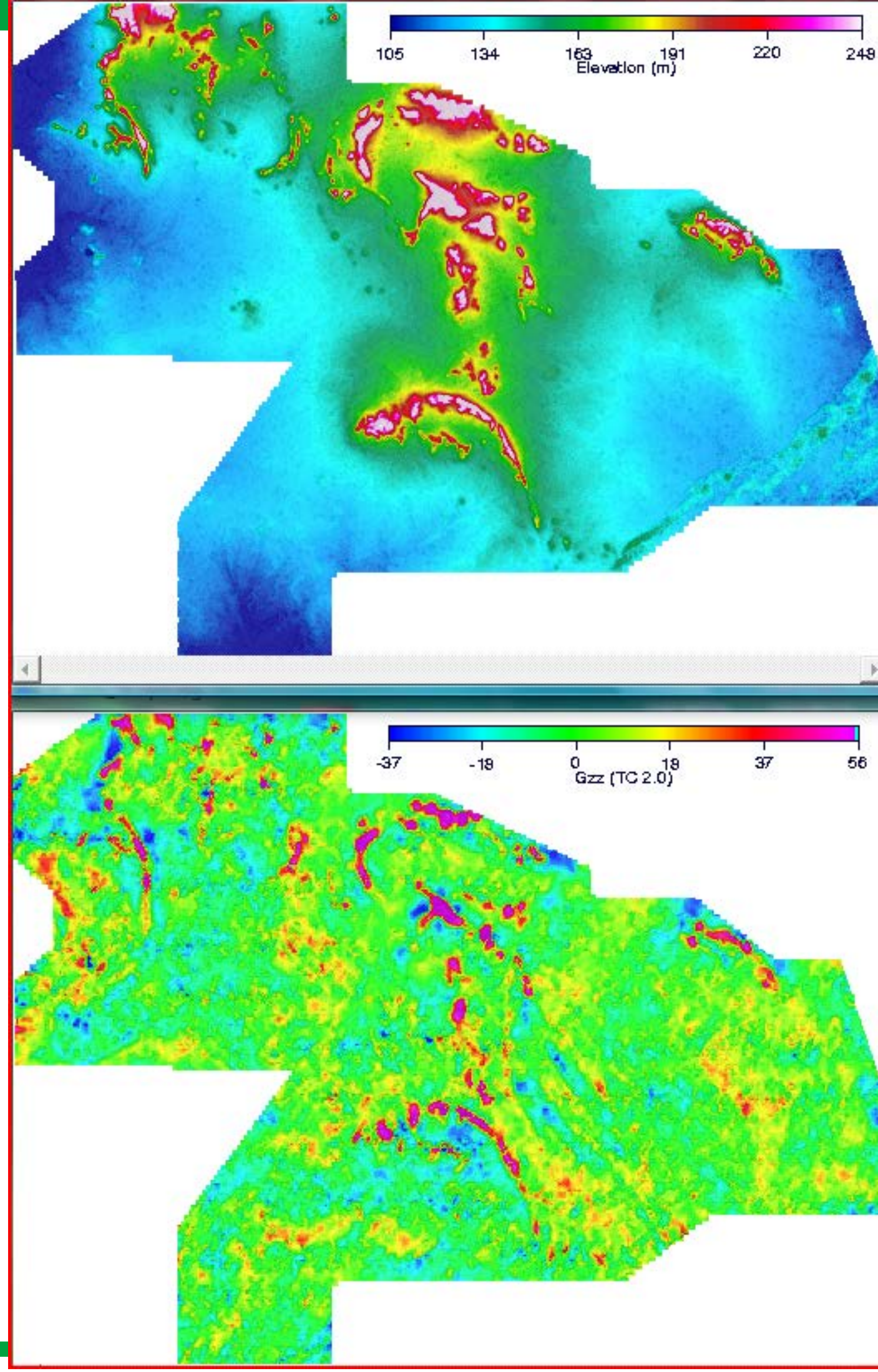


$\sigma_T = 1.0\ g/cm^3$

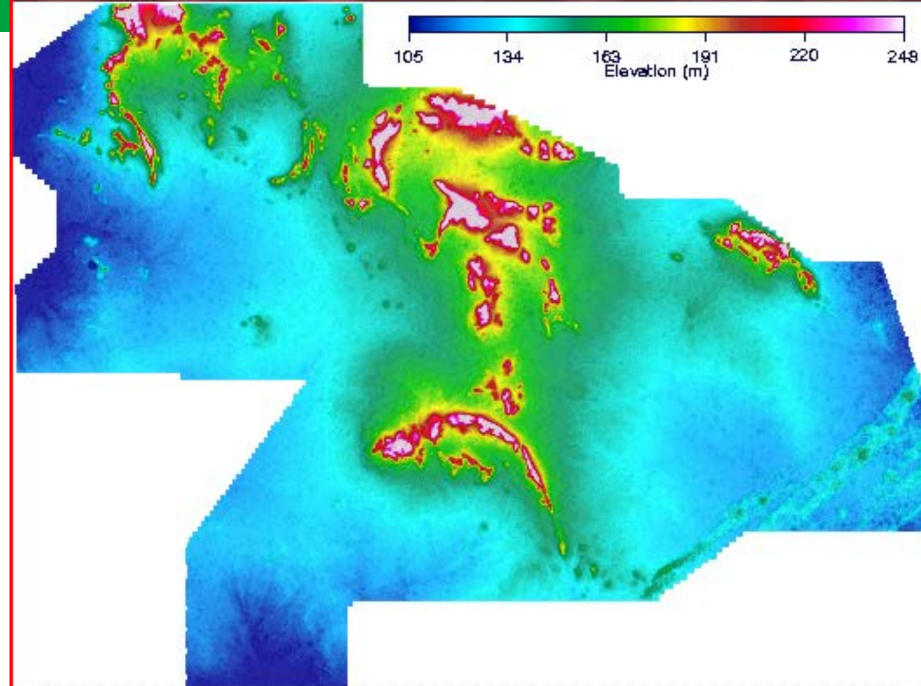
DEM

Terrain corrected G_{zz}

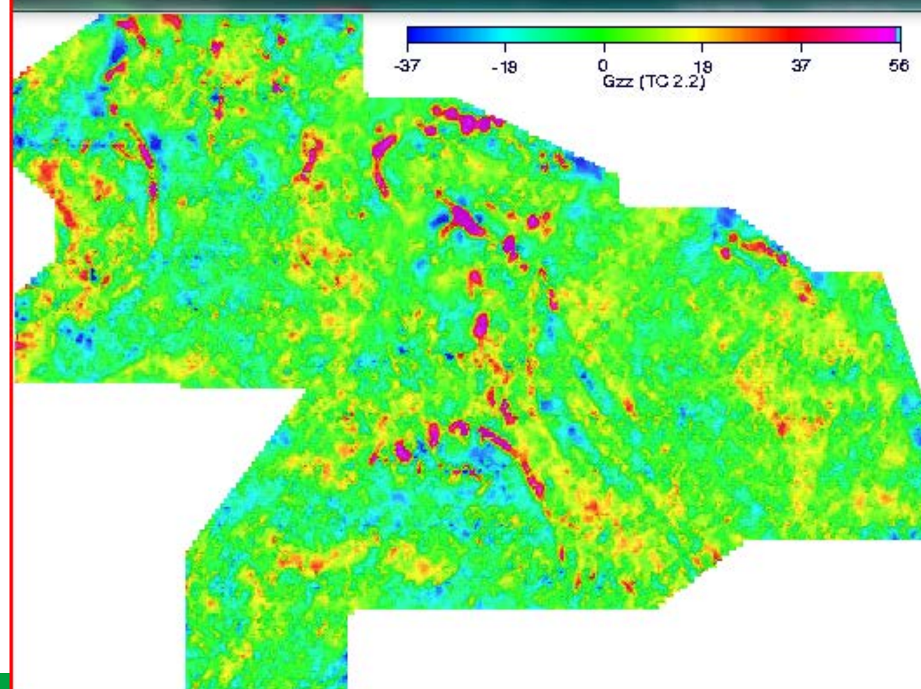
$\sigma_T = 2.0\ g/cm^3$



DEM



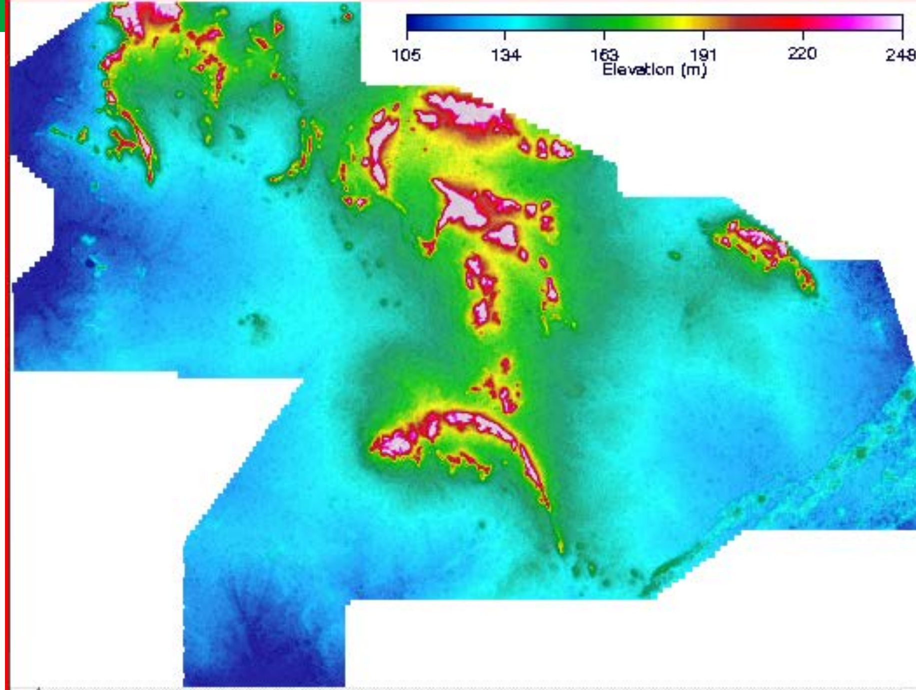
Terrain corrected G_{zz}



$\sigma_T = 2.2\ g/cm^3$

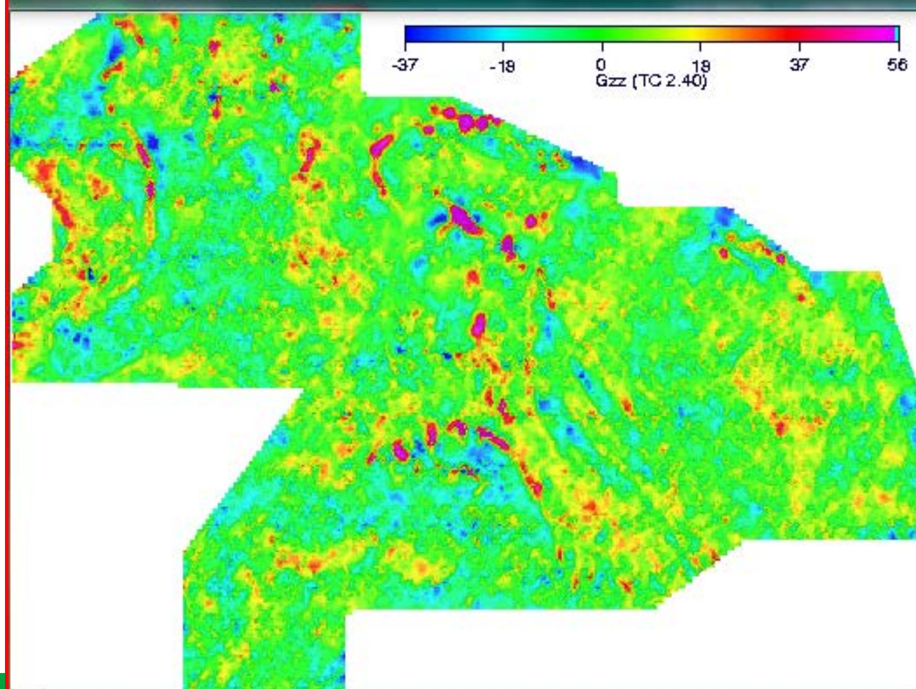
INTREPID Geophysics

DEM



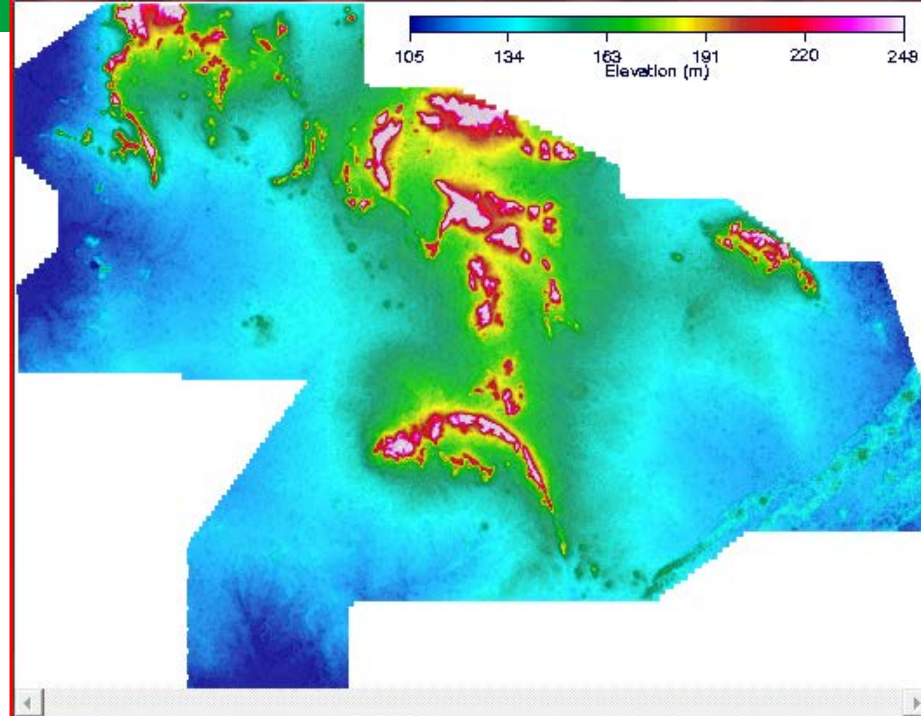
Terrain corrected G_{zz}

$\sigma_T = 2.4\ g/cm^3$

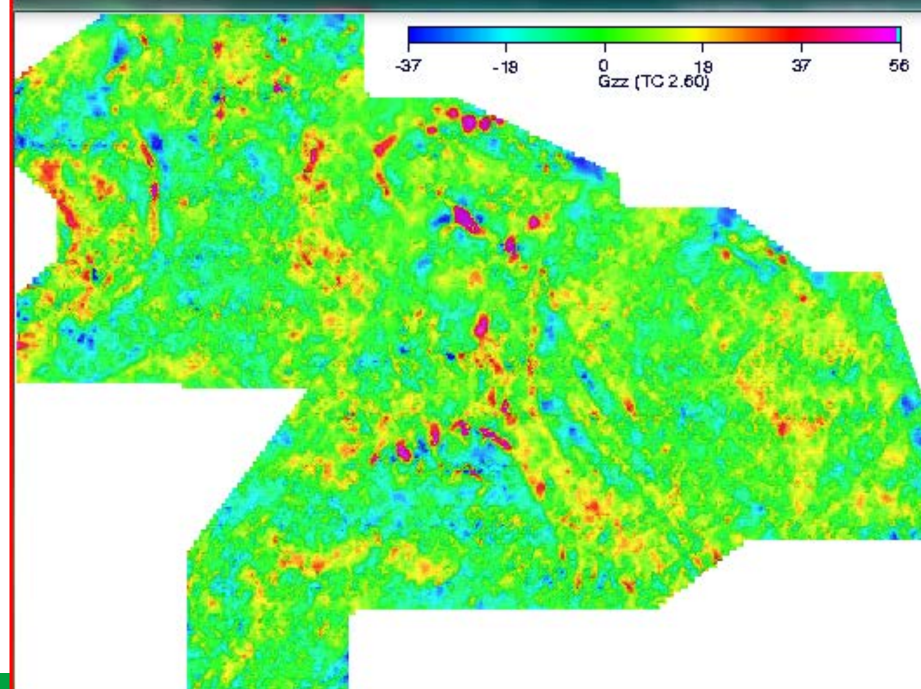


INTREPID Geophysics

DEM

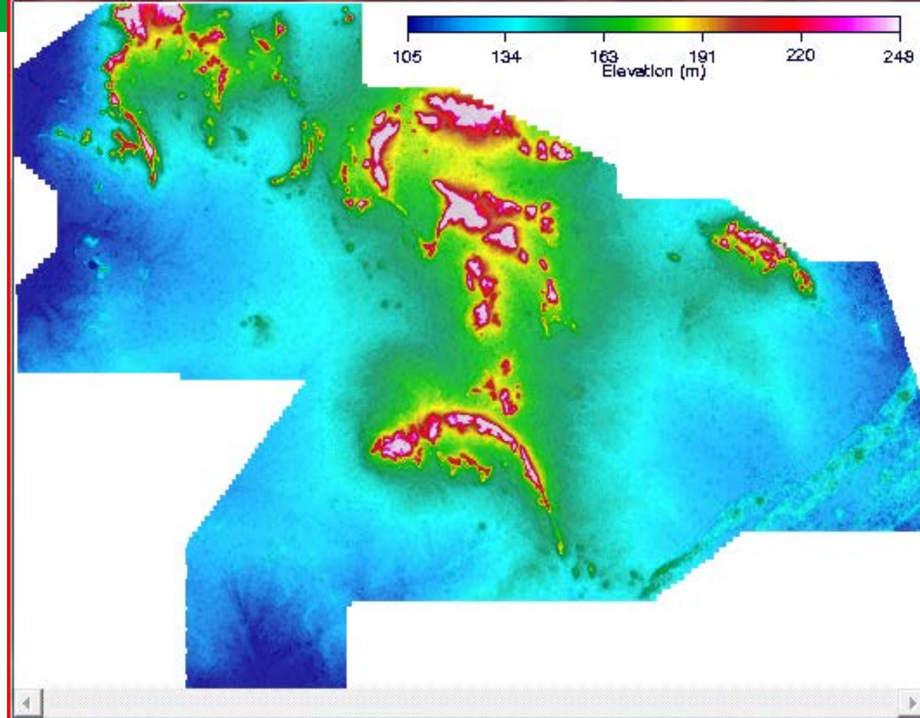


Terrain corrected G_{zz}

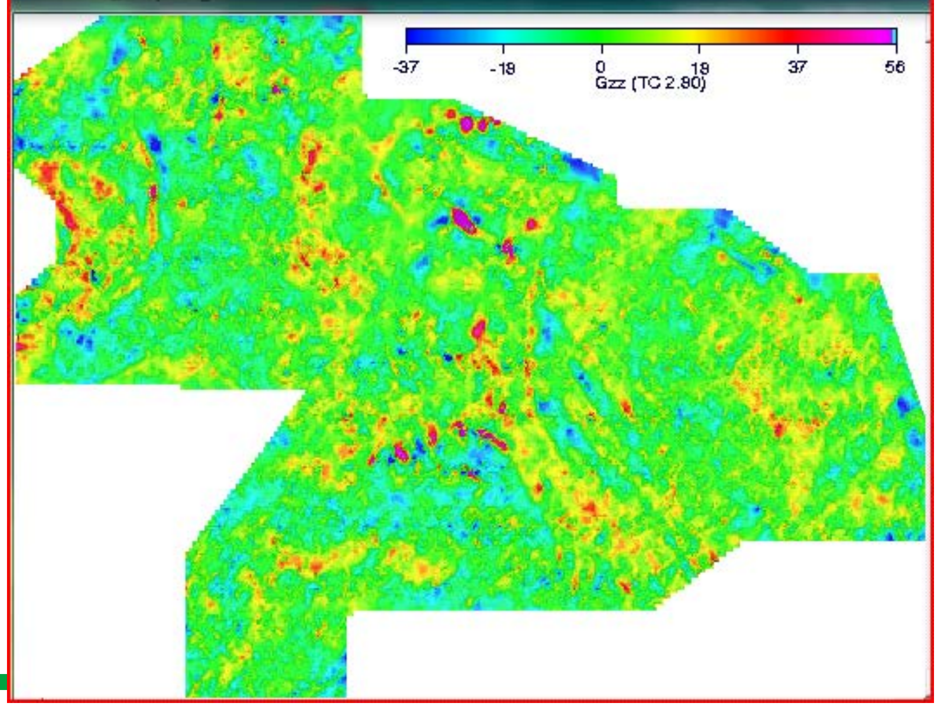


$\sigma_T = 2.6\ g/cm^3$

DEM

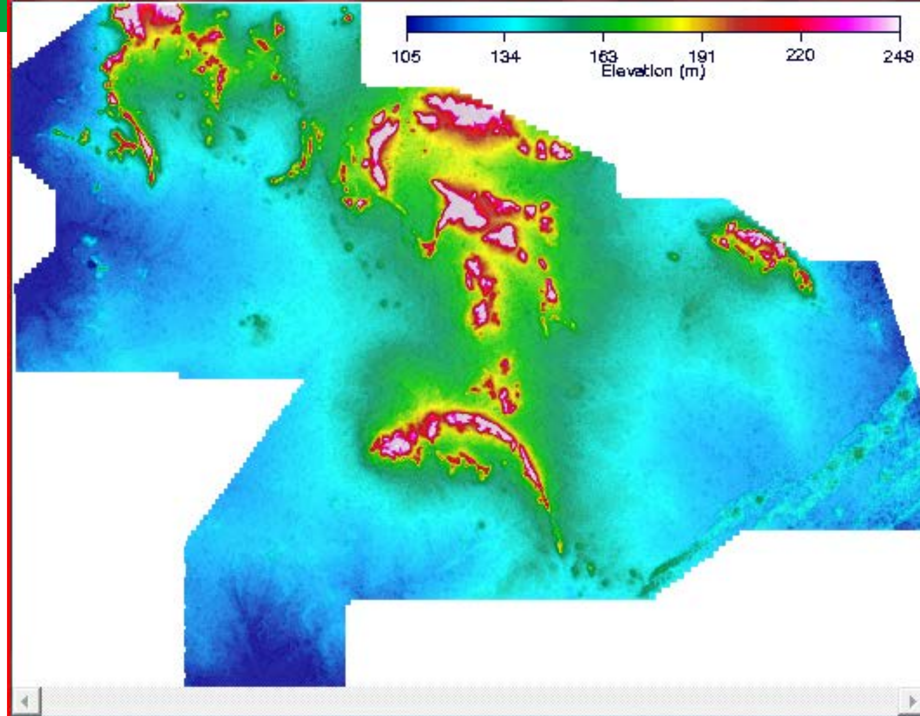


Terrain corrected G_{zz}

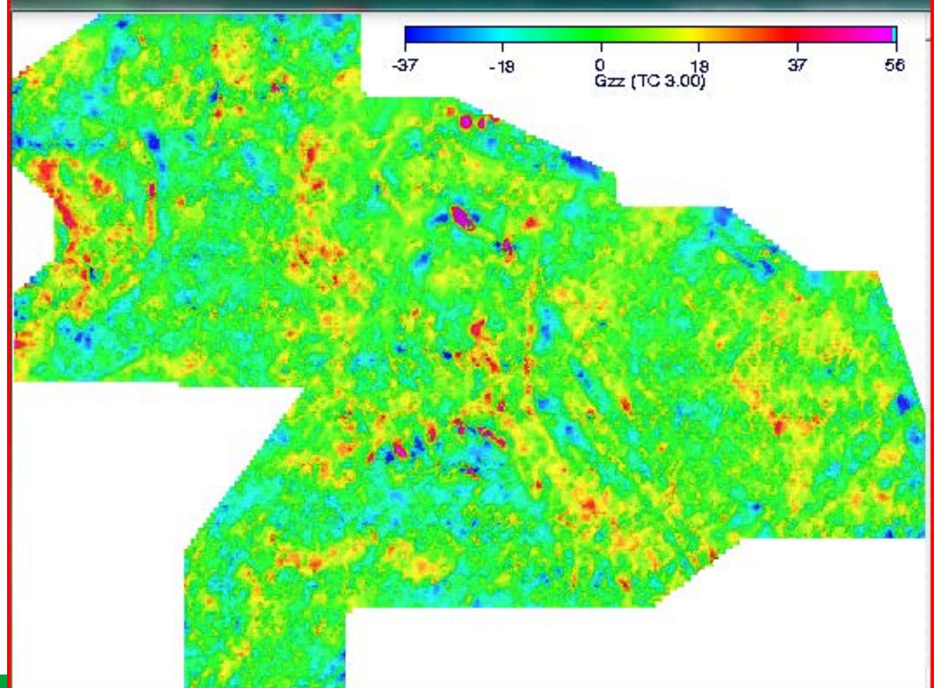


$\sigma_T = 2.8\ g/cm^3$

DEM

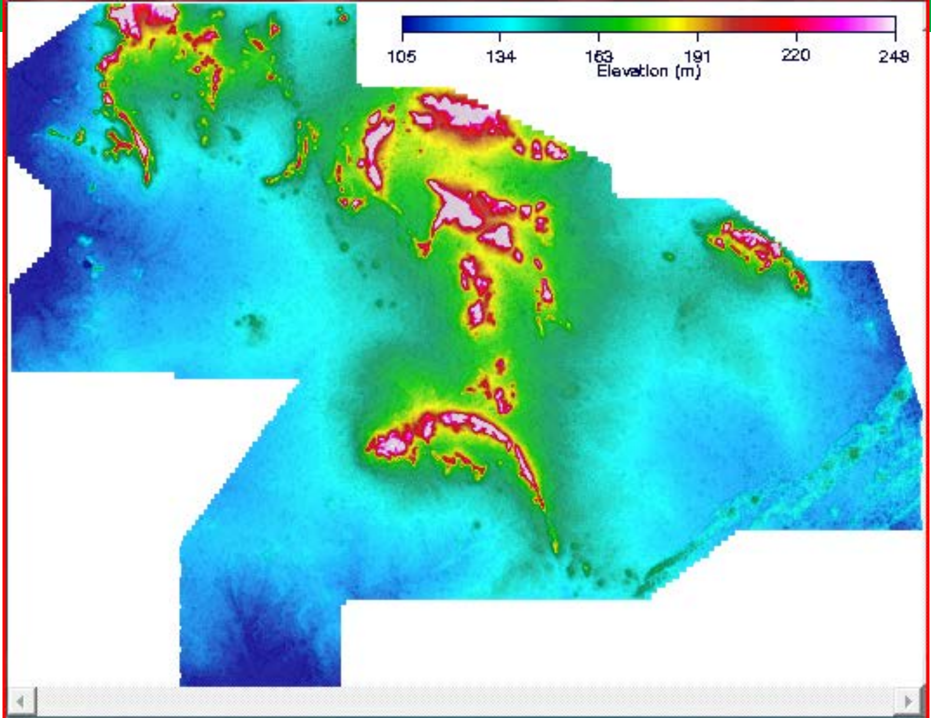


Terrain corrected G_{zz}

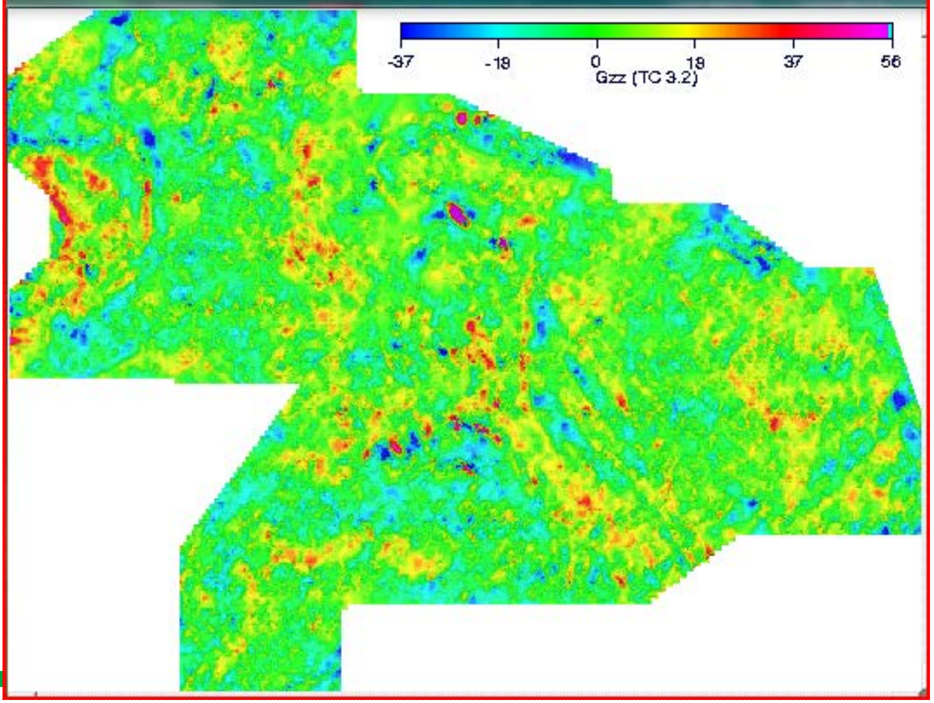


$\sigma_T = 3.0\ g/cm^3$

DEM

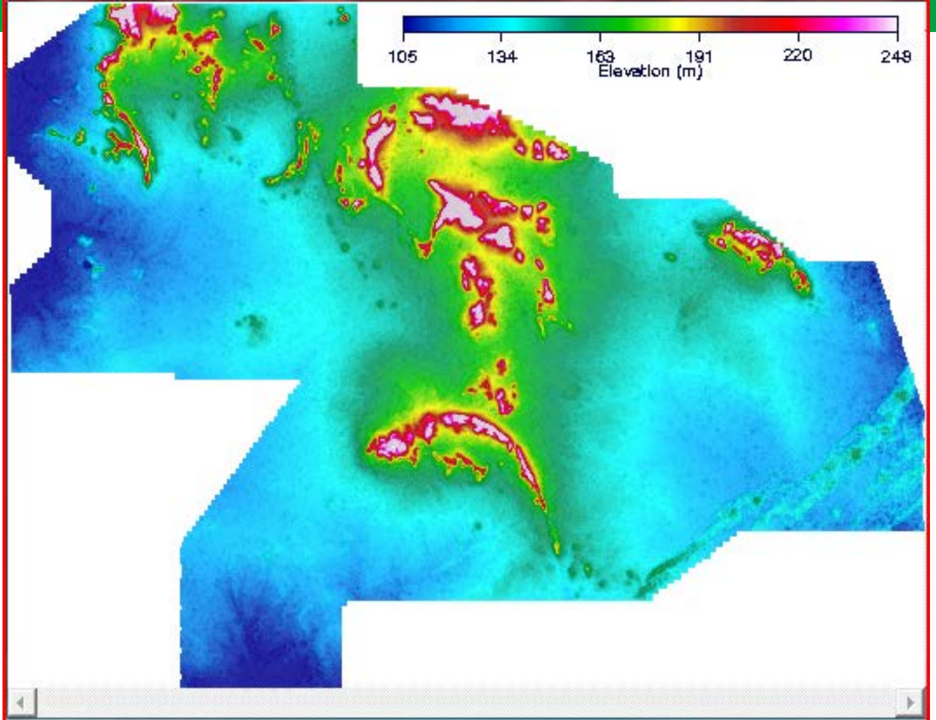


Terrain corrected G_{zz}

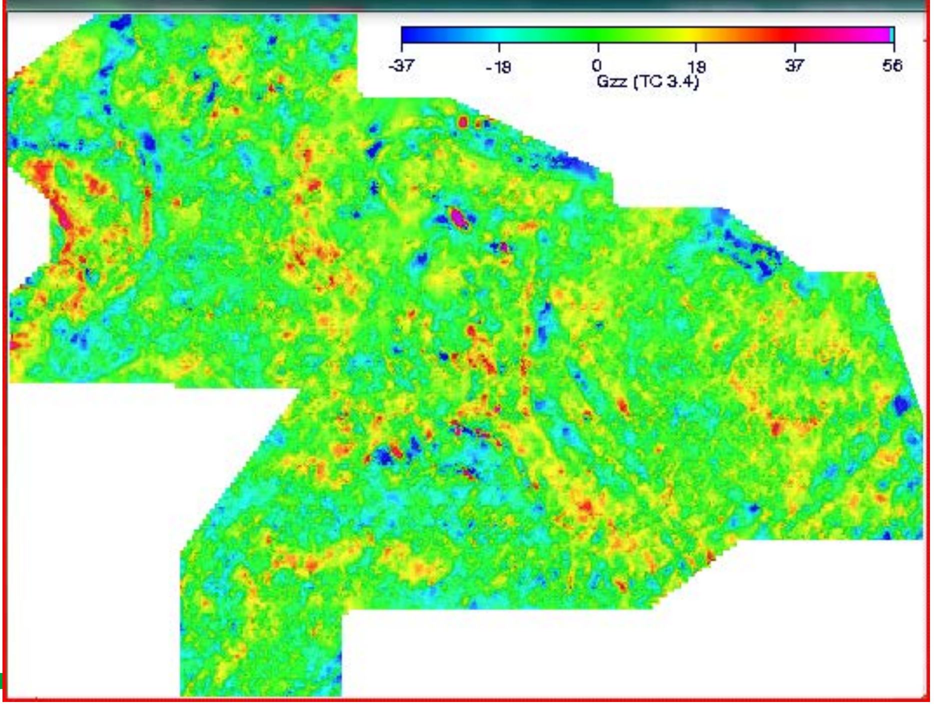


$\sigma_T = 3.2$ g/cm^3

DEM



Terrain corrected G_{zz}



$\sigma_T = 3.4\ g/cm^3$

Conclusions

Regional gravity surveys

1. give a reasonable depth to basement map,
2. some of the structural lineaments, including strike/dips,
3. solutions are only obtained at structural edges and contacts, so the depth map is incomplete.

Mining Prospecting

1. Requires high resolution gravity surveying
2. FTG is becoming useful, while expensive
3. Geological thinking always required

INTREPID GEOPHYSICS

The End