Interpretation of lithospheric magnetic signal – recent results (2009-2011)

D. Ravat
University of Kentucky

Recent reviews on lithospheric studies covering 2005-2009

- Thebault (2009) Sopron IAGA Reporter Review
- Purucker and Clark (2010) IAGA Div. 5 Book Chapter – published by Springer

Chapter 13

Mapping and Interpretation of the Lithospheric Magnetic Field

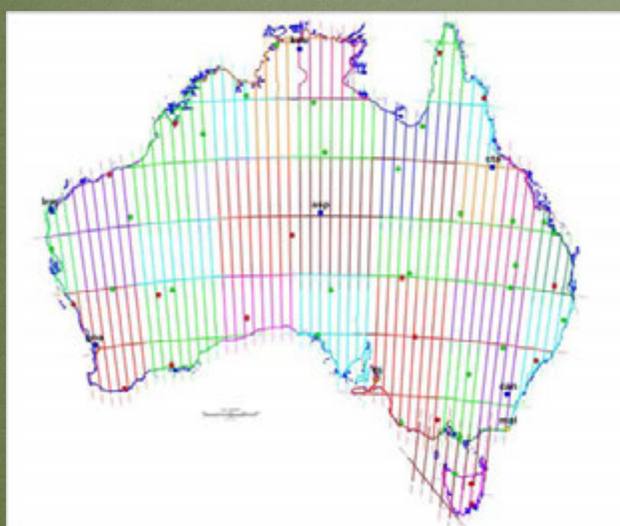
Michael E. Purucker and David A. Clark

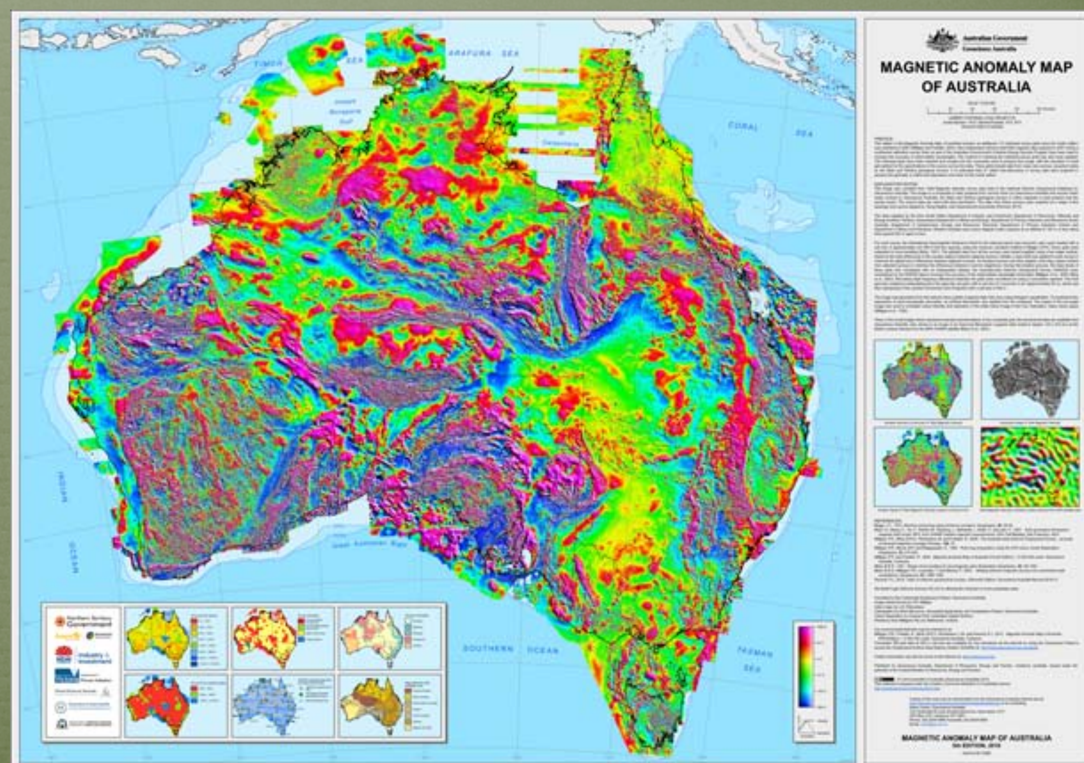
Themes Covered

- Regional and global anomaly maps and data sets for lithospheric fields
- Theoretical anomaly interpretation developments and their applications
- Connecting rock properties with crustal-scale interpretation of magnetic anomalies
- What new have we learned about magnetism of the lithosphere? And what new science could be done using the developments in the last couple of years?

Anomaly maps & Datasets

- AWAGS long-line, short-duration aeromagnetic and radiometric survey (2007)
- AWAGS leveled 5th edition Australian magnetic map (Milligan et al., 2010)

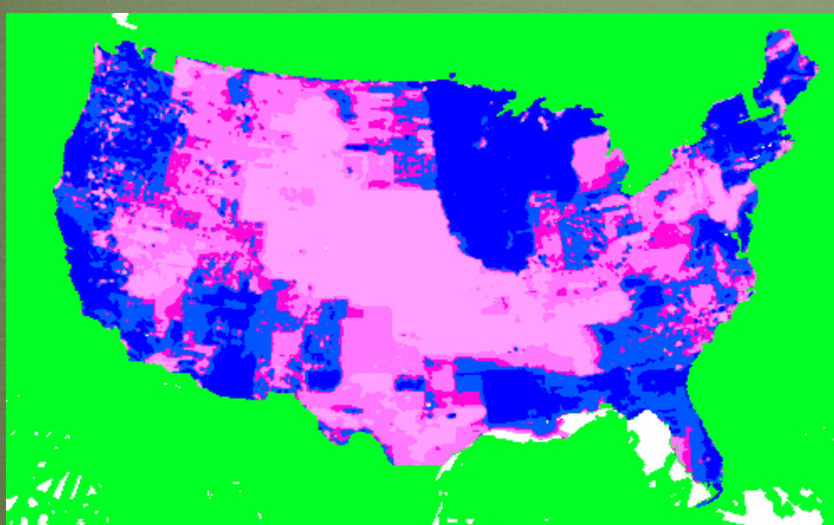


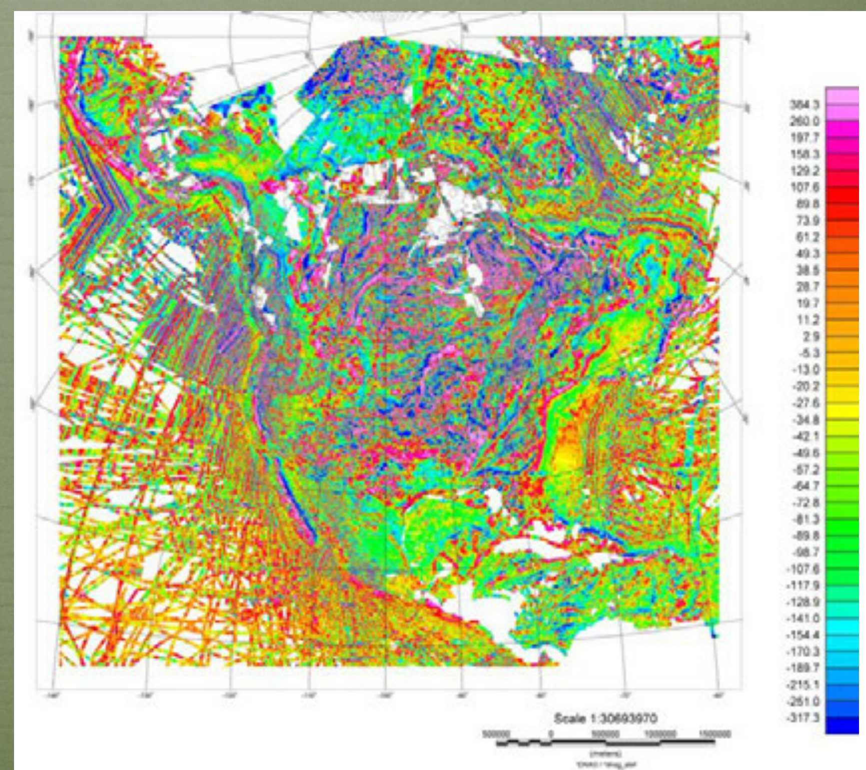


Anomaly maps & Datasets

- NURE_NAMAM2008 (Ravat et al., 2009) – Comprehensive Model CM4 corrected US NURE surveys

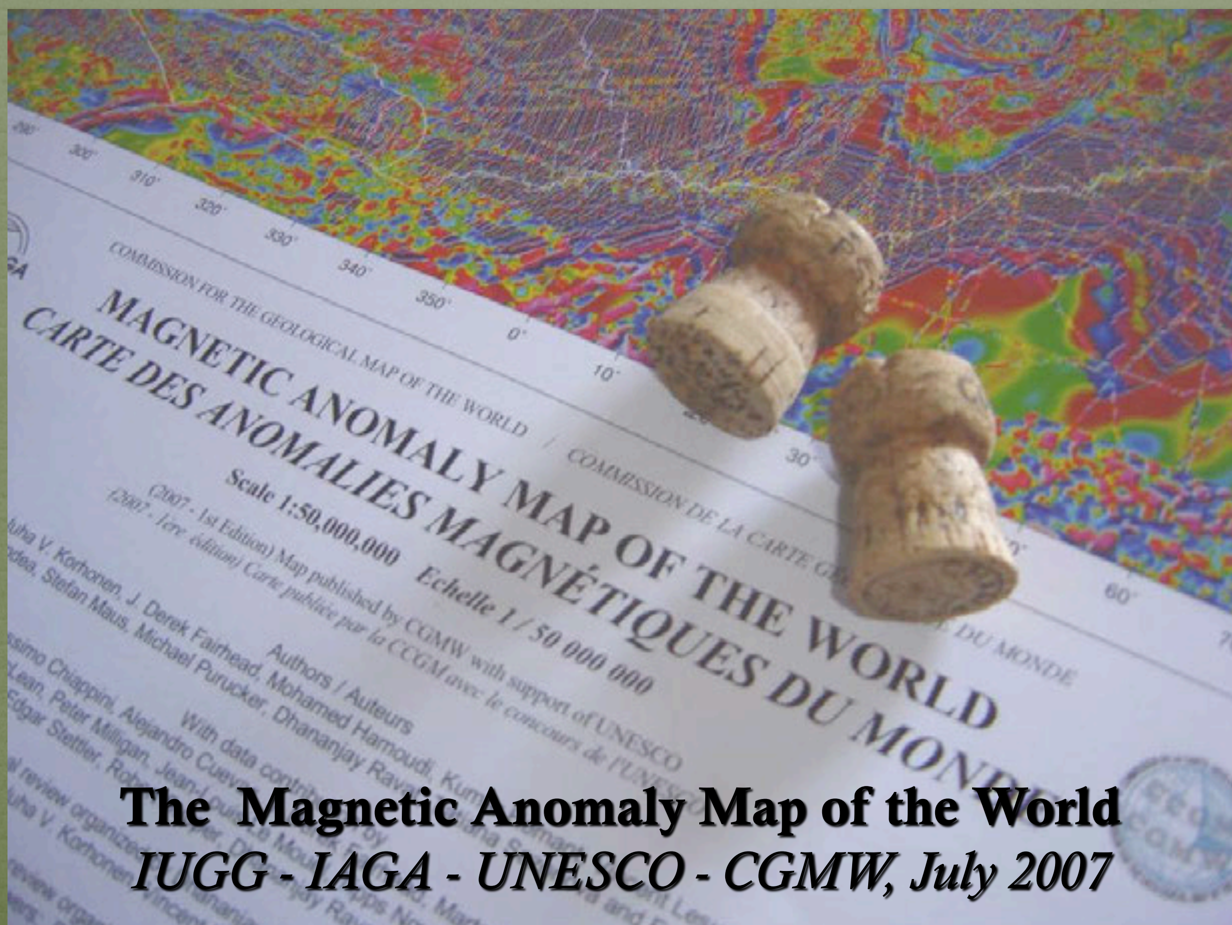
Blues and Magentas ±200-300 nT difference between Corrected NURE data set and NAMAM (2002) – The pattern of differences related to survey boundaries and the years of surveys (IGRF vs CM4)





Anomaly maps & Datasets

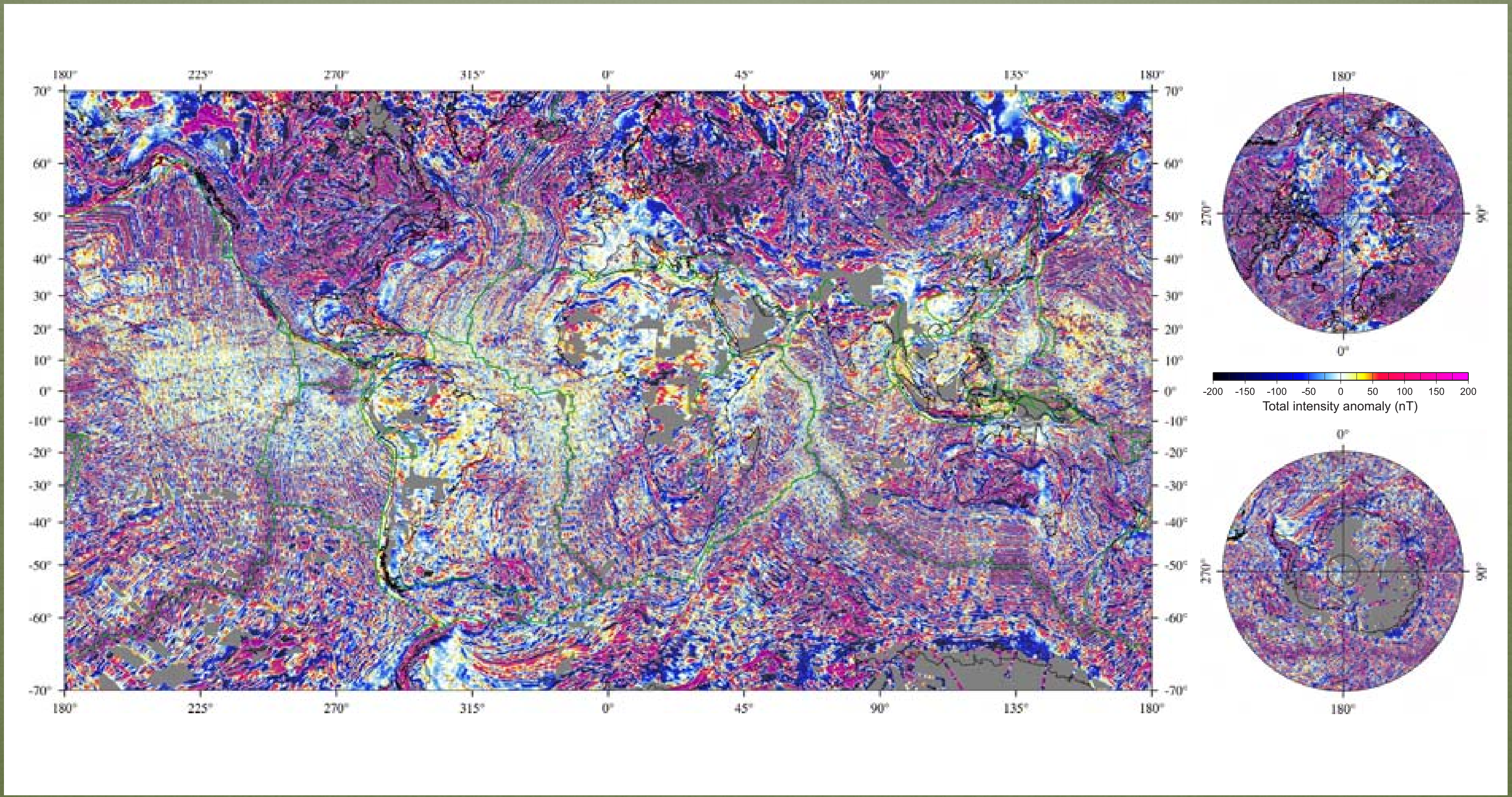
- WDMAM 2nd Edition – Available at the Int'l Geological Congress in Brisbane, August 2012 (Korhonen and the WDMAM group)



The Magnetic Anomaly Map of the World
IUGG - IAGA - UNESCO - CGMW, July 2007

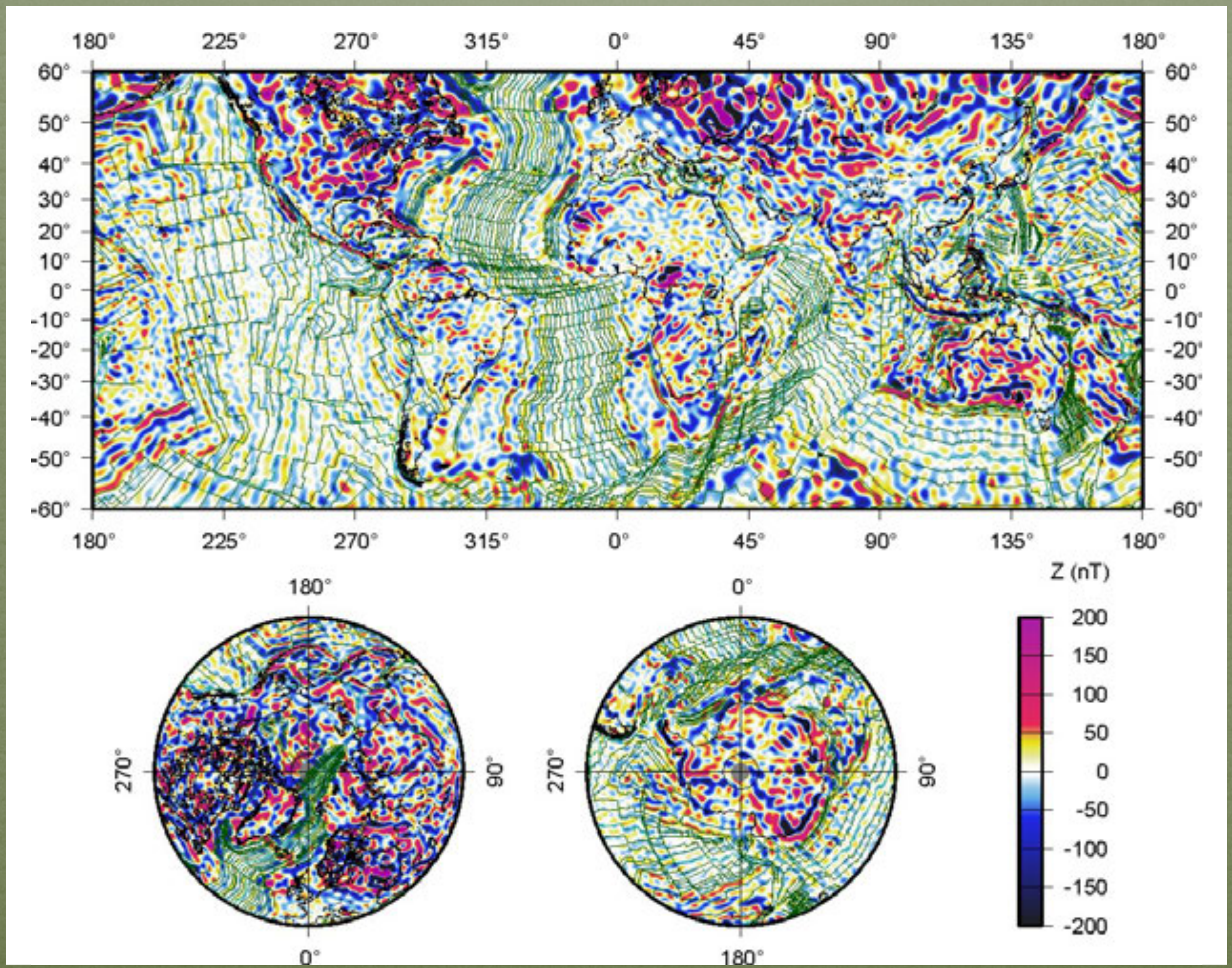
Anomaly maps & Datasets

- EMAG-2 (Maus et al., 2009)



Anomaly maps & Datasets

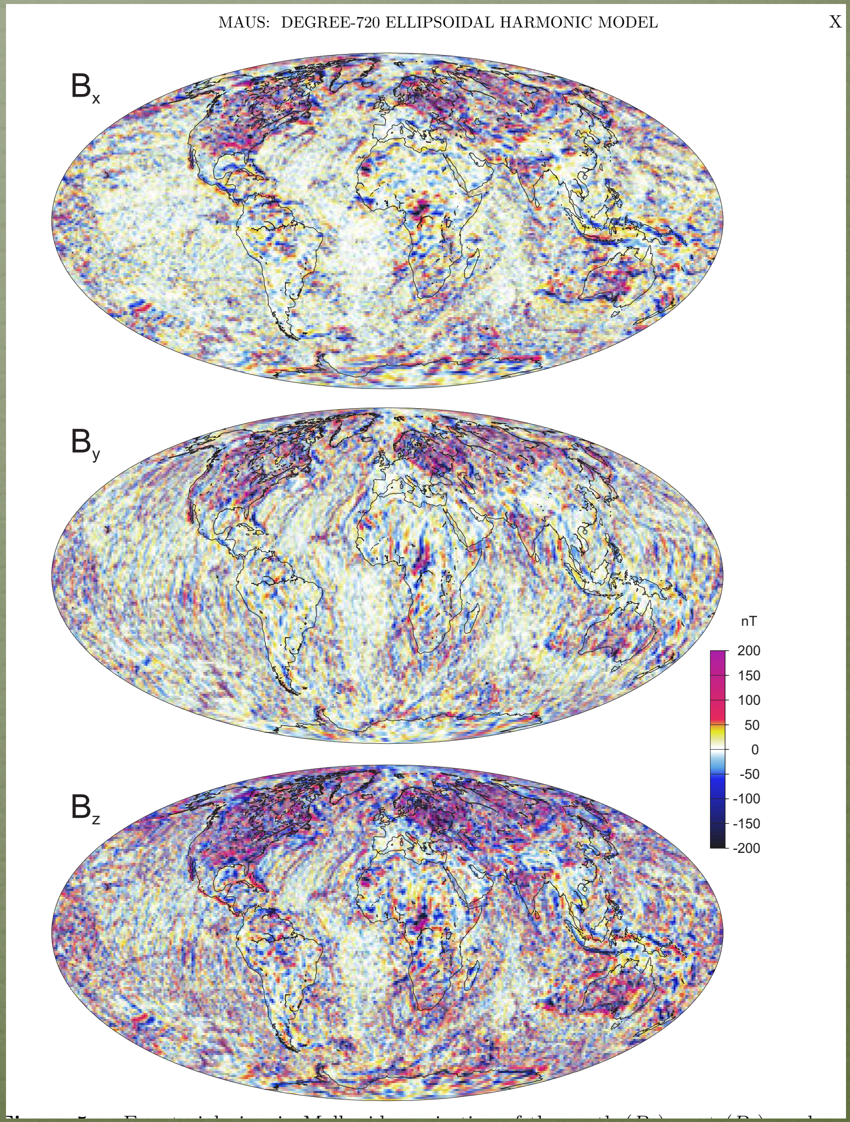
- CHAMP MF7 (Maus et al., 2010)



Anomaly maps & Datasets

Ellipsoidal harmonic representation

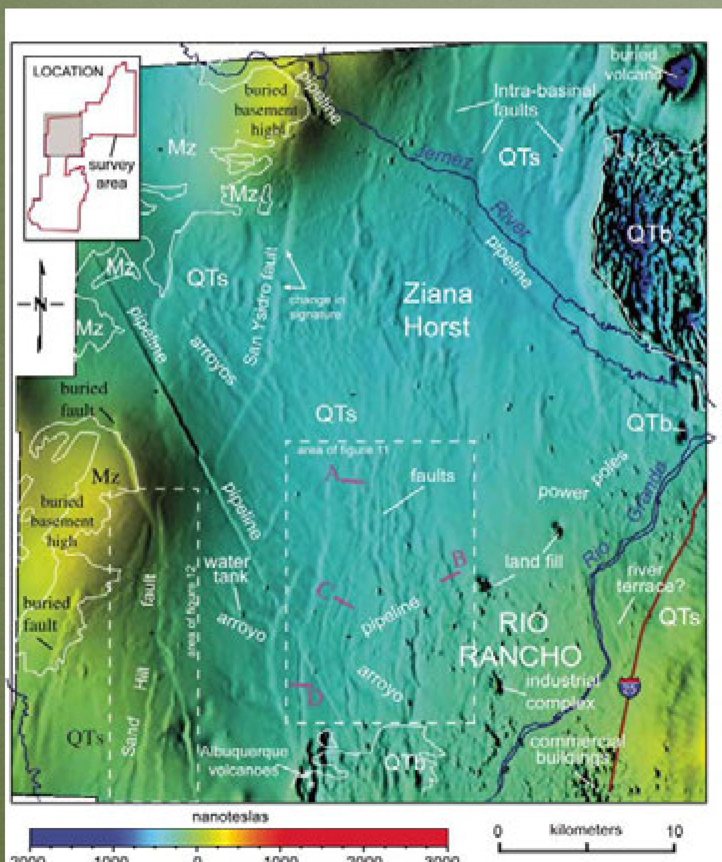
Maus, S. (2010) An ***ellipsoidal harmonic representation*** of Earth's lithospheric magnetic field to degree and order 720, *Geochem. Geophys. Geosyst.*, *11, Q06015*.



Theoretical anomaly interpretation developments and their applications

Sedimentary Magnetic Anomalies

- Grauch & Hudson (2007, 2011) …. aeromagnetic expression of faults in sedimentary basins…lessons from the Rio Grande Rift



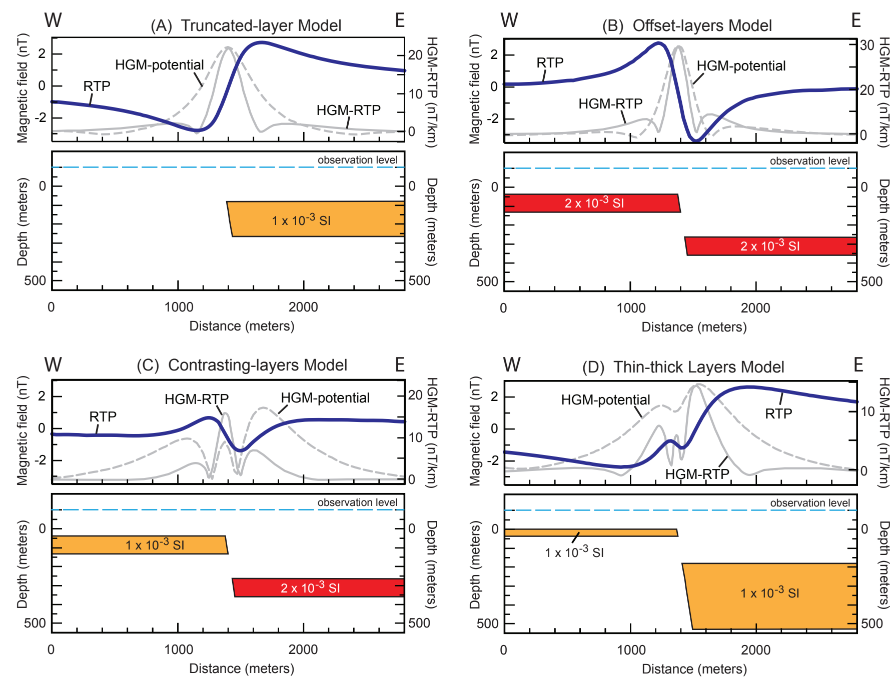
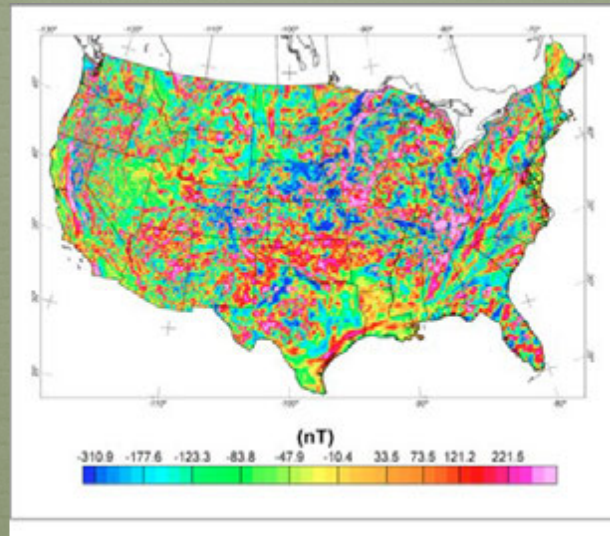
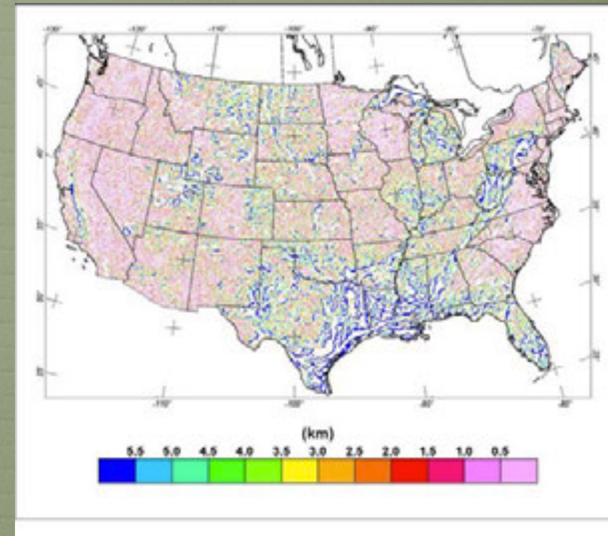


Figure 2. Simple 2D geophysical models illustrating the four main types of aeromagnetic signatures associated with intrasedimentary normal faults in the Rio Grande rift. Profiles are computed for the reduced-to-pole (RTP) magnetic anomaly (bold blue lines), the horizontal gradient magnitude of the RTP anomaly and of its potential (HGM-RTP—solid gray lines; HGM-potential—dashed gray lines). The anomalies for the truncated-layer and offset-layers models (A and B) are typical, whereas the contrasting-layers and thin-thick layers models (C and D) are unexpected. Note the multiple peaks in the HGM profiles for C and D, discussed in text. Magnetic susceptibilities are color-coded and labeled.

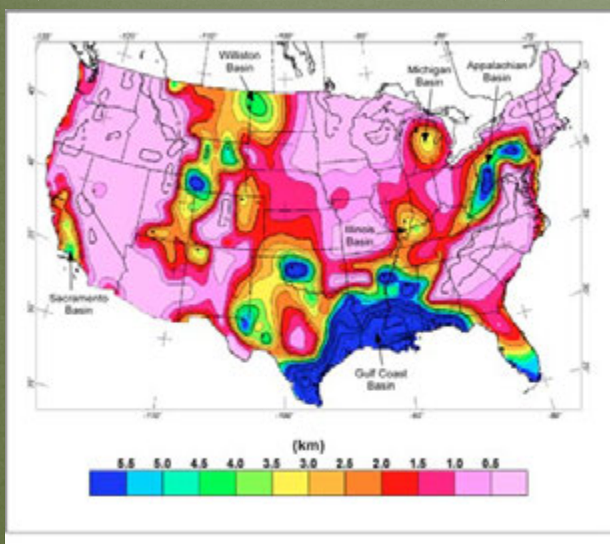
Tilt-Depth (Salem et al., 2007): Refinement + Error Analysis + First Regional Case Studies in Salem et al. (2010)



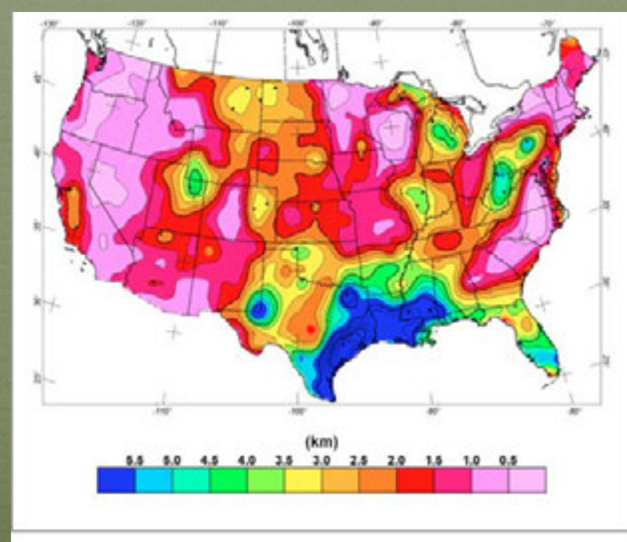


$$\theta = \tan^{-1}\left(\frac{\partial M / \partial z}{\partial M / \partial h}\right)$$

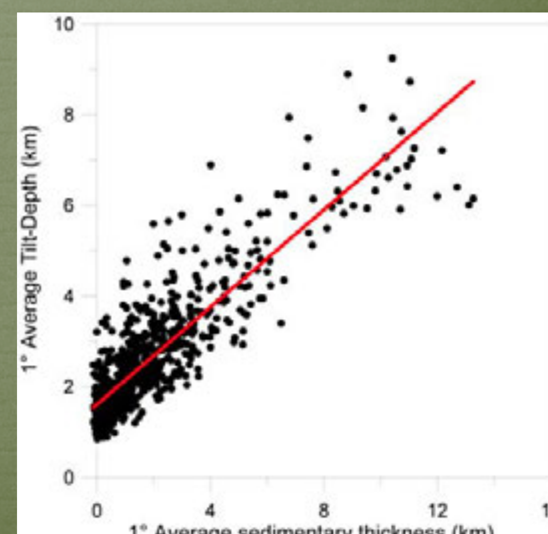
Sedimentary Thickness (Laske & Masters, 1997)



1° Ave. Tilt-Depths

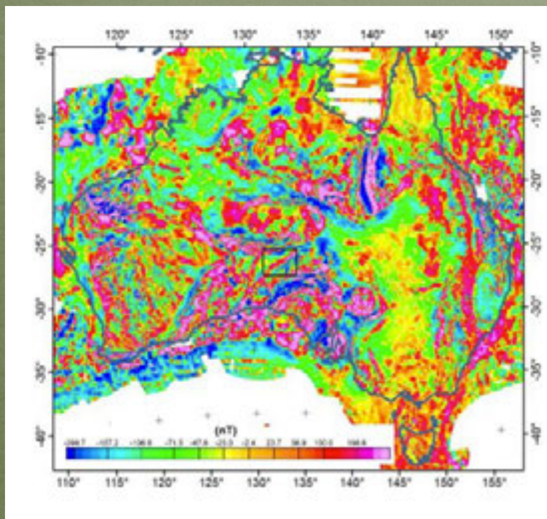


Corr. Coeff. = 0.87

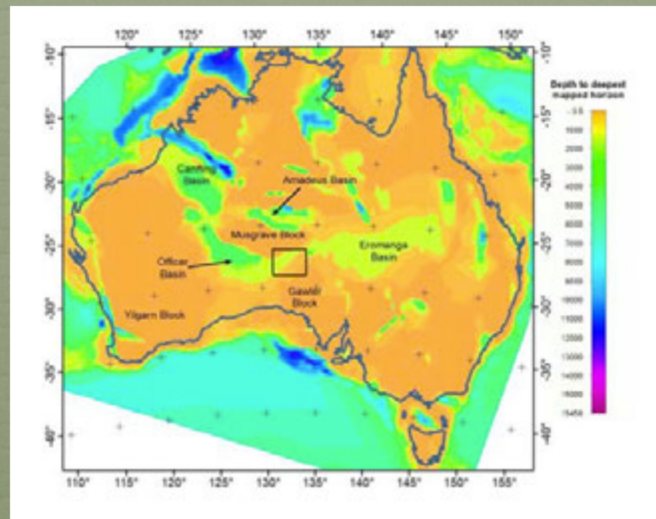


Tilt-Depth (Salem et al., 2010)

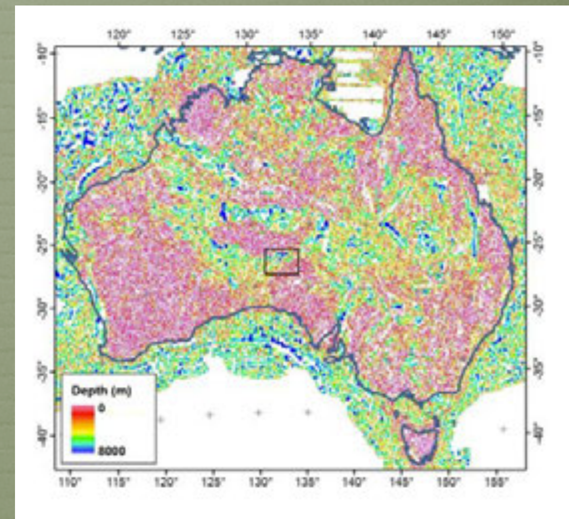
Variable RTP Australia
4th Ed. Aeromag



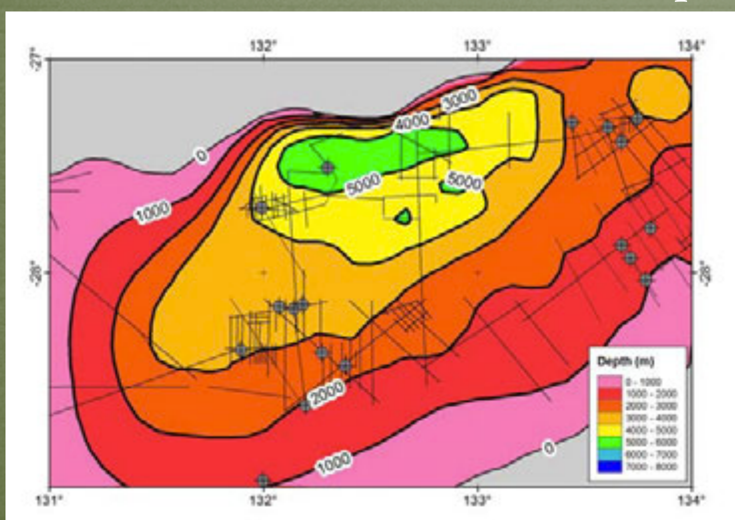
Deepest Sed. Drilled Depths



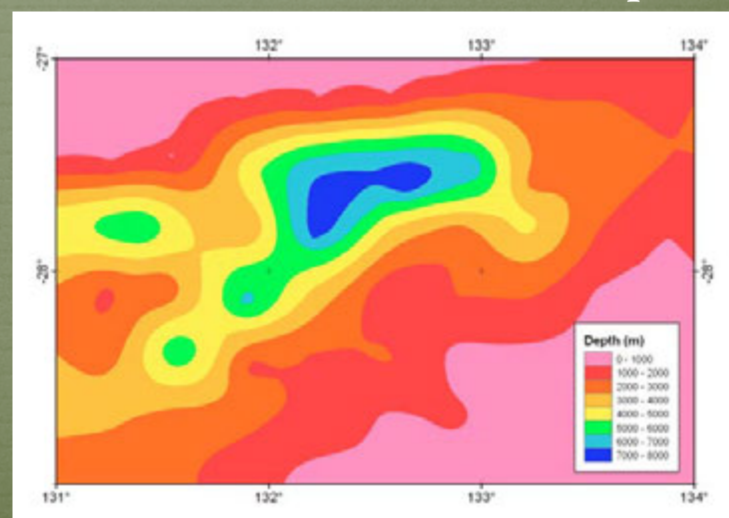
Tilt-Depths



Eastern Officer Basin Drillhole Depths



Eastern Officer Basin Tilt-Depths

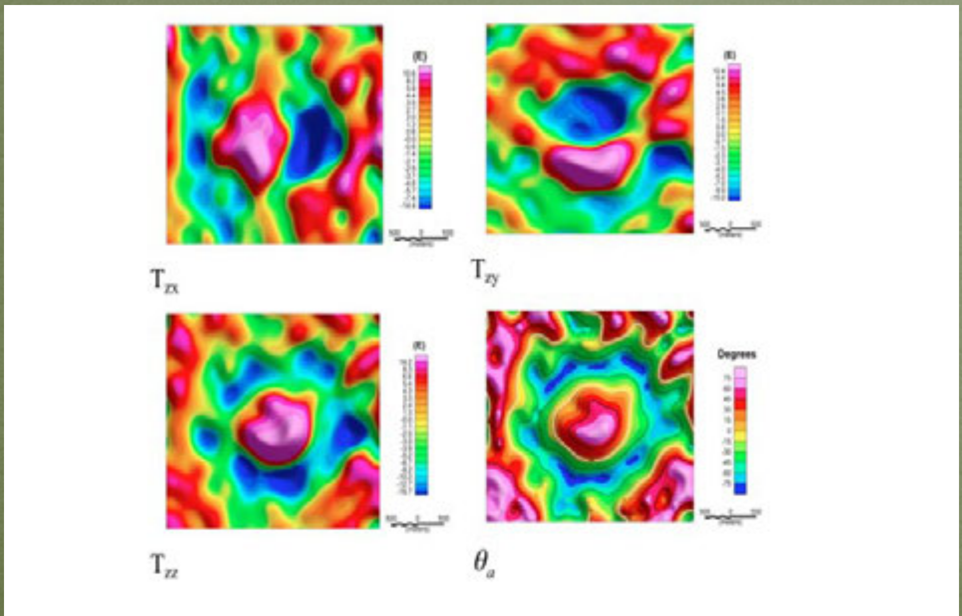


Tensor Potential Fields

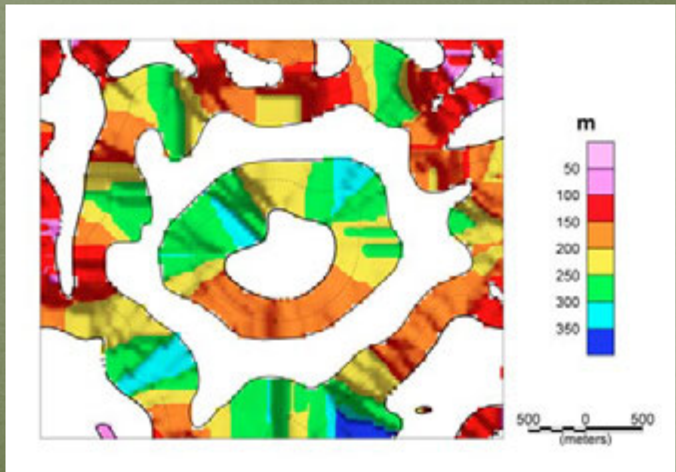
- **Adaptive tilt angle for depth determination of tensor gravity data (Salem et al., 2011)** — ***similar for magnetics***

$$\theta_a = \tan^{-1}\left[a\frac{T_{zz}}{\sqrt{T_{zx}^2 + T_{zy}^2}}\right]$$

with adaptation factors a =3 for point source and a =1 for several linear sources



Inferred Depths of Vinton Salt Dome, Louisiana, USA



Tensor Interpretation Methods

- Recognition of ***dikes, faults, and other thin bodies*** from Full Tensor Gradiometer Magnetics (FTGM) system (Fitzgerald et al., 2010)
  - IPHT (Institute for Photonic Technology) instrument: 6 cross-line mixed gradients using SQUID
  - Decomposition into invariant structural (eigenvalues) and rotational (eigenvectors) part using quaternions
  - Robust interpolation of tensor components using spherical linear interpolation of quaternions

Tensor Amplitude

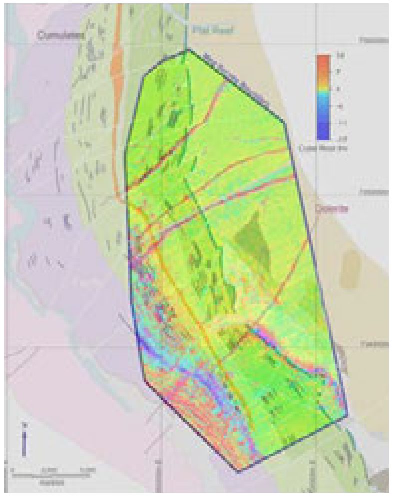


Figure 3: Tensor amplitude product one – cube root invariant. A composite with the geology in the background. Strong signal from the Hornfels bottom right hand side, and the magnetite cumulates in the Upper Zone. All dykes report very clearly.

Tensor Phase

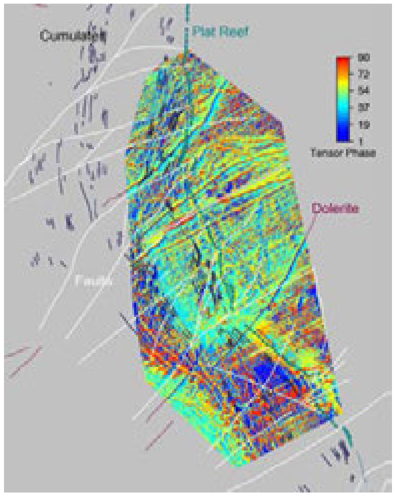


Figure 4: Tensor phase (0 to 90). The main structural geology posted as vectors. Muted signal from the Hornfels bottom right h and the magnetite cumulates in the Upper Zone. New detail appears here. All the successions in the reef are clearly evident.

Undercover Lithology Identification

- **Gettings (2009) Identification of Concealed Lithologies Using Possibility Theory and Aeromagnetic Data *in*** P. J. Williams et al. *(editors)* **Smart Science for Exploration and Mining**

- Pattern Recognition with Possibility Theory

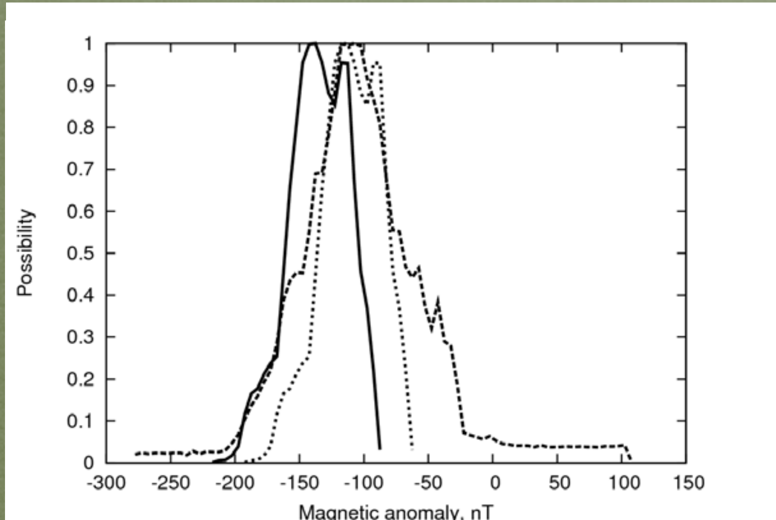


Figure 5. Solid line is the possibility function for the central target area "Ct" in the figures above. Dashed line is the possibility distribution for the Tertiary volcanic rocks "Tv", and the dotted line is the "Ct" distribution shifted for maximum correlation with the "Tv" unit distribution.

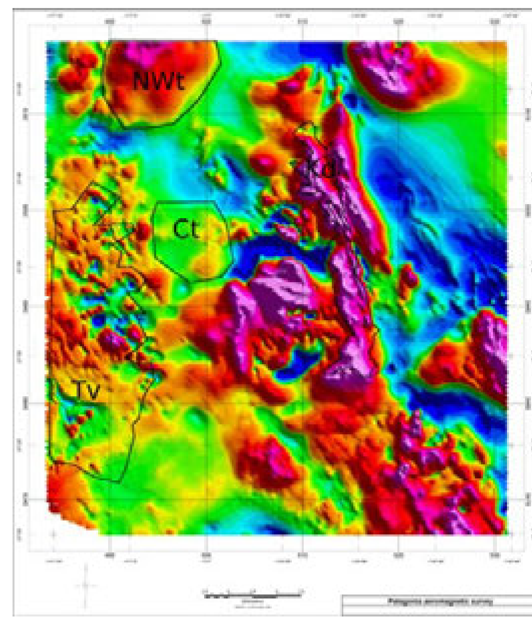
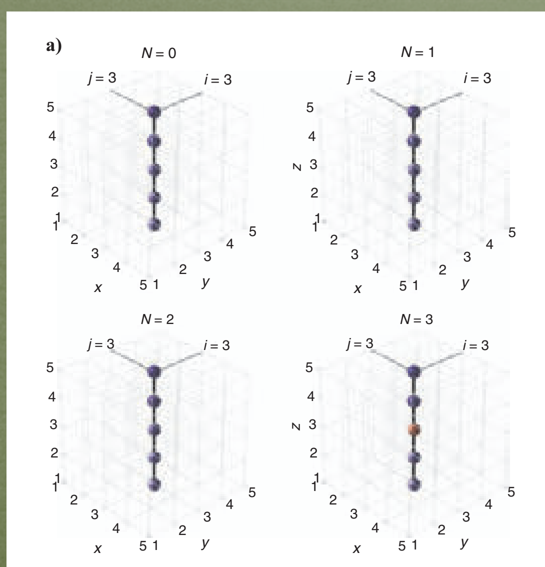


Figure 3. Aeromagnetic map of the study area in southeast Arizona. Note the areas labelled "Tv" (Tertiary volcanic rocks) , "Kd" (Cretaceous diorites), and the two target areas of cover "NWt" and "Ct". Scale bar is 10 km in length.

Theoretical Anomaly Interpretation Methods

- MagSoundDST (Gerovska et al., 2010)

  Anomaly at all locations w.r.t. the central point of the similarity transform (probing point) becomes linear when the probing point and the center of the source coincide



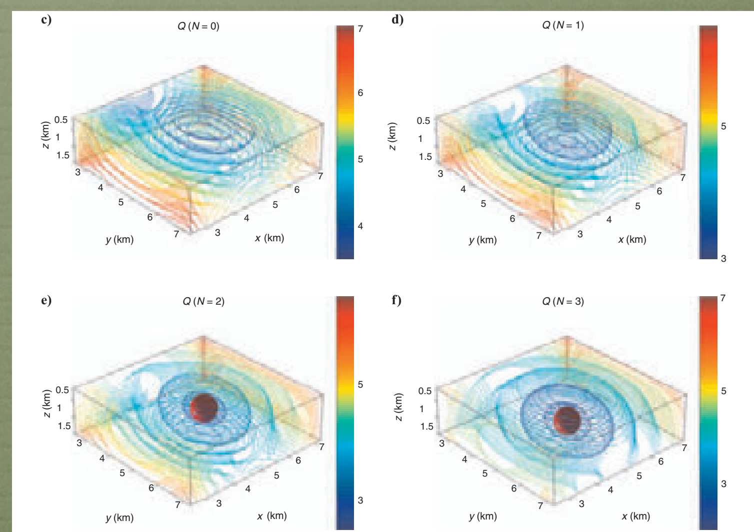


Figure 2. Model data set caused by a spherical magnetic source. (a) Anomalous magnetic field ΔT, in nT; (b) $Q(Q_{min})$ with minimum correctly locating the source position; (c-f) 3D maps of the estimator $Q(a,b,c;N)$ of DST for structural indices $N = 0, 1, 2,$ and 3. The red spheres denote the locations of local minima of Q and thus of the singular point (center) of the source. The view of the 3D contour maps Q has an azimuth of 48° and elevation of 30°.

Theoretical Anomaly Interpretation Methods

- Cooper (2008) **Wavelet-based semblance filtering**, Computers & Geosciences — to allow phase comparison of two data sets as a function of both time and wavelength
- Cooper & Cowan (2009) **Terracing potential field data**, Geophy. Prosp. — Improvement using zero contour of profile curvature
- Cooper (2010) **Enhancing ridges in potential field data**, Expl. Geophys. — a method of extracting ridges and valleys based on maxima and minima of a balanced plan curvature data set
- Cooper (2010) **Enhancing circular features in potential field data**, Expl. Geophys. — use of the generalized radial derivative filter
- Cooper & Cowan (2011) **A generalized derivative operator for potential field data**, Geophys. Prosp. — a new thoeretical derivative operator based on balancing horizontal and vertical derivatives leading to no directional bias

Tectonic Interpretations

Tectonics & Earthquakes

- Integration of ***Magnetic***, Paleomagnetic, Gravity, GPS, ***LIDAR***, Geologic, and ***Paleo-seismic*** data to constrain Holocene earthquake activity in Puget Lowland in NW United States (**Blakely and co-workers, 2009)**

Canoe-borne Magnetic Surveying

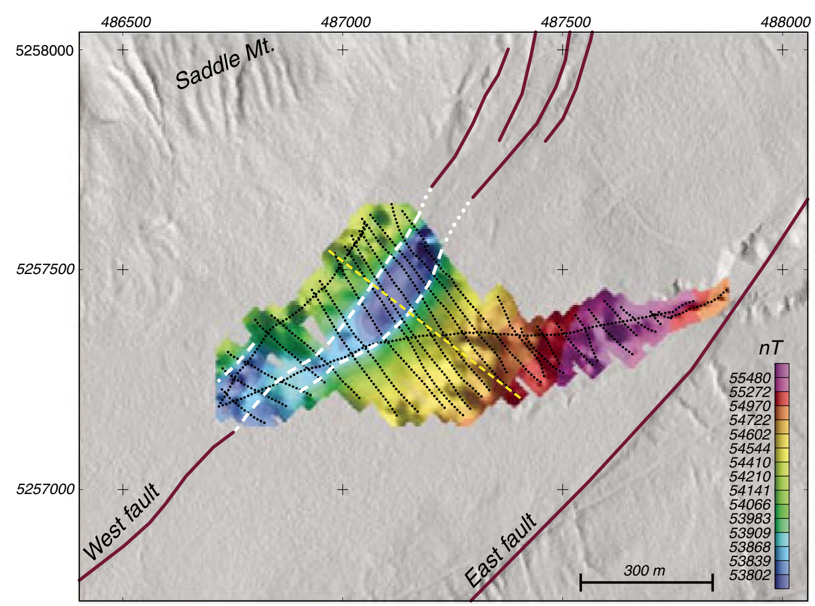


Figure 9. Magnetic anomalies over Price Lake, measured from nonmagnetic canoe. See Figure 2 for map location. Base map is LIDAR (light detection and ranging) image of Figure 2. Black dotted lines show location of canoe transects. Tick marks are Universal Transverse Mercator coordinates in meters. White dashed lines indicate magnetic trough on strike with LIDAR scarps (red lines). Dashed yellow line shows location of cross section shown in Figure 10.

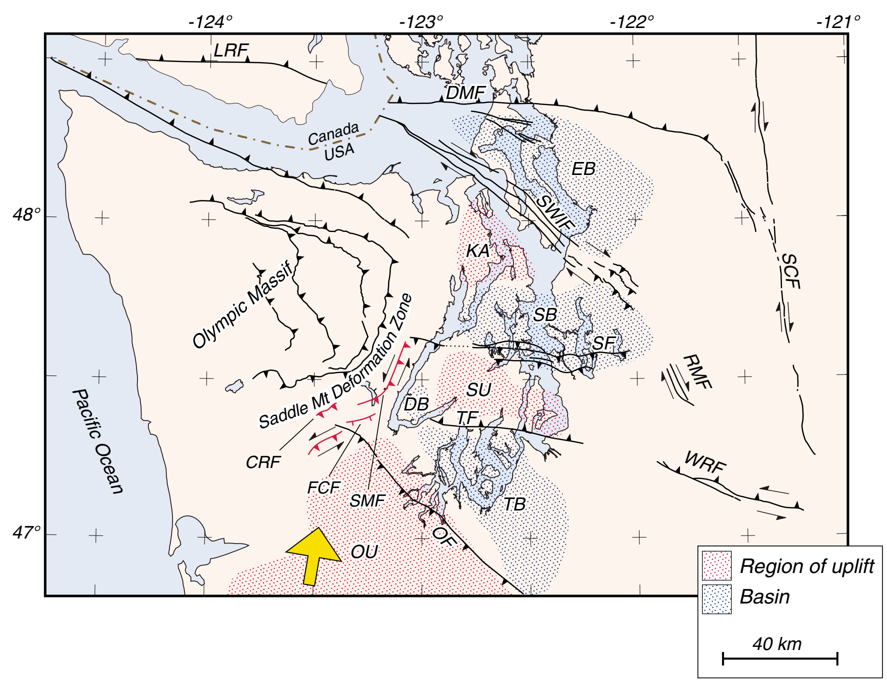


Figure 16. Tectonic setting of the Saddle Mountain fault. Red and blue stipple indicates Puget Sound uplift and sedimentary basins, respectively, as defined by regional gravity anomalies. Red lines are faults of the Saddle Mountain deformation zone. Yellow arrow indicates regional strain direction (McCaffrey et al., 2007). LRF—Leech River fault; RMF—Rattlesnake Mountain fault; WRF—White River fault; SCF—Straight Creek fault; OF—Olympia fault; OU—Olympia uplift; SU—Seattle uplift; KA—Kingston arch. Other labels are explained in Figure 1 caption.

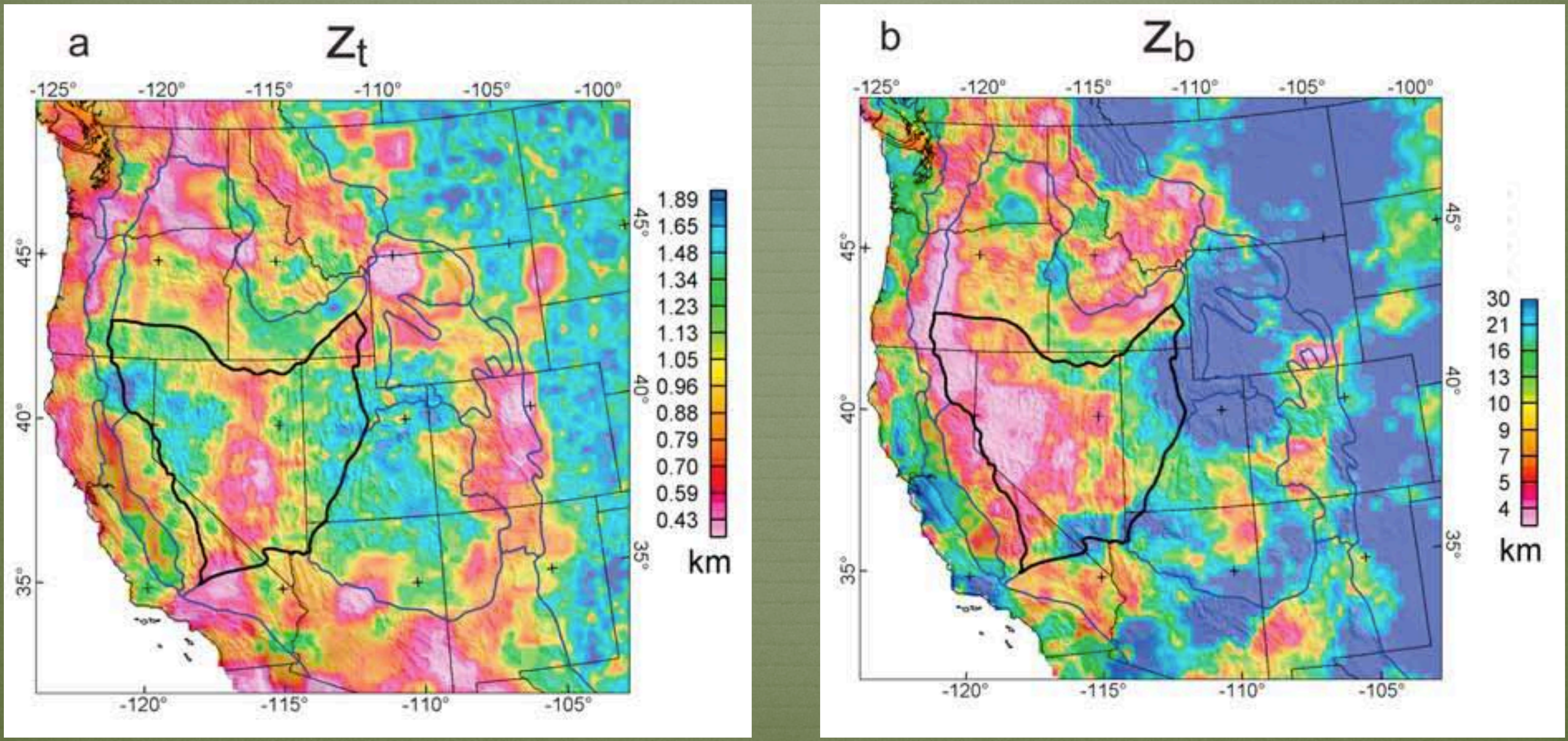
Tectonics & Lithospheric Temperatures

- **Magnetic Bottom / Curie isotherm using fractal magnetization** — ***Bouligand et al. (2009) found an analytical expression for Maus et al. (1997) integral***
  - Spectra are modeled with 3 parameters: Depth-to-Top (Z_t), Thickness (ΔZ), Fractal parameter (β)

$$\Phi_{B1D}(k_H) = C - 2k_H z_t - (\beta - 1)\ln(k_H) + \left[-k_H\Delta z + \ln\left(\frac{\sqrt{\pi}}{\Gamma(1+\frac{\beta}{2})}\left(\frac{\cosh(k_H\Delta z)}{2}\Gamma\left(\frac{1+\beta}{2}\right) - K_{\frac{1+\beta}{2}}(k_H\Delta z)\left(\frac{k_H\Delta z}{2}\right)^{\frac{1+\beta}{2}}\right)\right)\right]$$

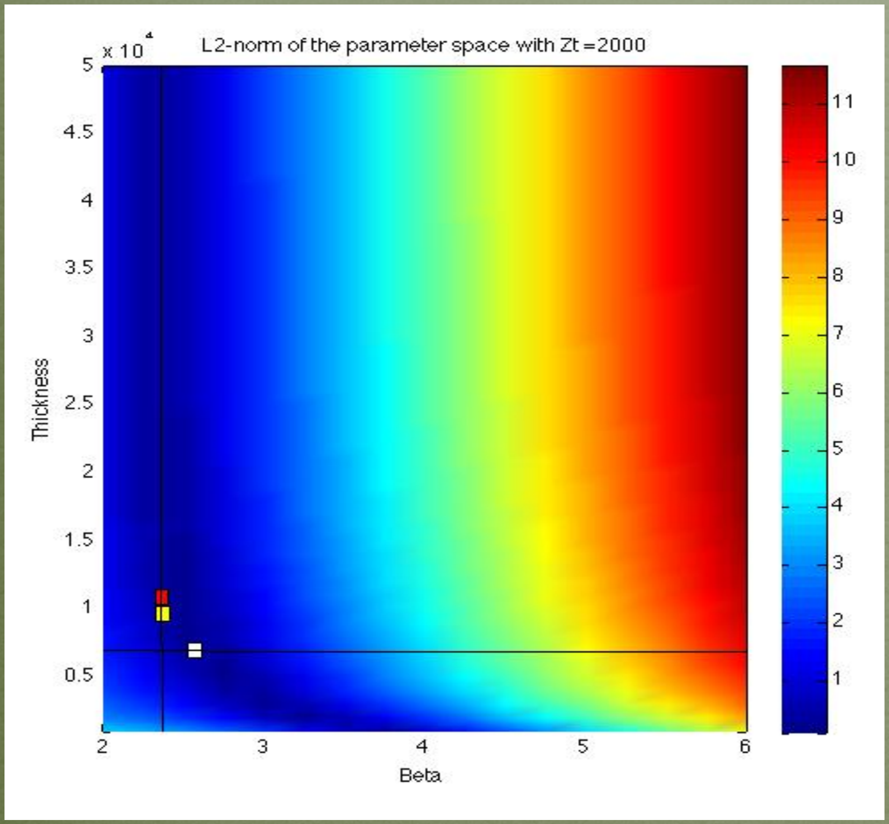
❖ *Bouligand et al. (2009) continued:*

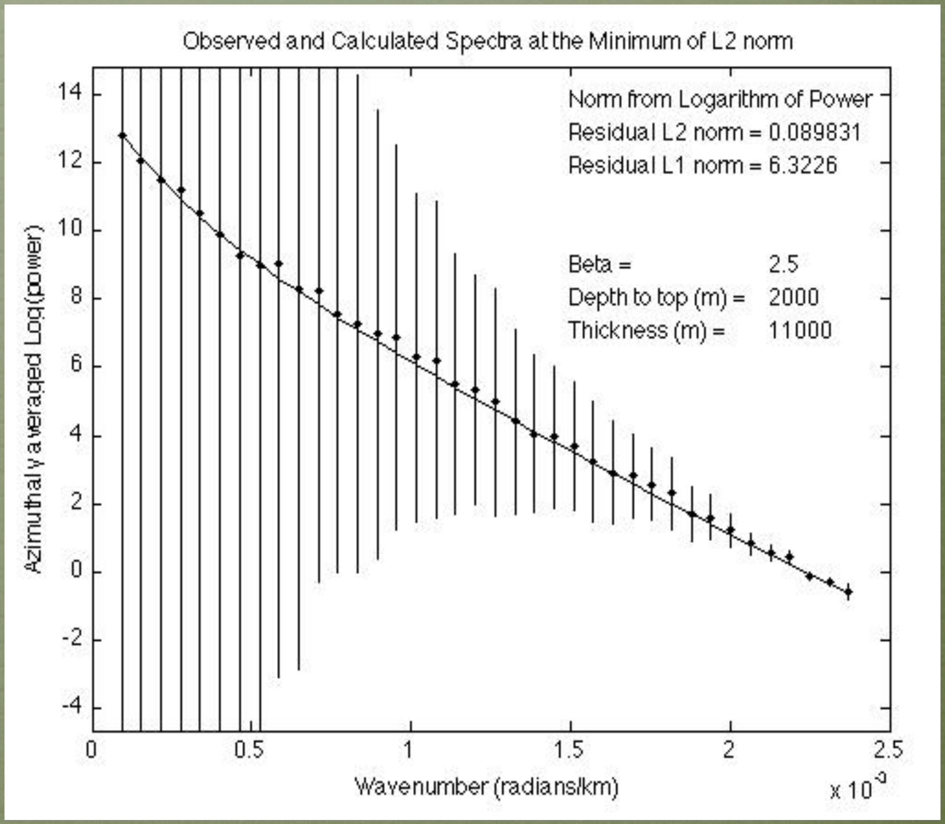
Based on model studies suggested an approach of automated non-linear fit to the spectra, fixing β to 3, and using variable window sizes



Ravat et al. (2011, in revision, Tectonophysics) - an alternative procedure in Egypt and the Red Sea Spectral Depth Study

First, ***derive Depth to Top by iterative forward modeling***, then map the parameter space of β and Thickness





- Residual L1 norm minimum
- Residual L2 norm minimum
- Knee of the minimum of the tradeoff space

Area 2

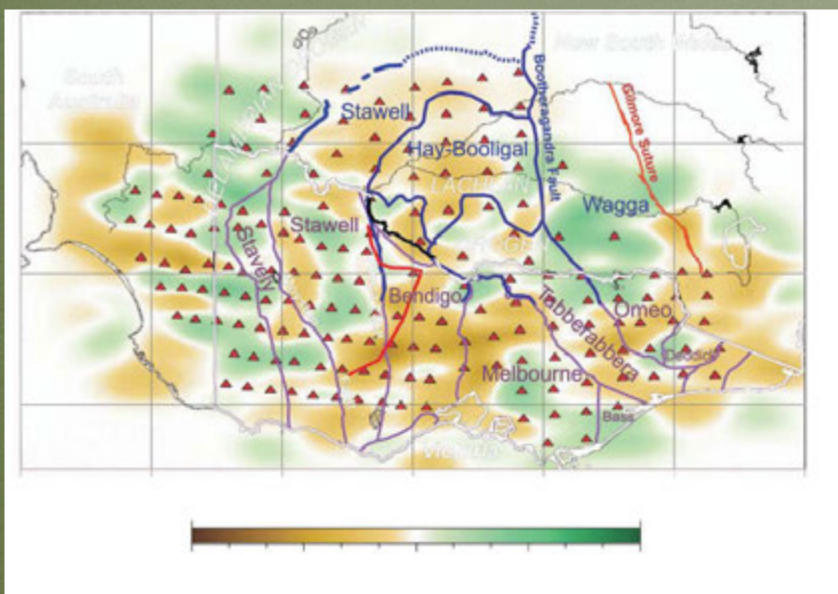
Fractal Magnetization based Depth to Bottom ~ 13 km

Centroid based Depth to Bottom ~ 14.8 km

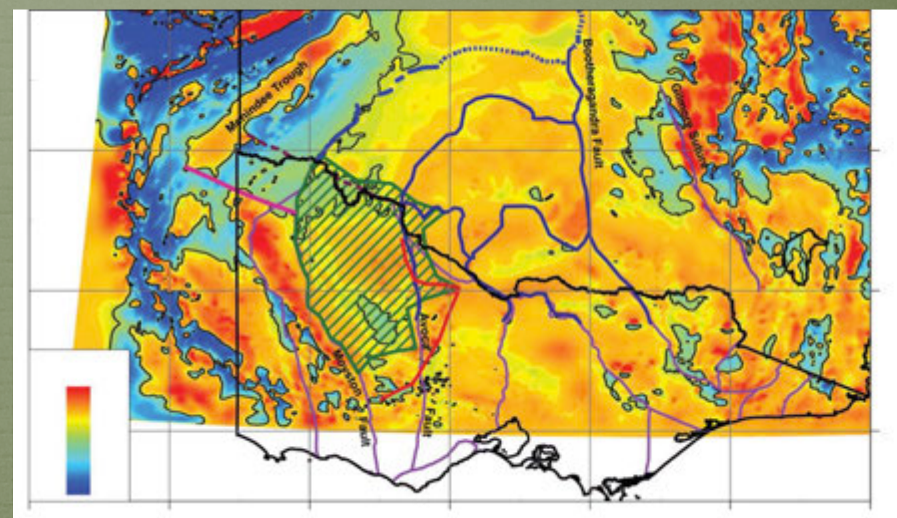
Top to Bottom Lithospheric Structure
Magnetics, Gravity & Seismic Tomography

- Musgrave & Rawlinson (2010) **Linking the upper crust to the upper mantle…SE Australia**, Expl. Geophys.

P-wave velocity anomalies at 150 km



TMI upward continued to 20 km



Purple – geologic; blue – Magn. 1VD
Dashed blue – Magn. Tilt, Red – division strong magn granite to W & weak to E

Rock Properties and Crustal Scale Interpretation of Magnetic Anomalies

Rock Properties and Crustal Scale Interpretation of Magnetic Anomalies

- Suzanne McEnroe and co-workers have published 22 reviewed articles related to relevance of nm-size lamellar hemo-ilmenite remanent magnetization to crustal anomalies and also the mineralogy of lamellar hemo-ilmenite magnetism

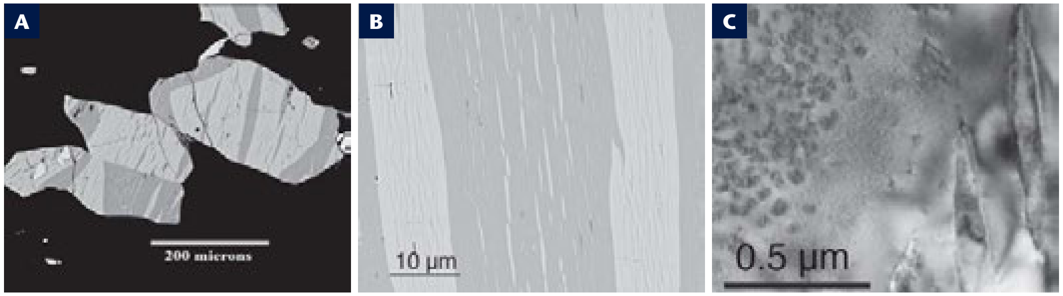
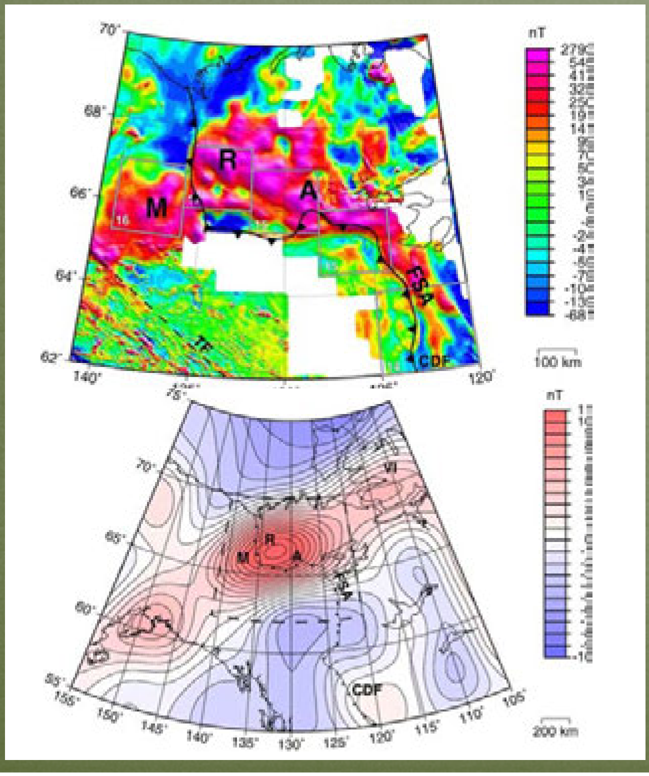


FIGURE 5 (**A**) Electron backscatter image of an intergrowth of exsolved hematite and ilmenite, and minor magnetite, from pyroxene granulite, SW Sweden. (**B**) Electron backscatter image of hemo-ilmenite; hematite lamellae are white and ilmenite gray. (**C**) High-resolution TEM image of hemo-ilmenite, COURTESY OF FALKO LANGENHORST

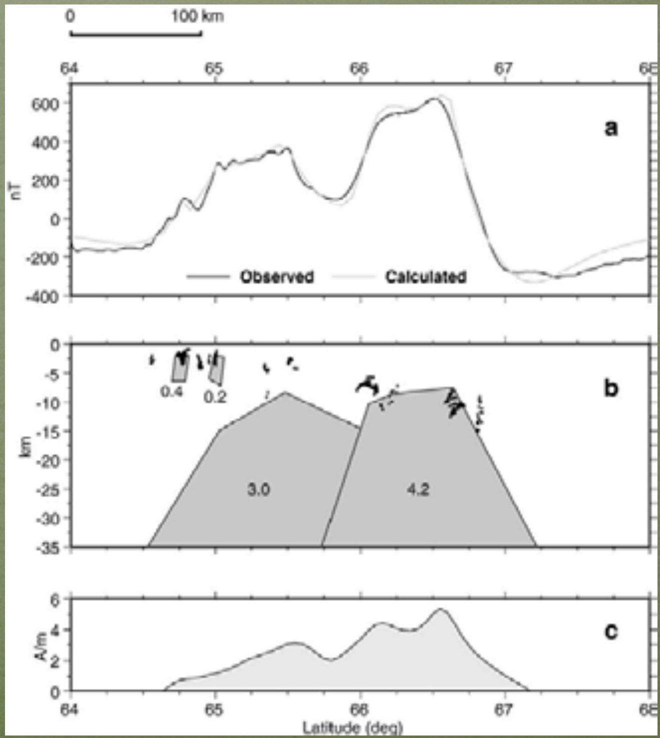
Rock Properties and Crustal Scale Interpretation of Magnetic Anomalies

- Pilkington and Saltus (2009) - McKenzie River Early Proterozoic Magmatic Arc Anomaly
  - Basement depth constrained from seismic data and Euler solutions
  - Magnetization: average 2.5A/m (from 15 to 35 km depth)



Aeromagnetic

CHAMP Satellite - MF1



Rock Properties and Crustal Scale Interpretation of Magnetic Anomalies

- *Rajagopalan, Schmidt, and Clark* (2010) Magnetic overprinting of the Brachina Formation/Ulupa Siltstone, Southern Adelaide Foldbelt, prior to Delamerian deformation, *Aus. J. Earth Sci.*

- *Schmidt and Clark* (2011) Magnetic characteristics of the Hiltaba Suite Granitoids and Volcanics: Late Devonian overprinting and related thermal history of the Gawler Craton, *Aus. J. Earth Sci.*

- *Greenfield et al. (2011)* The Mount Wright Arc: A Cambrian subduction system developed on the continental margin of East Gondwana, Koonenberry Belt, eastern Australia, *Gondwana Research.*

Rock Properties and Crustal Scale Interpretation of Magnetic Anomalies

- Dunlop et al. (2010) **Magnetic properties of rocks of the Kapuskasing uplift (Ontario, Canada) and origin of long-wavelength magnetic anomalies**, Geophys. J. Int.
  - 210 samples of anorthosite (NRM 0.001-0.3 A/m), tonalite (bimodal: strong ones NRM & IM 0.1–5 A/m), mafic gneiss (NRM 0.01-2 A/m and IM 0.01-0.6 A/m – resistant to thermal & AF demagnetization)
  - Thermoviscous magnetization acquired during Brunhes chron (since the past geomagnetic reversal)
  - Remanence - a larger role for mid-crustal sources where single-domain grains are well below their blocking temperatures

Rock Properties and Crustal Scale Interpretation of Magnetic Anomalies

- **"No Missing Sources of Lithospheric Magnetization – Not lost; looked in the wrong places"** ***Ravat (2011, this conference)*** – Previous controversy: Strong magnetization inferred from satellite data not seen in surface samples in some uplifted lower crustal cross-sections (Williams et al., 1985 & Shive et al., 1992)
- Detailed spectral magnetic depth determination studies of Pikwitonei, Kapuskasing, Minto Block (Can); SW Lofoten (Norway); Egypt-Red Sea (Ravat et al., 2011); Arunta Block (Aus)
- Pikwitonei and Kapuskasing – Not the locations of the strong anomalies - Max Magn 3-4 A/m - within the bounds of some of the surface rocks
- Lower crust reasonable high magnetization – **No sources of magnetic anomalies are missing!**

Rock Properties and Crustal Scale Interpretation of Magnetic Anomalies

- **Ravat and co-workers** ***Other major conclusions***
  - "The Moho as a magnetic boundary" Wasilewski et al. (1979) - Spectral magnetic bottoms determined in Canada, Egypt, and the Red Sea coincide with the Moho.

    The **first magnetic anomaly based confirmation of the magnetic petrologic inference (Ravat et al., 2011, Tectonophysics, in revision)**

  - SW Lofoten and the Red Sea – rift margin and oceanic setting - uppermost mantle could be serpentinized in some regions

What new have we learned in the lithospheric studies in the last couple of years?

- Rock Magnetism
  - Mineralogy of lamellar hemo-ilmenite magnetism and further relevance of hemo-ilmenite magnetism to intense remanent crustal magnetic features on Earth and Mars
- Crustal Scale Studies
  - The first magnetic anomaly based evidence for "The Moho as a magnetic boundary" concept (except where the mantle may be serpentinized)
  - No "missing" magnetization in the areas of uplifted continental lower crustal cross-sections

What new science could we do based on developments in the last couple of years?

- From High Resolution Datasets
  - Three dimensional near surface earth structure
    - Australian AWAGS-leveled 80 m grid is roughly similar in resolution to satellite-borne multispectral and InSAR-type pixels and can now be integrated for extending depth interpretation of satellite imagery and also LIDAR data
    - Blakely and co-workers (2009, 2010, 2011) Integration and detailed analyses of geology, paleoseismic, GPS, LIDAR, etc. to the high resolution magnetic surveys will lead to better earthquake hazard evaluation