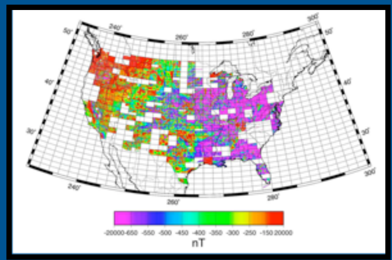
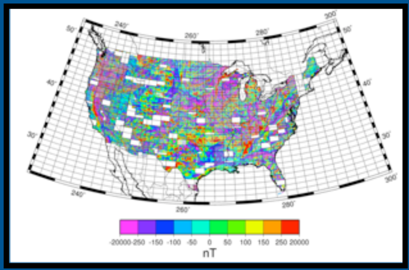
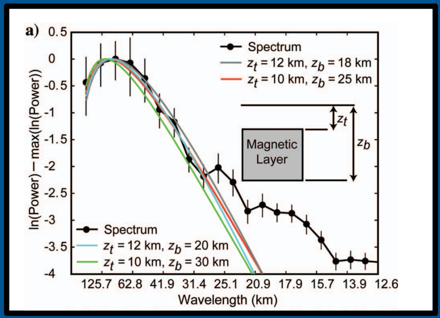
From Full Spectrum Continent-scale Magnetic Anomaly Mapping





To

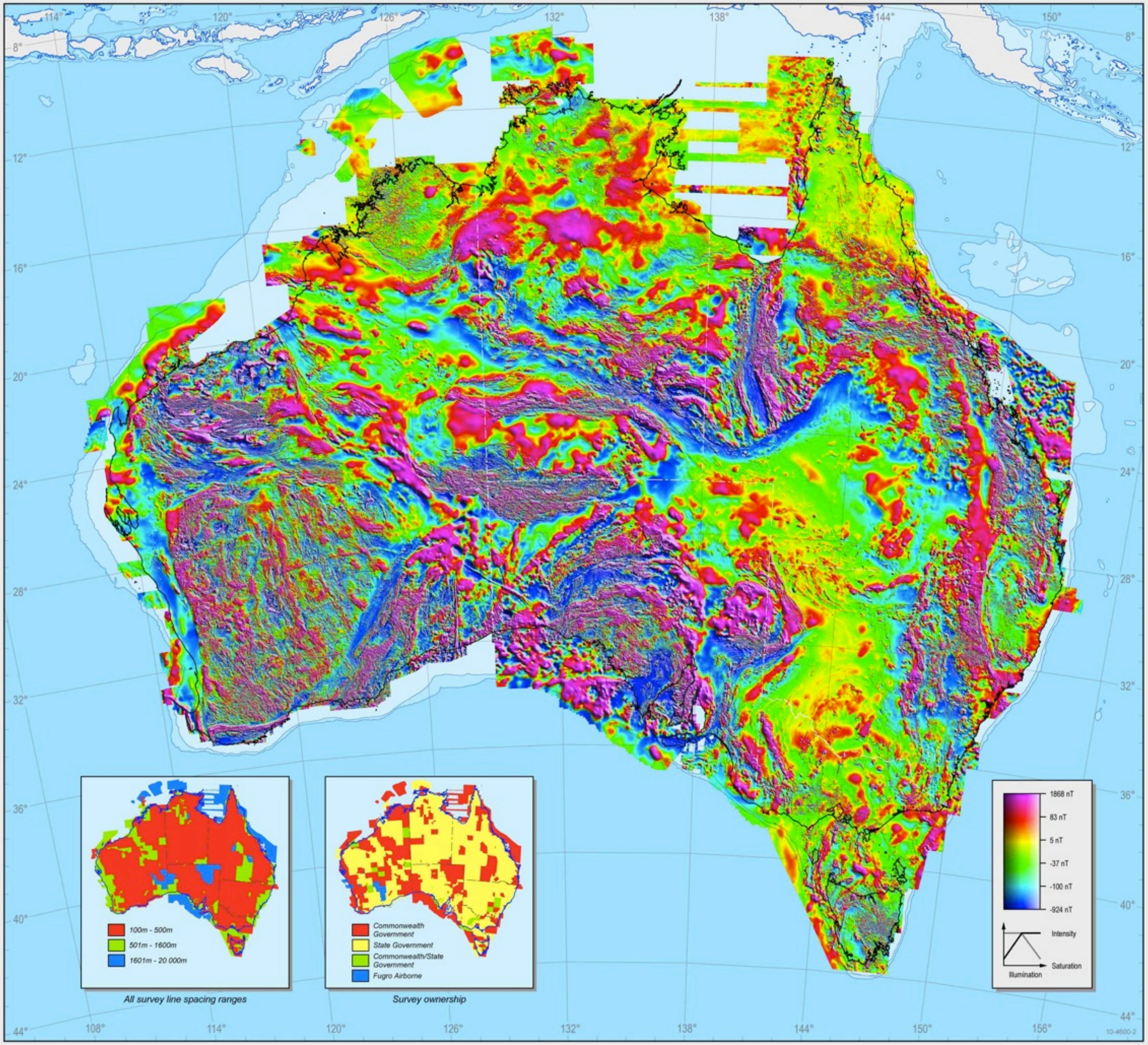
Curie Depth Determinations



D. Ravat

University of Kentucky

Magnetic Anomaly Map of Australia, 5th edition



Australian Government
Geoscience Australia

MAGNETIC MAP OF AUSTRALIA

SCALE 1:15 000 000

0 250 500 750 1000 km

LAMBERT CONFORMAL CONIC PROJECTION
Central Meridian: 134°E Standard Parallels: 18°S, 36°S
Geocentric Datum of Australia

This image was compiled from Total Magnetic Intensity survey data held in the National Airborne Geophysical Database by Geoscience Australia. The image is a composite of data acquired from surveys flown by Geoscience Australia, and surveys flown under contract to Geoscience Australia, the State and Territory geological surveys in either separate or joint projects and the private sector. The source data are used with their permission. The data from these surveys were acquired at a range of line spacings, flying heights, and measurement accuracies.

We thank Fugro Airborne Surveys Pty Ltd for allowing the inclusion of some proprietary data.

Compiled by the Continental Geophysics Project, Geoscience Australia.
Image enhancement: P.R. Milligan.
Index maps: L.M. Richardson.
Cartography: S. Mezzomo.

It is recommended that this map be referred to as: Milligan, P.R., Franklin, R., Minty, B.R.S., Richardson, L.M. and Percival, P.J., 2010. Magnetic Anomaly Map of Australia (Fifth Edition), 1:15 000 000 scale, Geoscience Australia, Canberra.

Composite TMI grid data at 80 m cell sizes are available for free download via the internet by using Geoscience Portal to access the Geophysical Archive Data Delivery System (GADDS) at: http://www.geoscience.gov.au/gadds

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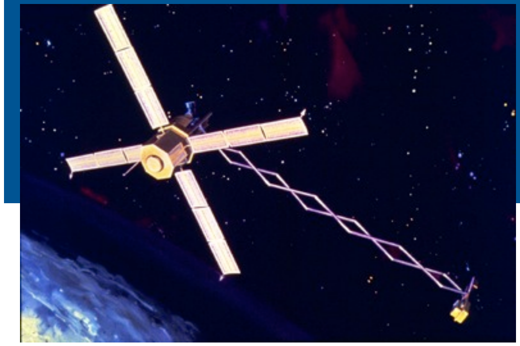
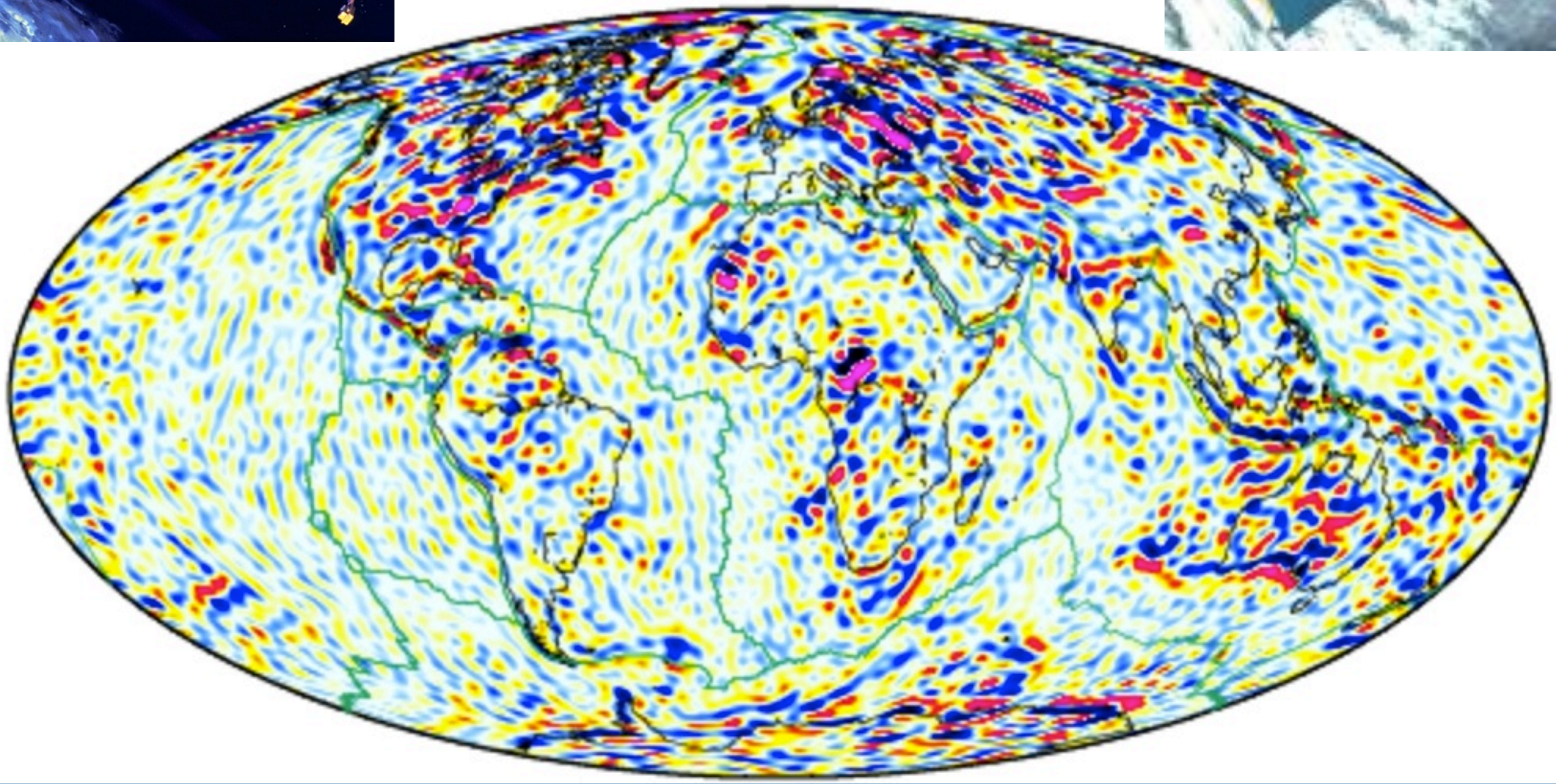
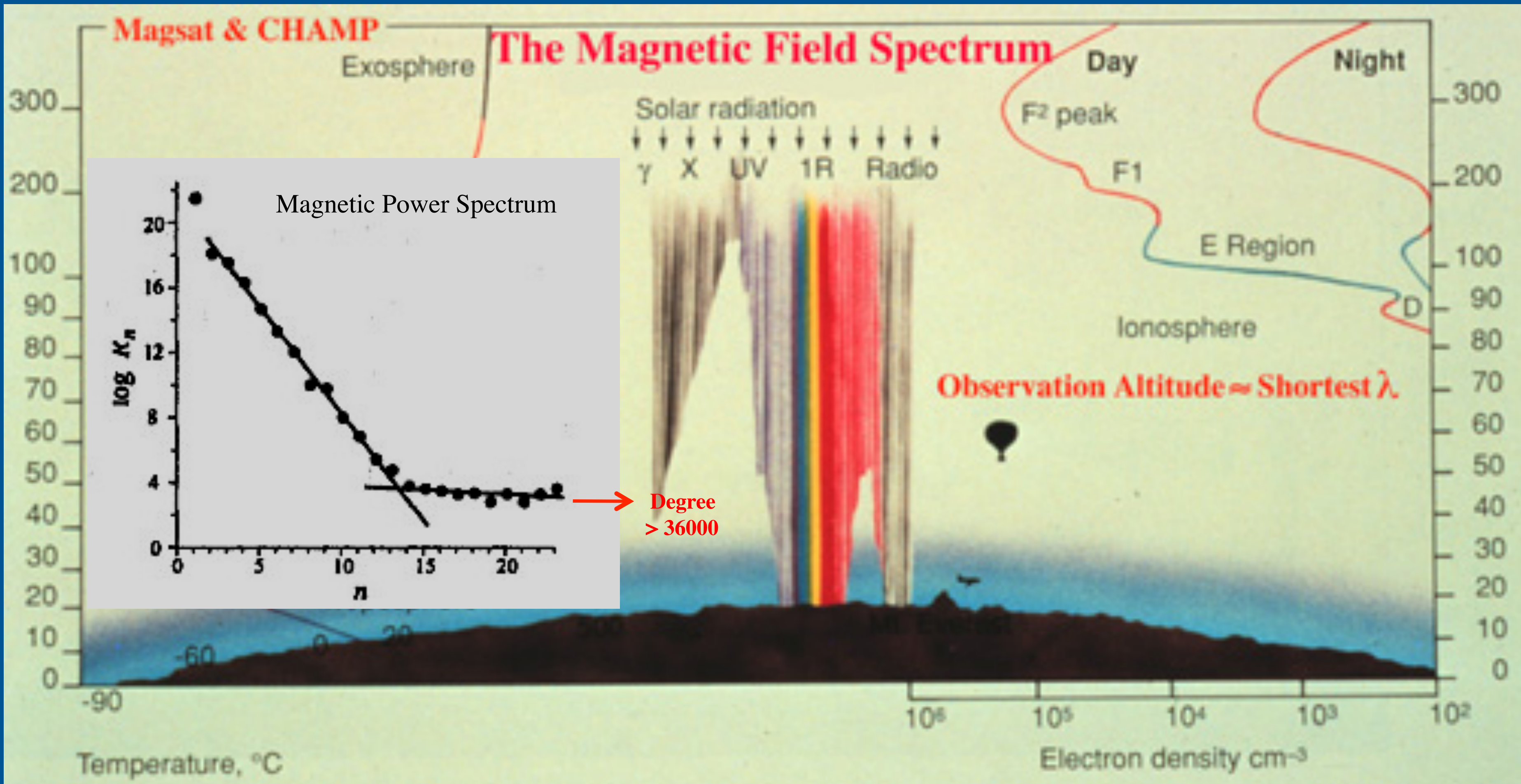
Cnr Hindmarsh Dr and Jerrabomberra Ave, Symonston, ACT
GPO Box 378, Canberra, ACT 2601
Phone (02) 6249 9966 Facsimile (02) 6249 9960
Email: sales@ga.gov.au

Long-wavelength Magnetic Anomaly Field from CHAMP Satellite

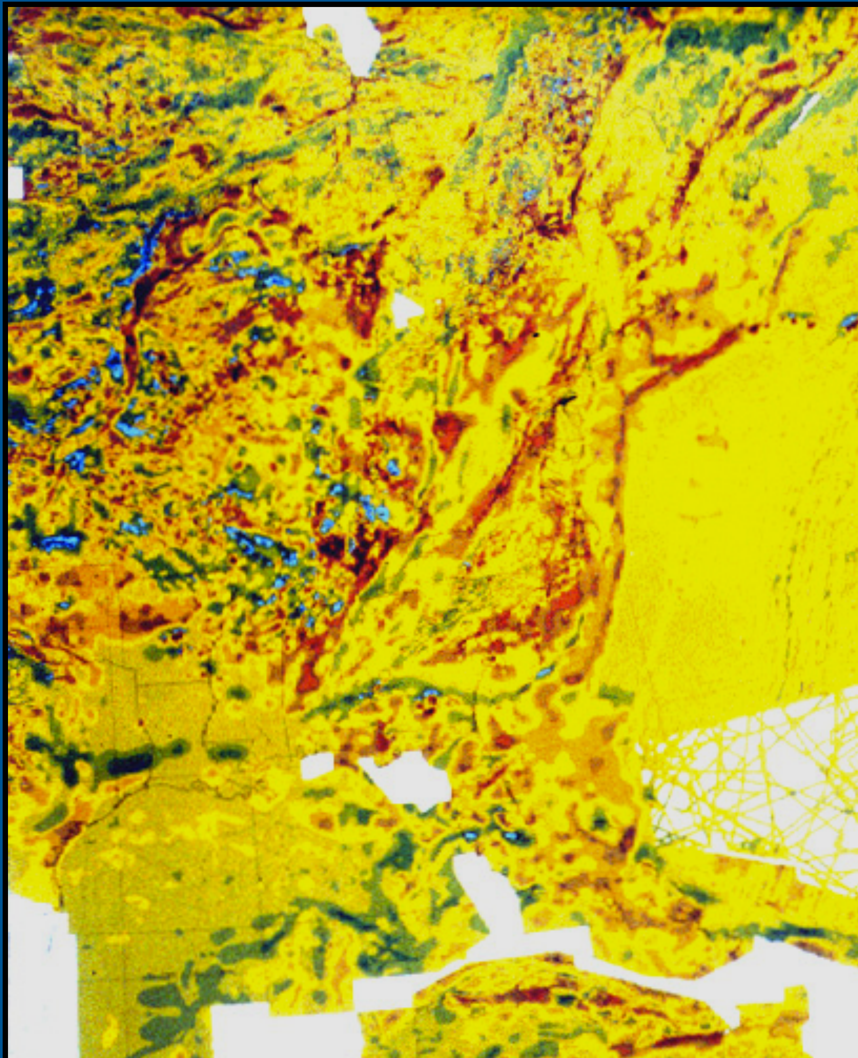


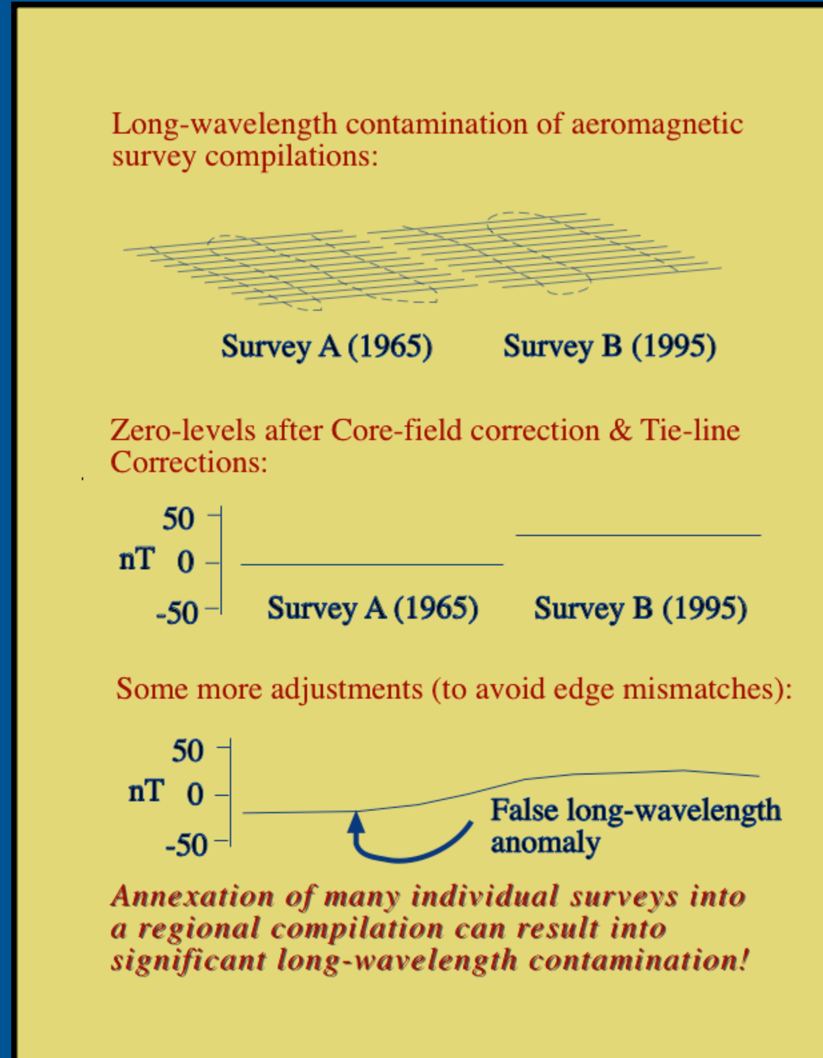




- **Advantages of Satellite-Altitude:** global & uniform coverage; sensitivity to **deeper magnetic sources**
- **Limitations of Satellite-Altitude:** only long-wavelength anomalies (~ 350 km to ~ 3000 km)

  ∴ geologic interpretation less direct; S/N



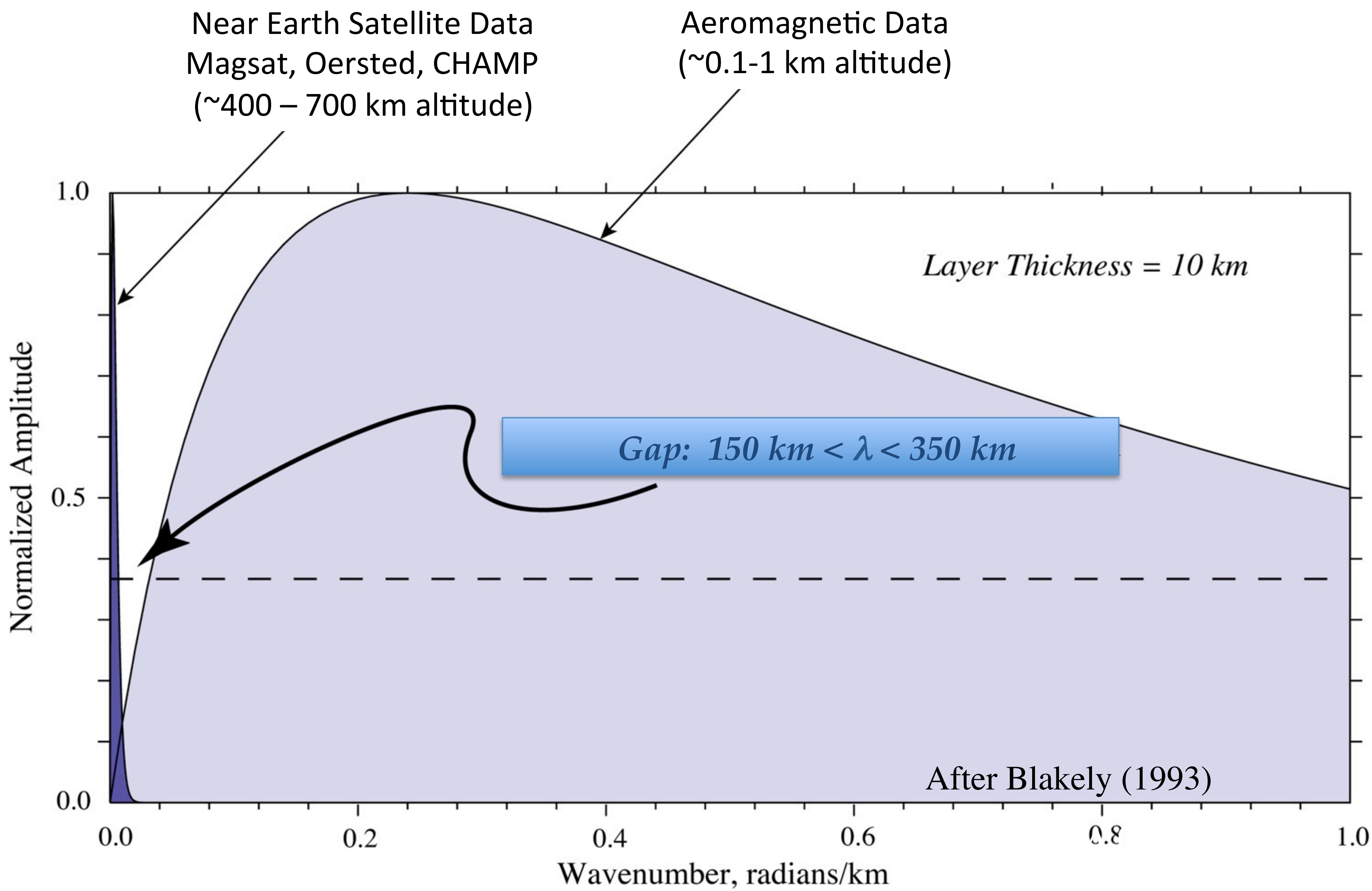


Opposite problem in aeromagnetic data

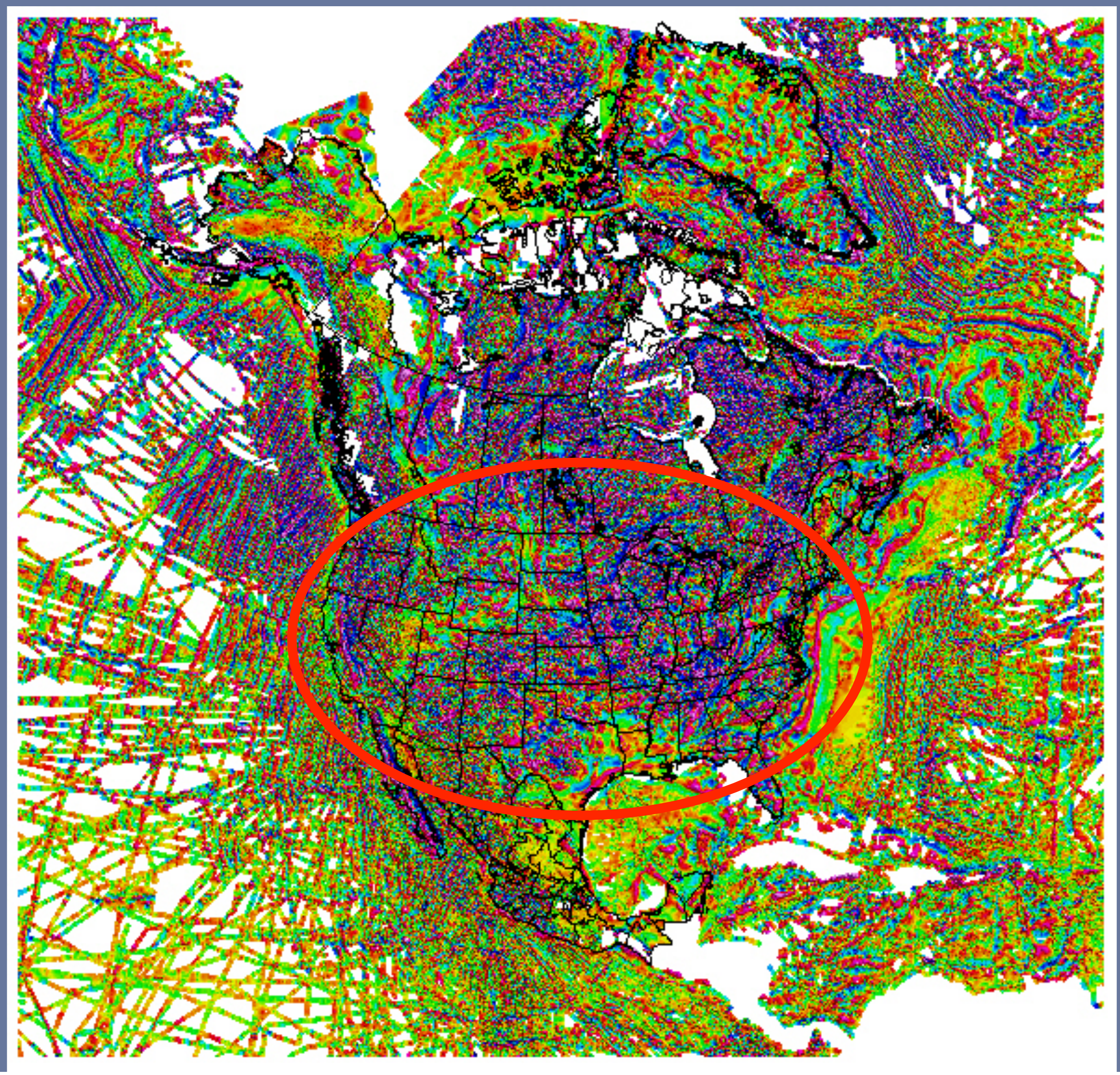
Example: Eastern US

- **Inaccurate IGRFs**
- **Mismatches at the edges of separately processed data**
- **Wavelengths < 200 km ??**

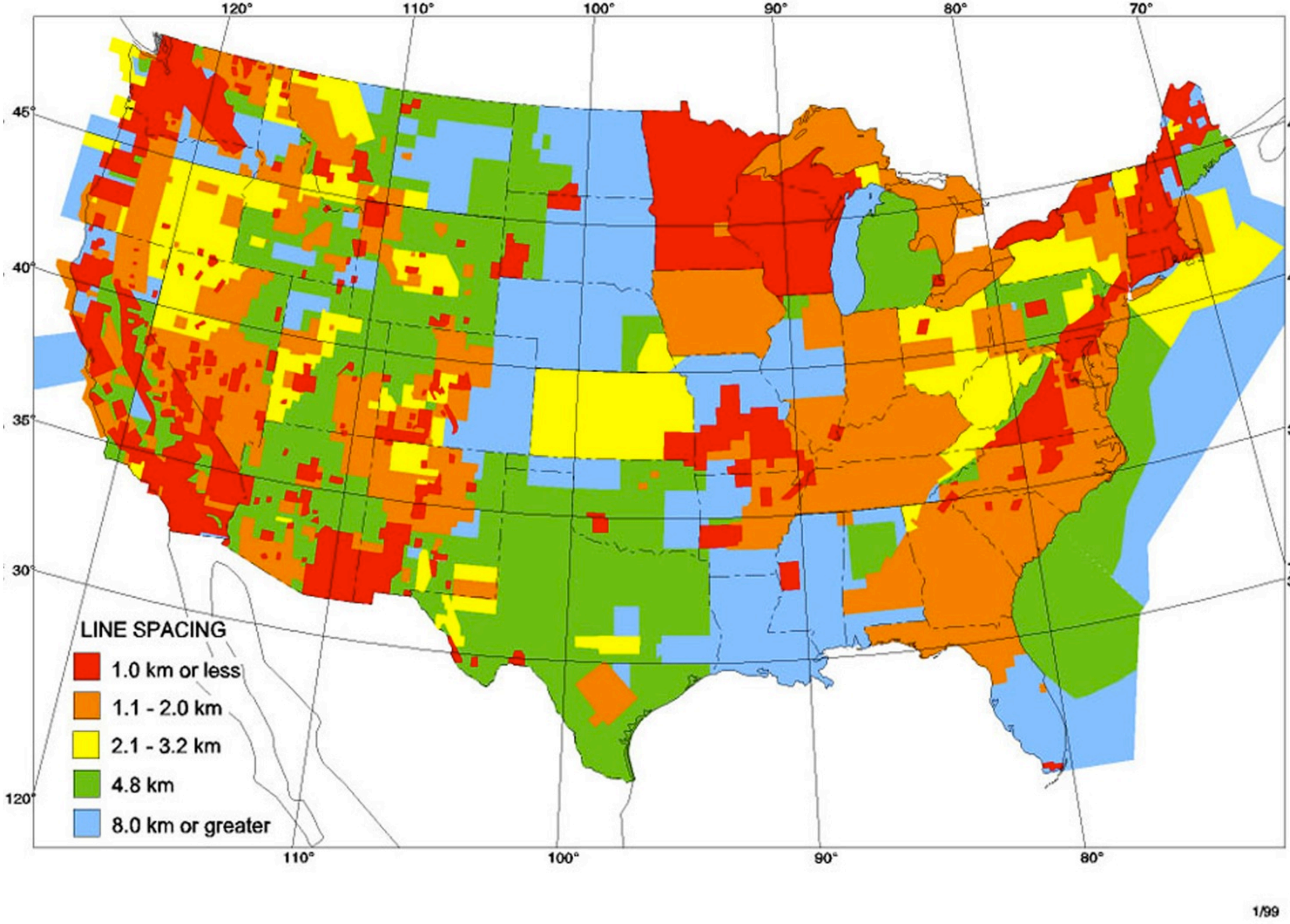
The "proverbial gap" in the spectral coverage of magnetic anomaly data



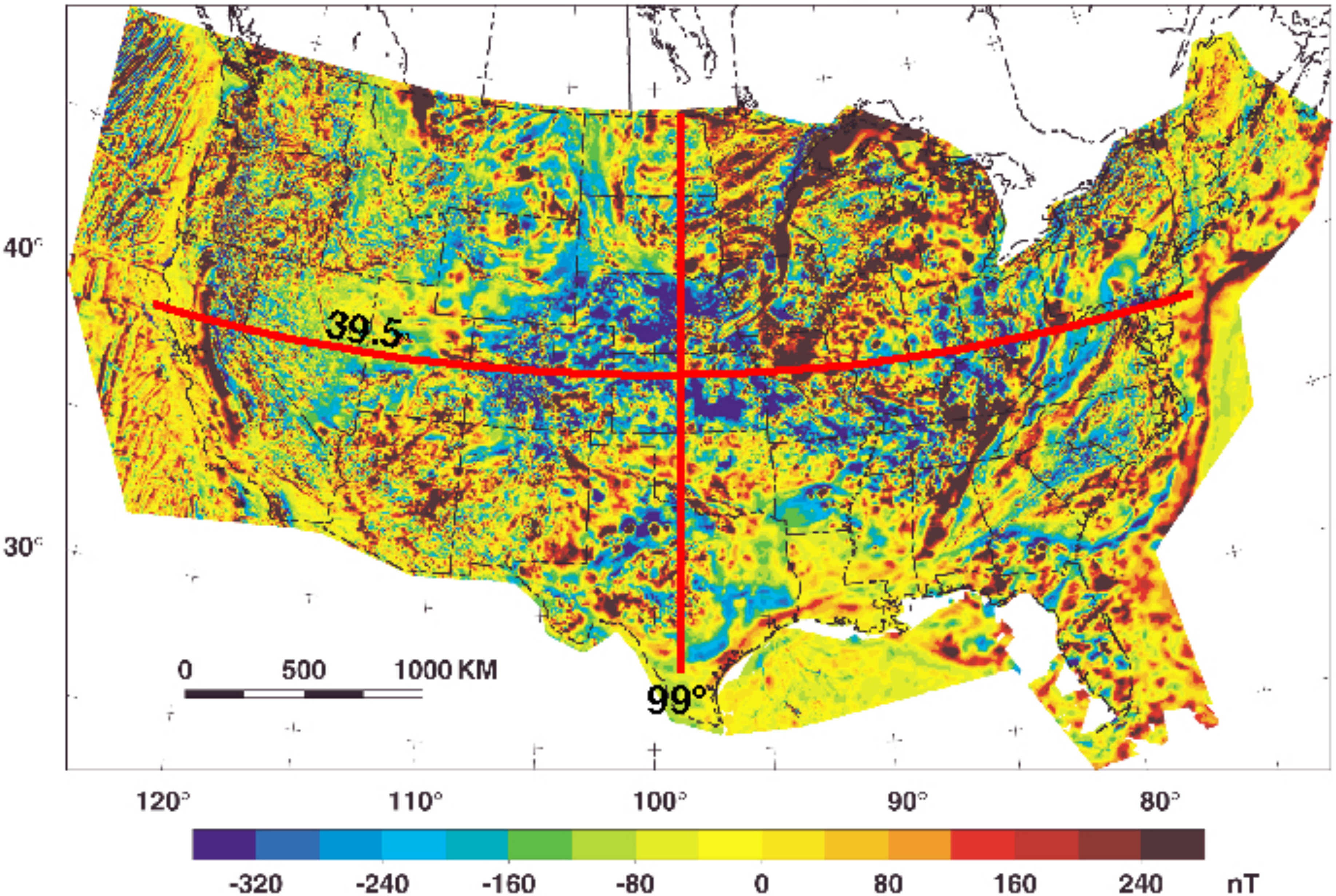
Long-wavelength Problems in the U.S. portion of the North American Magnetic Anomaly Map (c. 2002)

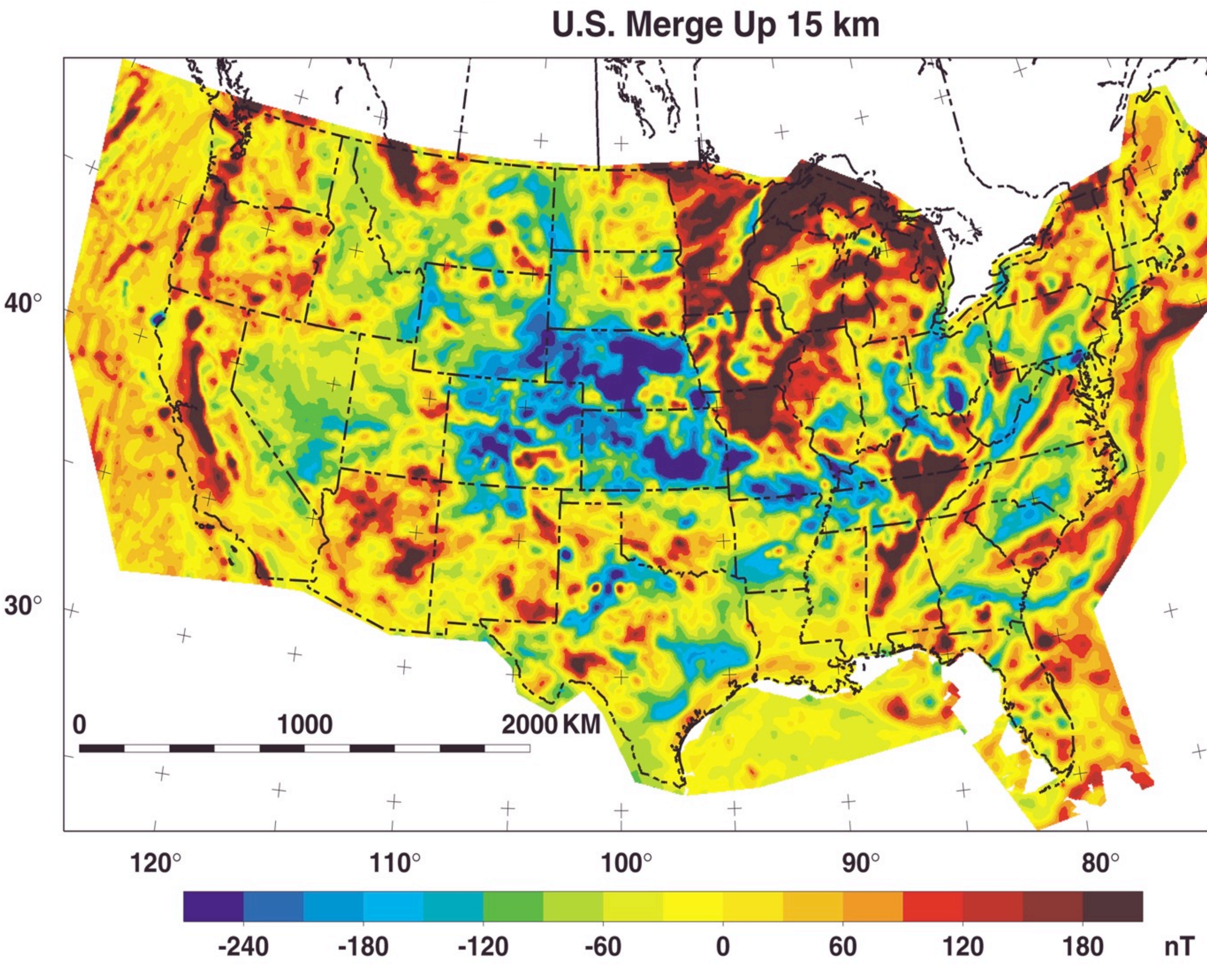


AEROMAGNETIC COVERAGE



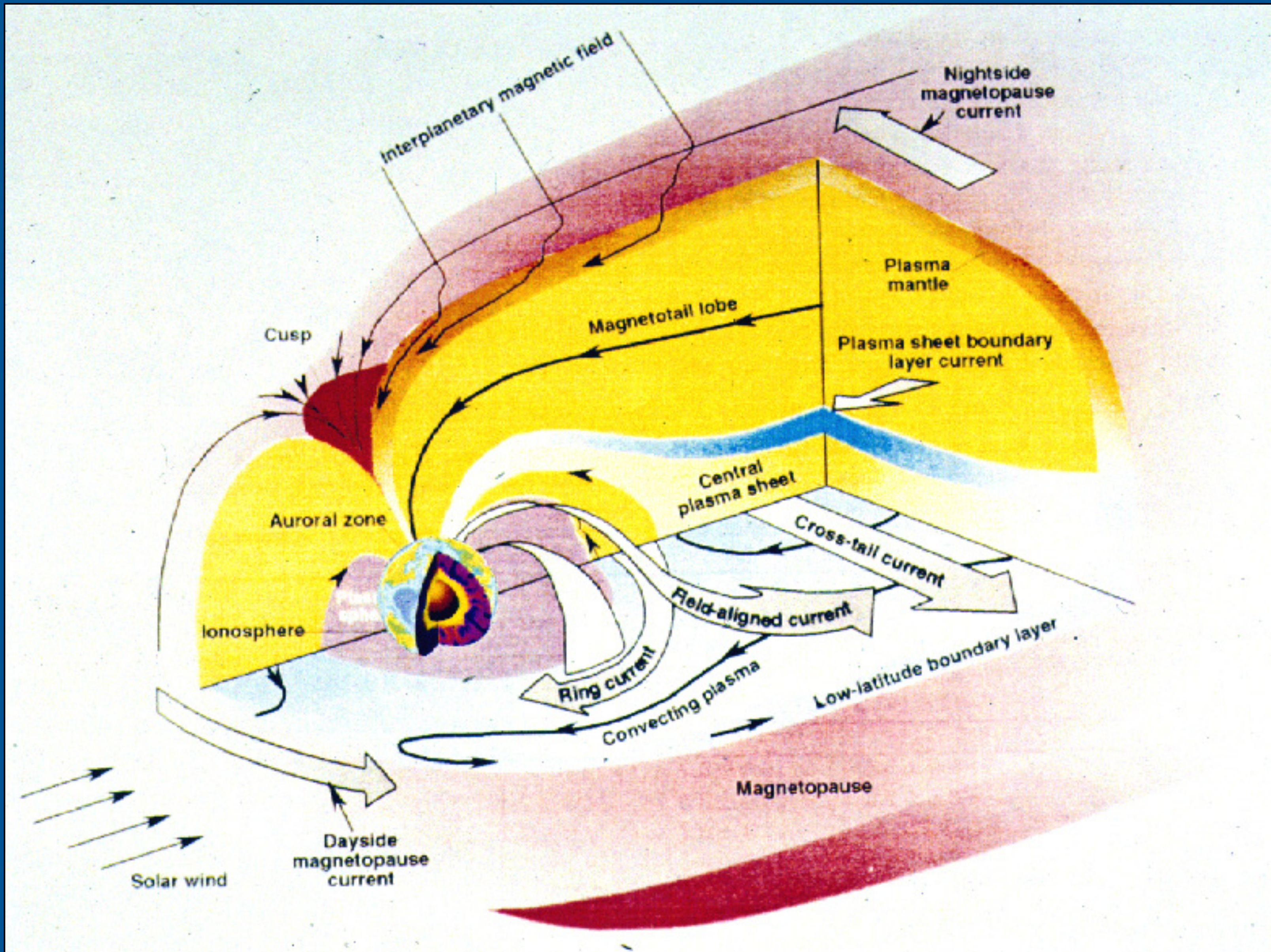
Digital U.S. Merge (2002)





U.S. Merge Up 15 km
40°
30°
0
1000
2000 KM
120°
110°
100°
90°
80°
-240
-180
-120
-60
0
60
120
180
nT

Earth's Magnetosphere: Complex magnetic field superpositions



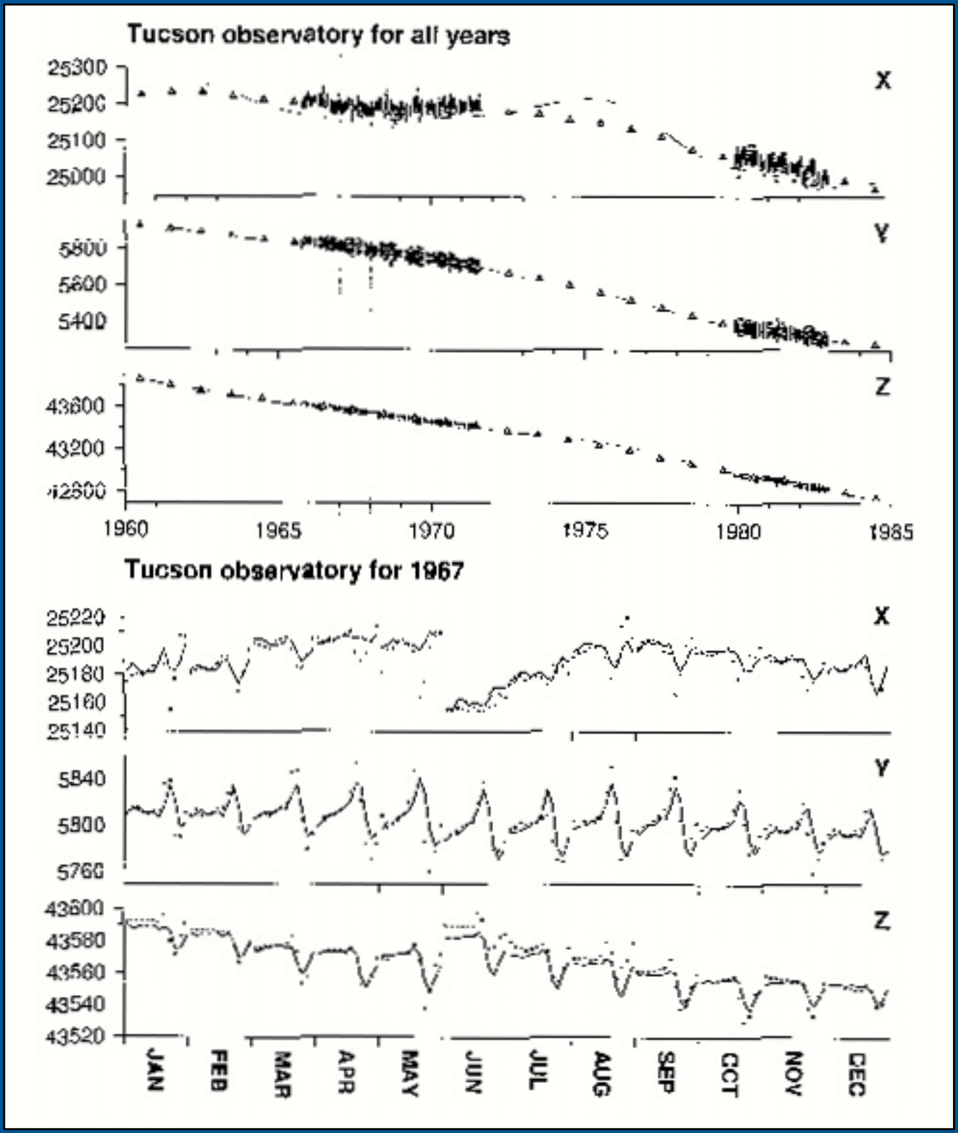
CM - The Comprehensive Model of the near-Earth Magnetic Field

Sabaka, Olsen, & Langel (2002+)

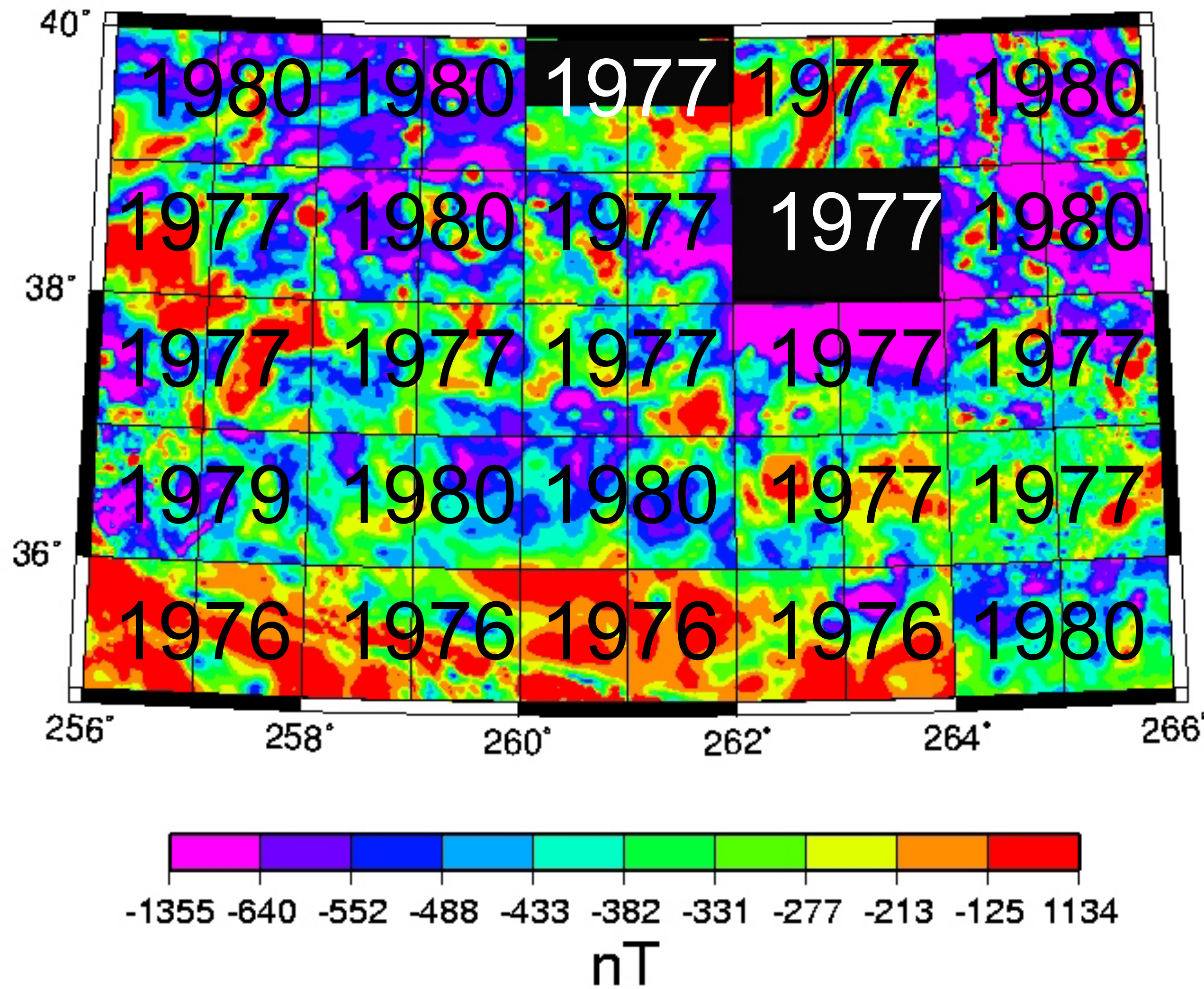
- ***Simultaneous modeling of core field, crustal field, and prominent quiet-time ionospheric & magnetospheric fields*** using worldwide observatory hourly data and POGO, Magsat, Ørsted, & CHAMP satellites
- Improved modeling of external fields necessary to isolate the most reliable lithospheric anomaly signal

- **Continuous from 1960 to ~2010 (?)**

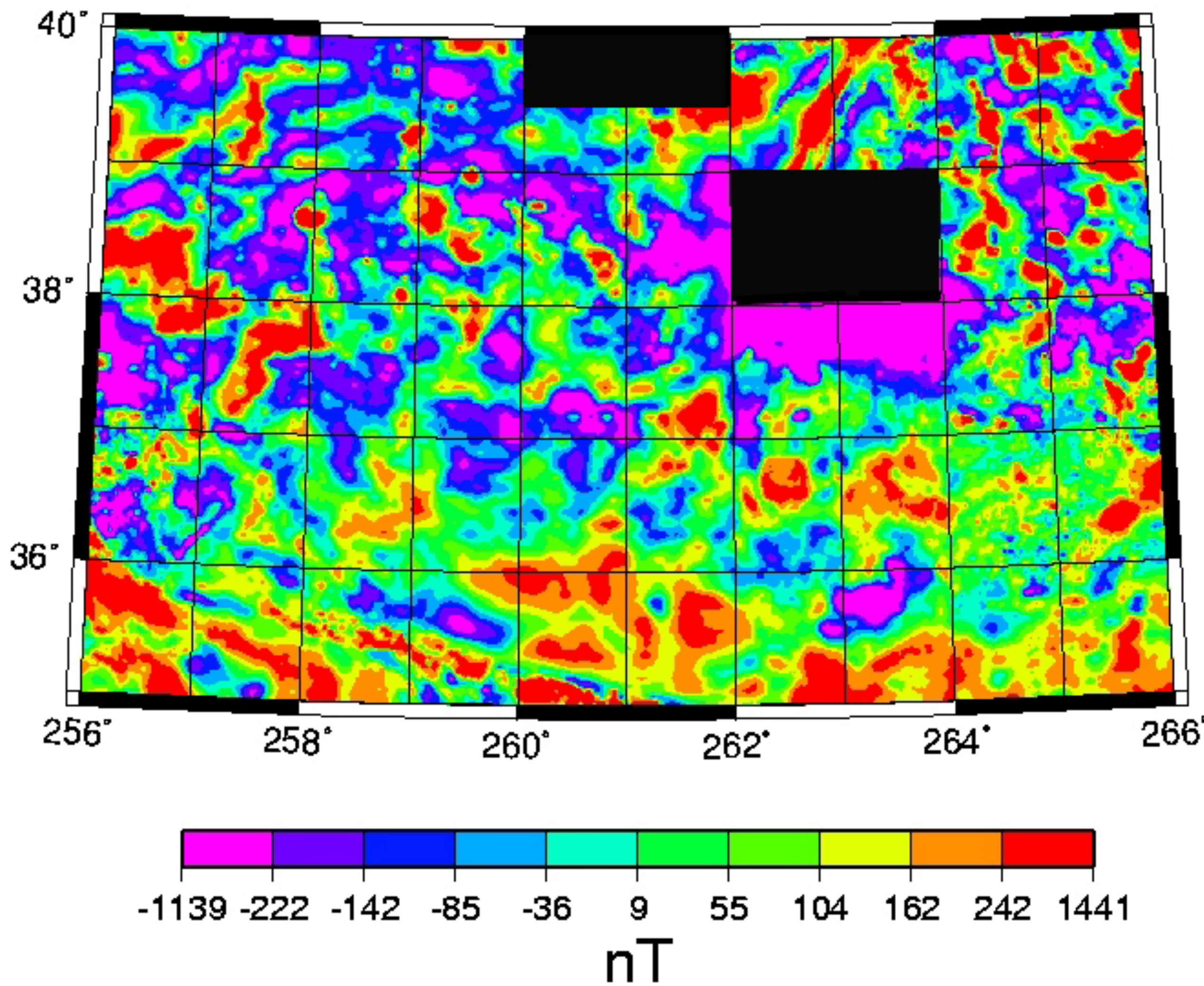
- ***CM can be used in place of IGRF for retaining correct baselevels***



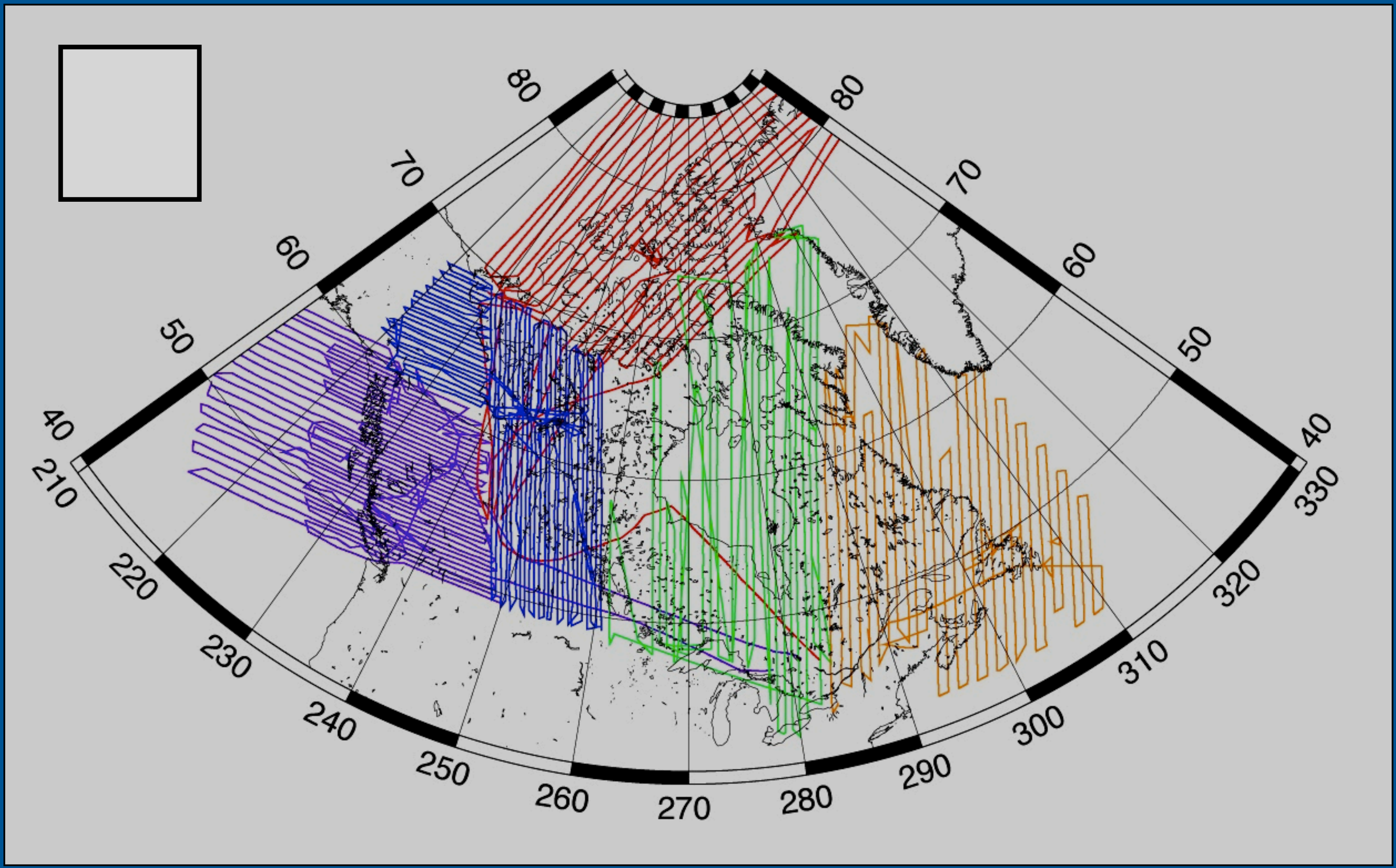
NURE Anomalies using IGRF



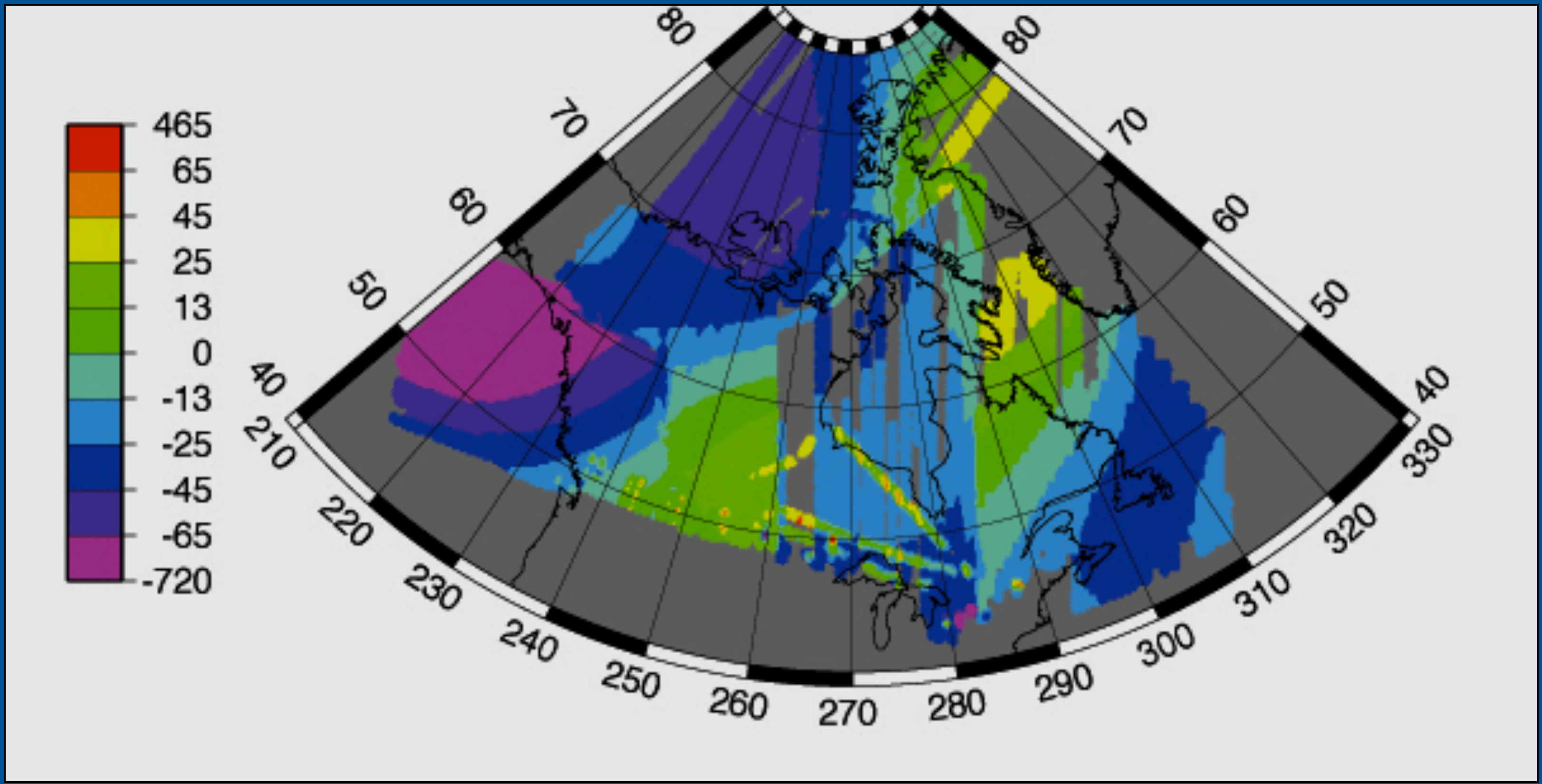
NURE Anomalies using CM



Earth Physics Branch (EPB) Long-Profile Surveys (1969-1976)

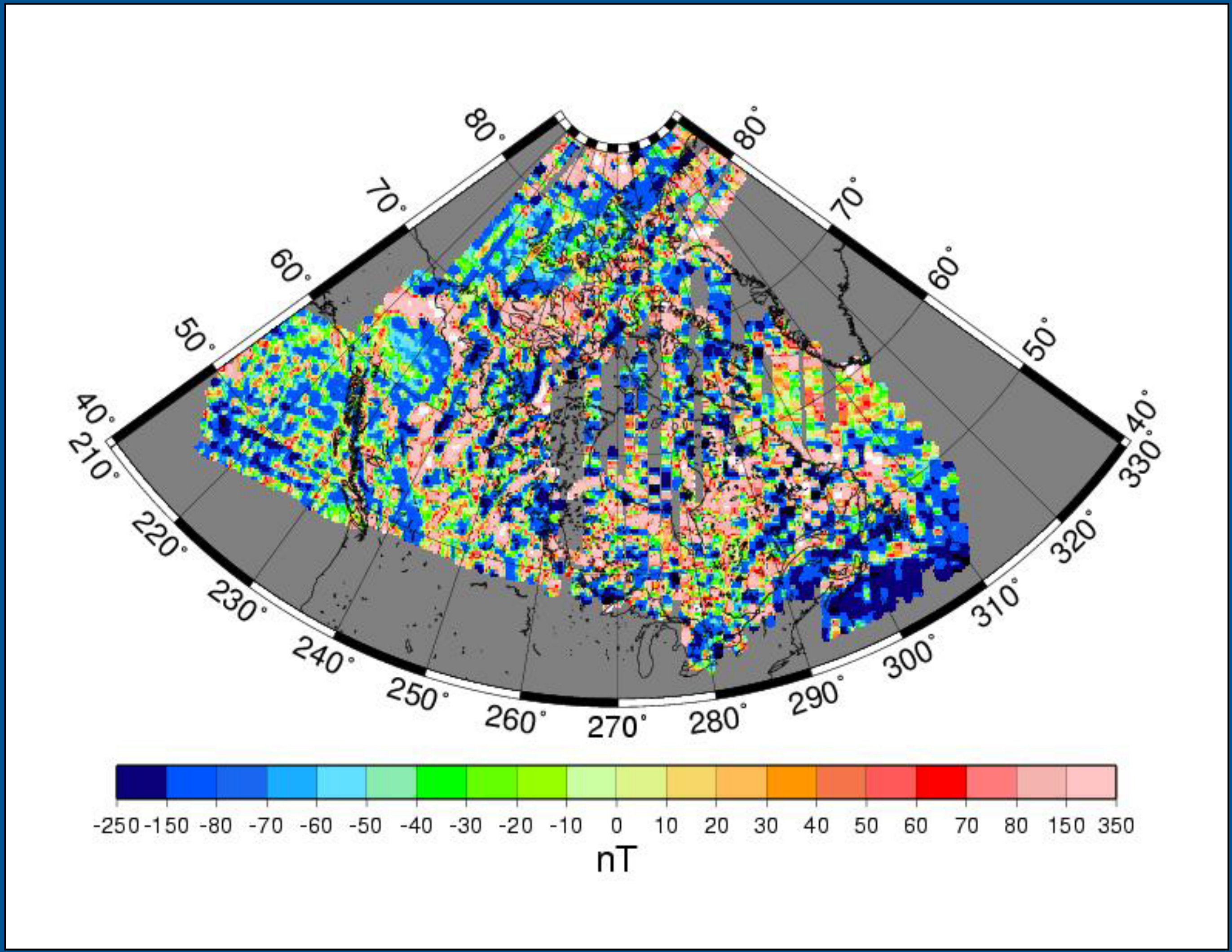


The difference between the CM main field (deg. 13) and the DGRF main fields (deg. 10) for the EPB surveys



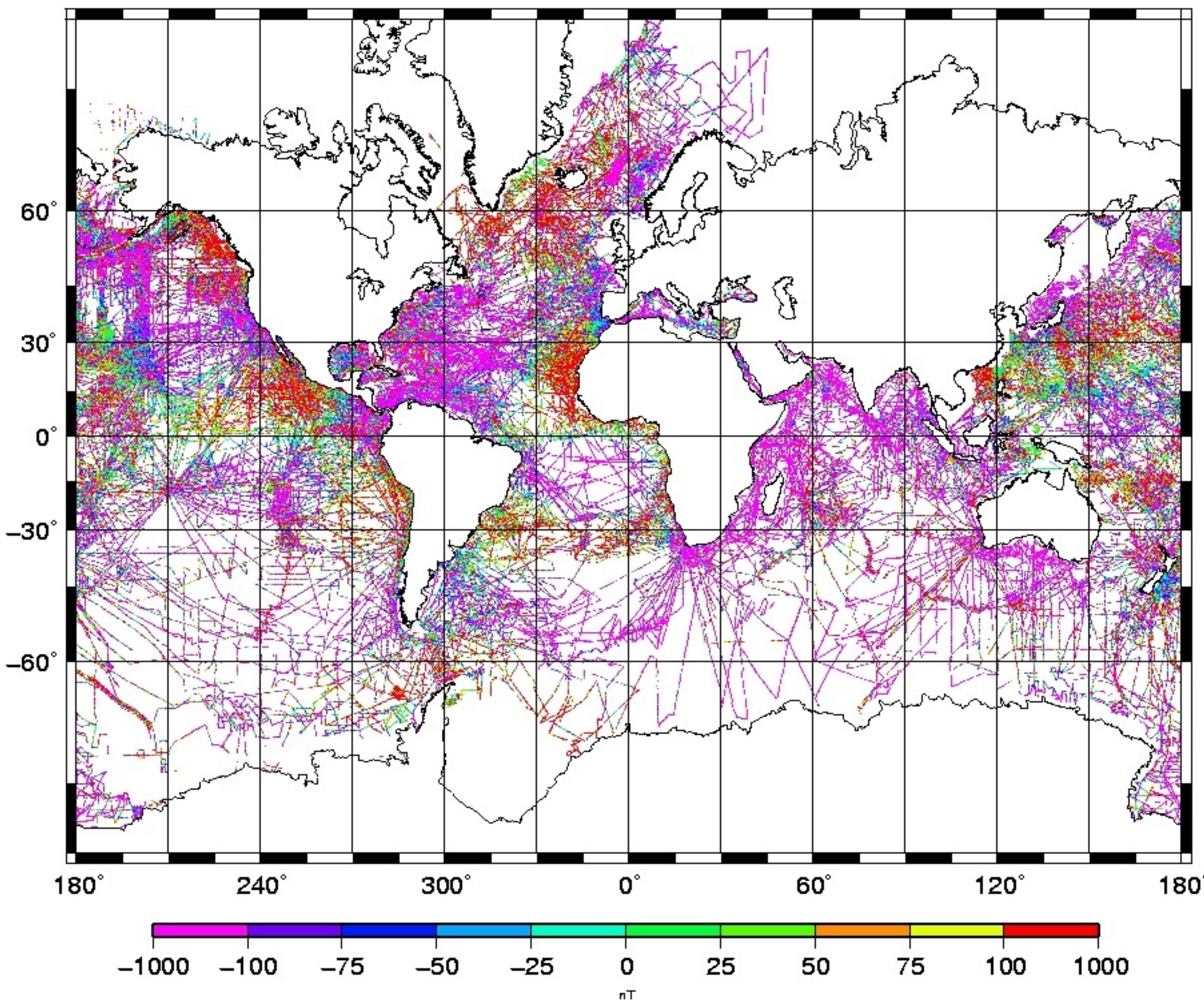
10 to 40 nT discontinuities at the survey edges

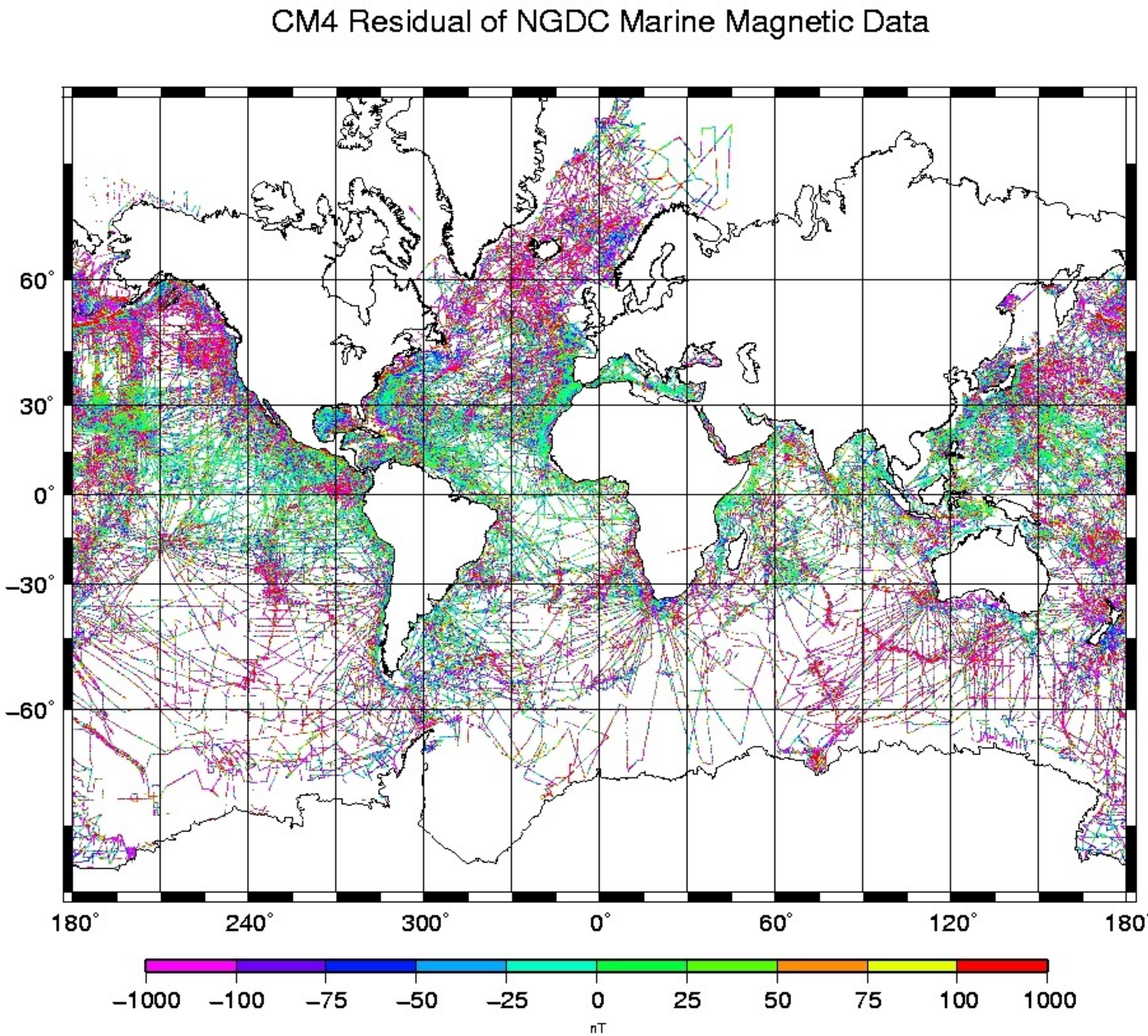
Earth Physics Branch (EPB) Long-Profile Surveys (1969-1976) corrected using the CM



Note: The Canadian portion of the North American Magnetic Anomaly Map (ca. 2002) based on Jointly inverted EPB and CHAMP satellite MF1 anomaly data

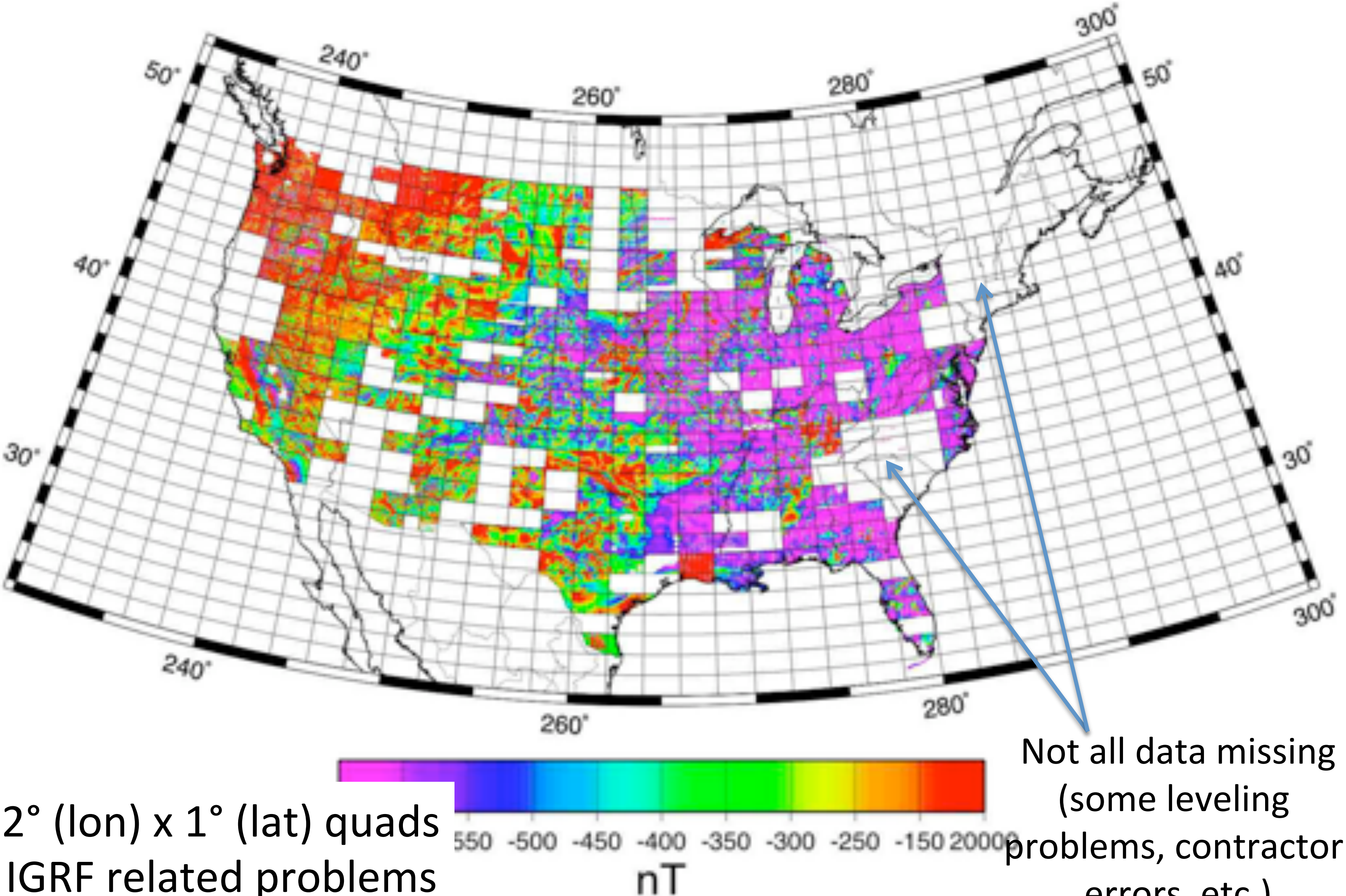
NGDC Residual of NGDC Marine Magnetic Data





CM4 Residual of NGDC Marine Magnetic Data
60°
30°
0°
−30°
−60°
180°
240°
300°
0°
60°
120°
180°
−1000
−100
−75
−50
−25
0
25
50
75
100
1000
nT

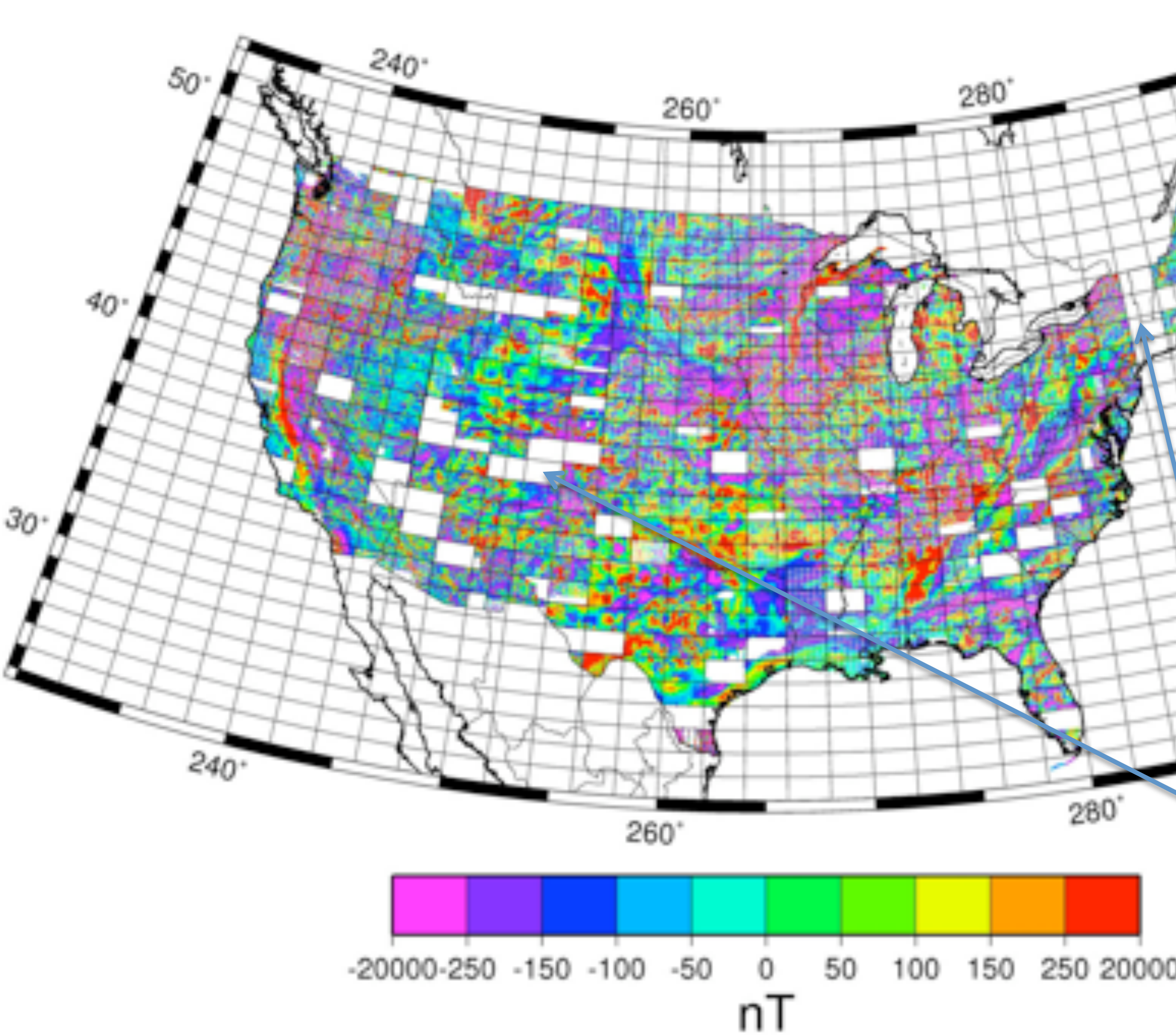
NURE – National Uranium Reconnaissance Evaluation (1970s)



- 2° (lon) x 1° (lat) quads
- IGRF related problems

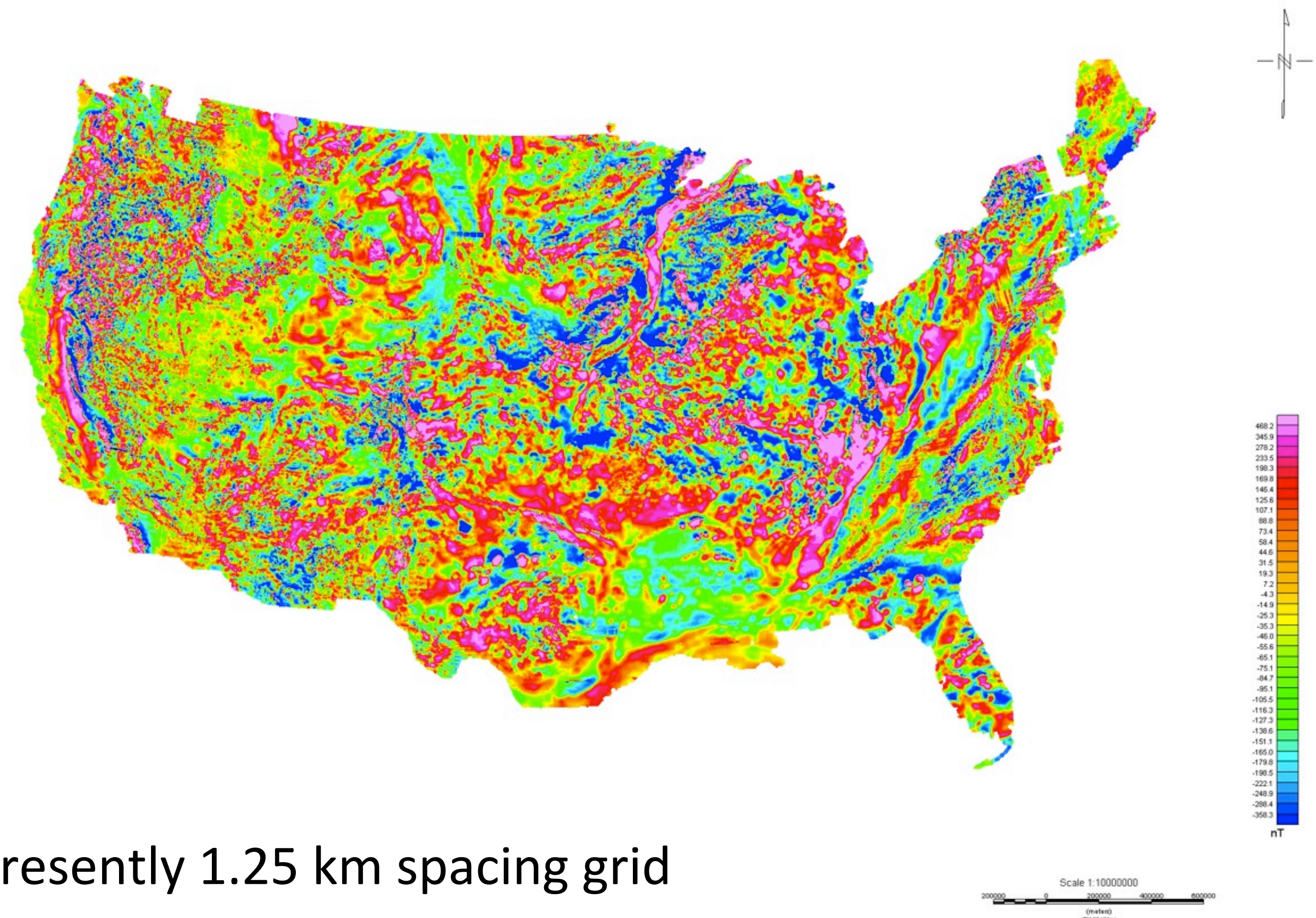
Not all data missing (some leveling problems, contractor errors, etc.)

NURE – Using the CM



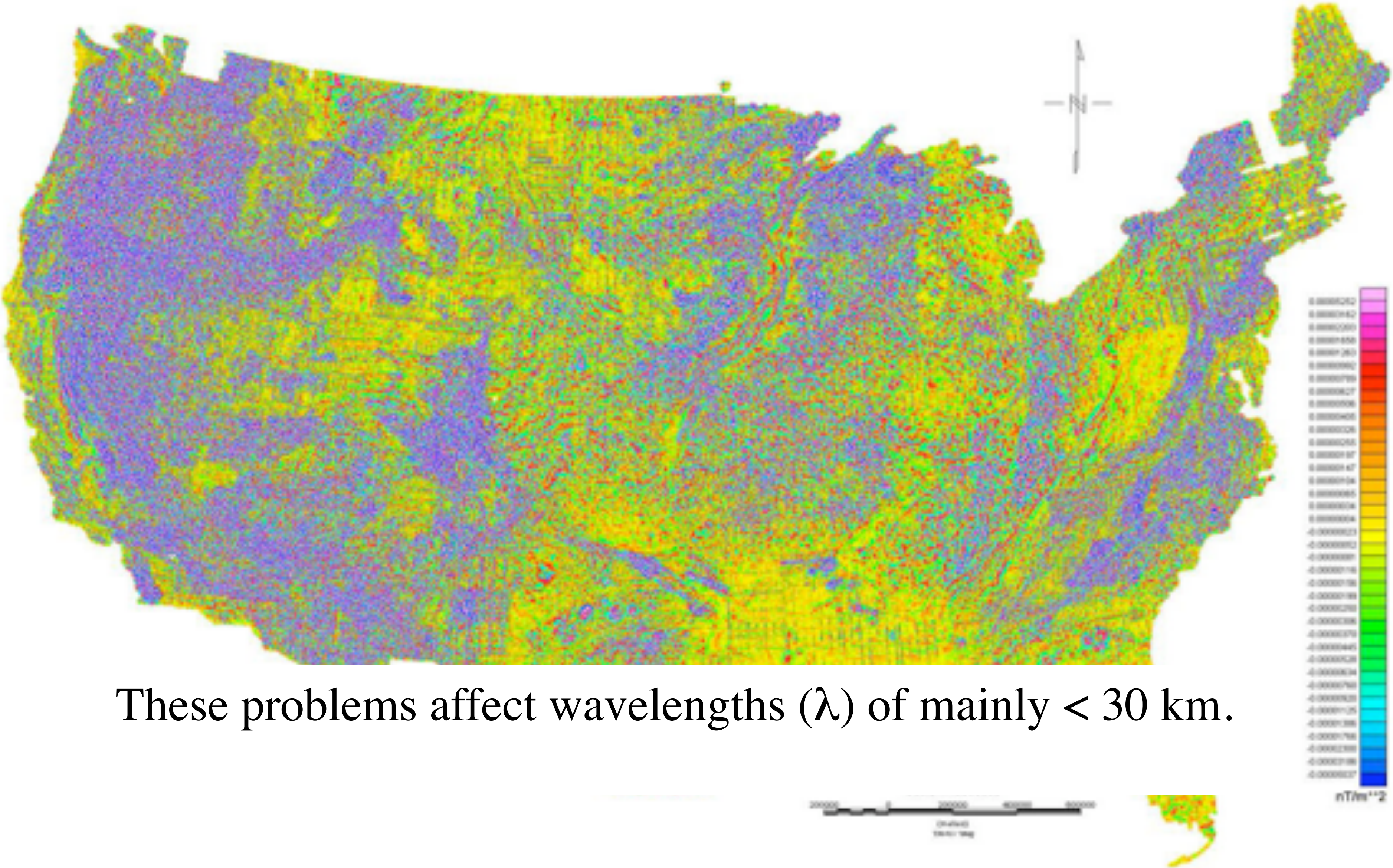
Some NURE quads very difficult to resurrect

Present NURE Magnetic Map of the Conterminous US
(NAMAM segments leveled & inserted in place of missing quads)



Presently 1.25 km spacing grid

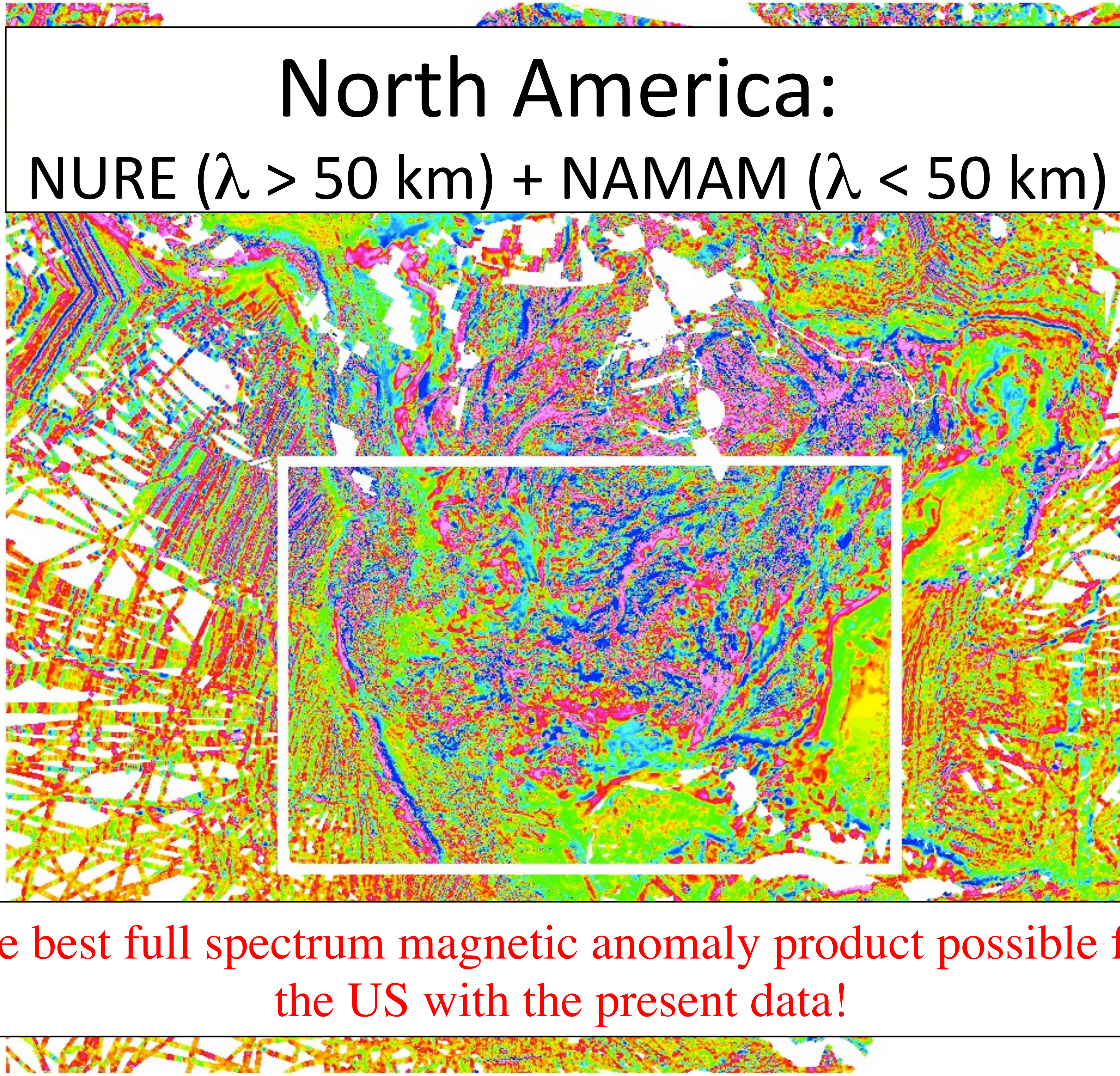
Second Vertical Derivative of NURE – short wavelength data integrity problems (correctable but time-consuming)



These problems affect wavelengths (λ) of mainly < 30 km.

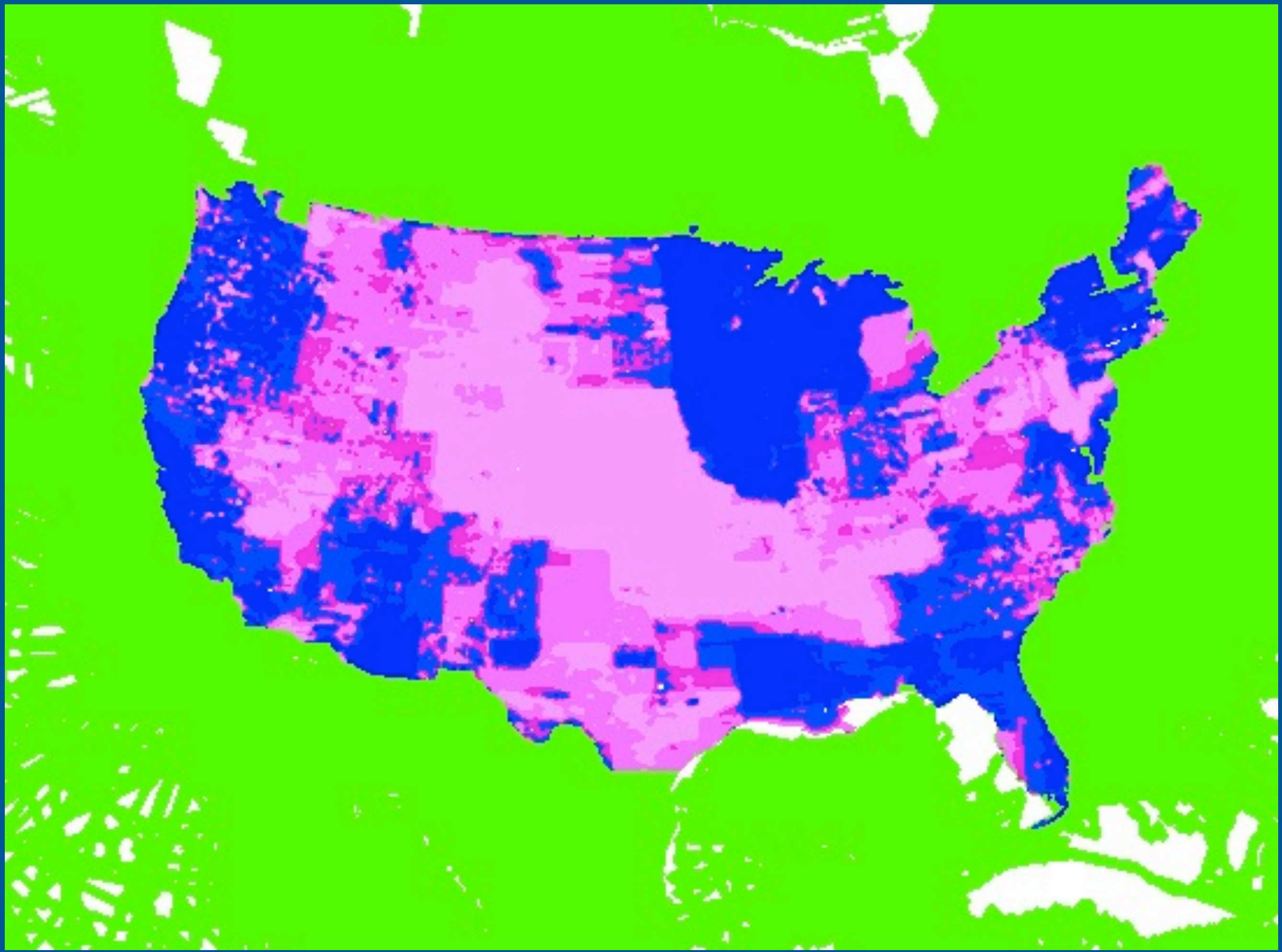
North America:

NURE (λ > 50 km) + NAMAM (λ < 50 km)

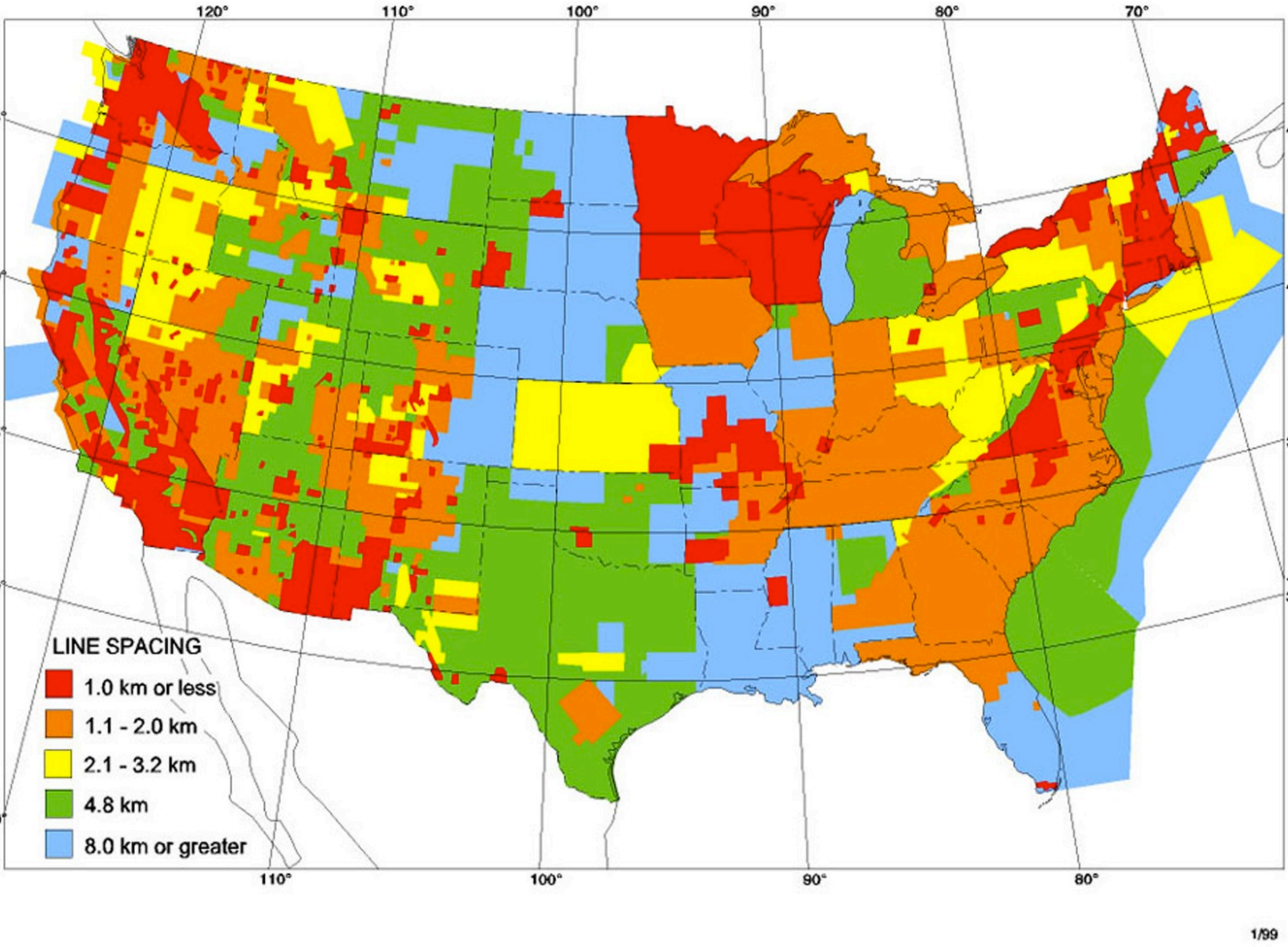


The best full spectrum magnetic anomaly product possible for the US with the present data!

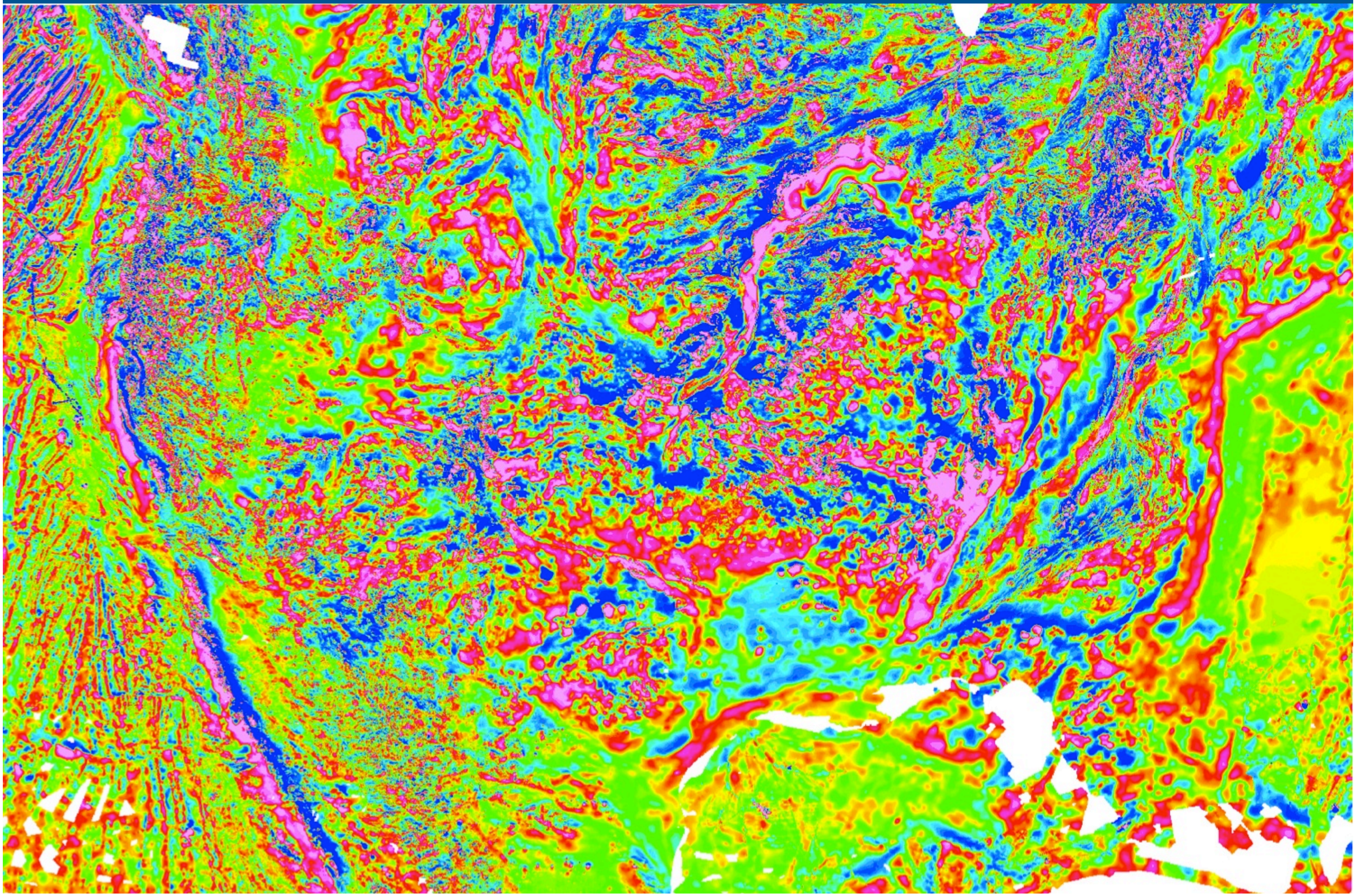
Difference between Corrected NURE data set and NAMAM (2002)



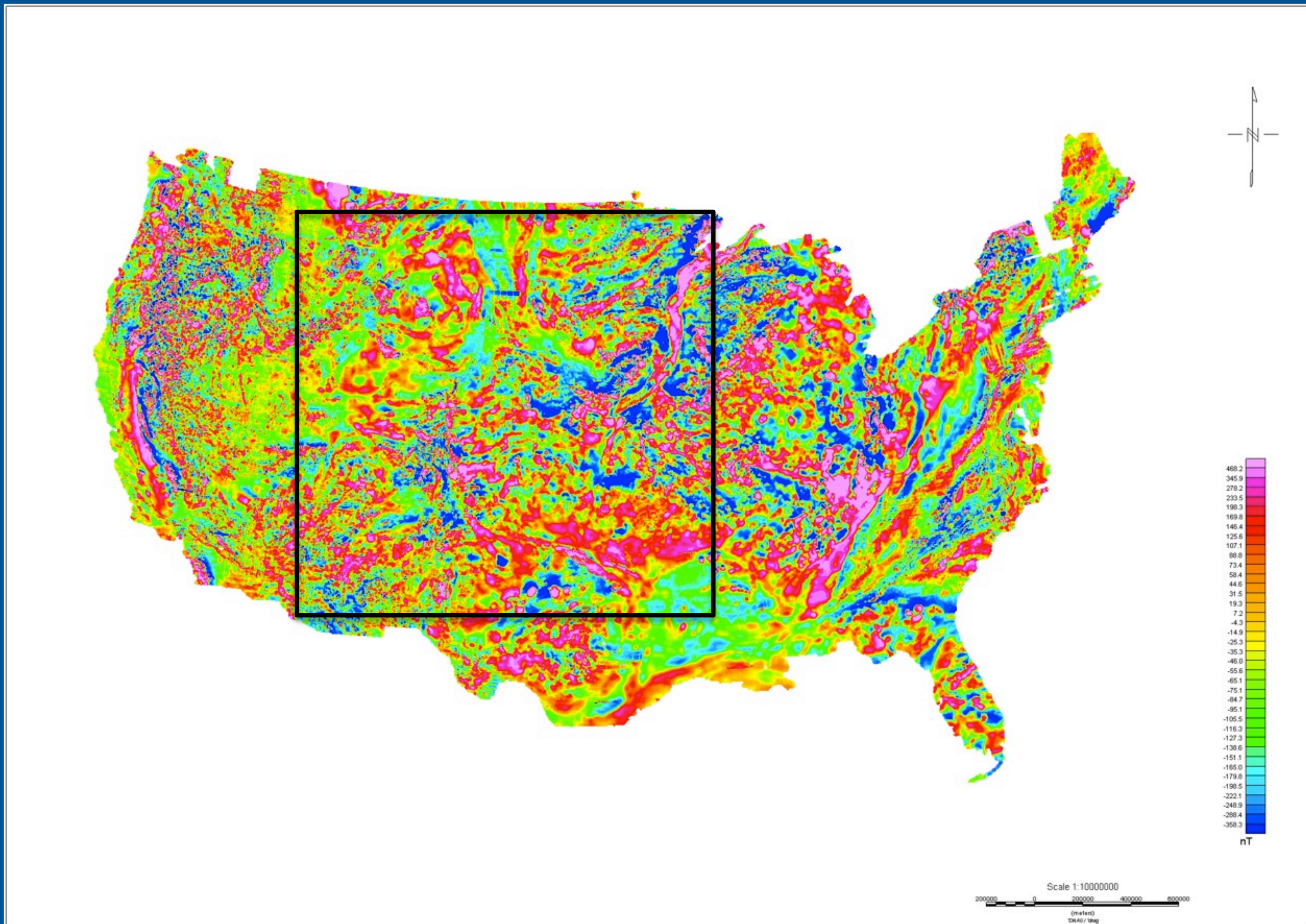
AEROMAGNETIC COVERAGE

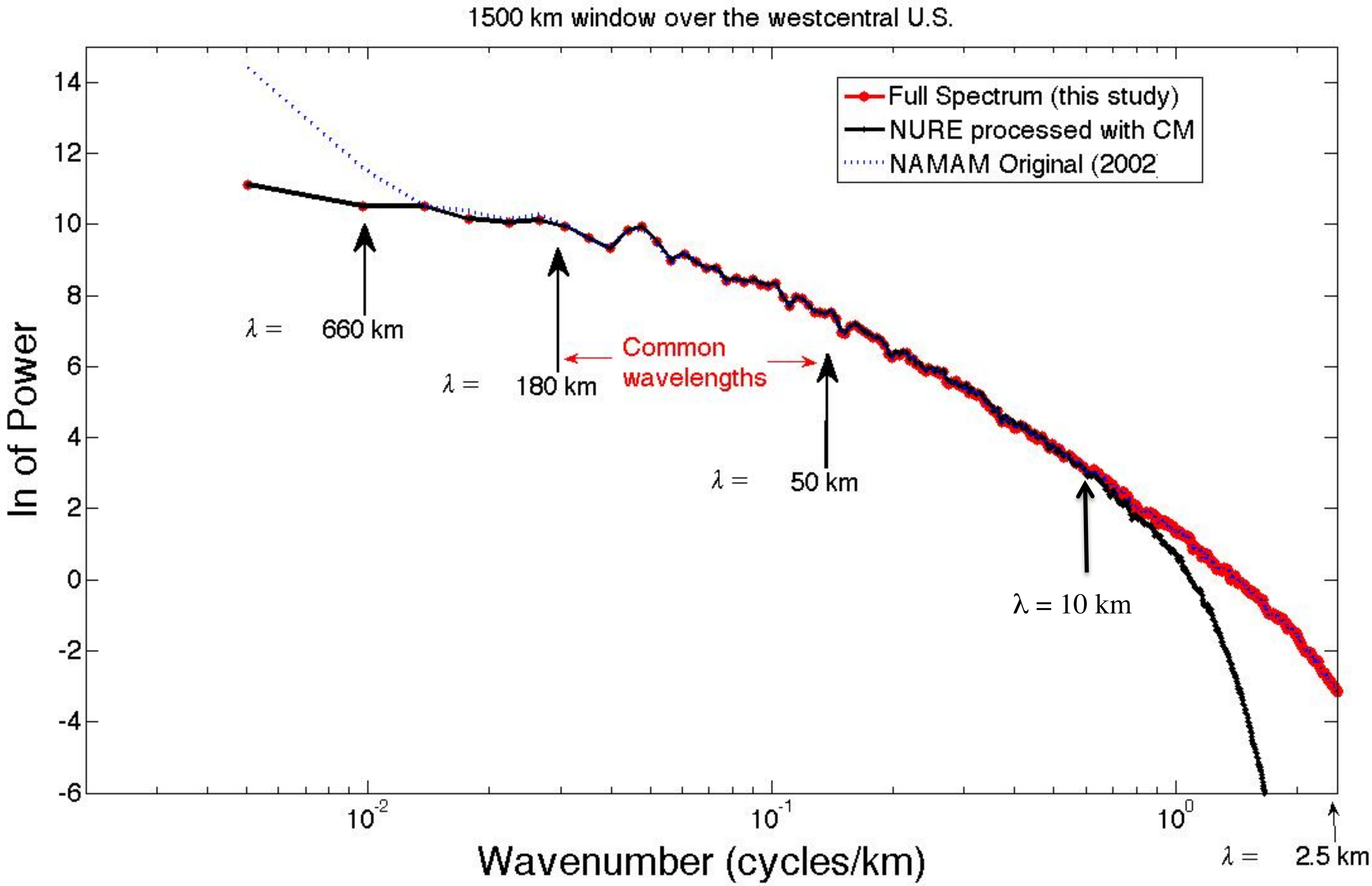


The US subset of NURE_NAMAM2008: NURE (λ > 50 km) + NAMAM (λ < 50 km)



Comparison of Azimuthally Averaged Spectra

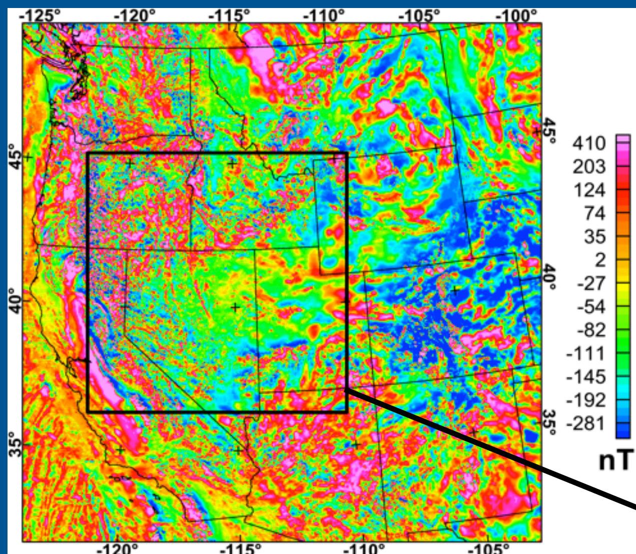




1500 km window over the westcentral U.S.
Full Spectrum (this study)
NURE processed with CM
NAMAM Original (2002
λ = 660 km
λ = 180 km
Common wavelengths
λ = 50 km
λ = 10 km
λ = 2.5 km
ln of Power
Wavenumber (cycles/km)

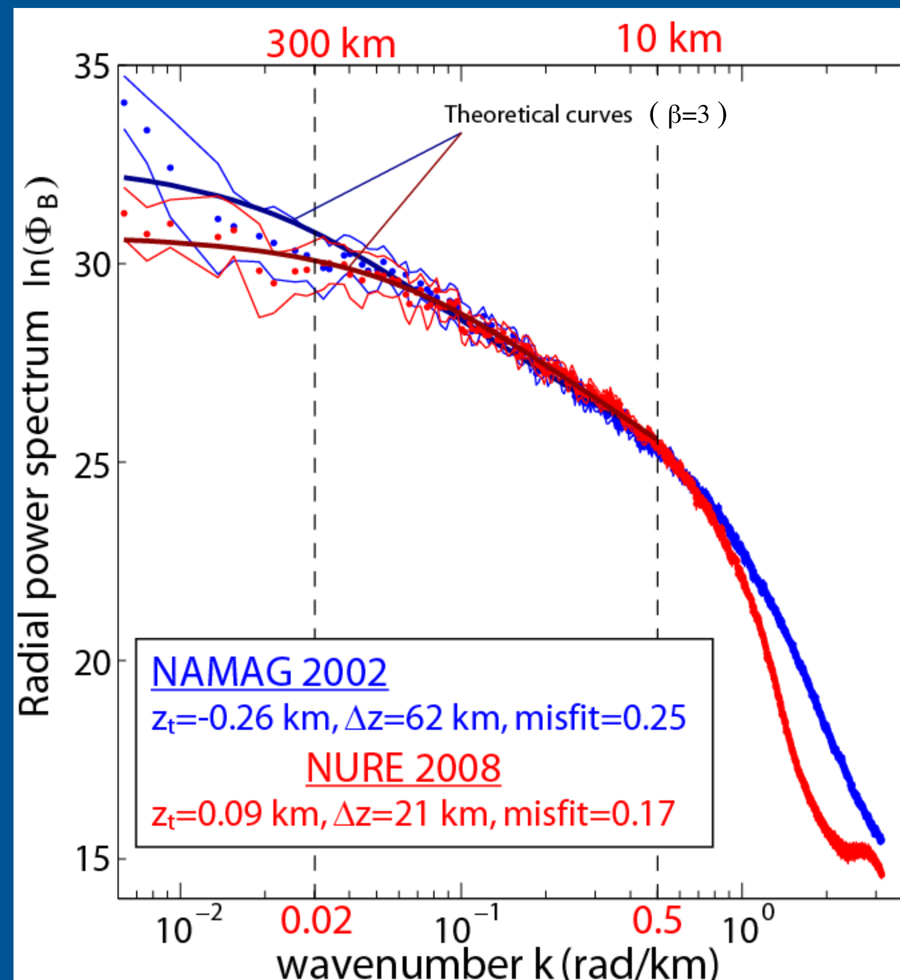
Implication of the new compilation for crustal magnetic thickness estimation

Spectral analysis of aeromagnetic anomalies for a model of fractal random magnetization
Bouligand et al. (2008)



Maus et al. (1997) Method:

Z_t depth to the top, Δz thickness, β fractal parameter for magnetization



→ Better representation of wavelengths > ~180 km than NAMAM

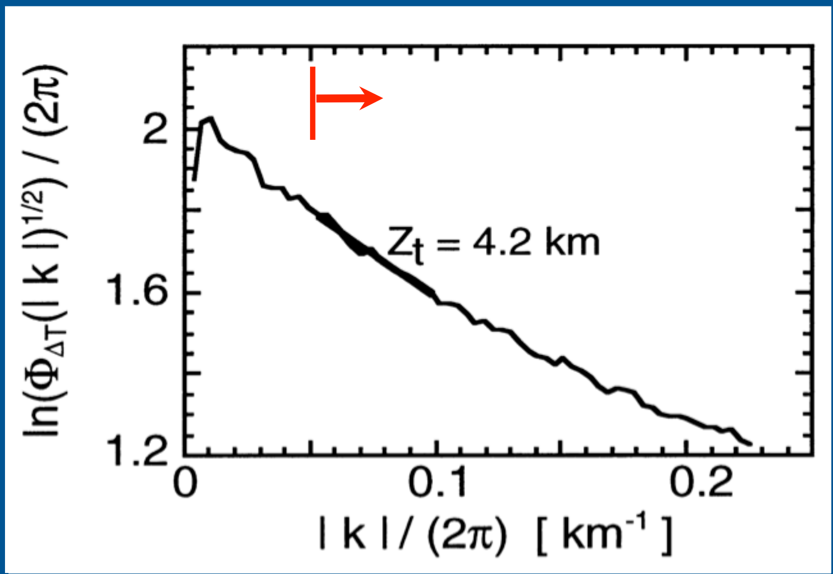
→ More realistic estimate for the crustal magnetic thickness

Four main approaches used to find magnetic bottom/Curie depth

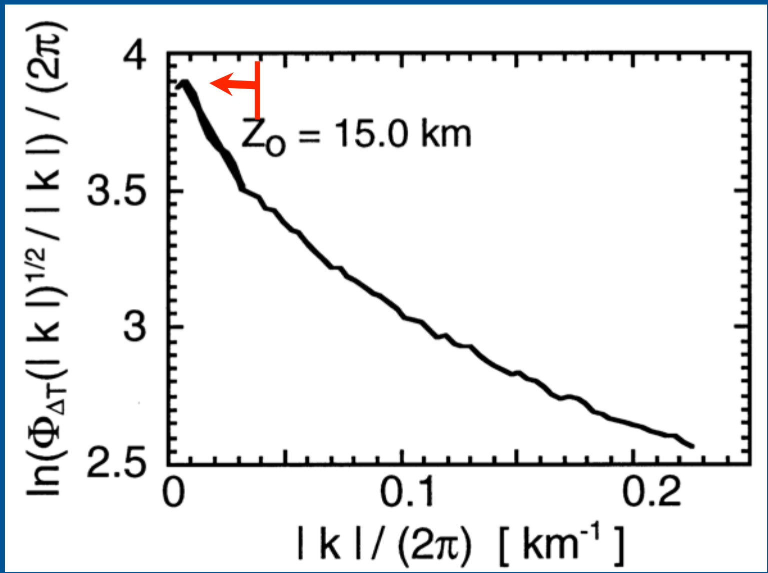
1) <u>The Centroid Method</u> (Bhattacharyya & Leu, 1975, 1977; Okubo et al., 1985; Tanaka et al., 1999)

- Magnetization is assumed to be uniform in the form of a parallelepided source
- Centroid is derived by 1/k scaling of the slopes of low-wavenumber part of the Fourier spectra

"F(k)" Spectra



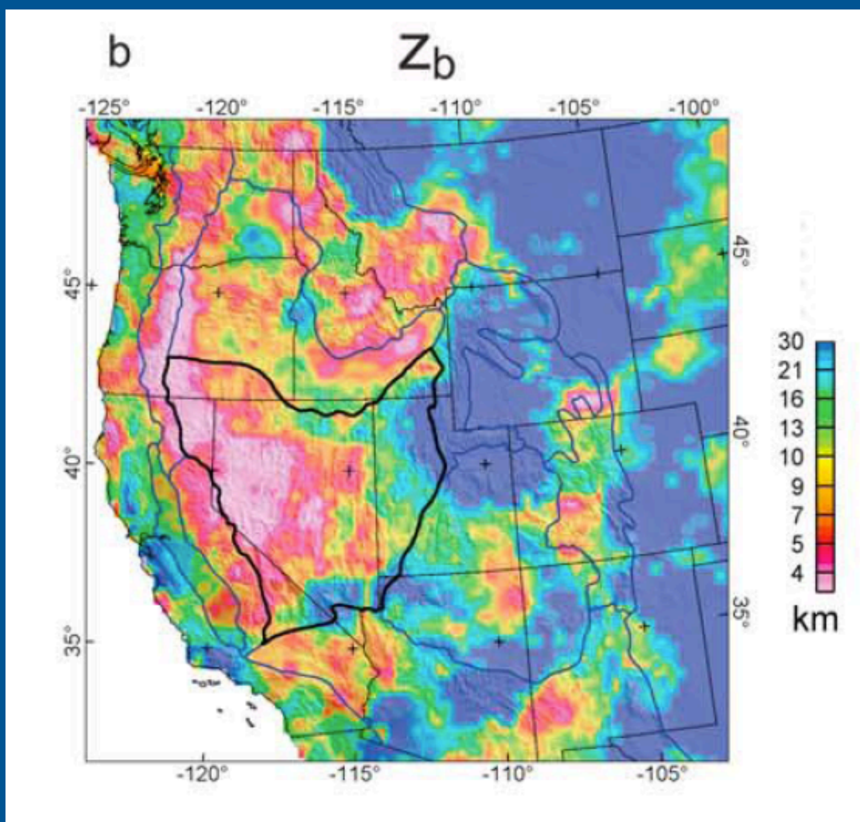
"G(k) = 1/k F(k)" Spectra



Valid argument, but one could end up picking slopes from different layers….especially in multi-layers situations

2) Fractal Magnetization Model (Maus et al., 1997) + Analytical Expression (Bouligand et al., 2009)

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

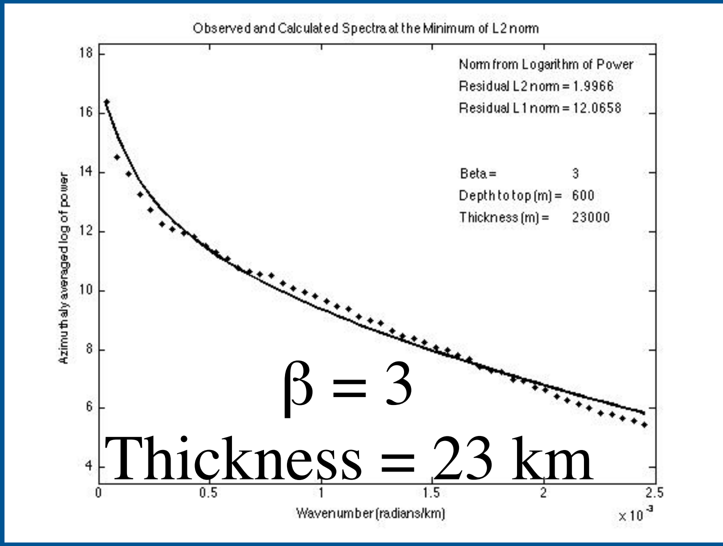


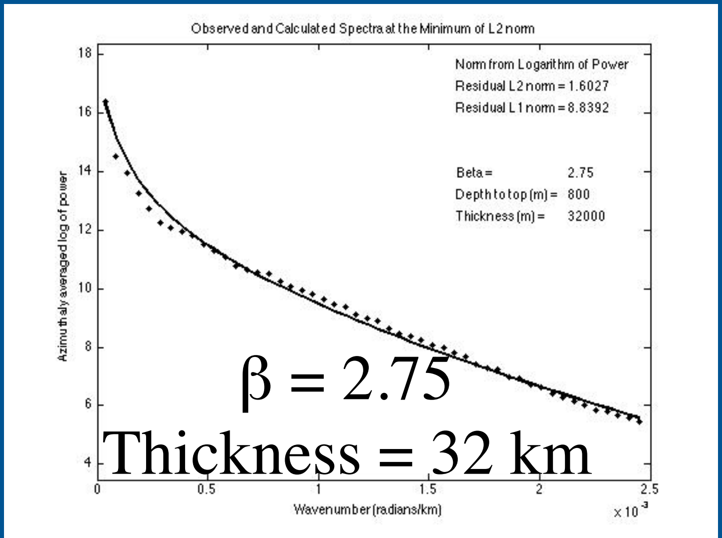
Automatic process may represent meaningful lateral geologic boundaries, but Zb not always the Curie point of magnetite

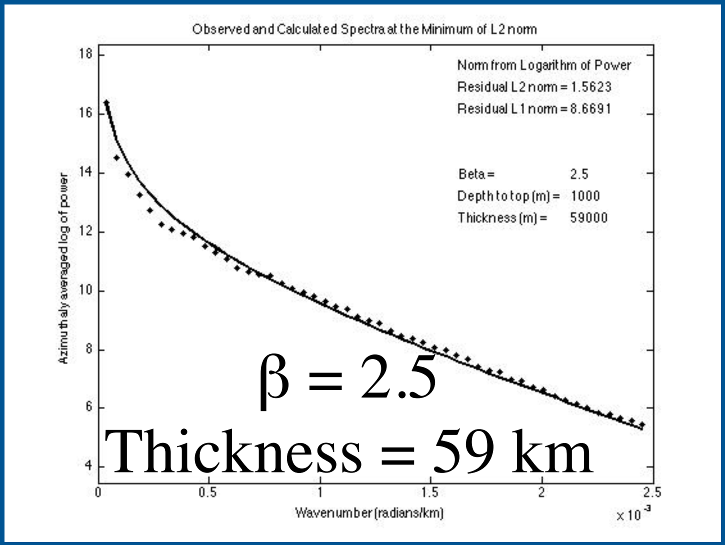
My model studies indicate:

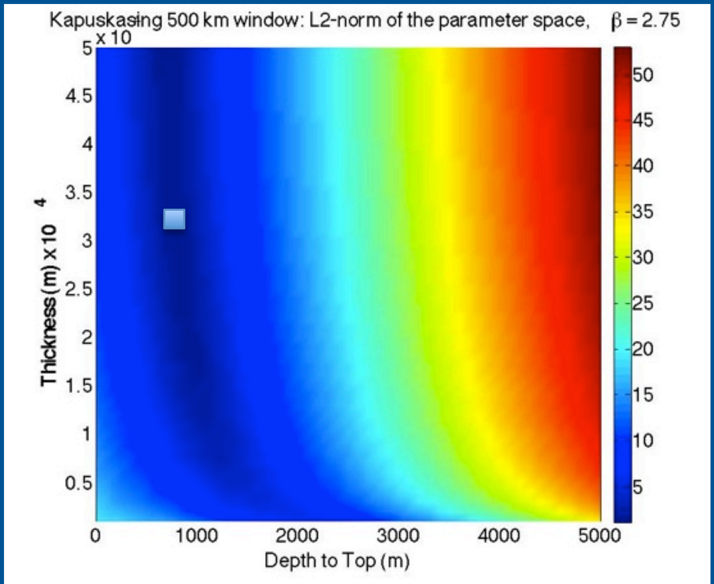
- *A range of feasible solutions exists*
- *Azimuthal average not valid for windows with strong 2-D trends*
- *Strong upper magnetization layer over a weaker one identifies shallower than true Zb*

Kapuskasing: Fractal Method Acceptable Spectra – *non-uniqueness*









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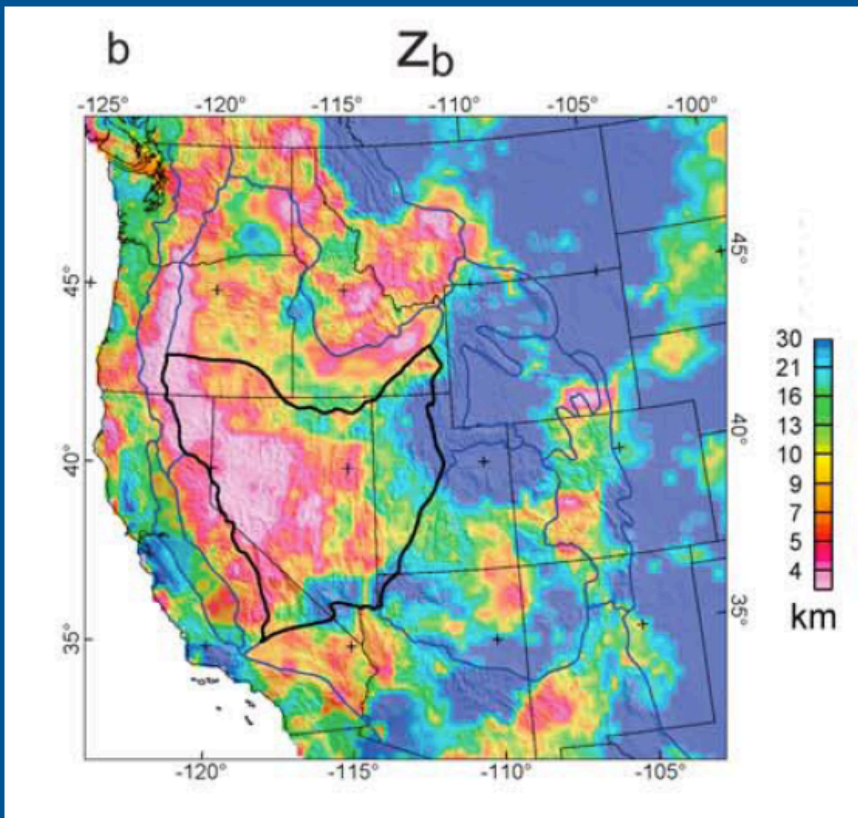

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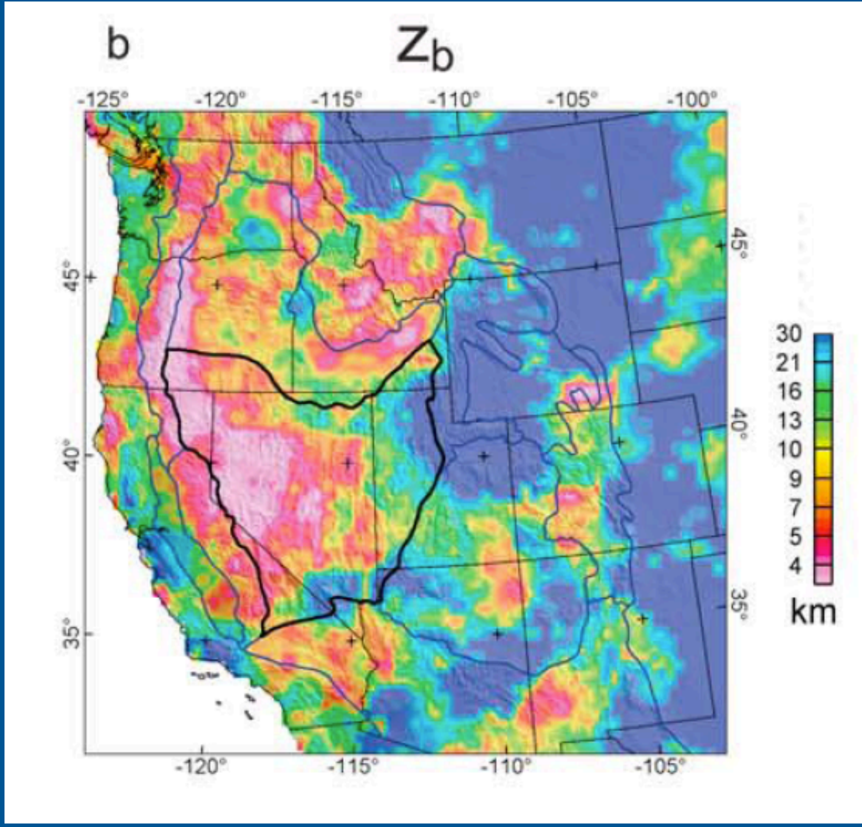

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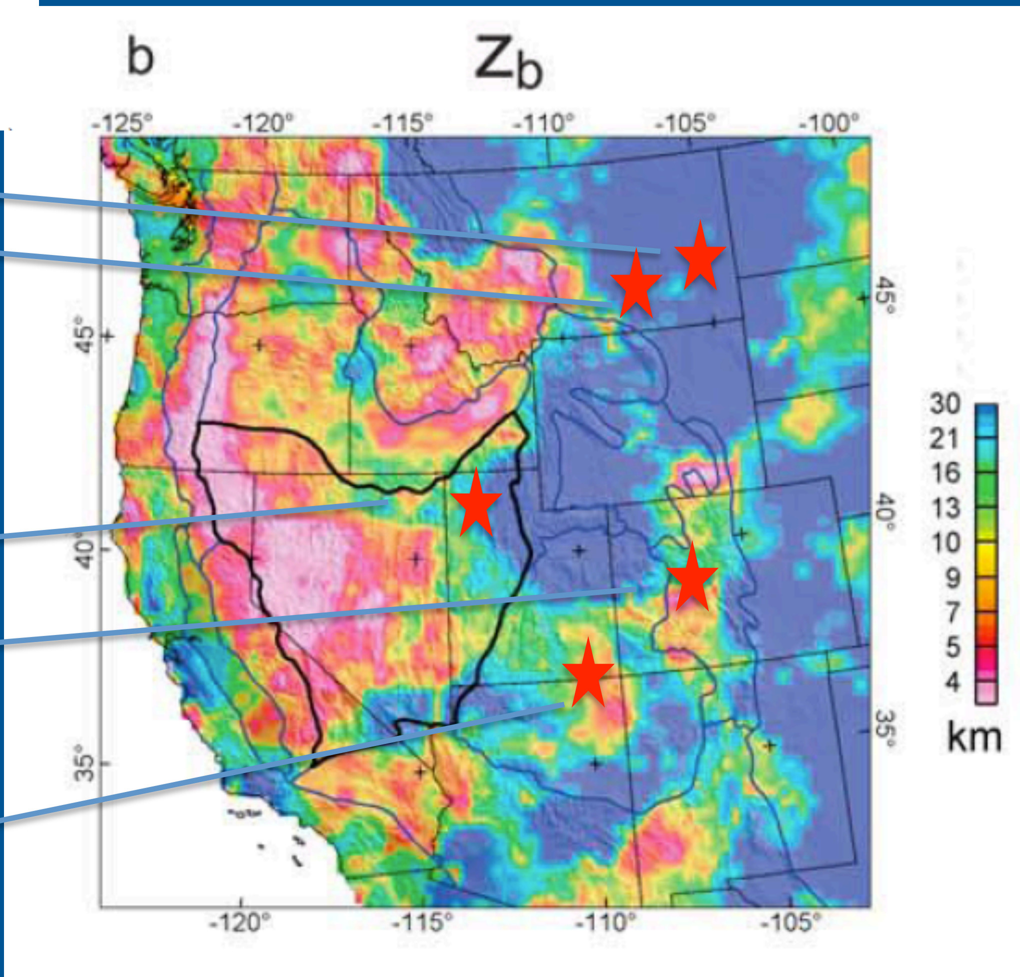
Great Plains – Bouligand Zb ~ 30 km; My Zb range 22-30 km

Wyoming Craton – Bouligand Zb ~ 30 km; My Zb range 38-43 km

Basin & Range (East) – Bouligand Zb ~ 20 km; My Zb range 19-25 km

Rio Grande Rift– Bouligand Zb ~ 20 km; My Zb 30 km

Colorado Plateau – Bouligand Zb ~ 10 km; My Zb 15 km



3) Hybrid Centroid - Fractal magnetization Method (Bansal et al., 2011)

Frequency domain magnetization parameterized as:

$$\phi_m \propto k^{-\beta}$$

where β is the fractal parameter.

For β ~ 3, corresponds to Fedi et al. (1997) ensemble modeling scaling exponent; it is also the most often encountered β in the continental crust (Bouligand et al., 2009). β = 0 random magnetization (no correlation); β = 1, layered magnetization; β = 5 – 6, sources with larger correlation length in three dimensions.

4) <u>Spectral Peak Method</u> – peaks meaningful and present only for $\beta = 0 - 2$

- Origin in the theoretical background outlined by Boler (1978) and Connard et al. (1983) – but incorrectly used in practice due to spectra showing false peaks
- $$k_{peak} = \frac{\ln Zb - \ln Zt}{(Zb - Zt)}$$
- Forward modeling of spectral peak avoids false identification of spectral peaks (Ravat, 2004; Finn and Ravat, 2004; Ross et al., 2004; Ross et al., 2006; Ravat et al., 2007)

Ravat et al. (2007)

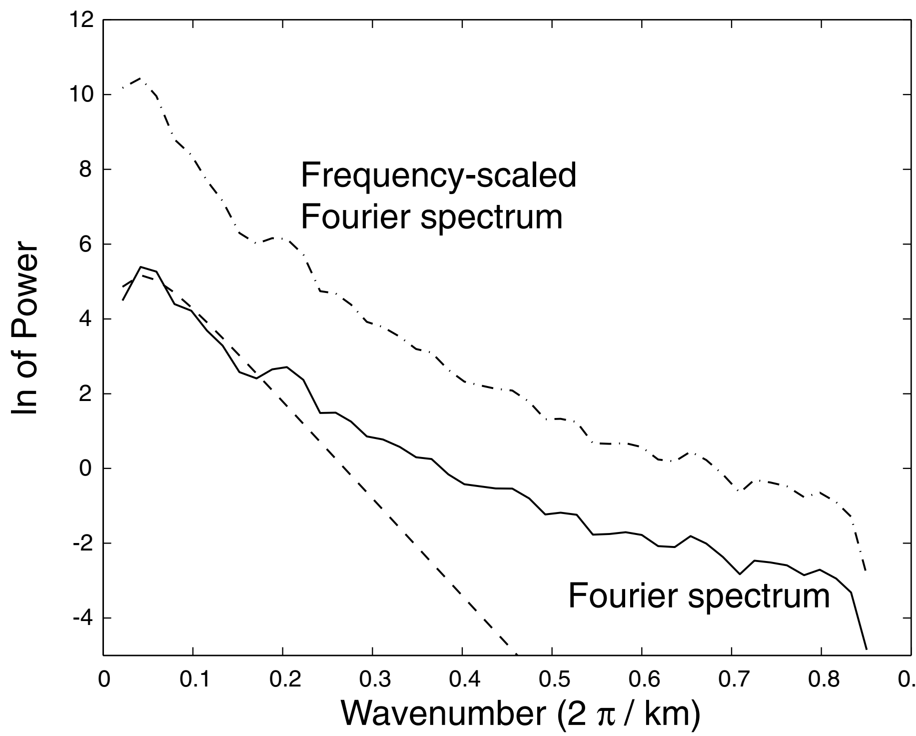
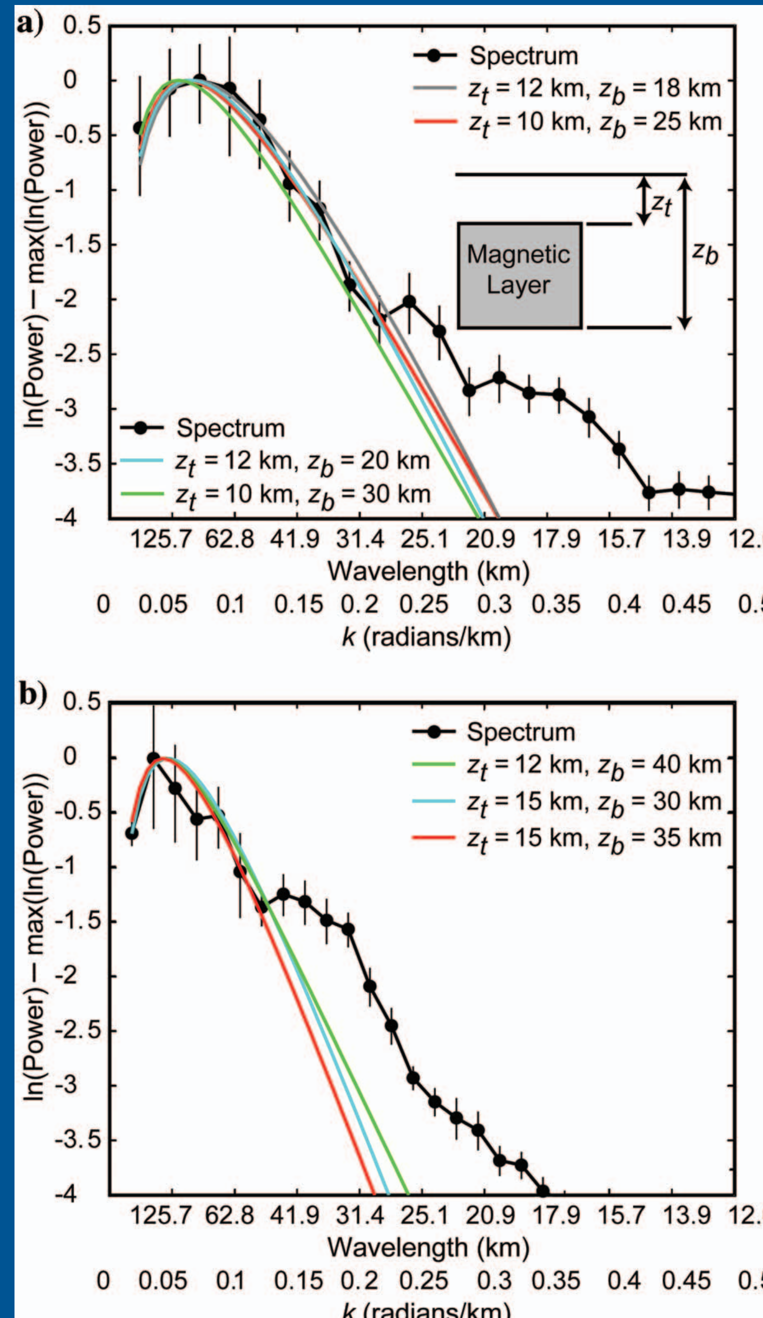


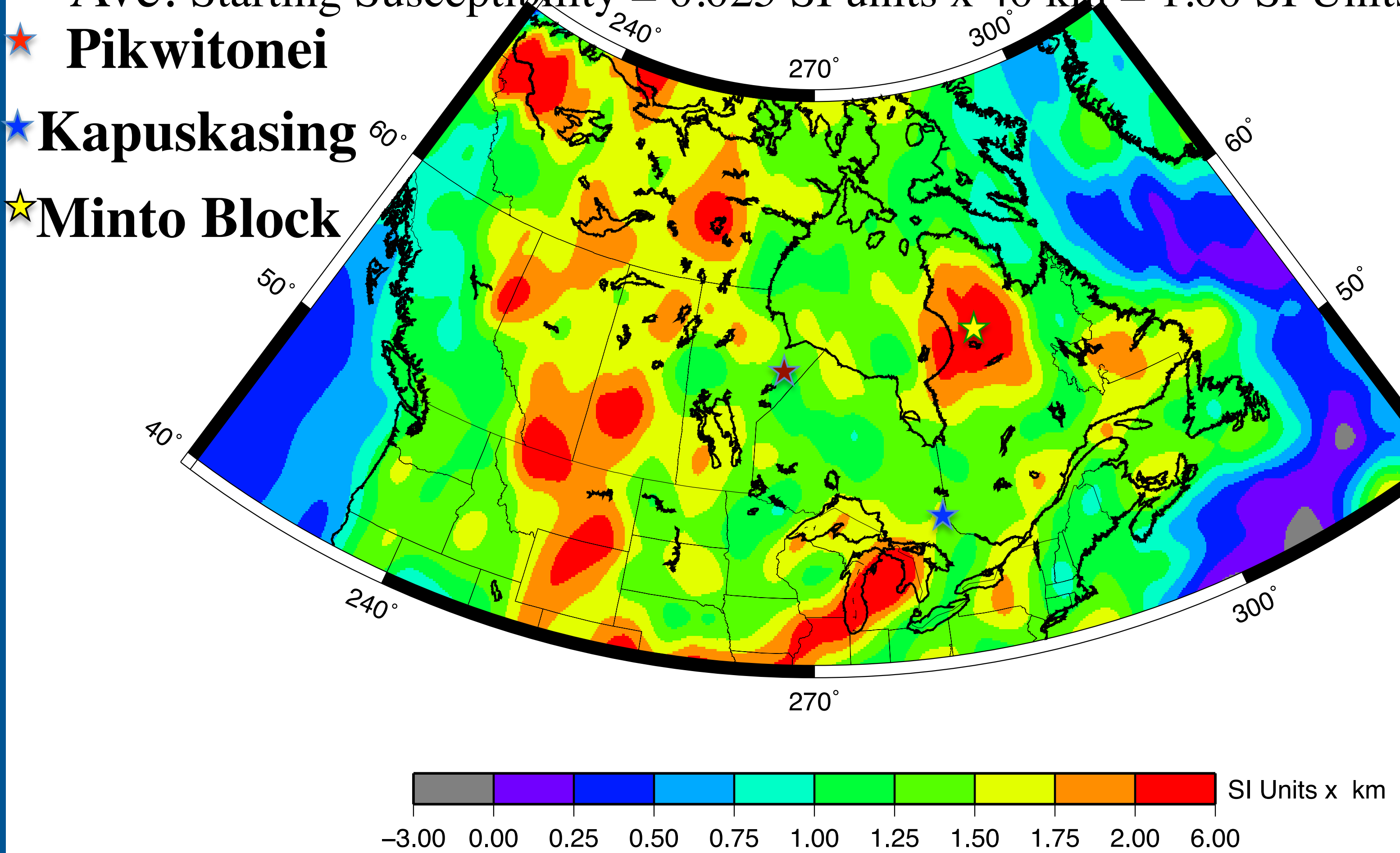
Figure 8. An example with real data. The depth to the top of the deepest layer from Fourier spectrum (continuous line) is ∼12 km and the depth to the bottom from the frequency-scaled Fourier spectrum (dash–dotted line) is ∼44 km. The forward modelling (dashed line) leads to the same depth to the top, and the bottom can be matched at ∼40 ± 10 km. The direct use of the spectral peak method (eq. 2) led to the bottom depth of 35 km.

Ross et al. (2006)



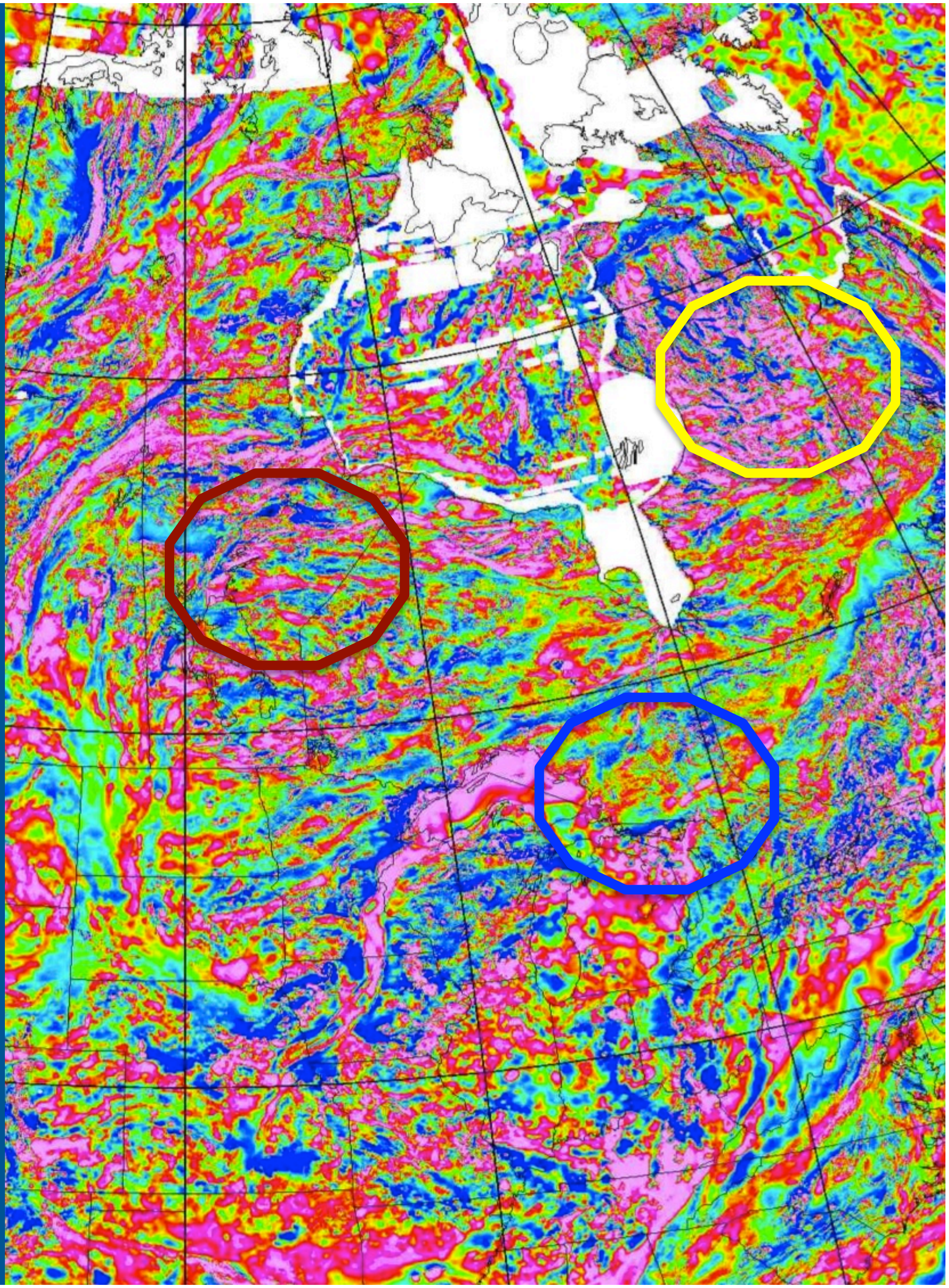
Depth Integrated Long-wavelength Susceptibility from CHAMP MF7 Model & SEMM

Ave. Starting Susceptibility = 0.025 SI units x 40 km ≏ 1.00 SI Units x km



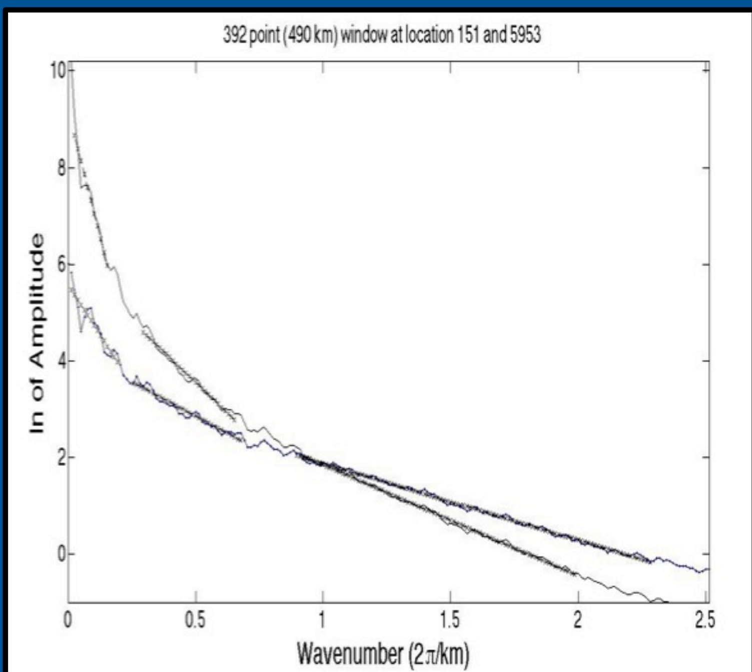
Pikwitonei, Kapuskasing & Minto Block Magnetic Anomaly Field from NURE-NAMAM 2008

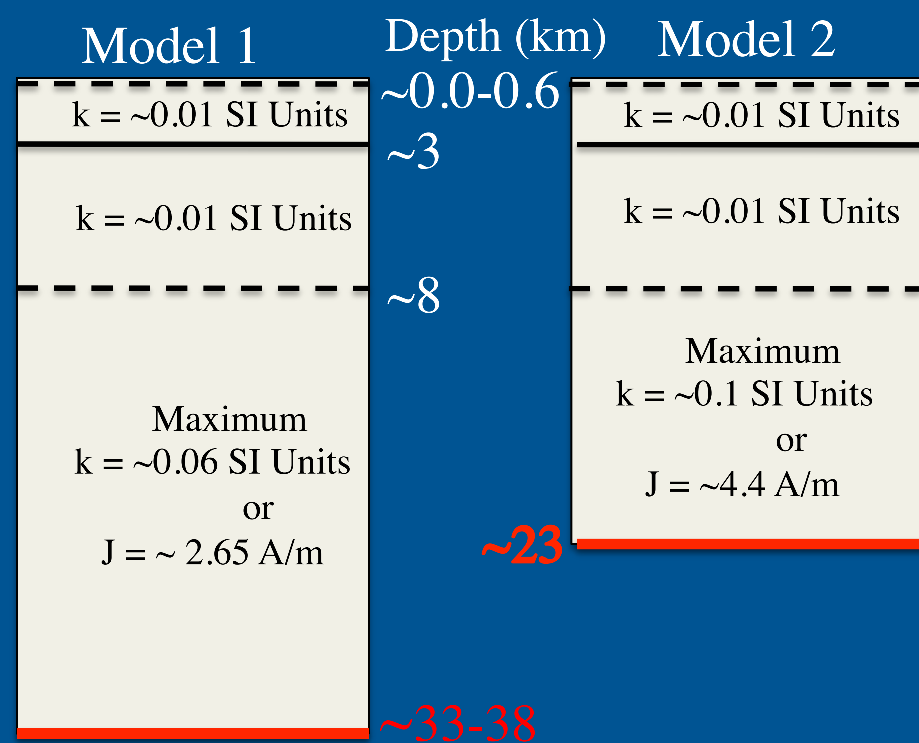
Large windows (500 km) to sample the magnetic bottom



Spectral depths from the Spectral slope method

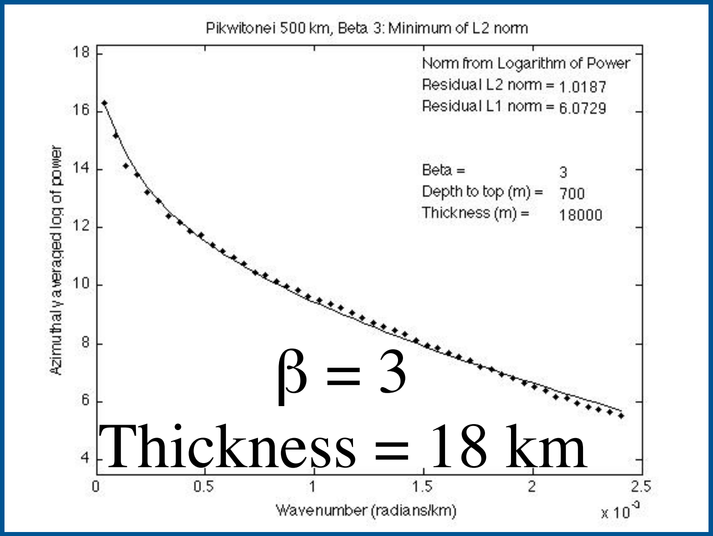
- Pikwitonei
  - Spectral slopes: Spector & Grant (1970) and Bansal et al. (2011) + Centroid method: Bhattacharyya & Leu (1977)

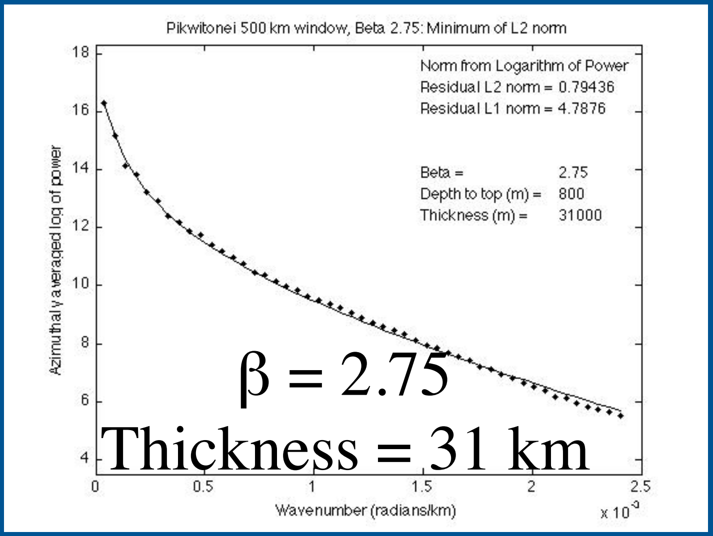


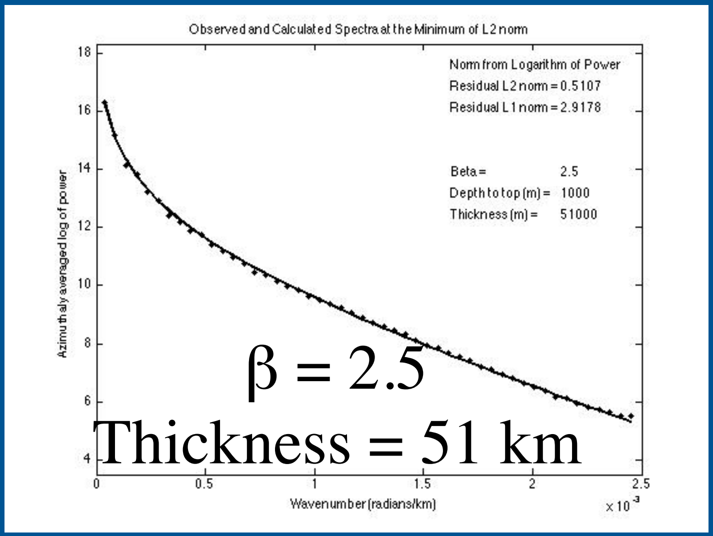


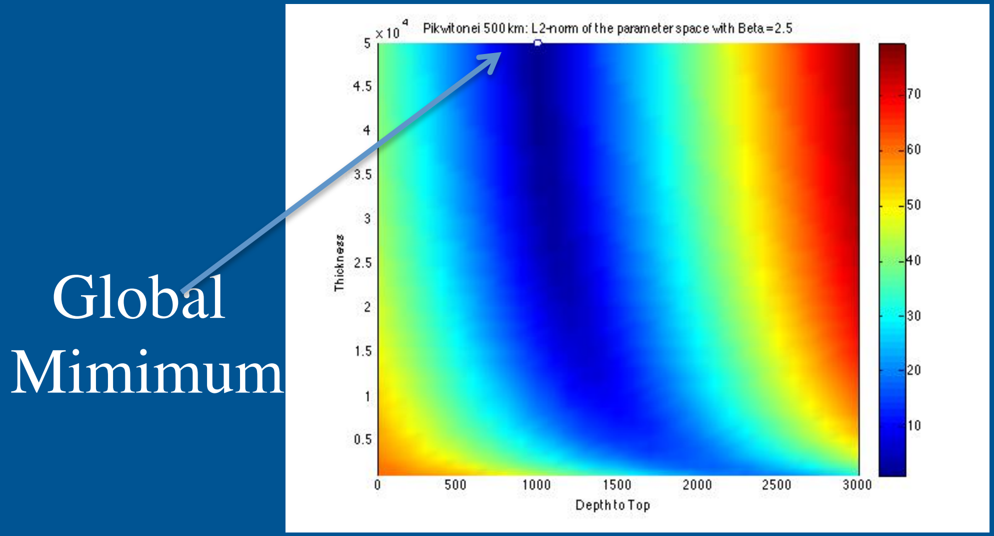
Detecting magnetic "layering" implies that layers have different bulk magnetization

Pikwitonei: Fractal Method Acceptable Spectra – *non-uniqueness*









Pikwitonei Region: Geophysical Information Pertaining to the Upper Lithosphere

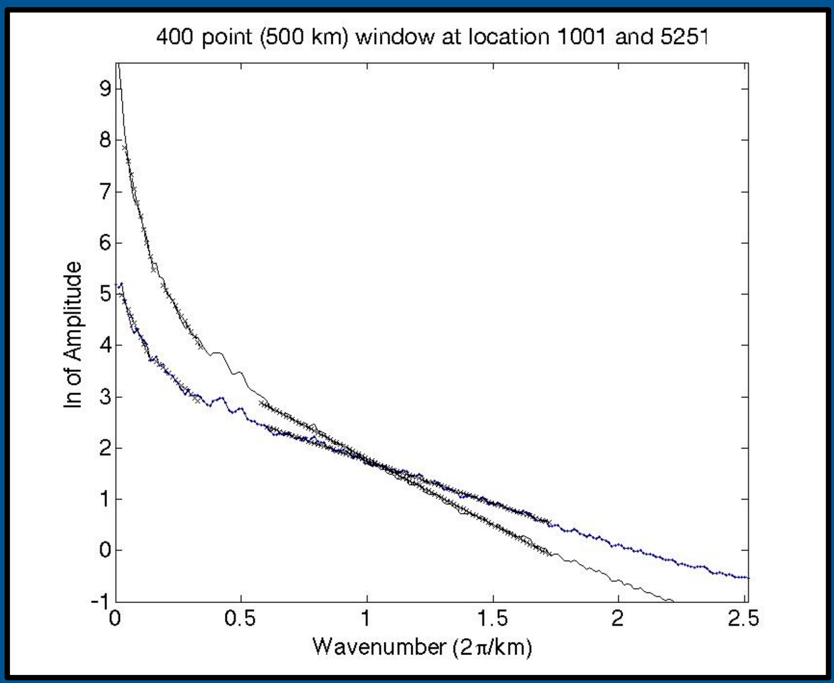
- Crustal thickness: 30-35 km (Chulick & Mooney, 2002)
- Low heat flow: 30-40 mW/m^2 (Levy et al., 2010)
- Sub-Moho temperature estimates ~ 200°-550°C (Shapiro et al., 2004)

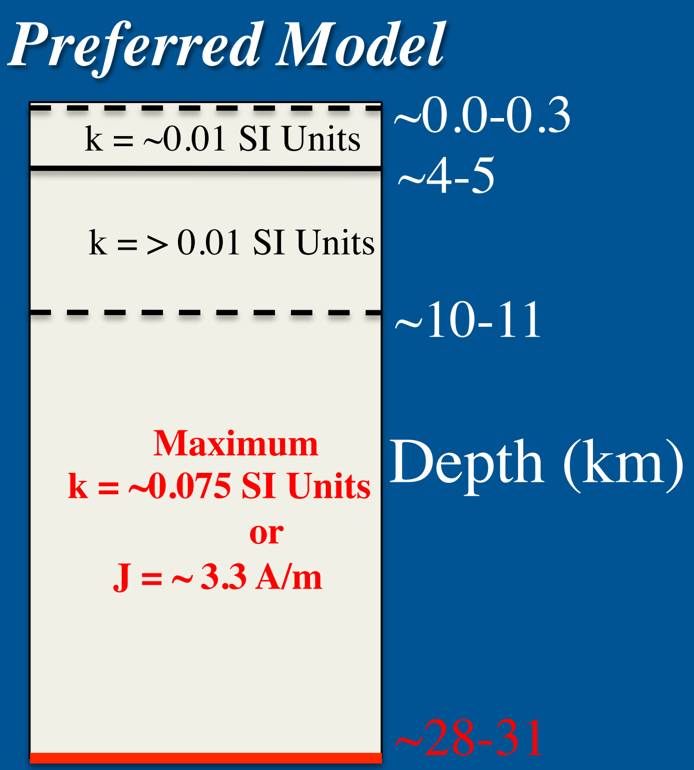
- Thus, thermally, the mantle has potential to be magnetic, but the magnetic bottom closer to the Moho depth and suggests that the mantle mineralogies here may be non-magnetic.

Among the first magnetic anomaly based confirmations of "the Moho as a magnetic boundary" idea of Wasilewski and co-workers (1979, 1992)

Spectral depths from the Spectral slope method

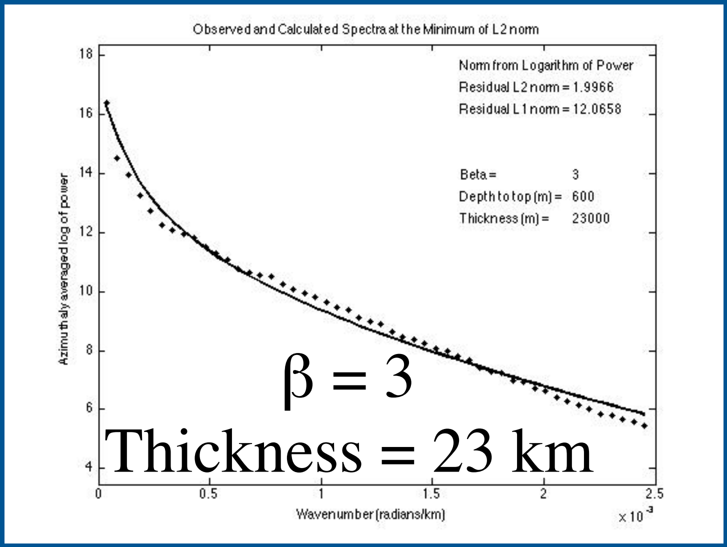
- ***Kapuskasing – 500 km window***
  - **Spectral slopes: Spector & Grant (1970) and Bansal et al. (2011) + Centroid method: Bhattacharyya & Leu (1977)**

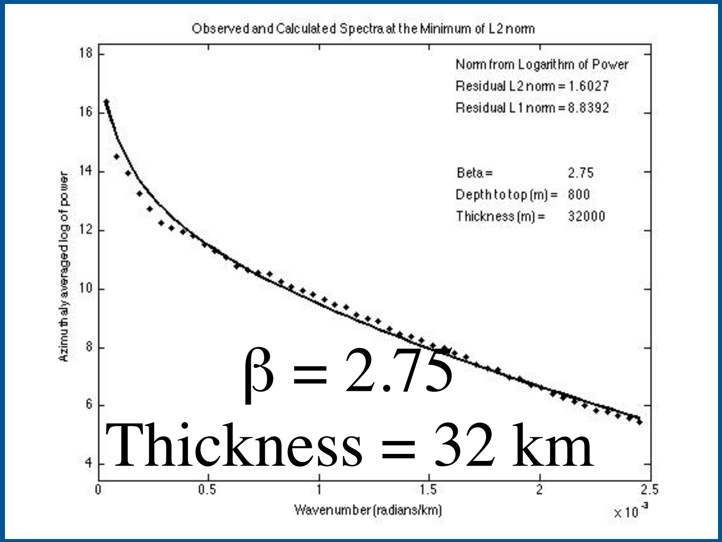


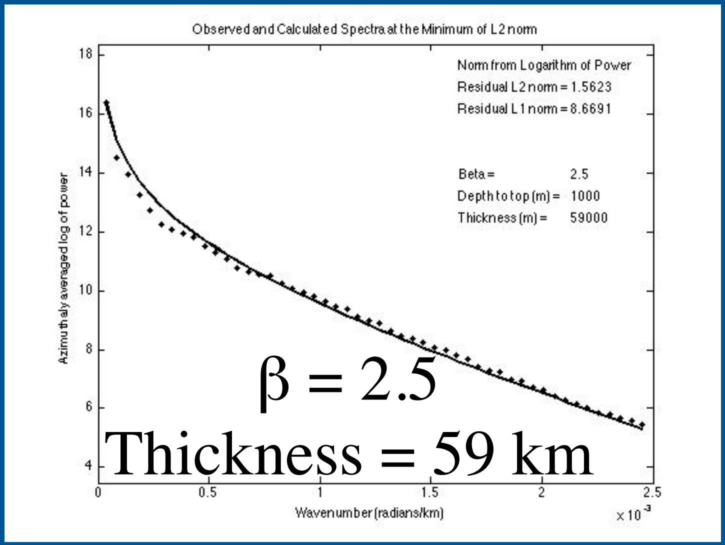


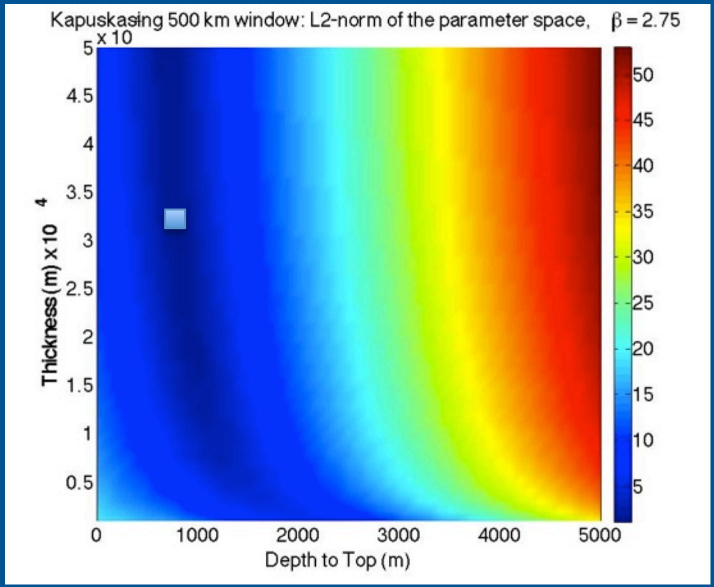
Detecting magnetic "layering" implies that layers have different bulk magnetization

Kapuskasing: Fractal Method Acceptable Spectra – *non-uniqueness*









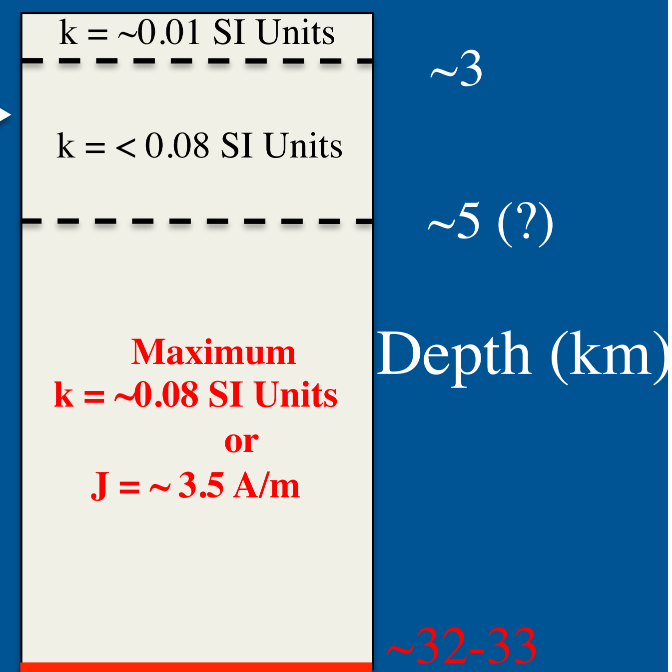
Minto Block, Superior Province, Canada (Pilkington & Percival, 1999, 2001)

- Supracrustal rocks susceptibility ~ 0.001 – 0.01 SI Units
- Charnockitic lithologies (igneous orthopyroxene-bearing diorite, granodiorite, granite) susceptibility ~0.08-0.10 SI Units

- Crustal thickness ~ 35-40 km (Chulick & Mooney, 2002)
- Elastic thickness > 70 km (Wang & Mareschal, 1999)
- Heat flow: 20-30 mW/m^2 (Levy et al., 2010)
- Lower crust temp.: 200-450°C (Shapiro et al., 2004)

- Fractal modeling results similar to layered modeling:
    - **Global Minimum**: Magnetic Top= ~0.6 km; **Magnetic Bottom = ~28 km;** β = ~2.5

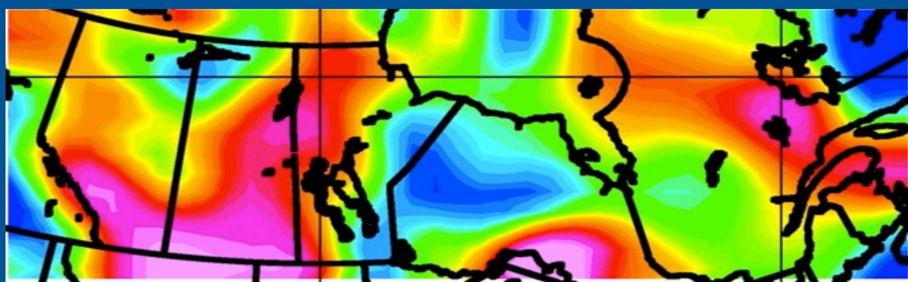
Preferred Spectral Layered Model



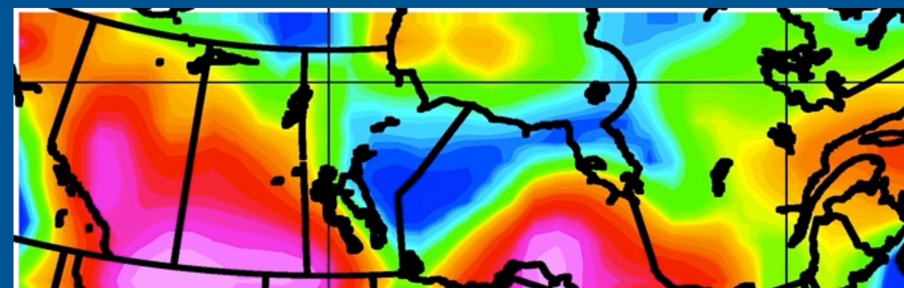
Charnockitic lithologies increase in proportion in the deeper crust

Differences in the Moho estimates from two sources

Moho 1 from CRUST2.0 (Bassin, Laske, Masters, 2000)



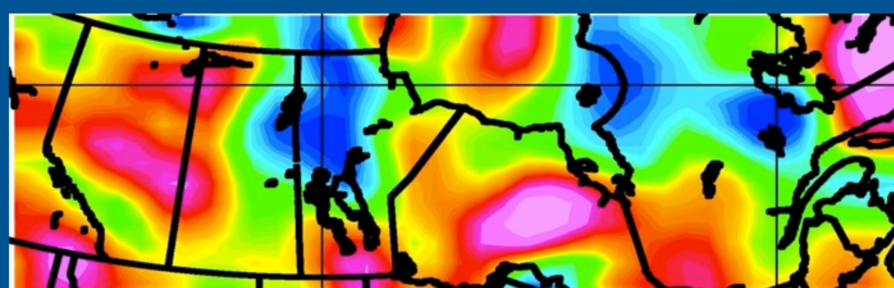
Moho 2 from NA04 (van der Lee & Frederiksen, 2004)

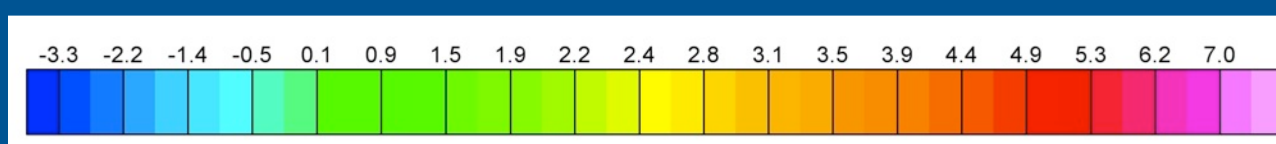


32 

44 km

Moho 1 – Moho 2



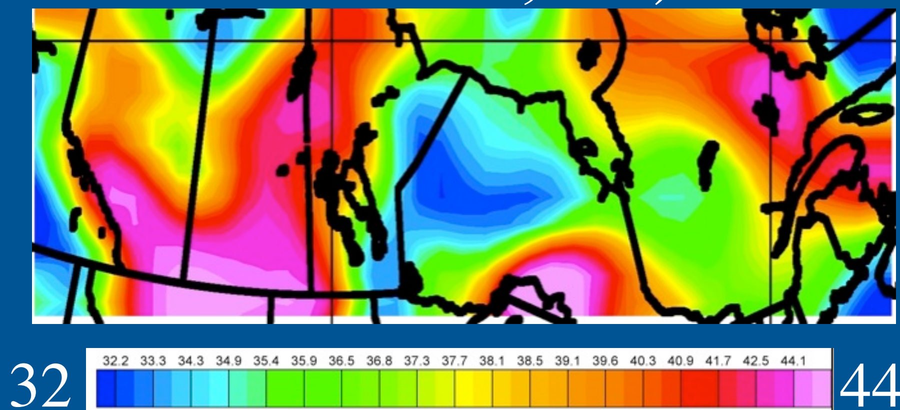


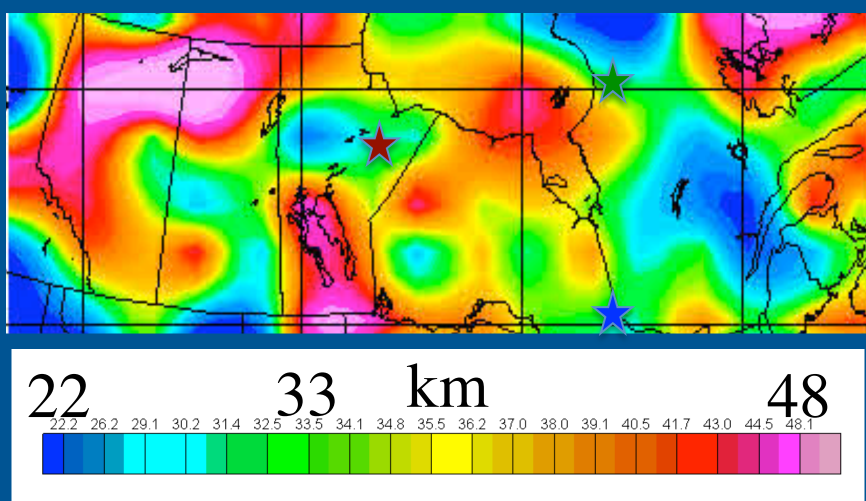
km

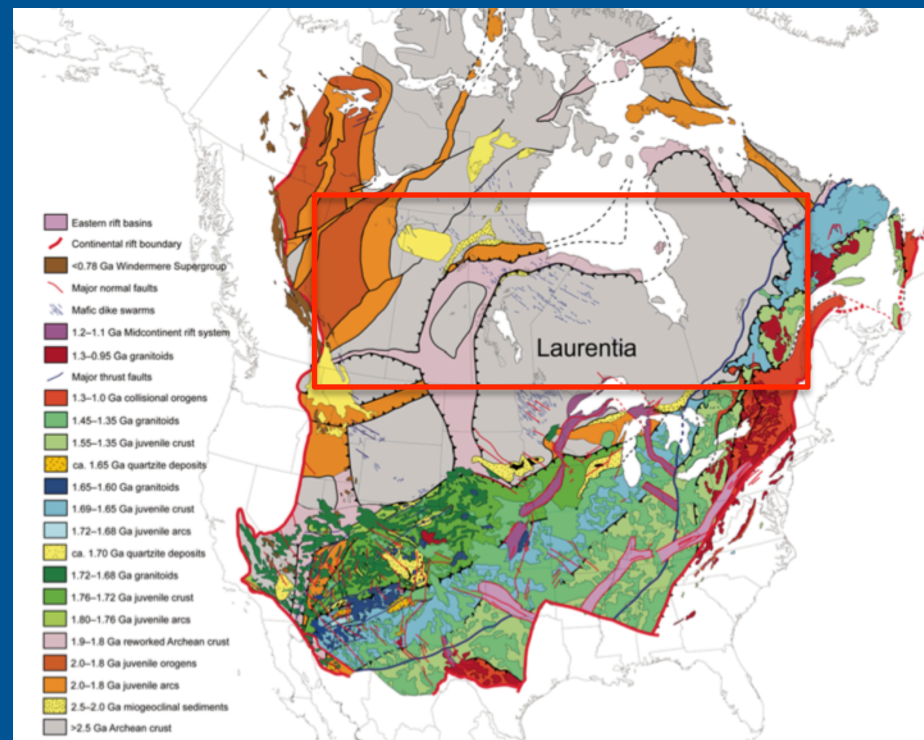
Centroid-based Magnetic Bottom & Geology

Investigating whether magnetic bottoms deeper than Moho may correspond to the relict of serpentinized subducting slabs

Moho from NA04 (van der Lee & Frederiksen, 2004)





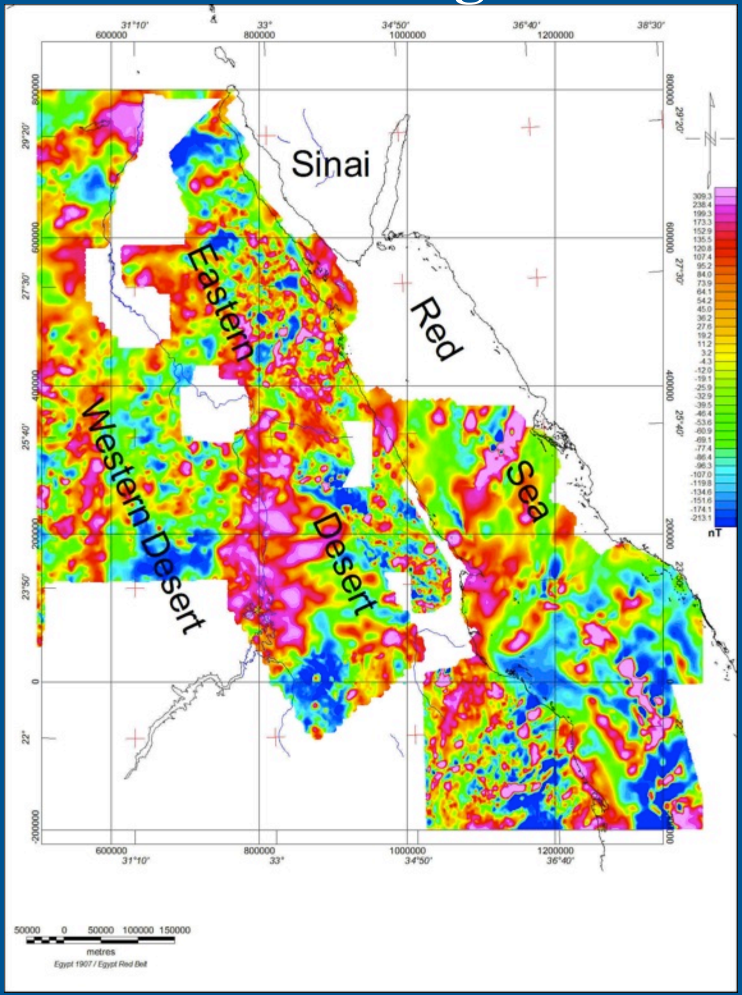


Whitmeyer and Karlstrom (2007)

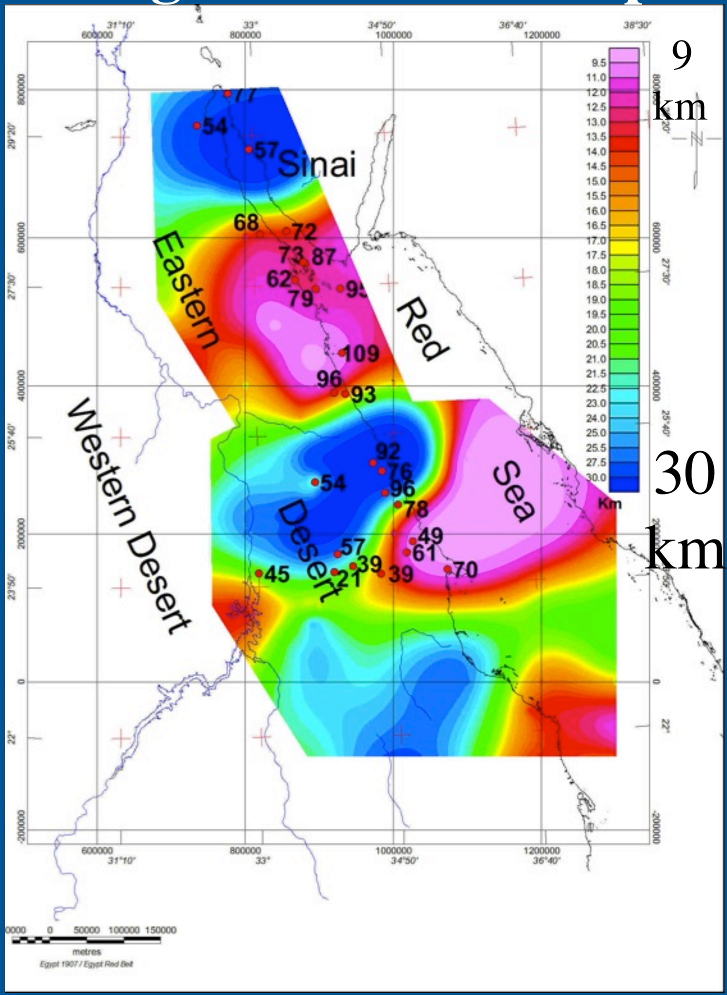
Centroid-based magnetic bottom

Eastern Egypt and the Red Sea

RTP Aeromagnetics

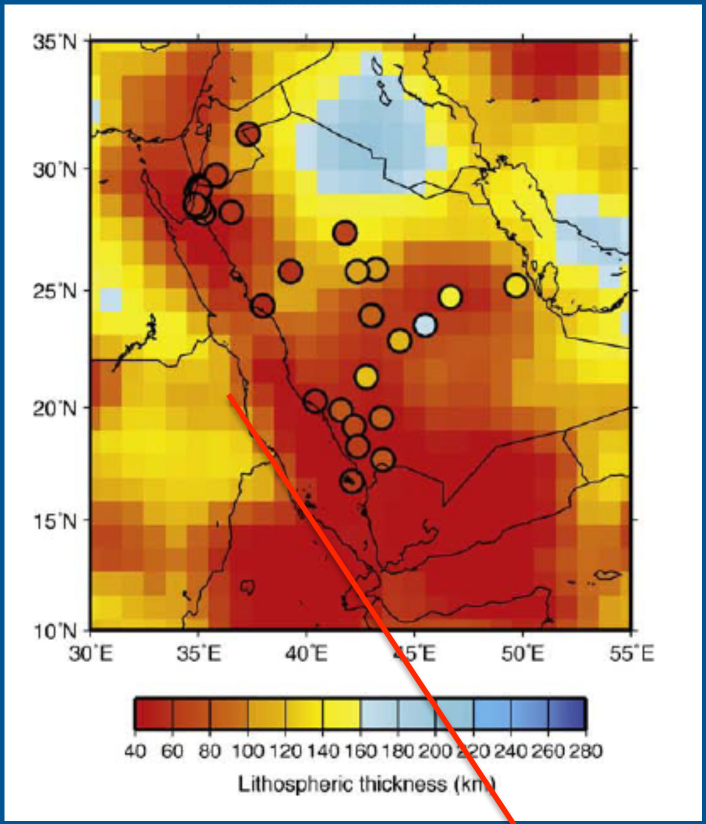


Magnetic Bottom Depths

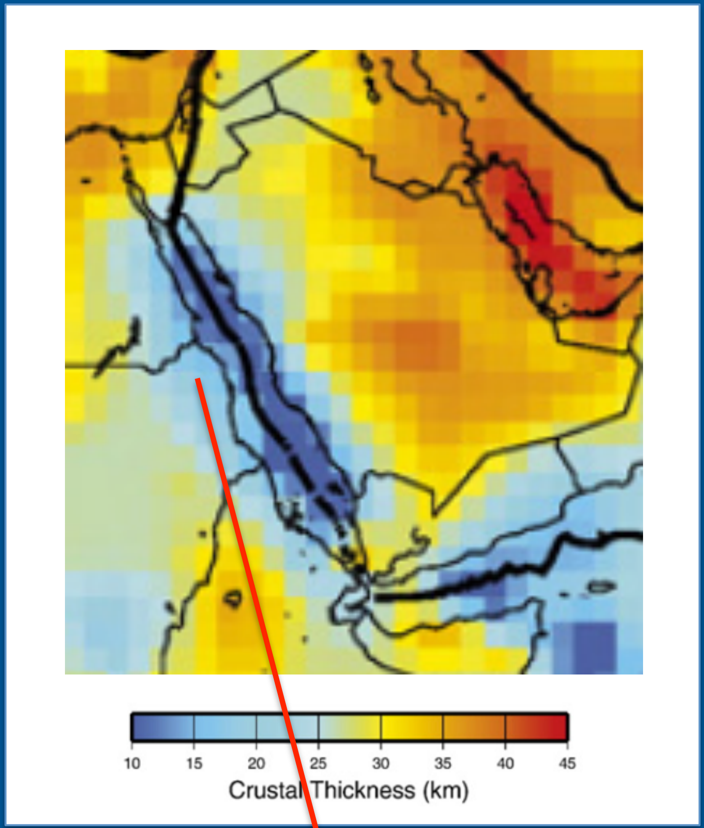


Ravat et al. (2011, Tectonophysics)

Lithospheric thickness (Pasyanos, 2010)

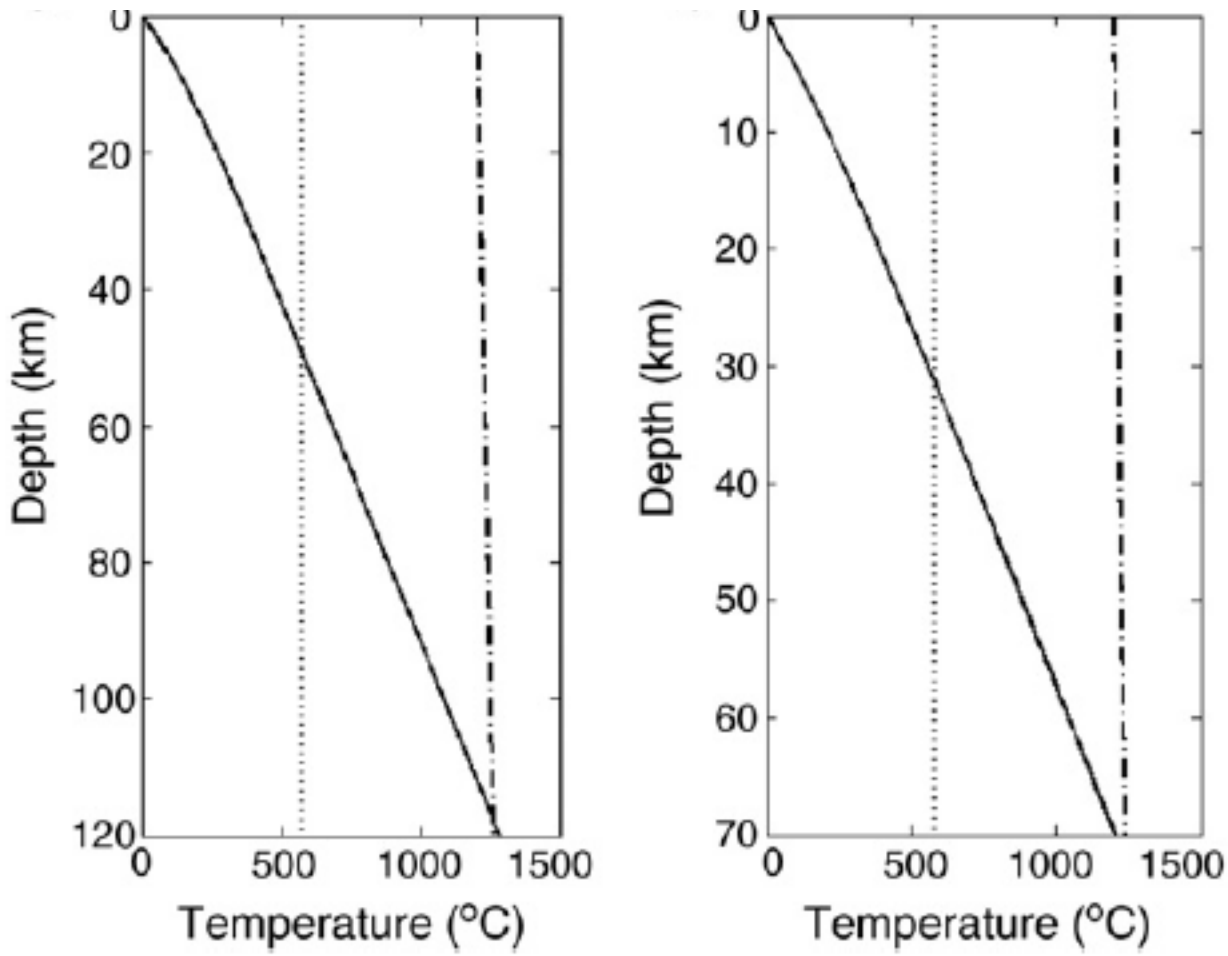


Crustal thickness (Pasyanos & Nyblade, 2007)



Distance from the Red Sea margin (km)	Mean observed and modeled (in [ ]) surface heat flow (mW m^{-2})	Lithospheric thickness (km)	Asthenospheric heat flow (mW m^{-2})	Depth (km) to 580 °C	Estimated crustal thickness (km)	Maximum magnetic bottom estimates (km)
50	60 [61]	70–80	40	~31	~26	~26
100	50 [51]	~100	30	~41	~28	~31–34
200	45 [46]	~120	25	~50	~25–32	~26–27

Geotherms 200 km and 50 km from the Red Sea margin



Distance from the Red Sea margin (km)	Mean observed and modeled (in [ ]) surface heat flow (mW m^{-2})	Lithospheric thickness (km)	Asthenospheric heat flow (mW m^{-2})	Depth (km) to 580 °C	Estimated crustal thickness (km)	Maximum magnetic bottom estimates (km)
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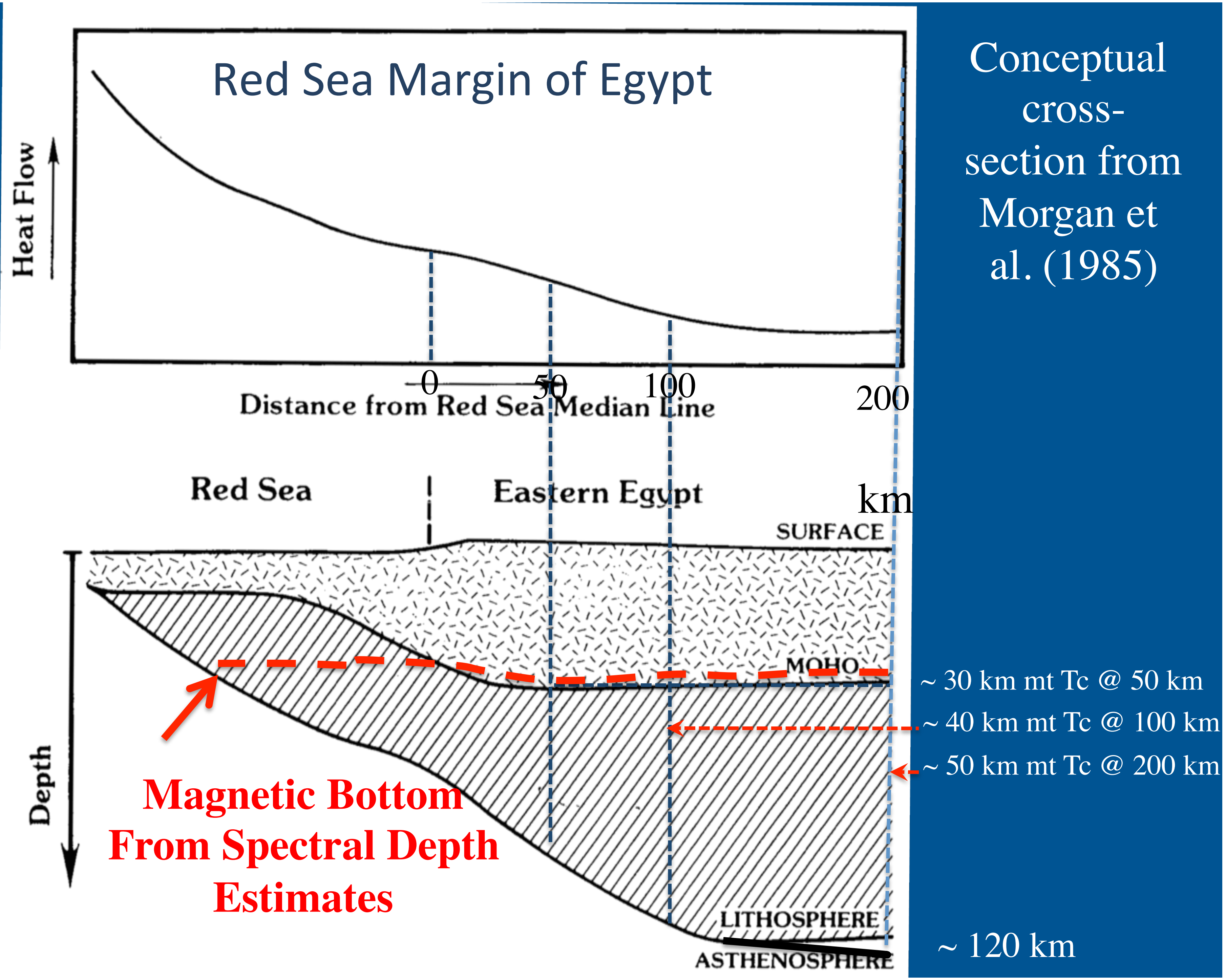
Conceptual cross-section from Morgan et al. (1985)



Conclusions from the Curie Depth Studies

- *Carefully determined magnetic bottom depths from Canada and Eastern Egypt appear to lie in the crust, suggesting that the upper mantle may be non-magnetic (when not serpentinized)*
- *Magnetic mineralogies with lower than 580°C Curie temperatures may be important in interpreting some of the derived magnetic bottom estimates*
- *When a strong magnetization layer overlies a weaker one, a shallower magnetic bottom is estimated using one layer fractal models*
- *The relationship between derived magnetic bottom estimates, the Moho depths, lithospheric temperatures, and geologic boundaries is complex*