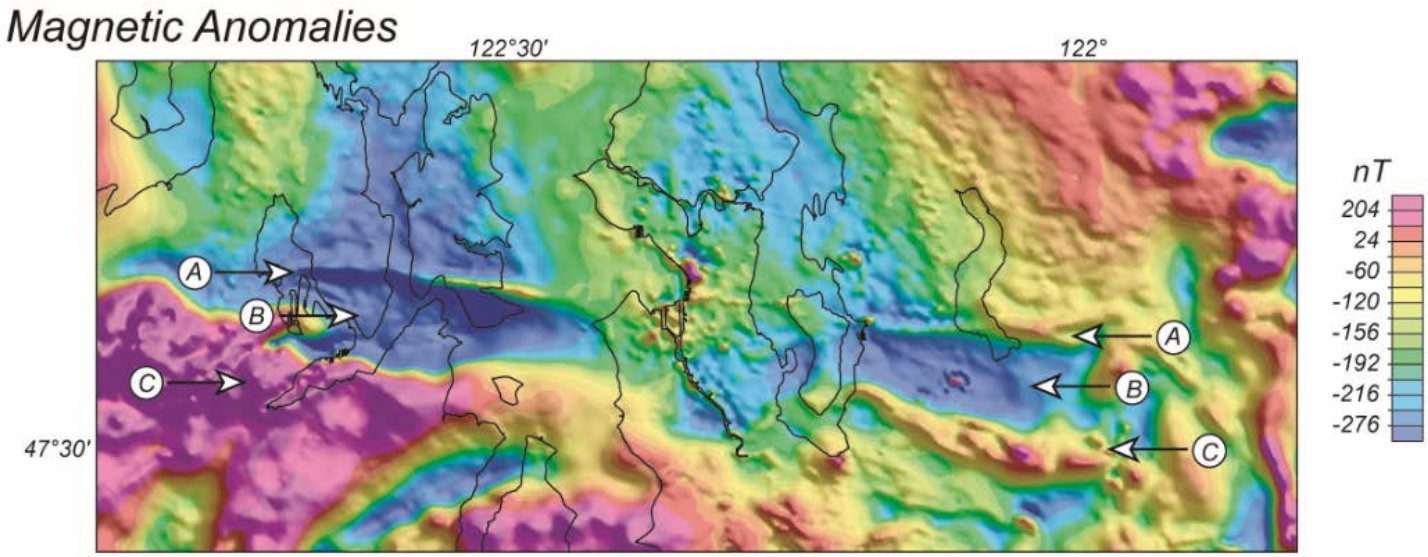
Crustal Field Anomalies

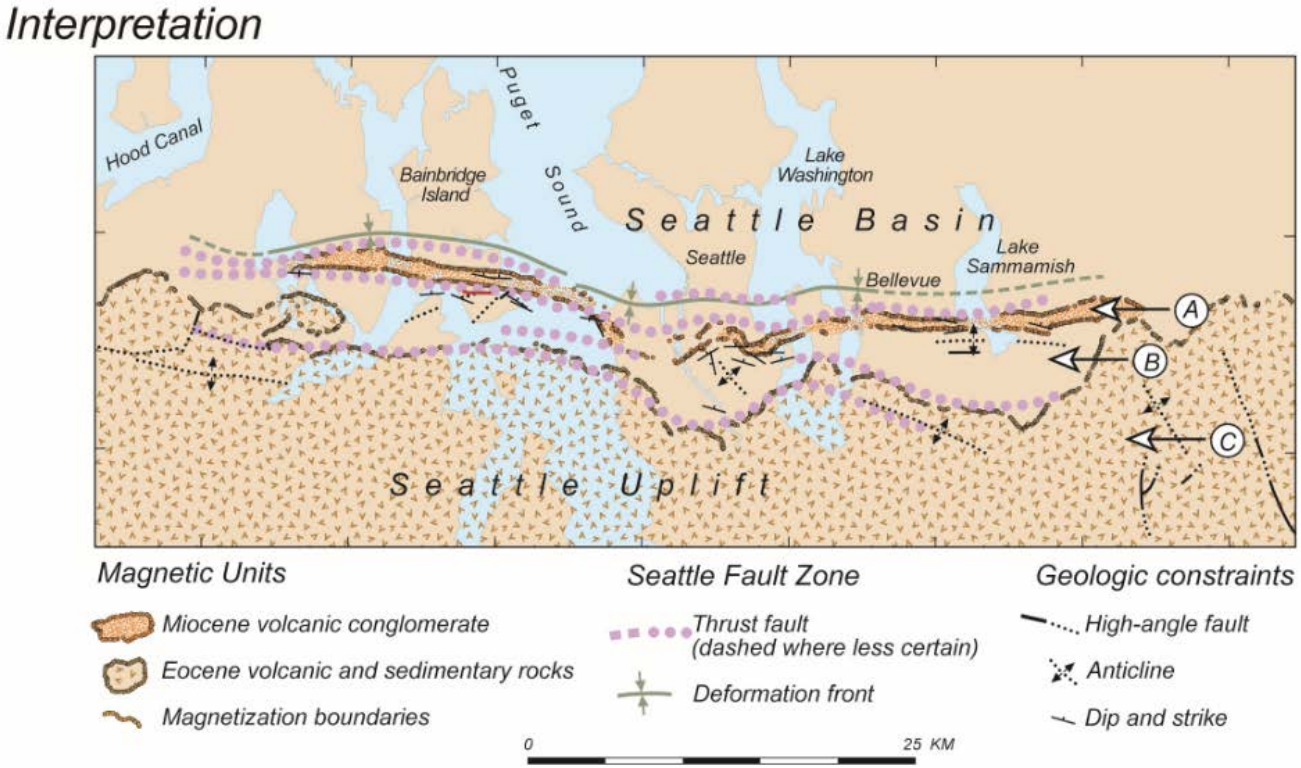
Rick Saltus
CIRES

MARCH 2

Rick Saltus
(CIRES)

Crustal Magnetic Field Anomalies – Measurement and Interpretation





Outline

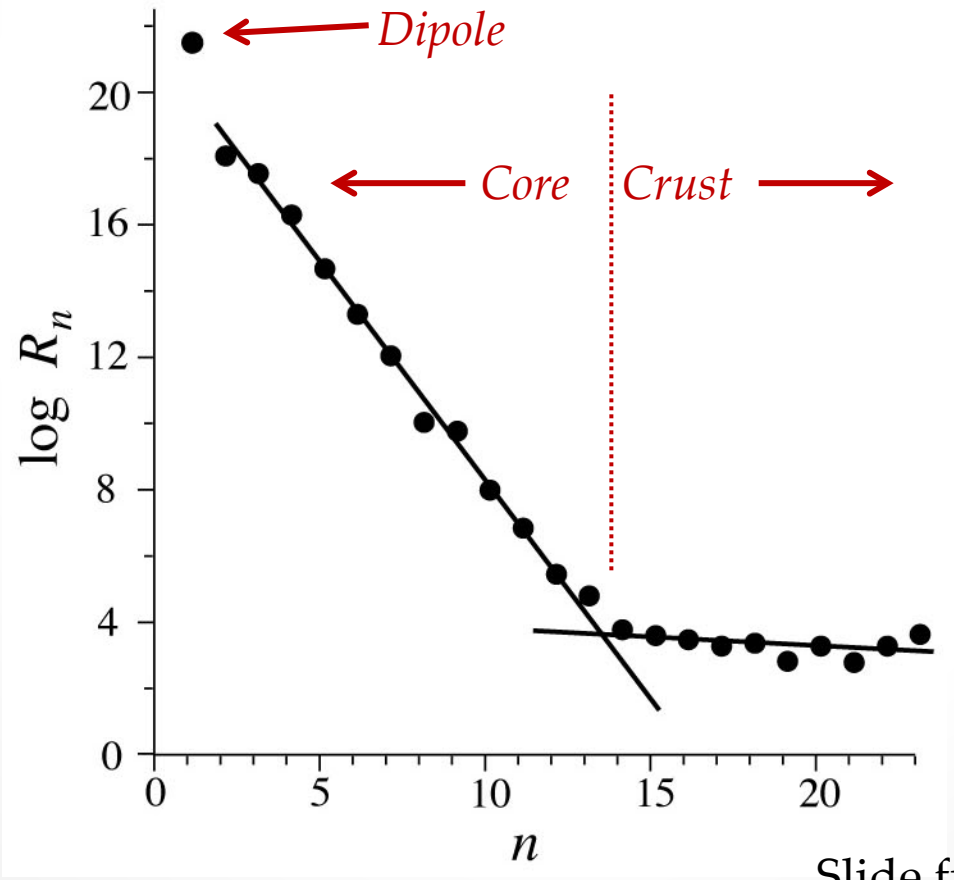
- Recap relationship between crustal magnetic anomalies and the complete geomagnetic field (review from talks by Manoj and Patrick)
- Data collection examples
- A case history of crustal magnetic data for Alaska
- Brief intro to important global grids/models
- Geologic interpretation of crustal magnetic anomalies
- Uncertainty in magnetic anomaly interpretation (ties into the reading assignment)
- A few examples (time permitting)
- Discussion

Who is this Saltus guy?

- Math (BS), Geophysics (MS, PhD) – Stanford
- Started at USGS in 1980 as a field assistant and computer tech
- Took leave and went to grad school 1986-1991
- Thesis involved Gravity and Heat Flow studies including Sierra Nevada (met Craig Jones then)
- USGS work mostly in Alaska and the Arctic since then – Minerals/Energy/Coastal Marine Programs
- Started new job at CIRES yesterday (March 1)

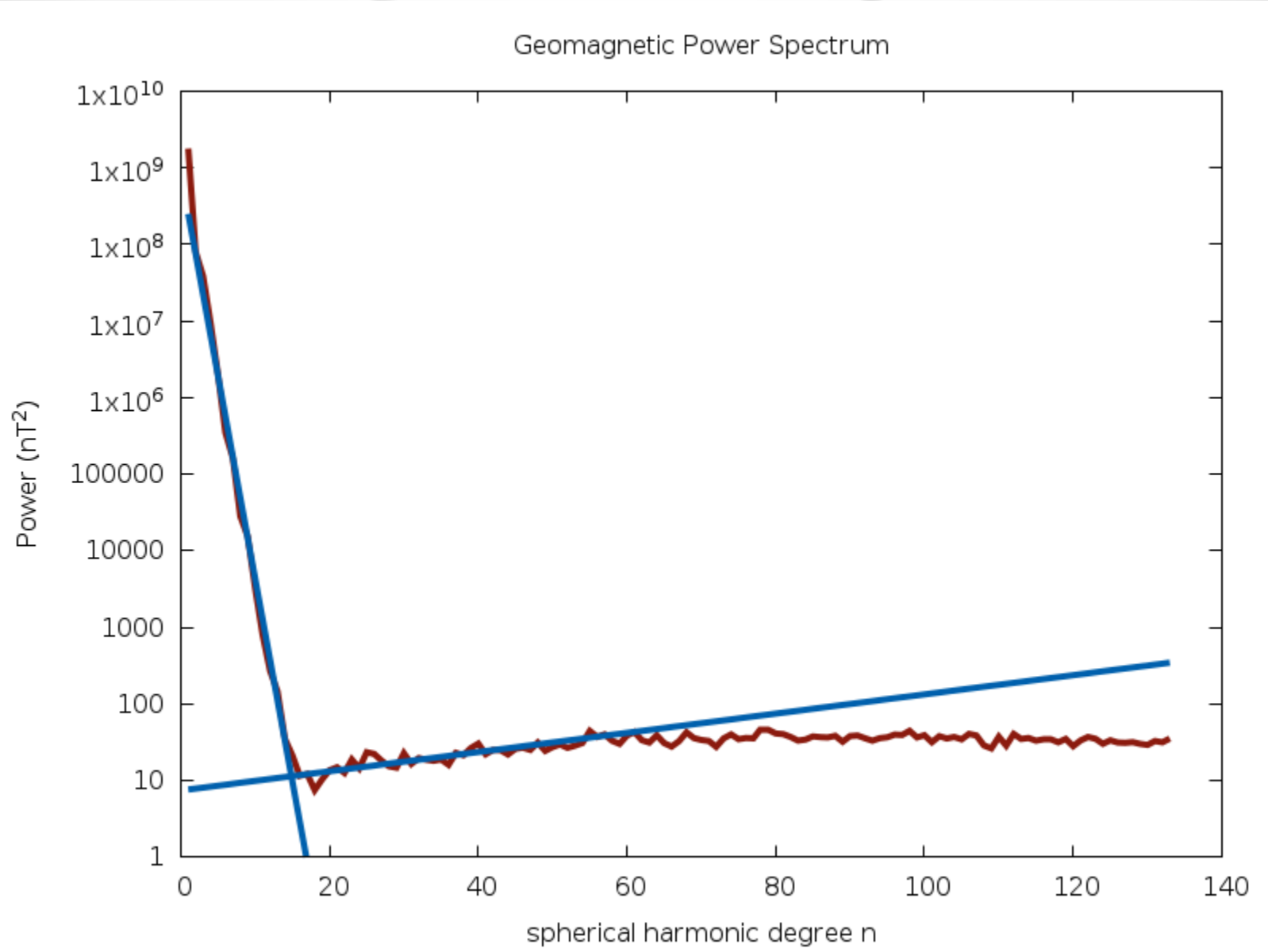
5f. Crustal magnetic anomalies

This graph shows the power spectrum of the geomagnetic field as a function of spherical harmonic degree.



Slide from Rick Blakely

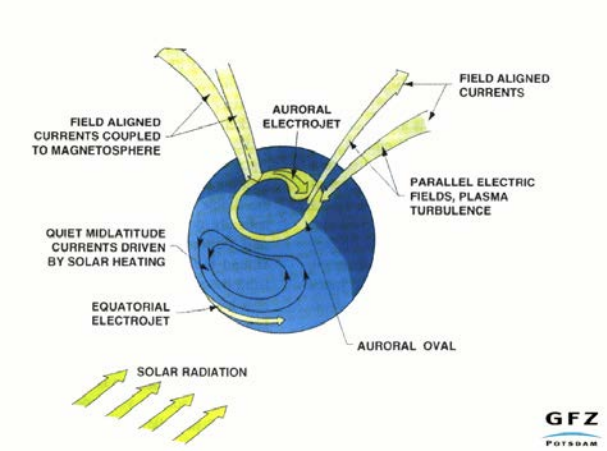
Geomagnetic Power Spectrum



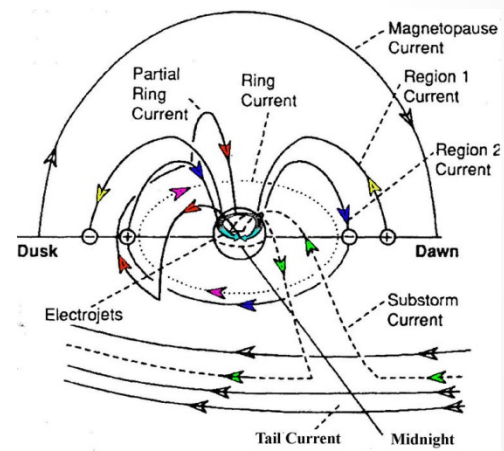
Slide from Patrick Alken

Geomagnetic Field Sources

$$\mathbf{B}_{measured}(\mathbf{r},t) = \mathbf{B}_{main}(\mathbf{r},t) + \mathbf{B}_{crust}(\mathbf{r}) + \boxed{\mathbf{B}_{ionosphere}(\mathbf{r},t)} + \boxed{\mathbf{B}_{magnetosphere}(\mathbf{r},t)} + \mathbf{B}_{induced}(\mathbf{r},t) + \mathbf{B}_{oceans}(\mathbf{r},t) + \mathbf{B}_{noise}(\mathbf{r},t)$$



$$\mathbf{B}_{EEJ}(\mathbf{r},t) + \mathbf{B}_{Sq}(\mathbf{r},t) + \mathbf{B}_{PEJ}(\mathbf{r},t) + \mathbf{B}_{grav}(\mathbf{r},t) + \mathbf{B}_{pg}(\mathbf{r},t) + \mathbf{B}_{FAC}(\mathbf{r},t)$$



$$\mathbf{B}_{RC}(\mathbf{r},t) + \mathbf{B}_{CT}(\mathbf{r},t) + \mathbf{B}_{MP}(\mathbf{r},t) + \ldots$$

Slide from Patrick Alken

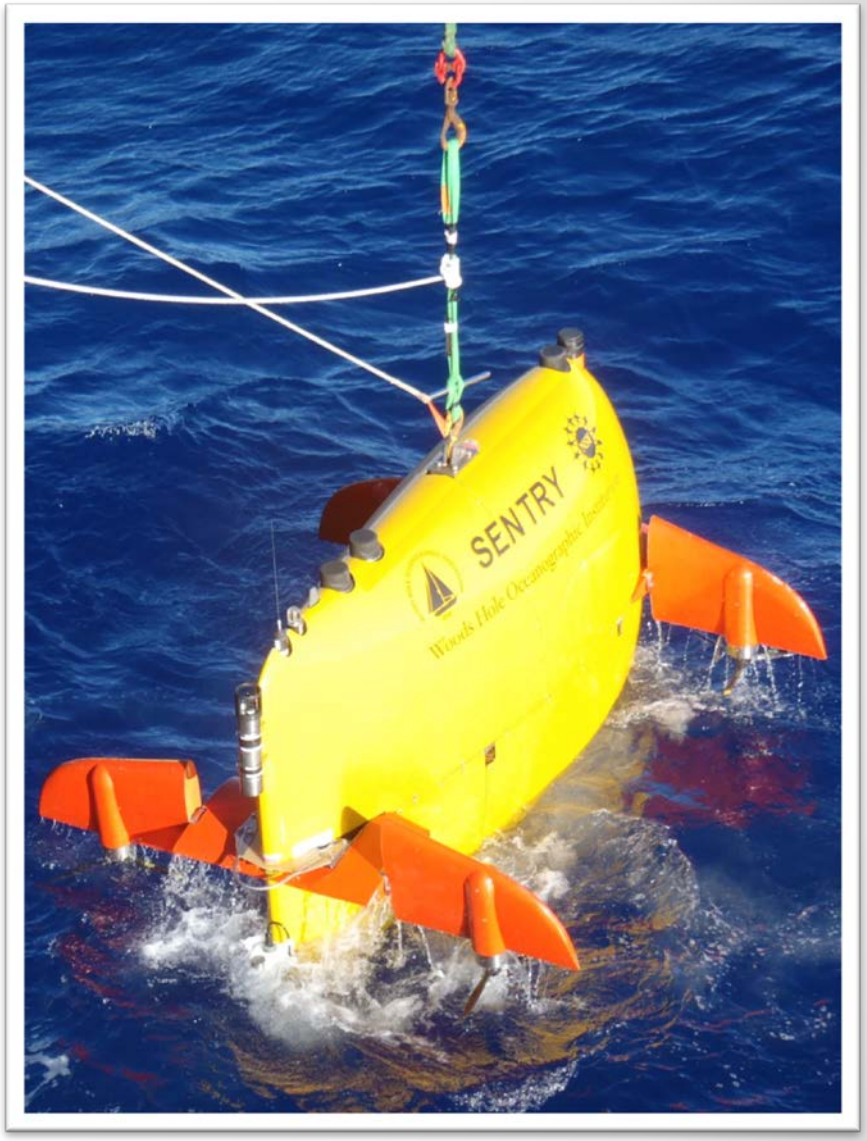
Data Collection

Helicopters

Fixed-wing aircraft

Sea surface

AUV (Autonomous Underwater Vehicle)



Photos provided by Fabio Caratori Tontini (GNS Science, New Zealand).

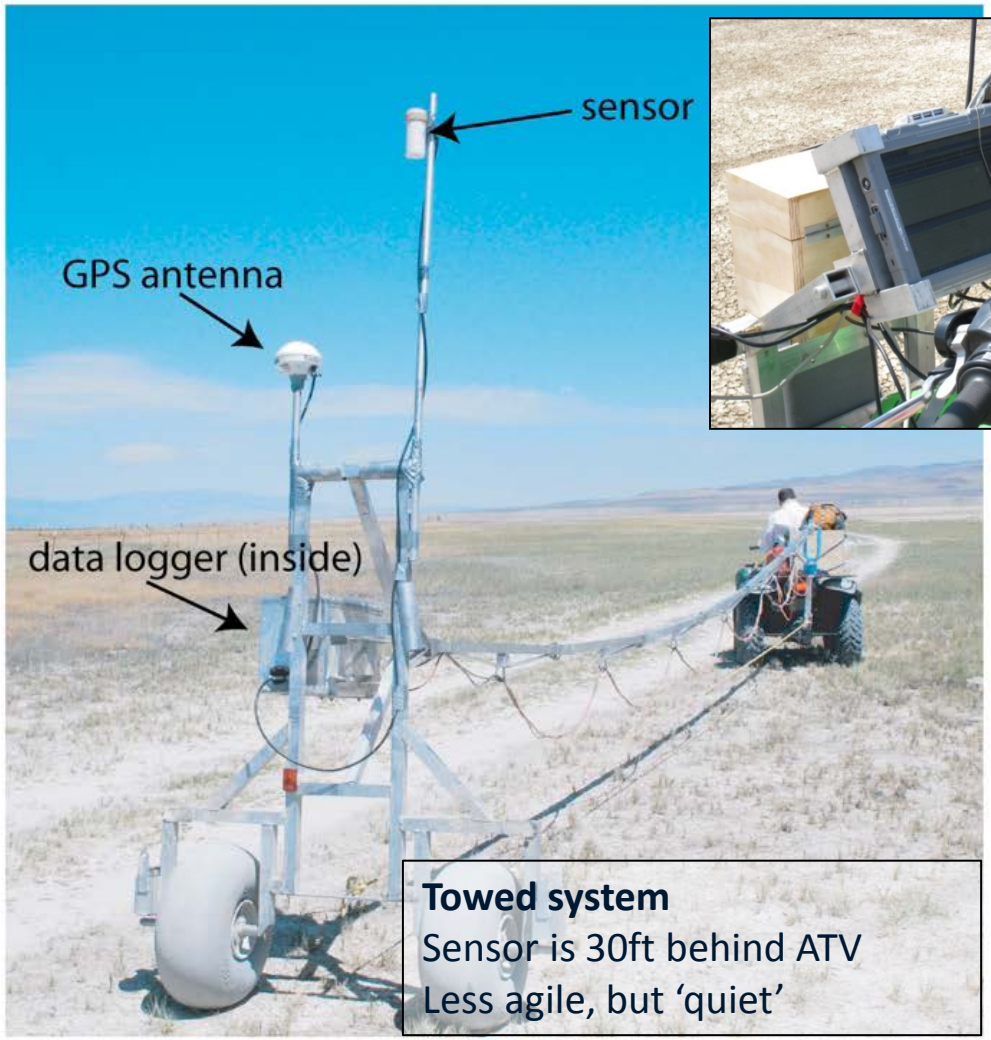
2011 New Zealand—American Submarine Minerals Sentry Cruise

Backpacks

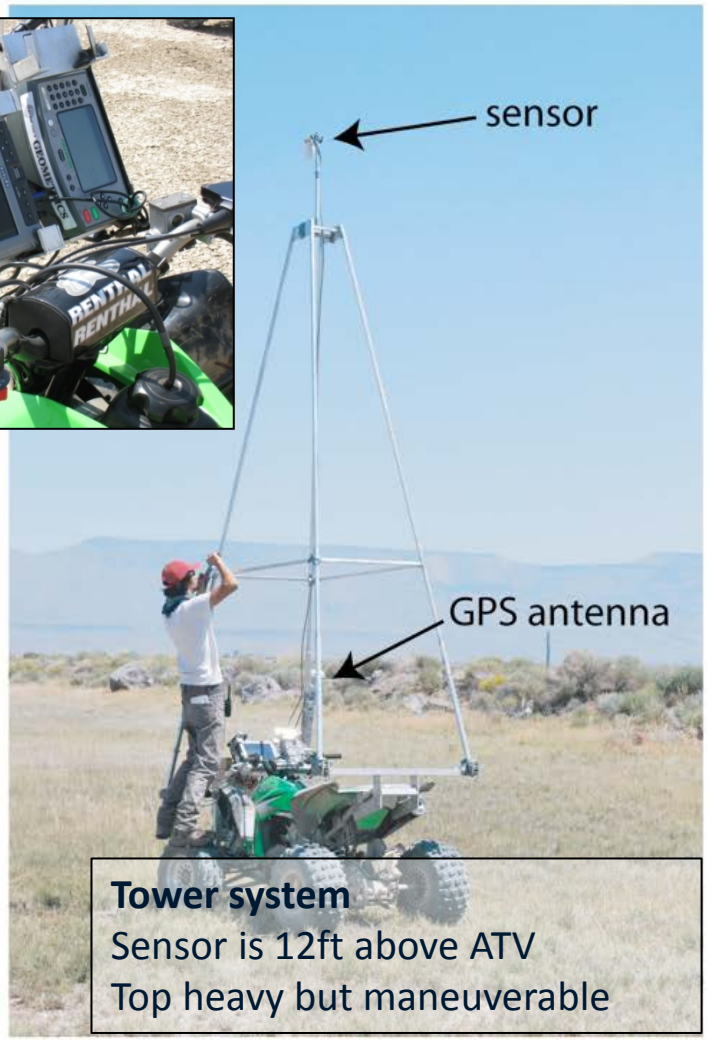
Geometrics cesium-vapor magnetometer system

Small boats

ATV (all-terrain vehicle) systems

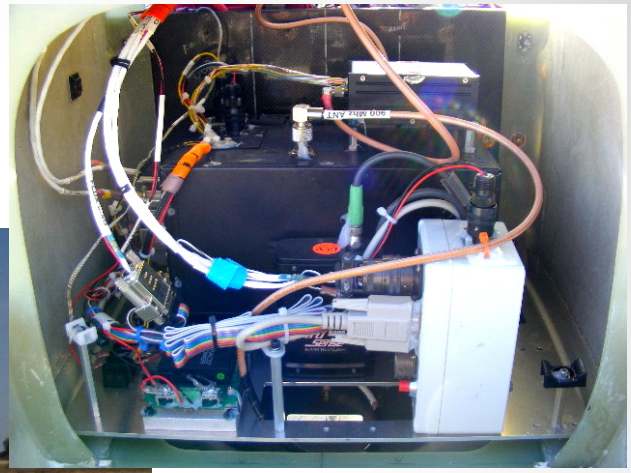


Towed system
Sensor is 30ft behind ATV
Less agile, but 'quiet'



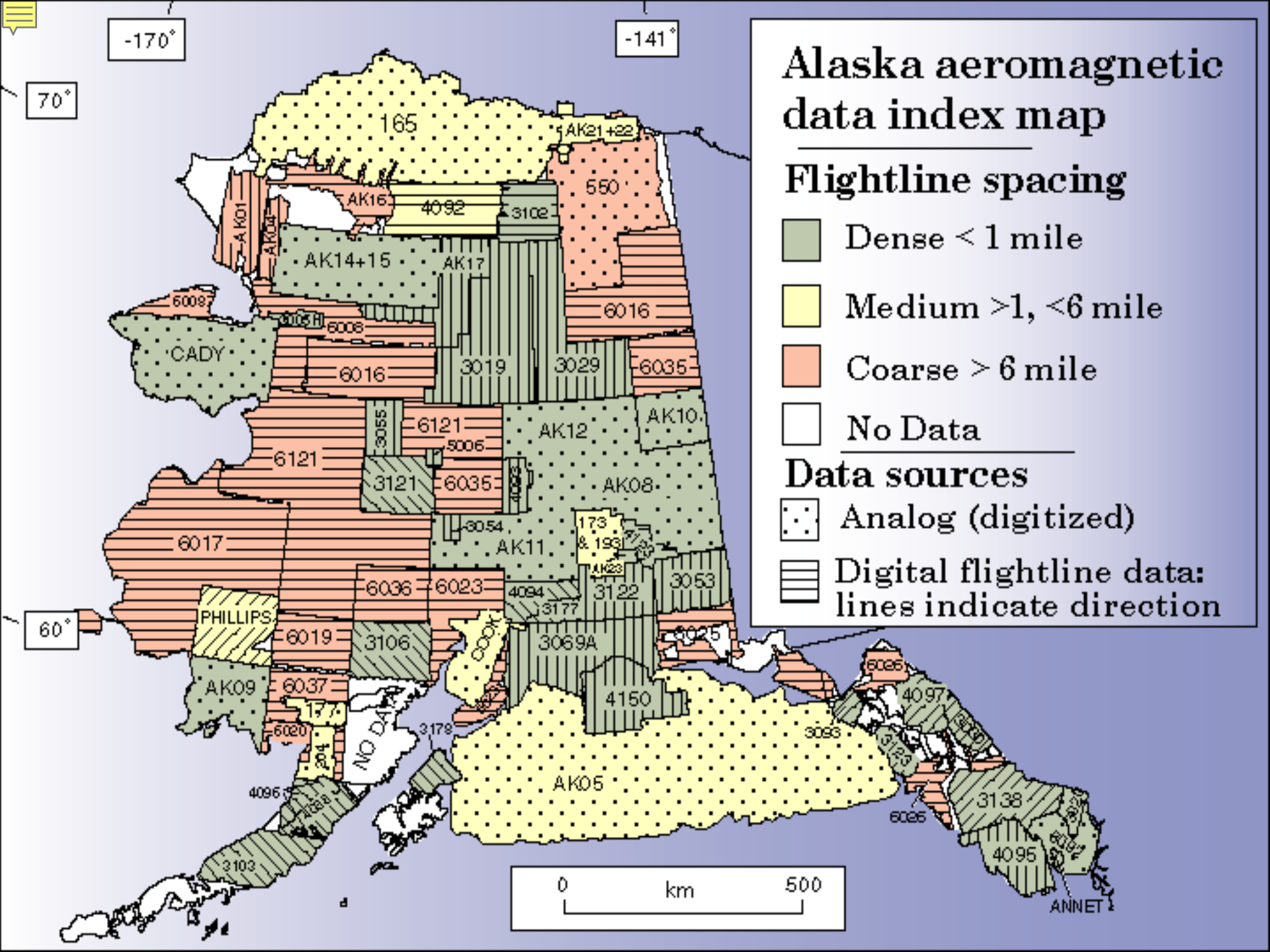
Tower system
Sensor is 12ft above ATV
Top heavy but maneuverable

UAV (Unmanned Aerial Vehicle), under development by Jonathan Glen, USGS



Alaska case study

U.S. Navy aircraft used for
1945/1946 aeromagnetic survey
of the National Petroleum Reserve,
Alaska
PBY-5A



Alaska aeromagnetic data index map
Flightline spacing
Dense < 1 mile
Medium >1, <6 mile
Coarse > 6 mile
No Data
Data sources
Analog (digitized)
Digital flightline data: lines indicate direction
-170°
-141°
70°
60°
165
AK21+22
550
AK16
4092
3102
AK01
AK04
AK14+15
AK17
6008
6016
CADY
6016
3019
3029
6035
AK10
3055
6121
AK12
5006
6121
3121
6035
AK08
3054
173 & 193
AK11
6017
AK23
6036
6023
4094
3122
3053
3177
PHILLIPS
6019
3106
COOK
3069A
6025
6026
AK09
6037
4150
4097
177
6020
NO DATA
3178
3093
AK05
3138
4096
6026
4095
3103
ANNET
0
km
500

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A New Magnetic View of Alaska

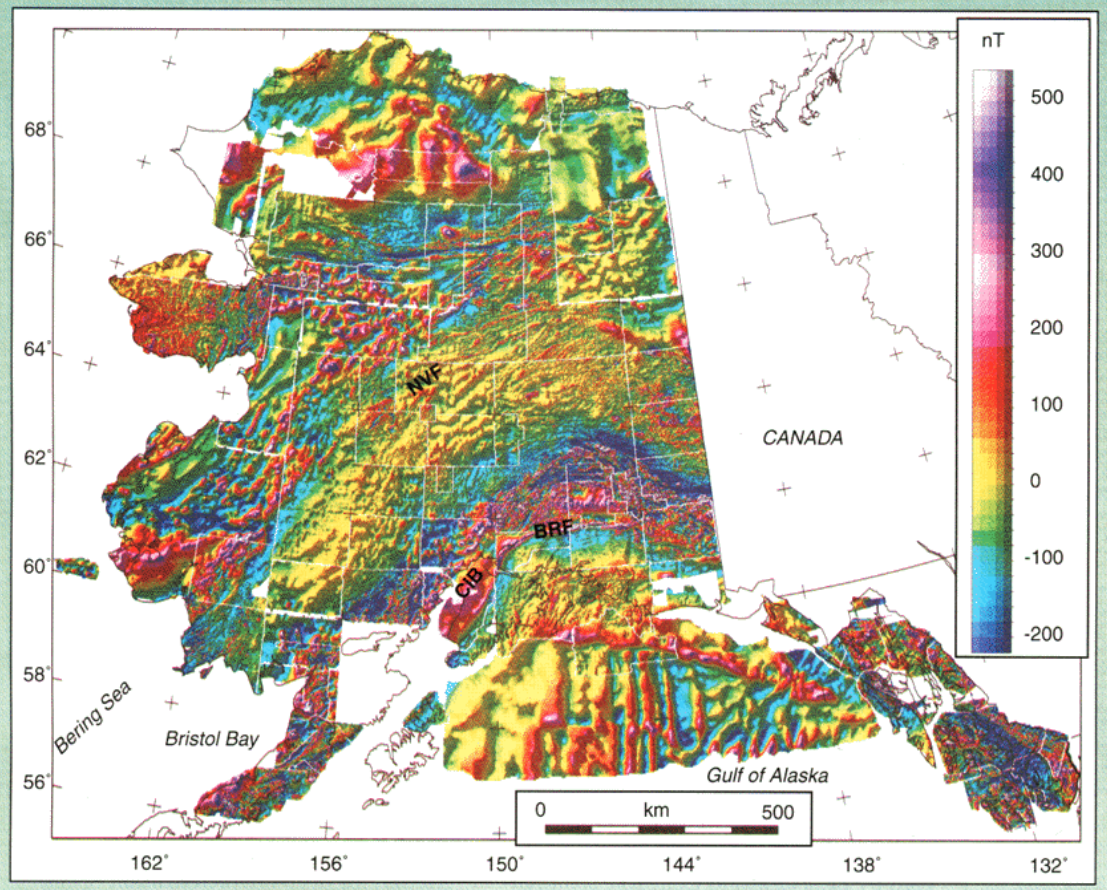

Figure 1. Composite aeromagnetic map of Alaska that depicts total field magnetic data values (International Geomagnetic Reference Field has been removed) from a compilation of 85 separate surveys and two grids. Thin data gaps mark the boundaries between data sets. CIB—Cook Inlet Basin, NVF—Nowitna volcanic field, BRF—Border Ranges fault. Data set can be downloaded from the Web at: ftp://greenwood.cr.usgs.gov/ pubs/open-file-reports/ofr-97-0520/data. A 1:2,500,000 plot file of this data set is available at: ftp://greenwood.cr.usgs.gov/pubs/open-file-reports/ofr-97-0520/plots.

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Travis L. Hudson, *Applied Geology, P.O. Box 1428, Sequim, WA 98382-1428*
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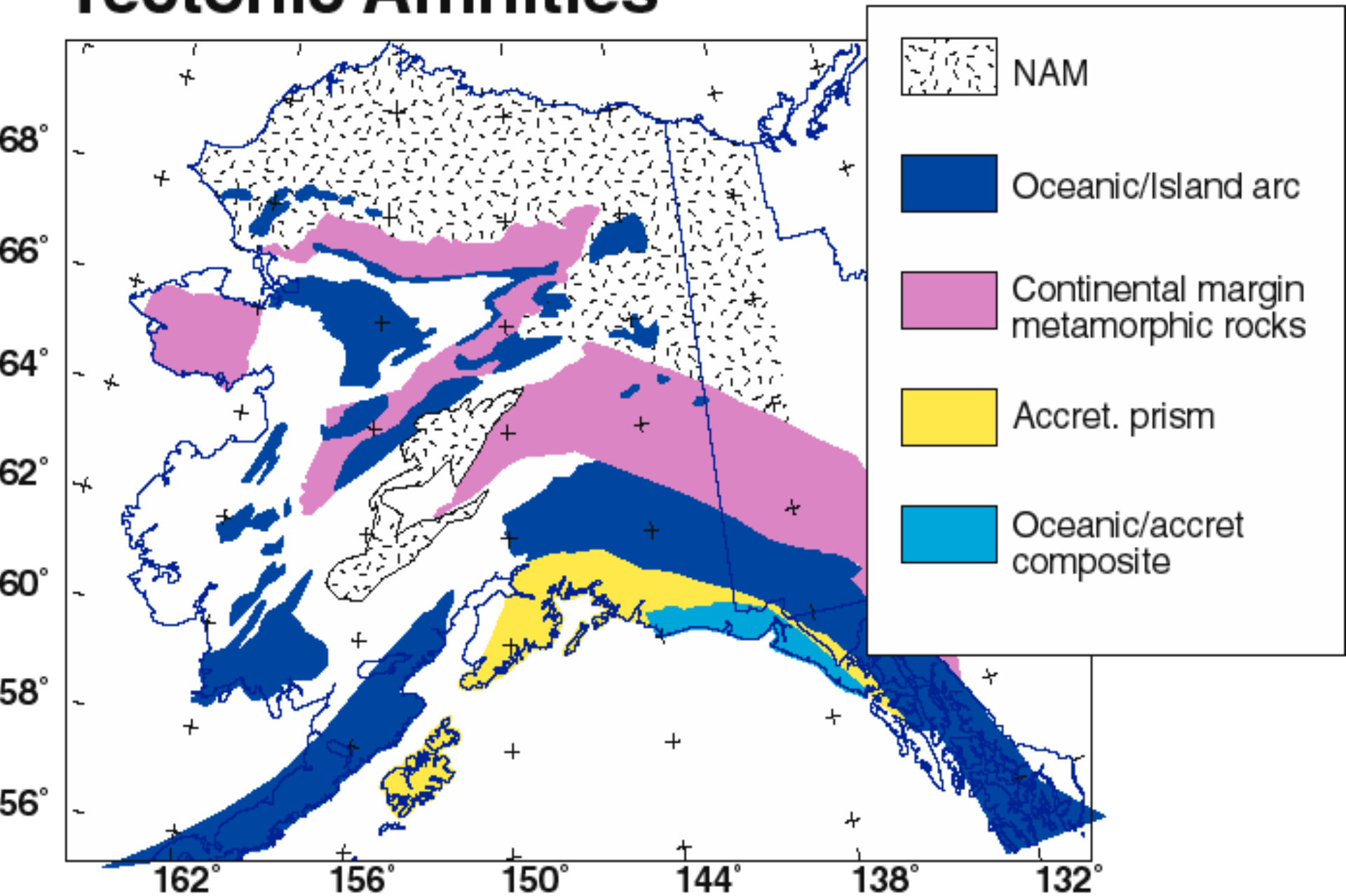
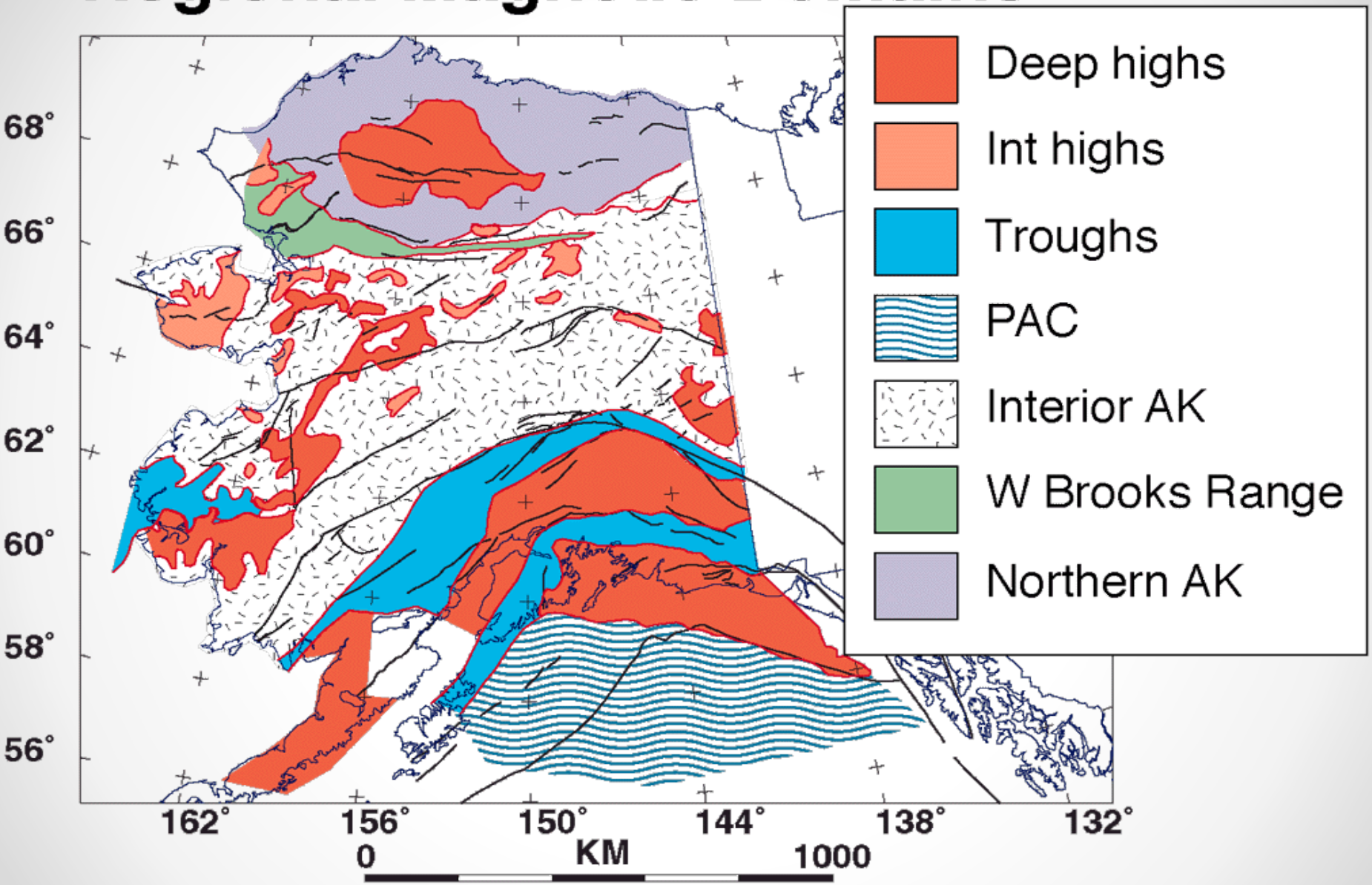
Tectonic Affinities

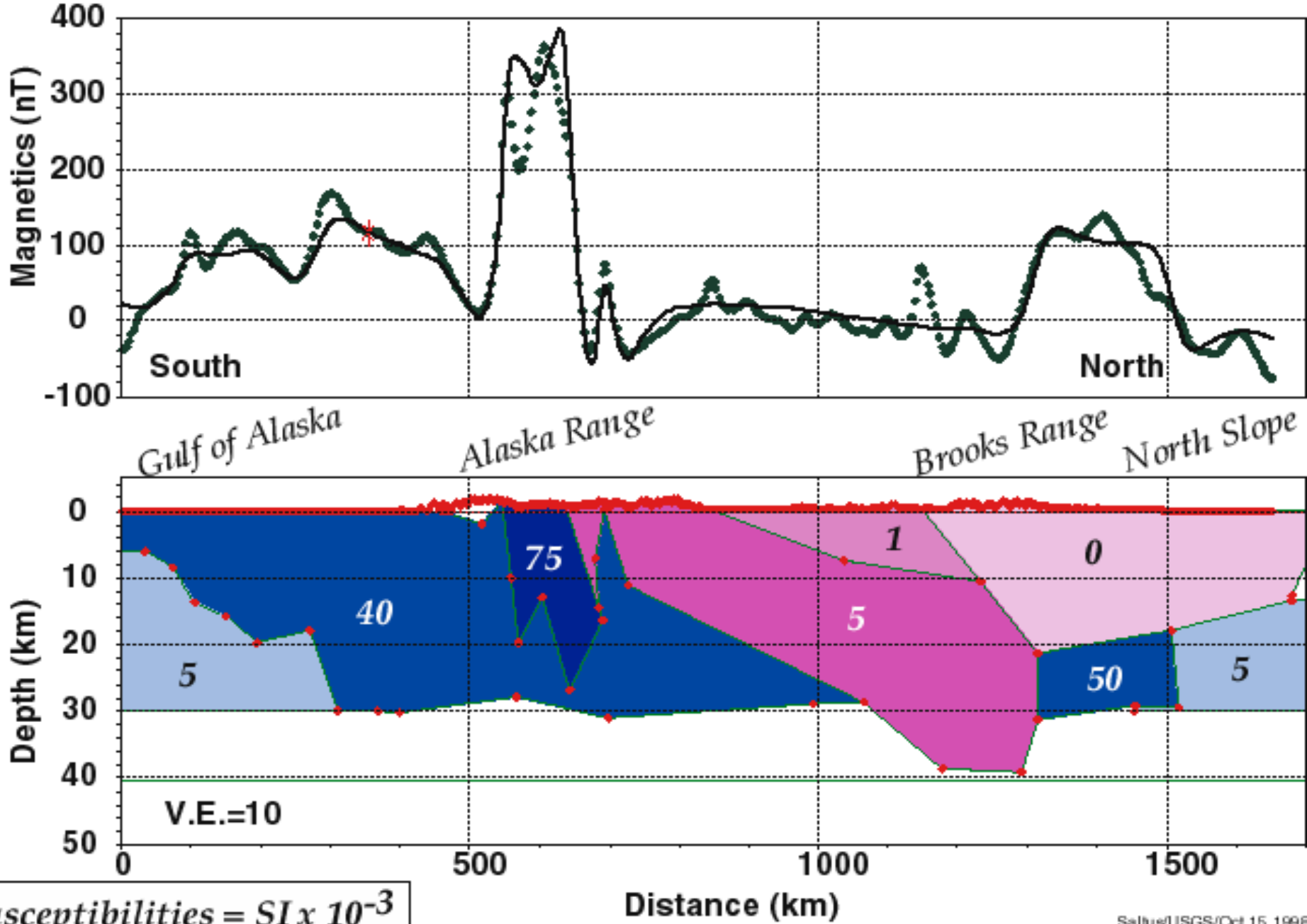


Generalized from Plafker and Berg, 1994

Regional Magnetic Domains



Alaska regional magnetic model



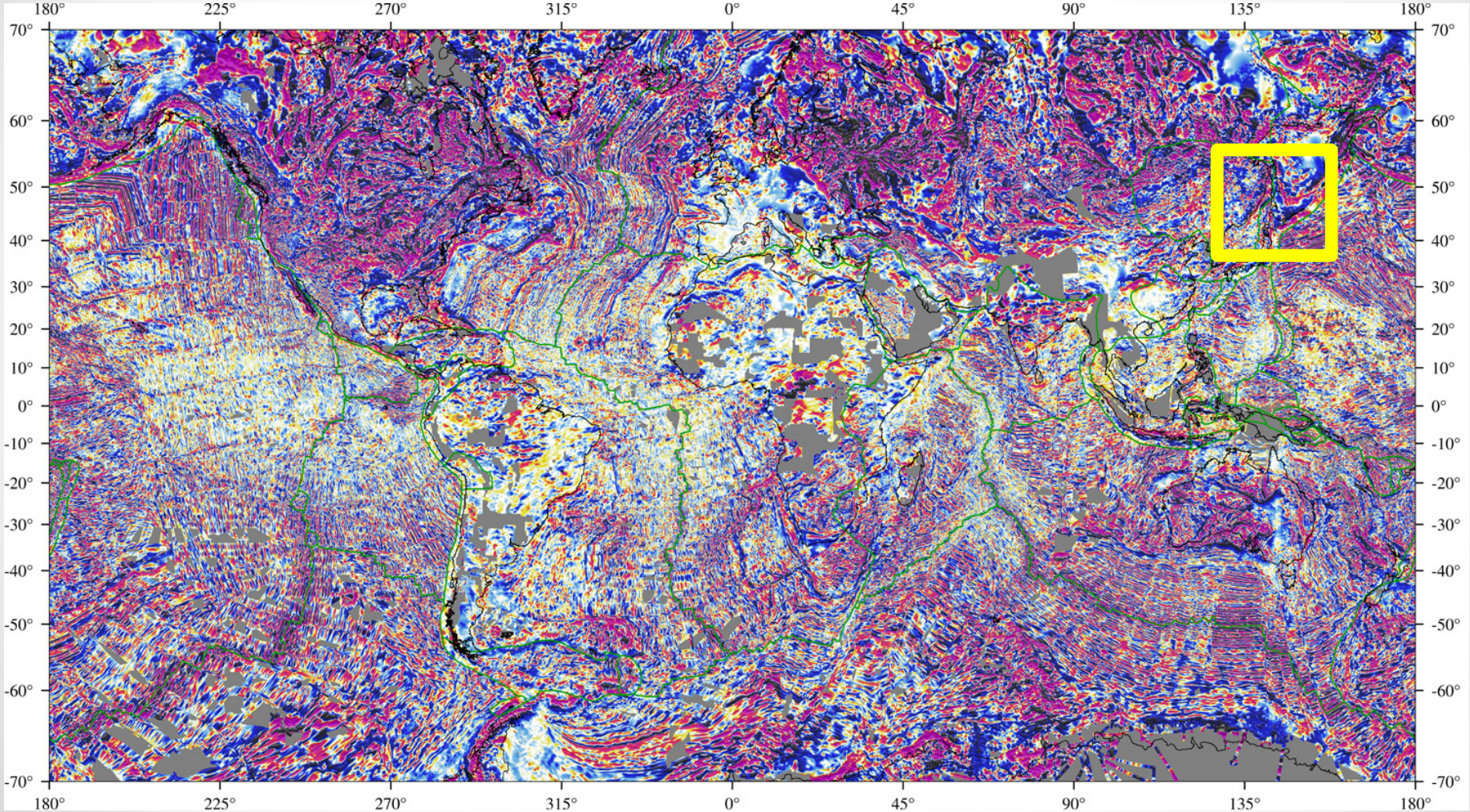
susceptibilities = SI x 10^{-3}

Saltus/USGS/Oct 15 1996

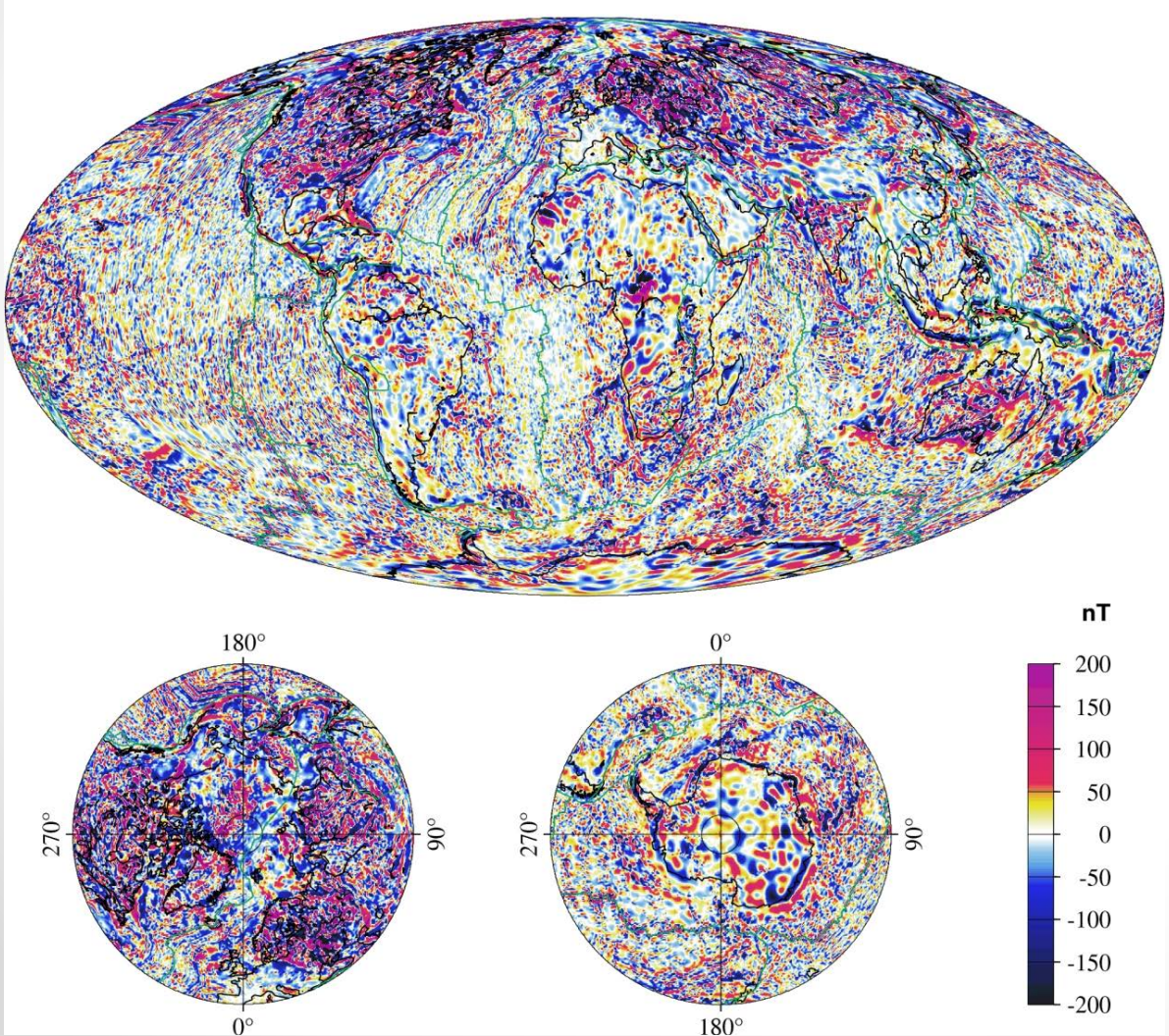
Global grids/models

- MF7
- EMAG2
- Other global magnetic maps
- Regional compilations
- Sources of individual survey data – maritime and airborne

EMAG2: Crustal magnetic field based on marine, airborne, ground, and satellite data. Available on the web as a 2-arc-minute database. From Stefan Maus, NOAA.



Global database of the crustal magnetic field, based on satellite, marine, airborne, and ground data. It is represented here as an ellipsoidal harmonic function, degrees 16 through 720.

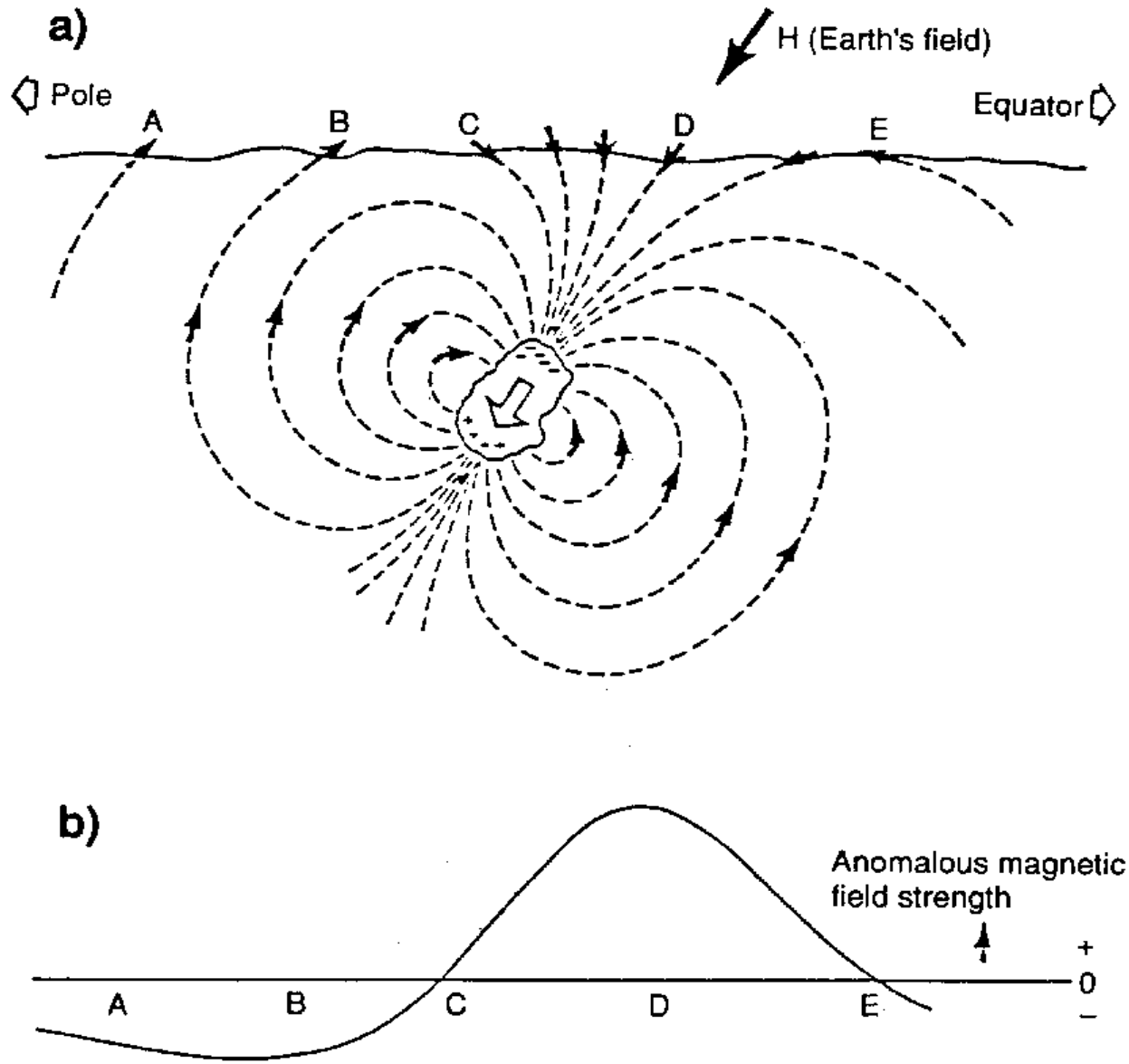


B_z at Earth's surface
NGDC-720, Version 3.0.
From Stefan Maus

Geologic Interpretation

- Intro to board exercise

Induced Magnetic Anomaly



Magnetic primer

Sphere of radius r_s:

Mag

$$\frac{\mathrm{M} r_s^3}{3z^3} \frac{2-(x/z)^2}{[1+(x/z)^2]^{5/2}}$$

Gravity

$$\frac{4\pi G\rho r_s^3}{3z^2} \frac{1}{[1+x^2/z^2]^{3/2}}$$

Horizontal cylinder of radius r_c:

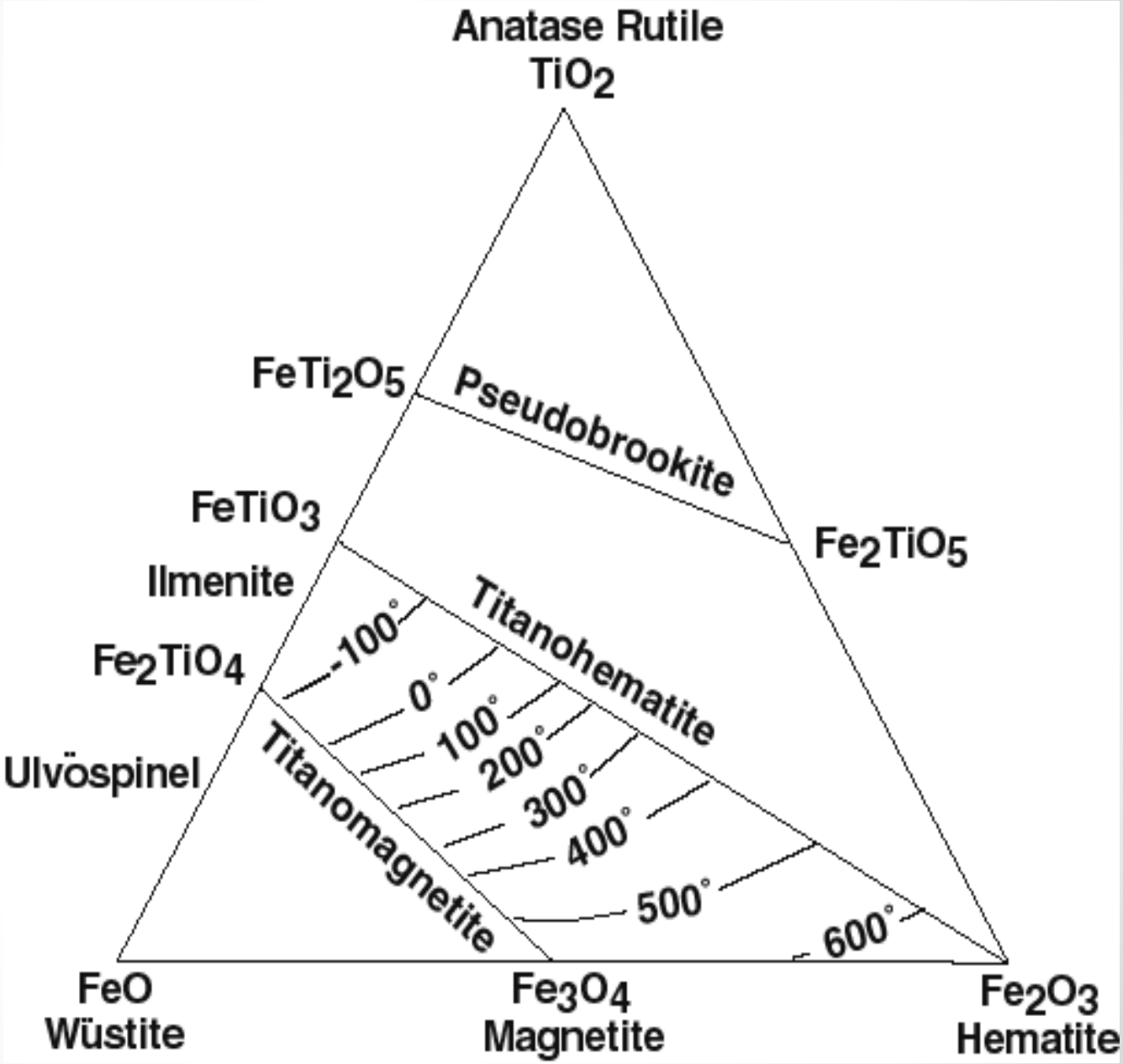
Mag

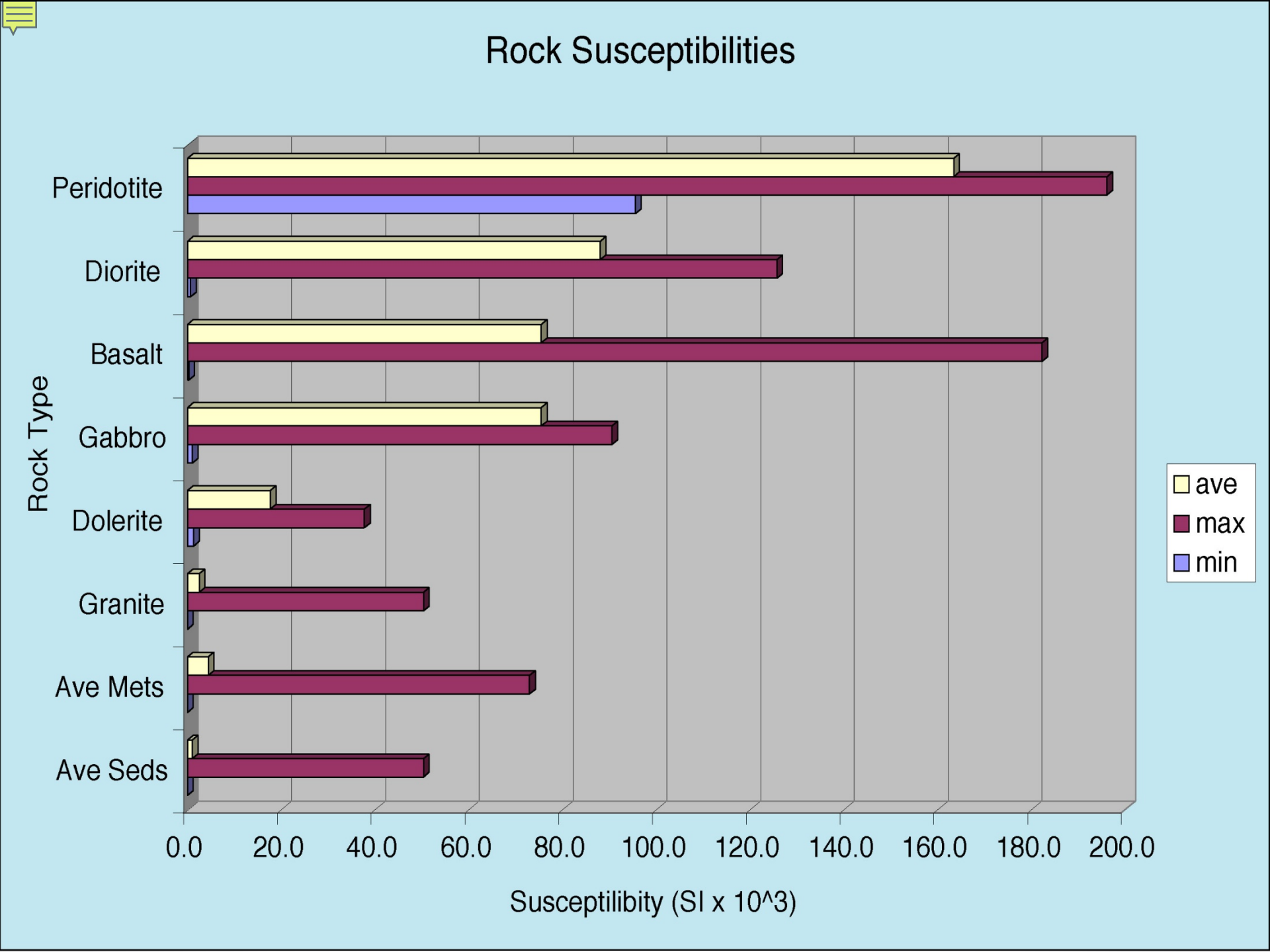
$$\frac{\mathrm{M} r_c^2}{2z^2} \frac{2-(x/z)^2}{[1+(x/z)^2]^2}$$

Gravity

$$\frac{4\pi G\rho r_c^2}{2z} \frac{1}{1+(x/z)^2}$$

Magnetic Minerals




Rock Susceptibilities
Rock Type
Peridotite
Diorite
Basalt
Gabbro
Dolerite
Granite
Ave Mets
Ave Seds
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
200.0
Susceptilibity (SI x 10^3)
ave
max
min

Fourier filters for magnetic data:

Upward continuation (by Δz):

$$F[h_U(x,y)] = F[h(x,y)]e^{-\Delta z|k|}$$

Downward continuation:

$$F[h_U(x,y)] = F[h(x,y)]e^{+\Delta z|k|}$$

Reduction to the pole (RTP):

$$F[h_P(x,y)] = F[h(x,y)]\frac{-2\pi}{\theta(k_x,k_y)}$$

Pseudogravity transformation:

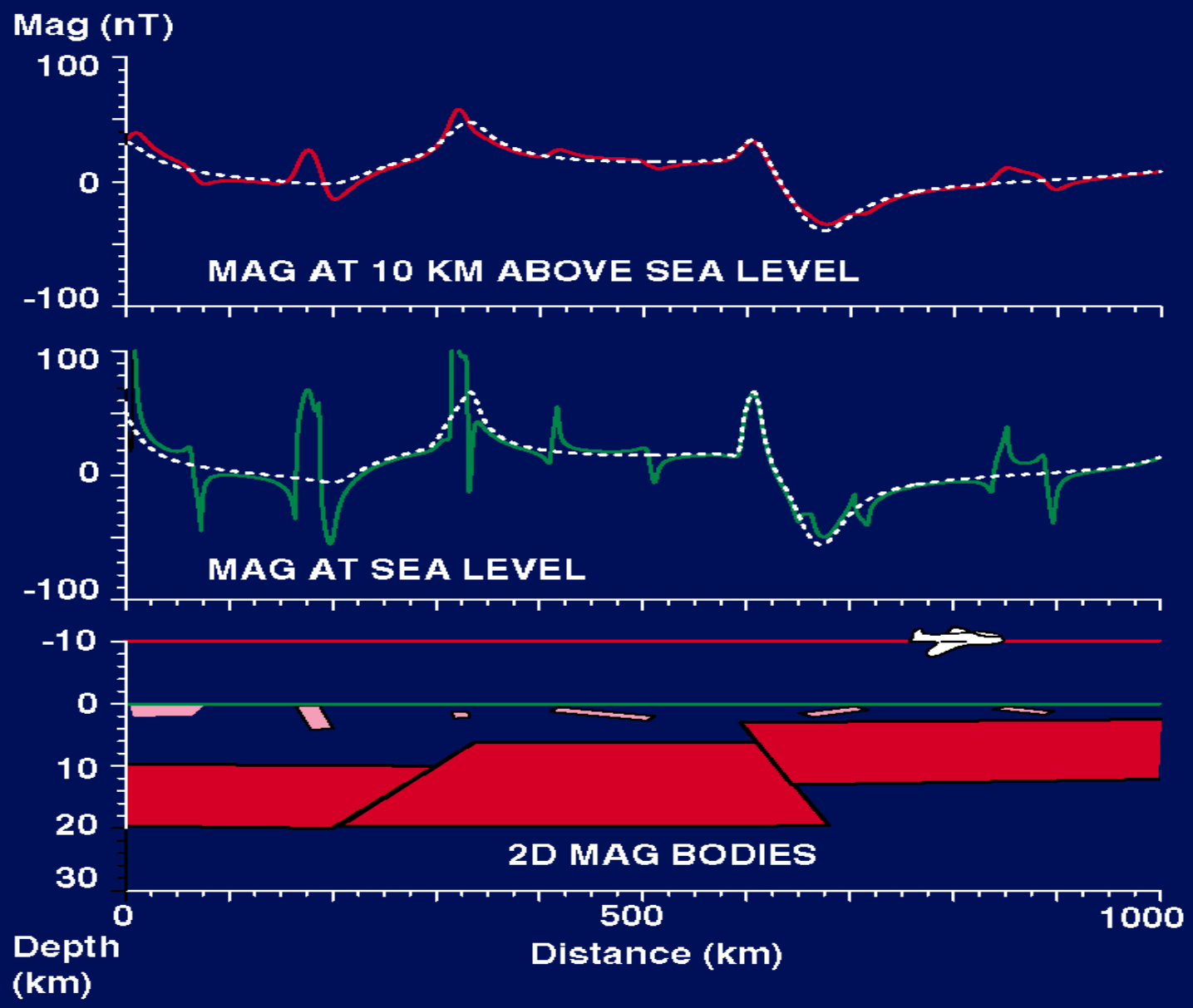
$$F[h_{PSG}(x,y)] = F[h(x,y)]\frac{-2\pi}{\theta(k_x,k_y)}\frac{A}{|k|}$$

k = wavenumber,

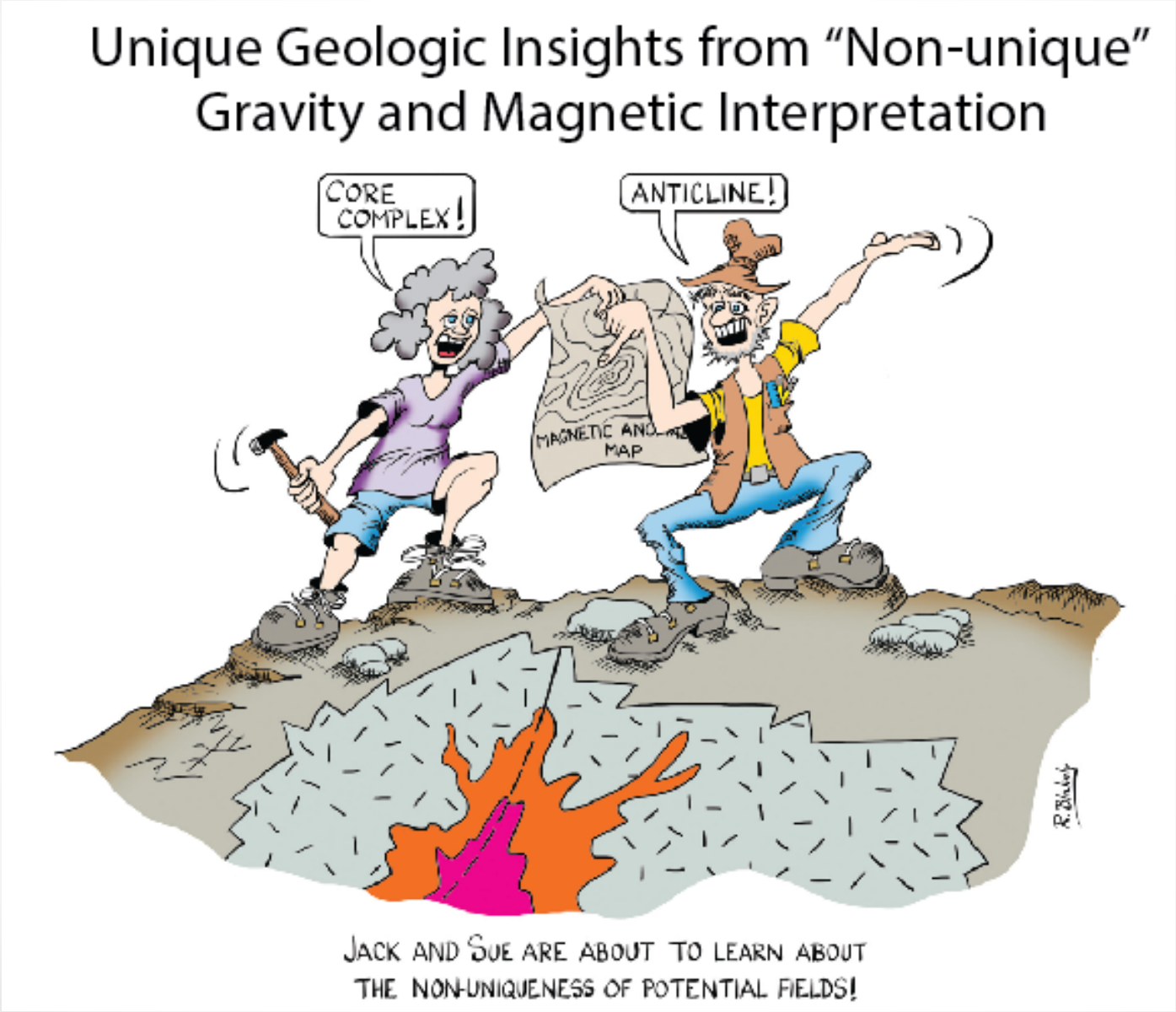
$\theta(k_x,k_y)$ = a complicated function that depends only on the direction and magnitude of the Earth's magnetic field.

A = a constant based on the expected ratio of pseudo-density to magnetization

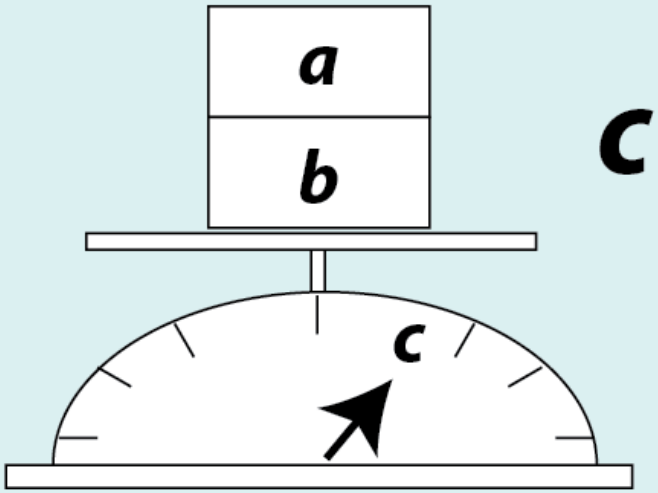
Upward Continuation of Magnetic Data



Uncertainty in magnetic interpretation



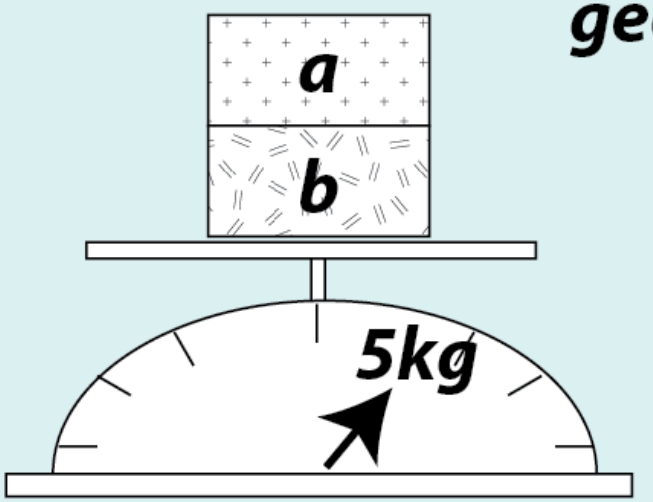
theoretical



$$c = a + b$$

NON-UNIQUE

practical



measured data

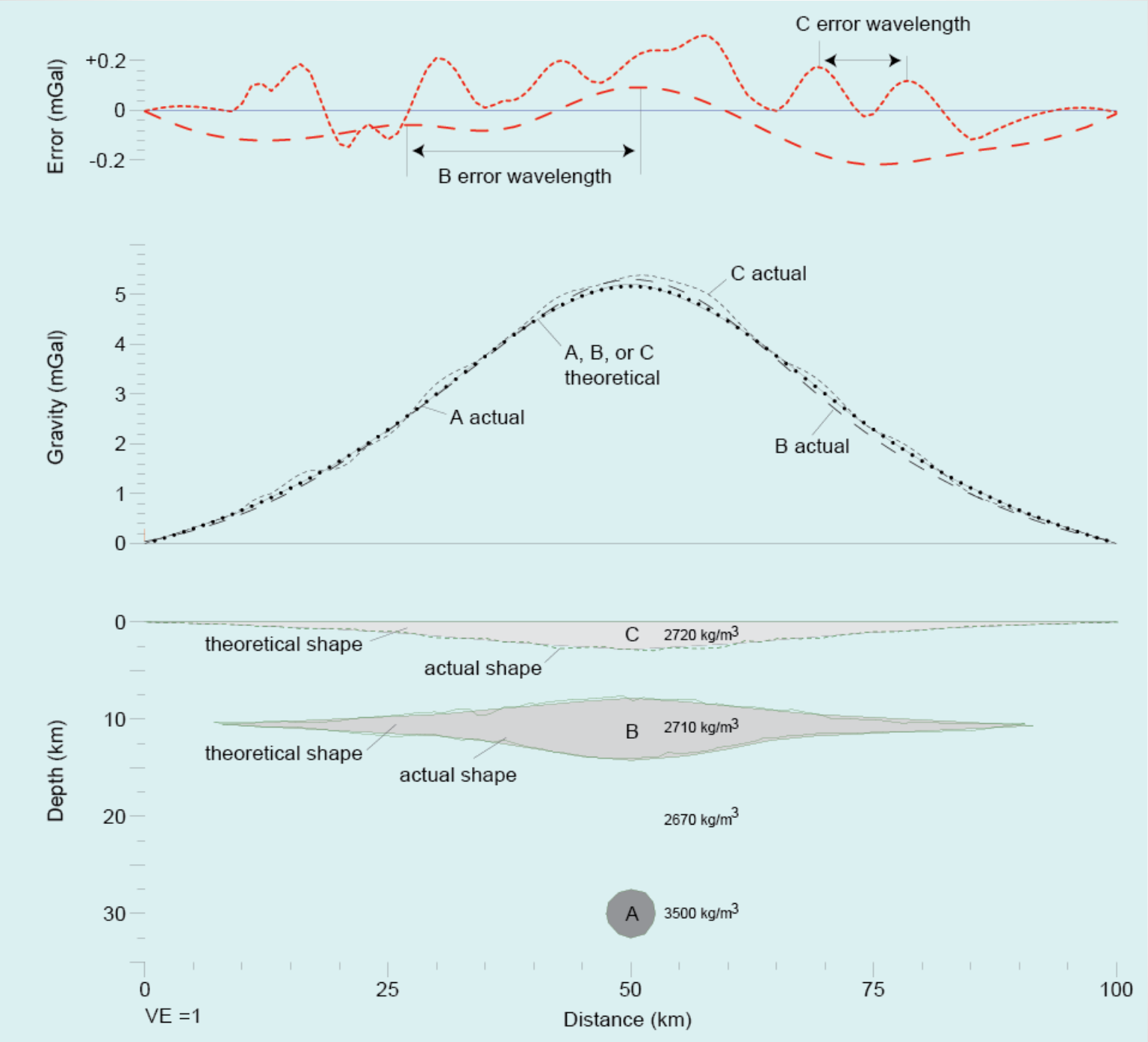
geologic constraints:

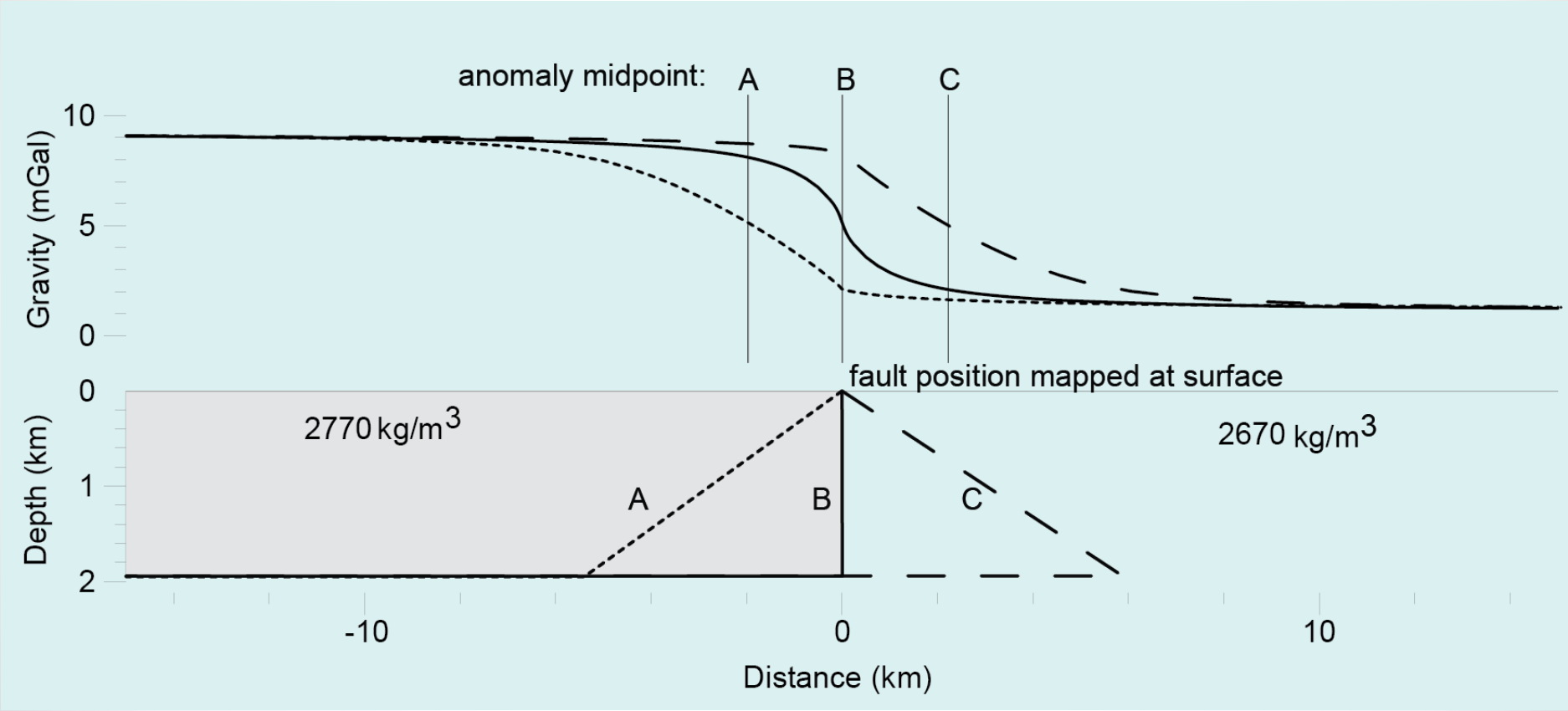
sandstone

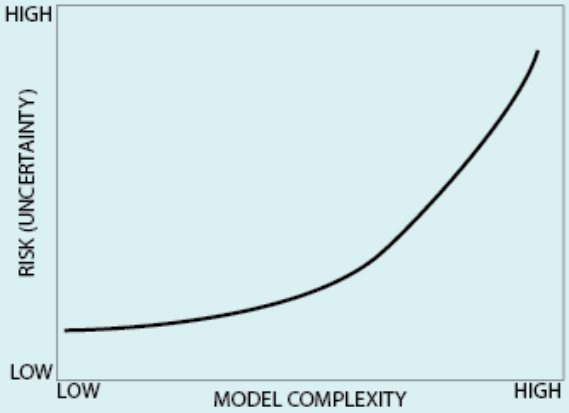
basalt

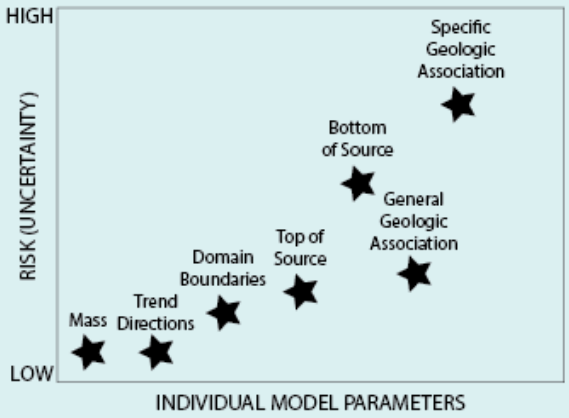
peridotite

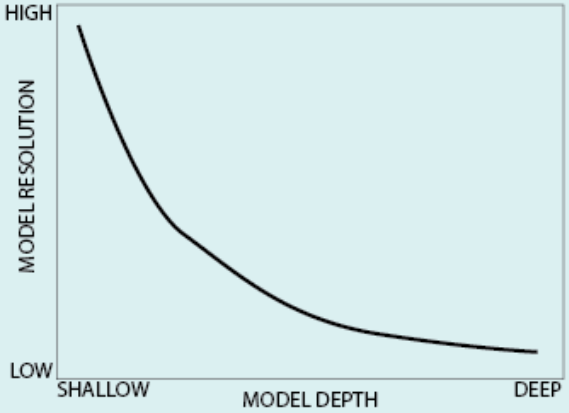
UNIQUE

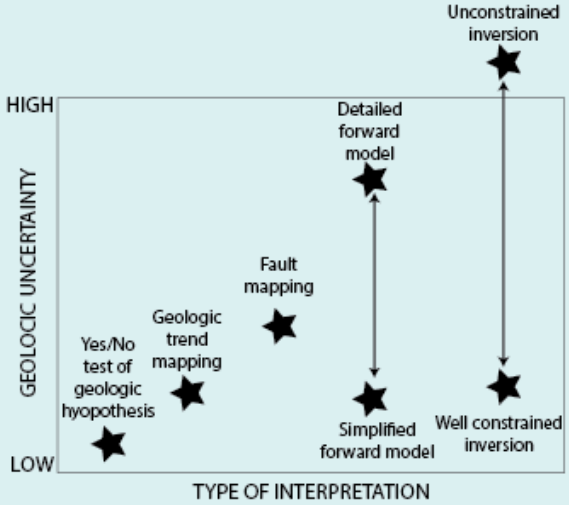

C error wavelength
Error (mGal)
+0.2
0
-0.2
B error wavelength
C actual
Gravity (mGal)
5
4
3
2
1
0
A, B, or C
theoretical
A actual
B actual
0
theoretical shape
C
2720 kg/m3
actual shape
Depth (km)
10
B
2710 kg/m3
theoretical shape
actual shape
20
2670 kg/m3
30
A
3500 kg/m3
0
25
50
75
100
VE =1
Distance (km)

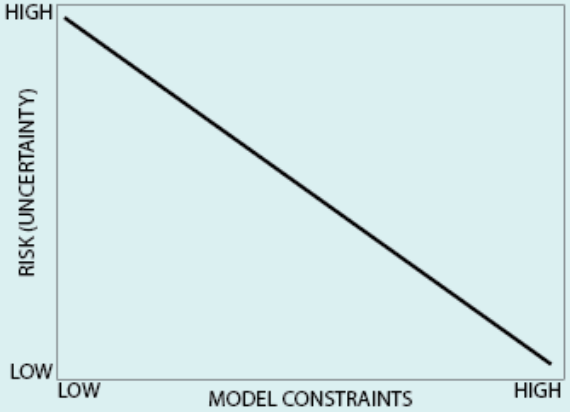

anomaly midpoint:
A
B
C
10
5
0
Gravity (mGal)
fault position mapped at surface
0
1
2
Depth (km)
2770 kg/m3
2670 kg/m3
A
B
C
-10
0
10
Distance (km)

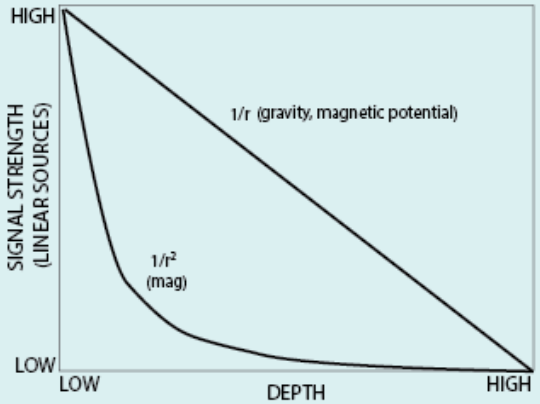

HIGH
RISK (UNCERTAINTY)
LOW
LOW
MODEL COMPLEXITY
HIGH


HIGH
RISK (UNCERTAINTY)
LOW
Specific Geologic Association
Bottom of Source
General Geologic Association
Top of Source
Domain Boundaries
Trend Directions
Mass
INDIVIDUAL MODEL PARAMETERS


HIGH
MODEL RESOLUTION
LOW
SHALLOW
MODEL DEPTH
DEEP


Unconstrained inversion
HIGH
Detailed forward model
GEOLOGIC UNCERTAINTY
Fault mapping
Geologic trend mapping
Yes/No test of geologic hyopothesis
Simplified forward model
Well constrained inversion
LOW
TYPE OF INTERPRETATION

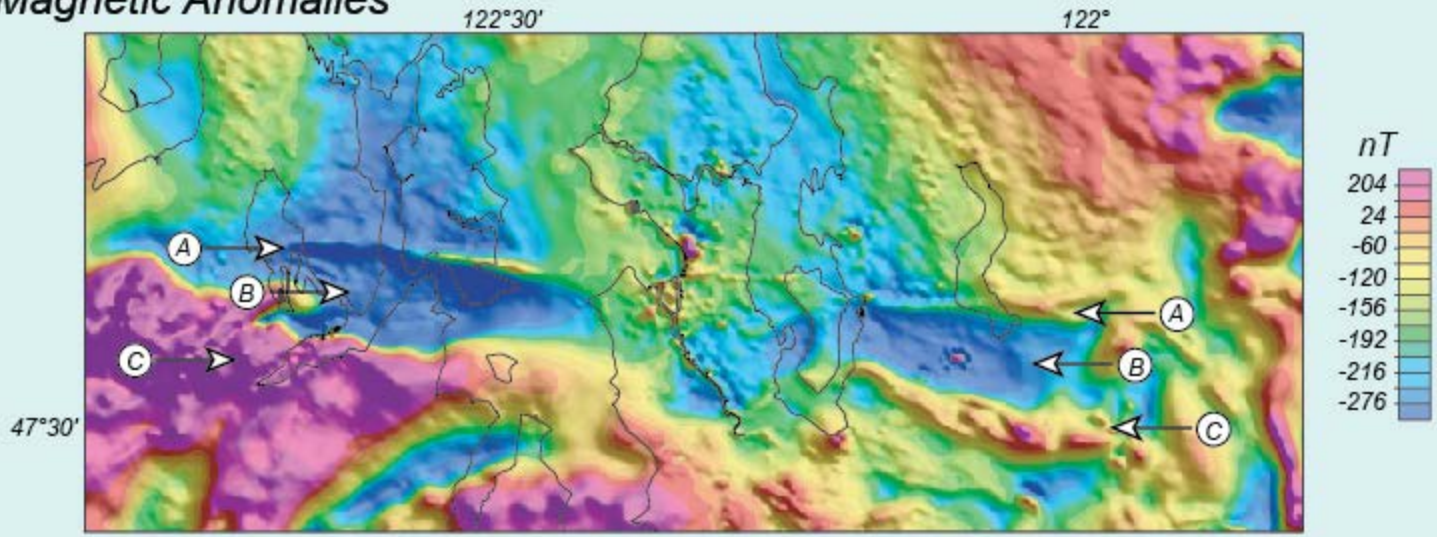

HIGH
RISK (UNCERTAINTY)
LOW
LOW
MODEL CONSTRAINTS
HIGH


HIGH
SIGNAL STRENGTH (LINEAR SOURCES)
1/r (gravity, magnetic potential)
1/r²
(mag)
LOW
LOW
DEPTH
HIGH

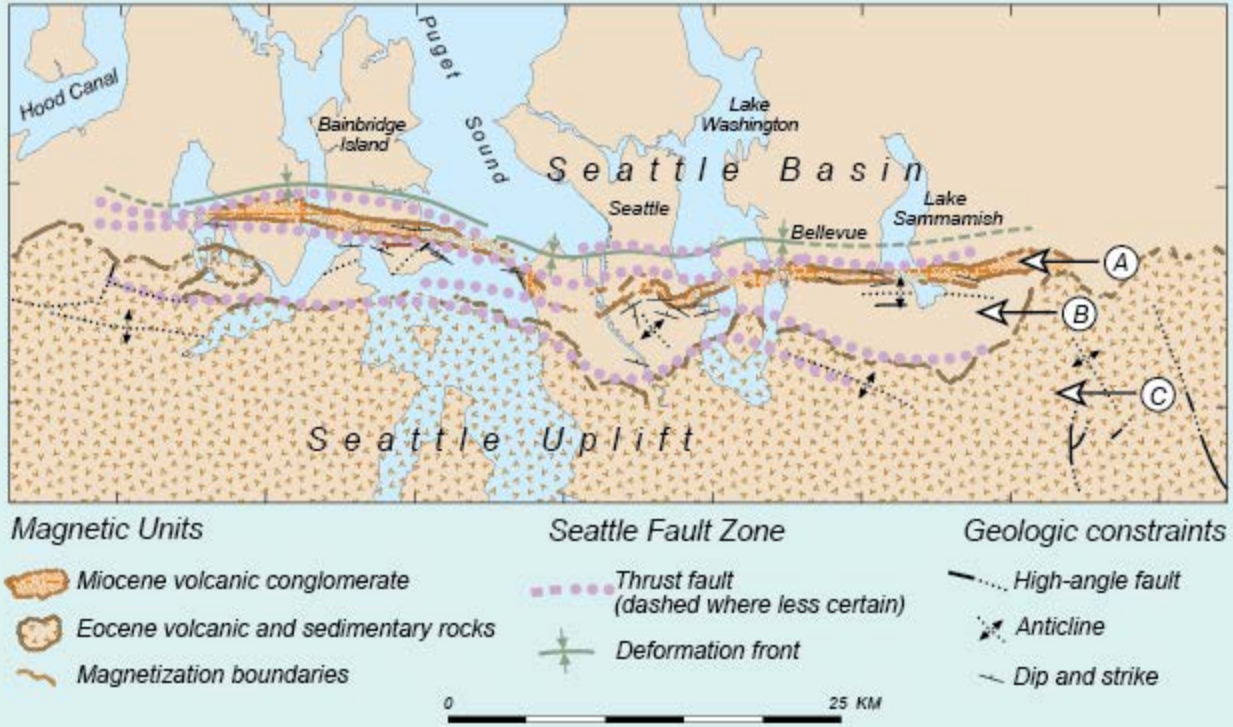
Some Interpretation Examples (time permitting)

- Copter Peak (Alaska)
- Wrangellia vs Peninsular Terrane (AK)
- Taylor Mtns (AK)
- HAMH/HALIP (Arctic)

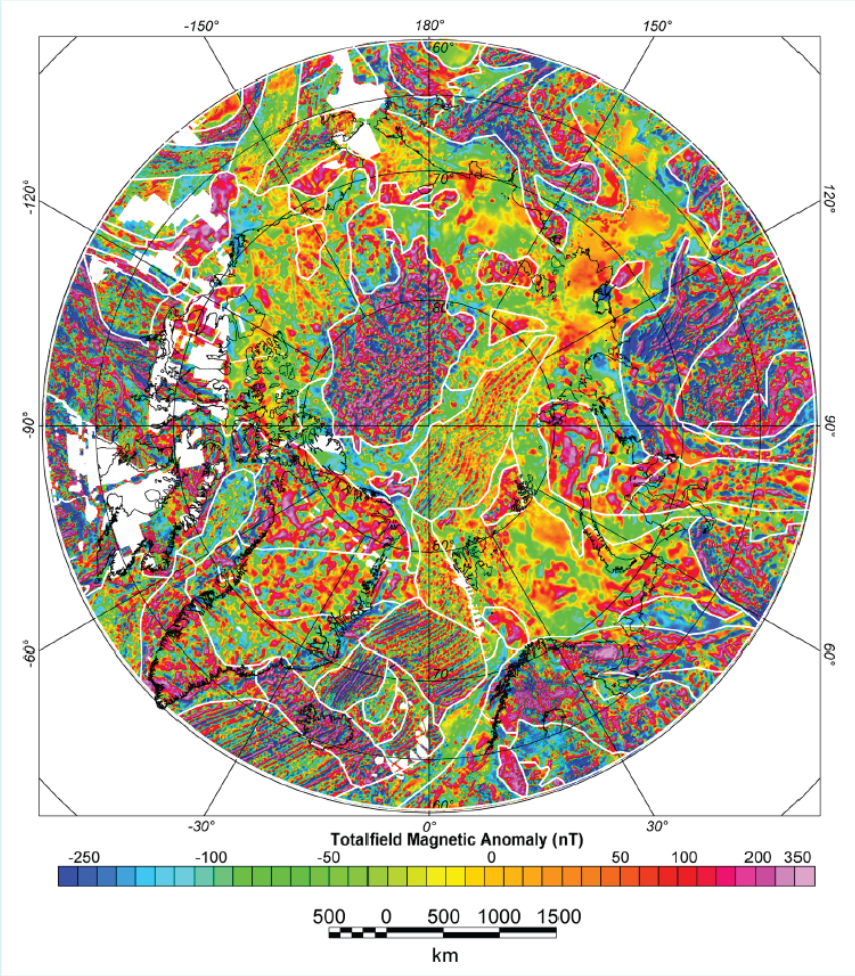
Magnetic Anomalies

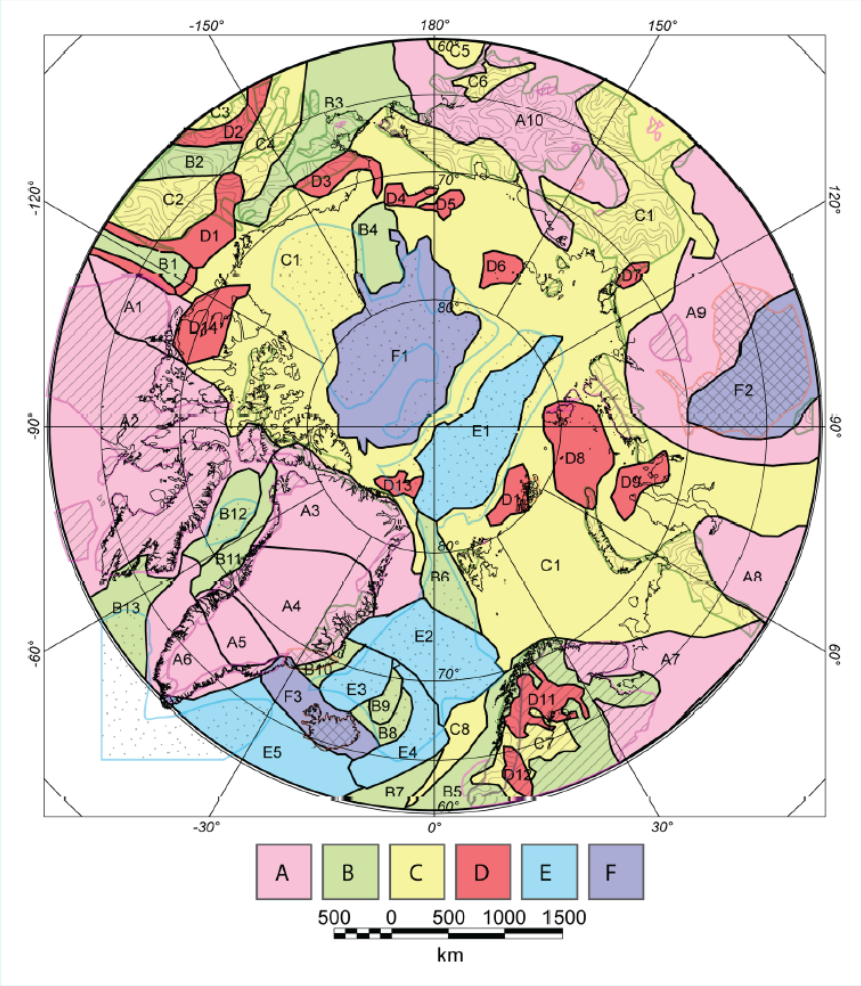


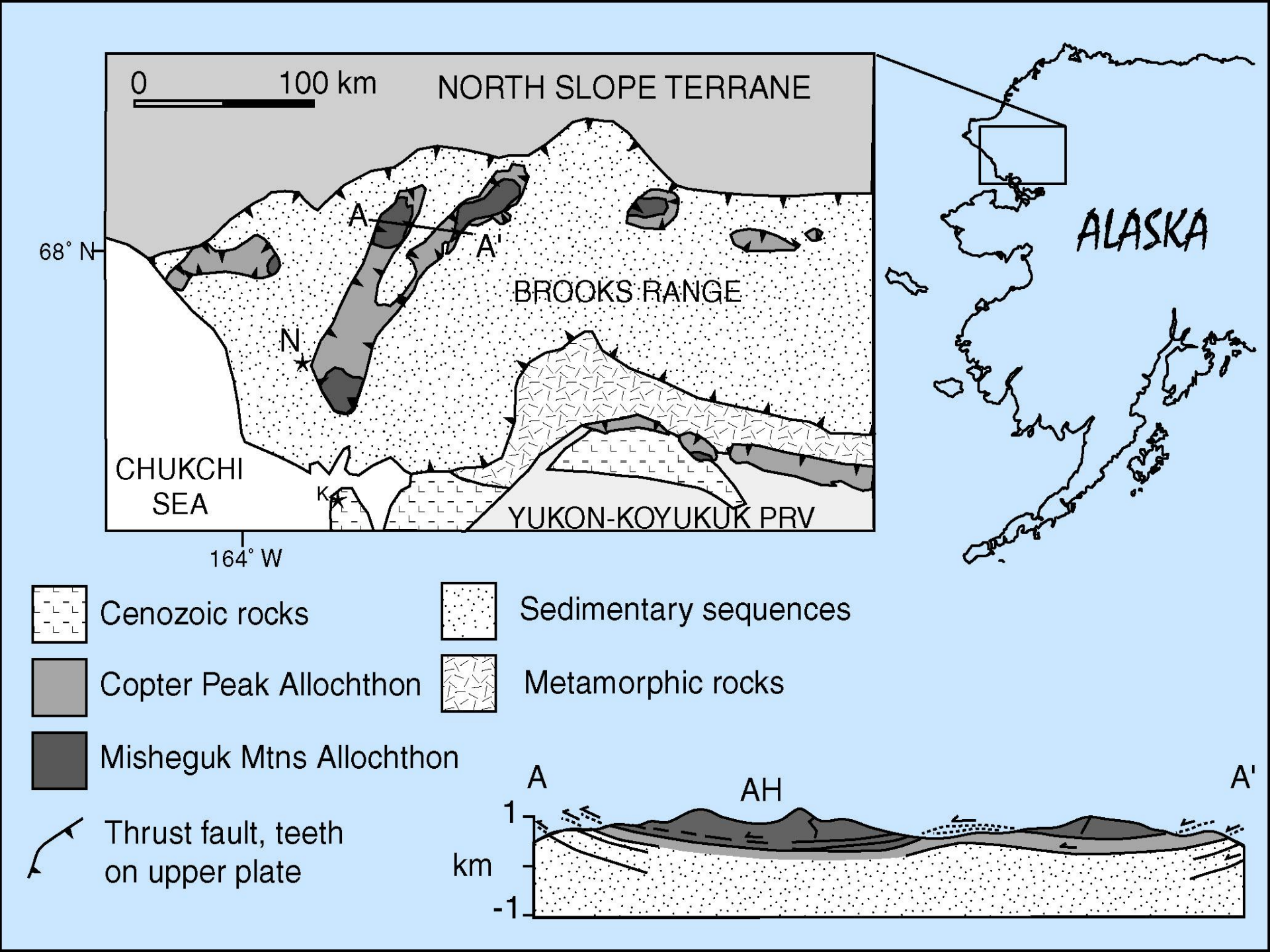
Interpretation

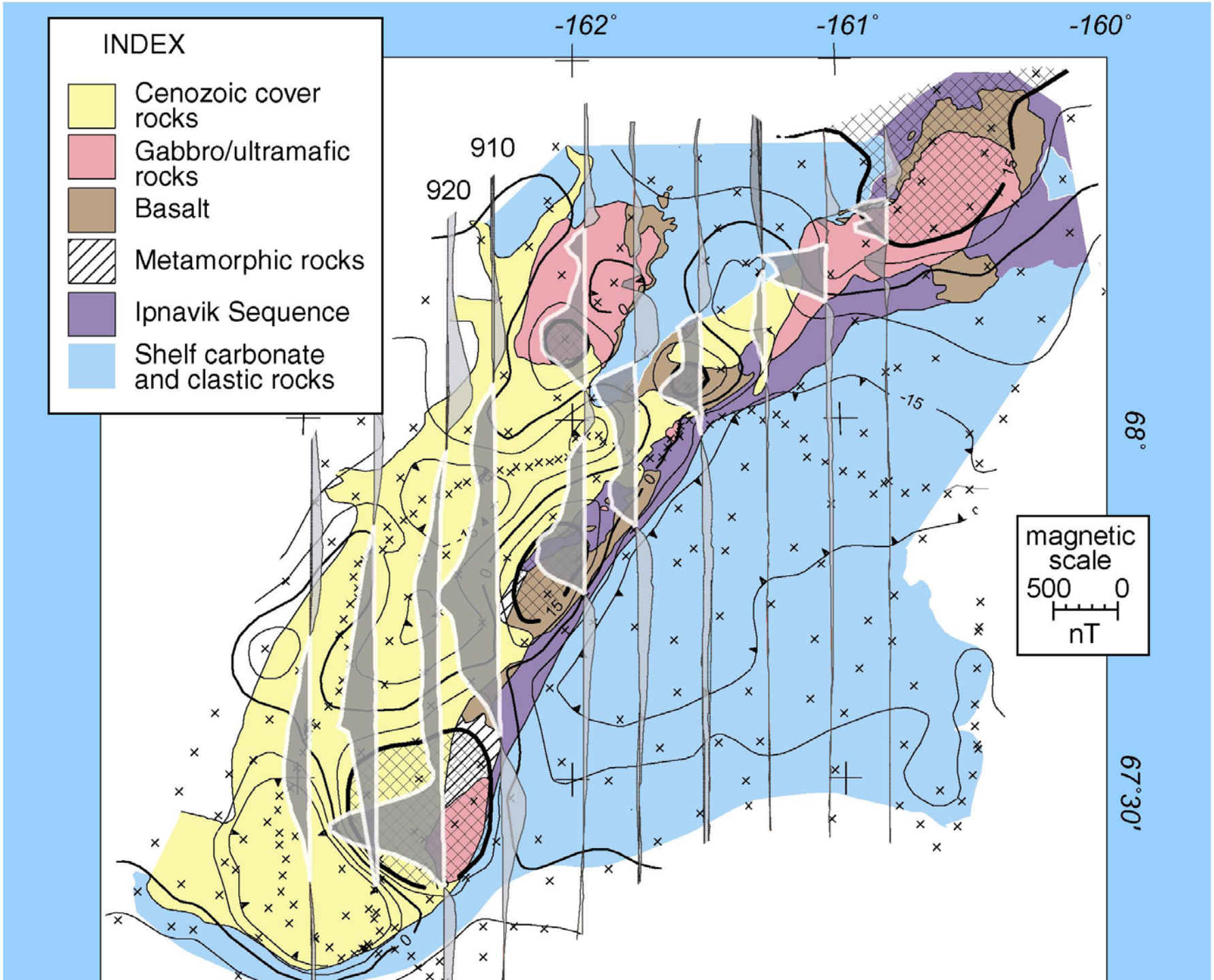


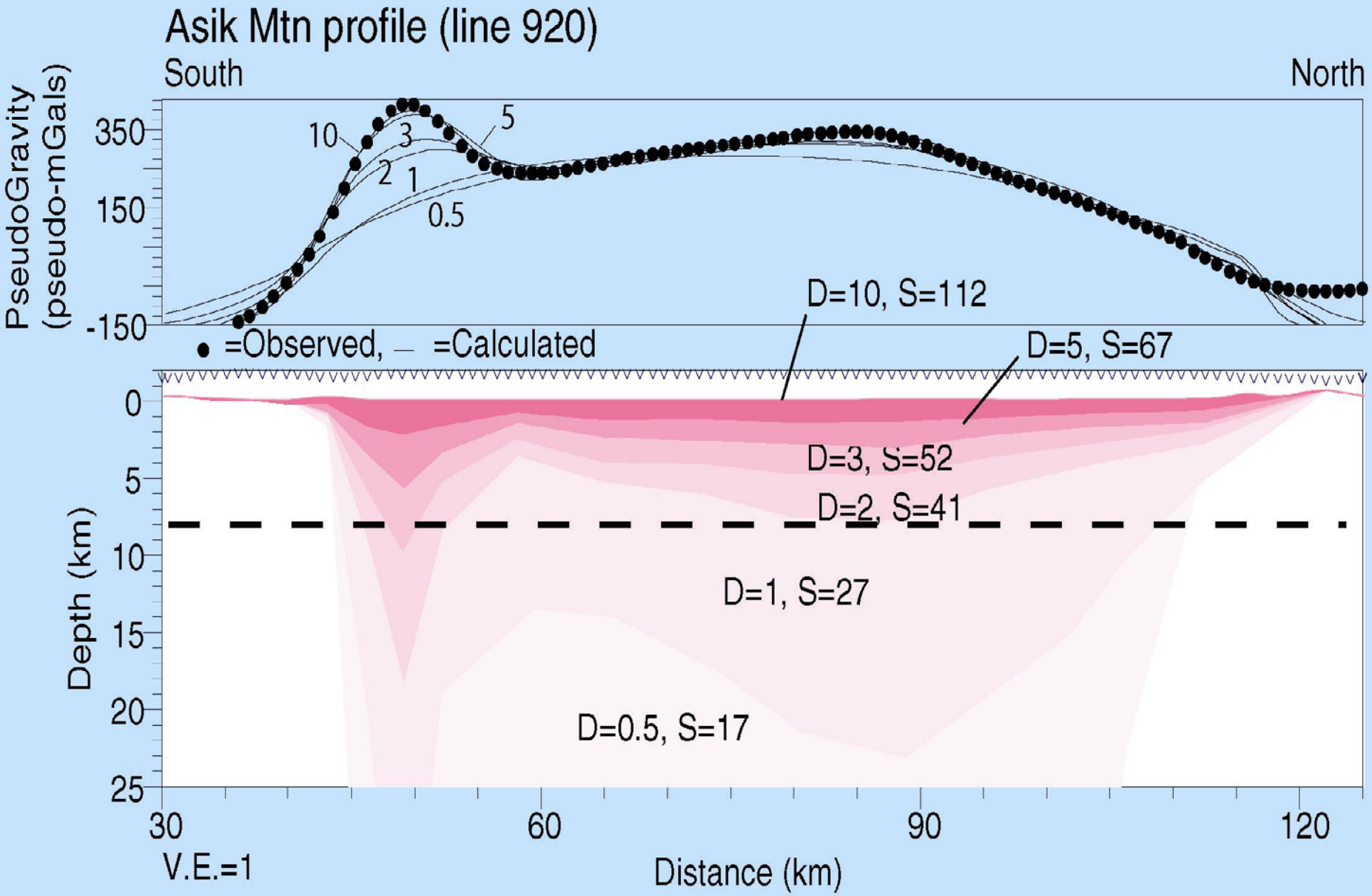
Arctic Magnetic Domains





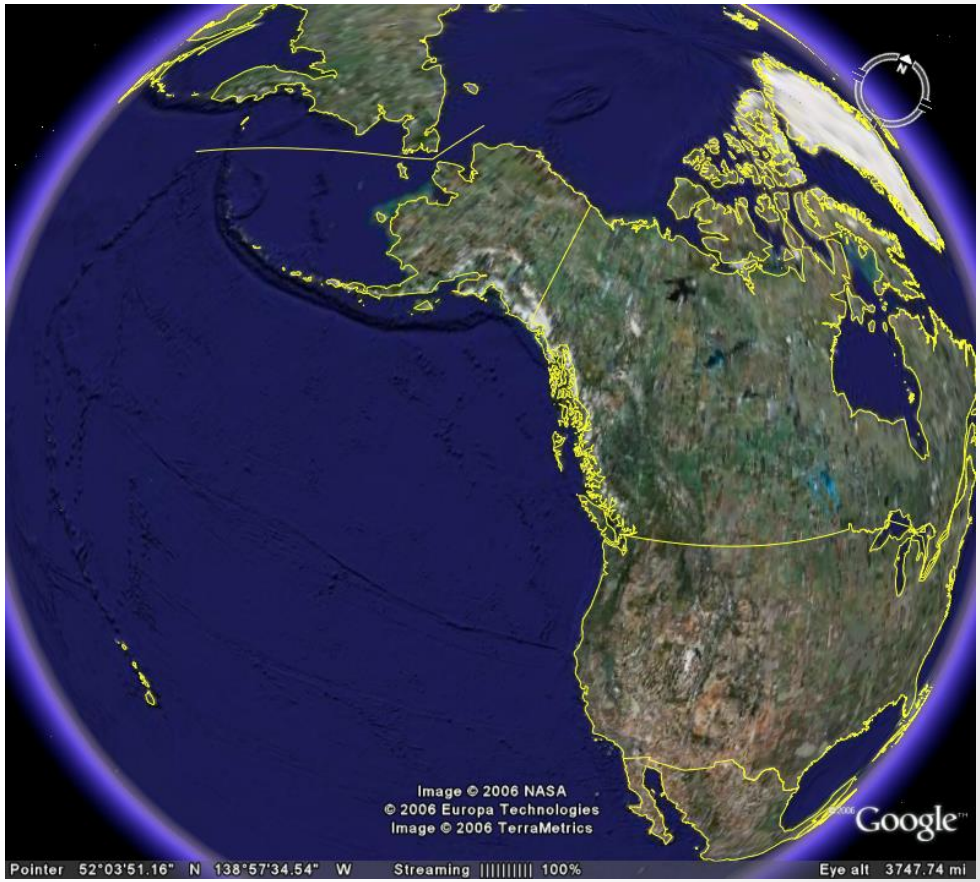

0
100 km
NORTH SLOPE TERRANE
68° N
A
A'
BROOKS RANGE
N
CHUKCHI
SEA
K
YUKON-KOYUKUK PRV
164° W
ALASKA
Cenozoic rocks
Sedimentary sequences
Copter Peak Allochthon
Metamorphic rocks
Misheguk Mtns Allochthon
Thrust fault, teeth
on upper plate
A
AH
A'
1
km
-1

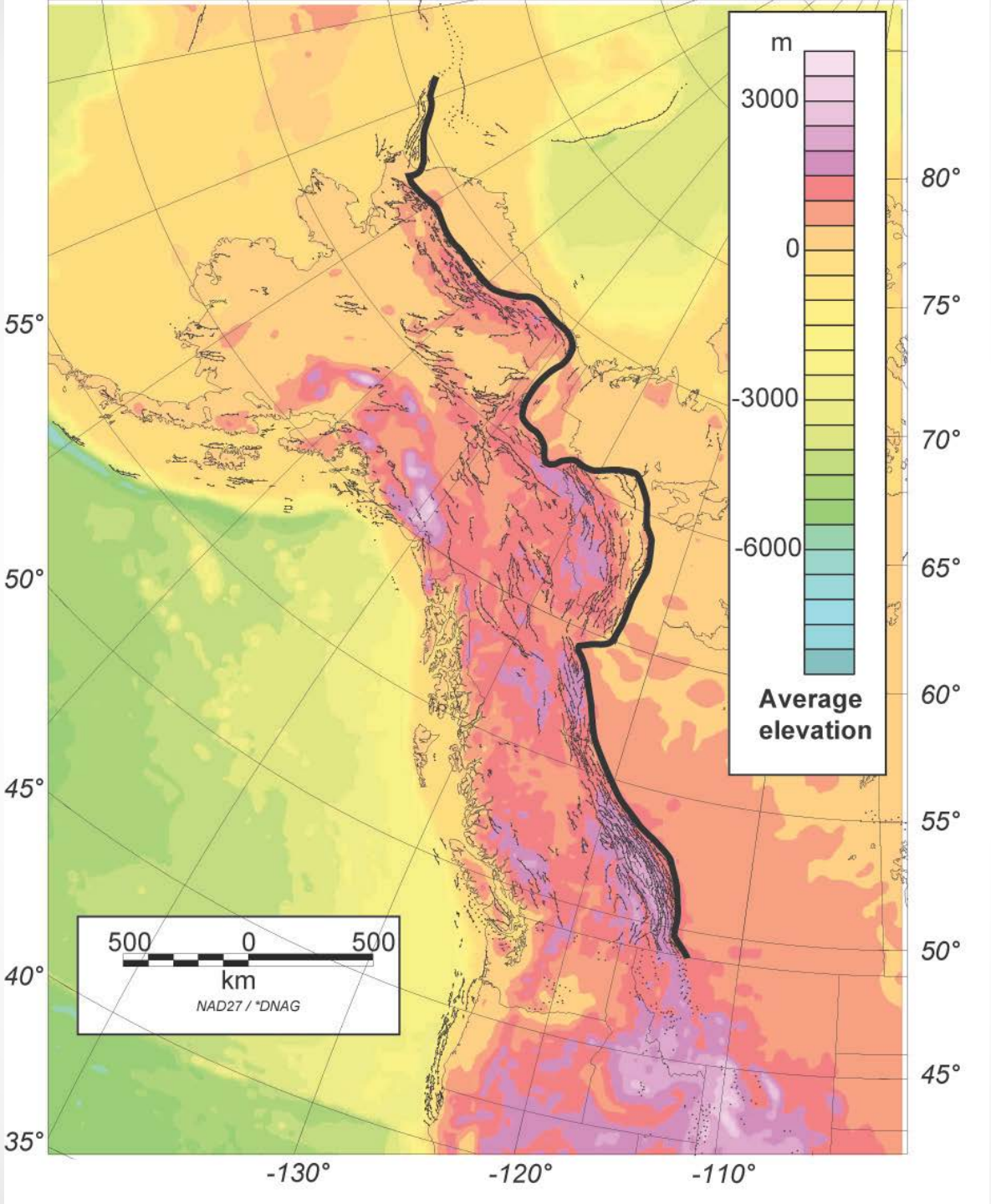

INDEX
Cenozoic cover rocks
Gabbro/ultramafic rocks
Basalt
Metamorphic rocks
Ipnavik Sequence
Shelf carbonate and clastic rocks
-162°
-161°
-160°
68°
67°30'
910
920
-15
15
0
magnetic scale
500
0
nT

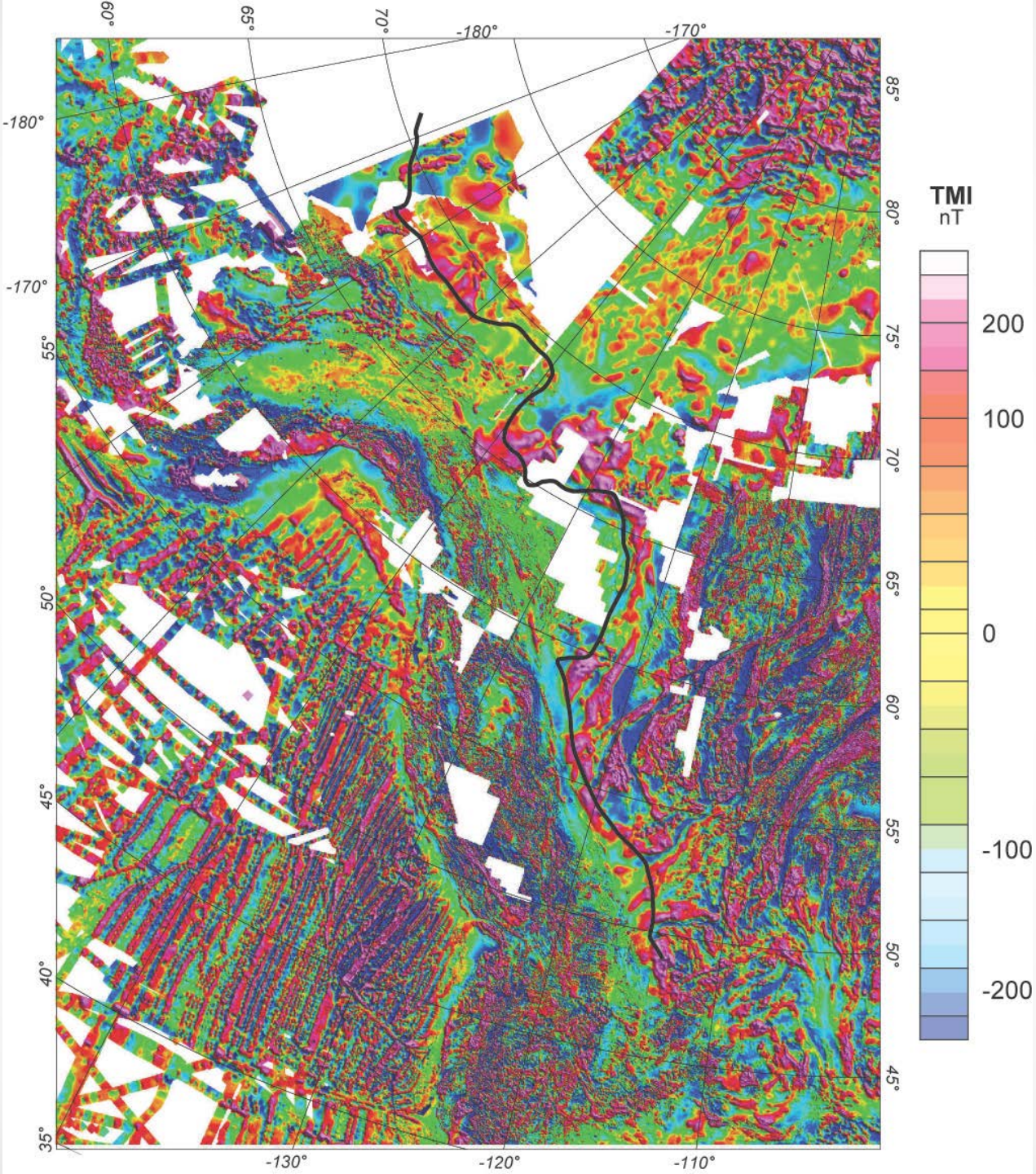

Asik Mtn profile (line 920)
South
North
PseudoGravity
(pseudo-mGals)
350
150
-150
10
3
2
1
0.5
5
● =Observed, — =Calculated
D=10, S=112
D=5, S=67
D=3, S=52
D=2, S=41
D=1, S=27
D=0.5, S=17
Depth (km)
0
5
10
15
20
25
30
60
90
120
V.E.=1
Distance (km)

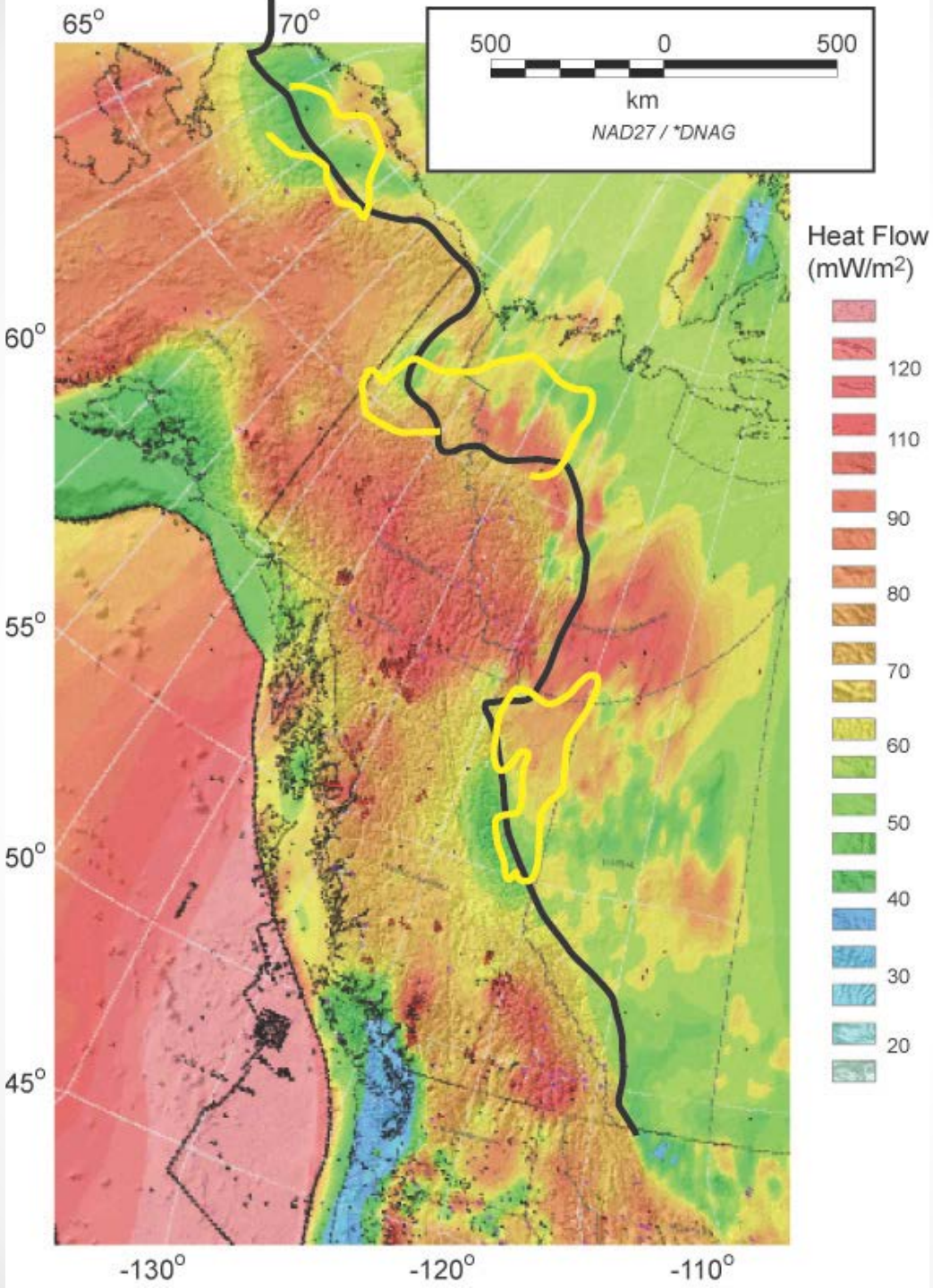
Regional magnetic anomalies, crustal strength, and the location of the northern Cordilleran fold-and-thrust belt

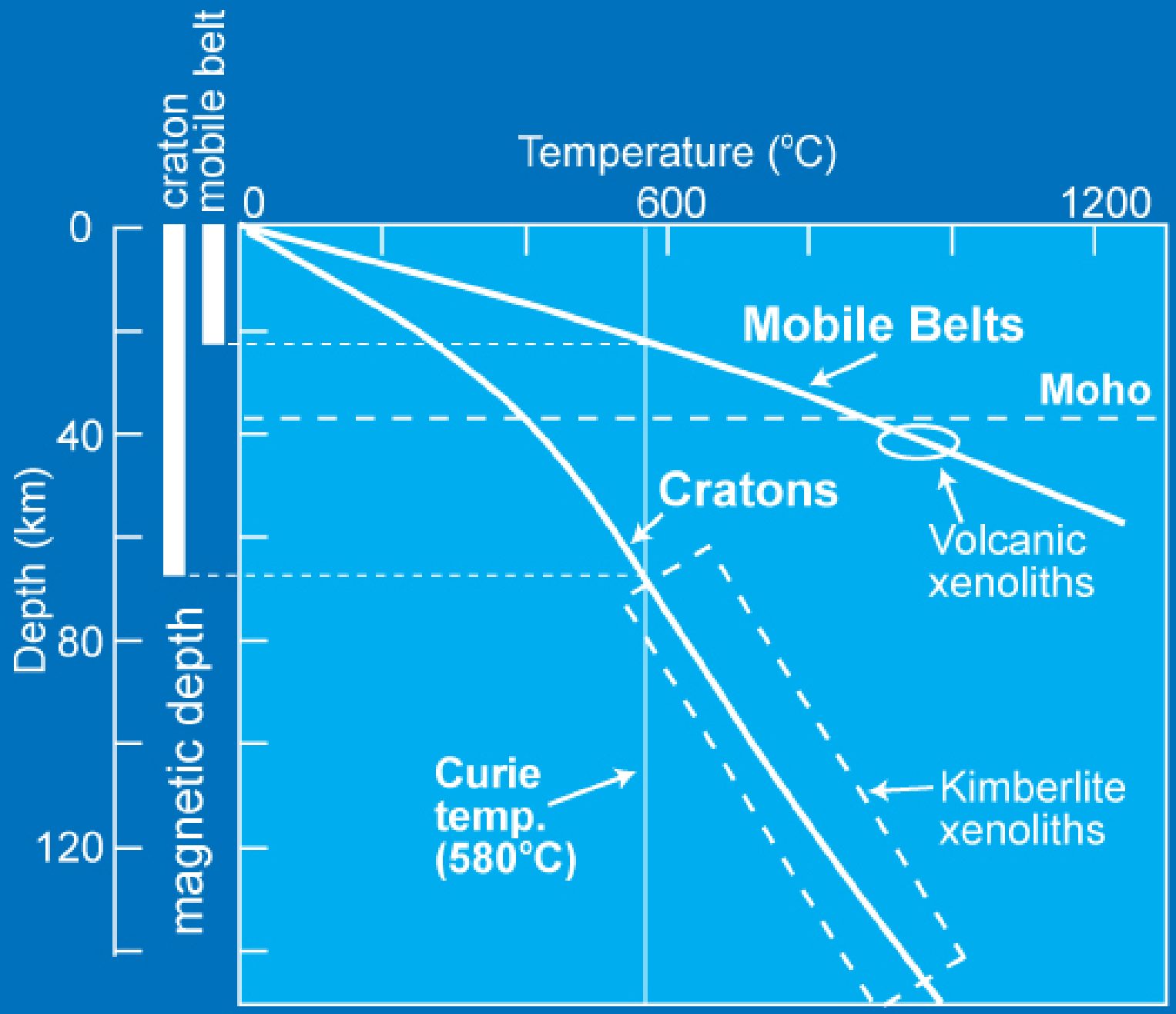
Saltus & Hudson, 2007



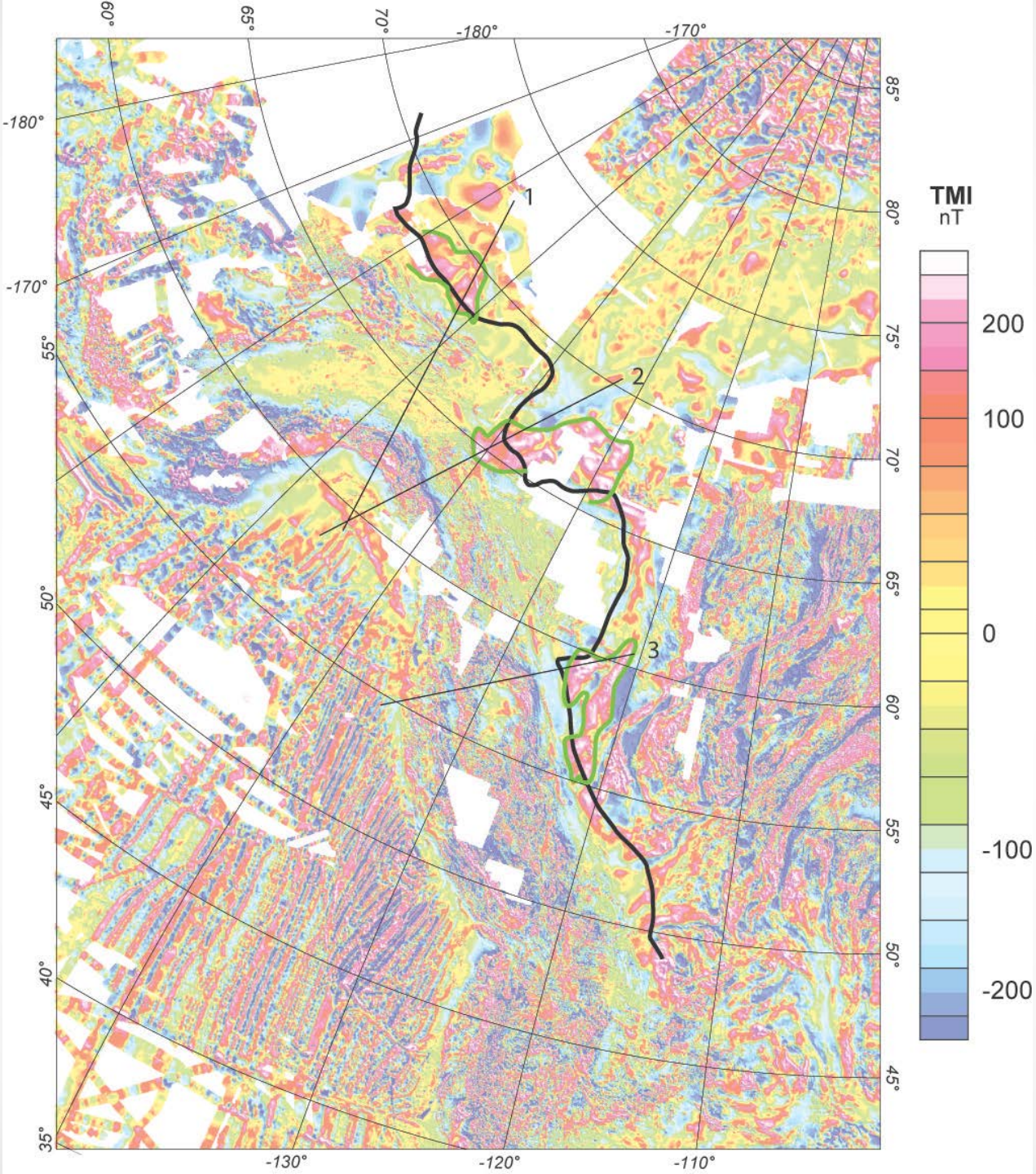

m
3000
0
-3000
-6000
Average elevation
500
0
500
km
NAD27 / *DNAG
55°
50°
45°
40°
35°
80°
75°
70°
65°
60°
55°
50°
45°
-130°
-120°
-110°

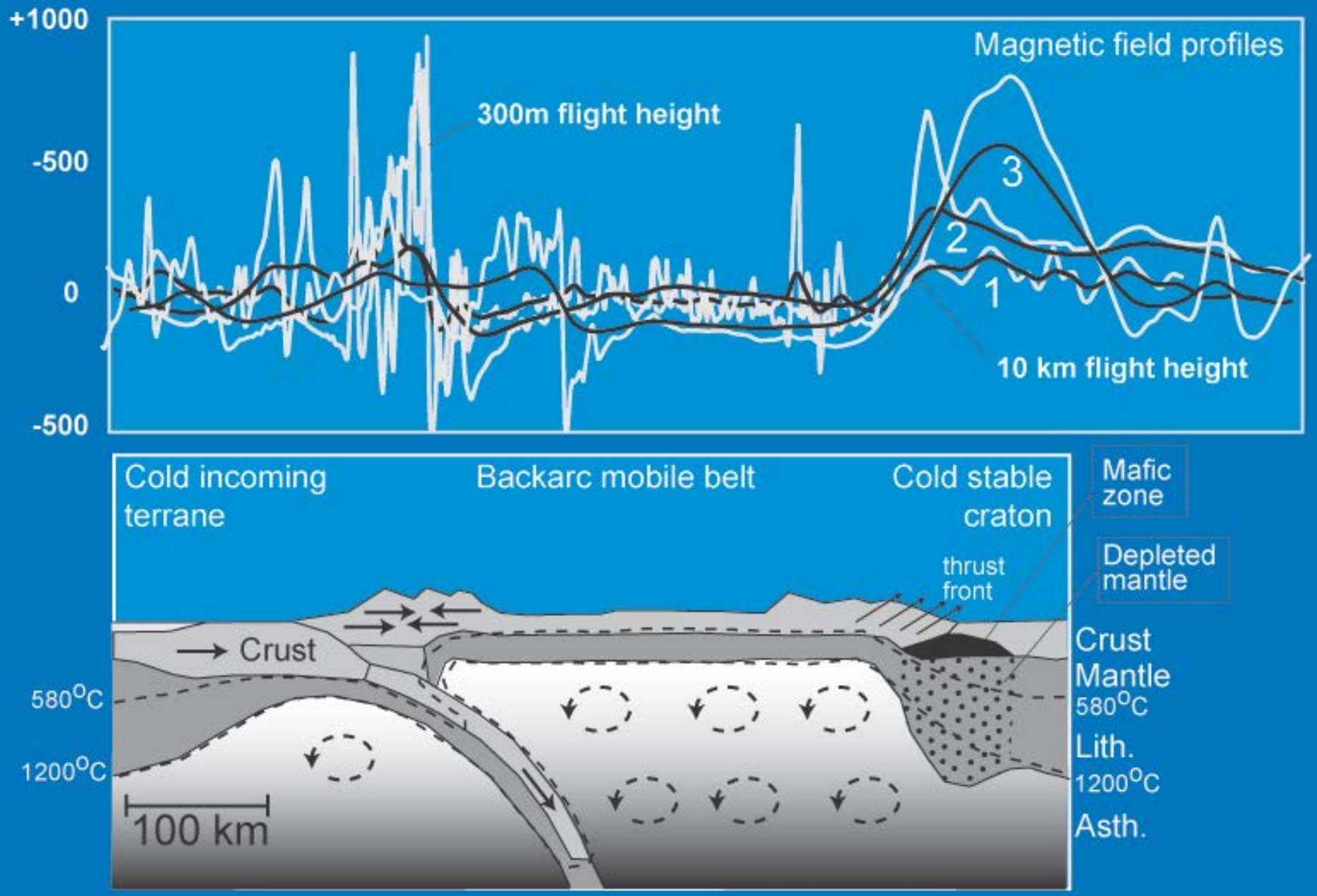

TMI
nT
200
100
0
-100
-200
-180°
-170°
-130°
-120°
-110°
60°
65°
70°
85°
80°
75°
70°
65°
60°
55°
50°
45°
40°
35°


65°
70°
500
0
500
km
NAD27 / *DNAG
Heat Flow
(mW/m2)
120
110
90
80
70
60
50
40
30
20
60°
55°
50°
45°
-130°
-120°
-110°



Modified from Hyndman et al. (GSA Today, Feb 2005)


TMI
nT
200
100
0
-100
-200
1
2
3
-180°
-170°
-130°
-120°
-110°
60°
65°
70°
85°
80°
75°
70°
65°
60°
55°
50°
45°
40°
35°



Modified from Hyndman et al. (GSA Today, Feb 2005)

Can't believe we got to this slide

- Global crustal field data coverage is incomplete – big data gaps in southern oceans, high mountains, etc.
- Even the United States (especially Alaska) has data gaps and regions of very sparse data coverage.
- A number of groups working on drones, etc. – technically this should be pretty easy to do with existing technology.
- Most of the existing data are un-interpreted or under-interpreted.
- Training in magnetic data understanding and interpretation is a great general training for a wide variety of scientific and technical endeavors.