Understanding How the Main (or Reference) Field Model Affects Computing the Vector Crustal Magnetic Field for Directional Drilling Applications

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- **Is the vector crustal magnetic field relative to a current main (or *reference*) field model for a current date still valid in the years (5, 10, 20) to come?**

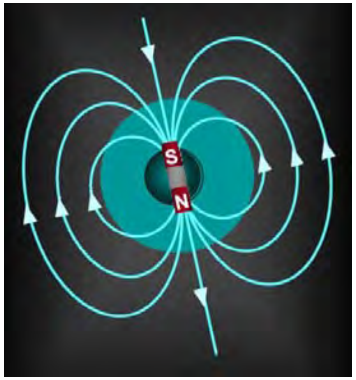
Given the following facts

- **The main field itself changes with time (secular variation)**
- **The degree/order of the spherical harmonic expansion used to define the main (reference) field model increases**
- **Directional drilling involves the main field at the aeromagnetic survey time and the main field at the drilling time**

The Earth's Magnetic Field

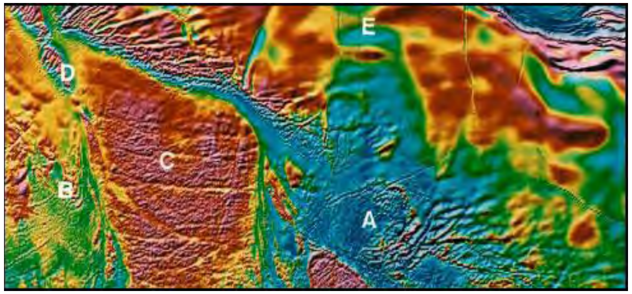
The observed Earth's magnetic field $\vec{B}$ is a vector sum of the three sources:

$$\vec{B} = \vec{B}_m + \vec{B}_c$$



Main field

$\vec{B}_m$



Crustal field

$\vec{B}_c$

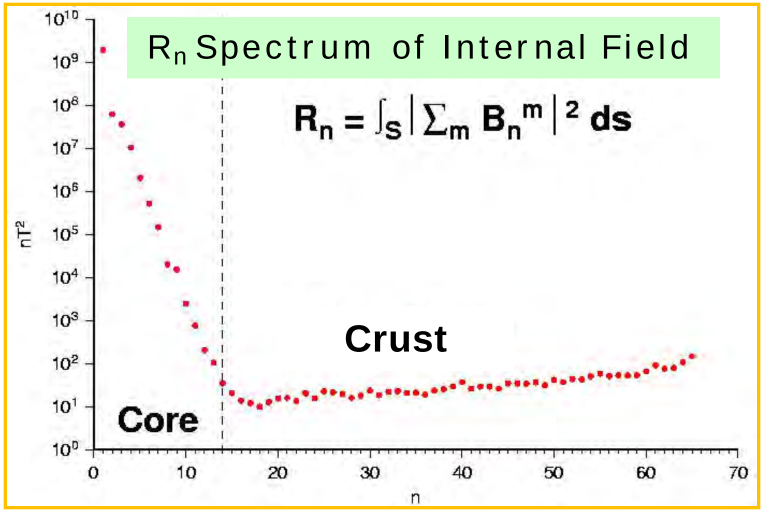
The main field is defined by

- **IGRF or**
- **BGGM ?**

Geomagnetic Reference Models: Current Status

	Updated	Main field	Secular variation	Crustal field	External field
IGRF	Five years	13	8	No	No
BGGM	Annually	15	13	16 – 50	1
HDGM	Annually	15	15	16 – 720	1

- The numbers are the degree/order used in spherical harmonic (SH) expansion.
- Only the IGRF is a model to define the pure main field.



Construction of the Vector Subsurface Crustal Magnetic Field

Computation of the main field (I_m, D_m, TMI_m) grids at airmag survey time

Computation of the observed TMI anomaly using the main field at airmag survey time

Computation of TMI anomaly at depth (TMI_c) by downward continuation or alike

Computation of the crustal (X_c, Y_c, Z_c) component grids

How about this?

Computation of the main field (X_m, Y_m, Z_m) grids at drilling date

Computation of the crustal I_c and D_c perturbations

Current deliverables

Computation of the baseline (I_b, D_b, TMI_b) values

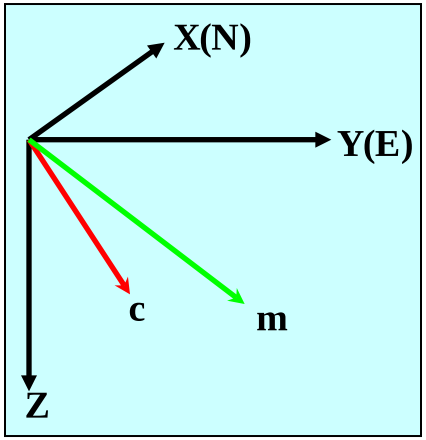
$D_b = D_m + D_c$ ...

The Crustal Declination and Inclination Perturbations

The crustal declination and inclination perturbations or the residual declinations and inclinations are defined as

$$D_c = \arctan\frac{Y_m + Y_c}{X_m + X_c} - \arctan\frac{Y_m}{X_m}$$

$$I_c = \arctan\frac{Z_m + Z_c}{\sqrt{(X_m + X_c)^2 + (Y_m + Y_c)^2}} - \arctan\frac{Z_m}{\sqrt{X_m{}^2 + Y_m{}^2}}$$

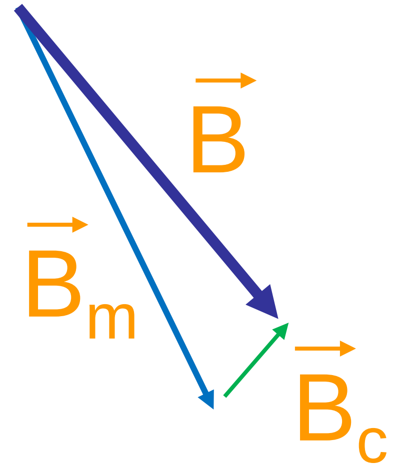


- (X_c, Y_c, Z_c) are the (north, east, vertical) components of the crustal magnetic field relative to the main field at the aeromagnetic survey time
- (X_m, Y_m, Z_m) are the (north, east, vertical) components of the main field at the drilling time.

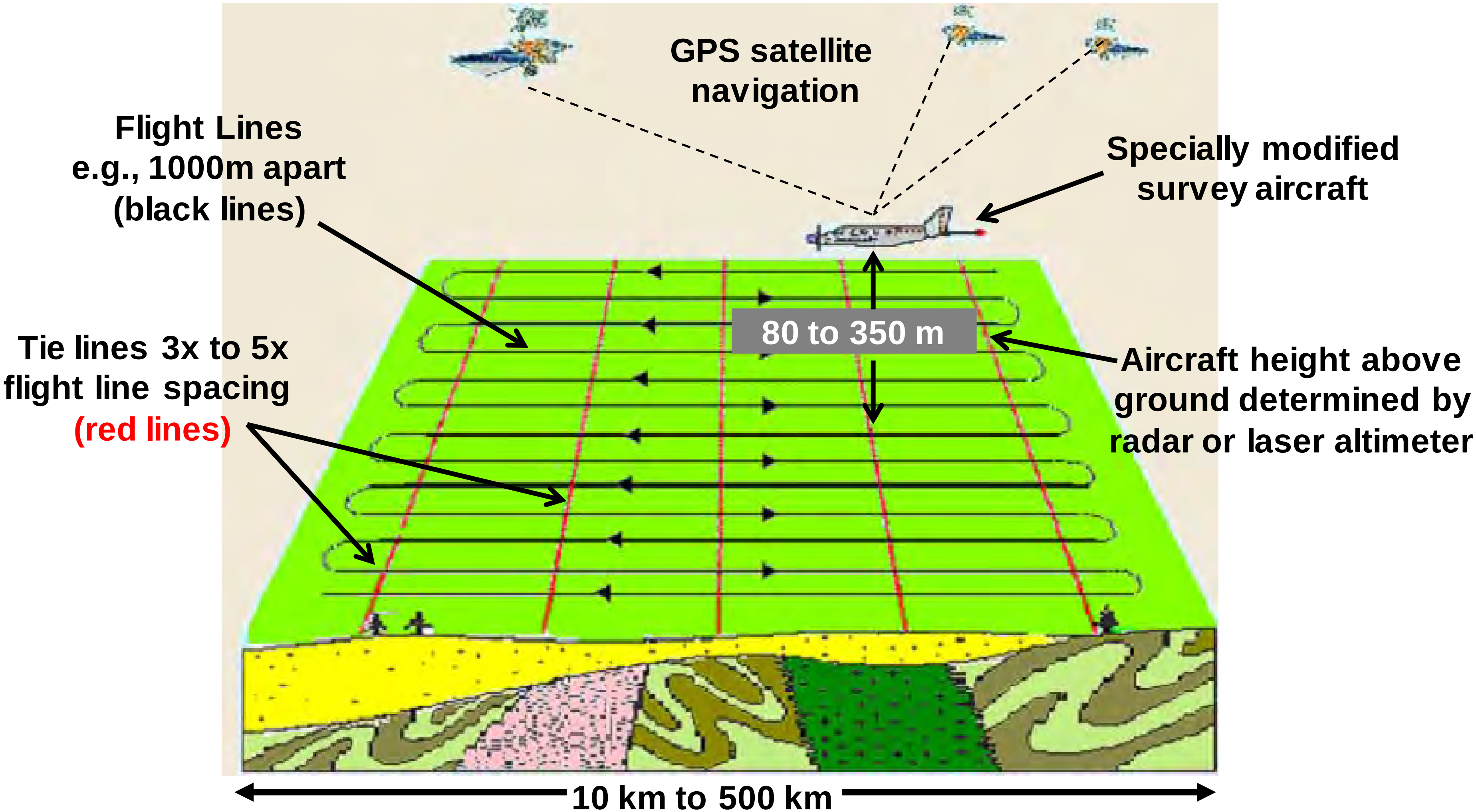
Conventional Surface Magnetic Surveys

- **Conventional magnetometers measure the Total Magnetic Intensity (TMI), a scalar quantity not the vector field.**
- **However, directional drilling requires**
  - **the vector magnetic field**
  - **at depths.**

$$TMI = \left|\vec{B}\right|$$



Aeromagnetic Survey



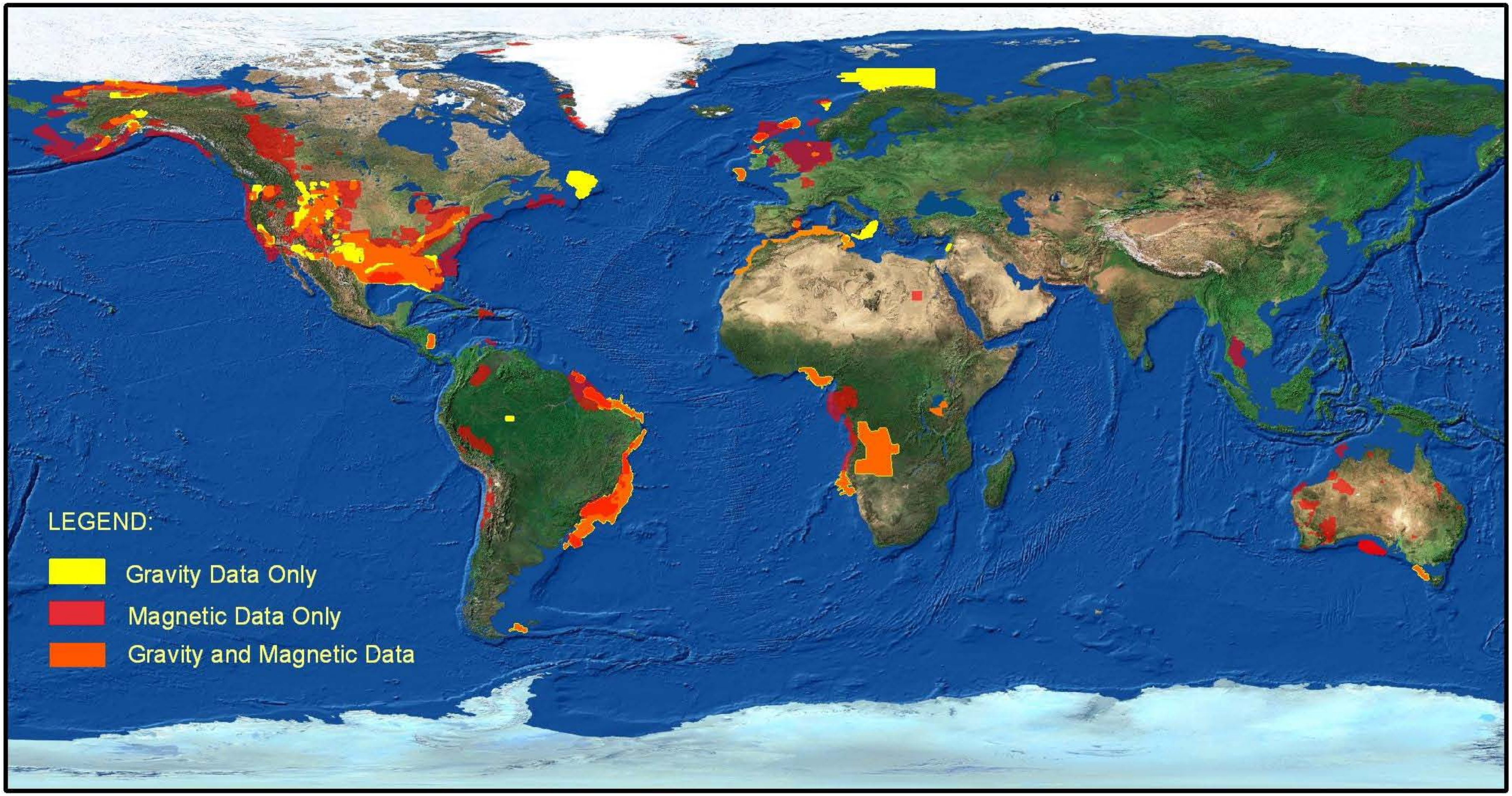
Safety – *DTM's, flight following, pilot training, vigilance.*

Average production ~1000 line km/day

Historical vs High-Resolution AeroMagnetic Surveys

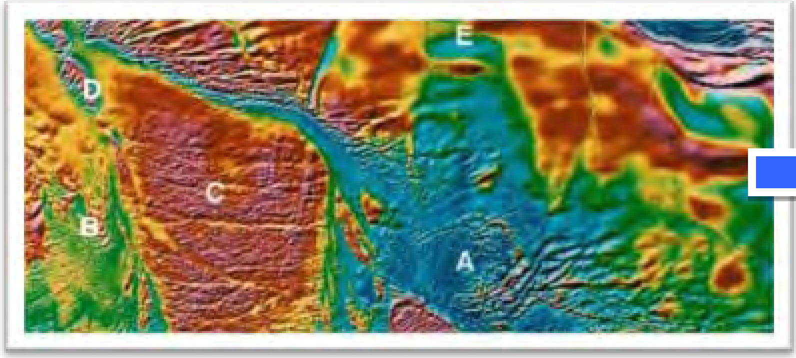
	Historical (pre-1990)	High Resolution
Magnetometer	Proton/Overhauser/Cs Vapour 0.5 – 0.01 nT	Cs Vapour 0.001 nT
Sampling	1 Hz (70 m)	10 Hz (7 m)
Navigation	Visual/Doppler/Radio 10’s m (maybe a lot more)	DGPS cm
Elevation	Typically 350 m with Barometric/Radar control – several m accuracy	80 m minimum with DGPS/Radar/Laser control - m accuracy
Line Spacing (Exploration)	Rarely <2 km	Typically 500 m
Processing	Hand reduction and contouring	PC based & portable
Display	Line contours	Colour displays, digital grids, enhancements, GIS

The “Lay of the Land” Fugro Non-Exclusive Database

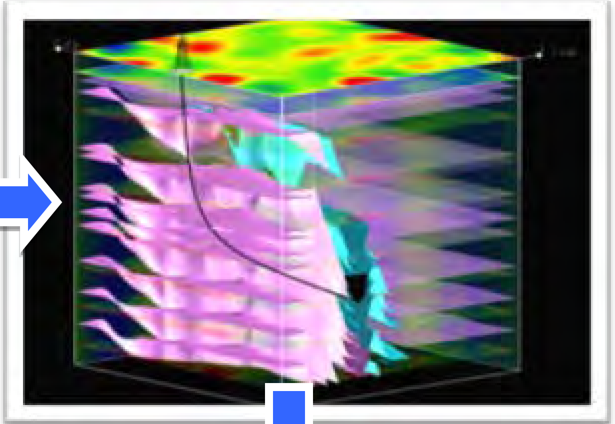


MagCUBE™: Crustal Magnetic Modeling

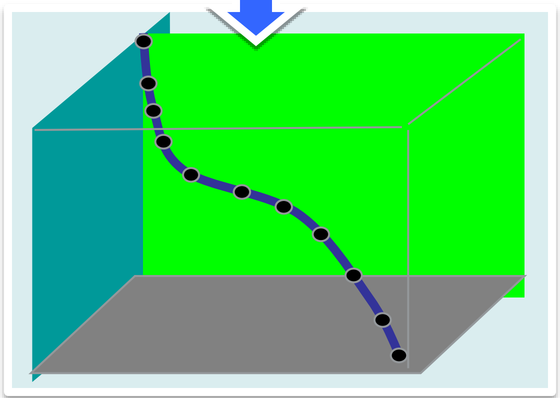
Scalar crustal Total Magnetic Intensity (TMI) anomaly on surface



Vector magnetic field at depths

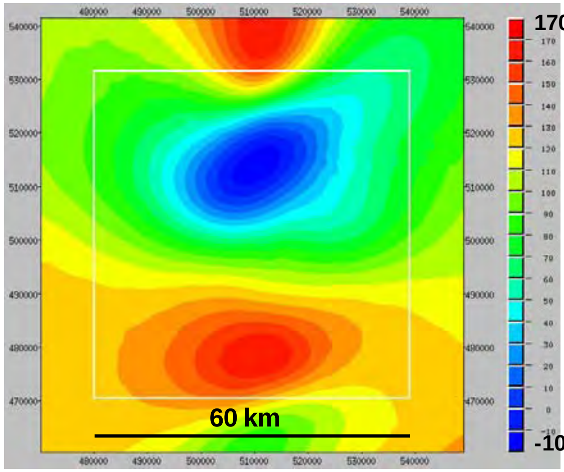


3D interpolation



A Field Example Offshore Ghana

IGRF-corrected TMI



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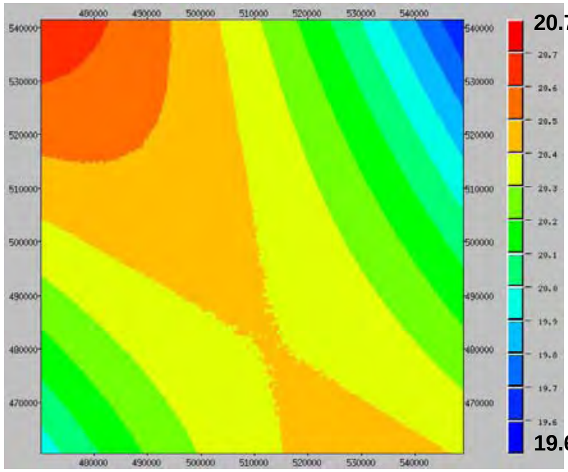
IGRF - BGGM



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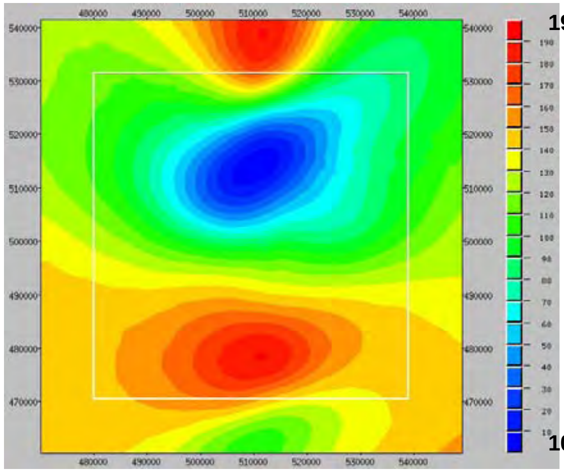
BGGM-corrected TMI

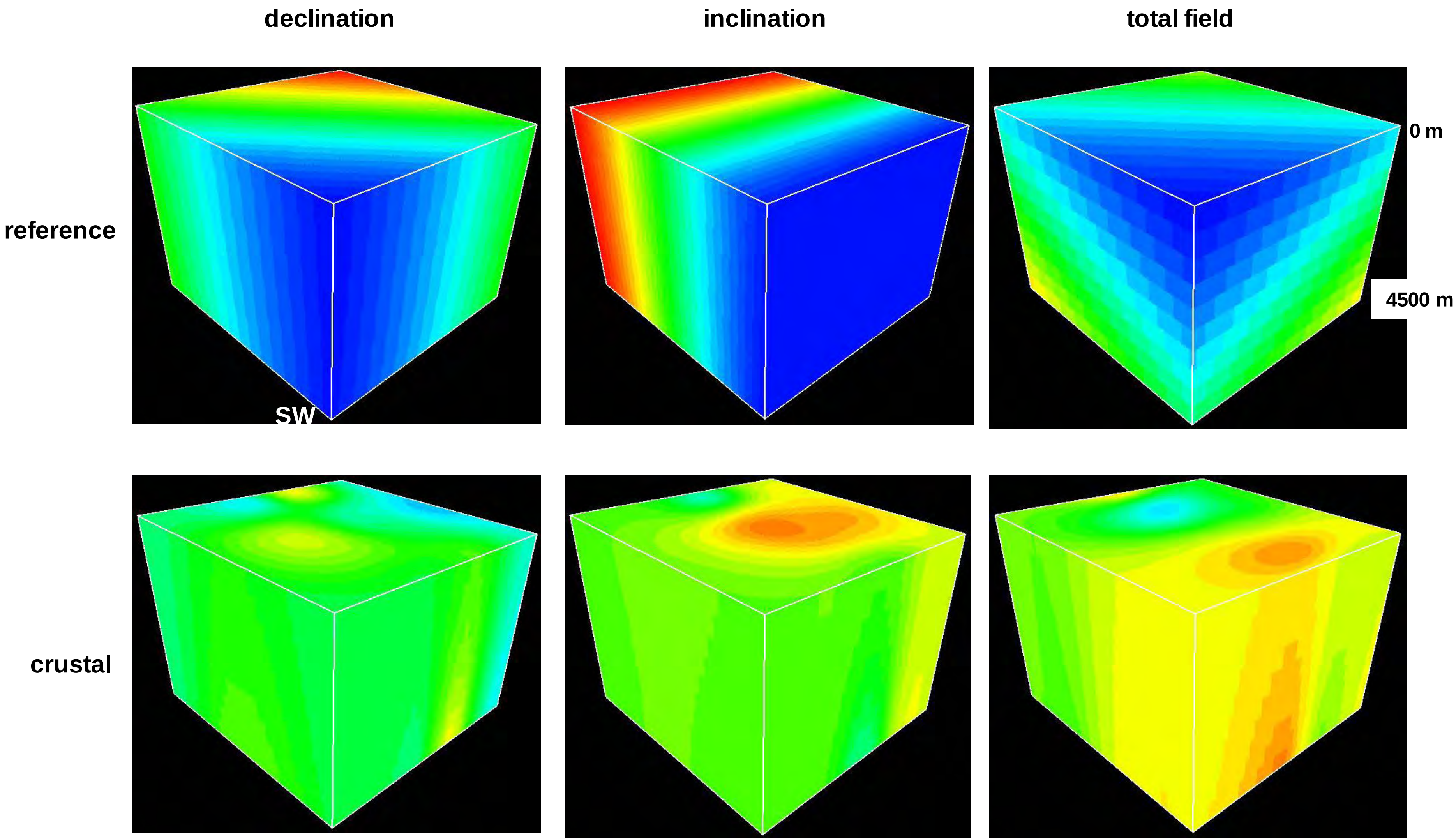


- The survey of 80 km by 80 km was flown at 80 m altitude with a mean date of Dec 28, 2009.
- The drilling date used was January 8, 2010; and the cube deliverables cover the white square area of 60 km by 60 km.

- The IGRF (11th generation) has a SH degree of 13.
- The BGGM (v2012) has a SH degree of 50.

- We run two MagCUBE computations, one using the IGRF purely and the other using the BGGM purely, by fixing all other parameters.
- The differences demonstrate the effects of a change in the SH degree (up to 50) describing the extremely-long wavelength (>700 km) crustal magnetic field.

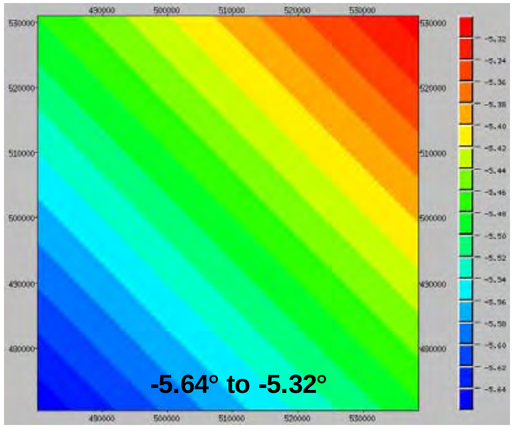
The Magnetic Field Cubes Using BGGM



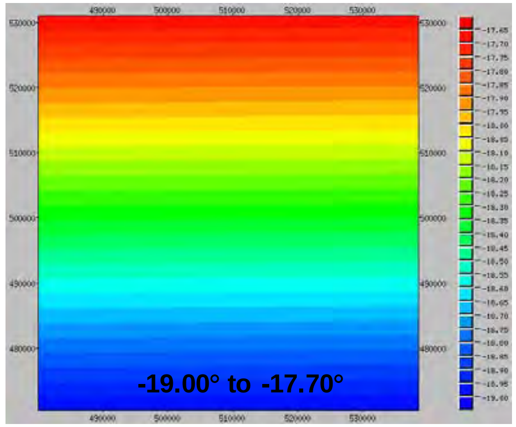
The Reference Field Values and Differences at Sea Level

BGGM

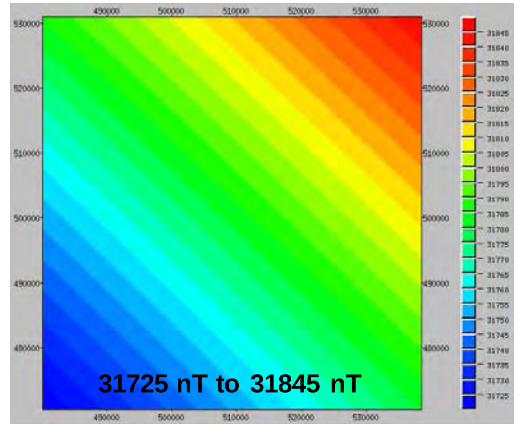
declination



inclination

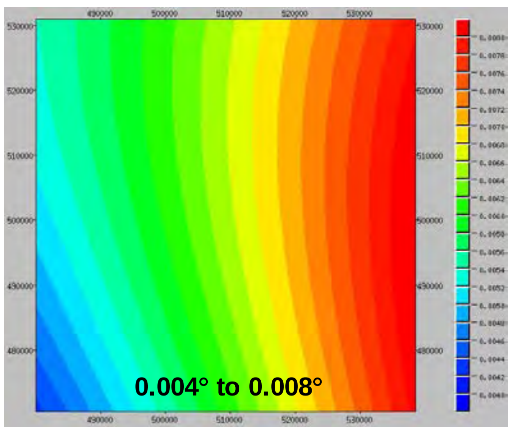


TMI

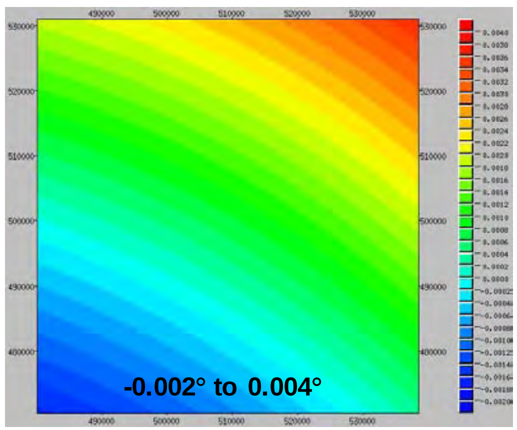


IGRF - BGGM

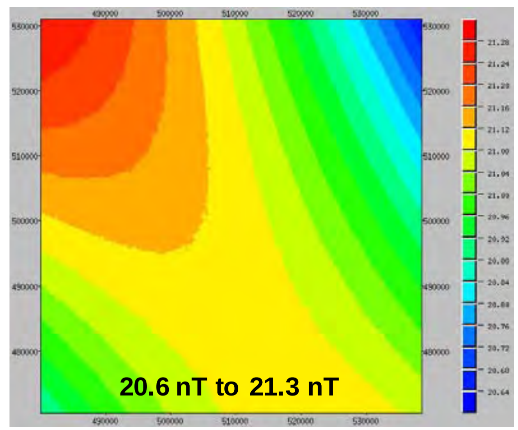
declination difference



inclination difference



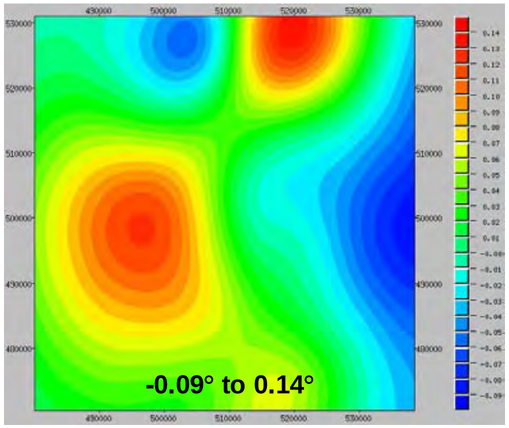
TMI difference



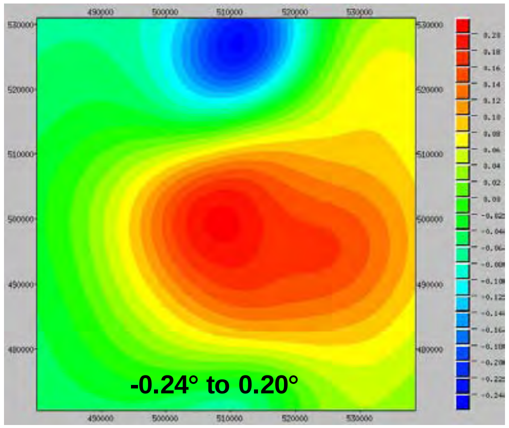
The Crustal Field Values and Differences at Sea Level

Processed using BGGM

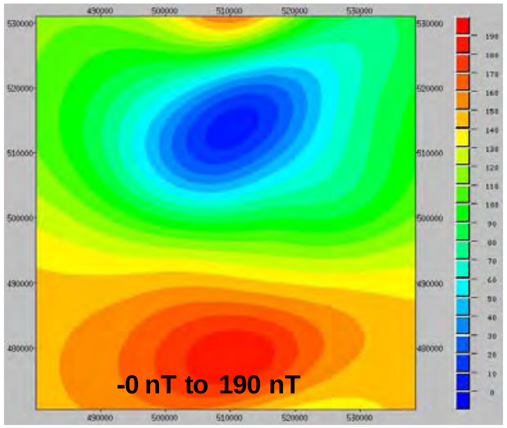
declination



inclination

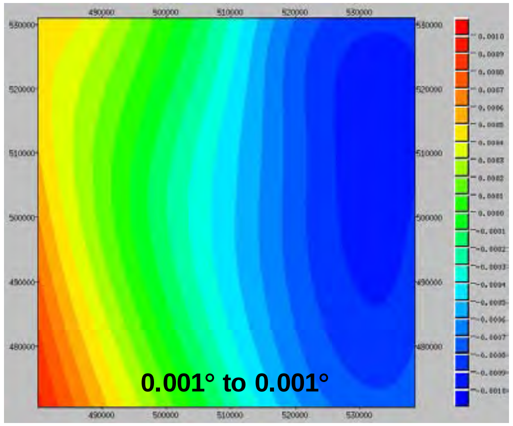


TMI anomaly

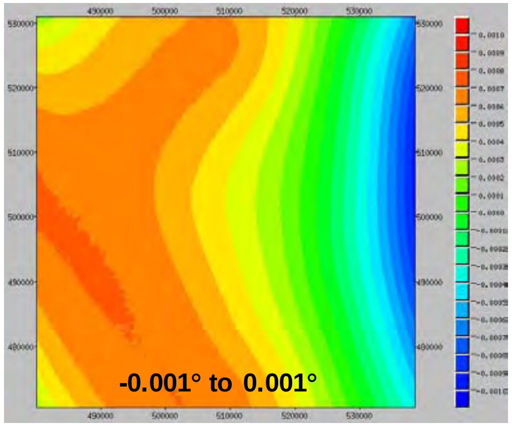


Differences of results processed using IGRF and results processed using BGGM

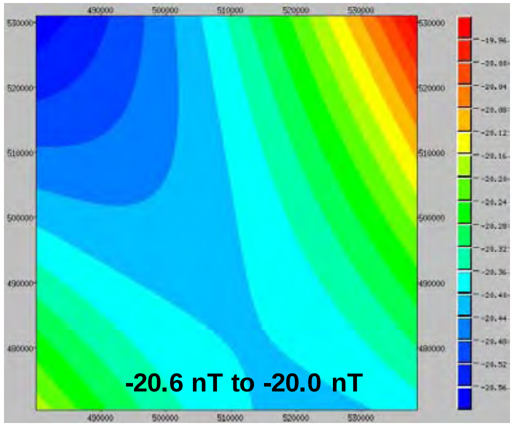
declination difference



inclination difference



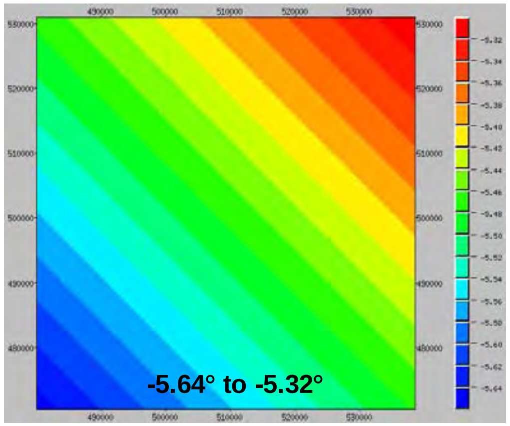
TMI anomaly difference



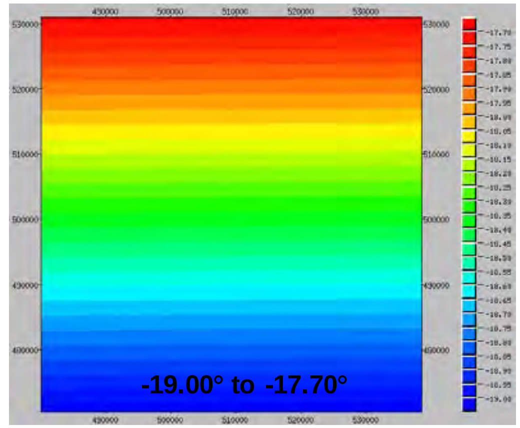
The Reference Field Values and Differences at 4500 m Depth

BGGM

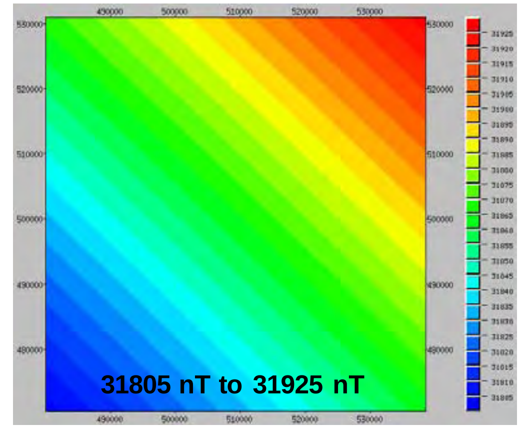
declination



inclination

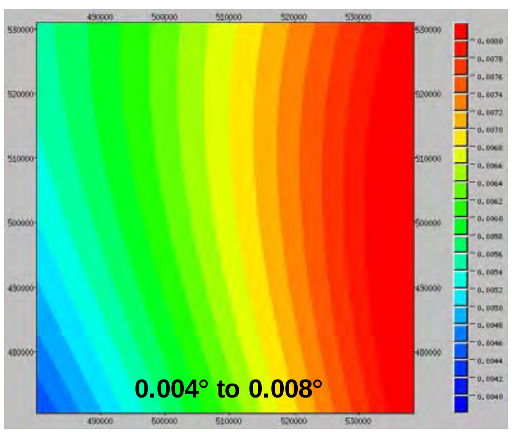


TMI

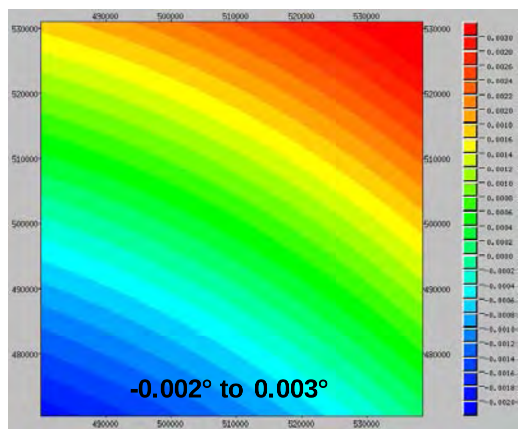


IGRF - BGGM

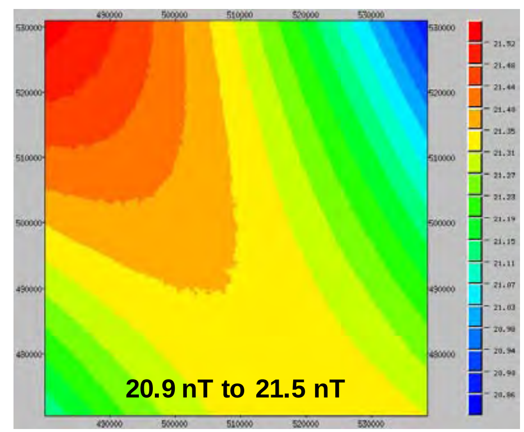
declination difference



inclination difference



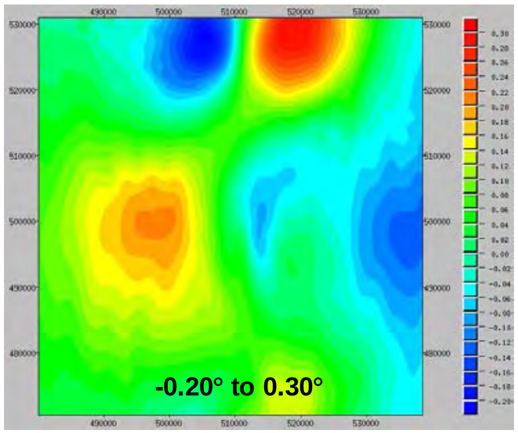
TMI difference



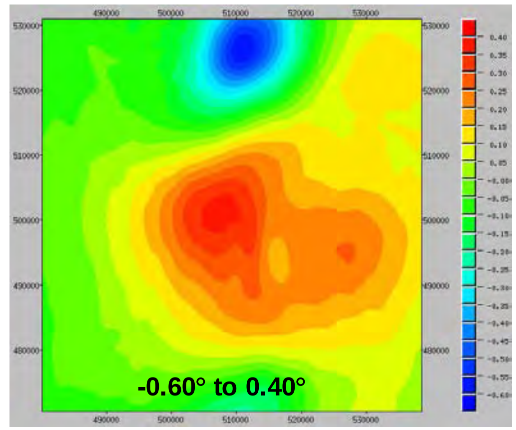
The Crustal Field Values and Differences at 4500 m Depth

Processed using BGGM

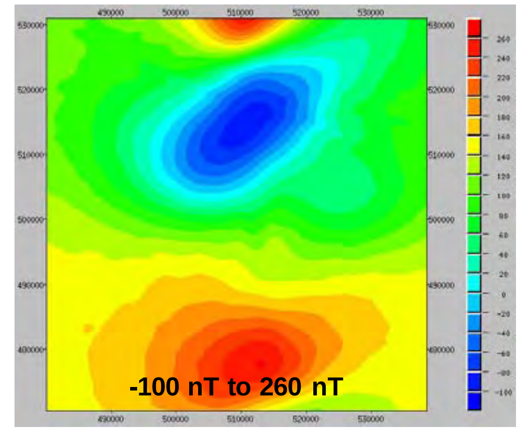
declination



inclination

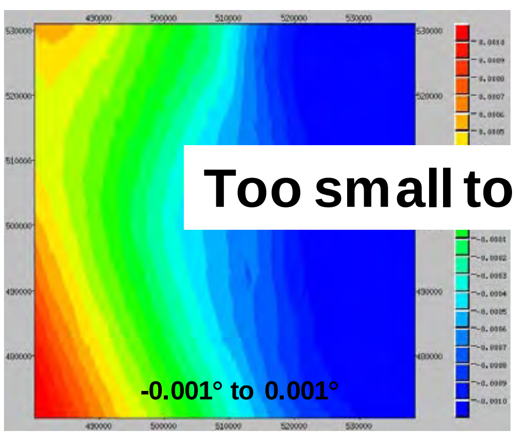


TMI anomaly

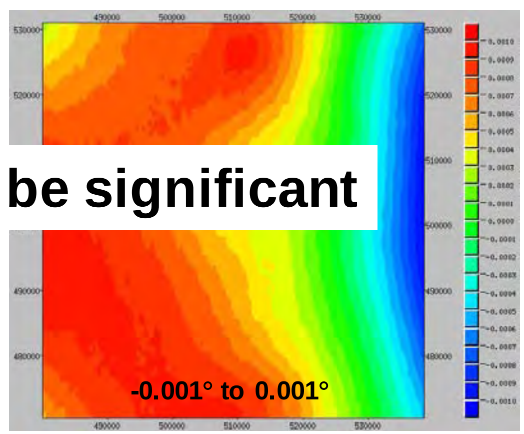


Differences of results processed using IGRF and results processed using BGGM

declination difference

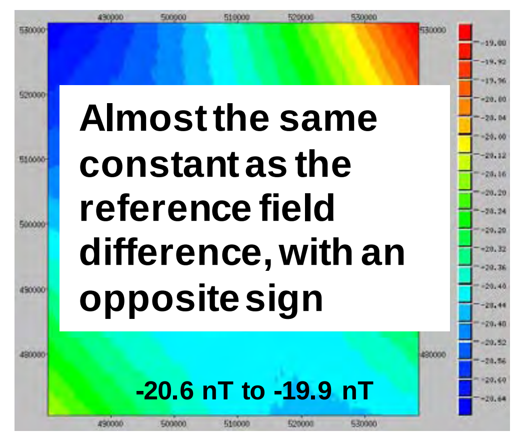


inclination difference



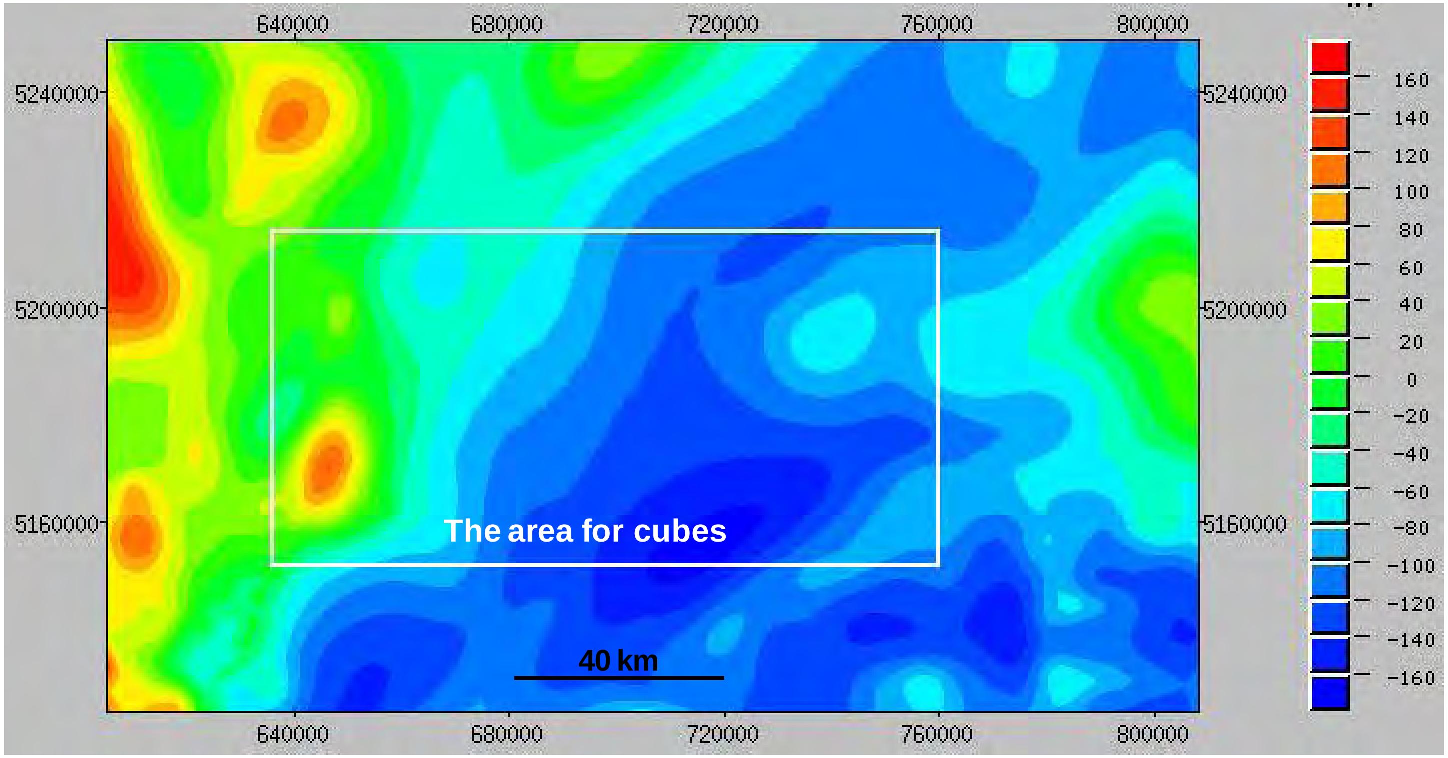
Too small to be significant

TMI anomaly difference



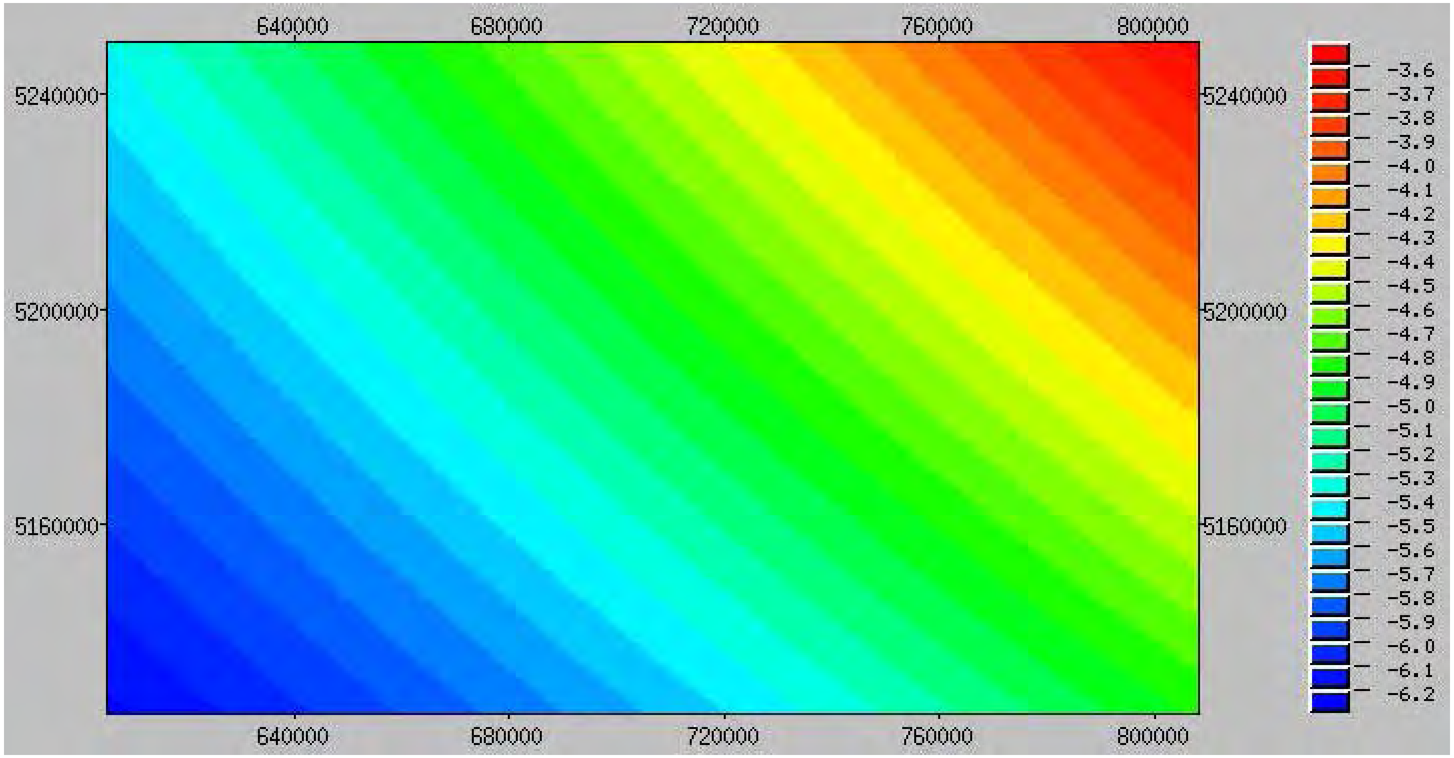
Almost the same constant as the reference field difference, with an opposite sign

Total Magnetic Intensity Anomaly Offshore Eastern Canada



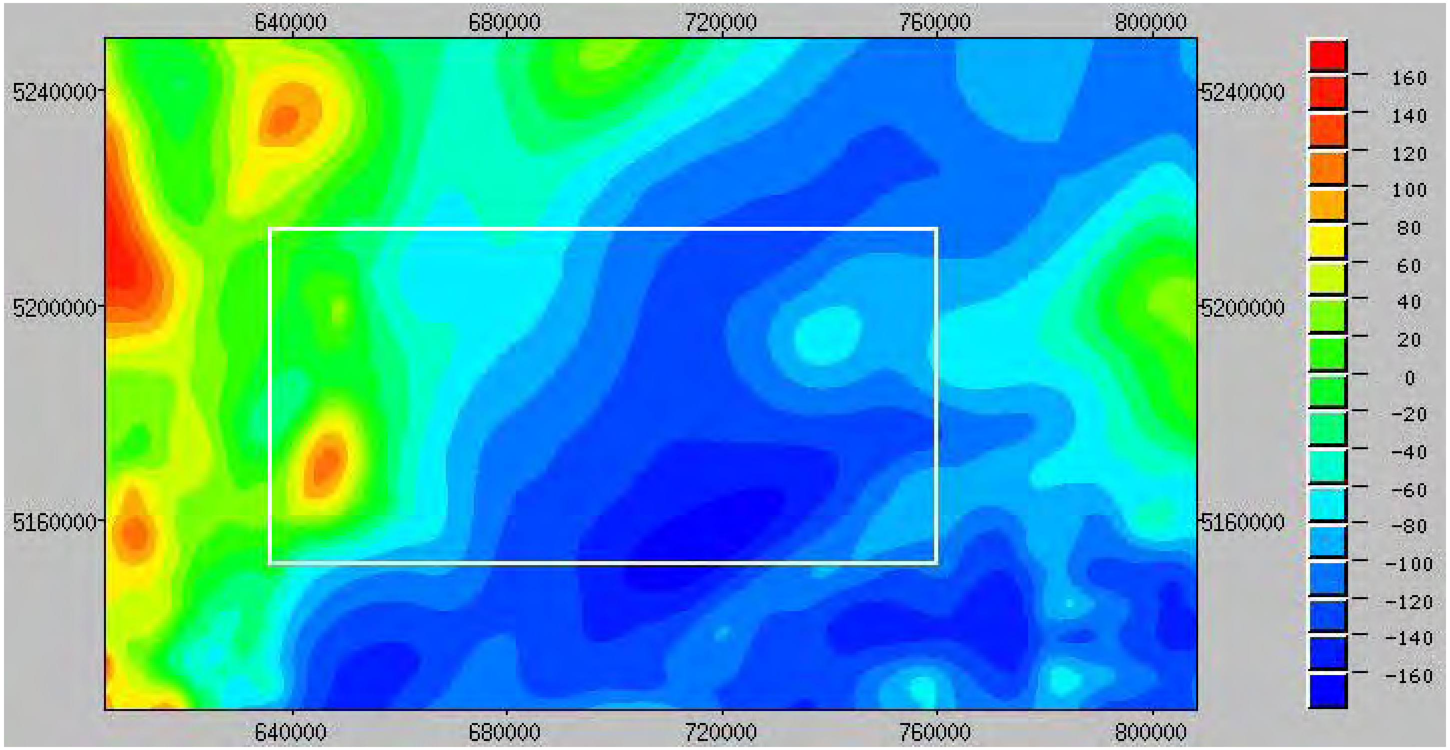
- **The IGRF-corrected TMI anomaly is from the 1-km GSC grid**
- **The only information about the aeromagnetic surveys**
  - The average flight height is 305 m above MSL
  - The survey date was about March 10, 1986

Differences in the Main Field Models



- **Both BGGM and IGRF use a spherical harmonic degree/order 10 for 1985.0.**
- **The small differences in the main field models don't affect the TMI anomaly significantly.**

The BGGM-Corrected TMI Anomaly



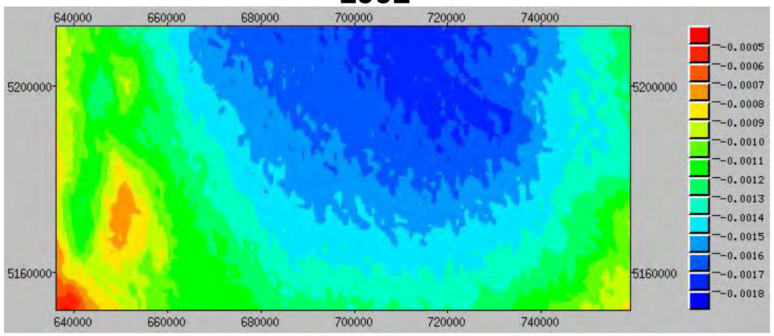
- **We compute the vector crustal magnetic field from this anomaly**
  - **using BGGM version 2012**
  - **for drilling dates of October 1 in 1992, 1997, 2002, 2007, and 2012.**
- **The estimates are for the PAST so that everything is "definitive".**

SH Degrees of the Reference Field Models

Year	IGRF	BGGM
1985.0	10	10
1990.0	10	13
2000.0	10	50
2005.0	13	50
2007.0	13	50
2010.0	13	50
2011.0	13	40

Differences between Two Crustal Declination Perturbation Results at 4500 m Depth

1992

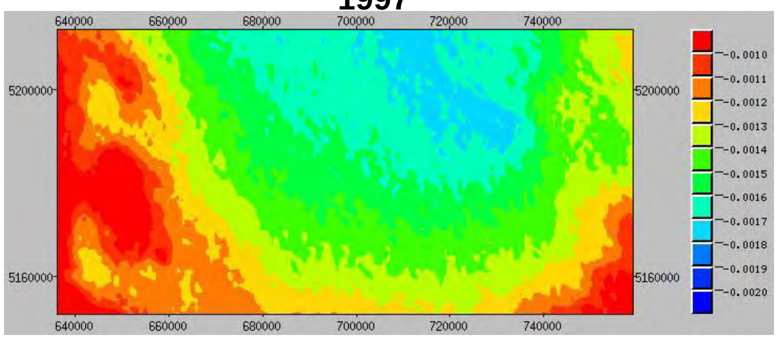


-0.0005°

-0.0018°

- **They are the IGRF-processed results minus the BGGM-processed results, for different years.**
- **The differences are too tiny to be significant.**

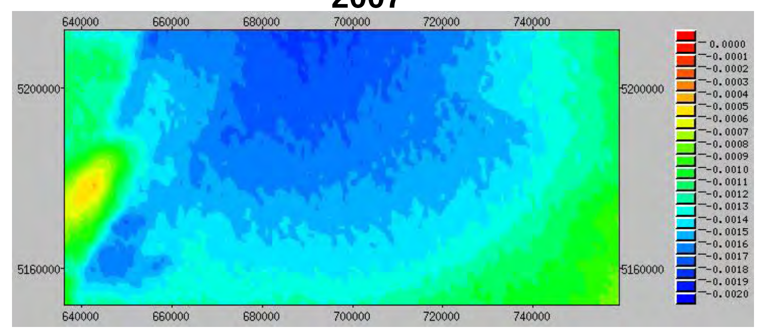
1997



-0.0010°

-0.0020°

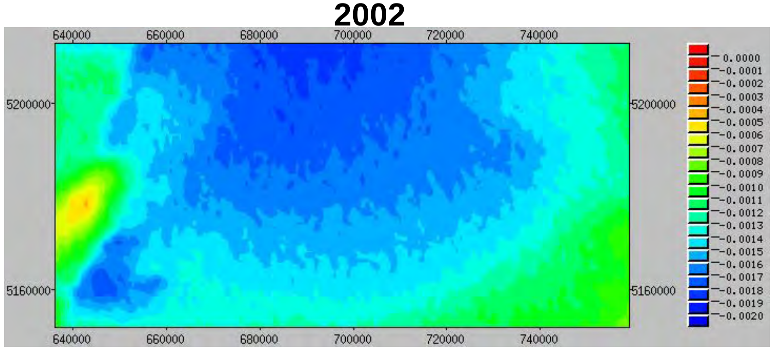
2007



0.0000°

-0.0020°

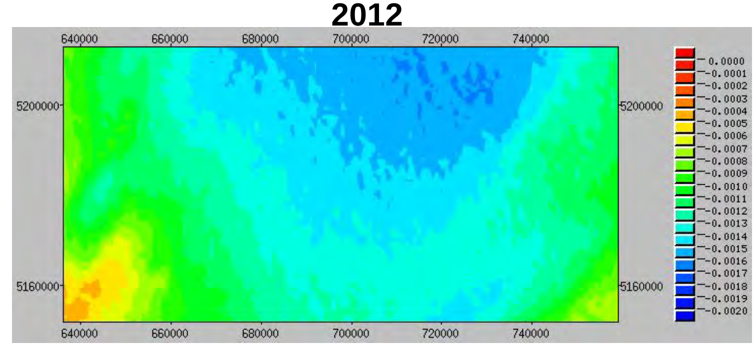
2002



0.0000°

-0.0020°

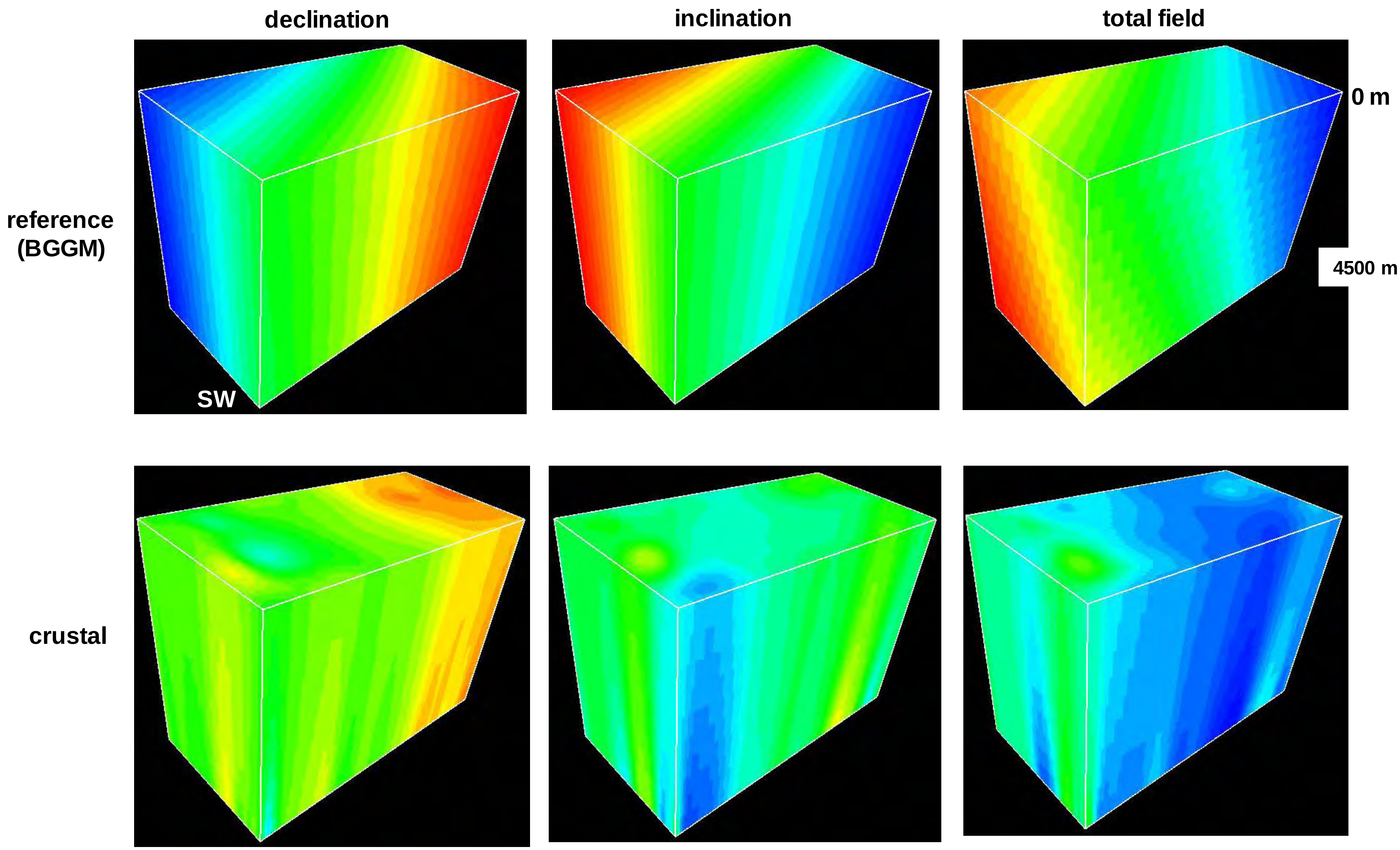
2012



0.0000°

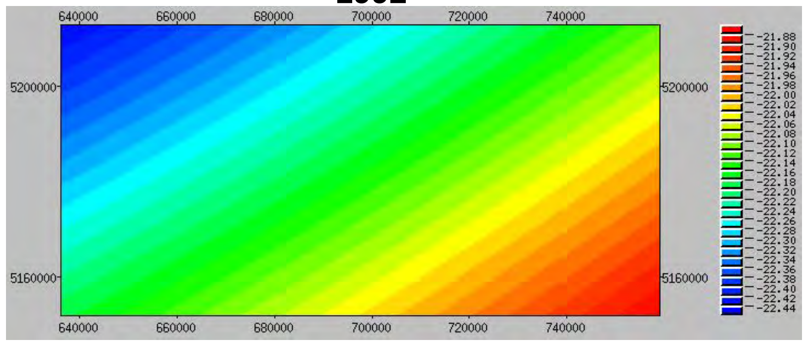
-0.0020°

The Magnetic Field Cubes on 1992-10-01



BGGM Declinations at 4500 m Depth

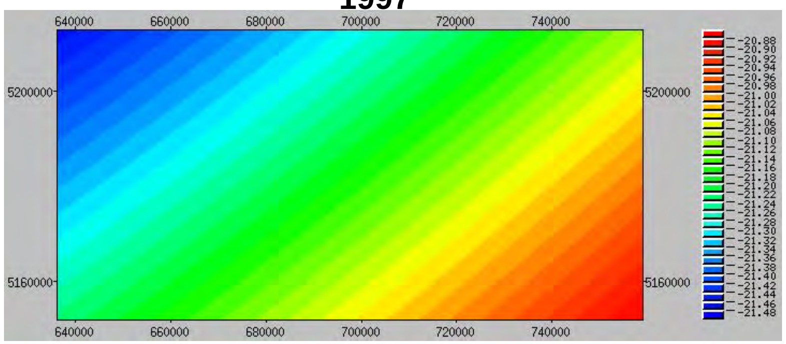
1992



-21.9°

-22.4°

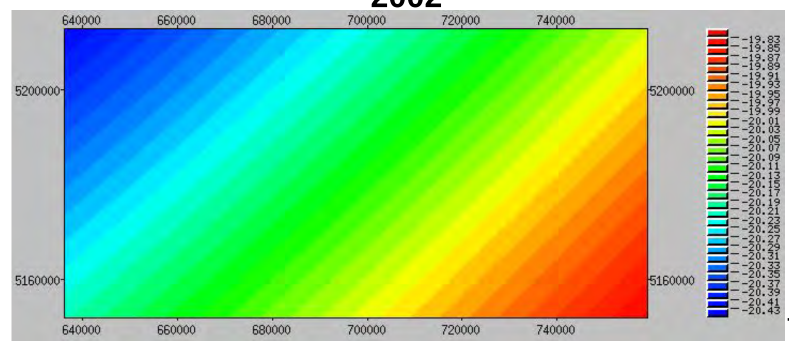
1997



-20.9°

-21.5°

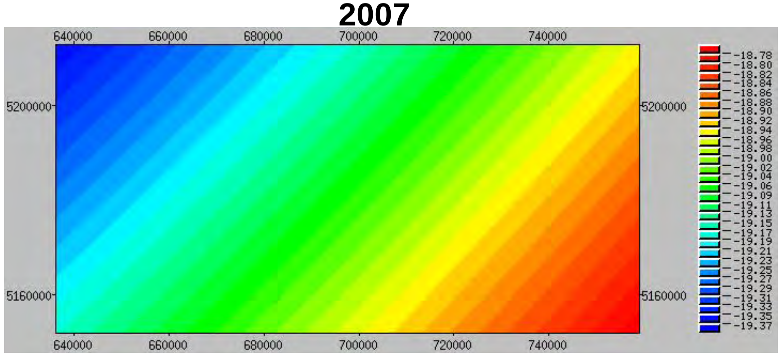
2002



-19.8°

-20.4°

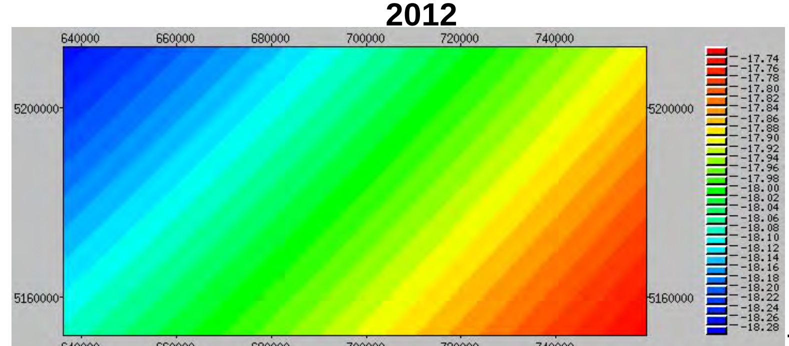
2007



-18.8°

-19.4°

2012

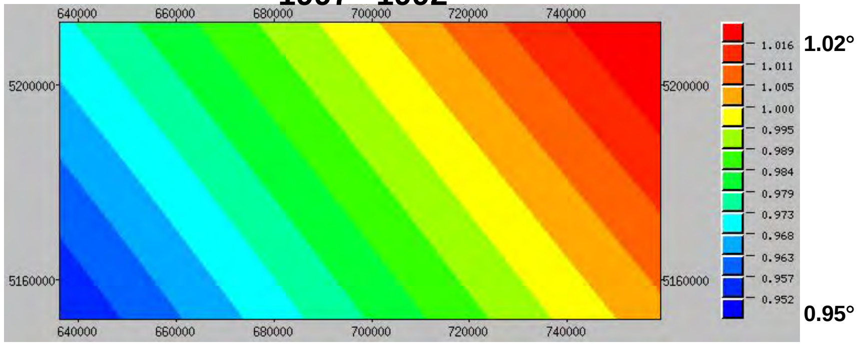


-17.7°

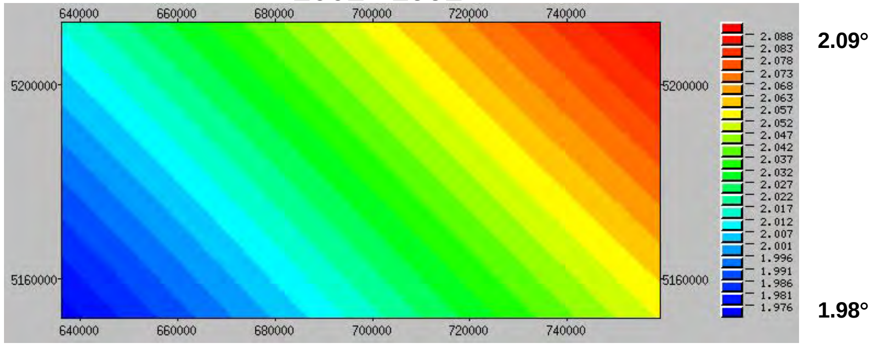
-18.3°

Changes in BGGM Declinations at 4500 m Depth

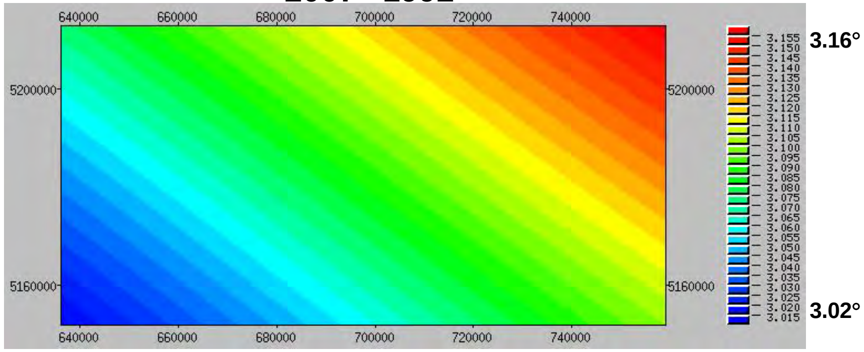
1997 - 1992



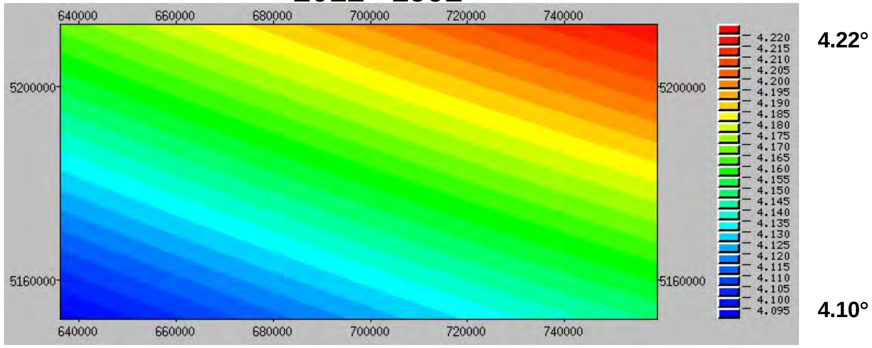
2002 - 1992



2007 - 1992

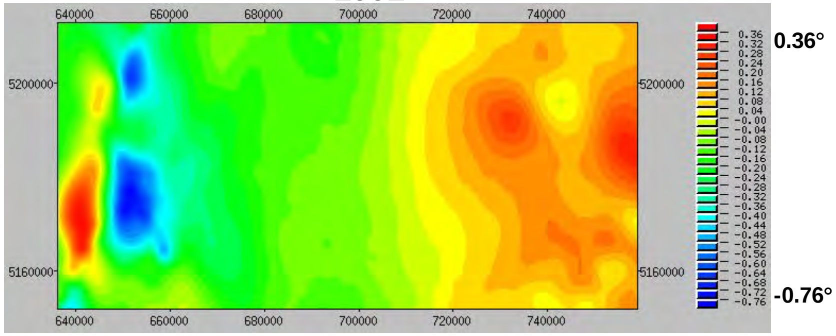


2012 - 1992

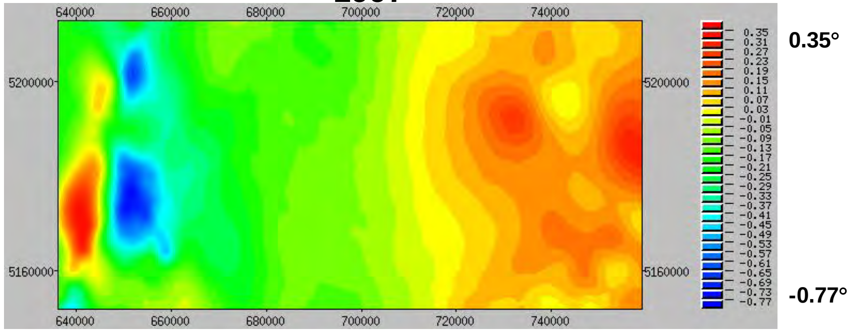


Crustal Declination Perturbations at 4500 m Depth

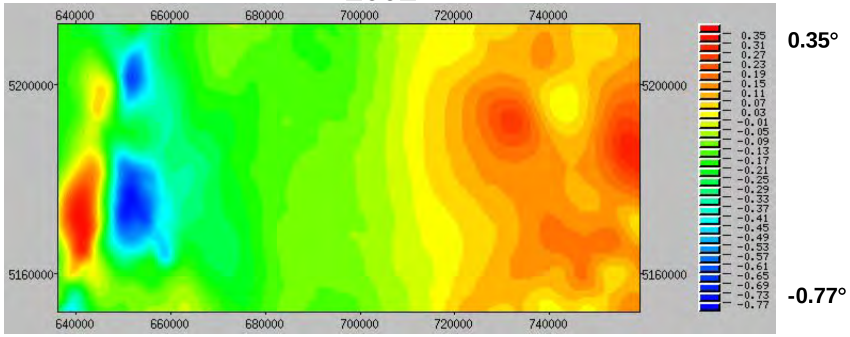
1992



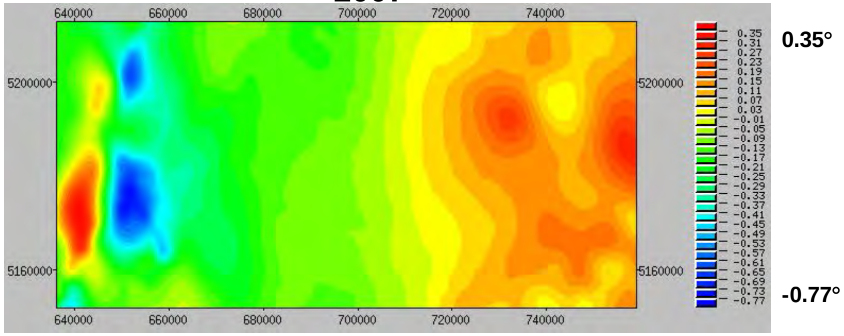
1997



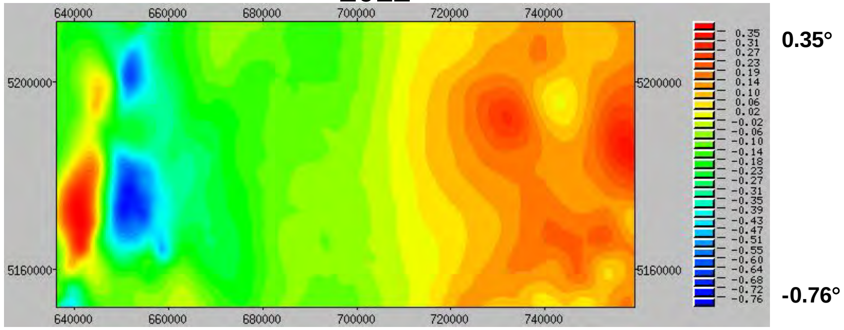
2002



2007



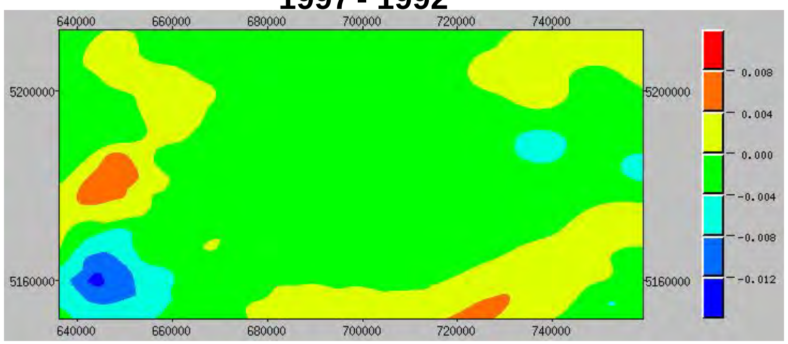
2012



Changes in Crustal Declinations at 4500 m Depth

The changes in 10 years are insignificant, and the changes in 15 or 20 years may be significant depending on the drilling location.

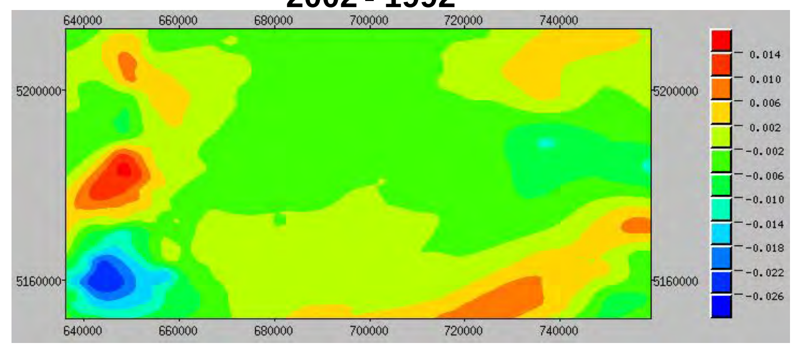
1997 - 1992



0.008°

-0.012°

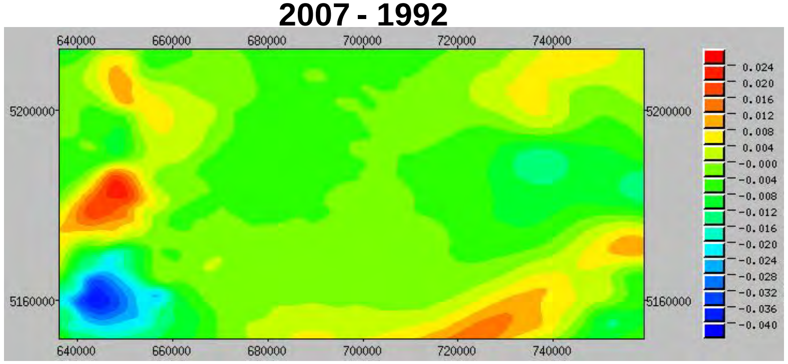
2002 - 1992



0.014°

-0.026°

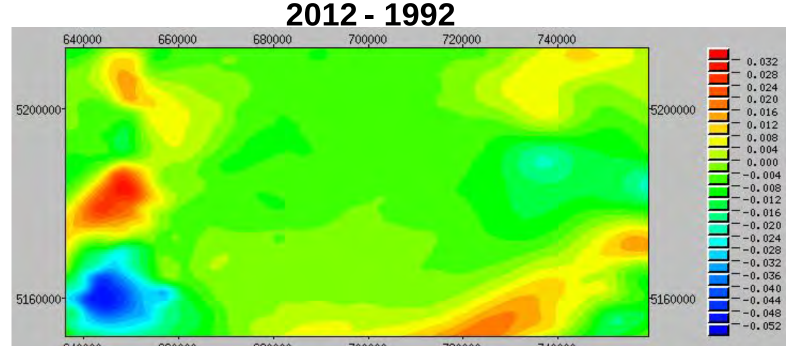
2007 - 1992



0.024°

-0.040°

2012 - 1992

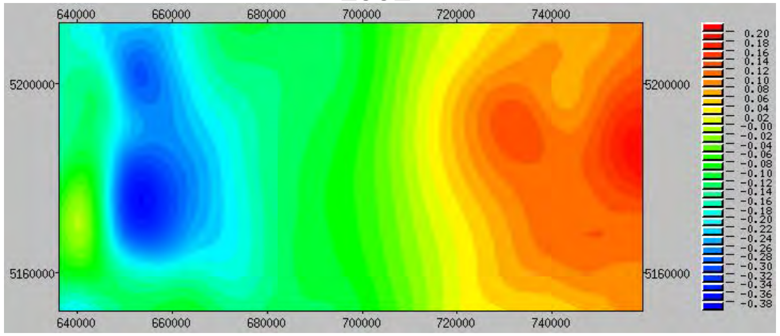


0.032°

-0.052°

Crustal Declination Perturbations and Their Changes at Sea Level

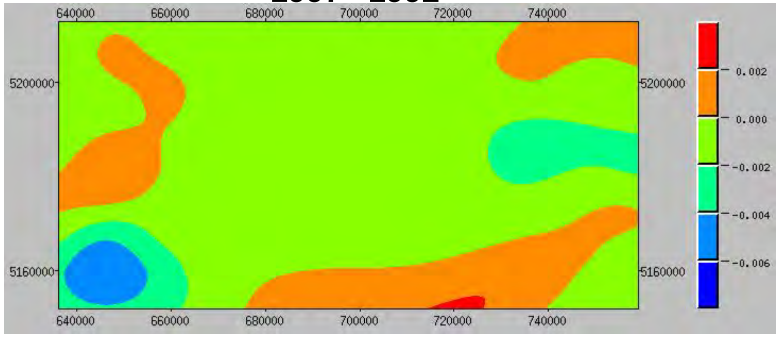
1992



0.20°

-0.38°

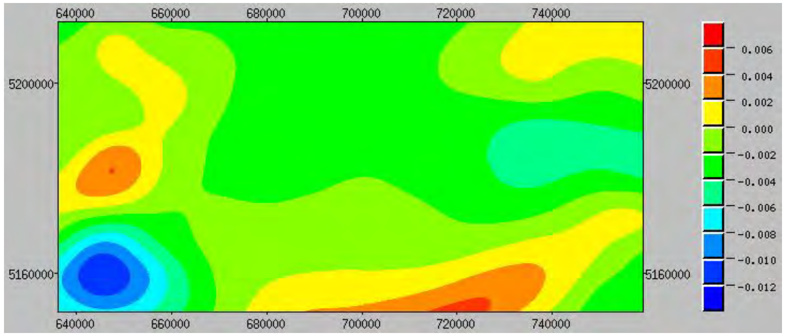
1997 - 1992



0.002°

-0.006°

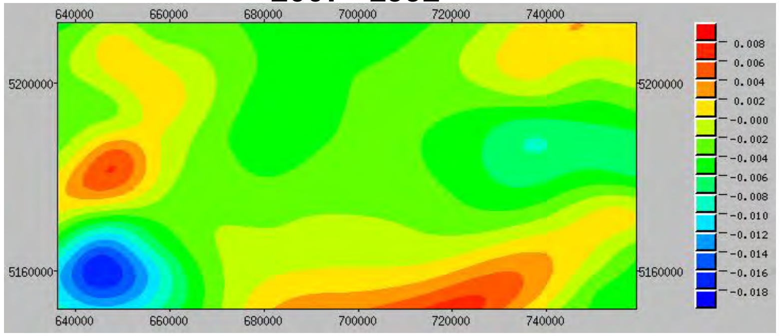
2002 - 1992



0.006°

-0.012°

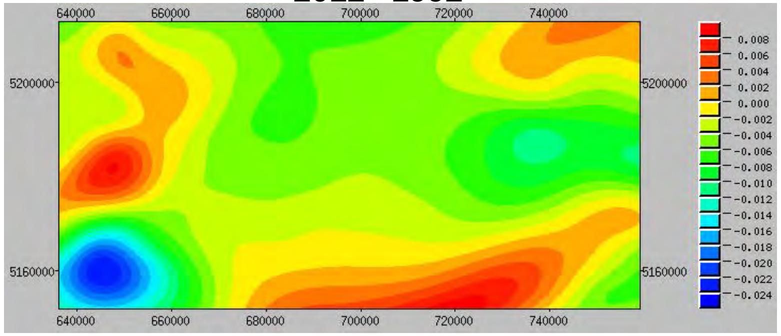
2007 - 1992



0.008°

-0.018°

2012 - 1992

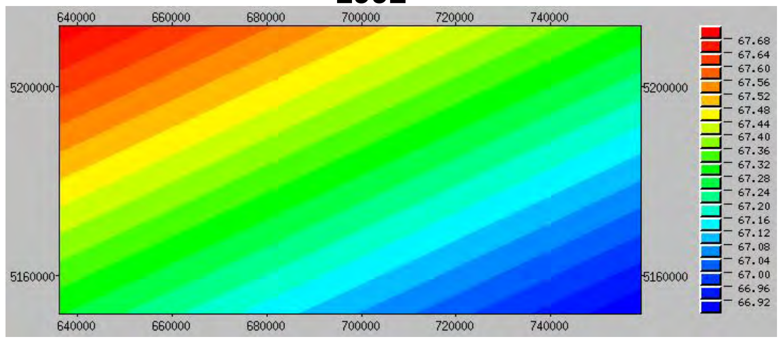


0.008°

-0.024°

BGGM Inclinations and Their Changes at 4500 m Depth

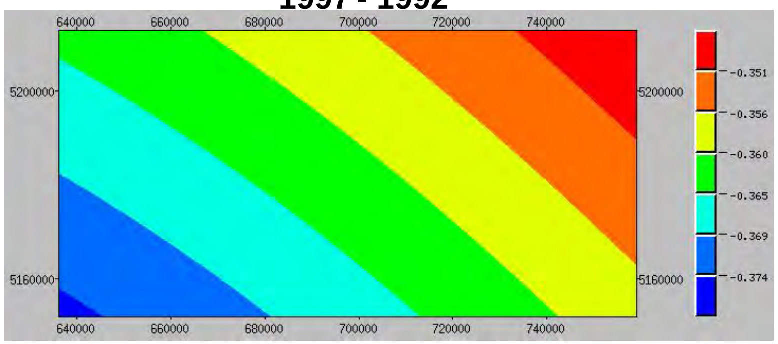
1992



67.7°

66.9°

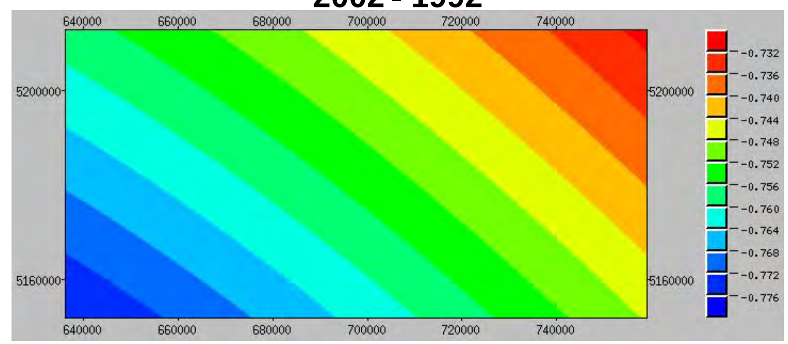
1997 - 1992



-0.35°

-0.37°

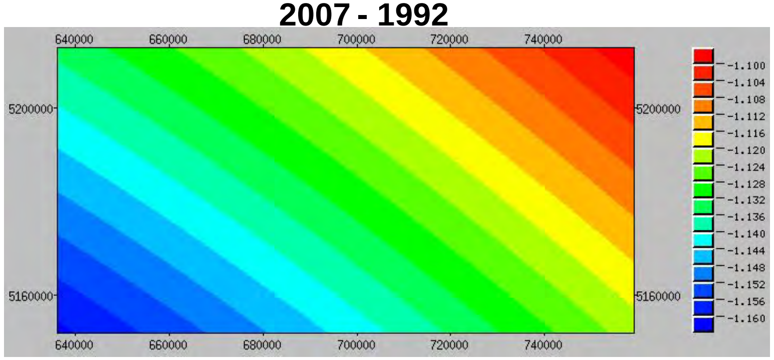
2002 - 1992



-0.73°

-0.78°

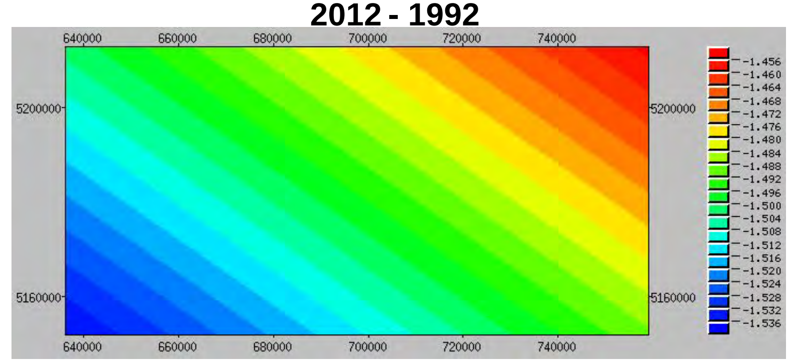
2007 - 1992



-1.10°

-1.16°

2012 - 1992

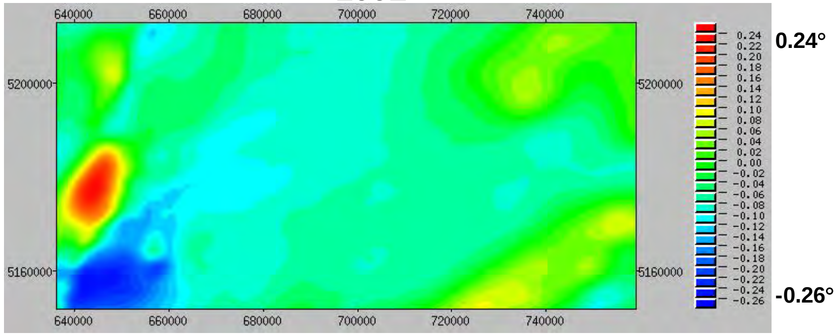


-1.46°

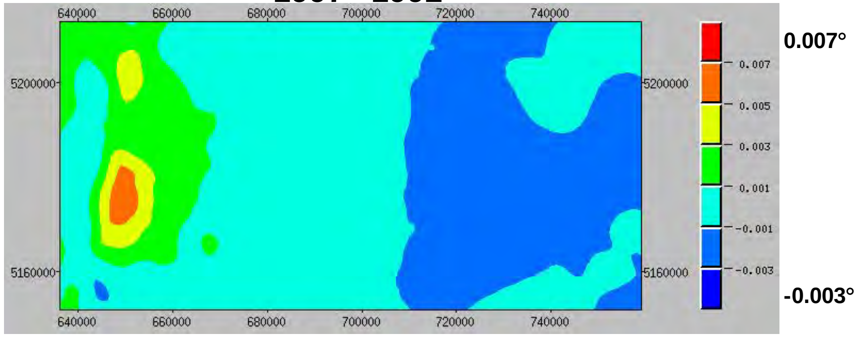
-1.54°

Crustal Inclination Perturbations and Their Changes at 4500 m Depth

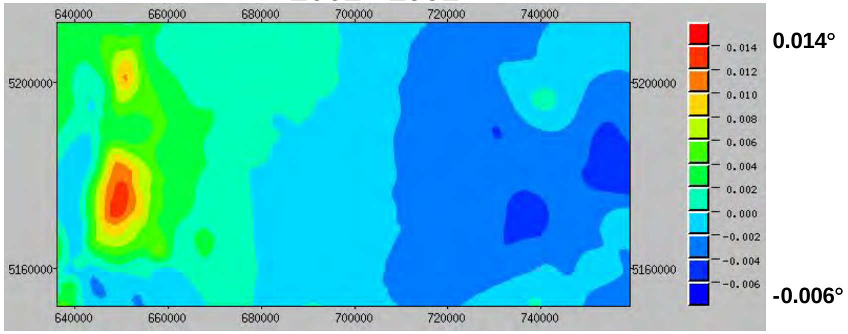
1992



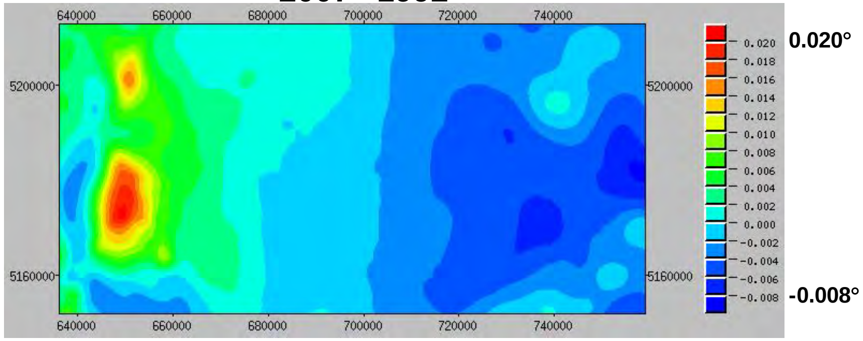
1997 - 1992



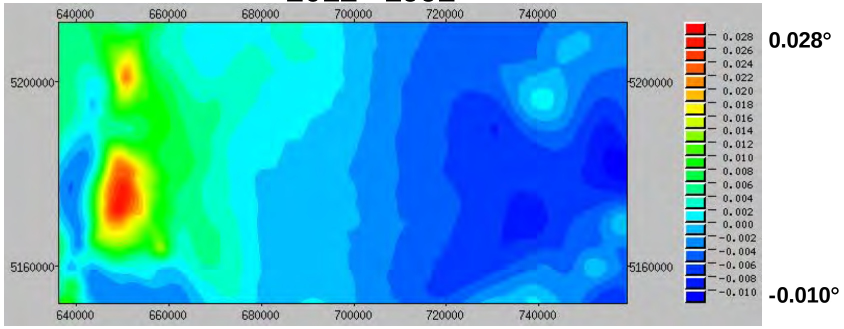
2002 - 1992



2007 - 1992



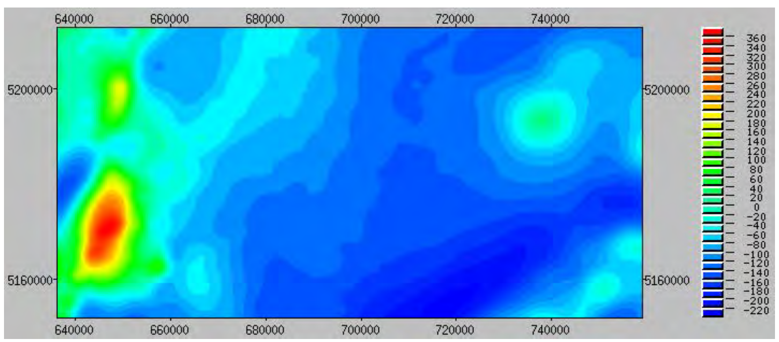
2012 - 1992



Deliver (X_c, Y_c, Z_c, TMI_c) Instead of (D_c, I_c, TMI_c)

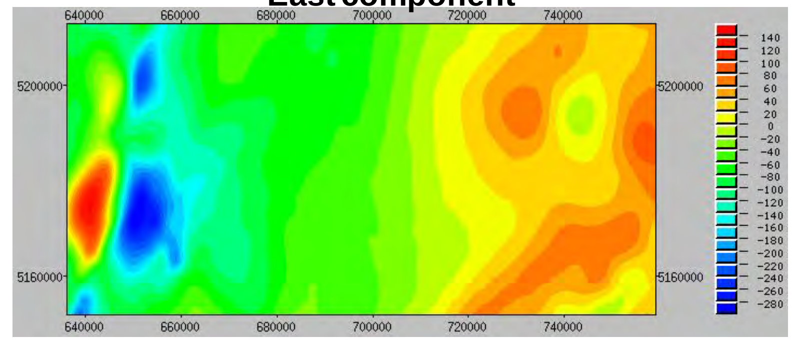
This removes the dependence of the subsurface vector crustal magnetic field deliverables on the main field model at the drilling time.

Crustal TMI anomaly

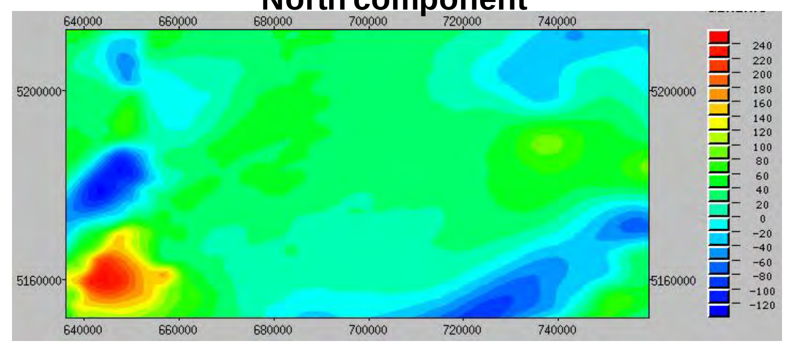


at 4500 m depth

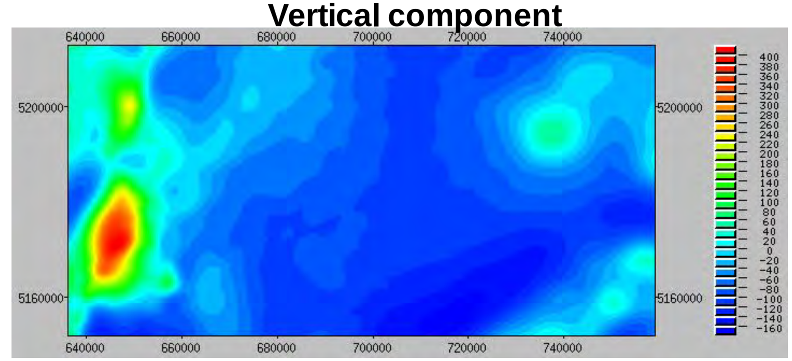
East component



North component



Vertical component



$$D_c = \arctan\frac{Y_m + Y_c}{X_m + X_c} - \arctan\frac{Y_m}{X_m}$$

$$I_c = \arctan\frac{Z_m + Z_c}{\sqrt{(X_m + X_c)^2 + (Y_m + Y_c)^2}} - \arctan\frac{Z_m}{\sqrt{X_m^{\ 2} + Y_m^{\ 2}}}$$

Conclusions

The current routine practice is to compute the crustal declination and inclination perturbations and the TMI anomaly: (D_c, I_c, TMI_c).

- **The differences in the crustal declination and inclination perturbations processed by the latest versions of IGRF and BGGM are insignificant (widely <0.001°).**
- **The differences in the crustal TMI anomalies due to different main (reference) field models, at different years, and at different depths are almost a constant and can be easily estimated and corrected.**
- **Crustal declination and inclination perturbations computed for a current date may be valid for up to 20 years in the offshore eastern Canada example (with an error of <0.05°).**
    - **Actual changes with time depend strongly on the project location.**
    - **It is likely that the “predictive” estimates for the future are similar to the “definitive” estimates for the past, in patterns and magnitudes.**

A Consideration and A Recommendation

- **If the HDGM is used as a reference model in this work, it is expected that changes with time in crustal declination and inclination perturbations are much smaller because the HDGM contains shorter-wavelengths (down to 55 km) of the crustal magnetic field than the BGGM (>700 km).**

- **An alternative is to deliver the crustal (X_c, Y_c, Z_c, TMI_c) components instead of (D_c, I_c, TMI_c), which removes the dependence on the main (reference) field at the drilling time.**