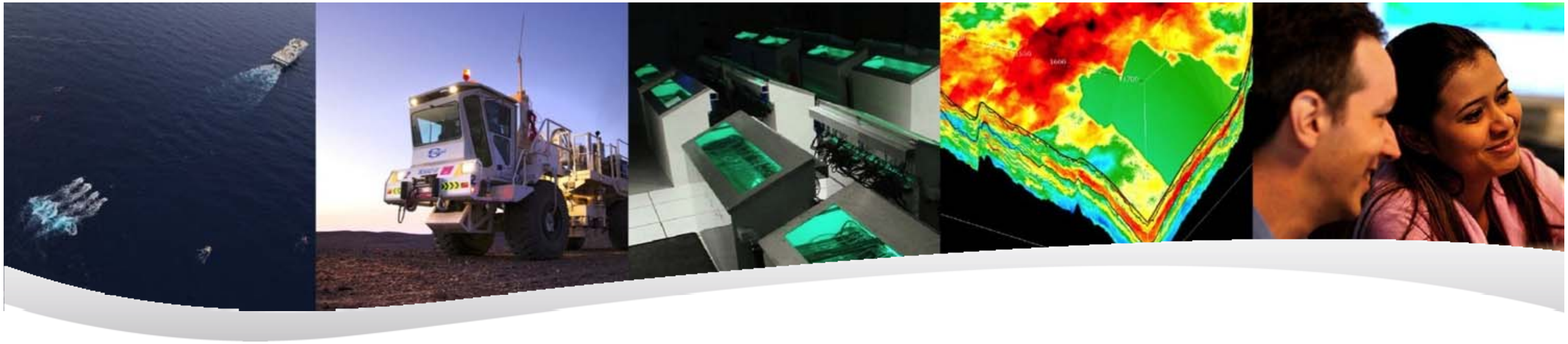


An Accurate Determination of the Crustal Magnetic Field for Any Reference Model and Any Drilling Time

Xiong Li and Benny Poedjono

in Paris on March 8, 2013

Passion for Geoscience

Schlumberger CGG

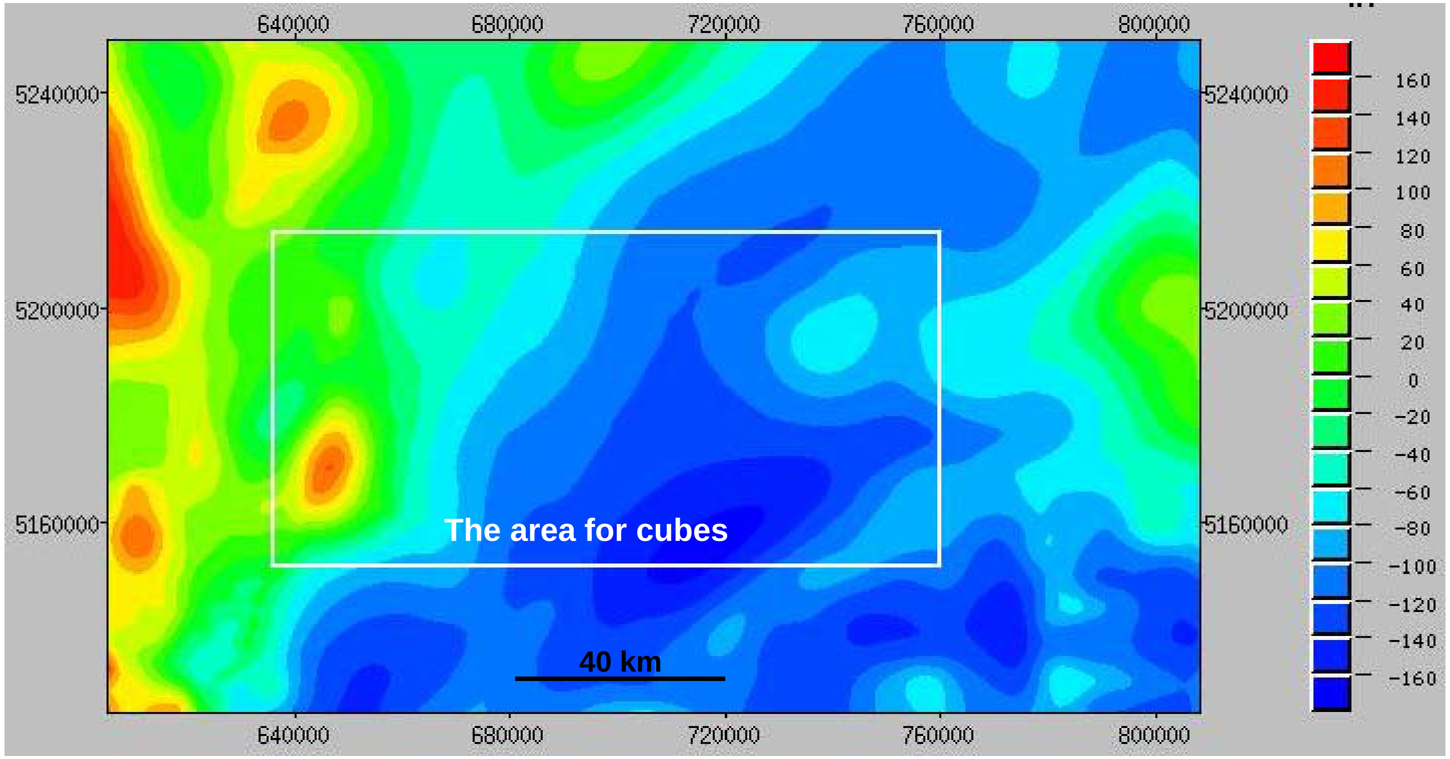
4 Slides from the Presentation in San Antonio

- **Is the vector crustal magnetic field relative to a current 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 (SH) expansion used to define the reference field model increases**
- **Directional drilling involves the main field at the aeromagnetic survey time and the main field at the drilling time**

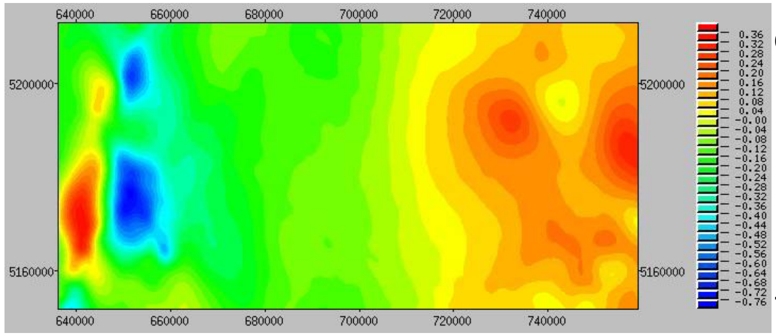
Total Magnetic Intensity Anomaly Offshore Eastern Canada



- **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

Crustal Declination Perturbations at 4500 m Depth

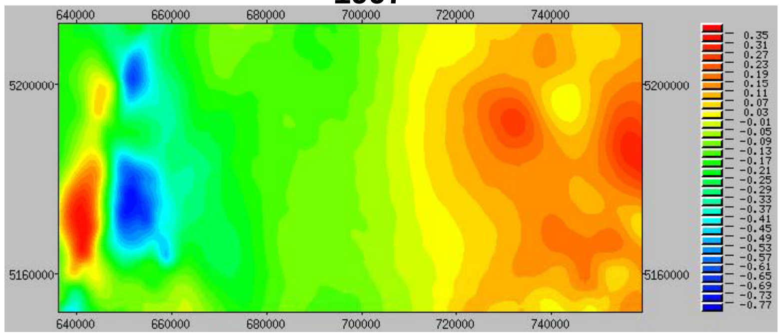
1992



0.36°

-0.76°

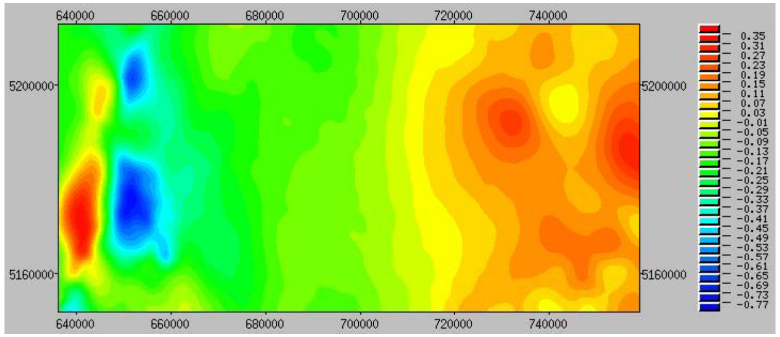
1997



0.35°

-0.77°

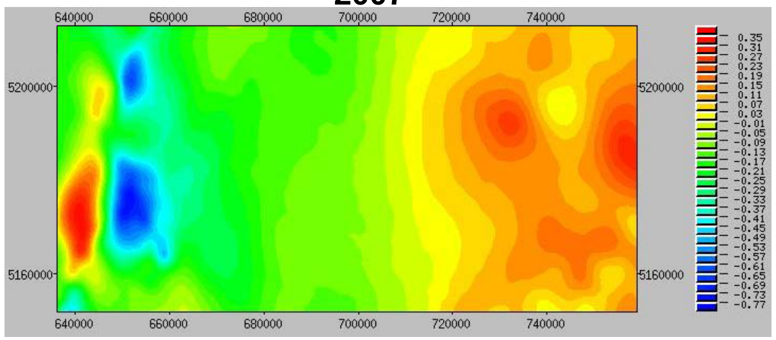
2002



0.35°

-0.77°

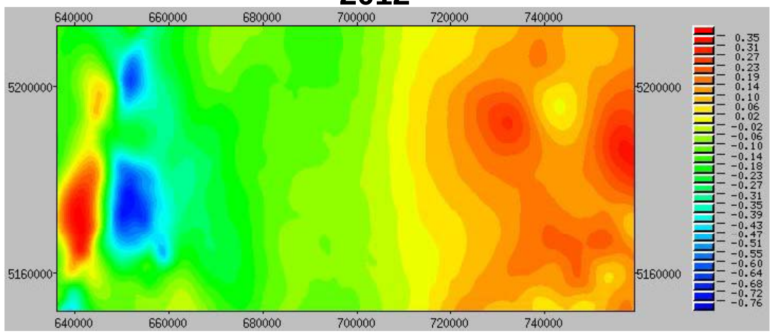
2007



0.35°

-0.77°

2012



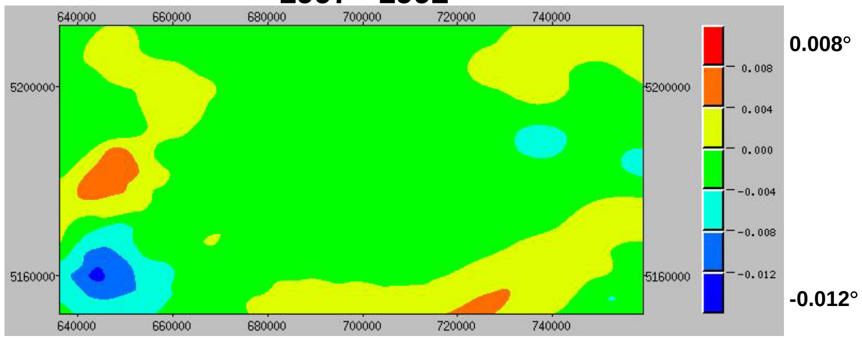
0.35°

-0.76°

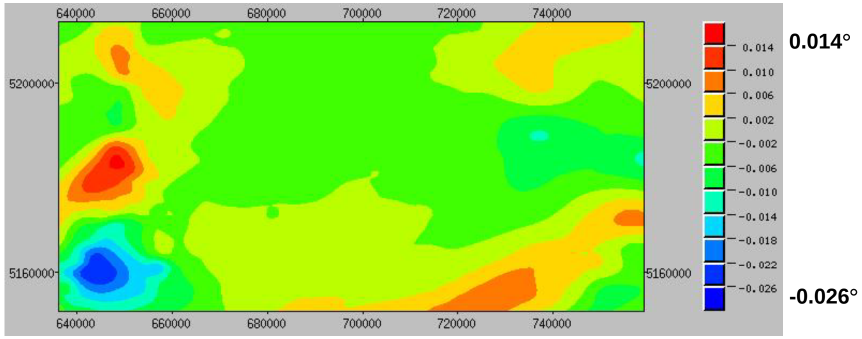
Changes in Crustal Declinations at 4500 m Depth

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

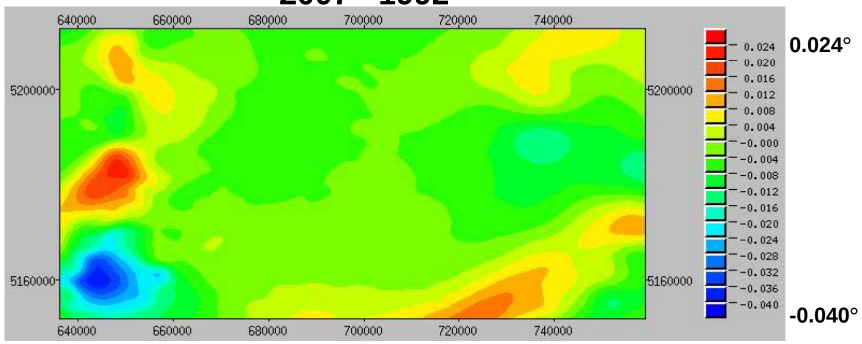
1997 - 1992



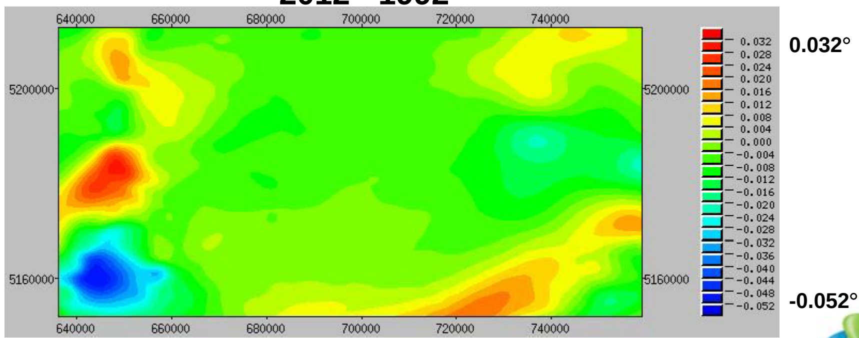
2002 - 1992



2007 - 1992



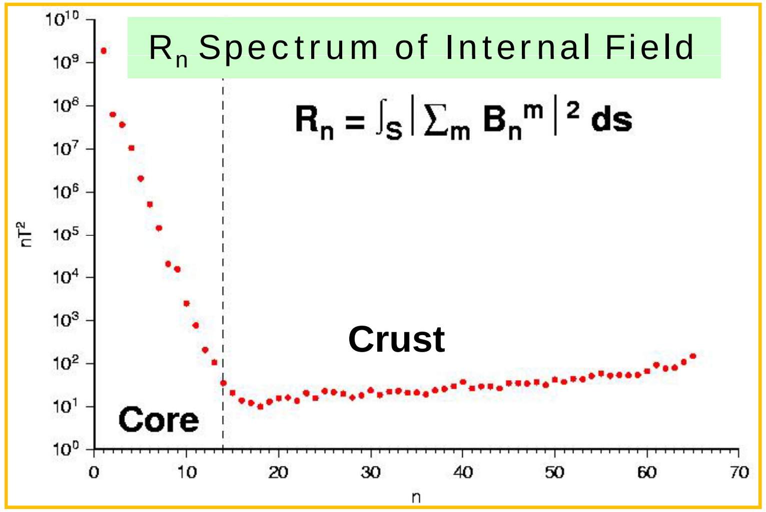
2012 - 1992



Geomagnetic Reference Models: Current Status

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

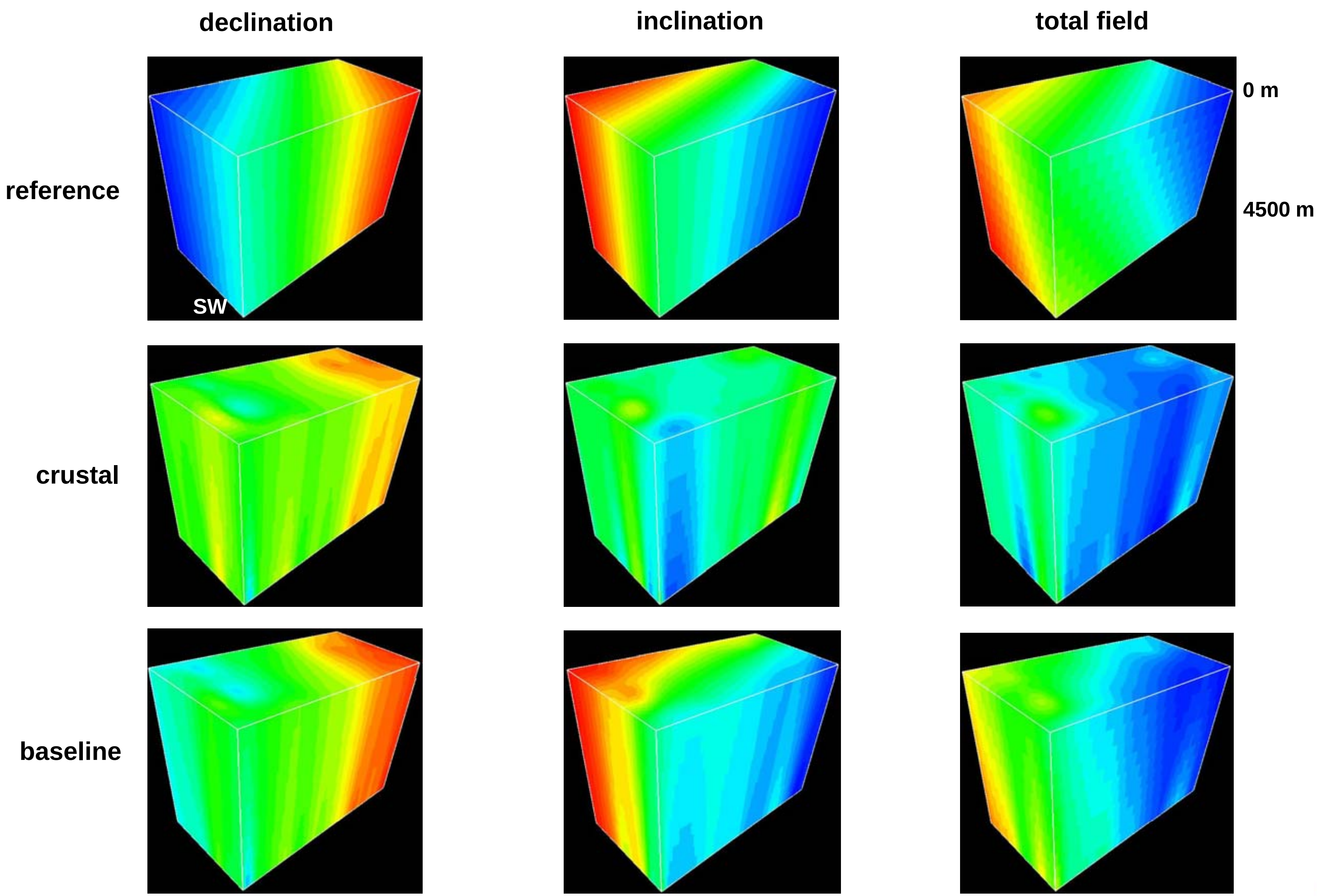


A Bigger Question

- From a crustal magnetic field model created earlier, can we compute accurately the crustal field
  - along any well path
  - at any future time
  - relative to a different reference field model?

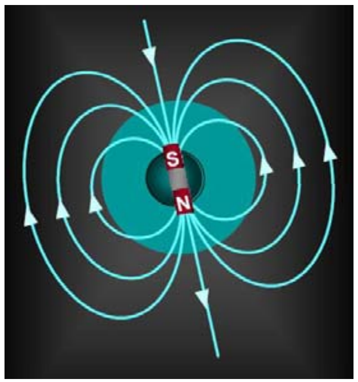
- YES, under two conditions
  1. The subsurface vector crustal magnetic field values together with its reference field model values are delivered in the volume format, and this volume contains all future wells.
  2. The future reference magnetic field model covers the year that the above crustal and reference field values are created.

The Magnetic Field Cubes

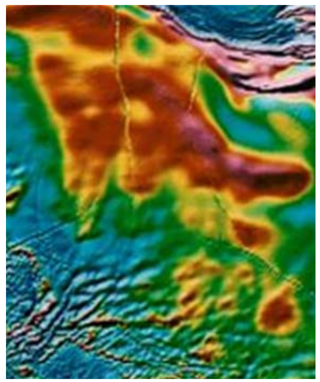


Some Symbols

- t1: **the time of the crustal field model created**
- m1**: the reference field model used to create the above crustal model**
- t2: **the future drilling time to use the crustal field model**
- m2**: the reference field model at the future drilling time**
- **C: the vector crustal field**
- **R: the vector reference field**
- **B: the vector baseline field (B = R + C)**



R



C

Parameters of the Magnetic Field

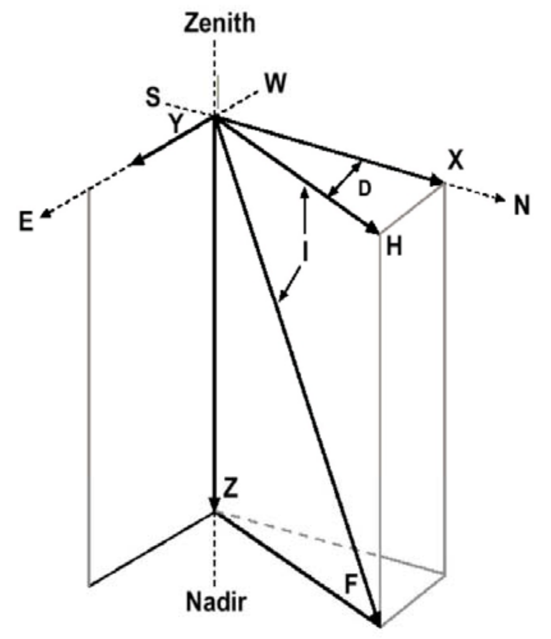
D:	Declination
I:	Inclination
F:	Total field intensity

OR

X, Y, Z components

They are linked by

$$
\begin{aligned}
F^2 &= H^2 + Z^2 = X^2 + Y^2 + Z^2 \\
H &= F \cos I \\
Z &= F \sin I \\
\tan I &= Z/H \\
X &= H \cos D \\
Y &= H \sin D \\
\tan D &= Y/X
\end{aligned}
$$



Recover the Baseline (*X*, *Y*, *Z*) Values at the Creation Time

The delivered crustal, reference and baseline field cubes are

$$D\left(\mathbf{C}_{m1}^{t1}\right) \quad I\left(\mathbf{C}_{m1}^{t1}\right) \quad F\left(\mathbf{C}_{m1}^{t1}\right); \quad D\left(\mathbf{R}_{m1}^{t1}\right) \quad I\left(\mathbf{R}_{m1}^{t1}\right) \quad F\left(\mathbf{R}_{m1}^{t1}\right); \quad D\left(\mathbf{B}_{m1}^{t1}\right) \quad I\left(\mathbf{B}_{m1}^{t1}\right) \quad F\left(\mathbf{B}_{m1}^{t1}\right)$$

Their relationships are

$$\begin{cases} D\left(\mathbf{B}_{m1}^{t1}\right) = D\left(\mathbf{C}_{m1}^{t1}\right) + D\left(\mathbf{R}_{m1}^{t1}\right) \\ I\left(\mathbf{B}_{m1}^{t1}\right) = I\left(\mathbf{C}_{m1}^{t1}\right) + I\left(\mathbf{R}_{m1}^{t1}\right) \\ F\left(\mathbf{B}_{m1}^{t1}\right) = F\left(\mathbf{C}_{m1}^{t1}\right) + F\left(\mathbf{R}_{m1}^{t1}\right) \end{cases}$$

The Baseline (X, Y, Z) are computed by

$$\begin{cases} X\left(\mathbf{B}_{m1}^{t1}\right) = F\left(\mathbf{B}_{m1}^{t1}\right)\cos\left[I\left(\mathbf{B}_{m1}^{t1}\right)\right]\cos\left[D\left(\mathbf{B}_{m1}^{t1}\right)\right] \\ Y\left(\mathbf{B}_{m1}^{t1}\right) = F\left(\mathbf{B}_{m1}^{t1}\right)\cos\left[I\left(\mathbf{B}_{m1}^{t1}\right)\right]\sin\left[D\left(\mathbf{B}_{m1}^{t1}\right)\right] \\ Z\left(\mathbf{B}_{m1}^{t1}\right) = F\left(\mathbf{B}_{m1}^{t1}\right)\sin\left[I\left(\mathbf{B}_{m1}^{t1}\right)\right] \end{cases}$$

NEW: **Drillers need to implement this computation.**

Effects of Two Different Reference Models

FACT #1 - ***The baseline (i.e., the vector sum of the crustal and reference fields) at the same time should not change***

$$\mathbf{C}_{m1}^{t1} + \mathbf{R}_{m1}^{t1} = \mathbf{C}_{m2}^{t1} + \mathbf{R}_{m2}^{t1} \quad \Rightarrow \quad \mathbf{C}_{m2}^{t1} = \mathbf{B}_{m1}^{t1} - \mathbf{R}_{m2}^{t1}$$

For each of the three components

$$X\left(\mathbf{C}_{m2}^{t1}\right) = X\left(\mathbf{B}_{m1}^{t1}\right) - X\left(\mathbf{R}_{m2}^{t1}\right)$$

$$Y\left(\mathbf{C}_{m2}^{t1}\right) = Y\left(\mathbf{B}_{m1}^{t1}\right) - Y\left(\mathbf{R}_{m2}^{t1}\right)$$

$$Z\left(\mathbf{C}_{m2}^{t1}\right) = Z\left(\mathbf{B}_{m1}^{t1}\right) - Z\left(\mathbf{R}_{m2}^{t1}\right)$$

NEW: **Drillers need to implement this computation of $\mathbf{R}_{m2}^{t1}$ & $\mathbf{C}_{m2}^{t1}$**

The Crustal Field in the Same Reference Model

FACT #2 - *The crustal field doesn't change with time (at least in tens of years) in the same reference model series*

$$\mathbf{C}_{m2}^{t2} = \mathbf{C}_{m2}^{t1}$$

For each of the three components

$$X\left(\mathbf{C}_{m2}^{t2}\right) = X\left(\mathbf{C}_{m2}^{t1}\right)$$

$$Y\left(\mathbf{C}_{m2}^{t2}\right) = Y\left(\mathbf{C}_{m2}^{t1}\right)$$

$$Z\left(\mathbf{C}_{m2}^{t2}\right) = Z\left(\mathbf{C}_{m2}^{t1}\right)$$

The Crustal Field in the Future

The crustal anomalies relative to a future reference model at a future drilling time are

$$D\left(\mathbf{C}_{m2}^{t2}\right) = \arctan\frac{Y\left(\mathbf{C}_{m2}^{t2}\right) + Y\left(\mathbf{R}_{m2}^{t2}\right)}{X\left(\mathbf{C}_{m2}^{t2}\right) + X\left(\mathbf{R}_{m2}^{t2}\right)} - \arctan\frac{Y\left(\mathbf{R}_{m2}^{t2}\right)}{X\left(\mathbf{R}_{m2}^{t2}\right)}$$

or

$$D\left(\mathbf{C}_{m2}^{t2}\right) = \arctan\frac{Y\left(\mathbf{C}_{m2}^{t2}\right) + Y\left(\mathbf{R}_{m2}^{t2}\right)}{X\left(\mathbf{C}_{m2}^{t2}\right) + X\left(\mathbf{R}_{m2}^{t2}\right)} - D\left(\mathbf{R}_{m2}^{t2}\right)$$

$$I\left(\mathbf{C}_{m2}^{t2}\right) = \arctan\frac{Z\left(\mathbf{C}_{m2}^{t2}\right) + Z\left(\mathbf{R}_{m2}^{t2}\right)}{\sqrt{\left[X\left(\mathbf{C}_{m2}^{t2}\right) + X\left(\mathbf{R}_{m2}^{t2}\right)\right]^2 + \left[Y\left(\mathbf{C}_{m2}^{t2}\right) + Y\left(\mathbf{R}_{m2}^{t2}\right)\right]^2}} - \arctan\frac{Z\left(\mathbf{R}_{m2}^{t2}\right)}{\sqrt{\left[X\left(\mathbf{R}_{m2}^{t2}\right)\right]^2 + \left[Y\left(\mathbf{R}_{m2}^{t2}\right)\right]^2}}$$

or

$$I\left(\mathbf{C}_{m2}^{t2}\right) = \arctan\frac{Z\left(\mathbf{C}_{m2}^{t2}\right) + Z\left(\mathbf{R}_{m2}^{t2}\right)}{\sqrt{\left[X\left(\mathbf{C}_{m2}^{t2}\right) + X\left(\mathbf{R}_{m2}^{t2}\right)\right]^2 + \left[Y\left(\mathbf{C}_{m2}^{t2}\right) + Y\left(\mathbf{R}_{m2}^{t2}\right)\right]^2}} - I\left(\mathbf{R}_{m2}^{t2}\right)$$

$$F\left(\mathbf{C}_{m2}^{t2}\right) = \sqrt{\left[X\left(\mathbf{C}_{m2}^{t2}\right) + X\left(\mathbf{R}_{m2}^{t2}\right)\right]^2 + \left[Y\left(\mathbf{C}_{m2}^{t2}\right) + Y\left(\mathbf{R}_{m2}^{t2}\right)\right]^2 + \left[Z\left(\mathbf{C}_{m2}^{t2}\right) + Z\left(\mathbf{R}_{m2}^{t2}\right)\right]^2} - F\left(\mathbf{R}_{m2}^{t2}\right)$$

Or Simply Use the Baseline Values at the Future Drilling Time

Baseline declination

$$D\left(\mathbf{B}_{m2}^{t2}\right) = \arctan \frac{Y\left(\mathbf{C}_{m2}^{t2}\right) + Y\left(\mathbf{R}_{m2}^{t2}\right)}{X\left(\mathbf{C}_{m2}^{t2}\right) + X\left(\mathbf{R}_{m2}^{t2}\right)}$$

Baseline inclination

$$I\left(\mathbf{B}_{m2}^{t2}\right) = \arctan \frac{Z\left(\mathbf{C}_{m2}^{t2}\right) + Z\left(\mathbf{R}_{m2}^{t2}\right)}{\sqrt{\left[X\left(\mathbf{C}_{m2}^{t2}\right) + X\left(\mathbf{R}_{m2}^{t2}\right)\right]^2 + \left[Y\left(\mathbf{C}_{m2}^{t2}\right) + Y\left(\mathbf{R}_{m2}^{t2}\right)\right]^2}}$$

Baseline total field intensity

$$F\left(\mathbf{B}_{m2}^{t2}\right) = \sqrt{\left[X\left(\mathbf{C}_{m2}^{t2}\right) + X\left(\mathbf{R}_{m2}^{t2}\right)\right]^2 + \left[Y\left(\mathbf{C}_{m2}^{t2}\right) + Y\left(\mathbf{R}_{m2}^{t2}\right)\right]^2 + \left[Z\left(\mathbf{C}_{m2}^{t2}\right) + Z\left(\mathbf{R}_{m2}^{t2}\right)\right]^2}$$

NEW: **Drillers need to implement this computation.**

Summary

- **From a crustal field computation**

$\mathbf{C}_{m1}^{t1}$ $\mathbf{R}_{m1}^{t1}$ $\mathbf{B}_{m1}^{t1}$

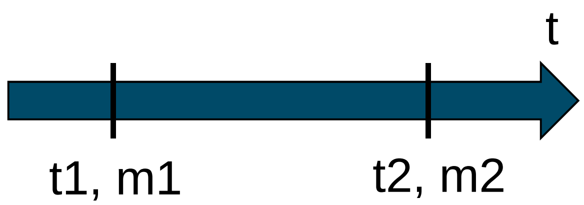
- **A driller computes at drilling**

$\mathbf{R}_{m2}^{t2}$

- **An accurate determination also requires a computation at drilling**

$\mathbf{R}_{m2}^{t1}$

- **All computations can be easily implemented**



How about the Crustal Field Changes in the Reference Field Model?

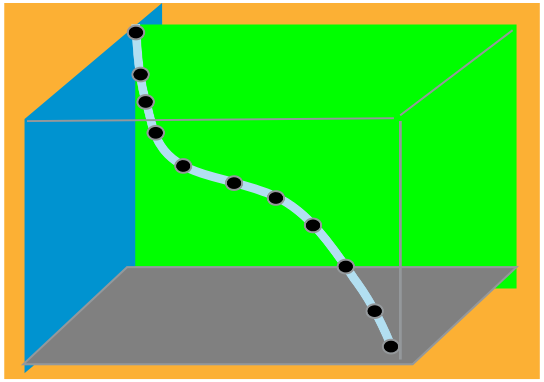
How about the reference field model used at the drilling time has different SH degrees for different years (higher for recent years)?

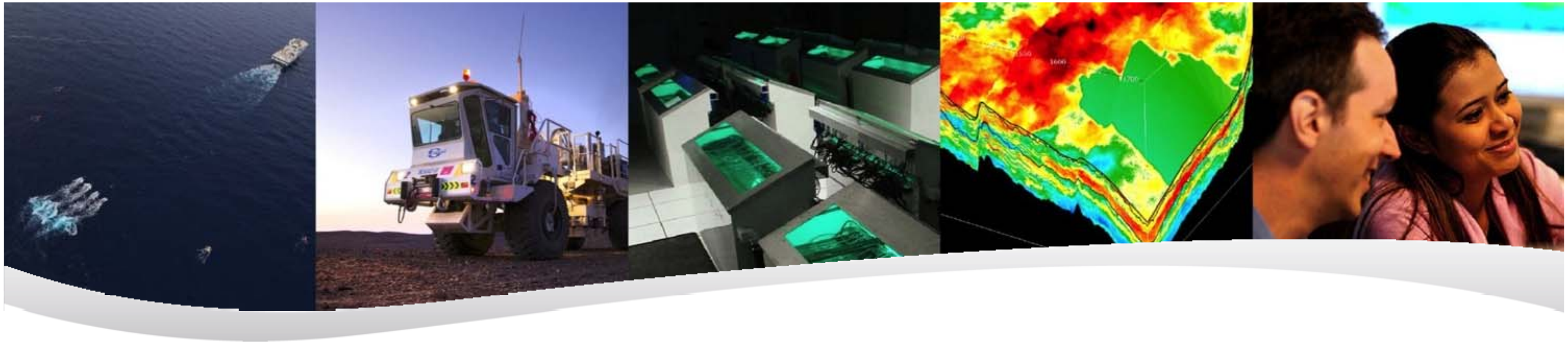
- **This means that different SH degrees are used to define the crustal fields at different years (the main field is sufficiently defined by SH degrees of up to 15)**
- **This should and can be avoided (the crustal field doesn't change with time, and may be updated when the crustal magnetic anomaly database has significant updates)**
- **If this does happen, the synthesis of the SH expansion for degrees 16 and up (e.g., up to** n1 **and** n2**) can give the crustal field differences (due to the SH degree differences,** $\mathbf{C}_{m2}^{t2} - \mathbf{C}_{m2}^{t1}$**) and the function for this difference computation should be provided by the reference model developer**

Conclusions

- **When the subsurface vector crustal magnetic field together with the reference field model used in the computation are delivered in the volume format and the volume contains all foreseeable wells, these two sets of magnetic field volumes and the future reference field model are enough to determine accurately the crustal and baseline field values along any future (or past) well path at a future (or past) time.**

- **It also implies that it doesn't matter to use IGRF, BGGM or HDGM as the reference model in the creation of the local crustal magnetic field volumes, and what is critical is to calculate and apply the difference while drilling.**





Thank you

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