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Using Geomagnetic Referencing Technology for Precise Wellbore Placement

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Abstract

Extensive faulting in the Jeanne d'Arc basin makes precise wellbore positioning a major challenge in eastern Canada. Accurate real-time surveys are required to identify multiple small geological targets and avoid costly collisions between adjacent wellbores.

Although gyroscopic surveys have long been considered the industry gold standard, recent advancements in magnetic surveying have made it an increasingly viable and more cost-effective alternative. New approaches to correcting the errors inherent in magnetic surveying techniques include the ability to create more accurate crustal modeling and to integrate real-time measurements from nearby magnetic observatories.

The new geomagnetic referencing techniques can produce significant savings in project costs, with no sacrifice in the ability to identify, reach and produce the most challenging targets.

Introduction

Hydrocarbons abound across a large area of offshore eastern Canada (Figure 1), from the Laurentian sub-basin, across the Grand Banks and the Jeanne d'Arc basin, through the Flemish Pass and Orphan basins, and northward along the Labrador shelf and slope.

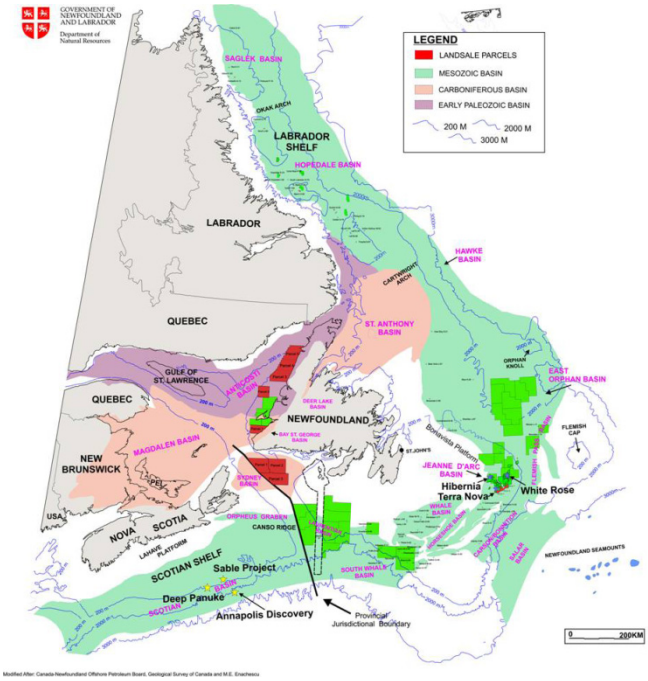

Figure 1: Regional map of the Mesozoic and Paleozoic basins of Atlantic Canada, including Newfoundland-Labrador (NL) land tenure as of summer 2006 that shows hydrocarbon potential.[1-3]

Currently, the most active basin in the region is the Jeanne d'Arc, a fault-bounded Late Jurassic–Early Cretaceous reactivated sector of the larger Late Triassic–Early Jurassic rifted area on the Grand Banks. This sedimentary basin reservoir consists of a series of thick layered sandstones separated by intermediate shales. It is subdivided into large compartments or blocks by a series of faults that run bidirectionally across the reservoir. These faults are highly sealing and form independent subreservoirs or "fault blocks."

Figures 2 and 3 illustrate the density and complexity of drilling and production activities in two of the region's most active areas.

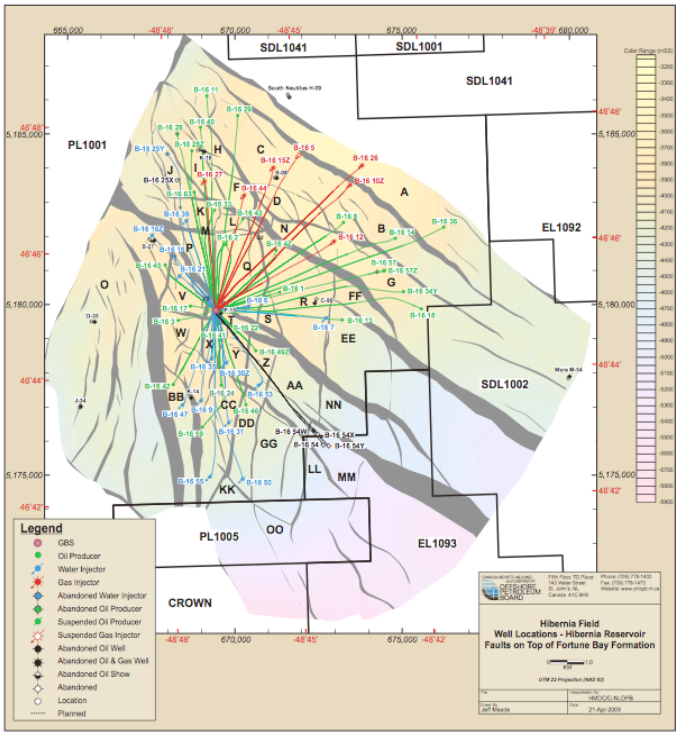

Figure 2: Map of production activity in Hibernia field offshore eastern Canada[1].

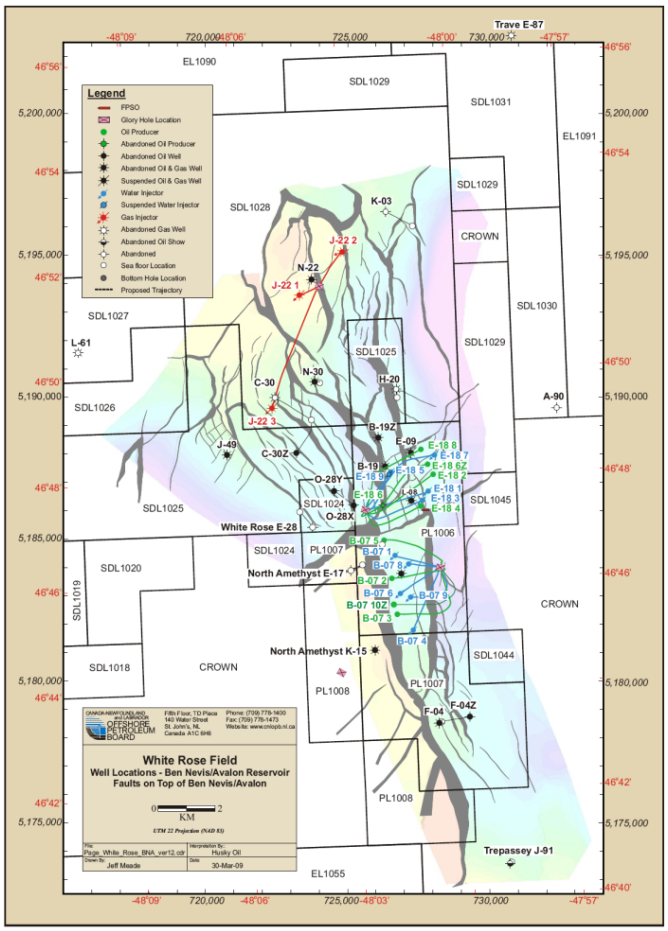

Figure 3: Map of production activity in White Rose field offshore Eastern Canada[1].

Although these reserves are large, developing them poses a number of significant challenges, including a long distance from shore bases and often extreme sub-arctic weather conditions, including icebergs, high waves, fog, and ice packs.

Producers have sought to minimize the costs of operating in such a harsh environment by designing damage-resistant, gravity-based platform structures housing many slots for extended-reach drilling (ERD) wells, a practice that has led to a very congested surface-hole environment requiring very precise wellbore positioning.

Additionally, the distance from surface locations to the geological targets requires more sophisticated drilling and surveying techniques to hit those targets while maintaining very restricted rules on wellbore trajectory designs, including dogleg severity, completion tangent criteria, navigation of problematic formations and faults, etc.

Other factors placing a special premium on obtaining precise, real-time positional data include the need to hit multiple, small target zones in these highly faulted formations.

Figure 4 illustrates a simplified cross section of the Jeanne d'Arc basin based on interpreted seismic data.

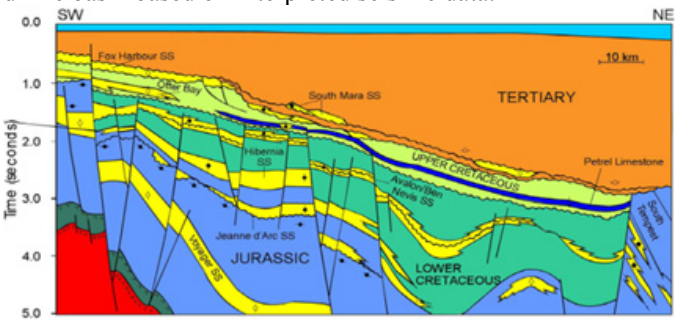

Figure 4: SW/NE cross section of complex formation in the Jeanne d'Arc basin offshore eastern Canada.

Taken together, these challenges require more accurate surveys, a better description of positional uncertainty, and a significant reduction in error ellipse size. For the driller, this translates into bigger targets, greater drillability, and a potentially significant reduction in drilling time and cost. Geologists and geophysicists also benefit by having higher confidence in the ability to successfully penetrate the geological targets.

Thus, precise wellbore placement is vital not only to protect assets and infrastructure, but also to reach and economically produce target resources. Achieving the required level of precision in wellbore placement relies on accurate, real-time survey data. Although acquiring this data has traditionally required the use of time- and cost-intensive

gyroscopic surveying techniques, an innovative and effective new approach to precise wellbore positioning takes advantage of advances in geomagnetic surveying technologies.

Improving the Accuracy of Magnetic Surveying

While the north-seeking gyroscopic (NSG) survey remains the most accurate means of determining wellbore position, it is also the most expensive. Drilling must be stopped, often for several hours, while the survey is in progress. It is also often necessary to run NSG surveys in cased hole to achieve the desired level of accuracy, so that correcting any positional errors detected may require an expensive and time-consuming redrilling of the hole. The latter problem can be avoided by performing a series of intermediate surveys as drilling progresses, but this can produce less accurate results and adds additional cost and delay.

Thanks to relatively recent advances, including improvements in crustal magnetic field modeling, magnetic survey techniques have matured to the point at which they can provide a viable and more cost-effective alternative to NSG surveys.

With the development of improved software to analyze incoming magnetic data from the sensors, and the development of more effective geomagnetic referencing techniques, measurement-while-drilling (MWD) surveys can now achieve an accuracy approaching that of a gyroscopic survey, while reducing the cost and time required.

Figure 5 illustrates a typical bottomhole assembly (BHA) incorporating magnetic survey instruments to provide the driller with real-time positional data without the need for a separate surveying run.

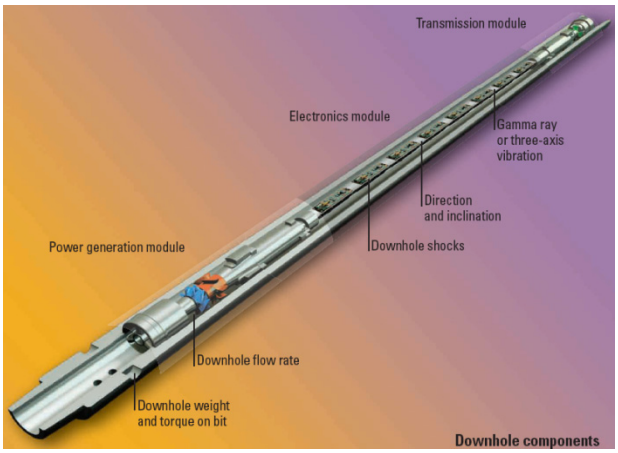

Figure 5: Magnetic survey tool in the BHA with high-speed mud-pulse telemetry system.

Two major sources of error must be accounted for or controlled to achieve the desired level of accuracy using magnetic survey tools: declination reference errors resulting from variations between magnetic north and true north and interference caused by magnetized elements in the drillstring. Figure 6 illustrates such a discrepancy between actual and observed magnetic field orientation.

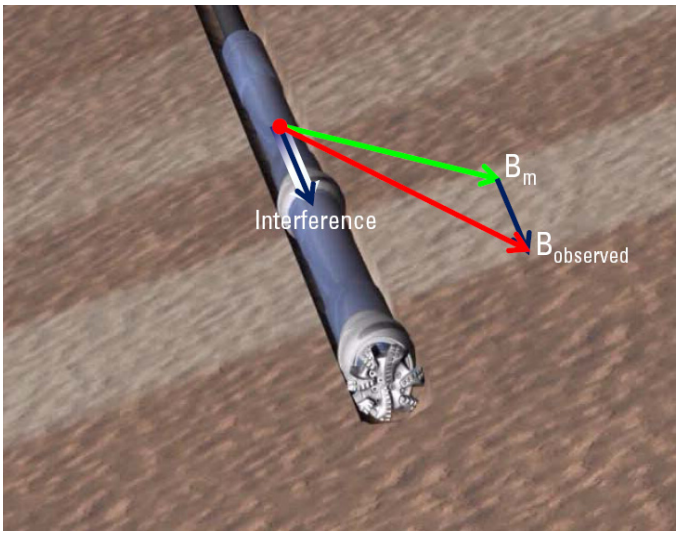

Figure 6: Discrepancy between main magnetic field B_m in green and observed field orientation reading in red, due to drillstring interference.

Essential to solving the reference error issue has been the development of improved geomagnetic referencing techniques through a better understanding of natural variations in the Earth's magnetic field and new methods of mapping local variations.

A key innovation has been development of more accurate and robust crustal modeling techniques that better account for diurnal variations in the local magnetic field. Another has been development of improved techniques for incorporating data from nearby magnetic observatories to improve the positional modeling. Together, these advances have enabled achievement of the desired accuracy even at higher latitudes, where more extreme variations in the local magnetic field would otherwise induce unacceptable positional errors.

To address the problem of magnetic drillstring interference, multistation analysis techniques have been developed.

Combined, these improvements have resulted in a degree of accuracy that approaches that of gyroscopic surveys while costing significantly less.

Achieving More Accurate Crustal Magnetic Modeling

Before discussing the recent improvements in real-time magnetic surveying, a brief review of the challenges posed by the planet's electromagnetic environment is in order.

At any location on or near the Earth's surface, the magnetic field **B** may be expressed as the vector sum of contributions from the main field $\mathbf{B_m}$ created by the planet's liquid core, the crustal field $\mathbf{B_c}$ arising from magnetic minerals contained in the local rocks, and a disturbance field $\mathbf{B_d}$ resulting from electrical currents flowing in the Earth's upper atmosphere and magnetosphere.

The relationship among these components can be summarized as

$$\mathbf{B} = \mathbf{B_m} + \mathbf{B_c} + \mathbf{B_d}. \quad (1)$$

The main field $\mathbf{B_m}$ accounts for approximately 95% of the total magnetic field and can be modeled as a geocentric axial dipole. Magnetic field intensity and inclination both increase toward the magnetic poles (i.e., at higher surface latitudes). The main field changes slowly over time; this change is referred to as secular variation. The International Geomagnetic Reference Field (IGRF) model, updated every 5 years, is a standard mathematical description of the main field. The change is assumed to be linear during the 5-year intervals between updates. For directional drilling, a refined British Geological Survey Global Geomagnetic Model (BGGM), updated annually, replaces IGRF.

The crustal field $\mathbf{B_c}$—associated with induced and remanent magnetization within the crust—is measured by land, marine, or airborne magnetic surveys.

The disturbance field $\mathbf{B_d}$ varies much more rapidly than $\mathbf{B_m}$, with significant changes on a daily basis. These diurnal variations can be tracked and corrected for by establishing a base magnetic station at the drillsite or through the interpolation of data from existing geomagnetic observatories in the region. In practice, $\mathbf{B_c}$ is extracted by removing $\mathbf{B_m}$ and $\mathbf{B_d}$ from the measured value of **B**.

The routinely used magnetometer measures only the magnitude of the total magnetic field **B** without regard to its vector direction. The total field anomaly or the total magnetic intensity (TMI) anomaly, often denoted as ΔT, is calculated from the total field measurements $|\mathbf{B}|$ by subtracting the magnitude $|\mathbf{B_m}|$ of the main field and the magnitude $|\mathbf{B_d}|$ of the disturbance field. This calculation can be summarized as

$$\Delta \boldsymbol{T} = |\mathbf{B_c}| = |\mathbf{B}| - |\mathbf{B_m}| - |\mathbf{B_d}|. \quad (2)$$

Processing and interpretation of the TMI anomaly in while-drilling applications often relies on two fundamental assumptions[3] : 1) the TMI anomaly is small compared with the magnitude of the main field, and 2) the direction of the main field remains constant throughout the survey area. Based on the first condition, the TMI anomaly is assumed to be approximately equal to that of the crustal field $\mathbf{B_c}$ in the direction of the main field. The second condition dictates that the TMI anomaly is a harmonic potential and satisfies Laplace's equation. Field studies have shown that both conditions generally prevail at local and exploration scales.

Constructing the Vector Crustal Magnetic Field

Recent developments have significantly improved the practical application of magnetic surveying at higher latitudes such as offshore eastern Canada. A new approach computes the vector magnetic field parameters at drilling depths from the scalar crustal TMI anomaly observed on or near the surface by land, marine, or airborne surveys. The computation involves three steps:

1. Downward continuation of the TMI anomaly from the surface observation altitude to a constant depth, assuming: a) there are no magnetic sources above the deepest level of interest, and b) the TMI anomaly magnitude is much smaller than the Earth's total field magnitude
2. Computing the three components of the vector field (north, east, and vertical) from the scalar TMI anomaly at each depth
3. Calculating declination and inclination perturbations due to the crustal magnetic anomaly, relative to the direction of the main magnetic field

A widely used main field model is employed in the second and third steps.

The techniques employed differ from others in two aspects: (1) downward continuation of the surface TMI anomaly by an equivalent source technique and (2) transformation of the scalar TMI anomaly into east, north, and vertical vector components with a consideration of variable declinations and variable inclinations of the main magnetic field. The following paragraphs examine these two aspects in detail.

Equivalent-Source Technique for Downward Continuation

The computation of level-to-level downward continuation in the wavenumber domain using the Fourier transform is expressed by

$$F(T_{down}) = e^{|kz|} F(T_{obs}), \quad (3)$$

where

$k = \sqrt{k_x^2 + k_y^2}$ = the wavenumber

z = the vertical distance between the observation and continuation planes

F = the Fourier transform

Noise in data often exists at short wavelengths (i.e., large wavenumbers). As a result, this routine computation of downward continuation becomes unstable, particularly with

increasing depth.

To overcome this instability, an equivalent-source technique is used to perform the continuation computation. This alternative technique can also produce a continuation between arbitrary surfaces, which becomes necessary when observations are made on an undulating surface, as is commonly practiced in onshore magnetic surveys.

The equivalent source technique works as follows: place an equivalent magnetization distribution on a horizontal plane below the deepest drilling depth and determine an equivalent magnetization distribution with TMI responses matching those of the observed TMI anomaly. Once the equivalent source on the plane is determined, the magnetic responses on any horizontal plane above the equivalent-source plane can easily be calculated.

Computation of the Vector-Anomalous Magnetic Field

A good description of the algorithm for transformation of the scalar TMI anomaly into the three components of the vector crustal magnetic field can be found in Blakely (1995)[3]. However, this algorithm assumes a constant geomagnetic field direction, an assumption that becomes invalid and will introduce significant errors when the working area is larger than a few degrees in any direction. Because directional drilling demands high accuracies (e.g., 0.1° in declination), the authors use an algorithm to compute the three components of the vector crustal magnetic field from the scalar TMI anomalies for variable inclinations and declinations. This algorithm is similar to the differential reduction-to-the-pole technique of Arkani-Hamed[4]. It iteratively transforms the scalar TMI anomaly located on a horizontal plane into potential U.

After the potential is obtained, we can easily compute the X, Y, and Z components of the crustal magnetic field in the wavenumber domain as follows:

$$F[X_c] = ik_x F[U] \quad (4a)$$

$$F[Y_c] = ik_y F[U] \quad (4b)$$

$$F[Z_c] = kF[U] \quad (4c)$$

Declination and Inclination Perturbations of the Crustal Field

Directional drilling applications require computation of the inclination and declination perturbations I_p and D_p, respectively, caused by crustal sources, relative to the main field direction. These perturbations can be computed by

$$I_p = \arctan\frac{Z_m + Z_c}{\sqrt{(X_m + X_c)^2 + (Y_m + Y_c)^2}} - \arctan\frac{Z_m}{\sqrt{X_m^2 + Y_m^2}}, \quad (5a)$$

$$D_p = \arctan\frac{Y_m + Y_c}{X_m + X_c} - \arctan\frac{Y_m}{X_m}, \quad (5b)$$

where (X_m, Y_m, Z_m) are the three components of the main field at the drilling time.

Trilinear Interpolation

Results of the TMI, declination and inclination perturbations at all depths are combined to form a voxet or cube. Estimation of the field value at a given point along the well path is thus a 3D interpolation process. A cubic cell that encloses the field point is determined, and trilinear interpolation is then applied.

The new computational process is summarized in Figure 7.

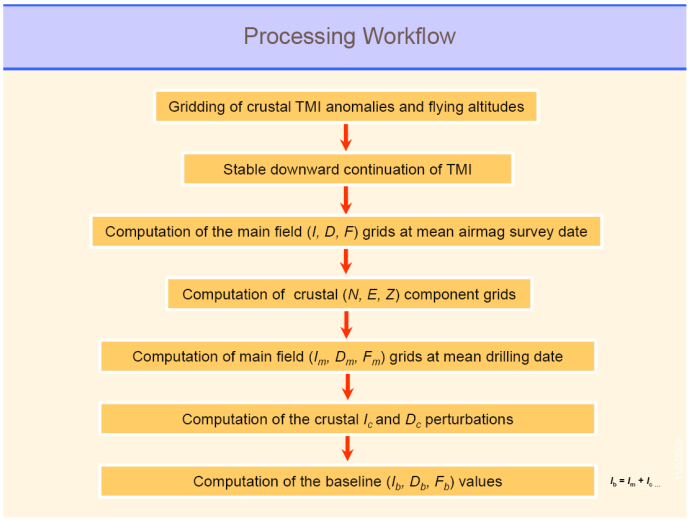

Figure 7: Steps required to compute baseline values for while-drilling processing.

The new approach offers four significant advantages over other processing algorithms:

- Because it uses the equivalent-source technique, the continuation computation becomes stable and results at different depths are consistent (i.e., produced by the same sources).
- The equivalent-source technique allows for a continuation from an undulating surface to a plane, necessary when a draped aeromagnetic survey is flown onshore.
- Variable declinations and inclinations of the main field are used in computing the components of the vector crustal field and the crustal declination and inclination perturbations. This becomes particularly

important in larger computation areas (> 2° in any one direction).
- The results are recorded in a cube format with a small cell size (e.g., 500 m × 500 m × 1000 m) to reduce errors in a 3D interpolation when the results are used (Figure 8).

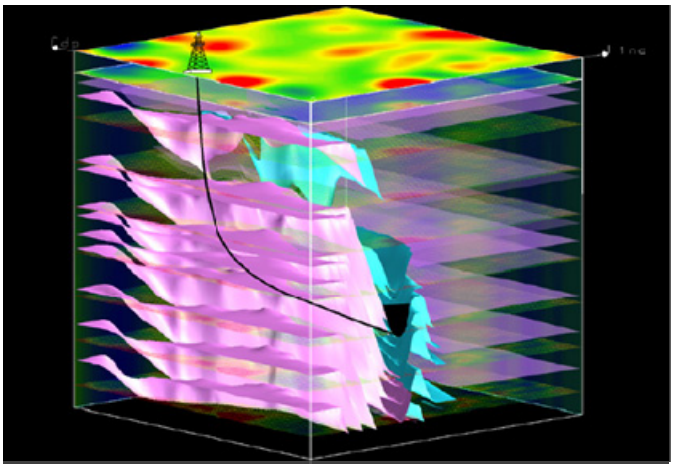

Figure 8: Cube-format display of well path and geomagnetically derived positional data.

Accounting for the Element of Uncertainty

A number of factors can significantly reduce the degree of positional accuracy attained by geomagnetic surveying techniques. These include limitations intrinsic to the measurement tools, magnetic interference from metallic components in the drillstring, and inaccurate reference data relating to planetary and solar magnetic influences.

Some degree of positional inaccuracy is always present with any surveying technique. Knowing and accounting for this uncertainty is essential to determining the confidence with which position-critical drilling decisions can be made. In practice, position is not stated as a point, but rather as falling within a cone-shaped area surrounding the wellbore, often referred to as the ellipsoid of uncertainty (EOU). Therefore, a surveyed wellbore position is expressed in geometrical terms—down, north, and east—accompanied by the uncertainty of that position as modeled by the EOU. Together, these elements represent a volume of uncertainty with a specified statistical level of confidence.

Components of Geomagnetic Referencing

Correction of magnetic sensor readings for local variations in the Earth's magnetic field is essential to an effective geomagnetic referencing service (GRS). Techniques used to measure or predict these variations include the use of land-surveying equipment to map local crustal variation, or the use of inverted aeromagnetic survey data.

Magnetic observatories may be required to make real-time corrections for the sometimes significant effects of solar activity and magnetic storms in projects at higher latitudes.

These techniques provide an accurate map of the local magnetic field and an accurate measurement of time-dependent local declination variations, both essential for precise geomagnetic referencing.

Using Multistation Analysis

An earlier approach to the problem of positional errors arising from magnetic interference from the drillstring itself relied on an independent estimation of deviation at each survey station. This single-station analysis (SSA) technique suffered from increased inaccuracies when the MWD sensor approached a horizontal inclination, especially when oriented closer to the east/west direction. A technique known as multistage analysis (MSA) was developed to overcome this limitation. With MSA, data acquired from a series of surveys are used to create a model of MWD sensor performance in a number of different drillstring orientations. Software is then used to analyze the actual sensor measurements for any given tool orientation by optimizing the solution of magnetic deviations for a particular MWD magnetic tool in a particular BHA configuration.

MSA is not limited by orientation, but it does require data from an adequate number of survey stations, usually six to more, depending on drillstring orientation. It may be necessary in some cases to acquire several sets of MWD rotation surveys to achieve an acceptable level of accuracy, but even in these cases, the cost and time involved are less than that of an equivalent gyroscopic survey.

Improved Estimation of the Local Magnetic Field

Achieving adequate positional accuracy with MWD surveys requires an accurate estimation of the local magnetic field. In high-latitude regions, this requires a reliable means of mapping the effects of external sources of variations in this field.

As explained above, the value for the local disturbance field $\mathbf{B_d}$ reflects both regular daily variations and irregular variations due to magnetic storm activity. The value for the Earth's main magnetic field $\mathbf{B_m}$ represents some 95% of the field strength at a given location and varies very slowly over time. The strength and direction of $\mathbf{B_c}$ is relatively stable, and may be regarded as a constant.

A much greater source of variation is $\mathbf{B_d}$, which can vary by hundreds of nanotesla (nT) in a matter of minutes and may deviate in any direction. This variability can result in shifting values for **B**—ranging from a few tenths of a degree to several degrees during high magnetic storm activity.

Surveyors often use a spherical harmonic model to estimate geomagnetic field strength and direction, but this approach provides only an estimated value for $\mathbf{B_m}$. The modeling can be improved by including longer-wavelength crustal field variation values and steady components of the disturbance field $\mathbf{B_d}$. But even with these additions to the model, the shorter-wavelength variations in $\mathbf{B_c}$ and the more rapidly fluctuating part of $\mathbf{B_d}$ may still be sufficiently large to cause unacceptably inaccurate estimations of $\mathbf{B}$.

To summarize the options, the surveyor may correct only for $\mathbf{B_m}$, which may result in large errors for the reasons just explained, or may correct for both $\mathbf{B_m}$ and $\mathbf{B_c}$, an approach known as the infield referencing technique (IFR), which can achieve acceptable accuracy in some locations, especially at lower latitudes where variations in $\mathbf{B_d}$ are relatively insignificant. But at higher latitudes, real-time corrections for $\mathbf{B_d}$ must also be included to achieve an acceptable level of accuracy.

Reducing Uncertainty to Acceptable Levels

Effective MWD surveys require data on the strength (F), declination (D), and inclination (I) of the local magnetic field B, as well as the degree and source of errors in the values for F, D, and I. In practice, the levels of accuracy required are 0.1° in D, 0.05° in I, and 50 nT in F.

The greatest uncertainty results from correcting for $\mathbf{B_m}$ but not for $\mathbf{B_c}$ or $\mathbf{B_d}$. As the latter two elements are added to the model, the area of uncertainty is reduced. While gyroscopic surveys still provide the least positional uncertainty, MWD surveys that account for local variations can also achieve an acceptable level of accuracy, often at a lower cost.

A Multitiered Geomagnetic Referencing Service

As outlined above, advances in the ability to identify and correct for the major sources of uncertainty in MWD magnetic data now make a multitiered geomagnetic referencing service a viable alternative to NSG surveys.

The middle tier of service would include a survey of local crustal magnetic variations. The cost of such a survey is comparable to that of a single NSG survey run, but does not need to be repeated for subsequent wells in the area and can be used for the life of the field. Even where the addition of the crustal survey does not significantly change predictions based on the main field model alone, it still adds value by improving the surveyor's level of confidence in those values.

For the top tier of service, modeling based on the crustal field survey and multistation analysis would be further improved by the addition of real-time magnetic observatory data. The additional cost of this top-tier service would in many cases be completely offset by a reduction in the number of NSG runs required. Results are sufficiently reliable that future drilling programs in a given area may be planned with only a few NSG runs in top hole. Additional cost benefits may be achieved by the avoidance of a correction run, such as would be required if an NSG survey revealed a positional error of unacceptable magnitude in cased and cemented hole.

Comparing the New and Old Crustal Models

Tables 1 and 2 detail the validation of the crustal model value by comparing the results of GRS processing for correcting magnetic surveys (azimuth) with results of in-hole referencing (IHR) procedures and continuous NSG measurements. The survey data used are from an actual well offshore eastern Canada.

Table 1: Comparison Summary

Note Previous crustal processing = average azimuth difference = 0.22 deg

BHA Run Number	IHR Interval	IHR Correction	Azimuth Difference IHR - GRS	Azimuth Difference Gyro - GRS
	(m)	(deg)	(deg)	(deg)
Run A	405 - 1605	-0.05	0.16	0.16
Run B	1620 - 2400	0.15	0.26	0.26
Run C	2415 - 3705	-0.41	0.22	0.22
Run D	3720 - 3840	-0.22	0.22	0.31

Table 2: Comparison Summary with New Crustal Processing

Note New crustal processing = average azimuth difference = 0.12 deg

BHA Run Number	IHR Interval	IHR Correction	Azimuth Difference IHR - GRS*	Azimuth Difference Gyro - GRS*
	(m)	(deg)	(deg)	(deg)
Run A	405 - 1605	-0.05	0.01	0.01
Run B	1620 - 2400	0.15	0.17	0.17
Run C	2415 - 3705	-0.41	0.1	0.1
Run D	3720 - 3840	-0.22	0.09	0.2

* New crustal processing

After applying the IHR azimuth corrections to the MWD surveys in the four different BHA runs, the average difference between the azimuth of GRS and IHR corrected is equal to 0.12°, and the GRS and NSG is equal to 0.15°.

Figures 9 through 13 illustrate the high degree of accuracy achieved by a GRS in three different wells. Figure 14 illustrates the reduction achieved in the area of positional uncertainty, plotting the GRS EOU inside the ellipses of uncertainty obtained using the standard MWD.

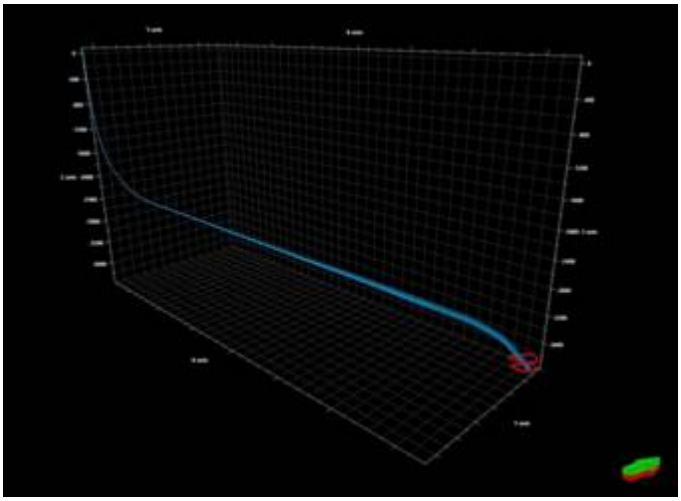

Figure 9: Well profile #1 is an ERD well with a drop into the targets.

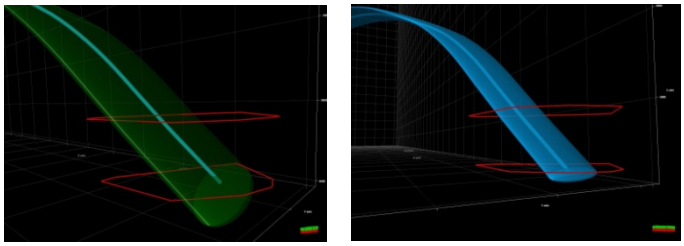

Figure 10: —Comparison of magnetic surveys without (left) and with (right) GRS. The lateral uncertainty without GRS is much too large to guarantee the well is inside the geological targets (red outline), whereas the GRS surveys leave adequate room to navigate into the targets.

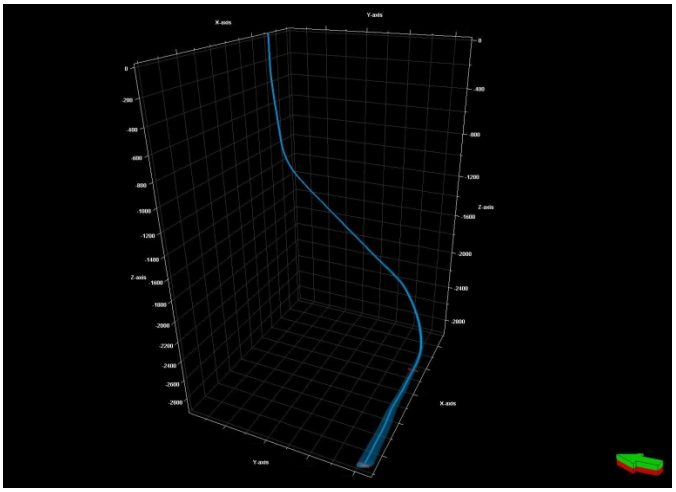

Figure 11: Well profile #2 is a complex 3D well geosteered through a long lateral section.

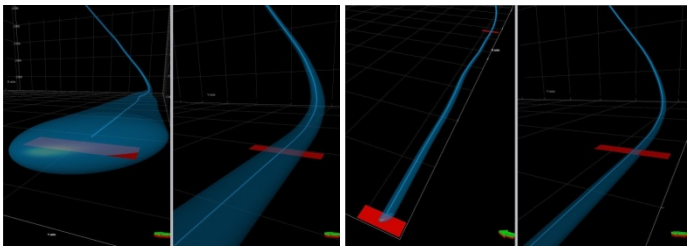

Figure 12: Reduction in positional uncertainty using GRS. Without GRS (two images at left) there is only a small driller's target when making the critical heel landing.

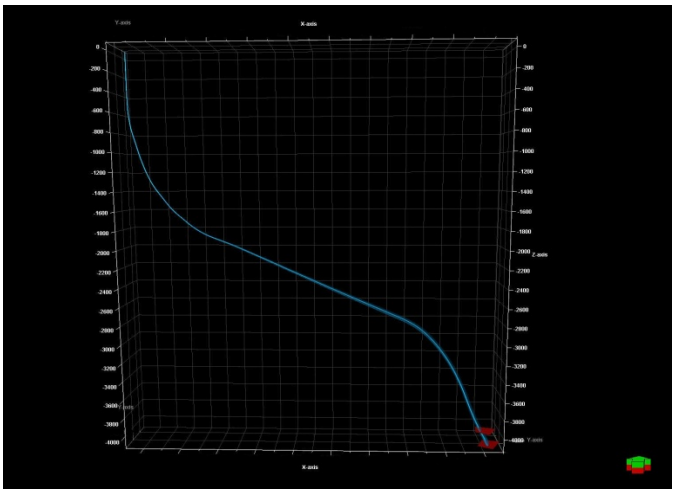

Figure 13: Well profile #3 is an S-shape well with significant step-out.

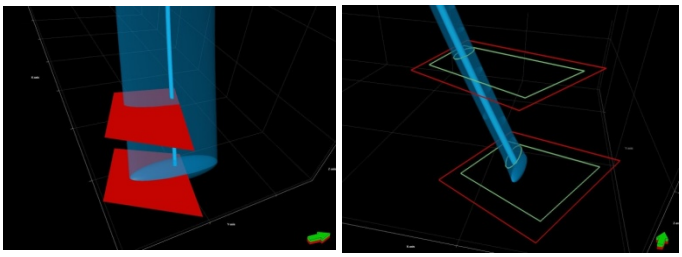

Figure 14: Without GRS (left), there is a very low statistical probability of achieving the geological target. With GRS (right), the well becomes drillable. Directional steering time is much reduced, creating significant savings.

Conclusion

In recent years, geomagnetic referencing technology has matured to the point at which it now can provide a cost-effective alternative to gyroscopic surveys in many of the most demanding drilling projects. A major key to improvement in GRS capabilities has been new and more economical methods for precise modeling of local magnetic variations, even at higher latitudes where these variations can be more extreme.

Of particular importance has been the development of new ways to incorporate data from existing magnetic observatories.

A tiered GRS service now represents a viable option for precise estimation of wellbore position, and can also offer significant savings in terms of time and cost.

Acknowledgments

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