Geomagnetic Referencing Techniques as Vital Directional Reference in Hydrocarbon Drilling

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***Abstract*—Uncertainties in directional referencing are of crucial importance in the hydrocarbon drilling industry. There is need for accurate placement of positioning referencing to improve target acquisition and avoidance of collision. Several sources of the geomagnetic field influence the magnetic field direction, constituting a significant impact on accurate wellbore placement, with each source presenting its own challenges when estimating the geomagnetic field at the wellsite. In this study, we analyze the geomagnetic referencing techniques that improves the accuracy of wellbore positioning based on local magnetic field estimates. We look at the different field models – BGS Global Geomagnetic Model (BGGM) and the High Definition Geomagnetic Model (HDGM) – that is able to predict the evolution of the field in near-term, and enhance the predictive capability. Also, referencing techniques that combine aeromagnetic data and data from nearby or remote geomagnetic observatories to estimate the real-time geomagnetic field at the wellsite and thus improve directional reference in hydrocarbon drilling is presented. Using the BGGM and the HDGM models, we show that there is significant difference between magnetic anomalies referenced to HDGM and anomalies referenced to BGGM. Observation also show that anomalies referenced to HDGM are significantly smaller than those referenced to BGGM model. Also, significant localization improvements occurred when geomagnetic referencing was used to correct MWD raw readings, and the estimated wellbore bottom hole locations shifted significantly.**

Keywords — Geomagnetic referencing, Geomagnetic field, Directional drilling, wellbore, MWD, BGGM, HDGM.

1. INTRODUCTION

The geomagnetic field is a vital directional reference when drilling for hydrocarbons (oil and gas) at oil and gas fields around the globe. One of the most important consideration for producers has been accurate wellbore positioning during drilling [1], [2], [3]. As oil wells have gone deeper and farther in search of smaller and more difficult targets, the degree of precision has become a necessity and has progressively increased. Oil wells are often drilled over considerable distances and in deposits already congested with existing wells. Using a combination of magnetic sensors and accelerometers in the bottom-hole assembly and accurate estimates of the local magnetic field, the drilling surveyor is able to safely direct the well towards its intended geological/geophysical targets (figure 1).

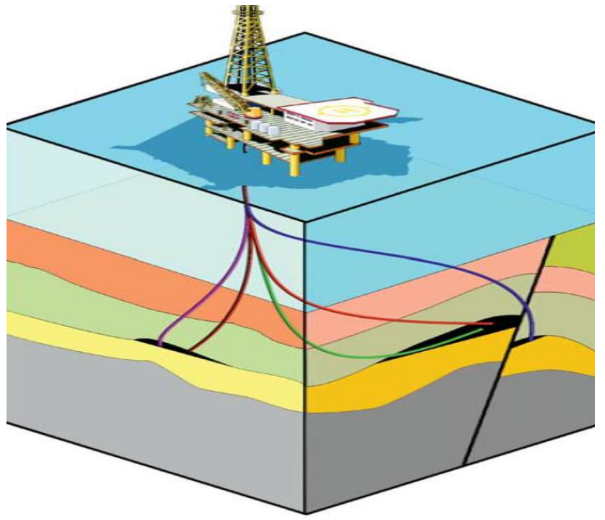

Figure 1: Schematic of a drill being safely directed towards its target.

In today's ever dynamic oil and gas industry, many of the oil and gas wells, both deviated and horizontal, no longer simply penetrates the reservoir environment. They must navigate it laterally to contact as much of the reservoir as possible. As a result, for a myriad of reasons, the operating companies has to know where their wells are as they drill. Accurate placement of well trajectories is needed to optimize oil and gas recovery, determine where each well is relative to the reservoir and avoid collision with other wells.

Historically, wellbores were drilled vertically and were widely spaced. This spacing decreased as oilfield matured, regulations tightened and reservoirs were targeted in remote areas [4]. Over the last few decades, the need to extract the maximum amount of oil reservoirs while continually striving to reduce drilling costs led to the development of directional drilling techniques. As a result the industry has acquired the capability to drill multiple wells from a single onshore drilling pad or offshore drilling platform. One of the directional drilling techniques which requires accurate positioning information developed by the industry to enable the maximum extraction of oil while minimizing costs is the geomagnetic referencing techniques. This is a magnetic survey technique which rely on the principle of measuring the direction of the local geomagnetic field [5]. This limits the accuracy by the accuracy with which the direction of the geomagnetic field is known at the location of the well. The geomagnetic field is known to vary slightly throughout the day, and highly (order of a few degrees) during magnetic storms [6]. This study analyses how geomagnetic referencing techniques developed by the industry has been able to remove error source and improve wellbore positioning using data from magnetic observatories.

2. GEOMAGNETIC REFERENCING

North-seeking gyroscopic (NSG) surveys have traditionally been considered the most accurate means of determining wellbore positions. However, two factors have made NSG a less-than-ideal approach for use as wellbore placement:

- The need to stop drilling and pull out of the hole while measurements are taken.
- The need, in many cases, to perform NSG surveys in a cased hole. In the case where a significant error is detected, a costly redrilling of a new hole may be required to correct it.

The quest for a more cost effective approach has led to significant improvements in measurement while-drilling (MWD) surveying techniques. With recent advances in crustal modelling, geomagnetic surveying can now determine wellbore positioning with accuracy on a par with NSG, and can do so in real-time, providing a more cost effective solution for drilling to even the most challenging targets. Geomagnetic referencing is such a technique.

Geomagnetic referencing uses the geomagnetic field to accurately determine wellbore positioning which is essential for success in complex drilling programs. It provides the mapping between magnetic north and true north that is necessary to convert magnetically determined orientations to geographic ones on a local scale. Geomagnetic referencing techniques build a custom model of the geomagnetic field, with all its magnetic field components, to minimize the error in the mapping between magnetic north and true north [10]. The mapping accounts for secular variations in the main magnetic field model and include an accurate field model. It also incorporates the time-varying disturbance field when significant. Geomagnetic referencing is used either as an alternative or a complement to NSG referencing.

Accurate crustal mapping and the monitoring of real-time variations by nearby magnetic observatories is crucial to achieving the required geomagnetic referencing accuracy. Fluctuations in the geomagnetic field makes the application of geomagnetic referencing more challenging, particularly at high latitude regions, or during periods of adverse magnetic conditions. The availability of real-time geomagnetic data leads to significant cost and time savings in wellbore surveying, improving accuracy and reducing the need for more expensive surveying techniques. Geomagnetic referencing simultaneously addresses the strict wellbore position requirements and the challenging surveying environment. Accurate real-time placement is possible by taking advantage of refinements in the latest developments in crustal model processing and improvements in the magnetic observatory design that measures disturbance field (see figure 2).

Geomagnetic referencing techniques have been used

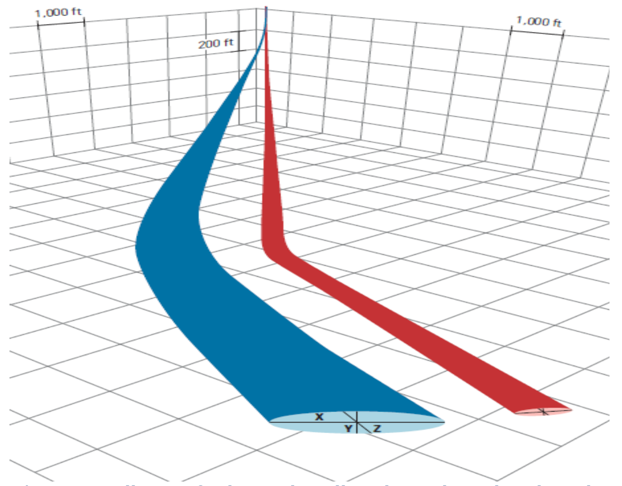

Figure 2: ***Slices of Planned well trajectories showing the difference in ellipses of uncertainty (EOUs) between standard measurement while drilling – MWD (in blue) and higher accuracy MWD - geomagnetic referencing (in red). The higher-accuracy method delivers a wellbore with smaller positioning uncertainty [4].***

to address challenges to survey accuracy inherent in difficult drilling zones/environment, especially in areas dealing with high-disturbance components of the geomagnetic field, as well as the need to compensate for the effect of drillstring interference [7]. Knowledge of the crustal field and real-time magnetic disturbance field is essential to provide an accurate wellbore placement while drilling in challenging environments. Recent improvements in geomagnetic referencing techniques have significantly increased MWD results. This is achieved by applying a better understanding of the natural variations in the Earth's magnetic field. Accurate knowledge of the orientation of the bottom-hole assembly (BHA) referenced to vertical (inclination) and to true north (azimuth) is required in directional drilling. Also, important are new approaches to connecting for daily variations in the local magnetic field, including the ability to incorporate data from nearby geomagnetic observatories. Combined, these improvements have made geomagnetic referencing a truly viable alternative to NSG referencing, achieving a comparable level of accuracy at a significantly lower cost.

3. THE GEOMAGNETIC FIELD

The total magnetic field (B) measured at or near the Earth's surface is the superposition of different magnetic fields arising from a number of time-varying physical processes that are grouped into three general components:

- The main magnetic field (B_m) generated in the Earth's core by the geodynamo. It is defined as the internal field of spherical harmonic degree 1-15 for practical purposes, excluding the time-varying fields with periods shorter than about 2 years.
- The crustal field (B_c) from magnetized rocks in the Earth's crust. It is defined as the static internal field of spherical harmonic degree 16 and higher. Figure 2 shows the contribution to the geomagnetic field by the main field and the crustal field.
- The magnetic disturbance field (B_d) – fields due to currents in the ionosphere and magnetosphere (electrical currents flowing in the upper atmosphere), and corresponding ''mirror-currents'' induced in the Earth and ocean.

$$B = B_m + B_c + B_d$$

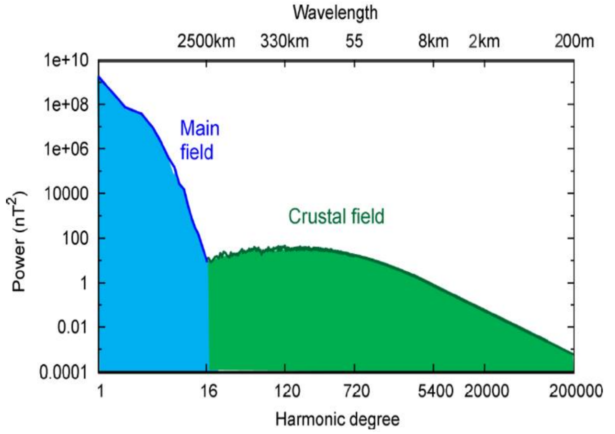

Figure 3: Shows the main field (in blue) and crustal field (in green) contribution to the geomagnetic field [7].

The disturbance field (B_d) varies much more rapidly than the main field (B_m) and the crustal field (B_c), with significant changes on a daily (or diurnal) basis. Correcting for these diurnal variations can be achieved by setting up magnetic station at drillsite, or by interpolation of data from existing remote geomagnetic observatories. B_c is measured by conducting land, marine or airborne magnetic surveys. B_c is extracted, in practice, by removing B_m and B_d from the measured value of B. The International Geomagnetic Reference Field (IGRF) model is a standard mathematical description of the main field. For directional drilling, a refined British Geological Survey Global Geomagnetic Model (BGGM) and the High Definition Geomagnetic Model (HDGM) produced by the U.S. National Geophysical Data Center, replaces the IGRF. The HDGM is a recent development which brings greater accuracy in challenging wellbore positioning.

The total field anomaly or total magnetic intensity (TMI) anomaly (ΔT) is calculated from total field measurements |B| by subtracting the magnitude $|B_m|$ of the main field and the magnitude $|B_d|$ of the disturbance field:

$$\Delta T = |B_c| = |B| - |B_m| - |B_d|$$

Processing and interpretation of the TMI anomaly in while-drilling applications, often relies on two fundamental conditions/assumptions – TMI anomaly is small compared with the magnitude of the main field, and the direction of the main field remains constant over the dimensions of the survey area [8]. The TMI anomaly, based on the first assumption, is assumed to be approximately equal to that of the B_c (crustal field) in the direction of the B_m (main field).

Geomagnetic field models generally provide values for magnetic declination, magnetic inclination and total field at points on the surface of the Earth [4]. The models are used to transform geomagnetic measurements to directions in the geographic coordinate system. In addition to the IGRF, BGGM and HDGM models, several other geomagnetic reference models have been developed using global geomagnetic field measurements taken from satellite, aircraft and ship. The models differ in their resolution in space and time. Some of these models are shown in table 1.

Model	Organisation	Order	Resolution, km	Update Interval
WMM	NOAA,NGDC and BGS	12	3,334	5 years
IGRF	IAGA	13	3,077	5 years
BGGM	BGS	50	800	1 year
EMM and HDGM	NOAA and NGDC	720	56	5 years and 1 year

Table 1: Some of the magnetic field reference models of differing resolution. These models construct the global magnetic field as a sum of terms of varying order and degree. The order refers to spherical harmonic models, and it increases with the complexity of the model. Resolution corresponds to the wavelength of the highest order term.

Directional drilling requires higher resolution models than WMM or IGRF alone. The BGGM, which is widely used in the drilling industry, provides the main magnetic field at 800km resolution and updated annually. The EMM and a successor HDGM, resolve anomalies down to 56km, an order of magnitude improvement over previous models. The HDGM improves the accuracy of the reference field by accounting for a larger waveband of geomagnetic spectrum, which in turn improves the reliability of wellbore azimuth determination, and enables the high accuracy drillstring interference correction [9].

4. ESTIMATING THE LOCAL MAGNETIC FIELD

Achieving the desired positioning accuracy using MWD surveys requires an accurate estimation of the geomagnetic field at the well site. At regions/areas where the magnetic activity is high/intense, it requires a reliable means of mapping the effects of external sources of variations in the field.

In directional drilling, magnetic declination i.e. the difference between true or geographic north and the magnetic north, is required to convert the survey measurements to the geographic reference frame. In addition, the inclination i.e. the angle the field makes with the horizontal plane, and the total field intensity are required for algorithms which remove interference from the drillstring. An estimate of B from a spherical harmonic model of the geomagnetic field can be made when using magnetic data to improve drilling accuracy, which includes secular variation element, such as IGRF. Spherical harmonic models of the geomagnetic field are only intended to provide estimates of B_m, but the contributions of B_c and B_d may be large enough to cause significant error if it is assumed that the model value alone is n estimate of the local field, B, particularly in many parts of the globe.

Geomagnetic referencing techniques must consider B_c and B_d sources. Detailed anomalies of the crustal field are obtained from aeromagnetic and marine surveys of the oil field areas. Both B_m and B_c are not influenced by external field factors. The disturbance or external field contributions, B_d are estimated for the location of the oil well using data from the magnetic observatories nearby. Figure 4 gives an indication of why the external field, B_d needs to be accounted for when drilling oil wells in some part of the globe and at certain periods of the day (taking into account the magnetic activity). Minute-values in declination, inclination and the total field are derived from oil wells using referencing techniques. Data for oil wells that are being drilled are made available to borehole surveyors/drillers throughout the day in close to real-time, with regular updates available every few minutes. Figure 5 is an example of a 24 hour data for a single oil well located at Lerwick in United Kingdom.

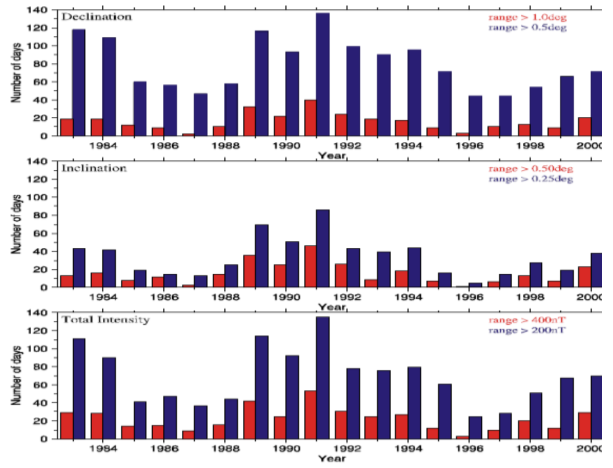

Figure 4: Frequency of magnetic disturbance at Lerwick observatory.

5. CRUSTAL VARIATIONS/CRUSTAL MAGNETIC MODELLING

In some situations, the main concern is not the time-varying field (B_d) but the crustal correction. In order to understand the challenges of accurate real-time magnetic surveying and the innovative approach to overcoming these challenges, we analyse a case where the BGGM and the HDGM models were used.

When specifying the crustal field, there is significant difference between magnetic anomalies referenced to HDGM and anomalies referenced to BGGM. A case in point is shown in figure 5 for a geomagnetic declination map at mean sea level for a location in offshore Brazil (red polygon). A large-scale magnetic field model with data from a local aeromagnetic survey were integrated to extend the spatial spectrum of the magnetic field from regional scales down to the kilometre scale. In figure 5, the standard model (left) shows smooth, large-scale variations in magnetic field declination in the vicinity of the hydrocarbon field (shown in red polygon). The higher resolution HDGM model is shown in the centre, and it includes more detail of the declination. The combined HDGM and the aeromagnetic survey model shown in the right contains the highest resolution information of all three models. Observation show that anomalies referenced to HDGM are significantly smaller than those referenced to BGGM model. This is because the HDGM already includes a large portion of the crustal field.

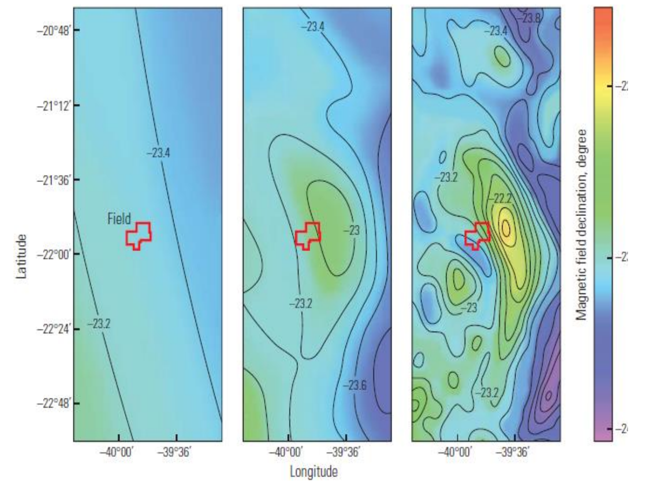

Figure 5: Geomagnetic declination map for an offshore deep-water hydrocarbon location in Brazil shown in red polygon [4].

The crustal magnetic model for this field was analyzed using two independent methods.

The First Method combined the BGGM with aeromagnetic survey data and employed an equivalent source method for downward continuation of the field to the reservoir depth. This allows for stability in the continuation computation and the continuation results at different depths are consistent (produced by the same sources). Also, this equivalent source method allows an undulating observation surface and can perform a continuation from an undulating surface to a plane.

The Second Method combined the aeromagnetic survey with a long-wavelength crustal field model provided by CHAMP satellite mission, and created a 3D magnetic model for the survey area. The strength of this second method is that it accurately accounted for the entire wavelength spectrum of the geomagnetic field. The validity of the second method is further established by comparing results with marine magnetic profiles passing through the vicinity of the survey area taken from Geophysical Data System (GEODAS) database. The comparison is shown in figure 6. Also, the magnetic field model attributes with these two methods at mean sea level and at 5,000m reservoir depth. The two methods can be seen to closely agree with each other at both depths as shown in figure 7.

The higher resolution geomagnetic reference models enabled more refined multistation compensation for drillstring interference. It was observed that multistation analysis improved when high-resolution geomagnetic models were used compared with the BGGM magnetic field predictions. Also, significant localization improvements occurred when geomagnetic referencing was used to correct MWD raw readings, and the estimated wellbore bottom hole locations shifted significantly.

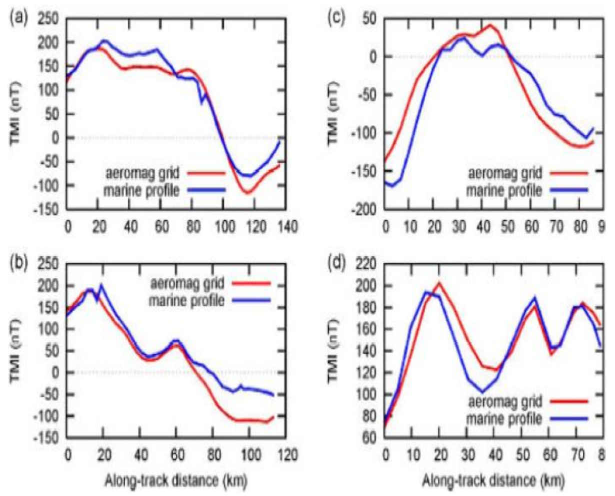

Figure 6: Comparison of results obtained using method 2 with marine magnetic profiles passing through the vicinity of the survey area. As can be seen, the comparison show remarkably good agreement, with discrepancies generally of the order of a few tens of nT. These data are completely independent of the combined satellite-aeromagnetic data [11].

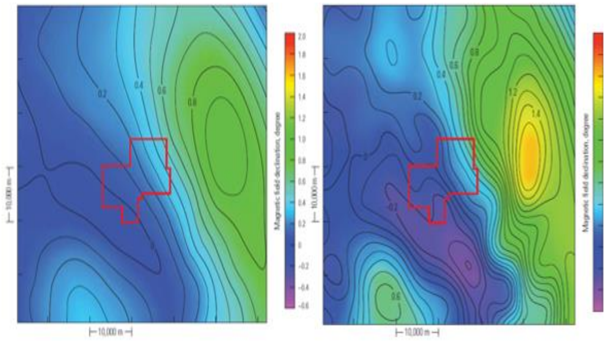

Figure 7: Crustal contribution to the magnetic field declination at sea level (left) and at 5,000m depth (right). The values were calculated using a method that combine aeromagnetic survey with a long-wavelength crustal field model provided by CHAMP satellite survey. The 3D magnetic field model created for the survey area by the method changes with depth in large part. This is adduced to the magnetic properties of the Earth's crust underlying the sediments in the survey area [4].

6. CONCLUSION

Accurate wellbore placement remains an important consideration for hydrocarbon producers as it is a necessity. As technology improves and new and more economic ways of including data on local magnetic variations in crustal modelling process are found, it is now feasible to rely on geomagnetic referencing techniques in directional drilling to reduce/eliminate the need for more costly surveys (i.e. gyroscopic surveys). While MWD tools provide the most efficient method of wellbore surveying, error sources associated with the magnetic component of MWD surveys continue to pose major obstacle to their implementation, especially at certain regions (high latitude) and periods (magnetically intense), with stringent well positioning needs. By implementing improved geomagnetic referencing techniques, the critical error sources associated with geomagnetic field can be eliminated.

The value of geomagnetic referencing has been clearly demonstrated in this study, as MWD surveys with geomagnetic referencing offer both operational efficiency and superior accuracy. By implementing improved geomagnetic referencing processes and using high quality data from geomagnetic observatories, the challenges of drilling wellbores with a high degree of difficulty in adverse magnetic conditions can be addressed in real-time. Geomagnetic referencing techniques removes variation in, and reduces the magnitude of the uncertainties. Quality control of downhole data from individual surveys is also improved. As the oil and gas industry moves forward, the ability to provide accurate wellbore surveys while optimizing efficiency will prove important as geological/geophysical targets become smaller and difficult, and the search for new oil and gas fields pushes the industry's knowledge and ability.

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