Borehole magnetics navigation: An example from the Stratmat Deposit, Bathurst, New Brunswick

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Information acquired from studies of borehole core or from borehole geophysical logs form an integral part of all mineral and oil exploration programs. Yet, as is the case of any survey, the value of that information is dependent upon how well the location of each observation point is known. Location information becomes especially critical when the resource target has limited depth extent. For example, a location error of 10 m when evaluating a 5-m thick gold vein can make the difference between an economic and noneconomic deposit. The trajectory of a borehole is commonly computed using an array of data points that are acquired progressively with increasing distance along the borehole. Depending on the type of survey employed, observation points may be sparse (static readings at a limited number of points) or redundant (dynamic surveys where the distance between observation points is less than the length of the rigid probe). At each observation point, three parameters are normally acquired: (a) inclination, dip of the borehole relative to horizontal; (b) dip direction, the orientation of the maximum dip direction relative to geographic north; and (c) depth, usually measured as distance along the borehole.

Estimates of these three parameters are made using data acquired from a suite of sensors encapsulated in a single instrument, commonly called a borehole deviation probe. Measurement of probe depth is perhaps easiest, but it is subject to error. Commonly the probe depth is estimated based on the length of logging cable that has passed over a calibrated digital encoder. The length of cable played out is generally considered equal to the distance the probe has moved down the hole. Corrections can be made to compensate for anticipated cable stretch that will occur in deep boreholes. However, as we will show, depth errors that might occur as a result of the probe being temporarily stuck in a borehole can be significant and are not accounted for using this measurement method.

Actual probe dip is simply computed from two measurements of apparent dip. This is achieved by measuring the response from two accelerometers, or mercury tiltmeters that are oriented orthogonally to one another, with their common plane perpendicular to the long axis of the probe. Comparing the magnitude of the response from the two tiltmeters also provides an estimate of probe rotation. However, this rotation is defined relative to the fixed reference frame of the tiltmeters in the probe.

Lastly, the most difficult task is establishing dip direction of the borehole probe relative to geographic north. This absolute orientation of the probe is usually achieved by using sensors that are capable of detecting reference signals external to the borehole. Commonly, this involves using the Earth's magnetic field direction via measurement of the whole magnetic field vector down the hole, or the use of gyroscopes to interrogate the local orientation of the Earth's spin axis. In this study, we focus solely on the magnetic option; most magnetic based navigation systems use a three-component fluxgate package.

Two fundamental assumptions are critical to use of the Earth's magnetic field as the external reference frame for borehole navigation studies. First, it must be assumed that the orientation of the local magnetic field vector relative to geographic north at the borehole collar is known to a high degree of accuracy. A 1° error in magnetic declination can correspond to more than 15 m in probe location at a depth of 1000 m. Second, it is assumed that the orientation of the local magnetic field vector does not change along the length of the borehole. It is these key assumptions and their impact we will discuss in this paper.

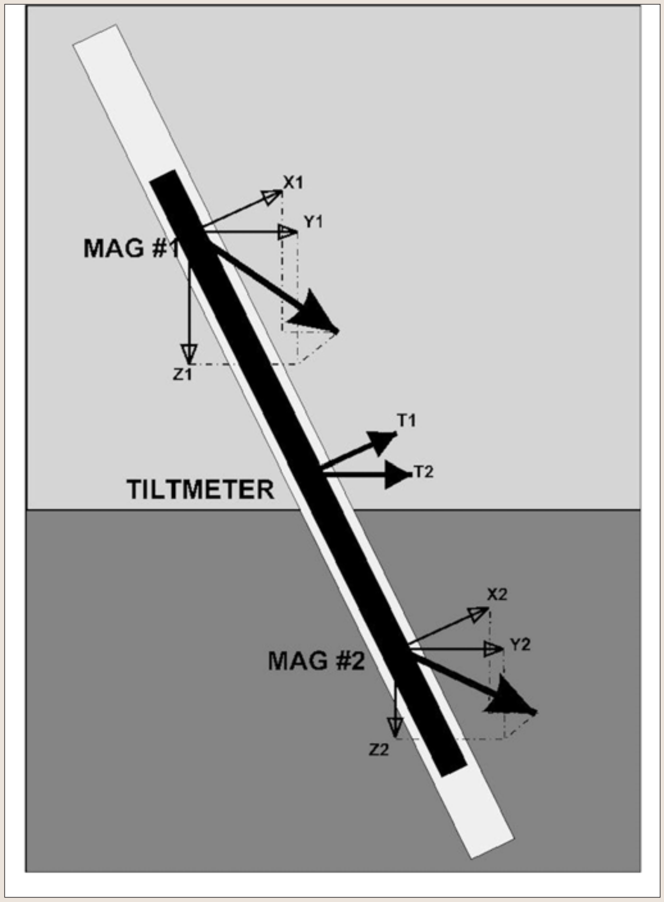

Figure 1. *Geometry of the probe and its two sets of fluxgate magnetometers (Mag #1 and Mag #2) and Tilt meters.*

Background. The magnetic field at any point on, or below the Earth's surface is the sum of three sources:

- Core—The magnetic field generated by the Earth's dynamo exhibits a broad regional scale distribution that is best described by the International Geomagnetic Reference Field.
- Crustal—The magnetic field generated by the Earth's crust comprises two elements—the induced and the remanent magnetic field. The induced component is generated by the interaction between the external sources of magnetic field (core and solar) and the magnetic mineral content of each rock unit. Magnetic susceptibility is essentially a measure of the degree of signal amplification of the external magnetic sources. The remanent component of the crustal magnetic field will have a constant amplitude and orien-

tation irrespective of any fluctuations in the external magnetic field sources.

- Solar—Commonly termed "diurnal" magnetic field fluctuations, the magnetic field strength at each point on the Earth's crust exhibits short-term variations which are related to the ionic flux from the Sun.

In situations where the core magnetic field is dominant, the orientation of the magnetic vector will be relatively constant. Fluctuations associated with diurnal magnetic change will for the most part have little influence on the orientation of the total magnetic vector, unless the survey was performed during a magnetic storm, in which case the magnetic vector might exhibit large directional and amplitude fluctuations. Lithology-related variations in magnetic susceptibility are the most common source of magnetic anomalies. However, since the crustal field amplifier (magnetic susceptibility) is usually less than 1, the vector summation of the core and susceptibility sourced crustal field, the total magnetic field vector, will rarely deviate from the orientation of the core magnetic field.

Remanent crustal magnetic field sources associated with strong magnetic remanence are the major problem. First, the amplitude of a remanence-sourced signal, especially in a borehole setting where the source–sensor distance is minimal, can easily exceed the amplitude of the combined core and crustal magnetic source signal. Second, depending on the time of remanence acquisition, the orientation of the remanence-sourced magnetic vector may vary greatly from the local orientation of the Earth's core and crustal signals. The orientation of the total magnetic field vector will depend on the relative magnitude of the individual components. In certain situations, most obviously the ocean floor, the remanence component can totally dominate the magnetic source signal. When this occurs, the external reference frame can no longer be assumed to have an orientation that matches the local IGRF field direction.

The problem of remanence-related borehole navigation error is not new. Instrument manufacturers have used different methods to overcome this problem with varying degrees of success for years. This remanence problem was the primary justification behind the development of north-seeking, gyroscope-based borehole probes. As the probe is lowered down the hole, it is free to spin at the end of the logging cable. However, if the probe is simultaneously moving past a contact between a susceptibility dominated lithology and a remanence-dominated lithology, the orientation of the total magnetic vector might exhibit an apparent rotation. It is therefore necessary to differentiate between probe rotation and magnetic field rotation to obtain a meaningful estimate of the borehole orientation.

A simple approach to solving this remanence problem is to compare the rate of probe rotation as estimated by the fluxgate and tiltmeter sensor packages. Since both systems are rigidly fixed inside the probe, they should exhibit exactly the same rate of rotation. This simple solution fails in a couple of common settings. First, when the borehole is near vertical, the amplitude of the signal associated with both tiltmeters is minimal and therefore calculation of probe orientation is poorly constrained. Second, to discriminate between probe rotation and magnetic field rotation requires the probe to rotate. If the probe is not rotating, then evidence regarding magnetic field rotation becomes uncertain.

Another approach to this problem utilizes the inclination of the magnetic vector. The base assumption is that if there is a remanence sourced problem, the inclination of the magnetic vector will be changed; therefore, one can identify any points that might have questionable reliability. This approach has two problems. First, it is quite possible to have a remanence problem that might affect magnetic declination only. Using the magnetic inclination approach, this problem could go unnoticed. Second, the magnetic inclination approach seeks to identify problematic observations but does not attempt to compute any solution.

Finally, perhaps the most successful approach to date is to introduce an additional sensor package that is capable of detecting probe rotation independent of the fluxgate and tiltmeter packages. This has been achieved by the incorporation of a vibrational gyroscope. While this system is incapable of detecting spin-axis north, it is capable of independently measuring probe rotation. Therefore, by comparing the three estimates of probe rotation (magnetic, tiltmeter, and gyroscope), it is possible to isolate rotation of the magnetic field.

The remainder of this paper introduces a new approach to borehole navigation that makes it possible to directly and immediately overcome the effects of a remanence magnetic source on the orientation of the effective magnetic vector. Critical to this new approach is the use of two (or more) three-component vector magnetometer packages rigidly fixed relative to one another in the single probe (Figure 1). With two magnetometers fixed at opposing ends of a single probe, any probe rotation will be reflected by identical changes in the magnetic fields recorded by both sensors at the same time. Any change in magnetic field orientation related to a change in the amplitude of the solar (diurnal) magnetic field will be minimized (but not totally eliminated). This is a direct consequence of both magnetic sensor packages simultaneously measuring the magnetic field with the only difference between the two measurements related to their magnetic susceptibility difference.

Finally, and most critical for borehole navigation, it is possible to measure magnetic field rotation effects by comparing the simultaneous declination values recorded by the two magnetometer packages without requiring the probe to rotate. Recording data from both sensor packages as the probe is lowered down the borehole provides a direct record of the systematic change of magnetic declination versus depth. Repeat passes of the probe up and down the borehole, or using multiple sets of magnetometers would result in data redundancy which could be used to assess the reliability of the magnetic vector estimate.

Instrumentation and corrections. The data presented in this study were collected using a probe with two three-axis fluxgate magnetometer packages and one pair of electronic tiltmeters (Figure 1). This probe was originally designed by the senior author in 1988 and built for the Geological Survey of Canada. No preborehole survey calibration files were recorded. So in this situation all sensor corrections are derived from the borehole survey data set. To minimize issues created by changes in the relative magnitude of vertical and horizontal components of total magnetic vector, corrections were derived from sections of the logs where the probe executes at least one full rotation with little, or no change in magnetic signal, or dip of the borehole. Three types of probe calibrations/corrections were necessary: (a) sensor offset; (b)sensor gain; and (c) sensor orthogonality. Many manufacturers embed these corrections into their data processing packages. (For a more complete discussion of cross calibration of multiple fluxgates, see Smith and Bracken's 2004 paper, "Field experiments with the tensor magnetic gradiometer system for UXO surveys: case history," SEG 2004 Expanded Abstracts.) All sensors used as part of this study output raw signal without corrections or calibrations.

Fluxgate magnetometers do not provide an absolute record of magnetic field strength. They commonly report a base value, even in the absence of an input signal. The magnitude of this base or offset value varies from sensor to sensor. An estimate of the offset value can be obtained by changing the polarity of a constant magnetic field. Gain is a unique property of each sensor and describes the relationship between input and output signal strength. An absolute estimate of sensor gain could be computed by sequentially placing a number of reference samples having known magnetic strength adjacent to the fluxgates. In the absence of absolute reference data, corrections are calculated by cross-referencing responses between individual sensors. With this approach it is necessary to arbitrarilly define one sensor as the master and then adjust all other sensors to exhibit the same fluctuation as the master sensor. For this study, the master fluxgate was chosen as magnetic sensor 1 in the X direction

The probe will rotate as it is lowered into the borehole on the logging cable. If the two magnetometers have identical offset and gain characteristics, the response of the X1 magnetometer versus the Y1 magnetometer as the probe rotates should define a perfect circle centered on zero. Deriving offset and gain corrections for each sensor requires finding corrections that optimize the circular, zero-centered fit of the observed data. Corrections for magnetic sensor 1 include offsets for X1, Y1, and Z1 and gain corrections for Y1 and Z1. For the second block of fluxgates, it is necessary to compute gain and offset corrections for all three sensors X2, Y2, Z2. This is achieved using a two-step process: first, optimization of X2, Y2, Z2 to be internally identical to magnetometer 1, and, second, the amplitude of the second set of fluxgates must be adjusted to be in agreement with the first set of fluxgates. This amplitude adjustment in the second step can be achieved by applying additional gain to all components of the second fluxgate package.

The probe rotation technique was not used to define the offset and gain for the Z fluxgates in this study; the corrections were derived directly from borehole observations. Corrections were estimated taking advantage of the fact that the radial and axial components of the magnetic field are directly linked. Both change as a consequence of the relationship between the dip of the borehole and the inclination of the magnetic vector. The cosine of the radial component is equivalent to the sine of the axial component. Given that relationship, and the knowledge they experience the same change in borehole dip over the length of the borehole, it should be possible to derive gain and offset corrections for the Z fluxgates. A similar process can be applied to determining corrections for the tiltmeters. In this case, there were only two tiltmeters with computation that resulted in one gain and two offset values.

The third calibration issue concerns the geometrical arrangement of individual sensors. Both the fluxgates and the tiltmeters are unidirectional sensors; that is, they measure the response in whichever direction they are pointed. The geometry and magnitude of the magnetic vector is derived from geometrical ratios of the three vector components. An accurate estimate of the orientation of the magnetic vector can only be determined when the three sensors are truly at right angles to one another. Generally, this issue is termed orthogonality. There are two orthogonality issues that need to be addressed: (a) orthogonality within each sensor package, and (b) orthogonality between sensor packages. Ideal orthogonality within a sensor package occurs when all components of a package are at right angles to one another. Orthogonality error is substantially smaller than offset and gain errors. During a complete rotation of the probe, perfect sensor orthogonality would produce a flat line relationship between calculated declination and the magnitude of the horizontal component of the magnetic field. Any nonorthogonality results in a sine wave whose amplitude is directly related to the degree of sensor misalignment. Correction is achieved by optimizing the best fit to a straight line. A second aspect of the orthogonality problem involves the alignment of the sensor packages within the probe. For example, misalignment of the X1 and X2 fluxgates would result in a constant bias between the two sensors. This can be approached by applying a simple dc shift between the two packages. As noted above in this study all data are referenced to the X1 fluxgate.

There are two main types of drift associated with a magnetic survey. The first is instrument drift and the second is the diurnal drift of the Earth's magnetic field. Instrumental drift refers to changes in the sensitivity of an instrument during a survey. As the probe travels down the hole, each sensor package passes the same point but at different times. It is logical to assume that both sensors record identical signals at the same point in the borehole. Since the data were corrected for offset, gain, and orthogonality errors, the only factor that could prevent both sensors from receiving the same signal at the same spatial and temporal point is instrument drift. Removing instrument drift was necessary with this data set and was achieved using a lower order polynomial that brought signals from two sensors into close agreement. Since the two magnetometer packages were measuring simultaneously, any diurnal field fluctuation would not have been observed and therefore had no impact on these data.

Results. Data for this study were collected in July 1992 by the Borehole Geophysics Group, Geological Survey of Canada. Borehole 61-17 is one of a series of eight holes surveyed to better define variations in magnetic properties with depth at the Stratmat Mine site, which is part of the Bathurst Mine Camp (New Brunswick). Initially these surveys were performed to complement a pre-existing aeromagnetic survey. Borehole 61-17 was originally drilled in 1956 and the core and borehole were re-examined again in 1988. The 1988 assessment file report details dip and dip direction measurements at just seven points along the 350-m long borehole with the following cryptic comment: "Possibly errant Tropari data due to magnetic influence." The original surveyor clearly recognized that magnetic remanence could be influencing the derived borehole geometry. This was not surprising since the core contained a number of zones of massive sulphide known to contain the magnetic minerals magnetite and pyrrhotite. While the surveyor did not know which readings were biased, or by how much, the assessment file does report both observed and corrected magnetic bearings but there is no indication how the "corrected" bearing was calculated.

Two data collection passes were run in each borehole during the downhole and uphole runs, resulting in four independent data sets. Different constant logging rates were used for each of the four surveys. Preliminary investigation indicated that all of the data sets needed internal cross-calibration to minimize the effects of variable sensor offset, gain, and orthogonality. Details of these corrections are not discussed here.

As noted above, it has been suggested that in the absence of a biased magnetic field, an anomalous magnetic declination will accompany an anomalous magnetic inclination. Plotting measured magnetic inclination versus observed probe dip is an easy method for assessing this problem (Figure 2). Each incremental change in probe dip should equate to an equivalent change in apparent magnetic vector dip. Note the magnetic dip is measured relative to the axis of the probe. Data from two passes in borehole 61-17 show the expected direct

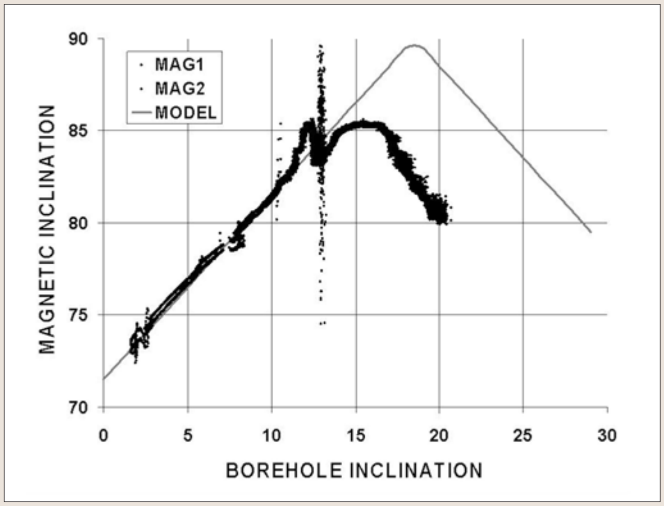

Figure 2. Magnetic inclination versus observed probe dip (borehole inclination), for borehole 61-17. Both passes (downward and up) are plotted for consistency. Incremental changes in probe dip should equate to equivalent changes in apparent magnetic vector dip. Note the magnetic dip is measured relative to the axis of the probe. The model curve indicates that the local magnetic vector has an inclination of 71.5°, and an anomalous area around 13°. See text for details.

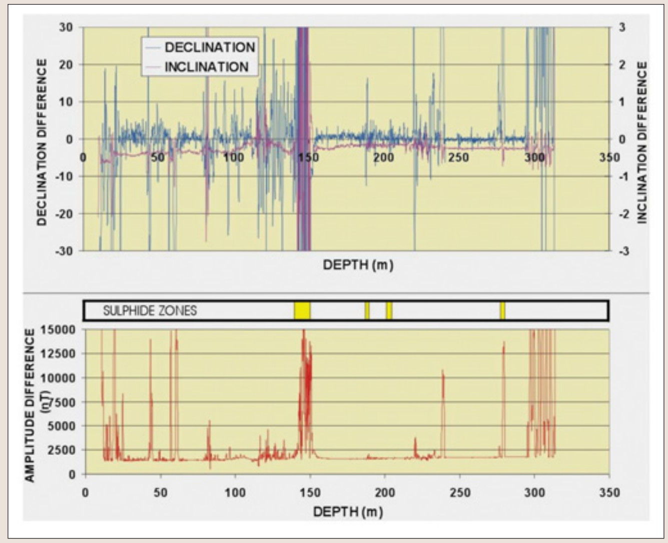

Figure 4. Magnetic inclination and declination differences (top) and magnetic intensity difference (bottom) from the four passes at borehole 61-17. The mapped sulphide zones are shown in the middle for clarity. Magnetically anomalous zones are always associated with intensity difference peaks. The anomalous zone at the beginning of the core is related to the presence of casing.

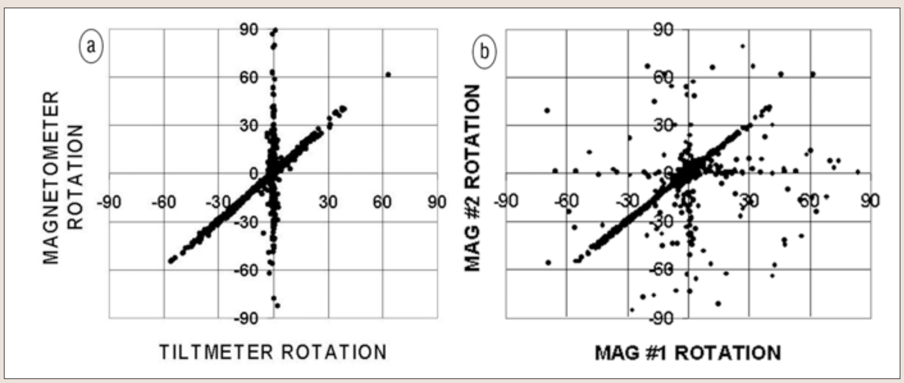

Figure 3. Probe rotation estimated from (a) both sets of fluxgate magnetometers, and (b) one set of fluxgate magnetometers and the tiltmeters. Both results should be the same in the absence of any magnetic anomalies. However, approximately 15% of the data in (a) do not conform to a simple 1:1 rotation between the two sensors. Those magnetic anomalous points are successfully separated in (b). See text for details.

correlation between the two observed dips. Projecting a best-fit line back to the origin indicates the local magnetic vector has an inclination of 71.5°. The plot also shows a number of other features (Figure 2). There are a couple of zones that exhibit wide ranges in magnetic inclination for little to no variation in probe tilt. These are clearly anomalous. In advance of the large magnetic inclination spread at a probe dip of around 13° the data shows a progressive increase in magnetic inclination. Should these be considered anomalous? All of the data points that occur after this point have magnetic inclinations that are systematically too shallow to be compatible with the observed 71.5° inclination. Are all of these anomalous? Probably not—because the observed magnetic vector for all these points below the strongly magnetized sulphide zone are influenced by the magnetic sheet.

A second possible approach is to compare estimates of probe rotation as defined by the magnetometers and the tiltmeters. Again, as noted above, in the absence of any biasing magnetic influence, the two sensor packages should report the same degree of rotation. In this situation, it is possible to compare rotations as defined by the two magnetometer packages. Data from two passes in 61-17 shows the majority of data does conform to a simple 1:1 rotation between the two sensors (Figure 3a). But approximately 15% of the data disagree with this trend. The 15% of the data clearly record the presence of some anomalous magnetic source. Comparing the average magnetic rotation with the temporally equivalent probe tilt rotation clearly separates points that are magnetically anomalous (Figure 3b). Probe rotation and magnetic field rotation directly correlate in the absence of anomalous declination changes. It is very easy to isolate the anomalous points which exhibit a large magnetic field rotation and little or no probe tilt rotation. The problem with this approach is establishing a lower threshold for determining which points are anomalous. Since the objective is to achieve the best possible estimate of the borehole geometry, one possible approach would be to eliminate all points that have low rotation. Unfortunately, the resulting data set is very small.

Having multiple fluxgate sensors permits a completely new approach to magnetic declination correction. Since the two sensor packages are rigidly fixed in the probe, it is possible to directly compute the change in magnetic vector orientation versus depth in the borehole. Combining results from all four passes in 61-17 highlights a direct correlation between the presence of magnetically enhanced sulphide-rich zones and anomalous magnetic vector changes (Figure 4). While the declination data appear to be noisy, it is readily apparent that for most of the core the declination difference is close to zero. There are no major changes in magnetic vector direction. Inclination difference data are much smoother than declination data. Again, as expected, the mean value is close to zero. Magnetically anomalous zones are always associated with intensity difference peaks. This is to be expected since an anomalous declination signal requires a strong remanence signal. The anomalous zone at the beginning of the core records the magnetic influence of the metal casing.

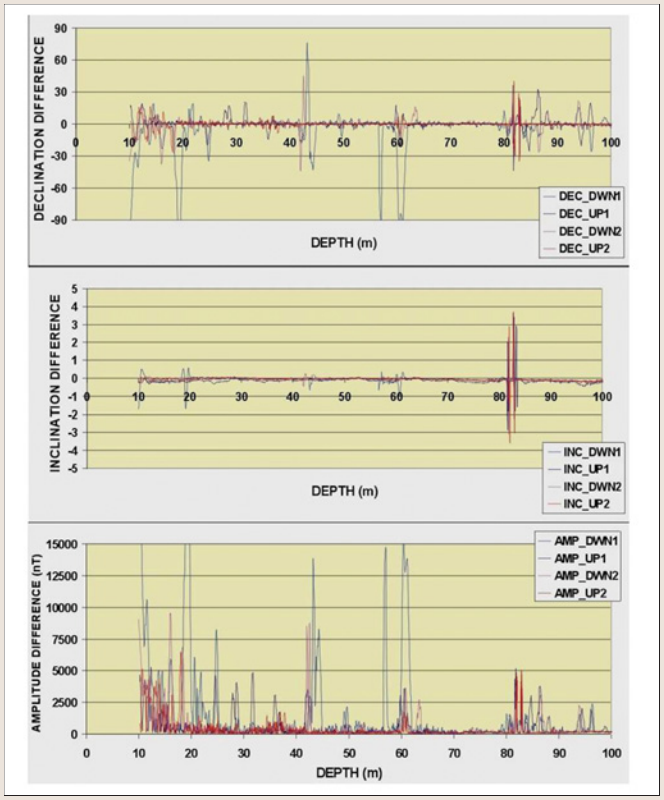

Figure 5. Magnetic declination difference (top), inclination difference (middle) and magnetic intensity difference (bottom) for the four passes at borehole 61–17, for the segment 0–100 m depth. Data for each of the four passes are shown separately for the purpose of separating the quality of the signal on each individual pass. None of this data was filtered.

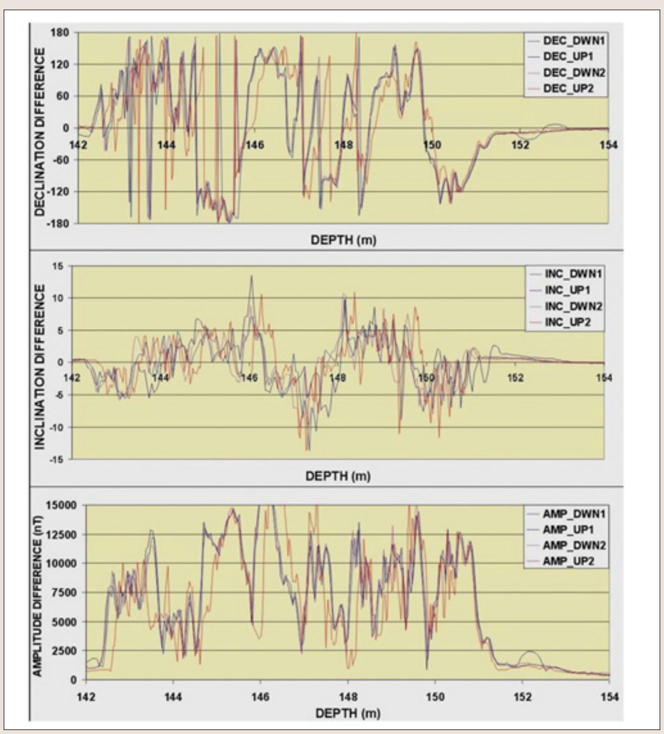

Figure 6. Magnetic declination difference (top), inclination difference (middle) and magnetic intensity difference (bottom) for the four passes at borehole 61-17, for the segment 142-154 m depth, which corresponds to the main ore zone. All passes are shown separately for the purpose of separating the quality of the signal on each individual pass. None of this data was filtered. Note apparent variable depth shift in log UP2. Actual motion of probe in hole was not fully reflected by depth encoder.

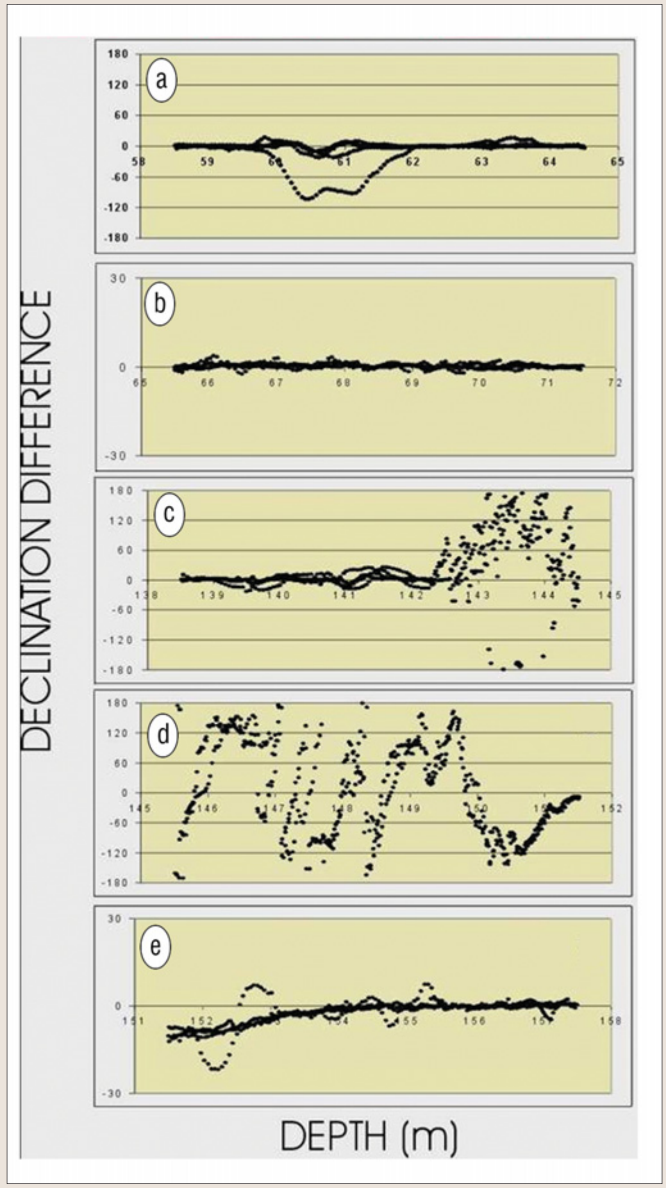

Figure 7. Plots of declination difference from four passes at borehole 61-17. Plotting observations as a series of points gives direct insight into reliability of magnetic declination rotation estimate. Using multiple sensors, or multiple passes permits use of a statistical analysis of rotation estimate. (a) One noisy channel, (b) ideal coherent data, (c) onset of anomalous zone, (d) complexly magnetised zone, and (e) slow change in magnetic declination with one poor channel.

Comparing the data from the four passes in 61-17 shows that much of the noise present in the average declination data (Figure 4) is directly attributable to one particular data set. Pass DWN1 was acquired with the highest logging speed as reflected in the large spikes observed in declination and amplitude data (Figure 5). Filtering was not applied to any data in this study. A simple low-pass, or nonlinear filter could have minimized much of the noise in this data set. Even with these noise problems one of the most surprising aspects of this study is the level of repeatability achieved with this dynamic navigation approach. The main ore zone which extends from 142 to 150 m depth comprises a number of sulphide lenses separated by gabbroic dykes. Through this zone the magnetic declination difference vector shows oscillations from -180 to +180°, yet these variations can be tracked from pass to pass (Figure 6). These data also show significant problems with probe depth estimates that have hitherto gone relatively unnoticed. The last pass, UP2, acquired with the slowest logging speed, was recorded as the probe was brought back to the surface. At depths below 150 m, all four logs closely agree. Above 150 m, the UP2 log shows variable displacements relative to the other three logs (Figure 6). This is due to the probe temporarily sticking in the borehole. The depth encoder keeps turning, the cable stretches, and probe jumps once it becomes free. More care regarding depth estimates is required.

Measuring multiple estimates of the total magnetic vector difference makes possible a new approach to borehole navigation using magnetic fluxgate sensors. With rigidly attached (no relative rotation permitted) multiple sets of fluxgates, it is possible to generate a plot of the difference in total magnetic vector between adjacent fluxgate sensors versus depth. This provides a direct measure of the absolute change in magnetic declination with increasing depth in the borehole. Adopting a data oversampling approach that can be achieved using multiple fluxgate sensors, or multiple passes in a single hole, would allow a probabilistic approach to computing the change of magnetic declination versus depth. This would effectively allow identification of: (a) ideal data (Figure 7a); (b) anomalous results from one or more magnetometers (Figure 7a, 7e); and (c) the change of magnetic declination through a strongly magnetized zone (Figures 7c, 7d). Knowing the change in magnetic declination, it is a simple step to incorporate this information into computation of the borehole geometry. This could be achieved by either eliminating those readings that exhibit magnetic declination changes and exceed some predefined threshold, or by including the observed magnetic declination values in the trajectory calculation.

Conclusions. Magnetic fluxgate sensor-based borehole deviation tools can be used to provide the high degree of navigation accuracy required by today's exploration industry. Critical to their use is a careful assessment of all possible errors associated with data acquisition. Magnetic remanence does compromise the orientation of the total magnetic vector. This can be overcome by using multiple sensor packages to either identify anomalous data points, or in a more advanced mode, measure the change of magnetic declination through the magnetically anomalous zone. Ideally one should have more than two sets of fluxgates with variable spacing such that ideally one fluxgate package will be outside the anomaly. Prior to performing high precision borehole navigation experiments, it is useful field practice to record a series of quality control files. Through careful experimental design and use of high precision GPS sensors, it is possible to generate control files that could provide a direct measure of the magnetic declination at the study site and a statistically controlled plot of magnetic declination changes versus depth.

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