Magnetic remanence constraints on magnetic inversion models

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A magnetic anomaly is produced when a rock unit has a magnetic contrast with a laterally adjacent rock unit. The cause of this magnetic contrast might be produced by a change in the magnetic susceptibility and/or magnetic remanence of the source bodies. After Vine and Matthews (1963) demonstrated that magnetic anomalies observed over ocean basins record a chronology of ocean floor generation, it was readily apparent that in some instances the genesis of a magnetic anomaly can be dominated by the remanence component. Surprisingly, few investigators have acknowledged that magnetic remanence can have a similar influence on continental magnetic anomalies. The incorporation of magnetic remanence data into a magnetic inversion scheme continues to present a major problem. In this note, we outline the problem and present some approaches that might be used to derive relevant remanence information.

Vector mixing and its effect. The Koenigsberger ratio (*Q*) describes the relative importance of the induced and remanent magnetic components. The significance of the *Q*-ratio can easily be demonstrated by computing the effective magnetic vector produced from the vector summation of the induced component (Earth's magnetic field multiplied by the susceptibility) and a hypothetical remanence component (Figure 1). For this simple model the inducing magnetic field was chosen to have a declination of 0°, an inclination of 75°, and a strength of 55 000 nT. The remanent magnetic field was given a declination of 90° and an inclination of –15°. The magnitude of the Koenigsberger ratio, and therefore the remanent magnetization, was incrementally increased from 0.0 to a value of 100.0. As *Q* is incrementally increased, the orientation of the effective magnetic vector swings from alignment with the present Earth's field orientation to alignment with the remanent magnetic vector (Figure 1a).

Independent of the orientation of the remanence vector it is within the *Q*-value range from 0.1 to 10 that the effective magnetic vector will exhibit its greatest range in orientation. Outside this range of *Q*-values the effective magnetic vector approximates the orientation of the respective end-member direction. That is, when *Q* is less than 0.1, the effective vector equals the Earth's field direction at the observation point; and when *Q* is greater than 10, it is the orientation of the remanence vector that dominates. All possible orientations of the effective magnetic vector are controlled by the absolute orientation of the inducing and remanent magnetic field components. The effective vector directions must fall somewhere on the great circle path between the induced and remanent vector directions. Vector summation of the induced and remanent magnetic components also affects the magnitude (or intensity) of the effective vector. In the simple example (Figure 1b), the intensity initially diminishes before starting to increase after a *Q*-value of 5.

A special case occurs when the induced and remanent magnetizations have opposite, or near opposite polarity (Figure 1c). In this situation when the two components have

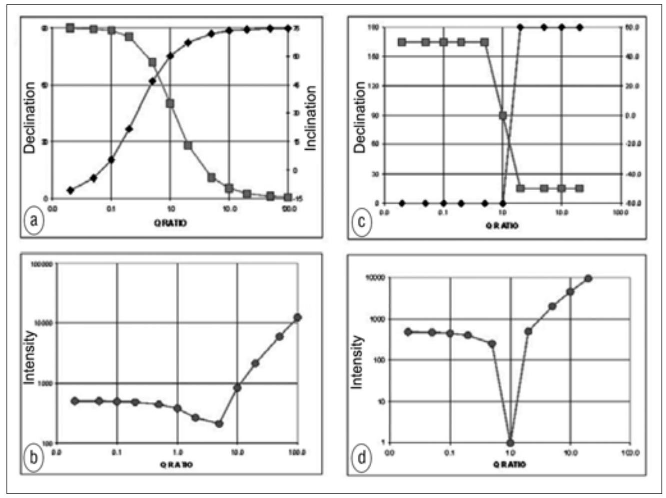

Figure 1. *(a) Diagrammatic representation of effective magnetic vector that will result from addition of an induced and a remanent magnetization component. (b) Effective magnetic vector resulting from summation of a northerly directed inducing field (D=0°, I=75°) and an easterly directed remanent magnetization (D=90°, I=–15°). (c) Magnitude and direction of magnetic vector show systematic changes between Q-values of 0.1 and 10. (d) Effective magnetic vector resulting from summation of a northerly directed inducing field (D=0°, I=75°) and a southerly directed reversely magnetized remanent magnetization (D=180°, I=–75°). Note that this case, which is probably quite common in recent rocks, produces a magnetic annihilation of the magnetization at a Q-value of 1.0. In this situation the rock would have a strong induced and a strong remanent magnetization yet produce little magnetic anomaly.*

similar magnitude, the effective vector direction will flip direction around the Q ratio of 1.0. More significant, however, is the possibility of magnetic annihilation of the intensity of the effective vector (Figure 1d). Even though both the induced and the remanent component might individually be quite strong, the vector summation would have intensity near zero.

All magnetic measurements, either of rock samples or mapped magnetic anomalies, represent the summation of contributions from a large number of individual crystalline magnets. The volume of individual magnets averaged by each observation depends on the scale of the survey. An airborne survey flown at 100 m will average signal from a smaller volume than a similar survey flown at 1000 m. Detailed magnetic susceptibility studies of granite plutons for the Canadian Nuclear Fuel Waste Management program (Chan et al., 1999) have shown that rock units are not characterized by a single susceptibility value, but rather a log-normal based population having a mean and standard deviation. Magnetic remanence intensity, which is mostly tied to similar mineralogy, also exhibits an analogous log-normal distribution.

In any regional aeromagnetic study it is to be expected that *Q* would vary much more than the orientation of the remanent magnetic vector. In this situation the resulting

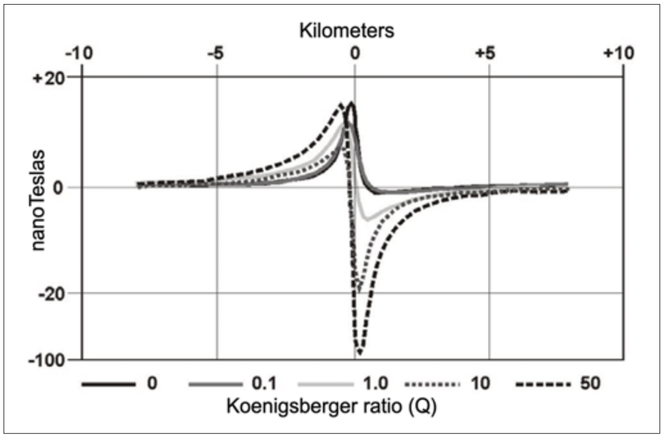

Figure 2. *Magnetic anomaly associated with an EW-striking and vertically dipping dike. Magnetic sources are a remanent direction directed due north (0°) with an inclination of –15° and an inducing field of D=0°, I=75°, and H=55 000 nT. Varying the* Q*-value produces a systematic change in the morphology of the magnetic anomaly. In the absence of any evidence to the contrary, this could be interpreted in terms of a more increasingly dipping dyke rather than a vertical dyke with varying remanent magnetization.*

magnetic anomaly profiles would reflect the lateral changes in the orientation of the effective magnetic vector. This was investigated using the same EW-striking and vertically dipping dike used above. To simplify the model, we used a remanent direction directed due north (0°) with an inclination of –15° and an inducing field of D=0°, I=75°, and H=55 000 nT. In this model the effective vector only changes inclination with increasing remanence. As shown by Figure 2, it is over the range of *Q*-values from 0.1 to 10, where the inclination of the effective vector shows the greatest change, that the shape of the magnetic anomaly also shows the biggest change in the relative magnitude of the positive and negative components of the magnetic anomaly. In most surveys there are a number of subparallel flight lines across the lateral extension of a source body.

If it is assumed that for each flight line the remanence direction is constant and the dip of the strata are known, then the computed apparent dip of the remanence vector will be intermediate between the true dip of the remanence vector and the true dip of the present Earth's field vector. If there is a range of *Q*-values (unknown) over the block of subparallel flight lines then the solutions from this block of data will define a great circle trend between the induced and the remanent magnetic vectors. The best estimate of the remanent vector is the direction furthest from the present Earth's field direction.

The question of scale introduces another issue: how accurately does one need to define the orientation of the remanence vector? Without engaging in any complex numerical analysis, a simple approach can be to determine the effect of varying the remanence vector on the effective magnetization vector, and the consequent magnetic anomaly. It should be readily apparent that defining the remanence direction to better than 10° is going to be sufficient for most modeling situations.

Remanence vector orientation. Magnetic inversion procedures seek to identify the optimum numerical match between the observed signal and a calculated response for a model defined by variable geologic boundaries and physical rocks properties. Most fully unconstrained inversions do not allow for the presence of magnetic remanence since by doing so the inversion would face the remanence-tectonic dip dilemma. As originally noted by Paterson and Reeves (1985), it is possible to observe the same TMI response from a dipping slab having only induced magnetization and a differently dipping slab which is remanently magnetized. The commonality is the relationship between the dip of the magnetic vector and the tectonic dip of the slab. When geologic boundaries have been predefined and fixed using borehole information, it is then possible to invoke the presence of a magnetic remanence component in the magnetic inversion model. The output of such an inversion will be a model that optimizes a statistically defined best-fit between the observed and computed magnetic fields by varying the magnitude of the magnetic susceptibility and the orientation and magnitude of a hypothetical remanence component. Without some prior constraint, this could easily result in the computation of a remanence vector that might be completely erroneous. From the discussion above, the effective magnetic vector and therefore the remanence vector cannot have any possible orientation; rather the orientation must be compatible with the expected age of remanence acquisition.

For over 40 years now, paleomagnetists have been measuring rock samples from a wide range of rock types on every continent. The original intent of these studies represented a wide variety of applications: from establishing detailed litho-chronostratigraphic correlations to plate motion reconstructions to structural evolutions of complex geologic terrains. The end result of this large number of studies is a series of *apparent polar wander paths* (APWP) for different continental and cratonic regions. Data points employed in the construction of APWPs are screened using criteria that selects only those points for which the timing of remanence acquisition is established, and for which the age of magnetization can be established by fossil or radiometric age control. APWPs covering the Phanerozoic time period (approximately 500 Ma and younger) are now well established for every continent. Additionally, for Phanerozoic time the magnetic reversal time scale, which describes periods of time when the Earth's magnetic field had reversed polarity, is also well known. So knowing the age of a rock unit the probability of a normal or reversed polarity magnetization can be quickly assessed.

Each APWP describes the locus of the magnetic pole relative to a specific continental region. Knowing the sampling location the APWP then provides direct information regarding the orientation of the remanence vector. These APWPs are capable of providing remanence direction information to better than 10°. Many exploration projects involve mineral deposits associated with Precambrian strata. There have been a lot of paleomagnetic studies of Precambrian rock units but, given the four-billion-year extent of this time period, there is still an inadequate number of observations to obtain the same level of detail that is available for Phanerozoic time. Nonetheless well-defined APWPs do exist for some tectonic cratons over some portions of Precambrian time. Historically, the popularity of paleomagnetism in Canadian academia during the period 1970–1990 has meant that APWPs are better defined for the Canadian Shield than any other comparable Precambrian terrane.

Irrespective of the age of a rock unit the actual orientation of the remanence vector is also affected by the degree of tilting (folding) that the rock has experienced. Paleomagnetists took advantage of this feature by using fold tests to establish the age of remanence acquisition relative to the age of rock deformation. For the geophysicist wishing to use remanence data in a controlled magnetic inversion, possible tectonic rotation of the effective vector adds another

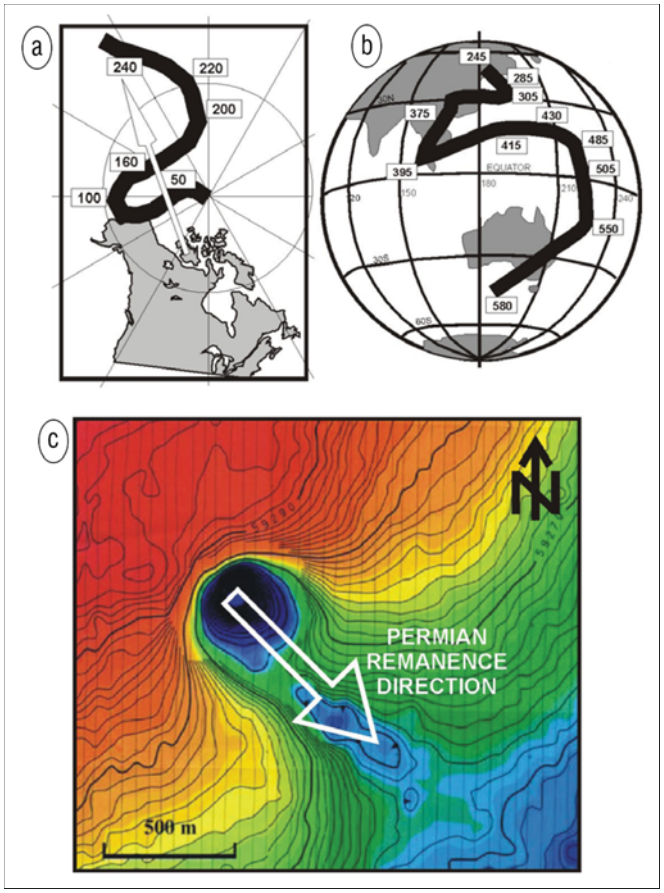

Figure 3. *(a) APWP for North America for Recent to Permian. Open arrow shows direction of pole from sampling site on Victoria Island. (b) APWP for North American craton extending back to late Cambrian. The ages of specific features on the curve were established by reference to known intrusions and paleontological record. (c) Example of a remanently magnetized kimberlite pipe on Victoria Island. The orientation of the magnetic dipole in the observed total magnetic field data is identical to the orientation of the Permian-age remanence vector for this location.*

level of directional complexity. However, the same logic applies for both the geophysicist and the paleomagnetist. That is, if a fold structure is known to exist then it is possible to compute the anticipated orientation of the magnetic vector for each limb of the fold. Any meaningful inversion must satisfy the computed vector for both limbs of the fold. Mariano and Hinze (1994), in their study of the Keeweenawan volcanics underlying northern Lake Superior, provide an excellent example of how to incorporate tectonically controlled varying remanence direction into a magnetic inversion model.

Some solutions. Recognizing that some knowledge of the orientation of the remanence vector could result in more geologically meaningful geophysical inversions, we offer a number of suggestions on how to acquire estimates of the remanence data.

Indirect approach: APWPs. How does this APWP approach work? First priority is to acquire some control information. Three criteria must be established. Of prime importance is the age of the rock unit for which you wish to seek remanence information. Second, as noted above, one should establish if the rock unit has been tilted. If the remanence was acquired before tilting, then one needs to apply a tilt correction. If the magnetization was acquired after tilting, this then presents another problem. Clearly, the representative point to be selected on the pole path must postdate the age of folding, but by how much? The best choice would probably be to select a time that postdates the timing of peak metamorphism, or regional metasomatism. It is assumed that once these processes are complete any mineral recrystallization and consequent remanence resetting might close. Third, one must establish which APWP is appropriate for the study site. Usually the exploration geologist will be well aware to which terrane the study site belongs. Knowing the latitude and longitude of the study site and the position of the appropriate paleomagnetic pole, calculation of the declination and inclination of the remanence vector is a matter of simple trigonometry (Figure 3a). This approach does not provide any direct insight into the intensity of the magnetic vector but in a geologically controlled magnetic inversion this could be calculated.

An excellent example of this type of approach is the diamondiferous kimberlites on Victoria Island. Radiometric age studies have established that emplacement of this suite of kimberlites occurred around 250 Ma. Comparing this age to the Phanerozoic APWP for North America (Figure 3b) and selecting a point on Victoria Island yields a remanence direction of D=315°, I=54°. Having derived the calculated remanence direction, it is useful to test if this direction is indeed appropriate. As originally noted by Zietz and Andreasen in 1966, when remanence is dominant (see discussion above) the alignment between the maximum and minimum of the observed anomalous magnetic field dipole defines the orientation of the effective magnetic declination (Figure 3c). If a valid remanence direction is derived from the APWP curve, then the calculated declination should agree with that associated with the observed magnetic field anomaly. In this instance the close agreement between the observed and calculated magnetic declination provides supporting evidence that this is a vertical pipe.

Direct approach: Sample measurement. By far the simplest method of achieving some estimate of the relative importance of the induced and remanent components of magnetization is to measure the magnetic susceptibility and magnetic remanence of a suite of representative rock samples. However, it must be recognized that, to obtain a valid estimate of the remanence direction, a full description of the original orientation and dip of the rock sample is mandatory. Estimation of the remanence vector is then achieved by measurement of the magnetic effect produced by the sample in a space where any influence of the Earth's magnetic field has been eliminated. Various types of measurement devices (pick-up coils, fluxgates, squids) with varying degrees of sensitivity are available to make these measurements. Since both susceptibility and remanence are best described as populations, it is better to measure a suite of samples rather than just one.

In many exploration programs, the most readily available rock material is core derived from a borehole. This has the advantage in that it can provide insight into the magnetic properties of geologic units that do not occur on the present-day surface. It is common for magnetic anomaly inversions to suggest the presence of some buried anomalously magnetic source body. Magnetic measurements on a suite of core samples also provide absolute depth constraints on the anomalous magnetic source bodies. This in turn provides additional constraints that can be input into the inversion model. Unfortunately, for most exploration boreholes the core samples are only partially oriented. The up/down sense of the core is controlled when the core is brought to the surface. Rarely is there any information regarding the orientation of the sample in the plane per-

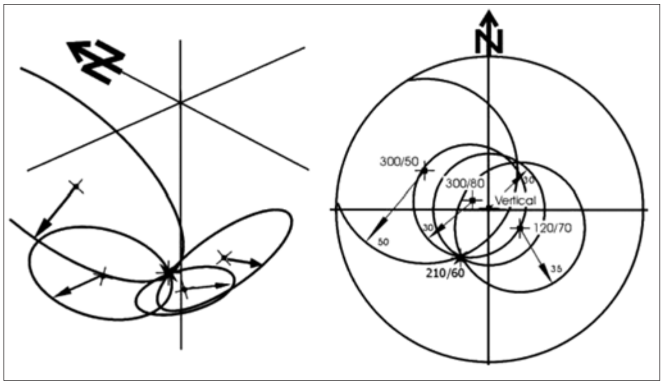

Figure 4. Diagrammatic representation of how the magnetic inclination of the remanence vector (D=210°, I=60°) measured in an individual borehole is a direct function of the orientation and inclination of each borehole relative the true magnetic vector. Intersecting the same remanence component with a number of boreholes that have different trajectories provides a determination of the true magnetic vector.

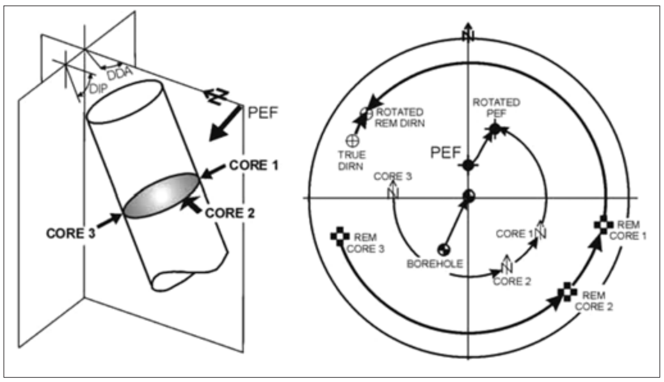

Figure 5. All rock specimens contain a hard and a more viscous remanent magnetic component. This viscous component has been acquired during the most recent geologic time and therefore must have an orientation parallel to the present Earth's field direction. Reorienting the magnetization measured in the sample core to match the Earth's field provides a means of determining the true remanence direction of the harder magnetic component. Measuring three or more specimens from the same core segment provides a measure of internal reliability. The differences in declination measured between the three specimens should equal the differences between their orientations around the core axis. To obtain the true remanence direction a final correction for dip of the borehole and/or dip of the geologic strata might be required.

pendicular to the borehole. In this situation it is possible to establish the magnitude and inclination of the magnetic vector relative to the geometry of the borehole at the core sample depth. Knowledge of the magnetic inclination makes it possible to establish if the remanence has positive or negative polarity. Without any additional experimentation this cannot provide any information regarding the declination of the magnetic vector.

There are a number of ways that one can overcome this problem:

- The easiest method would be to obtain fully oriented core. During the Canadian Nuclear Fuel Waste management studies of the 1980s full core orientation was achieved by marking the low point on the top surface of each core segment (Chan et al., 1999). Knowing the orientation of the borehole at the core sample depth it was then possible to achieve full core orientation.
- Some rock units have distinctive mineral fabrics. The orientation of the mineral fabric relative to the core axis can be established by either magnetic or optical measurements. The orientation of the same fabric in the borehole is often observed in borehole televiewer surveys. Combining the borehole log information with the core sample information provides an estimate of the full core orientation.
- If one assumes that the same remanence direction is present in the same rock unit in a number of boreholes, then it is possible to solve for the true remanence direction (Figure 4). For this approach to be successful, each of the suite of boreholes must have different inclinations and dips. Solving for the true remanence direction is then equivalent to the common point approach used in the GPS position derivation. And again, just like the GPS solution, it is necessary to have a minimum of four boreholes (satellites).
- The magnetization in most rock samples consists of two phases, the hard remanence component and a viscous component that the rock has acquired over the past 100 000 years. By applying demagnetization techniques, it is possible to obtain an estimate of this viscous component relative to the core axis. If the location of the sample site is known (to the nearest 50 km), as well as the dip and dip direction of the borehole at the sample depth, and which way is up on the core, then it is easy to derive the true remanence direction (Figure 5). Sometimes the core sample can become remagnetized during drilling. It is possible to test for this situation by taking three specimens from the same core sample. When drilling-induced remagnetization is not present, the difference in angular position of the three specimens around the perimeter of the core must equal the measured dif-

ference in magnetic declination. Oil companies have used this approach for more than 20 years to orient core segments that might have been retrieved from great depth.

Direct approach: Borehole vector magnetic survey. Many borehole deviation probes use the Earth's magnetic field direction to provide the external absolute reference frame that is necessary for defining the local dip direction of the borehole. The fundamental assumption behind this application is that the orientation of the Earth's magnetic vector is uniform over the full length of the borehole. However, it must be remembered that the borehole magnetic survey involves two conditions that are never realized in standard suprasurface magnetic surveys. First, only in the borehole setting is the magnetic sensor situated within the magnetic source body. For all ground and airborne magnetic surveys, the source is below the sensor. Numerous studies have shown that on-hole and off-hole magnetic sources result in characteristically distinct magnetic anomaly patterns. In an airborne setting this would be equivalent to differentiating between 2D and 3D source body geometry. Second, in the borehole, the sensor-source distance is much smaller. Magnetic anomalies observed in a standard mineral exploration borehole will have amplitudes at least 5000 times those of the equivalent magnetic anomalies measured 100 m above the surface. In this configuration, the magnetic sensor is much more sensitive to changes in magnetic vector orientation.

In a borehole deviation survey, it is the directional property of the Earth's magnetic field that is of prime importance. Borehole deviation probes commonly use three orthogonally oriented fluxgate sensors. In terms of magnetic surveying, this means that these borehole probes measure the full vector magnetic data, not just the scalar magnetic field measured by the cesium vapor or proton precession magnetometers used in standard suprasurface surveys. At any instant in time during all types of magnetic surveys, the sensor package records the vector summation of contributions from four different magnetic sources: (1) the core, or IGRF, magnetic field; (2) the "diurnal," or transient magnetic field created by fluctuations in solar wind activity; (3) the induced magnetic field produced through interaction between the core magnetic field and the magnetic susceptibility of the rock mass; and (4) the remanent magnetic field component. Using a targeted data processing approach, it is possible to analyze the magnetic data acquired during a borehole deviation study to provide direct insight into the subsurface distribution of magnetic sources.

The IGRF contribution can be eliminated by fitting a first- or second-order polynomial to the data that removes the long wavelengths associated with this component. The transient magnetic field component is minimized through reference to a contemporaneously operating base station magnetometer. Contributions from off-hole magnetic sources have diagnostic signal characteristics allowing them to be identified. Magnetic susceptibility contrasts between adjacent strata produce fluctuations in the orientation of the observed magnetic vector. At the contact between two lithologies the magnetic vector will migrate between opposing magnetic vector directions. When the contact corresponds to a magnetic remanence boundary the magnetic vector inside the new source body will represent a combination of the new body geometry, the Q-value and the orientation of the remanence vector. A simple approach to discriminate between induced and remanent magnetic sources can be achieved by testing the sense of correlation between the measured susceptibility and measured total magnetic field signals within sliding depth windows. Numerous authors have used this approach on Ocean Drilling Program to obtain in-situ magnetic reversal stratigraphy information (e.g., Roberts et al., 1997; Hayashida et al., 1999). When the Q-ratio is greater than 10, the observed vector near the center of a large source body will provide a direct estimate of the declination of the remanent magnetic vector.

When the rock strata are dipping, the borehole is inclined, or some combination of these two factors, it is possible to retrieve the true orientation of the magnetic vector by applying appropriate trigonometric rotations to the observed magnetic vector. Information regarding the orientation of geologic contacts can be derived from borehole televiewer surveys.

Conclusions. A number of possible approaches to obtain an estimate of the remanent magnetic vector in a rock unit are available. Clearly the requirements, knowledge base, and time commitment varies between each of the methods. The outcomes from the various methods are also quite varied, ranging from a simple estimate of what the remanent vector might be, to direct observation of both the magnetic vector and its spatial extent in a borehole. Each method is complementary.

The presence of remanent magnetization does complicate magnetic inversion. Taking the common Earth model approach, any approximation of the magnetic remanence vector derived from an inversion must be compatible with the known magnetic declination and inclination values for the given location at the appropriate geologic time provided by APWP paths. If the inversion approximated remanence vector significantly deviates from the APWP estimate, then further investigation is required. It is quite possible that this apparent error can be explained by failing to allow for tectonic-folding-related rotation of the magnetic vector. It must be remembered, however, that if the remanence vector for one segment of a fold is rotated then the remanence for the other segment of the fold must also be rotated but in the opposite sense.

Suggested reading. "Scaling behavior of magnetic susceptibility logs: examples from fractured and nonfractured granites" by Chan et al. (*EOS, Transactions*, AGU, 1999). "Magnetostratigraphy and relative paleointensity of late Neogene sediments at ODP leg 167 Site 1010 off Baja California" by Hayashida et al. (*Geophysical Journal International*, 1999). "Gravity and magnetic models of the Midcontinent Rift in eastern Lake Superior" by Mariano and Hinze (*Canadian Journal of Earth Sciences*, 1994). "Applications of gravity and magnetic surveys: The state-of-the-art in 1985" by Paterson and Reeves (GEOPHYSICS, 1985). "Relative paleointensity of the geomagnetic field over the last 200 000 years from ODP Sites 883 and 884, North Pacific Ocean" by Roberts et al. (*Earth and Planetary Science Letters*, 1997). "Magnetic anomalies over oceanic ridges" by Vine and Matthews (*Nature*, 1963). "Remanent magnetization and aeromagnetic interpretation" by Zietz and Andreasen (in *Mining Geophysics*, SEG, 1966). TLE

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