Borehole Magnetics: Magnetostratigraphy:
An example from UNAM-7, Chicxulub Impact Crater

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Summary

Magnetic reversal boundaries define global chrono-stratigraphic surfaces. As such, rapid identification of these boundaries is useful for constructing chronologically correct correlations and for defining fault displacements. Borehole deviation surveys which use a tri-axial fluxgate sensor to provide geographic orientation also contain a record of the variation of the vector magnetic field versus depth. When the crustal component of the observed vector magnetic field is dominated by remanence minor fluctuations in the orientation of the observed vector reflect the underlying magnetostratigraphy. UNAM-7 which was drilled on the periphery of the Chixculub impact crater, Yucatan peninsula, Mexico was logged using a standard deviation probe. Processing of this data revealed a magneto-stratigraphic reversal history that is compatible with the limited paleomagnetic database, the petrophysical data, and sedimentation rates as defined by results from other boreholes.

Introduction

The Chixculub impact crater underlying the northern portion of the Yucatan Peninsula, Mexico has been documented by numerous geological and geophysical mapping programs (Figure 1). According to Ebbing et al., (2001) the Chixculub crater has the morphology of a complex crater with a peripheral trough and central uplift. All complex craters are believed to evolve from an initial bowl-shaped transient impact cavity by processes that include: crater wall collapse, central uplift and isostatic rebound. Each of these crater modification processes involves rotation and / or vertical displacement of individual rock masses around the crater periphery.

If magnetic remanence acquisition predates tectonism then a record of the post-impact deformation should be present in the paleomagnetic record. To date most of the reported paleomagnetic studies from Chixculub have focused on establishing the age of the impact relative to the K/T boundary. Paleomagnetic studies of samples from the UNAM series of boreholes (Rebolledo-Vierya and Urrutia-Fucugauchi, 2006) and the ICDP sponsored Yaxcopoil-1 borehole (Rebolledo-Vierya and Urrutia-Fucugauchi, 2004) show that the base of the impact breccias is located within the Chron 29R of the magnetic reversal polarity timescale (Cande and Kent, 1995).

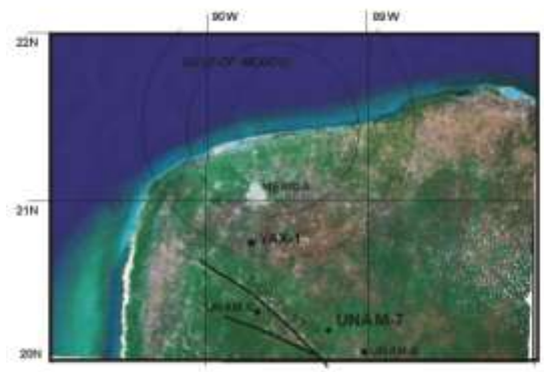

Figure 1 Location and geometry of the Chixculub impact crater and the position of borehole UNAM-7

Some evidence for post-impact fault displacement is available for the area outside the crater. The Chron 29R to Chron 29N boundary varies in depth from 282m in UNAM-6 to 222m in UNAM-7 and finally to 332m in UNAM-5 nearest to the crater. The same boundary in YAX-1 is found at a depth of 794m (Figure 1). To explain this marked change in depth of this chrono-stratigraphic boundary Stinnesbeck et al., (2004) proposed that YAX-1 penetrates "a single undisturbed megablock more than 600m thick, which tilted and slid into the crater basin essentially intact." However, because of the limited number of observations available it is not possible to fully investigate the geometry of other chronostratigraphic surfaces to verify this model. This is primarily related to the excessive amount of time required to process kilometers of weakly magnetized sediments. In this paper we describe an alternative, more rapid approach to documenting the depth distribution of magnetic reversal boundaries in boreholes. In this approach the magnetostratigraphy is derived from a vector magnetic survey of each borehole. Using data acquired from a survey of borehole UNAM-7 we first show how navigation data can be processed to provide magnetostratigraphy. Next we compare the magnetostratigraphy derived from a survey of UNAM-7 with other polarity records computed from borehole surveys and paleomagnetic studies of borecore. Sedimentation rates at UNAM-7 on the shoulders of the Chixculub impact crater are similar to those occurring in the immediately adjacent Gulf of Mexico.

This paper introduces a new approach to borehole magnetostratigraphy mapping based on a procedure whereby we extract the sequential change in the orientation of the observed magnetic vector versus depth from a magnetometer based borehole deviation survey. To better understand how it is possible to derive chrono-stratigraphic data from borehole deviation logs we develop a simple model approach. In a borehole survey it is possible to have two quite different source sensor configurations: a) off-hole sources in which the borehole never actually passes through the source, and b) on-hole sources where the borehole passes directly through the source body.

To better understand borehole magnetic signals we need to examine the effect of the vector addition of the core and crustal magnetic fields. Once inside the magnetic source body the orientation of the magnetic vector associated with the crustal induced field component will have an effective direction that is opposite that outside the source body. The actual direction of the induced field is also dependent on the geometry of the source body. For near flat-lying sediments as found at Chixculub the induced field inside a source body is near vertical and pointing upwards.

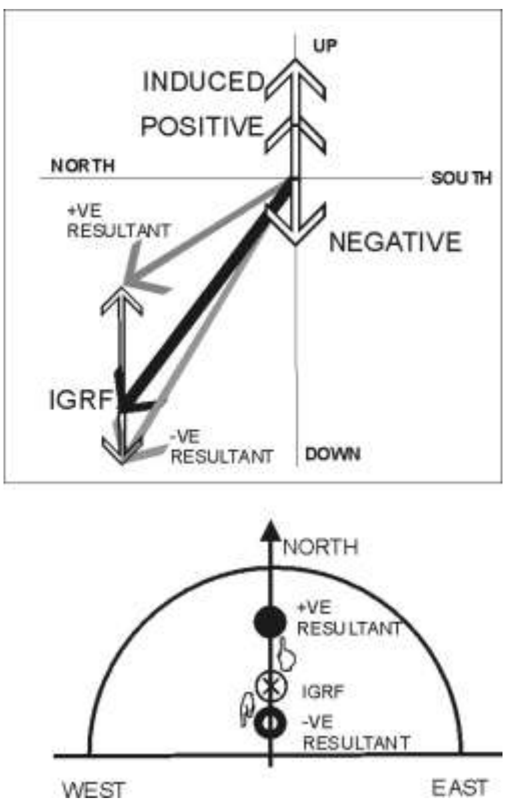

Figure 2 a) Diagrammatic representation of vector summation of induced and remanently magnetised crustal field components with core magnetic field. b) Stereonet representation showing the effect of vector addition on the observed magnetic inclination.

The field contribution associated with remanent magnetization is dependent upon the time of remanence acquisition, the geometry of the source body, and the presence of any post remanence acquisition tilting of the source body. For the Chixculub location the problem of remanence is simplified since the paleolatitude during the Cretaceous is similar to the Present Earth's field direction, and the strata are flat-lying. Any Normal polarity remanent magnetization will also produce an upward directed near vertical magnetic vector, adding to the induced field component (Figure 2a). A Reversed polarity remanent magnetization as seen from inside a source body will produce a downward directed near vertical magnetic. In summary, any incremental increase in susceptibility will produce an increase in the magnitude of this near vertical vector (Figure 3). The presence of remanently magnetized normal and reversely polarized magnetostratigraphy is defined by changes in the sense of the source body vector contribution.

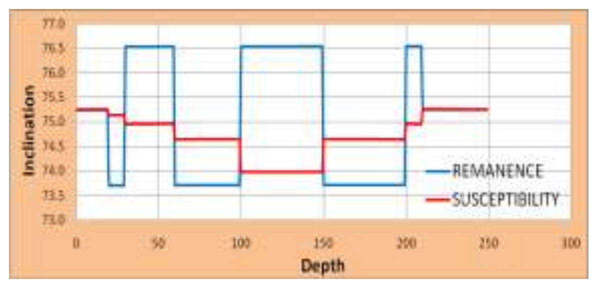

Figure 3 Diagram to show the effect of increasing magnetic susceptibility and alternating normal and reversed polarity remanence on the observed magnetic vector.

Assuming a simple North directed core magnetic vector and a remanent magnetization that has the same normal direction as the inducing field, will produce a reduction in the magnitude of the inclination of the observed magnetic vector (Figure 3). A reversed polarity remanence will produce a shift towards steeper magnetic inclination. Therefore differences in susceptibility and remanence should primarily produce a small spread in the observed inclination values (Figure 2b). The presence of reversed polarity remanence will always have the least influence on the inclination of the observed vector for two reasons. First, unless the remanence vector is very strong and has a direction that is strongly divergent from the IGRF field direction the resultant vector will always be close to the orientation of the core or (PEF) magnetic field. Second, the presence of reverse polarity remanence and induced field in the same source body will act in opposition to produce a composite reduced magnetic source signal.

In an ideal situation subtracting the known core / IGRF vector field from the individual observed vector field should produce a direct separation of the normal and reversely polarized zones. Normal polarity zones should have northerly directed residual vectors, while reversely polarized zones should have southerly directed residual vectors. For real data, which will always include some noise this simple model is complicated by limitations of the process. First, we may not know the actual orientation and magnitude of the core / IGRF field vector at the study site. It may differ from the global scale IGRF estimated value as a result of some localized magnetic field contribution. In this situation one could use the tilt corrected average vector direction calculated from all of the individual observations. The computed mean vector will be referenced to local geomagnetic field declination. Second even in the absence of any remanence one is still going to have a smear of inclination values that is a direct reflection of susceptibility fluctuations. This is similar to the DC shift problem identified by Williams (2006). Simple tests that might discriminate between susceptibility and remanence related field changes could involve comparing the interpreted polarity signal with known susceptibility record from the borehole, or with known local polarity record as established by a full paleomagnetic study. Hence, some care is needed in not misinterpreting the significance of the observed residual declination changes produced by this method.

Data Corrections

Two logs of borehole UNAM-7 were recorded. The down-hole survey was logged at twice the rate used for the up-hole survey. Data from each sensor package must be corrected for any inherent errors. Errors addressed in this step include any differential offset and gain response between the three fluxgate sensors and between the two tiltmeter sensors. Additional corrections are applied for any non-orthogonality. The second step involves use of the full magnetic vector to compute the 3D geometry of the borehole at each observation point. The third step, knowing local borehole geometry it is possible to compute the orientation of the observed complete magnetic vector relative to the local horizontal, and relative to geomagnetic north. Without independent external reference orientation it is not possible to derive the declination difference between magnetic and geographic North. For non-vertical holes it is possible to isolate portions of the borehole log where the observed magnetic vector is not dominated by the core / IGRF field component. With a constant reference field direction any rotation of the probe as defined by the tiltmeters must be matched by an equal rotation as defined by the fluxgates. The fourth step is equivalent to a standard IGRF correction where one subtracts the core magnetic field contribution to produce a residual that maps the crustal magnetic field. In a borehole setting an IGRF correction is a vector subtraction, not a simple scalar as in standard TMI surveys. The end product is a record of apparent magnetic vector orientation and magnitude versus depth.

Results

Converting the magnetic component data to polar coordinates reveals that the log contains a sequence of dramatic 180^{o} declination shifts (Figure 4). The more slowly acquired up-hole log differs from the down-hole log especially over the depth interval from 150 to 180m. The up-hole log gives a more consistent pattern with some minor fluctuations. It is believed that these changes in residual declination correspond to magnetic polarity changes in the sediments. The pattern we observe is identical to what we expected with our predicted model.

Discussion

Does this repeatable declination pattern then actually represent a record of magnetic polarity fluctuations versus depth? In the absence of any direct paleomagnetic sampling to directly verify this interpretation we need to look at indirect approaches to testing this hypothesis. We can simplify this problem by observing that for Hole UNAM-7 there is no reason to believe that there are any significant off-hole sources since the stratigraphic section covered by this study is all in near flat-lying sediments. Strongly magnetic horizons associated with the impact breccias are below the depth limit of surveyed in UNAM-7.

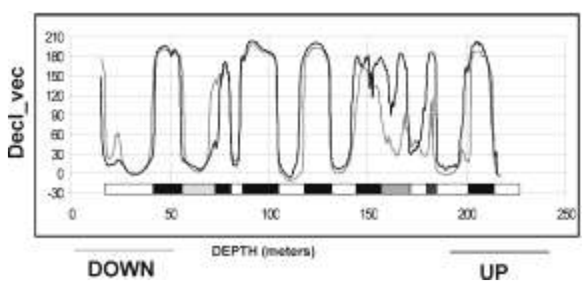

Figure 4 Plot of declination change versus depth for up and down hole logs from borehole UNAM-7. Up-hole survey was acquired at half the speed used in the down-hole survey.

All previous stratigraphic and petrophysical data available for this portion of UNAM-7 does not suggest that there are any significant lithology changes that could explain the observed pattern. Susceptibility logs derived from a study of the borecore material covered by this study has very low magnetic susceptibility with no apparent correlation with the declination data (Urrutia-Fucugauchi et al., 1996). A total gamma log of UNAM-7 indicates suggests existence of a lithological zonation that probably originates from minor fluctuations in potassium content, but again there is no similarity in the pattern between the declination and total gamma logs.

Previous paleomagnetic studies of core samples from UNAM-7 by Rebolledo-Vierya and Urrutia-Fucugauchi (2006) report that geomagnetic polarity zones Chron 29R to 28N corresponds to a 15m interval in UNAM-7. Based on the depths assigned to the borehole logs Chron 29N begins at 222.2m, while Chron 28N begins at 211.2m. The deepest point logged in this survey was 217m below the surface.

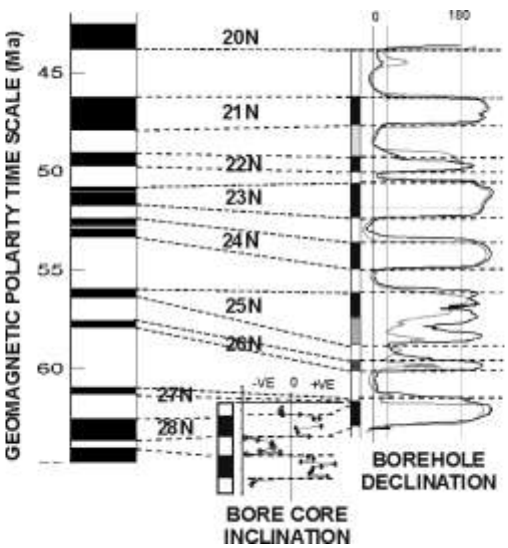

Figure 5 Comparison of magnetic reversal stratigraphic record as interpreted from borehole magnetic log of UNAM-7 and reference Geomagnetic Polarity Time Scale. Results of paleomagnetic study of core samples from UNAM-7 are used to establish reference point for matching borehole and reference polarity scales.

Assuming that these two surveys are using the same depth calibration routine then the base of this borehole survey should approximate to the transition between Chron 28R and the base of Chron 29N at 216.8m in the borehole log. Figure 5 shows that at approximately 213m our logs show a transition from a northerly directed to a southerly directed residual vector. We interpret this as suggesting that the basal anomaly recorded in these logs corresponds to Chron 28N identified in the borecore samples. Further confirmation of the validity of this log is provided by results from IODP study of borehole 1001A which is located to the east of the Yucatan Peninsula (Louvel and Galbrun 2000). Knowing the depth of each chrono-stratigraphic boundary it is possible to use this information to compute sedimentation rates. The rates defined by logs UNAM-7 and ODP-1001A are very similar as might be expected on a broad carbonate bank. However, the elevations of each chrono-stratigraphic boundary relative to local sea-level are quite different.

Conclusions

Borehole deviation surveys that employ a magnetometer sensor package to provide an absolute geographic reference orientation contain a record of the variation of magnetic properties versus depth. The tri-axial fluxgate sensor that is used in the magnetometer package provides a record of the variation of the orientation of the vector magnetic field versus depth. The orientation of the magnetic vector at any point in the borehole is a summation of Core and Crustal magnetic field contributions. Stratigraphic tied variations in magnetic susceptibility and remanence create changes in the orientation of the observed magnetic vector. In special situations where the Crustal magnetic field contribution is dominated by changes in magnetic polarity it is possible to derive a record of magnetostratigraphy from the borehole deviation logs.

Independent multiple surveys of borehole UNAM-7 located on the periphery of the Chixculub impact crater, Yucatan Peninsula, Mexico reveal a repeatable pattern of declination fluctuations. Computer modeling of a near flat-lying sequence demonstrates that this pattern is explainable by magnetic reversal stratigraphy. The polarity time scale derived from the borehole log is in agreement with paleomagnetic sample data from UNAM-7 and with the polarity time scale and sedimentation rate defined by logs from ODP 1001A.

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EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2008 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

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