High Resolution Magnetic Studies of the Magnetization of Oceanic Crust.

Maurice A. Tivey
Dept. of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA, 02543-1542.

Abstract Magnetic field profiles obtained by the deep submersible *SHINKAI 6500* are analyzed at two lithologically and morphologically contrasting sites located on the southern wall of the Kane transform which offsets the Mid-Atlantic Ridge in the North Atlantic. At the western ridge transform intersection (RTI) of the Kane and Mid-Atlantic Ridge, the exposed crust is primarily composed of extrusives and upper intrusive rocks. In contrast, only deeper crustal rocks and upper mantle are found exposed at a mid-transform transect of the south wall of the transform. Magnetic profiles show that both regions exhibit crustal magnetization that can give rise to the lineated magnetic anomaly reversal patterns.

Introduction

Submersible studies are of great use in the study of oceanic crustal magnetization and can provide unique insight into the structure and architecture of oceanic crust. The following paper presents results of a detailed submersible survey of oceanic crust formed at the slow spreading Mid-Atlantic ridge that is exposed in cross-section at a fracture zone. In 1994, a joint submersible dive program between the Japanese Agency for Marine Science and Technology (JAMSTEC) and Woods Hole Oceanographic Institution (WHOI) was undertaken to survey the western intersection of the Mid-Atlantic Ridge and Kane fracture zone (WMARK) using the Japanese deep diving submersible *SHINKAI 6500*. The WMARK program consisted of fifteen dives divided between two major objectives: seven dives surveyed the ridge-transform intersection (RTI site) while the remaining eight dives mapped the transform valley (Transform site) from the south wall (Figure 1) to the inside corner high on the north side of the transform adjacent to the spreading axis. On-bottom submersible magnetic field data were obtained by two fluxgate magnetometers mounted to the front of the submersible. In-hull gravity measurements were also made using a land meter at various fixed stations on the seafloor. In addition to geophysical measurements, geological mapping and observations, approximately 95 rock samples were obtained by *SHINKAI 6500*. These samples were measured for their paleomagnetic properties.

At the western RTI, the neovolcanic axis leading up to the ridge-transform intersection is marked by a very strong central anomaly magnetic high (CAMH) in the sea surface magnetic data. The CAMH is typically found associated with the spreading axis and the most recent lavas. This neovolcanic zone is found to continue right up to the transform fault and turns eastward along the trace of the transform for a distance of approx. 2 km. This hooked ridge morphology is a common feature of the crust found on the outside corner of a spreading axis and transform domain intersection. Submersible magnetic profiles show that this hooked neovolcanic ridge is highly magnetized similar to the axial volcanic ridges of normal midocean ridge segments. This is also supported by rock magnetic measurements which show a mean natural remanent magnetization (NRM) of 17.5 A/m for the sampled extrusive rocks. The principal zone of deformation of the transform fault at the RTI is very tightly defined, to less than a few hundred meters. The older crust (chron 5; 10.5 Ma) that comprises the south wall of the Kane fracture zone are composed of massive basalt, dolerite

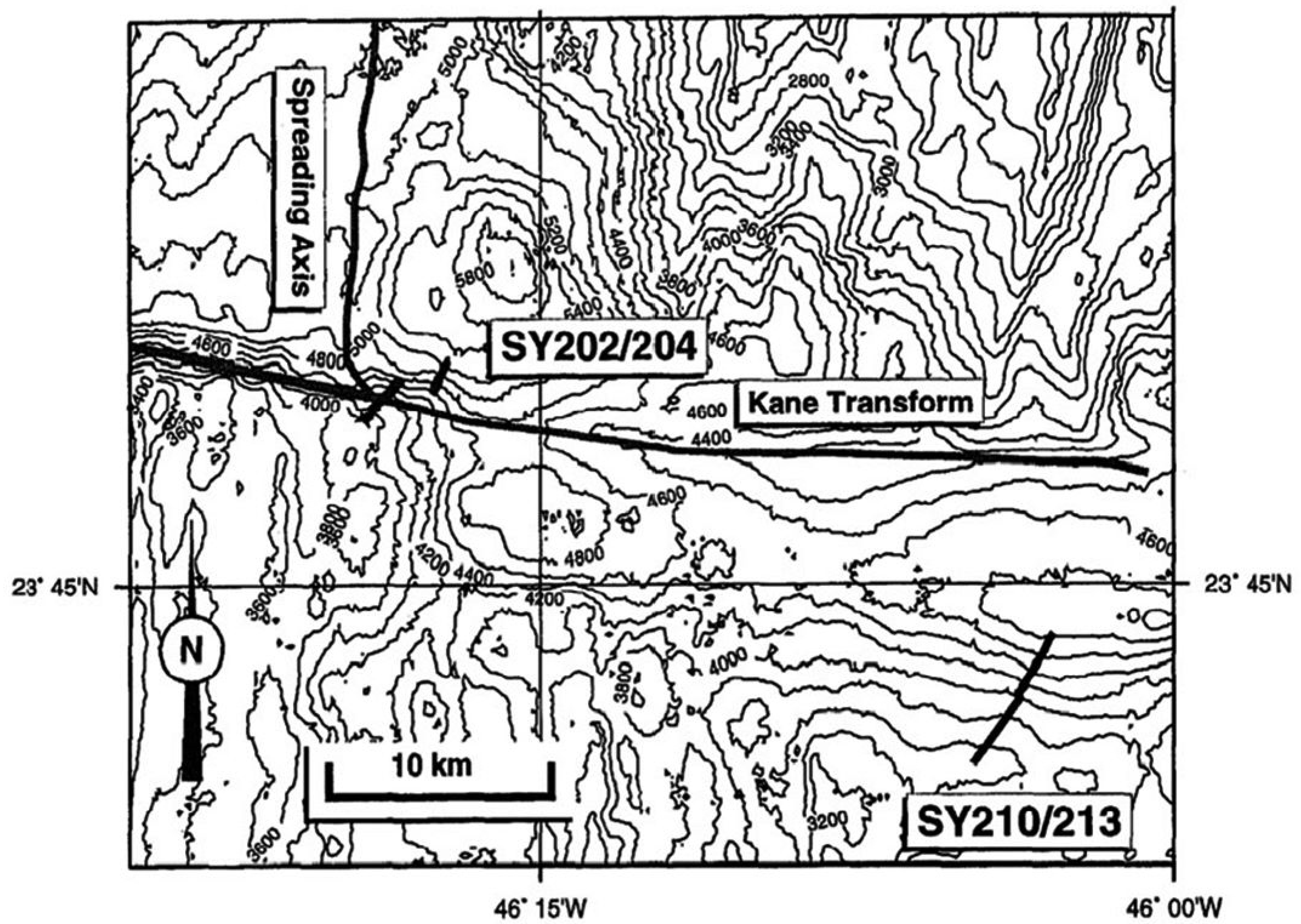

Figure 1 Bathymetry map of the western end of the Kane transform in the North Atlantic showing the location of SHINKAI 6500 dive transects (Black lines) that cross the south wall of the Kane transform zone. Grey line marks the ttrace of the active transform and the axis of spreading as indicated.

and basaltic breccia. No indications or samples of gabbros or other lower oceanic crustal rocks were seen or sampled. The mean NRM of rock samples collected from the south wall is 4.1 A/m, which is consistent with studies of aging of crustal magnetization [Johnson and Pariso, 1993].

The second survey, at the Transform site (Figure 1), was located on the south side of the Kane transform in younger crust than the RTI site. Crustal exposures at this location were dominated by serpentinized peridotites with a mean NRM of 0.98 A/m. These two lithologically contrasting regions provided an opportunity to investigate the magnetic response of these different crustal sequences using the recently developed method, of vertical magnetic profiling.

Methods and Analysis

The vertical magnetic profiling analysis approach, outlined in detail by Tivey [1996], employs a rotation of the survey geometry such that the scarp face is rotated into a horizontal plane by an amount equal to the scarp angle. By making the reasonable assumption that oceanic crust is horizontally stratified, these crustal units rotate to become dipping tabular bodies dipping at an angle equal to the scarp angle in the new geometry. The magnetic field vector is likewise rotated into this new geometry. The magnetic field data in this rotated reference frame can be interpreted in terms of dipping, semi-infinite tabular bodies for which there are analytical and Fourier transform solutions [e.g. Gay, 1963; Pederson, 1978]. The magnetic field collected up the scarp face can also be inverted for crustal magnetization by making the assumption that the dipping bodies extend to effectively infinite depth. Figure 2 shows a forward model for a north facing scarp slope at the Kane fracture zone with a positively magnetized unit overlying a relatively non-magnetic unit. The figure shows that a strong magnetic anomaly is expected. Inversion of the model recovers the appropriate magnetization.

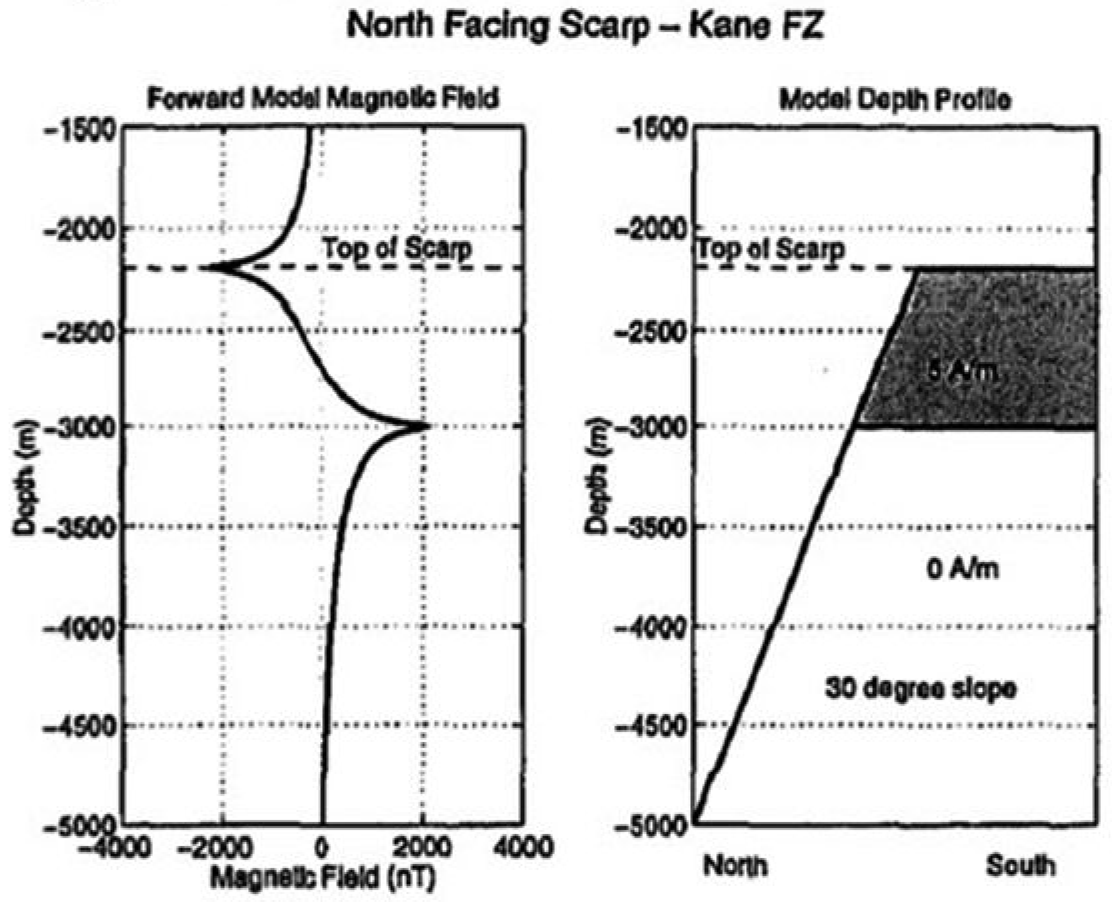

Figure 2 Forward magnetic model of a north-facing scarp slope with a scarp angle of 30° and a magnetic inclination of 45° simulating the effect of a magnetized layer in the Kane transform wall.

Results

We used the vertical magnetic profiling approach to analyze two sets of magnetic profiles collected up the north-facing scarp face of the Kane fracture zone. The first set of profiles (Dives SY202, SY204) were collected over crustal section exposed at the ridge-transform intersection, approximately 10.5 my. old (Figures 1 and 3). The scarp face has a slope angle of approx. 30 degrees and the regional magnetic inclination is approx. 45°. The magnetic data were first corrected for the effect of the submersible and then projected along a vertical cross-section of the scarp (Figure 3). The magnetic profile was inverted for crustal magnetization with the top of the scarp acting as a reference level with non-magnetic seawater. The magnetization profile shows an average of 3 A/m for the crust deeper than 4300 m and relatively non-magnetic crust above this depth (Figure 4). The magnetization amplitude is compatible with both inversion results of sea surface magnetic data over the same region and rock magnetic measurements.

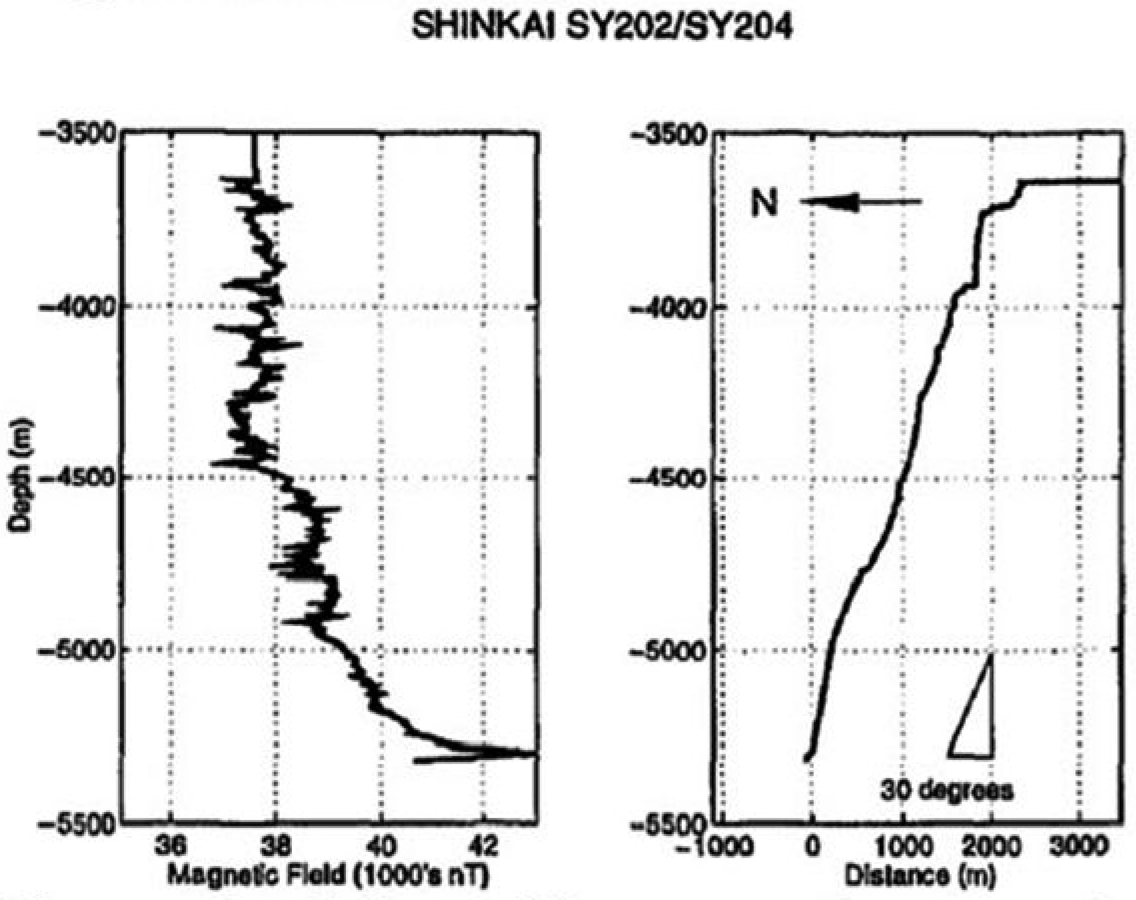

Figure 3 Submersible magnetic anomaly profiles (SY202/204) collected up the scarp face of the south Kane transform wall at the RTI site.

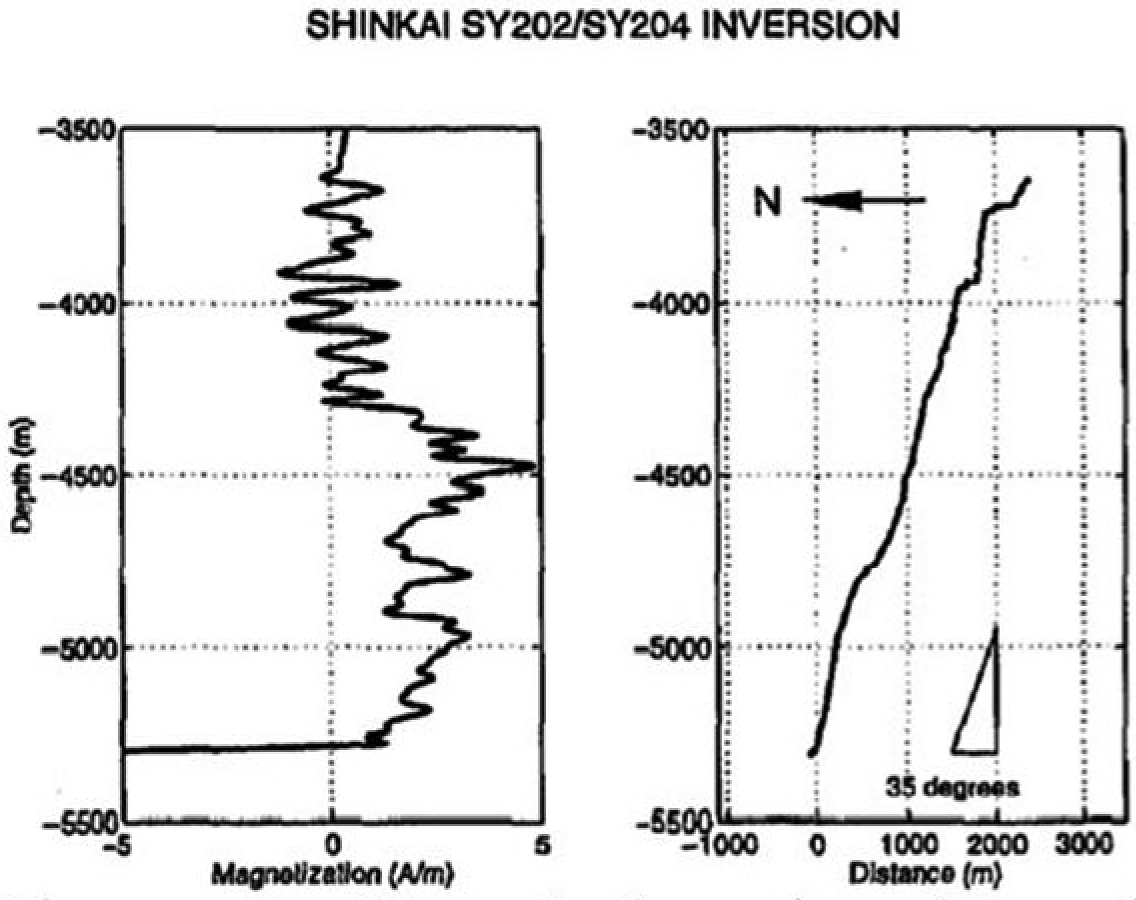

Figure 4 Magnetization inversion of SY202/204 scarp profile showing that the crustal section below 4300 m is generally more magnetic than the upper section.

At the transform site, magnetic field profiles from dives (SY210-SY213) were similarly processed and analyzed (Figure 5) for their crustal magnetization signal. The slope angle is only about 18 degrees, which is at the limit of the assumptions for the Fourier analysis techniques used in the vertical magnetic approach, so the result we have obtained must be treated carefully (Figure 6). The top of the scarp was not attained during the dives so that no zero reference could be obtained for the composite profile. The amplitude of magnetization is generally less than 5 A/m. A strong magnetization contrast is observed at 4200 m depth, which occurs within Dive SY210 and is not attributable to any overlap errors between the two dives.

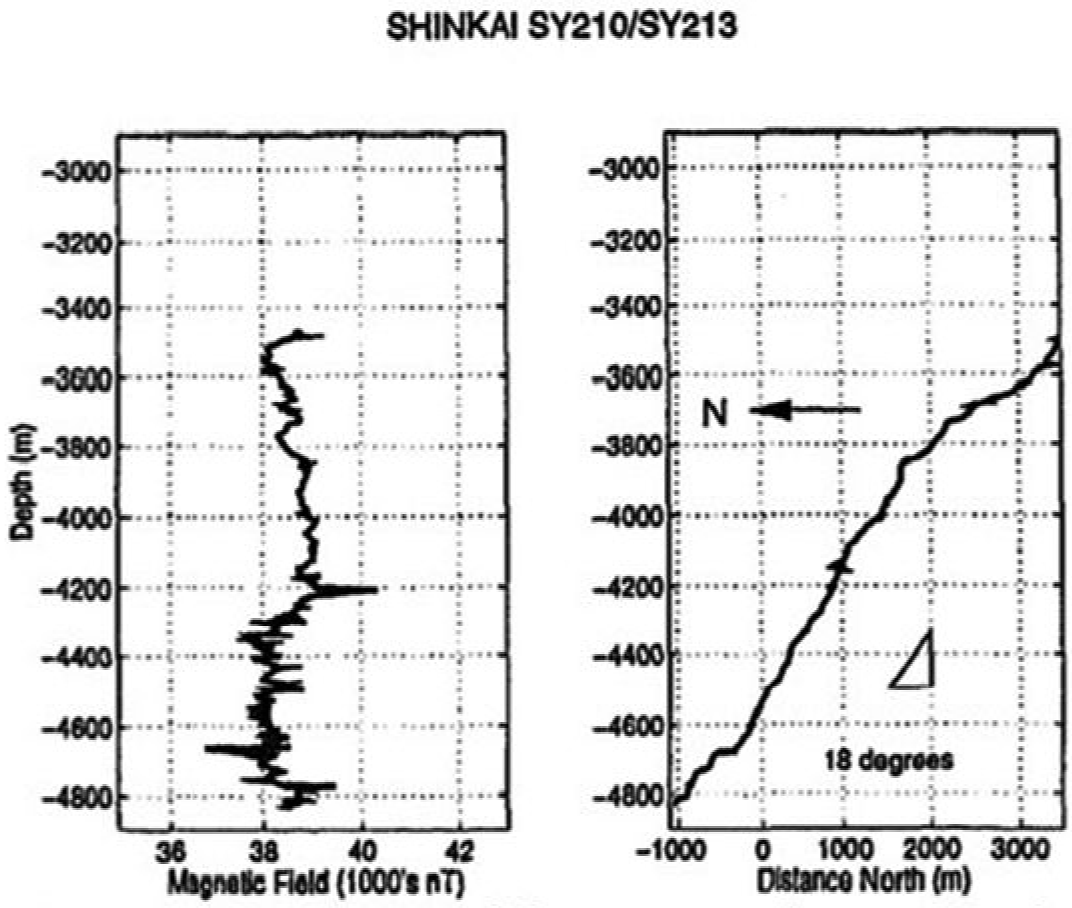

Figure 5 Submersible magnetic anomaly profiles (SY210/213) collected up the scarp face of the south Kane transform wall at the mid-transform site.

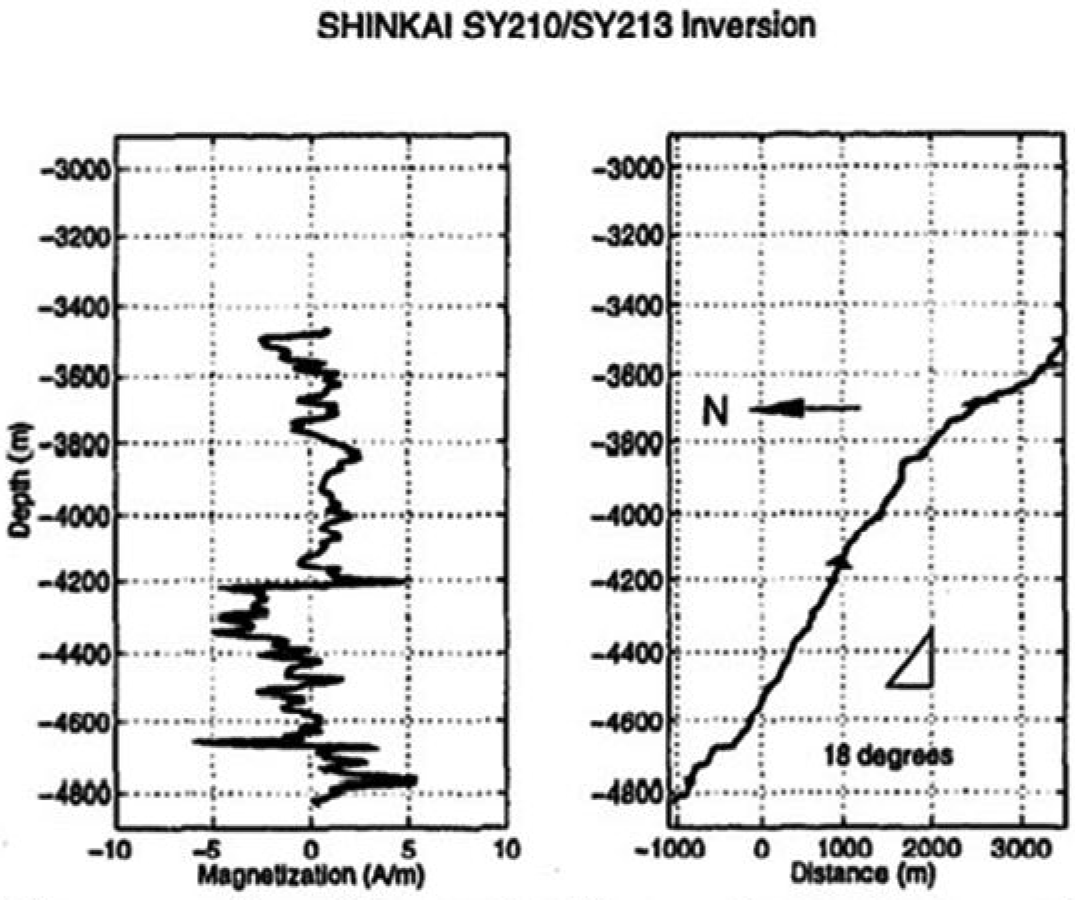

Figure 6 Magnetization inversion of SY210/213 scarp profile showing that the possibility of a polarity reversal at 4200 m depth.

Below 4200 m, magnetization is apparently reversed in polarity while above 4200 m magnetization is positive or near zero. Thus, a polarity reversal could have been encountered along this transect. However, because of a lack of zero reference, it remains ambiguous at this stage whether this transition is from near zero to strongly positive magnetization of from truly reversed polarity to weakly positive magnetization. From sea surface magnetic maps the dive transect does appear to be at the edge of polarity chron 4.

Discussion

In order to understand these results we undertook some forward modeling. This is particularly important for the scarps that form the walls of the Kane transform because they are known to be regularly interrupted by normal faults that step down into the transform [e.g. Wilcock et al., 1990; Auzende et al., 1994]. These normal faults can give a series of repeated crustal sections as the blocks form a progressively down-dropped series of blocks towards the transform valley, akin to a "slipped deck of cards". In the forward model, an upper highly magnetized crustal section is faulted three times producing three progressively deeper faulted sections (Figure 7).

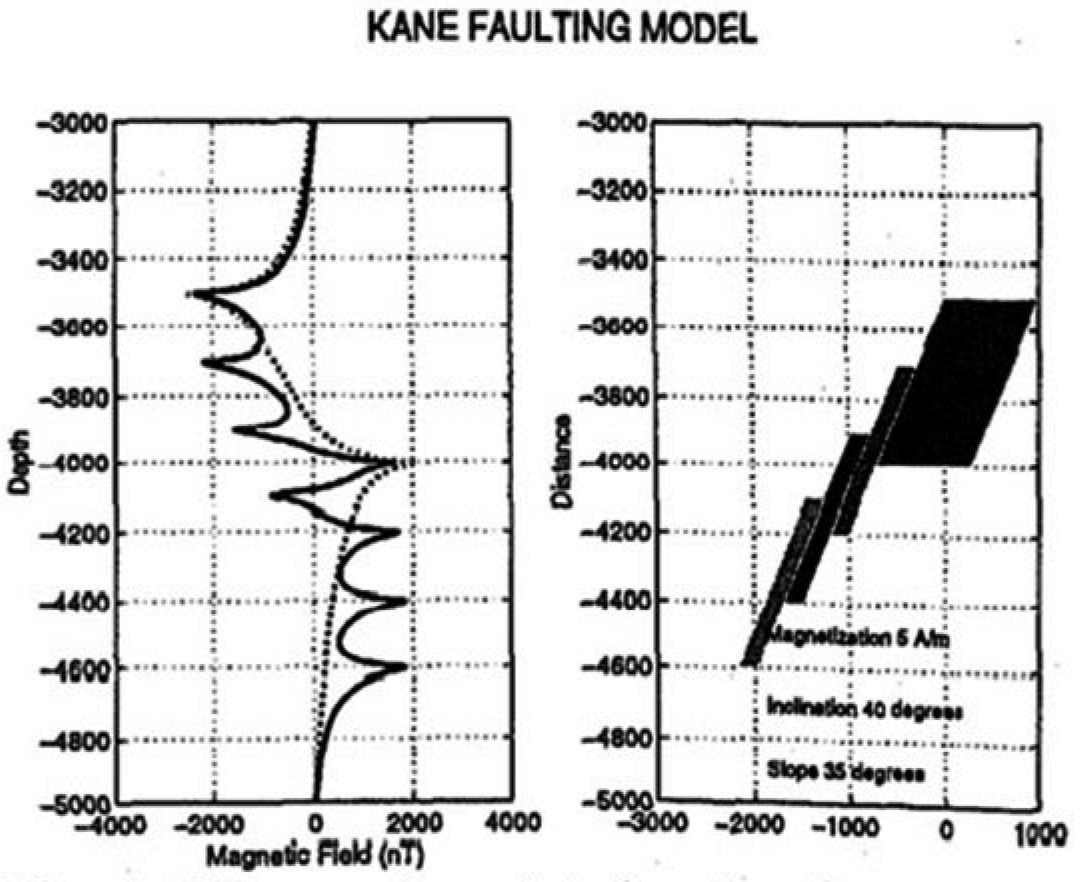

Figure 7 Forward model showing the effect of 3 slipped blocks upon the magnetic field. Dotted line is the magnetic response of the upper unslipped block alone.

From the submersible observers point of view, the lithology does not change over the section although fault zones and benches may be observed. The resultant magnetic field is shown for the upper magnetized unit alone and then for all the units (Figure 7). As can be seen from the forward model magnetic field, each slipped block produces a short wavelength anomaly with magnetic highs at the toe of each block and a low at the top of each block. The intact block at the top gives an overall longer wavelength signature. The forward model field was inverted for crustal magnetization using the VMP approach and is shown in Figure 8.

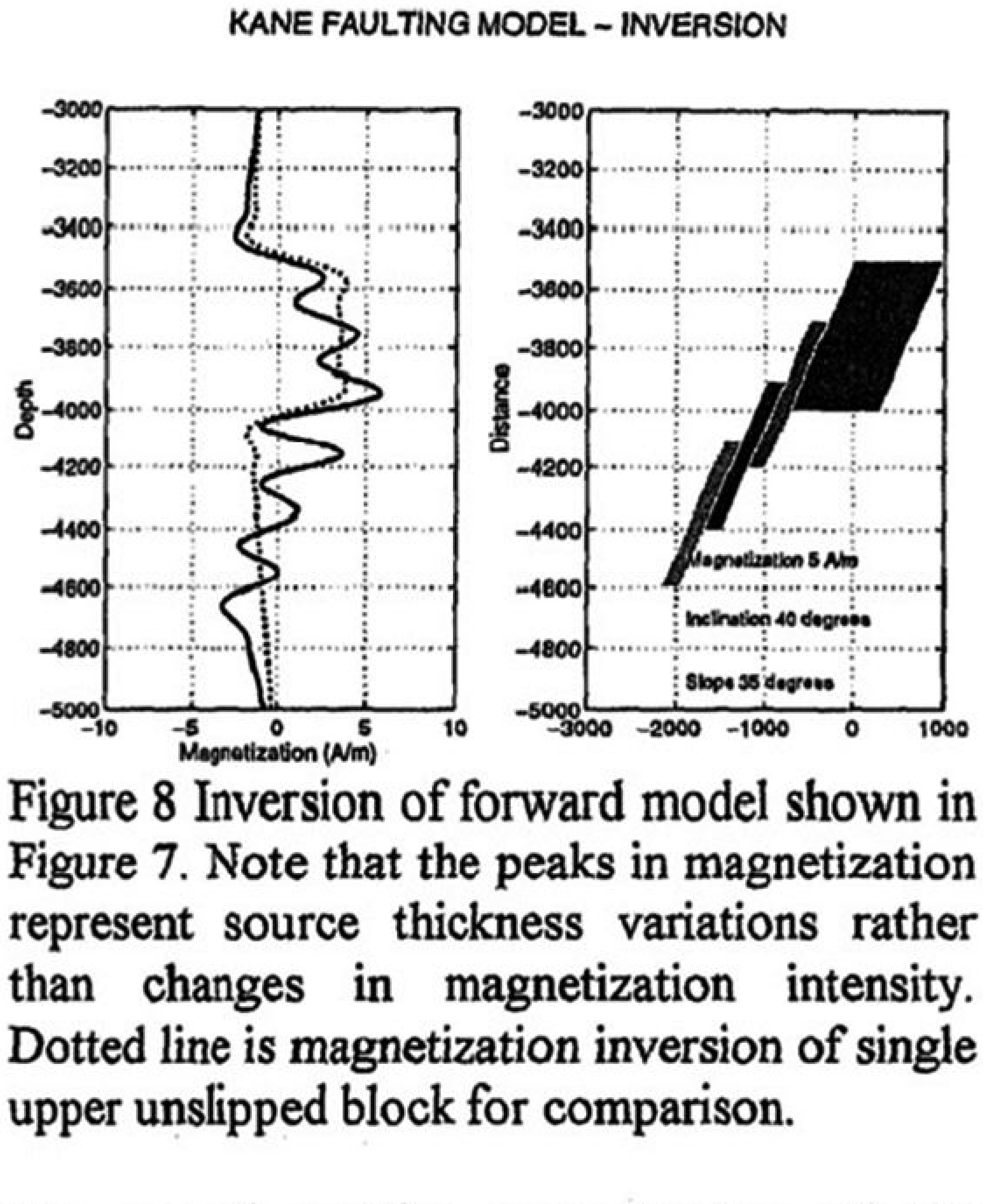

Figure 8 Inversion of forward model shown in Figure 7. Note that the peaks in magnetization represent source thickness variations rather than changes in magnetization intensity. Dotted line is magnetization inversion of single upper unslipped block for comparison.

The overall positive magnetization of the upper block is recognizable as a long wavelength positive zone, the slipped blocks give a slightly less intuitive result. The inverted model magnetization highs reflect the variable thickness of the source layer due to the overlapping of the blocks rather than any intensity difference in magnetization.

How do these models compare to the observed profiles? The Dive 202/204 transect magnetic field shows two positive rounded bumps between 4500 and 5000 m and a large spike at the beginning of the transect at 5300 m (Figure 3). From forward modeling, these anomalies would be interpreted as the top of a large magnetized block at 4450 m and the top of a faulted sub-block at 4800 m with a common base at 5300 m. Above 4450 m the anomalies show a repetitive sequence of short wavelength anomalies perhaps indicative of a highly faulted section. This view is supported by the submersible observations which find that above 4450 m, the scarp consists of a series of alternating outcrops with debris and talus fans indicating a highly faulted sequence. Below 4450 m, outcrops are not as profuse and the major breaks in slope appear to correlate quite well with the magnetic results.

Observations made during the Dive 210/213 transect show that while outcrops were very sparse, the first outcrops to occur were found at the same depth as the transition in magnetic field, i.e. at 4200 m depth. These outcrops were sampled and found to be serpentinized peridotite which from the magnetic field profile appears to have a relatively strong positive magnetization. The apparent reversed polarity below 4200 m depth is very intriguing. If indeed, these peridotite sequences are recording a magnetic polarity reversal this has important consequences for the source of the marine magnetic anomaly signal. Further studies are needed, however, to fully define this observation.

Conclusions

Vertical magnetic profiles over two morphologically contrasting portions of the southern scarp of Kane transform provide interesting insight into the structure of oceanic crust. The scarp in the western RTI region is highly faulted in the upper section with little or no magnetic signal while the deeper units are less faulted and have a magnetization intensity consistent with their age. No lithological differentiation is found and thus the magnetic signal contrast must be due to tectonic disturbance. At the younger transform wall site only serpentinized peridotite was recovered and yet crustal magnetization appears to be quite strong (3 A/m). This is compatible with the existence of a lineated magnetic anomaly sequence over the region as measured at the sea surface. If this magnetization is accepted then it could be speculated that a significant proportion of the source of the marine magnetic anomaly signal may reside in the deep crust and upper mantle.

Finally, why are the two areas so different morphologically? Both were formed on the inside corner of the eastern RTI of the Kane transform and Mid-Atlantic Ridge. It might be speculated that the crust of the south wall of the western RTI site formed during a period of robust magmatism that led to the neovolcanic reaching all the way to the active transform zone and building a substantial edifice [Pockalny et al., 1988]. In contrast, the more deeply exposed crust of the transform site is more typical of inside corner crust [Cannat et al., 1995]. The wall is displaced several kilometers from the principal transform displacement zone and exposes deep oceanic crust and upper mantle. The exposure of deep crust is generally attributed to the stripping away of the upper carapace by low angle faulting [Dick et al., 1981; Karson and Dick, 1983; Tucholke and Lin, 1994]. This may have been accentuated by a relatively quiescent period in magmatic activity.

References

Auzende, J-M, M. Cannat, P. Gente, J.P. Henriet, T. Juteau, J. Karson, Y. Lagabrielle, C. Mevel and M.A. Tivey, Observations of sections of oceanic crust and mantle cropping out on the southern wall of Kane FZ (N. Atlantic), Terra Research, 6, 143-148, 1994.

Cannat, M., C. Mevel, M. Maia, C. Deplus, C. Durand, P. Gente, P. Agrinier, A. Belarouchi, G. Dubuisson, E. Humler, and J. Reynolds, Thin crust, ultramafic exposures, and rugged faulting patterns at the Mid-Atlantic Ridge (22-24°N), Geology, 23, 49-52, 1995.

Dick, H.J.B., G. Thompson, and W. B. Bryan, low-angle faulting and steady state emplacement of plutonic rocks at ridge-transform intersections, EOS Trans. AGU, 62, 406, 1981.

Gay, S. Parker Jr. Standard curves for interpretation of magnetic anomalies over long tabular bodies, Geophysics, 28, 161-200, 1963.

Johnson, H.P. and J.E. Pariso, Variations in oceanic crustal magnetization: Systematic changes in the last 160 million years, J. Geophys. Res., 98, 435-446, 1993.

Karson, J.A. and H.J.B. Dick, Tectonics of ridge-transform intersections at the Kane fracture zone, Mar. Geophys. Res., 6, 51-98, 1983.

Pedersen, L.B., A statistical analysis of potential fields using a vertical cylinder and a dike, Geophysics, 43, 943-953, 1978.

Pockalny, R.A., R.S. Detrick and P.J. Fox, Morphology and tectonics of the Kane transform from Sea Beam bathymetric data, J. Geophys. Res., 93, 3179-3193, 1988.

Tivey, M.A. The vertical magnetic structure of ocean crust determined from near-bottom magnetic field measurements *Jour. Geophys. Res.*, 101, 20,275-20,296, 1996.

Tucholke, B.E. and J. Lin, A geological model for the structure of ridge segment in slow spreading ocean crust, J. Geophys. Res., 99, 11,937-11,958, 1994.

Wilcock, W.S.D., G.M. Purdy and S.C. Solomon, Microearthquake evidence for extension across the kane transform fault, J. Geophys. Res., 95, 15,439-15,462, 1990.