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Origin of the smooth zone in early Cretaceous North Atlantic magnetic anomalies

Masako Tominaga[1,2] and William W. Sager[1]

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[1] Late Jurassic-Early Cretaceous marine magnetic anomalies observed in the North Atlantic exhibit an abrupt change in character in M5-M15 crust. The anomalies are smoother with low amplitudes, and are difficult to correlate among nearby profiles. The accepted explanation for the origin of this smooth zone is diminished resolution and anomaly interference due to slow spreading rates, which narrows the widths of polarity reversals in the crust and causes interference among sea-surface anomalies. Magnetic modeling of these anomalies indicates that neither slow spreading rates alone nor slow spreading rates in combination with a decrease in geomagnetic field intensity can explain the basic character of the smooth zone. Combined with other geophysical evidence, our study suggests that one consequence of slow spreading rates that is responsible for the magnetic "smooth zone" is a thinned crustal basalt layer or a non-basaltic magnetic source layer resulting from low melt supply during a period of ultra-slow spreading. **Citation:** Tominaga, M., and W. W. Sager (2010), Origin of the smooth zone in early Cretaceous North Atlantic magnetic anomalies, *Geophys. Res. Lett.*, *37*, L01304, doi:10.1029/2009GL040984.

1. Introduction

[2] Linear magnetic anomalies are nearly ubiquitous in the ocean basins. These anomalies are attributed to the recording of the contemporaneous magnetic field by the upper oceanic crust. The remarkable consistency of anomaly shapes and spacing has allowed magnetic anomalies to serve as the basis for models of the geomagnetic polarity reversal sequence. However, in some places the magnetic anomalies are not so regular and clear. One such area is the magnetic "smooth zone" in the middle of the Late Jurassic–Early Cretaceous anomalies (M-anomalies) of the North Atlantic.

[3] This zone ("Atlantic M-anomaly Smooth Zone" or AMSZ) is located between M5 and M15 on conjugate sides of the Mid-Atlantic Ridge (MAR) and has been known for more than three decades [e.g., *Schouten and Klitgord*, 1977] (Figure 1a). Previous magnetic studies suggested that the origin of AMSZ was a decrease in spreading rate, which resulted in weak anomalies due to closely-spaced, polarity zones that induce overlapping, interfering magnetic anomalies [*Sundvik and Larson*, 1988]. This explanation is suspect because slow spreading elsewhere in the Atlantic has produced clear anomalies [*Vogt and Einwich*, 1979]. Today we have a much improved knowledge of crustal formation in slow to ultra-slow spreading regimes, so it is appropriate to re-examine the origin of AMSZ. In this paper, we present an analysis of magnetic anomalies and an interpretation of other geophysical data to shed new light on the origin of the AMSZ and changes in the spreading regime of Early Cretaceous North Atlantic Ocean crust.

2. Background: Atlantic M-anomalies

[4] M-anomaly lineations are well mapped and coherent in much of the north Atlantic; they include the Keathley lineations, located east of North America (29°–38° N, 73°–60° W) and their conjugate, the Canary lineations, located west of Africa (10°–35° S, 30°–10° W) (Figure 1a). Compared with Pacific M-anomalies, those in the North Atlantic are characterized by longer wavelengths due mainly to the superposition of anomalies from short chrons as a result of the slower spreading rates [*Larson and Pitman*, 1972]. Both the Keathley and Canary anomalies are clearly linear and consistent in shape between M0-M4 (6 m.y.) and M16-M21 (7 m.y.). In contrast, between M5-M15 (10 m.y.) and prior to M24 the anomaly shapes are less regular and amplitudes are weaker [*Vogt and Einwich*, 1979]. Also, M5-M10 (4 m.y.) only spans one fourth of the distance covered by M11-M15 (4 m.y.) (Figure 1), indicating that there was a change in tectonic regime within the AMSZ, with the slowest spreading between M5 and M10.

[5] The true extent of the AMSZ has remained undefined. The smooth zone was originally recognized between M5-M15 [*Larson and Pitman*, 1972] in the Keathley lineations where anomaly character does not closely resemble the contemporaneous anomalies in the Pacific. *Schouten and Klitgord* [1977, 1982] correlated anomalies in the AMSZ based on Project MAGNET aeromagnetic data; however, the anomalies showed less correlatability and repeatability relative to anomalies outside of the AMSZ. The AMSZ is also recognized between M5-M14 in the Canary Basin [*Hayes and Rabinowitz*, 1975]. There, the anomaly character is slightly more muted compared with the Keathley lineations due partly to the greater basement depth [*Ranero et al.*, 1997]. In this study, we define the AMSZ as occurring between M5-M15, based mainly on changes observed in the well defined Keathley lineations.

[6] Seismic studies have defined changes in basement topography, crustal structure and thickness, and mantle velocity gradient in the middle of the AMSZ (Figure 1b) [*Grow and Markl*, 1977; *Lizarralde et al.*, 2004]. Basement topography shows a transition from smooth to rough at around M11 in the middle of the AMSZ, observed in both

[1]Department of Oceanography, Texas A&M University, College Station, Texas, USA.
[2]Now at Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA.

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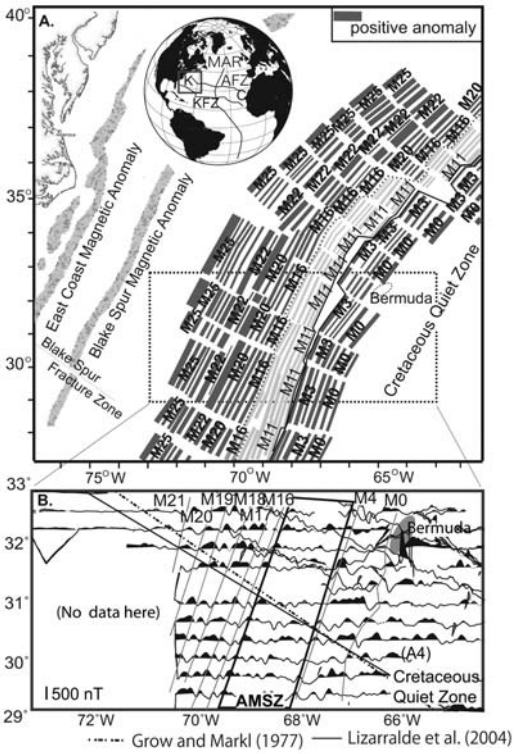

Figure 1. (a) Map of the North Atlantic M-anomaly lineations (modified from *Schouten and Klitgord* [1977]). The square on the globe shows the area of this map; MAR is Mid Atlantic Ridge, AFZ is Atlantis Fracture Zone, KFZ is Kane Fracture Zone. K is Keathley lineations, and C is Canary lineations. Lighter gray bands indicate positive anomalies with lower amplitudes and smoother character. The black dotted lines show the old end of the AMSZ, and the black solid lines show the bounds of the M5-M10 period. (b) Keathley M-anomalies analyzed in this study. Anomaly profiles are shown with positive anomalies (solid). Dotted lines indicate previously identified anomaly lineations [*Schouten and Klitgord*, 1982]. Profile A4 is compared to models in Figure 2. Two seismic lines mentioned in the text are indicated by solid [*Lizarralde et al.*, 2004] and hatched [*Grow and Markl*, 1977] black lines.

the Keathley and Canary crusts. Crust older than M11 displays smoother seafloor whereas younger crust shows rough, ~1.0 – 1.5 km topographic relief [e.g., *Grow and Markl*, 1977]. Seismic sections over crust older than M11 show a clear Moho and faulted lower crust and upper crust, suggesting stratified crustal structure, whereas these subsurface structures are not clearly observed in the younger crust [*Morris et al.*, 1993]. Together with decreasing spreading rates, this transition from smooth (older than the AMSZ) to rough topography implies a shift from magmatic-dominated spreading to tectonic-dominated extension in crustal construction at the MAR [e.g., *Lizarralde et al.*, 2004]. Abrupt lateral changes in bulk mantle seismic properties observed in crust younger than M11 indicate that retention and crystallization of melt occurred in the shallow mantle due to low melt extraction, resulting in ~1.4 km thinner crust than that prior to M11 [*Lizarralde et al.*, 2004]. The location of this transition is in the middle of the AMSZ. Seismic data acquired on the Canary side of the Atlantic shows several detachment faults, suggesting that lower crust exposure likely occurred within AMSZ crust between M11-M3 in the eastern north Atlantic [*Ranero and Reston*, 1999].

3. Methods: Anomaly Analyses

[7] We analyzed magnetic profiles from both the Keathley and Canary lineations. The Keathley magnetic profiles were evaluated in detail because they are covered by a comprehensive set of anomaly profiles. Previously, two sets of magnetic anomaly data were collected from the Keathley lineations, both with subparallel, east-west oriented track lines, nearly perpendicular to the magnetic lineations. One dataset of closely spaced aeromagnetic profiles collected by Project MAGNET [*Schouten and Klitgord*, 1977] is no longer available, so we used the other dataset of ship tracks, which consists of 37 km spaced lines collected during the 1967–68 USNS *Keathley* cruise (Figure 1b).

[8] We analyzed the magnetic lineations of the northern Atlantic crust from M0 to M25 by constructing polarity block models from a compilation of 7 Keathley (Figure 1b) and 4 Canary anomaly profiles (Figure S1 and Table S1).[1] Based on the correlation and identification of anomalies from previous studies [*Schouten and Klitgord*, 1982], we derived a polarity block model assuming that the correlated anomalies result from blocks of alternating polarity in the upper crust (Figure S1). A polarity block model was built for each profile using both inverse and forward modeling. Inverse modeling [*Parker and Huestis*, 1974] was used as an objective method to obtain a preliminary model of polarity zones (Figure S1). The inverse modeling outputs a magnetization distribution along the magnetic anomaly profile given a constant source layer and geomagnetic field direction for the magnetization. We used the computed magnetization distribution to make a preliminary estimate of the polarity boundaries. The locations of the polarity boundaries were then adjusted manually to improve the fit between the forward model and observed anomalies. A Gaussian smoothing filter was used in the forward modeling to give smooth, finite-width polarity transitions and a better match of calculated to observed anomalies (Figures S1 and S2).

[9] A polarity block model from each magnetic profile was normalized to the width of M0-M25 because different areas of the North Atlantic have somewhat different local spreading rates. Normalized locations of polarity boundaries were averaged to determine the average width of each polarity block in the M0-M25 span.

[10] For calibration, we used a polarity sequence derived from Pacific M-anomalies, which provides a detailed magnetic record because of the rapid spreading of Pacific crust (Table S1). We used our new model of the Pacific polarity sequence (M. Tominaga and W. W. Sager, Revised Pacific M-anomaly geomagnetic polarity time scale, submitted to *Geophysical Journal International*, 2008), which is not significantly different from previous, widely-accepted models. Polarity boundary ages for the averaged Keathley and Canary block models were then derived by assigning polarity boundary ages from the Pacific polarity sequence. Spreading rates for the Keathley and Canary lineations were

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL040984.

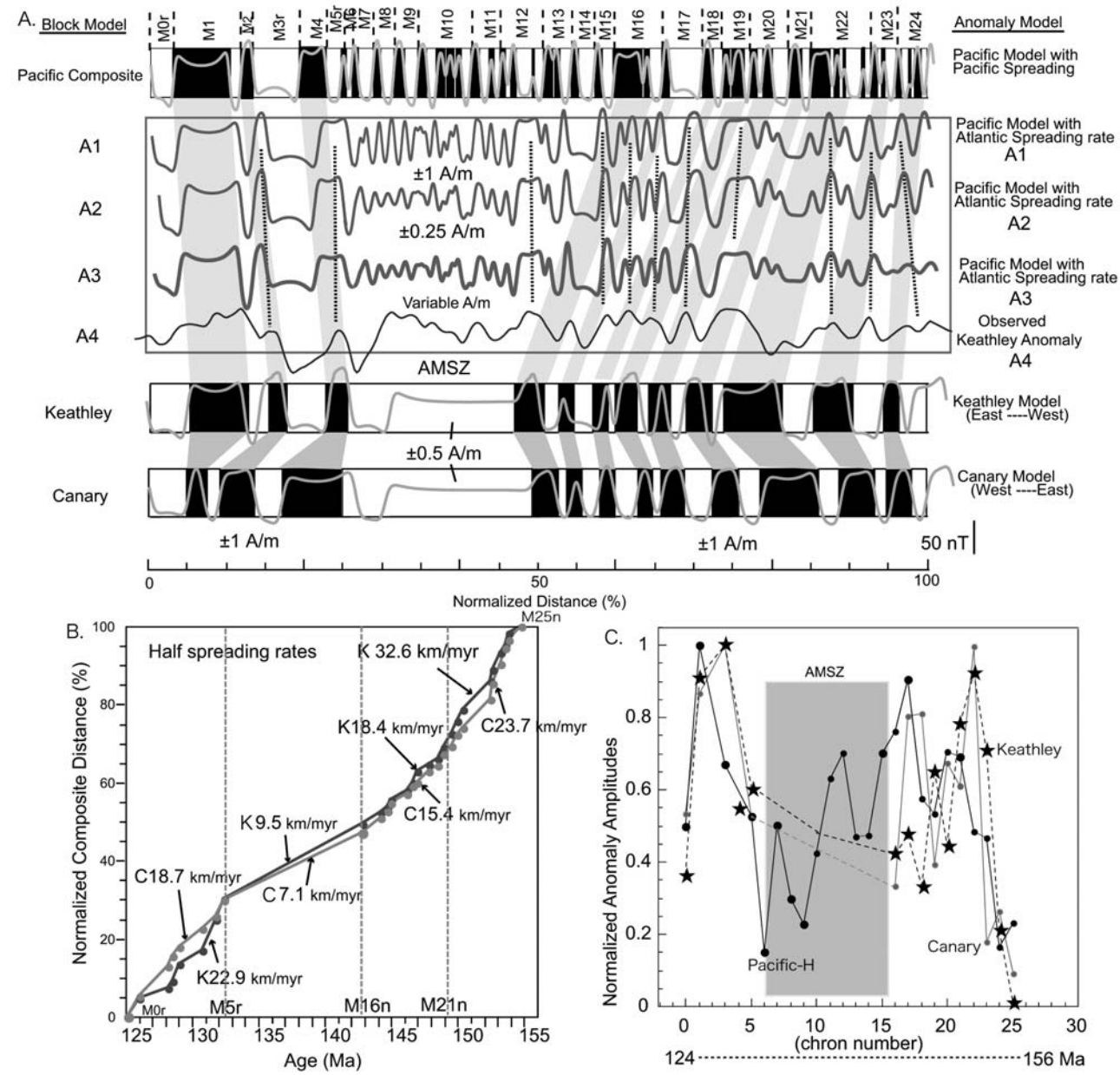

Figure 2. Results from anomaly analyses. (a) Normalized polarity block models built on the compilation of the Pacific, Keathley, and Canary anomalies (see text). The gray bands show the correlations of polarity blocks. The top block model represents the Pacific composite model. A1, A2, and A3 anomaly profiles show synthetic anomaly models calculated from the Pacific polarity model with the Keathley spreading rates and various magnetization values. A4 shows a representative observed magnetic profile from the Keathley lineation. The bottom two block models represent the Keathley and Canary models. Overlying anomaly profiles show synthetic anomaly models calculated from the block models. (b) Half-spreading rates for the Keathley (K) and Canary (C) magnetic lineations using the Pacific polarity model. (c) Normalized anomaly amplitudes plotted against chron numbers. The solid circles, stars, and gray circles indicate the Pacific (Hawaiian), Keathley, and Canary anomalies, respectively.

derived by computing age-distance curves from the averaged polarity block models (Figure 2b).

[11] Synthetic magnetic anomalies were calculated from these block models using 2D forward modeling with appropriate geographic parameters (i.e., ambient field direction and skewness factors). Depth to the source layer was derived from bathymetry along the magnetic profiles combined with observed sediment thickness (0.5–0.8 km). For simplicity, we assumed that the magnetic source is a homogeneously magnetized, constant thickness layer (1 km) with vertical polarity boundaries. For comparison, the Pacific model was computed and adjusted to the spreading rate of the Keathley lineations (Figure 2a).

[12] Normalized anomaly amplitude models for each of the Pacific, Keathley, and Canary lineation sets were derived from one representative, continuous observed magnetic profile from each of these lineation sets (Figure 2c). For each anomaly, we measured the peak-trough amplitude and

normalized by the maximum amplitude value in the magnetic profile from each lineation set. For comparison, we also computed similar models for Atlantic anomalies outside the AMSZ. Assuming that there were no wholesale changes in crustal chemistry, these amplitudes can be used as a crude proxy for geomagnetic field intensity [*McElhinny and Larson*, 2003].

[13] To test the effect of magnetization strength on the coherency of Atlantic anomalies, we calculated several synthetic anomaly profiles with different magnetization values (Figure 2a). These models are useful for investigating how changes in magnetization value affect the magnetic anomaly signature when the source layer is homogeneous and constant thickness. The first model used a magnetization value of 1 A/m because this provides a good match to anomalies outside the AMSZ. The second model used a magnetization of 0.25 A/m for the AMSZ to see if lower magnetization explains the observed low-amplitude anomalies. Another model was calculated using varying magnetization, derived from the curve of Pacific anomaly amplitude versus time (Figure 2c) to simulate possible geomagnetic field influence.

4. Results

[14] The polarity sequence for the Keathley and Canary models is similar for the M16-M24 period but is less similar for the M0-M4 period (Figure 2a).

[15] Paleomagnetic studies have suggested a long-term paleointensity-low during the period 120–160 Ma [e.g., *Tauxe*, 2006]. Both Pacific and Atlantic anomaly amplitude curves show synchronous peaks, trends, and transitions between peaks. They also show short-term variations but with overall the anomaly amplitudes low during this period (Figure 2c). Although spreading rates in the Pacific and Atlantic are different, the relative amplitude curves are consistent from one ocean crust to the other, implying a global geomagnetic field variation. Intensity increases from low values at M25 to a peak at M20; then decreases gradually between M20-M4, with values reaching a low of 20% of M25 amplitude at M6 before beginning to increase again. One of the causes of this weak magnetic field strength may be long transition widths during M5-M15 polarity reversals that reduced the overall field strength and smooth out anomaly shapes (Figure S2).

[16] Calculated Keathley and Canary spreading-rate curves show four distinct rates, similar to those recognized by *Sundvik and Larson* [1988] (Figure 2b). During the period M25n-M21n, average half-spreading rates were 32.6 km/Myr in the Keathley lineations (K) and 23.7 km/Myr in the Canary lineations (C). These were intermediate spreading rates, such as that observed on the modern Juan de Fuca Ridge (25–30 km/Myr half-rate). Average spreading rates decreased by a factor of two, 18.4 (K) and 15.4 (C) km/Myr, during M20r-M16n. In the AMSZ (M15-M6), the interpolated spreading rate dropped to 9.5 (K) and 7.1 (C) km/Myr; these are ultra-slow spreading rates (half spreading < 10 km/Myr) similar to those observed on the modern Southwest Indian Ridge (SWIR) [*Sauter et al.*, 2008]. Following the AMSZ, average spreading rate increased to 22.9 (K) and 18.7 (C) km/Myr, similar to the fastest of present MAR spreading rates.

[17] The synthetic anomaly profiles from the Pacific, Keathley, and Canary block models show obvious correlatability and repeatability of the M-anomalies in the M0-M4 and M16-M25 periods, but the Pacific model and the Keathley and Canary observed anomalies do not match the M5-M15 anomalies. Even using lower magnetization values for the M5-M15 anomalies still produces distinct anomalies in contrast to the observed anomalies (Figure 2a).

5. Origin of the AMSZ

[18] Previous interpretations of Atlantic M-anomalies suggested that the AMSZ correlates with a period of slow seafloor spreading [*Sundvik and Larson*, 1988], and our examination confirms this (Figure 2b). Although slow spreading can cause a reduction in anomaly amplitude and detail due to overlapping and interfering anomalies, our modeling shows that this does not explain the observed smoothed anomaly character (e.g., A4 in Figure 2a). Similarly, we have shown that a global geomagnetic reduction in field strength merely reduces anomaly amplitudes and doesn't explain the character of observed AMSZ anomalies (A3 in Figure 2a). Observed AMSZ anomalies are smoother than modeled anomalies, are not coherent from track to track, and have variable long-wavelength features (Figure 2a).

[19] These observations imply that there are other factors helping to cause the AMSZ.

[20] The effects of slow spreading accretion on the magnetic signal may be more than a simply compression of the polarity block sequence. In ultra-slow to slow spreading environments, a low melt supply results in the construction of a spatially heterogeneous crustal structure with thin or missing basaltic crust and lower crust exposed at the seafloor on long-lived low angle detachment faults [*Tucholke and Lin*, 1994]. The SWIR is one of the slowest spreading ridges with well organized crustal accretion, thin crust and exposed plutonic (gabbroic/peridotitic) basement [*Sauter et al.*, 2008]. At the modern slow spreading MAR crust between the Atlantis and Kane fracture zones, the same spreading center segment that created the AMSZ, extensive geophysical studies have been carried out showing many lower crustal exposures in various stages of growth formed by asymmetrically accreting ridges [e.g., *Escartin et al.*, 2008, Figure 1].

[21] In these spreading environments, both gabbroic and exhumed mantle rocks [*Cannat et al.*, 2006] can become the sole magnetic source. The gabbro layer typically has a weaker magnetization, with values as low as 25% of basaltic crust [*Sauter et al.*, 2008]. Exposed olivine-rich mantle rocks (i.e., peridotites) are also often serpentinized [*Cannat et al.*, 2006] which produces induced remanence magnetization that can contribute significantly to surface magnetic anomalies [*Tivey and Tucholke*, 1998; *Oufi et al.*, 2002].

[22] The relative abundance of basaltic crust and gabbroic and peridotitic rocks as the magnetic source can build a complicated magnetic source layer with a smaller effective magnetization values that result in low amplitude and complex anomalies. For the SWIR, the major transition from magmatic spreading with thick crust to amagmatic spreading with thinner crust and sporadic volcanic intrusions coincides with a decrease in full spreading rate from ~30 to ~14 km/Myr [*Cannat et al.*, 2006]. Although

anomalies are remarkably identifiable over the SWIR crust, anomaly amplitudes over gabbroic/peridotitic seafloor are lower than that of basaltic seafloor [*Sauter et al.*, 2008]. This crust shows zones with irregular crustal accretion patterns, detachment faults, the exposure of lower crust, and complex, low-amplitude magnetic signals compared to the young crust elsewhere.

[23] In this type of heterogeneous crust, magnetic carriers might have experienced multi-component magnetization indicating a later emplacement and/or cooling through successive polarity intervals [*Gee and Meurer*, 2002]. The juxtaposition of normal and reverse polarity rocks over short spatial scales can also attenuate coherency in magnetic signals.

[24] Furthermore, faults and associating crustal rotations in tectonically dissected crust at ultra-slow to slow spreading environments can lead to a less-coherent magnetic signature compared to crust formed at fast to intermediate spreading rate crust. This is because polarity reversal boundaries can be shallowly dipping and/or significantly overlapping in extrusive lavas, e.g., at hanging wall of core complexes. Also, polarity reversal boundaries within the lower oceanic crust can be shallowly inclined as described on the SWIR [*Allerton and Tivey*, 2001].

[25] Geophysical data suggest that the AMSZ is an area that has a number of slow spreading characteristics in crustal structure [e.g., *Grow and Markl*, 1977; *Morris et al.*, 1993; *Lizarralde et al.*, 2004]. Evidence of possible lower crustal exposure at the AMSZ is also inferred from seismic data acquired on the conjugate Canary lineation set of the AMSZ [*Ranero and Reston*, 1999]. If the AMSZ represents a period of amagmatic accretion and lower crustal exposure we would expect to see reduced coherency in the resultant sea surface magnetic signals. The AMSZ crust may be missing the extrusive lava section, may expose lower crust or upper mantle and thereby create a complex stratigraphy both vertically and laterally leading to weak and incoherent anomaly signals.

[26] In summary, we suggest that the causes of the AMSZ were both geomagnetic field behavior and a consequence of slow spreading. It is possible that a contemporaneous low intensity field with a minimum during the M5 to M15 period (143 to 132 Ma) contributed to the overall reduction of magnetic anomaly amplitudes over the AMSZ. However, this cannot explain the smoothed character and a lack of coherency of the anomalies. We suggest that observed slowing of spreading rates had two effects. First, closely-spaced interfering anomalies will reduce anomaly amplitude but again this appears unlikely to cause the lack of coherency. Second, crustal accretion patterns in slowly spread crust can lead to a transition from a magmatic-dominated crustal formation to tectonic extension, a thin or absent basaltic layer, and the exposure of gabbroic/peridotitic basement rocks, producing a less coherent magnetic source.

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W. W. Sager, Department of Oceanography, Texas A&M University, College Station, TX 77843-3146, USA.

M. Tominaga, Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA. (mtominaga@whoi.edu)