Collaborative Research: A deep-AUV magnetic and seismic study of the Hawaiian Jurassic crust - the global significance of Jurassic magnetic anomalies.

Introduction-Motivation

The geomagnetic field has varied in its direction and intensity throughout Earth's history on a variety of timescales. This behavior allows us to constrain not only the physical mechanisms required to generate a planetary magnetic field, but also allows us to use this past field history as a timescale to date geologic events. Marine magnetic anomalies, as recorded in oceanic crust, have played a central role in documenting Earth's magnetic field history, at least over the past 180 My. The oldest part of this record, the Jurassic Quiet Zone (JQZ), prior to 157 Ma (pre-M29 chrons), stands out as a unique period in terms of magnetic field behavior. While Earth's magnetic field has reversed polarity often in the past there are two prolonged periods during the last 180 My that show no obvious reversals. The Cretaceous Normal Superchron (CNS) from 84-124 Ma, is a well defined period of normal polarity during what appears to have been a period of strong field intensity (Biggin & Thomas, 2003; Tauxe et al., 2006). Reversal rate also appears to decrease into and then increase out of the CNS implying a long term changes in geodynamo behavior. The JQZ on the other hand, appears to behave quite differently. The JQZ appears to be a period when field intensity was decreasing rapidly (Cande et al., 1978; McElhinny and Larson, 2003), while reversal rate was apparently increasing. Based on new deep-tow magnetic results from the Japanese lineations in western Pacific Jurassic crust, we believe the lack of measureable anomalies in this oldest ocean crust record is a consequence of both weak field intensity and a high reversal rate. This deep-tow survey also found a period (162.5 to 167 Ma, Chrons M38 to M41) of apparently incoherent anomalies with short-wavelengths and anomalously low amplitudes called the LAZ or Low Amplitude Zone (Tivey et al., 2006; Tominaga et al., 2008). The LAZ is preceded by stronger anomalies that we believe represent polarity reversals. It is unknown if the LAZ is the result of local tectonic or crustal complications or if it truly represents geomagnetic field behavior, in which case it represents a unique period of geomagnetic field behavior when Earth's magnetic field was in a prolonged unstable, perhaps non-dipolar state. While terrestrial magnetostratigraphy provides some support for the rapid polarity reversal nature of the late Jurassic (M25-M38), there are no records of this LAZ behavior, although it would be difficult to verify this with terrestrial records alone because of the apparently incoherent nature of the field. The best way to test if the LAZ period is truly a globally significant event is to survey Jurassic crust formed at a different spreading center.

The main hypothesis we propose to address is: *Was the geomagnetic field behaving in a globally coherent way during the Mid-Jurassic?* We wish to verify if the LAZ period is a globally occurring phenomenon implying quasi-unstable field condition with possibly no fixed direction. To test this hypothesis we need to measure the marine magnetic record of Jurassic crust formed at other ridges to compare with the new Japanese magnetic lineation results. The western pacific Jurassic crust offers the best opportunity to obtain a coherent sequence of magnetic signals with three sets of magnetic lineations (Japanese, Hawaiian and Phoenix) converging on an area centered at 12°N and 160°E (Fig.1). The Japanese lineations were targeted by both aeromagnetic (Handschumacher et al., 1988) and deeptow magnetic surveys (Sager et al., 1998; Tivey et al., 2006; Tominaga et al., 2008) and provide the basis for comparison. The Hawaiian lineations offer the next best choice of obtaining a Jurassic anomaly record. Larson and Hilde (1975) used the Hawaiian lineations as the basis for their M-series magnetic anomaly correlations, which was subsequently extended to M25 and M29 by Cande et al. (1978); Nakanishi et al., (1989, 1992); and Channell et al. (1995). Similar to the Japanese lineations, the sea surface magnetic signal becomes difficult to correlate in the pre M25/M29 chrons of the Hawaiian lineations and the reasons are similar. The water depth is great (ca. 6000 m), the region is equatorial and so subject to greater diurnal noise from the equatorial ring current, and the field strength is weakest at the equator. These effects compounded by what we believe to be a rapidly reversing magnetic field with weak overall amplitude leads to difficult-to-measure magnetic field signals from sea surface vessels.

We propose a 42-day cruise (including 10 days transit) to collect high-resolution near-bottom magnetic data over the Late- to Mid-Jurassic section of ocean crust in the Hawaiian magnetic anomaly sequence of the central western Pacific. We propose to use the Autonomous Underwater Vehicle (AUV) *Sentry* operated by the National Deep Submergence Facility (NDSF) to collect two parallel survey lines of pre-M29 magnetic anomalies on the Hawaiian portion of the Pacific JQZ. These magnetic profiles will provide an opportunity to correlate between the Hawaiian pre-M29 anomalies and the Japanese lineations to construct an accurate Geomagnetic Polarity Time Scale (GPTS) model that is more representative of global magnetic field behavior. We will also collect multi-channel seismic reflection and refraction data during the cruise on days the AUV is recharging its batteries. These seismic data will allow us to image depth to basement and Jurassic crustal structure and to evaluate whether the crust has been affected by intra-plate volcanism that is widespread in the western Pacific (e.g. Schlanger et al., 1981; Abrams et al., 1993; Tarduno et al., 2001). Collection of near-bottom magnetic and seismic surveys on the same cruise is made possible because of the use of AUV technology.

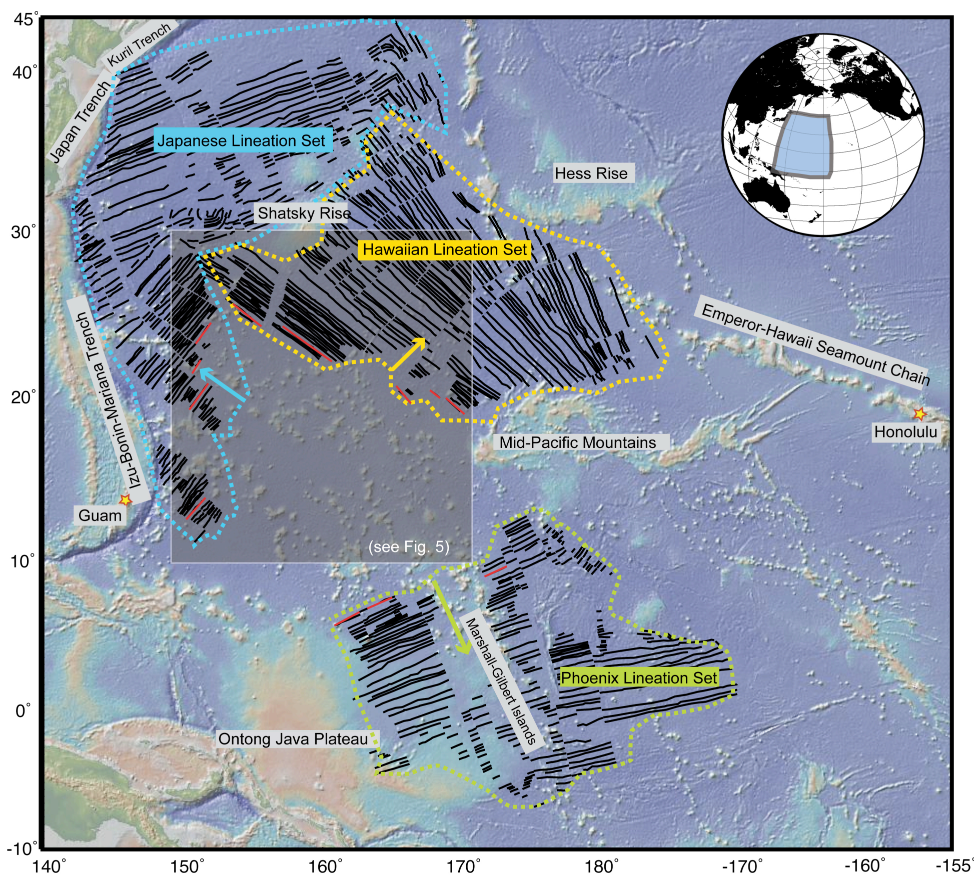

Figure 1. A map of the western Pacific Mesozoic lineations (modified from Nakanishi et al., 1992). Blue, yellow, and green bounds indicate the Japanese, Hawaiian, and Phoenix lineation sets. Red lines indicate M29, the widely accepted oldest seafloor chron. The colored arrows indicate the approximate spreading direction of the Pacific-Farallon-Izanagi ridges. The shaded box indicates the area of interest shown later in Figure 5.

In terms of broader impacts, and as part of advancing education, discovery and outreach, we will bring a number of graduate students from Texas A&M University and the MIT/Woods Hole Joint Program and undergraduate students from a public liberal arts college (The Kutztown University of Pennsylvania) on our cruise to provide sea-going experience and training for hands-on geophysical data acquisition, processing, and interpretation.

By defining the global nature of this unique JQZ magnetic behavior, we will be contributing to fundamental aspects of geophysics, such as dynamics in the Earth's deep interior including the core and deep mantle, provide constraints for geodynamo models, and improve our understanding of the overall evolution of planet Earth. A key transformative deliverable from these marine magnetic anomaly studies will be an improved Geomagnetic Polarity Time Scale (GPTS) model, providing a more reliable magnetic polarity reversal model for the Mid-Jurassic, which will help resolve the uncertainties currently plaguing the Geological Time Scale (Gradstein et al., 2005; Walker and Geissmann et al., 2009) and provide a framework for the research efforts of magnetostratigraphers.

Background and Rationale of the Proposed Research

History of Earth's Geomagnetic Field

The geomagnetic field displays one of the largest dynamic ranges of Earth's physical properties, varying in intensity and direction on timescales from seconds to millions of years (Courtillot and Le Mouël, 1988). Short (<1 sec) field variations are generally attributed to solar, orbital and Earth's magnetospheric variations (Jacobs, 1959; Onwumechili, 1967; Campbell et al., 1985) while longer field variations (> a few years) are attributed to Earth's internal geodynamo (Elsasser, 1946; Bullard, 1949). Over the past two decades, numerical and laboratory models have been developed that successfully reproduce Earth's geomagnetic field behavior on a basic level complete with spontaneous polarity reversals (Love and Gubbins, 1996; Glatzmaier, 1999; Constable, 2003; Takahashi et al., 2005; Berhanu et al., 2007; Ravelet et al., 2008; Pétrélis et al, 2009; Driscoll and Olsen 2009; Olsen and Driscoll, 2009). The better we can define the past history of geomagnetic field behavior, the better we can inform these geodynamo models to reproduce an accurate model response and thereby provide insight into the mechanisms that drive the geodynamo and its proclivity for polarity reversal. The geologic record has provided evidence that for most of Earth's history the geomagnetic field has been reversing polarity (Layer et al., 1996; Algeo, 1996; Irving and Parry, 1963; Johnson et al., 1995; Khramov and Rodionov, 1980; Trench, 1991) and varying in geomagnetic field intensity (e.g., Biggin and Thomas, 2003; Tauxe et al., 2006). By combining the geomagnetic intensity and reversal records, many studies have investigated the possible correlation between reversal rates and the dynamics of the geodynamo process (Gallet and Hulot, 1997; McFadden and Merrill, 2000; Lowrie and Kent, 2004; Pétrélis et al., 2009), the correlation between intensity and reversals (Merrill and McFadden, 1999), and even a possible link between the Earth's magnetic field and climate change (Courtillot et al., 1982; Le Mouël et al., 2005; Gallet et al., 2005; Courtillot et al., 2007; Bard and Delaygue, 2008; Courtillot et al., 2008). Thus, by improving our measurements of Earth's past field behavior we can advance our understanding of Earth's processes.

While terrestrial records have given us important insight into past geomagnetic field behavior, our best and most comprehensive record by far has been from the magnetic record of seafloor spreading magnetic anomalies, which extend back in time to ~180 Ma (Fig. 2A). The existing GPTS is well-defined from the present back to Chron M29 time, but it is very poorly constrained prior to this period (Fig. 2C). The marine magnetic record not only allows us to build a continuous and detailed timescale reference frame, but to also accurately quantify reversal rates and to define the relationship between reversals and field intensity fluctuations as a measure of overall geomagnetic field behavior. While the 180 Ma marine record of geomagnetic field behavior shows almost continuous polarity reversal there are two prolonged periods that show quite different behavior. One period is the well-documented Cretaceous Normal Superchron (CNS) from 84-124 Ma, when the field had a constant polarity that is confirmed by its global occurrence in the marine record and also by the magnetostratigraphic record (Fig. 2B). The second period of unusual geomagnetic field behavior is the more poorly known Jurassic Quiet Zone (JQZ) (>155 Ma), when the reversal rate may have been higher than at any other time (Tivey et al., 2006). The JQZ period provides a much different picture of field behavior compared with the CNS period. Reversal rates decrease into the CNS and then increase after the CNS (Fig. 2B, Lowrie and Kent, 2004; Valet et al., 2005; Coe and Glatzmaier, 2006), while field intensity appears strong (Biggin and Thomas, 2003; Tauxe et al., 2006). The JQZ on the other hand has high reversal rates while field intensities are low (Tominaga et al., 2008). This fundamental dichotomy makes it important that we capture and quantify this period in Earth's magnetic field history in order to fully understand the full spectrum of geomagnetic field behavior. Below we discuss what we know about the Jurassic portion of the marine magnetic record and the apparently anomalous field behavior observed during this period.

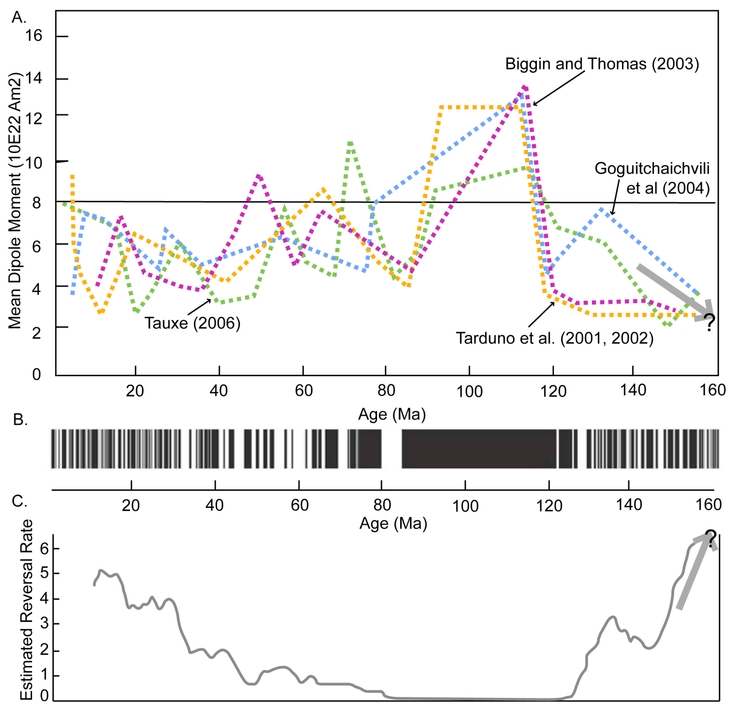

Figure 2. History of Earth's geomagnetic field variations 0-160 Ma. (A) Mean dipole moment (field intensity) variations from publications, each of which has different styles of data compilation (references are indicated in the figure). Despite these differences, the overall trend of dipole intensity low during Mesozoic (before 120 Ma) is indicated. (B) Polarity reversal sequence from Cande and Kent (1995) and Channell et al. (1995). Black and white stripes show "normal" and "reverse", respectively. The long normal polarity indicates Cretaceous Normal Superchron. (C) Polarity reversal rate curve that was calculated using polarity sequence data shown in (B) with 10 m.y. window. The estimated reversal rates are increasing towards the JQZ (155 Ma).

<u>The Late-Mid Jurassic (155-180 Ma) Magnetic Anomalies</u>

Mesozoic (M-series) marine magnetic anomalies were first mapped and correlated in the northeast Atlantic in the Keathley sequence (Vogt et al., 1971). Subsequent mapping and correlation of magnetic anomalies in the Pacific revealed a concurrent sequence of correlatable anomalies on several different sets of lineations (Larson and Chase, 1972), which allowed for a world-wide correlation of M-series anomalies to be constructed and added to the GPTS, previously established for the Late Cretaceous and Cenozoic by Heirtzler et al., (1968). Revised Mesozoic timescales primarily based on the faster spreading pacific crust were subsequently generated (Larson and Hilde, 1975; Cande 1978; Nakanishi et al., 1989), leading to the most recent revisions by Channell et al., (1995). While M-series anomalies are identified in the oldest part of the major ocean basins (e.g. Klitgord and Schouten, 1986; Vogt et al., 1971; Hayes and Rabinowitz, 1975; Cooper et al., 1976; Verhoef and Scholten, 1983; Roest et al., 1992; Sager et al., 1992; Ramana et al., 1994; Rybakov et al., 2000; Roeser et al., 2002; Ramana et al., 2001; Gurevich et al., 2006), the most complete sequence of Late- to Mid-Jurassic anomalies is only available in the western Pacific (Fig. 1). These Pacific anomalies occur as three distinct sets of lineations, the so-called Japanese, Hawaiian, and Phoenix lineations (Fig. 1) that record the early spreading history of the Pacific plate at the fast-spreading circum-Pacific ridges (Nakanishi and Winterer, 1998).

The "Jurassic Quiet Zone"

From the earliest studies of the Mesozoic anomalies (Larson and Chase, 1972) it was clear that the correlations began to breakdown around M22 time (150 Ma) as the anomalies became weaker and less distinctive. This pre-M22 period was termed the Jurassic Quiet Zone (JQZ) and considerable debate has continued as to the true nature of this period. The onset of the JQZ (Larson and Chase, 1972) was first determined based on the disappearance of correlatable anomalies in both the Atlantic and Pacific (Larson and Chase, 1972; Larson and Hilde, 1975; Cande et al., 1978; Vogt and Einwich, 1979). The younger boundary of the JQZ has changed through time as resolution has improved from M22 (Larson and Chase, 1972), to M25 (Larson and Hilde, 1975), to the present M29 age (Cande et al. 1978; Kent and Gradstein, 1985; Channell et al., 1995). The JQZ was thought to be analogous to the Cretaceous Normal Superchron (CNS) i.e., a period of single polarity but there are several lines of evidence that dispel this view. First, anomaly amplitudes monotonically decrease in amplitude from M19 toward M29 (Fig. 3, Larson and Hilde, 1975; Cande et al., 1978; McElhinny and Larson, 2003) and this decrease continues until M39 (Tivey et al., 2006), suggesting low field intensities compared to the CNS (Fig. 2A, Biggin and Thomas, 2003; Tauxe, 2006). Second, a number of efforts to investigate the pre-M29 magnetic anomalies have been undertaken in the Japanese lineations of the Pigafetta basin in the western Pacific revealing magnetic anomalies that appear to be correlatable (Handschumacher et al., 1988; Sager et al. 1998; Tivey et al., 2006; Tominaga et al., 2008). Third, terrestrial stratigraphy suggests that there were reversals during the JQZ (Steiner et al., 1986; Steiner et al., 1987; Ogg and Gutowski, 1996) and more recent results appear to confirm polarity reversals during the M25 to M38 period (Ogg et al., 2010; Przybylski et al., 2010a, 2010b). However, as anomalies become weaker in amplitude it is difficult, if not impossible, to know, whether these anomalies are the result of true polarity reversal or are simply fluctuations in field intensity (Cande and Kent, 1992; Roberts and Lewin-Harris, 2000; Bowles et al., 2003) without independent terrestrial magnetostratigraphic control. If the field is truly incoherent it may be very difficult for even magnetostratigraphy to verify field behavior and global correlation becomes an important factor. Regardless of their cause, however, if a magnetic anomaly can be correlated globally then it is still useful as a time marker.

Recent Results from the Japanese Jurassic Crust

Early studies could not resolve pre-M29 magnetic anomalies (>157 Ma) by surface-towed magnetometer because of the reasons mentioned above (Fig. 3). To overcome the diurnal noise issue, Handschumacher et al. (1988) conducted an aeromagnetic survey over the Japanese lineations of Pigafetta basin and found correlatable anomalies from M29 to M38 (162.5 Ma). Two deep-tow magnetic surveys were subsequently conducted in the same region of the Pacific Japanese lineations (Sager et al., 1998; Tivey et al., 2006; Tominaga et al., 2008). Deep-tow surveys can overcome the signal-to-noise issue because the magnetic sensor is towed near the seafloor and recovers the maximum amplitude and spatial resolution without suffering the distance from source attenuation and lateral smoothing inherent in surface towed measurements (Fig. 3A). Sager et al. (1998) collected two 800-km-long deep-tow magnetic profiles that extended the correlations of Handschumacher et al (1988) from M38 to M41 (167 Ma). A second deep-tow magnetic survey (Tominaga et al., 2008) extended the correlations to M44 (170 Ma). These deep-tow data reveal that magnetic anomalies are present throughout the time period from

M38 to M44 (Tominaga et al., 2008). Anomaly amplitudes decrease to about M39, which marks the onset of a confused period of low amplitude anomalies that are difficult to correlate – the low amplitude zone or LAZ. Prior to the LAZ, correlatable anomalies reappear and become stronger in amplitude starting at M42 (167 Ma) and continue to M44 (ca. 170 Ma). Chron M42 provides a tie with downhole magnetization logs and samples of ODP Hole 801C that strongly suggest that polarity reversals are present, consistent with the overlying anomaly sequence (Steiner et al., 2001; Tivey et al., 2005). Chron M44 marks the transition from rough to smooth (RS) basement topography and is thought to mark the limit of pristine Jurassic-aged crust and the appearance of Cretaceous sills overlying and intruding Jurassic basement (Abrams et al., 1993). M44 may mark the edge of a Cretaceous volcanic province overprint (Abrams et al., 1993) or it may be a fossil plate boundary, a fracture zone trace, or mark a change in spreading rate or direction (Handschumacher et al., 1988). The deeptow magnetic data also suggest that reversal rate is high during this pre-M29 period assuming that all anomalies are caused by polarity reversals. Even if we discount the low amplitude anomalies in the LAZ, we still calculate reversal rates of 10 rev/My, which is very fast compared to Cenozoic rates of 0 to 5 rev/My (Opdyke and Channell, 1996; Tivey et al., 2006). These results are problematical when we seek to expand their significance to more global proportions. For example, we have made correlations on only two profiles from one part of the Pacific basin and so we need confirmation from a separate record formed at a different midocean ridge spreading center to verify that these correlations are more global in their significance, i.e., geomagnetic in origin. Similarly, we have found a zone of poor correlation with low amplitude anomalies (the LAZ), but we cannot tell if this is due to local tectonics or crustal contamination from later stage volcanics or it truly reflects geomagnetic field behavior. Only by surveying the same age crust that has formed at a different mid-ocean ridge spreading center can we begin to make a case for the global significance of these observations.

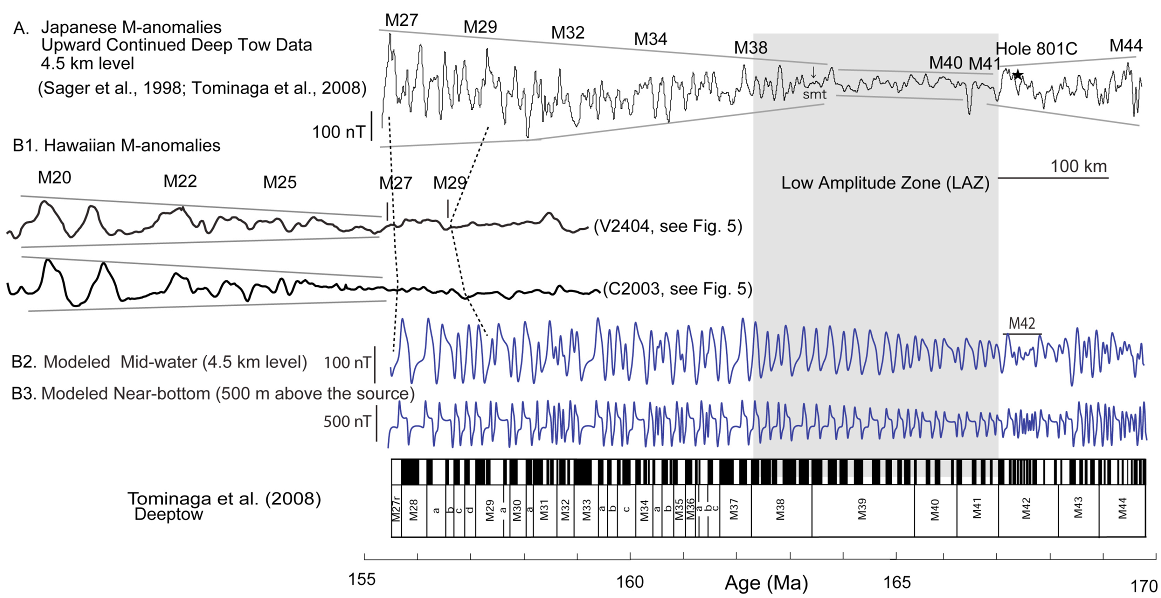

Figure 3. Summary of previously collected deep-tow magnetic data from the Japanese anomalies (A, Tominaga et al., 2008) and sea surface Hawaiian anomalies (B1, Larson and Hilde, 1975; Cande et al., 1978) lineation sets, and predicted pre-M29 Hawaiian anomalies at different survey levels (B2 and B3). Shaded box indicates the Low Amplitude Zone (LAZ, see text). The sea surface data become ambiguous around M20-M25 time. Sufficient resolution to address the field behavior will be obtained only from deep-towed data. We calculated pre-M29 Hawaiian anomalies by near-bottom survey assuming the magnetic anomalies appear coherently in both the Hawaiian and Japanese pre-M29 seafloor. Note differences in anomaly amplitudes. These synthetic profiles are calculated from the M27-M44 polarity block models with transition widths created by a Gaussian filtering technique.

We have some hope that some of these observations are supported by independent observations. In the Atlantic, Roeser et al. (2002) presented the correlations of Atlantic pre-M29 anomalies to M41. Although hampered by the slow spreading regime, the Atlantic work gives hope that the existence of correlatable pre-M29 anomalies is verifiable in a global context. Confirmation that these pre-M29 anomalies are truly polarity reversals is also beginning to be supported by terrestrial magnetostratigraphic work. A compilation from Mesozoic Tethys sections clearly shows clear pre-M29 reversals back to M38 (Ogg et al., 2010; Przybylski et al., 2010a, 2010b). We do not have any corroboration of the LAZ at the present time, which more than any other result appears to be the most confounding observation of Jurassic Earth's magnetic field so far. Below we outline the details of a plan to confirm the existence of this potentially unique period in Earth's geomagnetic history.

Key Questions in the Proposed Field Program

Our main hypothesis is that *the geomagnetic field during the Jurassic was behaving in a globally coherent way*. If we can confirm the global coherency of field behavior, we will be able to define a unique style of field behavior, the LAZ, that appears to be the antithesis of the CNS. We will also be able to build a foundation for a better Late- to Mid-Jurassic GPTS extending the timescale to approximately M44 (~170 Ma). Even if we cannot correlate between the Japanese and Hawaiian JQZ anomalies, we will have important information about Earth's geomagnetic field and advance both numerical and laboratory modeling of field behavior. More specific questions that we can address with our proposed field program are as follows:

(1) Is the M29-M38 anomaly sequence measured on the Japanese lineations characteristic of field behavior during this period?

The deep-tow results from the Japanese lineations (Tivey et al., 2006; Tominaga et al., 2008) reveal a decreasing anomaly intensity and variations in reversal rate over the M29-M38 period. A new Hawaiian Jurassic seafloor magnetic record would allow us to confirm and refine a geomagnetic polarity time scale (GPTS) for this period with more confidence. It would help the ongoing terrestrial magnetostratigraphy efforts by proving a broader context for their results.

(2) What is nature and origin of the LAZ (M39 to M41 anomalies)

Results from surveys of the Japanese lineations (Tivey et al., 2006; Tominaga et al., 2008) reveal a period when magnetic anomalies are weak and apparently incoherent – the LAZ. It is important to identify if the LAZ is a local phenomenon due to tectonic or crustal influences or if it truly is representative of geomagnetic field behavior. By measuring the magnetic record for this period at a different spreading center we will be able to either verify or eliminate any local tectonic or crustal variations as a source of the LAZ. Our seismic results should also allow for better characterization of tectonic and crustal effects.

(3) Does M44 mark the end of the marine magnetic Jurassic record?

We do not know if M44 is the oldest identifiable marine magnetic record based solely on the data from the Japanese Jurassic seafloor. It also marks the onset of rough-to-smooth basement topography (Abrams et al., 1993). Both our magnetic and seismic data should help to verify if this zone also occurs on the Hawaiian lineation sequence and at the same time period. If the M42-M44 anomalies can be verified, it may be possible to extend the magnetic record beyond the M44 chron. The older we extend our correlation of the marine magnetic record, the better we will constrain the birth of the Pacific plate in time and space.

Key Deliverable from the Proposed Research

In addition to addressing questions about Jurassic field behavior, we expect a key deliverable will be a more robust and improved geomagnetic polarity time scale (GPTS) model for the Mid-Jurassic. When one looks at a commonly available Geological Time Scale, such as the recently published Geological Society of America (GSA) Time Scale (Fig. 4; Walker and Geissmann et al., 2009), it is immediately obvious that the GPTS begins to break down in the Jurassic (145 to 201 My) period, typically around the M25-M29 chrons, the last presently accepted magnetic chron of the GPTS.

There are two long-standing difficulties in improving the accuracy of the Late- to Mid Jurassic (M25-M44) geologic timescale. One is a dearth of reliable high-resolution radiometric dates and the other is a lack of a definitive Jurassic geomagnetic polarity time scale (GPTS) model that extends beyond M29. It has been an ongoing challenge for the International Commission on Stratigraphy (*www.stratigraphy.org*) and associated researchers (e.g. Pálfy, 2008; Przybylski et al., 2010a, 2010b; Ogg et al., 2010) to obtain data for this period because of the limited geologic exposure of well-preserved Late- to Mid-Jurassic sections across the globe. The duration of stages and the location of stage boundaries in the present Jurassic timescale are calculated from a simple interpolation of sparse data (see Ogg and Smith chapter *in* Gradstein et al., 2005). Absolute dates are difficult to obtain because fresh igneous rocks, which are amenable to precise radiometric dating and tied to the GPTS, are needed for dating. Usually such rocks come from ocean drilling (e.g. Ludden, 1992; Pringle et al., 2003; Koppers et al., 2003), so new dating will not provide an immediate solution for improving the Late- to Mid-Jurassic timescale in the near future. However, we can build a better GPTS model, if we can measure a coherent sequence of marine magnetic anomalies in Late- to Mid-Jurassic time period. This is a readily achievable goal if we can find the requisite Jurassic ocean crust with measurable anomalies and if we can correlate between crust created at different spreading centers.

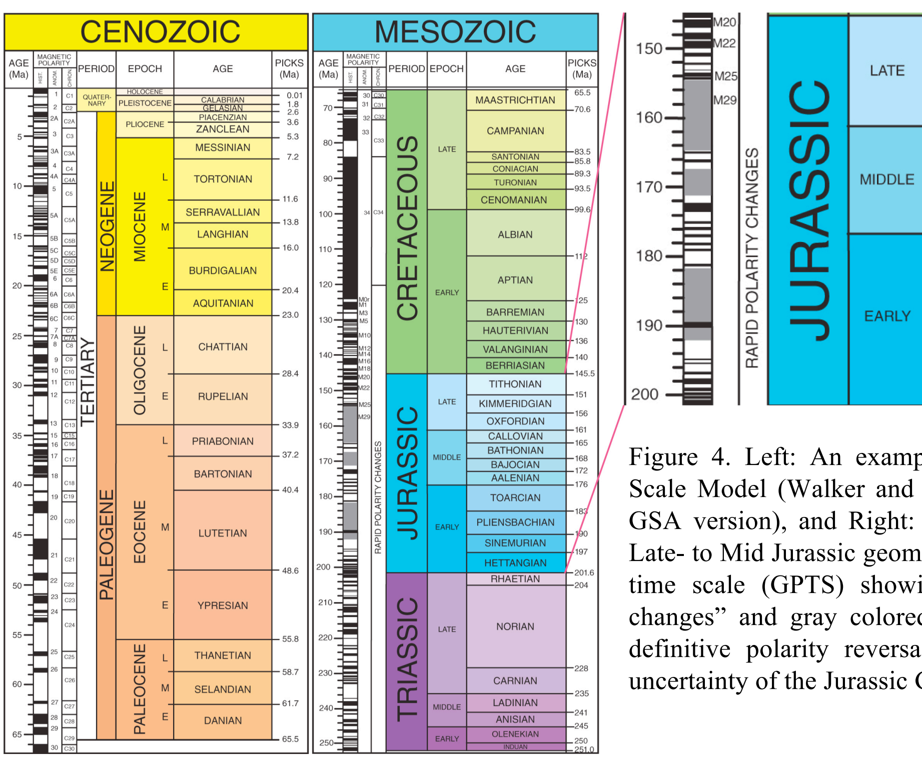

Figure 4. Left: An example of Geological Time Scale Model (Walker and Geissmann et al., 2009 GSA version), and Right: a magnified version of Late- to Mid Jurassic geomagnetic polarity reversal time scale (GPTS) showing the "rapid polarity changes" and gray colored GPTS model without definitive polarity reversal sequences, indicating uncertainty of the Jurassic GPTS model.

Cruise Plan

We propose a near-bottom magnetic survey in a corridor approximately 3600 km west of Honolulu in the Hawaiian magnetic anomaly lineation set that minimizes the influence of seamounts and fracture zones (Figs. 1 and 5). We have specifically picked this corridor because it is located between two previously collected sea surface magnetic data profiles (V2404 and C2003, National Geophysical Data Center). These profiles were used to determine the original M25-M29 Hawaiian lineation correlations (Larson and Hilde, 1975; Cande, 1978) and thus provide an appropriate context for anchoring any new seafloor survey in the area. We are advocating two profiles approximately ~10 km apart in order to verify lateral correlatability of magnetic anomalies – an important aspect of constructing a GPTS. The cruise plan consists of a 42 day cruise, which includes 10 days of transit (ports Honolulu to Guam) and 32 days on station. There are three major operational parts to the cruise:

1) Two 800 km long near-bottom magnetic profiles collected by AUV.

2) Conventional sea surface magnetic and multibeam bathymetry acquisition, which will be collected concurrently with the near-bottom AUV survey. We may also use the MISO TowCam to collect additional near-bottom magnetic data.

3) A seismic reflection and refraction survey to constrain crustal thickness and possible Cretaceous volcanic overprint.

Near-bottom magnetic survey: In order to collect 2 near-bottom magnetic profiles we plan to use the autonomous underwater vehicle (AUV) *Sentry*. *Sentry* is the new AUV that is scheduled to replace ABE in the National Deep Submergence Facility (NDSF) (http://www.whoi.edu/page.do?pid=38095). *Sentry* navigates independently from any surface vessel using its onboard doppler velocity sonar (DVL) and inertial navigational system (PHINS). *Sentry* carries two 3-axis magnetic sensors arranged in a vertical gradiometer mode along with multibeam sonar, bottom photography and water property sensors. To save power we would only operate the magnetometer, depth sensor, altimeter, and water column properties, which are all low power sensors compared to the multibeam sonar. *Sentry* completed its first field trials in the summer of 2008 and had two field science deployments in 2009. The first deployment in 2009 suffered from several problems (Fisher cruise) that included mechanical and instrument/sensor failures but the second cruise (Valentine cruise) was largely successful and indicated that *Sentry* was maturing as a platform (See http://www.unols.org/meetings/2009/200906des/200906desap18.pdf). *Sentry* has a science cruise scheduled for 2010, which should provide confidence that the vehicle is ready for science missions. Based on a conservative estimate of *Sentry's* current capabilities we propose to operate *Sentry* in a long-endurance mode to cover ~65 km at a conservative speed of 1.5 kts (0.75 m/s) over a ~24 hour period. It may be possible for *Sentry* to operate at faster speeds and thereby cover greater range (i.e. 100 km) over the same 24 hour period, especially if we are not using the multibeam bathymetry sonar, however, this is as yet unproven and so we have chosen to be very conservative in our estimates of *Sentry's* range and speed.

Our plan calls for *Sentry* to survey at a nominal speed of 0.75 m/s (1.5 kts) to cover ~65 km over a 24 hour period of bottom time. *Sentry* was designed to descend and ascend rapidly and we have budgeted a generous 4 hours for deployment and descent and 4 hours for ascent and recovery. *Sentry* also needs to recharge its batteries and we have budgeted 16 hours for each dive. *Sentry* does have a spare battery pack if needed. The total *Sentry* dive mission cycle time is therefore 2 days (48 hours). We will need 12 dives to complete one ~800 km profile or 24 days. This would leave 8 more days for 4 more *Sentry* dives, which would enable us to complete another 260 km along a second profile. Again, if Sentry is able to survey faster and go further (100 km) within the 24 hour or slightly longer period, we can cover a greater proportion of the proposed survey with the AUV. However, the advantage of using an AUV is that we are able to conduct additional operations with the ship and we plan to use the MISO (Multidisciplinary Instrumentation in Support of Oceanography) TowCam (http://www.whoi.edu/page.do?pid=13576) to collect concurrent deeptow magnetic data using a deep towed system along a track parallel to the AUV track. The MISO-TowCam operates from the CTD winch and with its real-time telemetry link, will be able to relay magnetometer data to the surface from a sensor mounted on the TowCam. By operating both AUV *Sentry* and the MISO-TowCam we can obtain the two 800 km long near-bottom magnetic profiles required for our program.

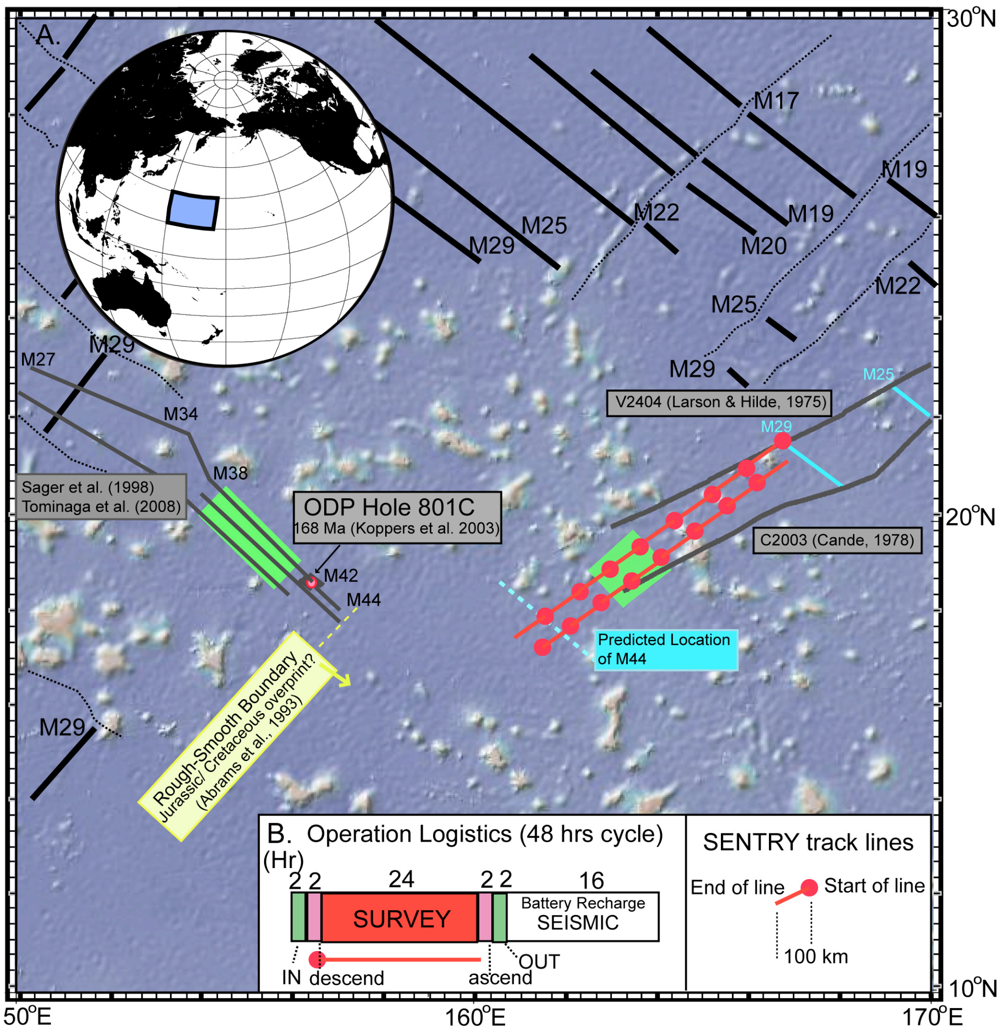

Figure 5. (A) A map of our proposed field program (basemap, Ryan et al., 2009). Black solid and dotted lines indicate the oldest part of the Japanese and Hawaiian M-series lineations and fracture zones, respectively (Nakanishi et al., 1992). Gray solid lines are previously collected deep-tow and surface-towed magnetic profiles. Green patches indicate the locations of Japanese Low Amplitude Zone (LAZ, Tominaga et al., 2008) and predicted Hawaiian LAZ. Red drops and lines indicate the locations of Sentry deployment and proposed dive lines. (B) A diagram of 48 hour cycle of operation logistics, including Sentry deployment (IN), descend, survey, ascend, recovery (OUT), and seismic survey while Sentry battery recharge. We plan to conduct this operation cycle for 16 cycles.

While the AUV Sentry can navigate itself independently using its onboard DVL and PHINS sensors, we plan to track the AUV from the surface ship using an Ultra-Short Baseline (USBL) acoustic system. *Sentry* can also send periodic messages and data back to the ship acoustically while submerged and we will use this to monitor the AUV magnetic readings in real-time. The MISO-TowCam can be navigated using a simple layback calculation from the ship.

***Shipboard Geophysics*:** While the AUV *Sentry* is surveying the seafloor we plan to deploy the MISO-TowCam to collect magnetic data in a near-bottom profile parallel to the AUV track as outlined in the previous section. We will also collect sea surface magnetic and gravity data, ship-based multibeam and 3.5 khz chirp subbottom data along the same ship track. The ship will be tracking the AUV using a USBL system and will be receiving periodic data updates from the vehicle.

Seismic Data Collection: The seismic component of the proposed work is designed to distinguish between "unmodified" Jurassic crust and crust that has been modified by Cretaceous volcanism and, where modified, to characterize the Cretaceous igneous additions to the crust. Cretaceous volcanism was widespread in the western Pacific, producing seamounts and extensive submarine lava flows and sill intrusions (Abrams et al., 1993). While we have chosen a corridor that hopefully minimizes the influence of Cretaceous volcanism, the surrounding seamount distribution is similar to the region slightly south that was surveyed by Abrams et al. (1993), and it would not be surprising to encounter Cretaceous igneous flows and sills similar to those that they observed. Seismic operations will be conducted during the 16-hour AUV battery recharge cycles. With gear deployment and recovery time, this translates into ~100 km of seismic profiling per cycle at a survey speed of 4 knots. There will be 16 cycles, enabling a complete survey of the proposed transects.

We will use the Scripps high-resolution multi-channel seismic (MCS) system to image the igneous basement and, where present, sills intruded into sediment. This system consists of a 600-m-long, 48-channel Geometrics GeoEel streamer and a 2-GI-gun cluster. The GI gun configurations range from 45/105 cubic inches (cu) for the generator/injector chambers, giving a total effective volume of 90 cubic inches for two guns, to 105/45, with an effective volume of 210 cubic inches. Abrams et al. (1993) present a number of 2-channel MCS sections from the Pigafetta and East Mariana basins, settings very similar to the transects proposed here. Those lines were shot with two 80-cu water guns and provide adequate imaging down to igneous basement or to the top of massive Cretaceous volcanic flows. Our recent experience with the Scripps GI guns off of the New England shelf showed that even one gun in the 45/105 configuration yielded impressive penetration to >1 km below the seafloor in shallow-water, hard-bottom conditions, providing high-resolution images of Plio/Pleistocene through Cretaceous stratigraphy and Jurassic igneous basement. The excellent performance of these guns is due in large part to their wide and flat frequency response between 10-200 Hz. We are confident that two clustered GI guns in the 45/105 configuration will outperform the 2-watergun source, and the signal/noise enhancement provided by the low-noise 48-channel streamer will yield excellent images of stratigraphy, sills, basement, and possibly some sense of sub-basement volcanic structure.

We will also deploy Ultra Electronics sonobuoys to acquire wide-angle seismic data, enabling us to invert for seismic velocity to at least the top of oceanic Layer 3. The refraction data are a critical component of the seismic survey. Previous surveys in the area have shown that MCS data, even with large volume sources and long streamers, cannot adequately image beneath Cretaceous volcanics, where present. The MCS data we acquire will image to the top of the first volcanics encountered. The reflectivity of that surface, lateral variability of that reflectivity, possible deformation above the surface, and potentially internal structure imaged just beneath the surface will all inform an interpretation of the origin of the shallowest volcanic layer as pristine Jurassic basement, intruded basement, or Cretaceous flows or sills. However, only the refraction data will be able to determine the depth of Jurassic basement beneath a Cretaceous sill or flow, for example, or reveal lateral variations in Layer 2 seismic structure that may be indicative of intrusions into Jurassic crust.

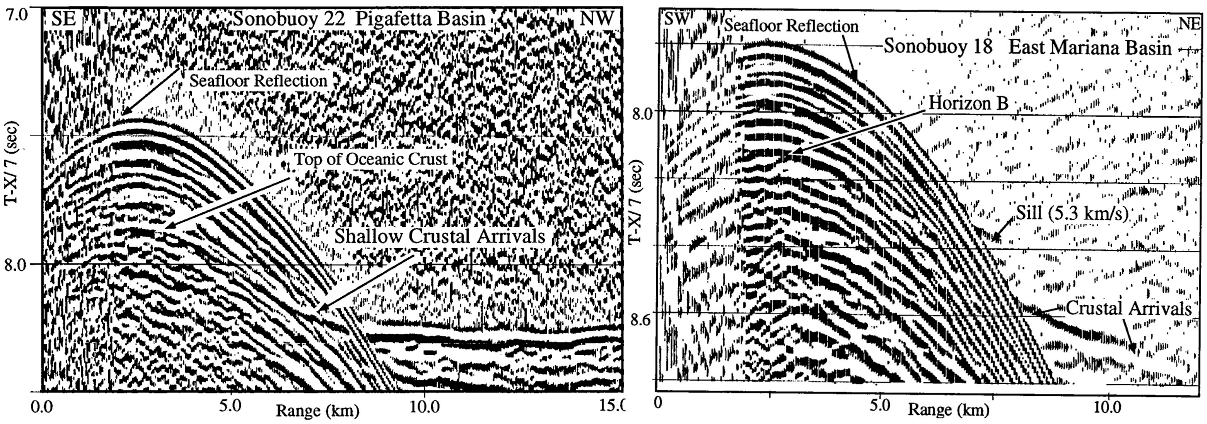

Figure 6. Sonobuoy profiles from the Japanese JQZ in the (a) Pigafetta and (b) East Mariana Basins, located near ODP Site 801C and Tominaga et al. (2008) deeptowed magnetic survey lines (from Abrams et al., 1993). Labelled "shallow crustal arrivals" are from Layer 2, and arrivals with an apparent velocity of ~7 km/s are from Layer 3. In (b), a refraction from a sill is evident, with the deeper crustal refraction shingled beneath it. These profiles demonstrate that offsets of no more than 15 km are necessary to delineate the velocity structure through oceanic Layer 2.

Sonobuoy profiles presented by Abrams et al. (1993) indicate that refractions from the top of Layer 3 become first arrivals beyond ~10 km range, and shingled first arrivals from Cretaceous sills or flows above the Jurassic crust are observed between 5-10 km range (Fig. 6). We believe that the 2-GI gun cluster configured as 45/105 will provide a more than adequate source for sonobuoy recording of arrivals out to at least these ranges. We will, however, conduct a gun-only test with an initial sonobuoy as our first seismic operation, and if we are not satisfied with the source strength we will modify the chamber configuration. We also plan shooting during the AUV survey. With slower cruising speed during the AUV survey, we will be able to shoot at much longer interval that will have effect on moving previous shot noise well-outside of the useful offset range of 0-30 km.

We specifically budgeted sonobuoys manufactured by Ultra Electronics because of their high success rates from previous surveys (87% in Canada Basin survey by Geological Survey of Canada; Mosherm et al., 2009), and we will employ the "stacked antennae" configuration that was used on that survey to enhance received signal strength. This configuration employs two antennae to beam steer the radio signal from the sonobuoy at the modest cost of ~15° reduction in beam width. We will deploy a total of 50 sonobuoys at a spacing of ~30 km.

Post Cruise Research and Work Plan

The AUV *Sentry* magnetic, depth and vehicle navigation data will be processed at sea to build a preliminary magnetic profile along with the sea surface magnetic data. Tominaga and Tivey will be responsible for this initial magnetic processing while the *Sentry* technical group will provide the processing of the *Sentry* navigation data. Once back at Woods Hole, the magnetic data will be post-processed by Tominaga under Tivey's supervision. The *Sentry* magnetic data will be corrected for diurnal variations and vehicle motion to recover the full vector data and then will be corrected for the International Magnetic Reference Field (IGRF). For diurnal field variations, we will use hourly average data from USGS magnetic observatories at Guam and Hawaii that are publicly available from their websites (http://geomag.usgs.gov/observatories/). After merging with the navigation data, the magnetic profile will be sampled into equally spaced data points and then upward continued to a level plane (Guspi, 1987) prior to inversion for crustal magnetization using the Fourier inversion method of Parker and Huestis (1974). *Sentry* altimeter data and ship-based chirp sonar and multibeam data along with the seismic data will be used to extract depth-to-source information (regional sediment thicknesses). To construct a polarity timescale the magnetic analysis will follow the procedures outlined in Tominaga et al. (2008). Crustal magnetization will be modeled as magnetic reversals (Talwani and Heirtzler, 1964), which will be correlated and compared with the pre-M29 anomalies from the Japanese lineation set (Tominaga et al., 2008) to establish an averaged geomagnetic polarity sequence for more robust Jurassic geomagnetic polarity time scale. All the magnetic data analyses will be performed using MATLAB based scripts available through the Ocean Bottom Magnetology Laboratory at WHOI (http://deeptow.whoi.edu/). We will also utilize the vector analysis software available from Jun Korenaga to extract strike and linearity information (Korenaga, 1995). Tivey will pursue this part of the analysis.

Shipboard bathymetry and chirp sonar data will be processed onboard by student watchstanders under the supervision of Adrienne Oakley (Kutztown University of Pennsylvania). These students will be responsible for post-cruise undergraduate projects using these data. We will use MBsystem to process the multibeam data and create swaths that we can import into the IVS3D Fledermaus software package. The sub-bottom Chirp data will also be processed by the Kutztown group at sea. The shipboard gravity data will be processed after the cruise has been completed so that appropriate corrections for the tie points can be included in the processing.

Sager will supervise the seismic data acquisition at sea. Both seismic reflection and refraction data will undergo preliminary processing onboard by Steve Swift and a WHOI graduate student. The processing will be completed at WHOI by the graduate student under the direction of Daniel Lizarralde. Lizarralde provides expertise working with seismic reflection and refraction data, and he will supervise Tominaga and the graduate student on the technical aspects of the data collection, post-cruise processing and preliminary interpretations of both reflection and refraction data. The seismic reflection data will be processed through time-migrated stacks. Horizon times from these stacks and seismic velocity control from ODP Sites 307, 801, and 866, near our survey area, will be used to constrain a two-dimensional traveltime inversion of the sonobuoy records, yielding a seismic velocity model along both of the transects and providing excellent depth constraints to the top of igneous basement. The processed MCS data will be interpreted at Texas A&M University by Sager and his MS student. Sager holds a site license for ProMAX and seismic processing packages by a Landmark and Kingdom Suite seismic interpretation software (KINGDOM 2d PAK) by Seismic Micro Technology, and WHOI has the full Paradigm suite of seismic processing software, along with Sioseis and Kingdom Suite.

Broader Impacts

Understanding the nature of the Jurassic Quiet Zone (JQZ) is of fundamental importance to many earth science disciplines ranging from global geomagnetic research in terms of geodynamo models, polarity reversal mechanisms and geomagnetic field behavior, to marine magnetic anomaly research into how and what portion of the ocean crust records and preserves the geomagnetic field, to the tectonic implications for the early evolution of the Pacific plate. In particular, having accurate time scale is the first-order requirement to all the earth science disciplines. The accuracy of this early Late to Mid Jurassic time scale depends on a reliable geomagnetic polarity reversal time scale (GPTS) model, which is only obtained from advancing our knowledge on the JQZ.

Exposure to Field Oceanography

Our program will provide an opportunity for two young scientists (Tominaga and Oakley) to learn and gain experience under the tutelage of Sager and Tivey, who both have extensive field experience in leading cruises. We will advance scientific discovery while promoting teaching and training by providing at-sea research experience for several graduate and undergraduate students. We will provide thesis research material for an M.S. student at Texas A&M University and a PhD student in the WHOI-MIT Joint Program. Dr. Adrienne Oakley, Assistant Professor of Geology and Marine Science at Kutztown University of Pennsylvania (KUP) will work closely with Tominaga to establish research opportunities for undergraduate students. Tominaga and Oakley are alumni of the Marine Geoscience Leadership Symposium (March 2009 at the Consortium of Ocean Leadership, Washington D.C) and strongly agree on the significance of establishing a collaboration between teaching-oriented and research-oriented institutions in order to enhance infrastructure for research and education and to support the future generation of marine scientists. KUP is a public, undergraduate liberal arts college where 42% of students are first-generation college students. Oakley teaches courses in marine science and geology that reach a wide range of students from freshman to seniors and will be able to recruit 5 highly motivated junior/senior undergraduate students for this cruise. Oakley and Tominaga will mentor these students during the cruise, providing on-board lectures as well as experience in equipment deployment, monitoring and retrieval and data processing. They will also work with these students post-cruise to create group research projects that will result in written publications as well as presentations at national conferences (e.g. AGU). To reach a broader cross-section of the KUP community, Oakley plans to broadcast live from the cruise back to students at KUP and will use the general oceanographic and shipboard geophysical data acquired during the cruise in her classroom.

Broad Dissemination to Enhance Scientific and Technological Understanding

We will broadly disseminate results in peer reviewed journals, public presentations at science meetings, and in WHOI outreach facilities, such as a public exhibit center, press-kits and the Oceanus magazine. We will bring our discovery on the magnetism of the seafloor to broader audiences by providing public access to the results on the WHOI Ocean Bottom Magnetology Lab website (http://deeptow.whoi.edu/). Other geophysical survey data will be disseminated to the community through the Marine Geoscience Data System.

Junior Scientist Education and Mentoring

Tominaga is a Postdoctoral Scholar at WHOI and will be Co-Chief Scientist, conducting magnetic data analysis and interpretation and taking the lead in this proposed project under Tivey's supervision. Tominaga will also mentor a MS student together with Sager for processing and interpretation of seismic reflection data during and post cruise activities. Leading a project and mentoring a graduate student will enhance Tominaga's current skills in geophysics cruise operations and research as well as teaching experience.

Graduate Training

Lizarralde will train a PhD student in MIT-WHOI Joint Program in refraction data processing and interpretation. Sager will train an MS student at Texas A&M for reflection data interpretation. Providing a hands-on project to an MS student from the beginning (data acquisition during cruise) to the end (accomplish research and publish the results) is the first-order suite of training to produce a new generation of marine geoscientist.

Prior NSF Support

Tominaga and Oakley do not have previous NSF support.

M.A. Tivey (WHOI) and W.W. Sager (TAMU): Collaborative Research: A Deeptow Magnetic Study of the Jurassic Quiet Zone. OCE-00932700 (WHOI), $332,476, 11/15/01-10/31/04; OCE-0090161 (TAMU), $153,584, 09/01/01-08/30/05.

In a project to investigate the oldest known marine magnetic anomalies remaining in the world we used near-bottom magnetic surveys to: 1) investigate the presence or absence of Jurassic magnetic lineations related to seafloor spreading around ODP Hole 801C, 2) extend the magnetic anomaly mapping south to the Rough-Smooth (RS) boundary, the limit of the oldest Pacific crust, 3) extend and confirm correlations of previously collected deeptow results and 4) investigate a period of apparently extremely rapid field reversal in the M33-M34 sequence.

Sager, W.W. and M.A. Tivey, 2003, Chapman Conference on Timescales of the Geomagnetic Field, Gainesville, FL, 9-11 March.

Tivey, M. A., et al., 2003, Deeptow magnetic survey of the Pacific Jurassic Quiet Zone: Implications for the marine magnetic anomaly timescale, Eos Trans. AGU. 84 (46), Fall Meet. Suppl., Abstract GP32A-07.

Tominaga, M., et al., 2004, Deep-tow Study Magnetic Anomalies in the Pacific Jurassic Quiet Zone, Eos Trans.AGU, 85(47), Fall Meet.Suppl., Abstract GP43B-0856.

Tivey, M.A., et al., 2005, Downhole magnetic measurements of ODP Hole 801C : Implications for Pacific oceanic crust and magnetic field behavior in the Middle Jurassic, Geochem. Geophys. Geosys., 6, Q04008.

Tivey, M.A., et al., 2006, Origin of the Pacific Jurassic Quiet Zone, Geology, 34, 789-792.

Tominaga, M., et al., 2008, Deep-tow Magnetic Profile Study of the Pacific Jurassic Quiet Zone and Inferences for the Geomagnetic Polarity Reversal Time Scale and Jurassic Geomagnetic Field Behavior, JGR, 113, B07110.

D. Lizarralde and J.B. Gaherty (GIT), J.A. Collins and G. Hirth (WHOI): Collaborative Research: Oceanic upper mantle seismic structure from very large offset refraction measurements.
OCE-002417 (GIT), $106,718, 4/01 - 3/03

The 2001 Far-Offset Active-source Imaging of the Mantle (FAIM) experiment was designed to test the effectiveness of airguns in such an application and to image slow-spreading lithosphere upper-mantle. The experiment was successful, recording P-wave refractions to ranges of 375 km, with penetration to a depth of ~35 km, along an 800-km-long transect in the western Atlantic. A range of paleo-spreading rates along this transect enable us to relate spreading rate to upper-mantle structure, and we find that seismic structure is sensitive to spreading rate. An abrupt transition in velocity gradient correlates with a transition from slow to ultra-slow paleo-spreading rate. Positive mantle velocity gradients over much of the transect can be explained by the presence of a gabbroic phase resulting from incomplete melt extraction at the MOR. An estimate of the volume of retained melt required to explain the observed gradients roughly balances the crustal-thickness deficit of the slower-spreading crust, suggesting that changes in spreading rate affect melt-extraction processes rather than total melting.

Lizarralde, D., J.B. Gaherty, J.A. Collins, G. Hirth, and S.D. Kim, Spreading-rate dependence of melt extraction at mid-ocean ridges from mantle refraction data, *Nature, 432*, doi:10.1038/nature03140, 744-747, 2004.

Gaherty, J.B., D. Lizarralde, J.A. Collins, G. Hirth, and S.D. Kim, Mantle deformation during slow seafloor spreading constrained by observations of seismic anisotropy in the western Atlantic, *Earth Plan. Sci. Lett.*, doi:10.1016/ j.epsl.2004.10.026, 2004.

Kim, S.D., Spreading Rate Dependent Mid-Ocean Ridge Processes Expressed in Wesern Atlantic Lithosphere, Ph.D. Thesis, Georgia Institute of Technology, 2006.