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Key Points:
- Refining and reidentifying M sequence anomalies
- Verify globally coherent Jurassic geomagnetic field behavior
- Expand the oldest trace of the early Pacific plate formation and evolution

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Nature of the Jurassic Magnetic Quiet Zone

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Abstract The nature of the Jurassic Quiet Zone (JQZ), a region of low-amplitude oceanic magnetic anomalies, has been a long-standing debate with implications for the history and behavior of the Earth's geomagnetic field and plate tectonics. To understand the origin of the JQZ, we studied high-resolution sea surface magnetic anomalies from the Hawaiian magnetic lineations and correlated them with the Japanese magnetic lineations. The comparison shows the following: (i) excellent correlation of anomaly shapes from M29 to M42; (ii) remarkable similarity of anomaly amplitude envelope, which decreases back in time from M19 to M38, with a minimum at M41, then increases back in time from M42; and (iii) refined locations of pre-M25 lineations in the Hawaiian lineation set. Based on these correlations, our study presents evidence of regionally and possibly globally coherent pre-M29 magnetic anomalies in the JQZ and a robust extension of Hawaiian isochrons back to M42 in the Pacific crust.

1. Introduction

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 [e.g., *Courtillot and Le Mouel*, 1988]. This behavior not only allows us to constrain the physical mechanisms required to generate a planetary magnetic field [*Takahashi et al.*, 2005] but also allows past field history to be used as the basis of a timescale to date geologic events [*Gradstein et al.*, 2012].

Marine magnetic anomalies are a continuous record of Earth's geomagnetic field variations preserved in oceanic crust and have played a crucial role in documenting a detailed record of Earth's magnetic field history and plate tectonics over the past ~160 Myr [*Müller et al.*, 1997; *Gradstein et al.*, 2012]. The oldest part of the oceanic record, the Jurassic Quiet Zone (JQZ), occurs prior to ~157 Ma (pre-M29 chrons) and stands out as a unique period in magnetic field behavior [*Larson and Pitman*, 1972]. Unlike the Cretaceous Normal Superchron (CNS), which is a well-defined, prolonged period of almost single polarity (i.e., no reversals) with strong field intensity [*Prévot et al.*, 1990; *Biggin et al.*, 2012; *Tauxe*, 2006; *Tauxe et al.*, 2013], the JQZ appears starkly different. In contrast with the high field intensity of the CNS, bracketed by low reversal rates entering and leaving the superchron, the JQZ has low field intensity and high reversal rate [*Ogg et al.*, 2010], while field intensity increases and reversal rate decreases exiting the period [*Cande et al.*, 1978; *Sager et al.*, 1998; *McElhinny and Larson*, 2003; *Tivey et al.*, 2006; *Tominaga et al.*, 2008].

Although the anomalously low field intensity during the JQZ is well documented by paleointensity data and appears to be the weakest field intensity of the past 400 Ma [*Biggin et al.*, 2012; *Tauxe et al.*, 2013], the existence of field reversals during the JQZ is still under debate. The most recent Oxfordian-Callovian (Middle to Late Jurassic) magnetostratigraphy [*Ogg et al.*, 2010; *Przybylski et al.*, 2010; *Gipe*, 2013] documents the terrestrial reversal record from M28 to M39 and confirms multiple reversals within the JQZ. Deep-tow magnetic data from the Japanese magnetic lineation set in the western Pacific JQZ crust (Figure 1) have been interpreted as a continuous record of magnetic reversals, extending back to M44 [*Tominaga et al.*, 2008]. However, Pacific JQZ studies have focused on a single spreading center so that regional and global implications are unclear.

In this study, we analyze newly acquired high-resolution sea surface magnetic anomaly profiles, from the Hawaiian JQZ (Figure 1) for comparison with the Japanese JQZ magnetic lineations in order to investigate the coherency in the JQZ magnetic record. These new data provide more detailed insights of anomaly characteristics (shapes and amplitudes) than the widely utilized magnetic grid (e.g., EMAG2 (Earth Magnetic Anomaly Grid (2-arc-minute resolution) by *Maus et al.* [2009]) which is constructed from lower

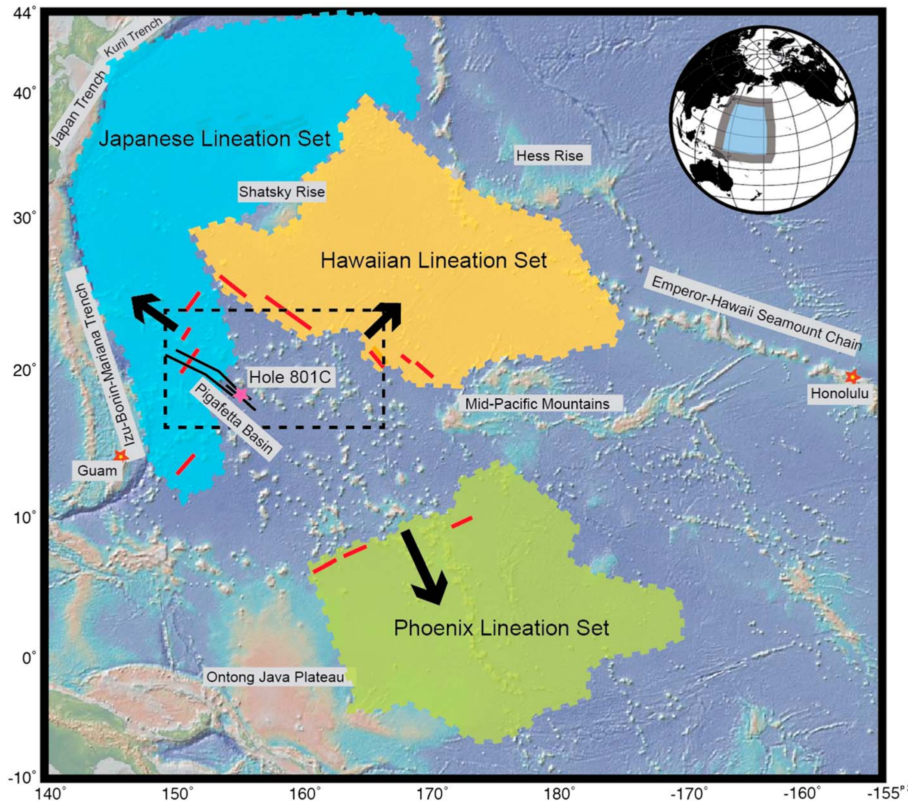

Figure 1. A summary map showing the western Pacific Jurassic Quiet Zone. Blue, yellow, and green colored areas indicate seafloor where, respectively, the Japanese, Hawaiian, and Phoenix lineation sets are identified [e.g., *Nakanishi et al*., 1989]. Arrows indicate the spreading direction of the early Pacific plate. Red lines indicate the location of the M29 lineations [*Nakanishi et al*., 1989]. The black solid lines indicate the locations of Japanese M anomaly profiles [*Sager et al*., 1998; *Tivey et al*., 2006]. The dotted square indicates the area shown in Figure 3. Underlying bathymetry is based on *Smith and Sandwell* [1997, v.18.1] map.

resolution data with irregular spacing. The Hawaiian anomalies are also located in the western Pacific, which means the comparison is inherently regional. Nevertheless, because of the large area of preserved Jurassic crust and high spreading rates, the Pacific JQZ record is the most complete [*Tominaga and Sager*, 2010] and highest fidelity recording [*Tivey et al*., 2006], so it is the most likely region to display significant large-scale correlations. Indeed, we find analogous anomaly shapes and amplitudes in the two anomaly sets, which we infer to be the result of global geomagnetic field behavior.

2. Background

The M series anomalies are identified in the oldest parts of all the major ocean basins [*Tominaga and Sager*, 2010, and references therein], but the most complete sequence of Late to Middle Jurassic anomalies is only available in the western Pacific (Figure 1). 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, representing the early evolution of the Pacific plate by the Phoenix-Izanagi-Farallon mid-ocean ridge system [*Nakanishi et al*., 1989] (Figure 1). Despite great water depth (~6000 m), only a few hundred meters of sediment cover the fast-spreading crust, which allows us to obtain a relatively high resolution magnetic anomaly record. Chron M29, currently dated at 157 Ma [*Gradstein et al*., 2012], is the oldest and most widely accepted magnetic lineation in the western Pacific marking the youngest end of the JQZ (Figure 1).

The origin and nature of the Pacific JQZ has mostly been documented from detailed studies conducted in the Japanese lineations of the western Pacific Pigafetta Basin (Figure 1). Following an aeromagnetic survey that revealed the presence of lineated anomalies from M29 to M38 (~163.8 Ma) [*Handschumacher et al*., 1988;

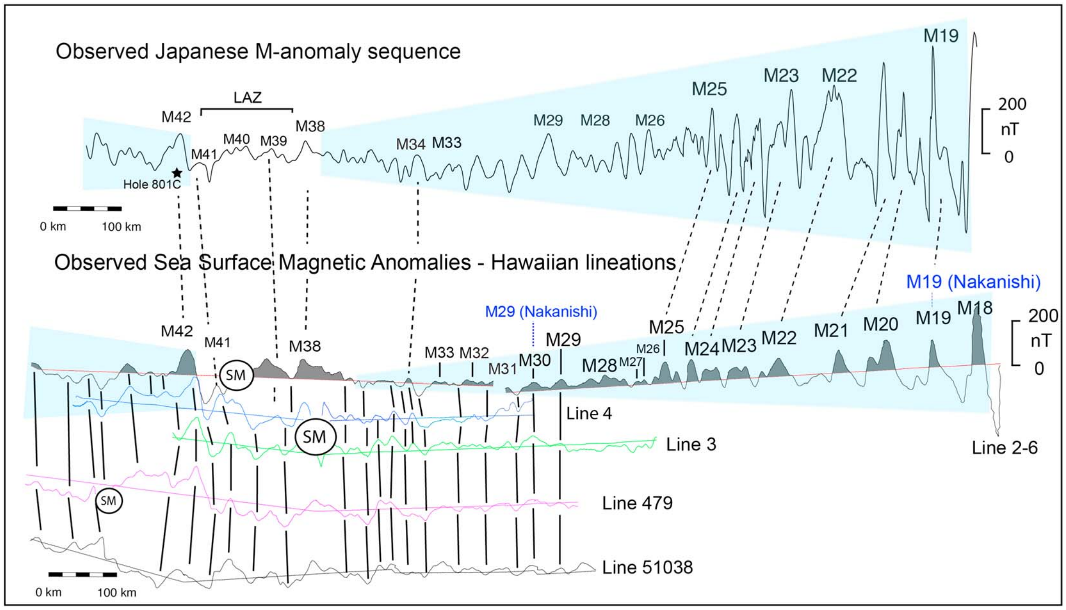

Figure 2. A summary of the Japanese JQZ magnetic anomaly record (upward continued to the sea surface) and Hawaiian JQZ sea surface M anomaly profiles. Anomalies are all plotted as observed, without phase shifting. Chron labels in the Japanese lineation record are based on *Tominaga et al.* [2008]. Black and blue letters in chron numbering on the Hawaiian profiles are based on this study and *Nakanishi et al.* [1989], respectively. As explained in the text, we renumbered anomalies M24–M29 based on magnetic modeling. Solid lines between the Hawaiian profiles indicate anomaly correlations. Dashed lines show correlations between the Japanese and Hawaiian magnetic anomalies. The locations of each of the Hawaiian profiles are shown in Figure 3. SM: seamount. The LAZ period from the Japanese lineation is unfortunately distorted in the Hawaiian profiles due to seamount anomalies, so it is difficult to confirm this period from these sea surface data.

Gradstein et al., 2012], two deep-tow magnetic surveys were conducted in the same region of the Pacific Japanese lineations [*Sager et al.*, 1998; *Tivey et al.*, 2006; *Tominaga et al.*, 2008]. The first survey collected two 800 km long deep-tow magnetic profiles, extending the correlations of *Handschumacher et al.* [1988] from M38 to M41 (~167.4 Ma) [*Sager et al.*, 1998; *Gradstein et al.*, 2012]. The second survey extended the correlations to M44 (~169.9 Ma) [*Tominaga et al.*, 2008; *Gradstein et al.*, 2012]. These deep-tow data revealed lineated magnetic anomalies throughout the time period from M38 to M44 [*Tominaga et al.*, 2008; *Gipe*, 2013]. Magnetostratigraphic studies [*Ogg et al.*, 2010; *Przybylski et al.*, 2010; *Gipe*, 2013] correlate the terrestrial magnetic records to the polarity block models produced from the midwater level upward continued anomalies by *Tominaga et al.* [2008] and confirm that the Japanese M anomaly sequence contains magnetic reversals back to M39. The nature of the higher-frequency anomalies observed in the deep-tow profiles is still uncertain and may record either short-lived polarity periods or geomagnetic field intensity fluctuations [*Tominaga et al.*, 2008].

A monotonic decrease in anomaly amplitude has been widely observed in the M anomaly sequence in all three lineation sets going backward in time to M29 [e.g., *Larson and Chase*, 1972; *Hilde et al.*, 1976; *Cande et al.*, 1978]. In the Japanese lineation set, anomaly amplitude decreases back 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 [*Tivey et al.*, 2006]. Prior to the LAZ, correlatable anomalies reappear and become larger in amplitude further back in time starting at M42 (167 Ma) and continue until M44 (~170 Ma) (Figure 2). Chron M42 provides a tie with downhole magnetization logs and a precise date from Ocean Drilling Program Hole 801C (Figure 3) [*Koppers et al.*, 2003] that strongly suggests that polarity reversals are present, consistent with the overlying anomaly sequence [*Steiner*, 2001; *Tivey et al.*, 2005].

The Hawaiian lineations offer an analogous set of Jurassic-aged lineations albeit at a slightly slower spreading rate [*Larson and Hilde*, 1975]. *Larson and Hilde* [1975] used the Hawaiian lineations as the basis for their M series magnetic anomaly correlations, which were subsequently extended to M25 and M29 [*Cande et al.*, 1978; *Nakanishi et al.*, 1989, 1992; *Channell et al.*, 1995].

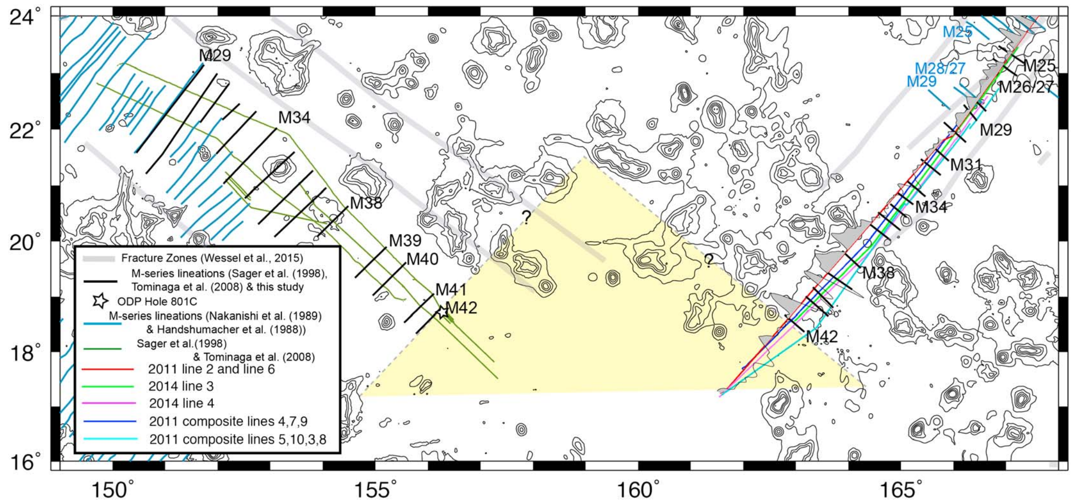

Figure 3. A detailed map of the Japanese and Hawaiian lineations (a dotted box indicated in Figure 1) resulted from previous deep-tow and new sea surface magnetic anomaly profiles, respectively. Blue colored lineations and chron numbers are after *Nakanishi et al*. [1989]. In Japanese profiles, black colored chron numbers and solid lines are based on *Sager et al*. [1998] and *Tominaga et al*. [2008]. In Hawaiian profiles, black colored chron numbers and solid lines are refined and newly identified chrons and lineation in the Hawaiian JQZ based on the correlation in Figure 2. Underlying satellite-gravity-derived bathymetry is contoured with 1000 m interval [*Smith and Sandwell* 1997, v.18.1]. Light gray color lines indicate fracture zones traced by *Wessel et al.* [2015].

3. Method

We obtained a total of 2200 and 1370 km of high-quality sea surface marine magnetic profiles of the Hawaiian anomaly sequence during the TN272 cruise on R/V *Thomas G. Thompson* (2011) and SKQ2014S2 cruise on R/V *Sikuliaq* (2014), respectively, using a SeaSpy Overhauser magnetometer with a sampling frequency of 1 Hz and a resolution of 0.1 nT. We specifically targeted a spreading corridor that minimizes volcanic overprint (based on satellite-detected seamounts) to limit interference with the Jurassic basement magnetic signals (Figure 3).

To extract crustal magnetic signals, the magnetic anomaly data were corrected for ship-to-sensor offset using the ship's GPS, ship heading effects, diurnal effect using time-shifted Guam magnetic observatory data, and present-day ambient geomagnetic field values using the International Geomagnetic Reference Field (IGRF-12) [*Thébault et al*., 2015]. The coherency and correlation in anomaly character between the Japanese and Hawaiian mid-ocean ridge systems was verified by comparing the new data with the deep-tow Japanese M anomaly sequence that is upward continued to the sea surface level [*Sager et al*., 1998; *Tominaga et al*., 2008] (Figure 2).

We first located pre-M18 magnetic chrons from M18 to M29 based on the location of a previously identified Hawaiian lineation by *Nakanishi et al*. [1989] (Figure 2); then, we reexamined the labeling of each chron by comparing to the Japanese M anomaly sequence (Figures 2 and 3).

4. Results

The new Hawaiian sea surface marine magnetic anomaly profiles show excellent repeatability in anomaly character (i.e., shape and amplitude) among the 2011 and 2014 survey lines over a ~20 km wide corridor (Figure 2), demonstrating that these magnetic anomalies are lineated. When compared to the Japanese M anomaly sequence, we were able to establish one-to-one correlations between peaks and troughs of each anomaly from M19 to M42 (Figure 2). Lines 3, 479, and 2–6 crossed over seamount flanks in pre-M37 seafloor, disrupting anomaly character (Figure 3). Nevertheless, the correlations among the new lines are clear.

The monotonic decrease in anomaly amplitude back in time, originally observed by *Cande et al*. [1978] back to M29, is pronounced and can be extended back to M38, where it is preceded by low-amplitude anomalies between M39 and M41 (Figure 2) in the Hawaiian sequence. A minimum amplitude around M41 is preceded by an increase in anomaly amplitude from M42 and older anomalies in the Hawaiian record.

Each of the magnetic anomalies from M19 to M24 in the new data is consistent with those of *Nakanishi et al.* [1989]. However, examining the locations of M25–M29 in our survey corridor clearly indicate that the locations of M26 and M27 should be shifted to the two peak-to-trough combinations adjacent to the oldest end of the M25 anomalies (Figure 2). This shift is followed by further shifts of the M28 and M29 lineations by about 40 km to younger seafloor with respect to the originally identified M29. For these correlations, we used a phase shift of −160°, which is the average of values in the M29–M42 sequence based on the *Larson and Sager* [1992] paleopole.

5. Discussion and Conclusions: The Globally Coherent Jurassic Magnetic Signals

Currently available isochron maps that document plate tectonic history of the western Pacific are limited to identifying M29 as the oldest and most commonly accepted chron [e.g., *Müller et al.*, 2008] in the Japanese and Hawaiian lineation sets [*Cande et al.*, 1978; *Nakanishi et al.*, 1989, 1992; *Channell et al.*, 1995]. Although Japanese pre-M29 anomalies have been extensively studied over the past two decades [*Handschumacher et al.*, 1988; *Sager et al.*, 1998; *Tivey et al.*, 2006; *Tominaga et al.*, 2008], there has been no comparable example of pre-M29 anomalies from other anomaly sets to verify the anomaly record.

The correlation and coherency in anomaly character between our new, high-resolution Hawaiian profiles and the previously established Japanese pre-M29 lineation sequence supports a more global relevance of these pre-M29 anomalies in the JQZ (Figure 2). Except for the places where the extension of sediment-buried seamount flanks distort anomaly shapes and amplitudes (SM in Figure 2), the distinctive anomaly characters of M19, M25, M29, M34, M38, and M42 guide the identification of all chrons between M29 and M42 and make it possible for the first time to confidently establish a new extension of the Hawaiian M anomaly lineation sequence in the oldest Pacific crust.

An equally important finding that confirms the global coherency of the JQZ magnetic signals is their amplitude envelope (Figure 2). Regionally, the backward-in-time decrease in anomaly amplitude in the pre-M19 sequence in the western Pacific has long been recognized [i.e., *Larson and Pitman*, 1972; *Cande et al.*, 1978] and originally defined the extent of the JQZ [*Heirtzler and Hayes*, 1967; *Hayes and Pittman*, 1970; *Vogt et al.*, 1971; *Larson and Chase*, 1972; *Hayes and Rabinowitz*, 1975]. Globally, the anomalously low field intensity during the Mesozoic (~140–180 Ma) is a well-documented phenomenon based on various rock magnetic records [*Prévot et al.*, 1990; *Tarduno et al.*, 2001; *Biggin and Thomas*, 2003; *Tauxe*, 2006; *Tauxe et al.*, 2013]. Based on the premise that relative amplitude change in marine magnetic anomalies can be used as proxy for geomagnetic field intensity behavior [*McElhinny and Larson*, 2003], the Japanese pre-M29 anomaly sequence demonstrates that Jurassic field intensity decreased back in time until M38, bottomed out around M41 but then at M42 and further back in time shows increased intensity (Figure 2) [*Tivey et al.*, 2006]. The new Hawaiian magnetic data follow the same amplitude trend and, together with the excellent correlation and coherency in anomaly character, support the idea of a regionally and possibly globally coherent geomagnetic field behavior during the Jurassic (Figure 2). A combined Japanese and Hawaiian pre-M29 record can be compared with terrestrial magnetostratigraphic records [*Ogg et al.*, 2010] to provide a framework for resolving Jurassic geomagnetic reversal history.

This extension of the Hawaiian M anomaly sequence in the pre-M19 magnetic lineations allows us to define the oldest and correlatable magnetic lineations in the western Pacific to the end of the available record. To date, widely available Pacific tectonic reconstruction models [e.g., *Müller et al.*, 2008] still incorporate the location of M29 (Figure 1) [*Nakanishi et al.*, 1989] as the oldest recognizable trace of the mid-ocean ridge systems that formed the present-day Pacific plate. Spreading directions and rates in pre-M29 seafloor has relied largely on backward extrapolation of the younger record [*Crosby et al.*, 2006; *Müller et al.*, 2008; *Seton et al.*, 2012]. Our new Hawaiian lineation record combined with the Japanese pre-M29 anomaly sequence make it possible to extend the location of the oldest recognizable trace of the mid-ocean ridge systems (Figures 1 and 3) back to M42 (167 Ma), inviting an update of the Pacific plate tectonic history in pre-M29 time period.

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