The implications of long-lived asymmetry of remanent magnetization across the North Pacific fracture zones

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Large marine magnetic anomalies accompany the Pacific fracture zones (FZs) for thousands of kilometers. Although the origin of these anomalies is poorly understood, their underlying magnetization contrasts should reflect the temporal record of crustal accretion as well as geomagnetic field variations. Here we present an analysis of archival and newly collected magnetic anomaly profiles measured across three FZs from the North Pacific Cretaceous Quiet Zone (120.6 to 83 Ma) that are characterized by a remarkably uniform shape. Forward and inverse modeling indicate that these anomalies arise from remanent magnetization, with enhanced remanence located on one side of each FZ along the entire studied area. A comparison of geochemical and magnetic data from active ridge discontinuities and transform faults suggests that elevated iron content near segment ends is likely responsible for the observed anomalies in the Cretaceous Quiet Zone as well. A more complex magnetization setting is observed where the FZs contain multiple faults. There, the simple model of one-sided enhancements is only partly valid. Comparison between 3D forward modeling of the Quiet Zone magnetization and the calculated magnetization contrasts found across the Pioneer and Pau FZs suggests that the intensity of the geomagnetic field during the Cretaceous superchron had less than 50 percent variability about its average value. No major trends in the strength of the geomagnetic field during the superchron are observed. The presence of long-duration (>30 m.y.) zones of enhanced magnetization along the young/old sides of the Pioneer/Pau FZs (both left-stepping) requires some long-lived asymmetry in crustal construction processes near ridge-transform intersections. Although the underlying mechanism that controls this long-lived asymmetry remains unclear, absolute plate motions might explain this asymmetry. Shorter period (few m.y.) variations in the amplitudes of the enhancements probably result from oscillations in crustal construction.

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1. Introduction

Marine magnetic anomalies, typically measured along the direction of seafloor spreading, are used to study the geomagnetic reversal sequence as well as the kinematics of lithospheric plates (using polarity and skewness). The integrated magnetization of the oceanic crust also reflects its tectono-magmatic evolution (i.e., geochemistry and magnetic source layer geometry) and fluctuations in geomagnetic field behavior (Gee and Kent, 2007). For example, higher amplitude magnetic anomalies are associated with iron-rich lavas, particularly near ridge crest discontinuities (Sempere, 1991; Carbotte and Macdonald, 1992), and variations in the source layer thickness also appear correlated with anomaly amplitude (e.g., Bazin et al., 2001). Coherence between multiple profiles and similarity globally (e.g., Cande and Kent, 1992; Bowers et al., 2001) suggest that many short wavelength magnetic anomalies (“tiny wiggles” within constant polarity intervals) are related to variations in geomagnetic field intensity.

Magnetic anomalies observed across fracture zones (FZs), where crust of different age that formed at two adjoining spreading segments is juxtaposed, can provide insights into aspects of crustal construction and, potentially, geomagnetic field behavior. Indeed, studies from the fast spreading East Pacific Rise (Carbotte and Macdonald, 1992) and from the intermediate spreading Juan de Fuca-Gorda ridge area (Detrick and Lynn, 1975; Vogt and Byerly, 1976) revealed high-amplitude magnetic anomalies that parallel the transform faults and FZs. These higher amplitude anomalies have been attributed to enhanced low pressure fractionation leading to iron enrichment at colder segment ends. Transform faults may also be characterized by variations in crustal thickness (Barth, 1994; Gregg et al., 2007) and secondary volcanism (Menard and Atwater, 1969) or alteration (Hosford et al., 2003) that may modulate magnetic anomaly amplitudes. For example, a pattern of more positive magnetization at the ends of slow-spreading segments, regardless of the polarity, has been interpreted as reflecting a significant contribution from induced magnetization, presumably as a result of serpentinization of mantle peridotite (Twigt et al., 1983; Collette et al., 1984; Tivey and Tucholke, 1998; Hosford et al., 2003).
In this paper, we focus on anomalies over FZs in the North Pacific that separate fast to intermediate-spread crust located in the Cretaceous Quiet Zone (the term Quiet Zone will be used here when discussing oceanic crust formed in the period between chron M0 and C34, 120.6 to 83 m.y., respectively; Cande and Kent, 1995; He et al., 2008). The North Pacific provides an ideal location to study the origin of FZ anomalies owing to the simple polarity setting, reducing the number of edge-effects, and the good magnetic coverage available. In addition, time-dependent magnetization changes that might affect young crust near active transforms (e.g., from ongoing alteration) should be minimal in Cretaceous crust.

Archival and newly collected magnetic and bathymetry data from the Pau, Pioneer and Murray FZs (Fig. 1), show a remarkably uniform magnetic signature for nearly 2000 km (Fig. 2). We examine the origin of magnetization along the FZs using forward and inverse models and show that the magnetic contrast typically originates from a one-sided enhancement of remanent magnetization. We suggest that this remanent enhancement is likely controlled by the degree of fractionation and iron content in the crust. We next show the limitations of our model in regions where complex crustal accretion processes took place. The Pau and Pioneer FZs provide two very long records of magnetization contrasts. These magnetization variations could also preserve information about the geomagnetic field (e.g., the degree of field variability, long-term trends in the strength of the dipole) during the unique 37 m.y. Cretaceous normal superchron (CN5, the time-equivalent of the Quiet Zone). We discuss possible scenarios and inferences on the long-term geomagnetic field behavior using a set of 3D forward models. Finally, we conclude with new insights and future approaches in the study of crustal accretion near ridge-transform intersections (RTIs).

2. Tectonic setting

We compiled topographic and sea-surface total-field magnetic profiles collected within the Quiet Zone crust in the North Pacific, a region formed by relatively smooth spreading along the Pacific-Farallon spreading system (Atwater et al., 1993). At the end of the Cretaceous Superchron the Pacific-Farallon Ridge in this region was dominated by the right-stepping Murray FZ which offset the ridge axis about 400 km, and the left-stepping Pioneer, Pau and Mendocino FZs which collectively offset the ridge axis roughly 1000 km (Fig. 1). The Murray FZ is topographically complex and is composed of many small-offset strands that vary in width over short distances. The Mendocino FZ in this region is also very complex, having an enormous left-stepping offset which responded to the major counter-clockwise change in plate motion around chron C33R by developing numerous high relief, short-offset ridge segments between 195°E and 210°E (Atwater et al., 1993). The Pioneer FZ has the most straightforward topographic signature; the fracture zone is generally characterized by a simple topographic step up from the older, southern side to the younger, northern side. This step is largest, roughly 500 to 700 m, in the eastern, younger end of the Quiet Zone and gradually diminishes to about 300 to 500 m, towards the western (older) end of the Quiet Zone (see Figs. 2e and 3b). Although in places the topography of the Pau FZ is characterized by a small escarpment separating the older southern side from the younger northern side, as along most of the Pioneer FZ, in the section south of the region where the Mendocino FZ developed multiple splays at chron C33R, the Pau is often characterized by a narrow ridge that can probably be attributed to extensional stresses during the ridge re-orientation (Hall and Gurnis, 2005). Cooling and subsequent subsidence of the Pacific crust has created a long wavelength (~40 km) flexural bending that overprints the initial topography of the fracture zones (Sandwell, 1984). Overall, the topography and gravity signatures of the studied FZs reflect the cumulative effects of both the spreading-related processes (e.g., by modulating the thickness of the crust) and post-spreading lithospheric processes (e.g., changes in topography related to the changes in plate motion and local mantle convections, Hall and Gurnis, 2005).

Because of the sparsity of east-west oriented magnetic lines north of the Pau FZ, the exact location of anomalies 34 and 330 between the Pau and Mendocino FZs is unknown. However, the swathmap bathymetry at 205°E shows that the orientation of abyssal hills north of the Pau FZ (Fig. 4c) have the post C33R azimuth which constrains C33R crust to lie to the west. In addition, the large amplitude of the

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**Fig. 1.** North Pacific tectonic map. Thick lines delineate anomalies M0 and 34 that mark the old and young edges of the Cretaceous Quiet Zone, respectively. The studied FZs are highlighted with black boxes. Thin black line outlines cruise track MGLN/44MV. Thin gray lines define the interpolated ages as described in the text.
Fig. 2. Oblique projections of Pau (a–c) and Pioneer (d–f) FZs. The observed magnetic anomalies (a, d, projected over the free-air gravity map of Sandwell and Smith (1997)), bathymetry (b, e) and 2D inversion solutions (c, f, positive shaded) are plotted with positive values projected westward, as for all the figures in this study. Locations of archival data were corrected to match the synthetic trace (thin red lines) of the FZs. Light gray shaded areas are the −15 and −25 mGal free-air gravity contours for the eastern and western plots, respectively. The corners of the black squares shown in panels c and f delineate the locations of the enlarged maps shown in Fig. 4. All inversion models in this study assume a kilometer thick magnetic source layer starting at the seafloor depth. Other parameters: present inclination and declination was determined for every profile, remanence directions were calculated using the interpolated paleopoles of Wessel and Kroenke (2008) based on the interpolated ages shown in Fig. 1. The track lines correspond with zero value for the anomalies and inversions panels, and with the average depth for the bathymetric panels.
magnetic anomaly over the Pau FZ between 202°E and 204°E suggests that anomaly 34 is located near 202°E as we will discuss later in the text.

Spreading rates and ridge geometry are only constrained outside of the Quiet Zone edges (Fig. 1). In the studied area, half spreading rates just prior to and just after the Quiet Zone were 50 mm/yr and 33 mm/yr, respectively. The anomaly pattern requires a ridge jump that may have taken place early in the superchron (Rea and Dixon, 1983; Atwater et al., 1993), in crust older than the crust studied here (Fig. 1). To estimate seafloor ages within the Quiet Zone we use the half spreading rate between anomalies 34 and 33 (33 mm/yr), the width of Quiet Zone crust as measured along the Pioneer FZ (2420 km), a ridge jump (700 km) assumed to have occurred older than the oldest profile data considered here, and assume a constant deceleration to interpolate spreading rates. These assumptions result in a fast (85 mm/yr) half spreading rate for the old-end of the Quiet Zone which is 35 mm/yr faster than the rate observed for M0 to M4. Using these interpolated velocities we predicted the ages within the Quiet Zone (Fig. 1). Shallow remanence directions and nearly east–west orientation of the FZs result in calculated magnetizations that are only slightly susceptible to the pole uncertainties. In fact, even a conservative 20° misfit in the resultant skewness angle (reflecting uncertainties in the orientation and position of the studied blocks, uncertainties in the position of the paleomagnetic poles, and uncertainties in the age of the crust) would have only a minor effect on the magnetization (see below and Fig. 7a and b). Therefore, although the calculated spreading rates may be an overestimate of the true rates (e.g., Heller et al., 1996) they do not affect the results of this study.

Fig. 3. Magnetization contrasts from the Pau (a) and Pioneer (b) FZs. The upper diagrams show the topographic escarpments of the FZs as calculated from the single beam data shown in Fig. 2b and e. Estimates of magnetization contrasts (lower panels) were obtained using both the peak-to-trough amplitudes of the deskewed anomalies (red circles) and the hand-picked magnetization contrasts measured from the inversion solutions shown in Fig. 2c and f. The error bar for the magnetization contrasts is calculated by taking the difference between the average value of the first and last quintile of the profile (darker portion of the representative profile). This error estimate mimics the uncertainty of the longer wavelength signal (i.e., uncertainty in the location of the baseline), located outside the influence of the FZ magnetization. A representative profile and the corresponding estimated contrasts and error are shown in the inset. Temporal uncertainties increase from near zero in the end of the Quiet Zone to a few million years near the 110 Ma crust.
3. Data and methods

The magnetic anomaly data used here were gathered from the U.S. National Geophysical Data Center (NGDC) and augmented by recent magnetic, swath bathymetry, and 3.5 kHz seismic profiler data collected aboard the R/V Melville (cruise MGLN44MV). Overall, we use 180 profiles that cross the FZs at an angle larger than 45° and extend for at least 40 km on each side of the FZ. The average sampling distance between successive magnetic measurements, which were primarily collected in the 1960s, is 1.7 km ($\sigma = 1.5$ km). The geomagnetic field at the time of acquisition of the observed magnetic profiles was subtracted using the appropriate coefficients from the International Geomagnetic Reference Field (ICRF 10; Macmillan and Maus, 2005). We used the well-navigated swath bathymetry data to constrain a best-fit line for each FZ (pseudo synthetic flow-line). These synthetic flow-lines were used as the reference for a latitudinal re-positioning of the poorly navigated profiles. The correction was based on the along-track single-beam bathymetry soundings. The average latitudinal correction was 3 km.

The magnetic data were measured above an uneven seafloor and due to the absolute northward motion of the Pacific Plate and the curvature of the studied FZs, the magnetic anomalies are increasingly skewed in the old parts of the Quiet Zone. To account for these effects we calculated equivalent magnetizations using the Fourier method of Parker and Huestis (1974). The resulting inversion solutions offer estimates of the magnetization across FZs for a uniform 1 km thick magnetic source layer. The thickness of the imaged sedimentary sequence was minimal throughout the studied area (<50 m), allowing us to use seafloor depth as the top of the magnetic source layer. We have estimated remanence directions using the interpolated locations of chron M0 and C34 paleomagnetic poles of Wessel and Kroenke (2008) (58°N, 350°E and 51°N, 335°E, respectively), using the estimated crustal ages as described above.

Because the results from the two-dimensional (2D) inversions are poorly constrained at long and short wavelengths, we applied bandpass filtering allowing wavelengths between 10 and 200 km to pass unattenuated. In the case of seafloor spreading anomalies the magnetization solution is often adjusted by addition of an annihilator, a magnetization distribution for a given topography and thickness of source layer that produces no external magnetic field (Parker and Huestis, 1974), in order to balance the positive and negative sources that are assumed to be of equal magnetization. Since no such constraint is available for the FZs anomalies, we do not apply the annihilator and rather view the results as an estimate for the relative magnetization contrasts.

4. Magnetic observations and their inversion solutions

The magnetic anomaly profiles are remarkably uniform across the Pioneer and Pau FZs for nearly 2000 km (Fig. 2a and d), with a mean peak-to-trough amplitude of 340 nT ($\sigma = 110$ nT). The 2D inversion solutions of these profiles show that an enhanced magnetization zone is located, for most of the studied area, on one side of the FZs (Fig. 2c and f). This zone is located on the younger, northern side of the Pioneer FZ whereas it is located on the older, southern side of the Pau FZ. These enhanced magnetization zones begin on, or very close to, the morphological slope that marks the fault-line and gradually diminish over a distance of 15 to 40 km (Fig. 2). The absolute values of crustal magnetizations are unknown, yet the anomalies require a typical contrast in magnetization of 5 to 16 A/m (Fig. 3) for a 1 km thick source layer. If there are no spreading discontinuities between the Pioneer and Pau FZs, as appears to be the case, one of the more intriguing observations in this study is that the enhanced magnetization zones north of the Pioneer and south of the Pau are at opposite ends of the same ridge segment.

The peak-to-trough amplitude of the 2D inversion solutions across the Pau and Pioneer FZs, when viewed with respect to their flow-line locations, provides a temporal view of the evolution of magnetization contrast during the Quiet Zone (Fig. 3). Quantifying these temporal changes is somewhat subjective, since the amplitude of the magnetization contrast depends on the location where one picks the maximum and minimum magnetization values. Because the inversion process applies a bandpass filter to the magnetic data, variations in the peak-to-trough amplitude of the inversion solutions may be influenced by the parameters of the bandpass filter. We measured the peak-to-trough amplitude of both the deskewed anomalies and the inversions on the side of the anomaly facing the fracture zone as a measure of the magnetization contrasts. Both of these values reveal similar patterns (Fig. 3), confirming the minimal effect of bandpass filtering.

In general, the magnetization contrasts along the Pioneer FZ display values averaging around 8 A/m (Fig. 3). Two episodes of higher values, averaging about 15 A/m, occur at 101 and 93–91 Ma. A zone of higher magnetization contrasts at the Pau FZ between 90 and 85 Ma is probably the result of the presence of reversed polarity crust, associated with chron C33R, located on the northern side of the FZ. On crust older than 90 Ma, the average magnetization contrast across the Pau is similar to the Pioneer (about 8 A/m). Higher scatter at the Pau FZ is apparent in the western region, between 108 and 114 Ma.

Although a one-sided magnetization enhancement accounts for observations along FZs characterized by a single fault strand (e.g., Fig. 4c and d), the calculated magnetization deviates from the simple...
one-sided enhancement model in more structurally complex areas. Multiple enhancement zones appear to be present in places where the FZs are composed of multiple sub-parallel faults. Here each fault is usually associated with a single, distinctly separated enhancement zone (e.g., Fig. 4a), but may in places also be associated with an unusually low magnetization (Fig. 5, northern strand). A prime example of the multiple and complex magnetization setting is found near the Murray FZ, where three strands of faults are found in the Quiet Zone (Fig. 5). These faults merge into a single fault system during the major change in plate motion that took place in chron C33R. Each strand is composed of several sub-parallel faults, which together have accommodated the lateral offset. The enhanced magnetization zone is located south of the southernmost strand (see also Fig. 6c and d) but is found on the north side of the two other strands. Later in the text we will further discuss the possible mechanisms that created these magnetization contrasts. For the purpose of this paper, when investigating the evolution of the magnetization contrasts, we will focus on the Pau and Pioneer FZs as their structural and magnetization settings display a relatively simple pattern.

5. Discussion

5.1. Nature of magnetization

The magnetization contrast that generates FZ anomalies may be either remanent or induced and may vary at different spreading rates and tectonic settings. For example, the enhanced magnetization at slow-spreading segment ends may reflect a significant induced magnetization contribution (Pockalny et al., 1995; Tivey and Tucholke, 1998; Hosford et al., 2003) from serpentinized peridotites. In contrast, the thermal structure at fast-spreading transforms suggests that little serpentinization may occur (e.g., Gregg et al., 2007) since the mantle will likely be at temperatures above the stability field for serpentine (<500 °C; Chen, 1988; Ulmer and Trommsdorff, 1995). Several lines of evidence suggest that FZ magnetic anomalies at fast-spreading ridges are dominantly remanent in origin. The most compelling evidence comes from the shape of the FZ anomalies, which change abruptly across isochrons (Figs. 2d and 5) implying that their magnetization is dominated by thermoremanent magnetization. If induced magnetization were dominant then the anomalies should show a pattern of positive anomalies to the south and negative anomalies to the north of the fracture zone, regardless of the polarity of magnetization of the confining crust. This predicted anomaly pattern is not observed (Figs. 6c and 7d).

To quantify the contribution of induced magnetization we make use of a modified version of the method first introduced by Tivey and Tucholke (1998). The premise that underlies this method is that magnetic blocks (single spreading segments in Tivey and Tucholke (1998); here, the confining crust of the studied FZs, Fig. 6a) have similar magnitude of magnetizations on opposite sides of a polarity reversal (far from the boundary itself), when remanence dominates the magnetization. Therefore, adding and dividing by two the results from the inversion solutions collected across FZs and from opposing sides of a polarity reversal (i.e., isochron) provides an estimation of the amount of induced magnetization (Fig. 6b). Similarly, the subtraction of the magnetizations from opposing sides of a polarity reversal (and dividing by two) yields the average remanent magnetization in the crust (Fig. 6b). We carried out this approach in the southern strand of the Murray FZ, from both sides of anomaly 34, where sufficient data exist to stack multiple profiles. Presumably, local variations in the magnetic signal are averaged out by the stacked profiles (Fig. 6d). The results from this exercise confirm that more than 90 percent of the
magnetic signal originates from remanent magnetization (Fig. 6d), with induced magnetization apparently contributing less than ~2 A/m of the magnetization contrast.

Comparison of the observed anomaly data with two- and three-dimensional forward models near the Pioneer FZ where the location of polarity reversals is well defined, further supports a remanent magnetization as the source of the anomalies (Fig. 7). The observed anomalies require a distinct asymmetry in the magnetization, with an elevated magnetization located north of the FZ, regardless of the polarities of the confining crust (i.e., more positive magnetization within the Quiet Zone crust and more negative magnetization within the C33R crust). Particularly the anomalies within the Quiet Zone crust, where both side of the FZs are normally magnetized, require an enhanced magnetization zone (for example see west region of Fig. 7d).

Although the observations above strongly suggest that the observed FZ magnetic anomalies are remanent in origin, it is conceivable that the remanence along the FZ might be acquired later than for crust far from the transform. Such secondary magnetization could result from chemical acquisition (e.g., alteration, hydrothermal

Fig. 6. Data from the southern strand of the Murray FZ illustrating how induced and remanent magnetization contributions may be estimated. (a) Schematic magnetization pattern near the southern strand of the Murray FZs and the location of two representative profiles shown in panel b. (b) Two conceptual end-member models of magnetization setting (left) with their predicted results shown on the right. The upper model assumes only enhanced remanence as the source of the anomalies whereas the lower model assumes that the anomalies result from induced magnetization near the FZ. (c) Observed magnetic anomalies, positive values are projected westward, color coded with respect to the two stacks. (d) Stacks of the bathymetry and 2D inversion solutions shown in panel c. Stacks of the solutions west (red, 6 profiles) and east (blue, 7 profiles) of chron C34 are shown with standard errors. The resultant calculated remanence contribution is shown in the top most plot. Contribution from induced magnetization is shown below. Tie point used in the stacking procedure was the steepest gradient of bathymetry.
activity) or from post-accretion volcanic activity (e.g., the “leaky" transforms of Menard and Atwater, 1969) that may overprint the original remanent magnetization. For example, a “leaky" transform near the end of the Quiet Zone might result in magnetizations with mixed polarities that would not be expected to coincide with the isochron and would probably not generate a uniform signature over many million of years. Moreover, secondary volcanism is likely to fill the fractured area and create a magnetic signature that is centered along the FZs (e.g., Gregg et al., 2007) instead of being offset to one side. Acquisition of chemical magnetization should also have significant variability both spatially and temporally, and should result in spatial disassociation between the magnetization of FZs and isochrons. Therefore, we argue that secondary magnetization may only have a negligible contribution to the magnetization of the studied FZs.

Curved abyssal hills approach the FZs in several localities and are located on the younger (north) side of the Pau and Pioneer FZs implying that they were accreted in the outside corner of the RTIs (e.g., see Fig. 4). This observation suggests that curvature is not related to post-spreading shearing (transform fault-related) but rather reflects the original curved orientation of the abyssal hills (“J ridges", presumably formed as a result of the change in the stress field near the RTI (Morgan and Parmentier, 1984)). There is potentially a link between J ridges and geochemistry if these are formed as propagating cracks, where one might expect more fractionation (Sinton et al., 1983). The magnetization enhancement near the Pau and Pioneer FZs, located in their old and young sides, respectively (Fig. 2), shows no spatial correlation to the curved abyssal hills (Fig. 4). We conclude therefore that the enhancement of magnetization near the studied FZs is not dominated by vertical axis rotations (no bathymetric evidence is found for rotations) or by the propagation of ridges toward the transform faults.

5.2. Source of magnetic enhancement

The one-sided enhancement may result from an asymmetric thickness of magnetic source layer (e.g., ponding of extrusives at segment ends) or from a zone of iron enrichment located at segment ends. Currently, neither seismic nor geochemical data are available to

Fig. 7. The enhancement in remanent magnetization north of the Pioneer FZ (straddling the end of the Quiet Zone), as been calculated using 2D and 3D forward modeling. (a, b) Projected bathymetric (shaded) and magnetic profiles compared to magnetic 2D forward models. The four profiles are from bottom to top: magnetization setting used in the forward models, deskewed anomalies, observed anomaly, and result from the forward 2D modeling. Gray lines in the pole-reduced profile illustrate the effect of 20° uncertainties in theta that result from uncertainties in the paleomagnetic pole position and location of the ridge axis at the time of accretion. Locations of these profiles are shown in panel d. The bathymetric profiles were used as the top of a kilometer thick magnetic source layer. (c) Magnetization setting for the 3D forward modeling shown in panel d. (d) Predicted anomalies (red) as calculated by 3D forward modeling and compared with the observed anomalies (black) projected over the bathymetry that was used in this model (1 km source layer). The anomalies are plotted with positive values projected westward. Black stars delineate the location where the gradient of magnetization is steepest as calculated from the 2D inversion solutions. Gaussian smoothing across the reversal boundary is 2 km. The northern two flow-line profiles were used to calculate magnetization of 6 A/m at the crust located far from the fracture zone.
distinguish these two different mechanisms in the studied area. Nonetheless, based on the characteristics of the magnetic contrasts, and on data gathered from dense surveys at the Clipperton Transform, a few initial suggestions can be made.

We can estimate the amount of source layer thickening required to account for the observed enhanced magnetization zone in the following manner. We use two flow-line parallel magnetic anomaly profiles across anomaly 34 away from the Pioneer FZ (Fig. 7d) to provide an estimate of the source layer magnetization. A 2D inversion of these data, assuming a source layer thickness of 1 km, yields magnetization values of ±6 A/m. For anomaly profiles crossing the FZ entirely within the Quiet Zone, a uniformly magnetized layer (+6 A/m) would require an increase in source layer thickness from 1 km to 2.5 km to match the observed ~450 nT anomaly. The increase in thickness would be correspondingly less if the magnetization of the source layer were higher (corresponding to a thinner magnetic source). Since some contribution from deeper layers is likely (e.g., Dyment et al., 1997; Gee and Kent, 2007), we suggest 1 km as a plausible lower bound for the thickness of the extrusives and the portion of the sheeted dike layer that together constitute the dominant magnetic source. Although we cannot exclude the possibility that thickening of source layer could account for the enhanced magnetization, a long-lasting prominent (>1 km) contrast in the thickness of source layer, between two adjoining ridge segments seems unlikely, and has never been documented. The asymmetric high magnetization at the FZ is more likely related to geochemical variations.

Shallow (low pressure) fractionation of basaltic melt increases iron content (FeO*, total iron as FeO) (Rubin and Sinton, 2007), leading to the enrichment of titanomagnetite concentration and thus to higher rock magnetization (natural remanent magnetization, NRM) and ultimately to stronger magnetic anomalies (Vogt and Johnson, 1973; Gee and Kent, 1997). An increase of 1% FeO* in the basalts, formed under the present day geomagnetic field strength, leads to an increase of 6.6 A/m in NRM (Gee and Kent, 1997). This relationship, together with a 1 to 6 percent enhancement of FeO* observed near several active discontinuities and transform faults (Fig. 8) (Sempere, 2007).

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**Fig. 8.** Comparison between FeO* content in dredged basalts and results from magnetic inversions near the Clipperton Transform fault. (a) Bathymetric map with dredge locations (black dots). All dredges are located within 3 km from the ridge axis. Data from PetDB, www.petdb.org. (b) Iron (FeO*) content of the dredged rocks shown in panel a are indicated by the black dots. Running average is determined every 1 km, filtered with a cosine arch width of 4 km (blue dots). (c) Comparison between crustal magnetizations (gray shaded area) and the predicted magnetization (blue dots). Crustal magnetizations are based on the 3D inversion from Carbotte and Macdonald (1992). We calculated ridge parallel profiles every 10 km within the Brunhes and stacked them to get the average magnetization of the crust (gray shaded area delineates the standard error). The predicted magnetization is based on the running mean FeO* content of the dredge samples shown in panel b and the relationship of Gee and Kent (1997).
et al., 2001; Tarduno and Cottrell, 2005; Granot et al., 2007). These numerous studies using both absolute and relative paleointensity drillcore sampling (Emmermann, 1985; Teagle et al., 2006), that geochemistry of surface lavas is broadly representative of the bulk ridge axis near the Clipperton Transform, East Pacific Rise (Fig. 8), shows a fairly good correlation (Fig. 8b and c). Unfortunately, no detailed layer 2A thickness is available across the Clipperton Transform. Nonetheless, the correlation between the geochemical and magnetic data further support the degree of low pressure fractionation as the dominant cause of Pacific FZs anomalies, as has been argued before by investigations of fast spreading discontinuities and transform faults (e.g., Sempere, 1991; Carbotte and Macdonald, 1992; Bazin et al., 2001) and Oligocene Pacific FZs (Vogt and Byerly, 1976). Still, the underlying mechanism that generates this asymmetric iron signature at RTIs is not clear. Possible hypotheses will be discussed later in the text.

5.3. Complex magnetization pattern near multiple-stranded faults

Our simple model of one-sided enhancement of magnetization does not satisfactorily explain the observed signal where the FZs are made from several closely-spaced faults (Figs. 4a and 5). In these cases, each fault seems to serve as a magnetization discontinuity that is accompanied by either an increase or decrease, or both, in magnetization. The shape of anomalies located near the middle strand of the Murray FZ is consistent with the location of the area of reverse magnetization between anomalies 34 and 33o (Fig. 5) suggesting that their magnetization results, predominantly, from remanent magnetization. A pronounced reduction in magnetization is also observed in places (for example, see northernmost strand of the Murray FZ between 202°E and 205°E, Fig. 5). This pattern of magnetization may result from several processes. Abnormally highly fractured crust, located within these particularly faulted areas, may be associated with enhanced alteration or physical disruption that reduces the remanent magnetization. Alternatively, the close association between magnetization pattern and faulting (e.g., Figs. 4 and 5) may also be related to our simple model where, presumably, end-of-segment-enrichment in iron increases magnetization, even in these fine scale segments. The available data are not sufficient to produce a detailed and well-constrained magnetic model for these structurally complicated regions. Further evaluation of the magnetization, crustal and mantle structure, and geochemistry of these complex zones will require detailed and focused investigations.

5.4. Long-term behavior of the CNS geomagnetic field

The observed anomalies, as discussed earlier in the text, reflect the original crustal accretion processes that took place near the RTIs. Although variability in these processes undoubtedly contributes to fluctuations in anomaly amplitudes across the FZs, the magnetization contrasts should also reflect variations in geomagnetic intensity when the source rocks were magnetized. The FZ magnetic anomalies from the North Pacific therefore may provide information about the geomagnetic field during the CNS, a particularly interesting interval, as it constitutes one extreme end member of geomagnetic field behavior, when a stable normal polarity state prevailed for 37 m.y.

The strength and variability of the CNS field have been the focus of numerous studies using both absolute and relative paleointensity methods (e.g., Pick and Tauxe, 1993; Cronin et al., 2001; Tarduno et al., 2001; Tarduno and Cottrell, 2005; Granot et al., 2007). These studies have yielded contradictory views of the geomagnetic field. Some studies have suggested very high dipole moments accompanied by low (<10%) variability about the average field (Tarduno et al., 2001, 2006), consistent with the prediction made by numerical geodynamo simulations (e.g., Glatzmaier et al., 1999). Other studies have suggested lower dipole moments and higher (>40%) field variability (Riisager et al., 2003; Zhao et al., 2004; Tauxe, 2006; Granot et al., 2007; Zhu et al., 2008), implying that the behavior of the superchron field is comparable to the observed Cenozoic geomagnetic field, a time of frequent reversals (Selkin and Tauxe, 2000). Part of the controversy is linked to the reliability of the magnetic recording media but partly it is linked with sparse temporal sampling.

Marine magnetic anomalies provide an alternative means to investigate geomagnetic intensity fluctuations since they can provide nearly continuous and spatially/temporally averaged estimates of the geomagnetic field (Gee and Kent, 2007). Despite uncertainty in crustal accretionary processes that affect the magnetic anomalies over FZs, some aspects of geomagnetic field behavior may still be discernable.

To illustrate the types of geomagnetic behavior that might be recovered, we generated 3D forward models for various crustal magnetization patterns (Fig. 9), where the crustal magnetization is proportional to the geomagnetic intensity (with Gaussian noise). We used an average crustal magnetization of 6 A/m (based on the magnetization contrast at anomaly 34), with the exception of the model shown in Fig. 9b where the average strength was set to be highest (12 A/m) in the center of the Quiet Zone. The magnetic source geometry simulates the setting of the Fau and Pioneer FZs, where one side of the FZ has enhanced magnetization of up to 70% relative to the background magnetization.

Results of the first forward model (Fig. 9a) illustrate that large amplitude, long period geomagnetic intensity fluctuations appear to be incompatible with the pattern of FZ anomalies in the Quiet Zone. The geomagnetic field for this model has large (50% of mean) 5 m.y. sinusoidal variations and small (10% of mean) Gaussian noise on shorter time scales. Such a field model produces magnetization contrasts where the side of higher magnetization changes frequently (from north to south and vice versa). This magnetization setting may yield both positive and negative magnetic anomalies (Fig. 9a, right), in conflict with the observed uniform polarity of anomalies across the Pau and Pioneer FZs. Although low Gaussian noise was chosen to highlight this effect, the same pattern of mixed positive and negative anomalies would also be present for any field variation models that result in the lower (but still positive) magnetization crust occurring on alternate sides of the FZ. These results suggest that the long wavelength magnetization contrasts along the Pau and Pioneer FZs (Fig. 3) are unlikely to be the result of long period geomagnetic intensity fluctuations.

Magnetic anomaly variations along FZs might also allow some proposed correlations between geomagnetic intensity, variability and reversal frequency to be addressed. Some geodynamo numerical models predict that the geomagnetic field during superchrons is both stronger and less variable than the field in times with frequent reversals (e.g., Glatzmaier et al., 1999). Alternatively, other studies of the geomagnetic field argue that the characteristics of the field during superchrons are fundamentally similar to the field at times of frequent reversals (e.g., Ryan and Sarson, 2007). Although neither the numerical models nor paleointensity data from rock samples provide any specific predictions of long-term variations within the Quiet Zone, Fig. 9b illustrates how FZ anomalies might show whether a slow (long wavelength) increase or decrease in geomagnetic intensity took place within the superchron. The geomagnetic field for this model has lower intensity and higher variability (60% of mean) at the ends of the superchron and significantly higher intensity and lower variability (10% of mean, as suggested by some absolute intensity estimates; e.g., Tarduno et al. (2001, 2006)) in the middle of the superchron. The predicted evolution of magnetic contrasts (Fig. 9b, right) does not
bear a resemblance to the observations (Fig. 3), illustrating how such long-term variations might be tested with FZ anomalies. Since no mutual long wavelength (> 10 m.y.) trends are observed in the Pau and Pioneer FZs (Fig. 3), we conclude that overall, the strength of the geomagnetic field in the CNS was relatively steady, at least for the period younger than 114 Ma.

Finally, the variability of geomagnetic intensity should also be reflected in the variability of magnetization contrasts across FZs (Fig. 9c). Variability of 80% in the geomagnetic field about its average overestimates the observed scatter in the FZ magnetic anomalies. Fifty to twenty percent variability predicts a typical 5 to 3 A/m scatter, respectively, similar to the typical spread of our calculated contrasts (Fig. 3). We therefore deduce that the long-term variability of the geomagnetic field during the Cretaceous superchron likely was not larger than ~50%. Variability smaller than 20% cannot be implicitly excluded as some of the observed scatter may result from crustal accretion variability. CNS paleointensities from sediments (Cronin et al., 2001) and igneous rocks (e.g., Granot et al., 2007; Zhu et al., 2008) have shown similar range of variability (40–60% of mean). Our observations, however, suggest that this variability lasted for 30 m.y. and further support the notion that the variability of the geomagnetic field in the Cretaceous superchron was probably similar to the variability at times with frequent reversals.

### 5.5. Tectonic implications

Our observations indicate that the Pacific FZs are characterized by enhanced remanent magnetization zones located on one side of each of the FZs, for thousands of kilometers (Fig. 2). The enhancement in magnetization may be explained by an increase in the degree of fractionation at segment ends, leading to iron-rich melts (our preferred model), or alternatively, by thickening of the magnetic source layer. The resultant magnetic anomalies therefore provide a very valuable insight into the long-term crustal construction (e.g., melt delivery). The consistency of magnetic anomalies across the Pioneer and Pau FZs suggests that spatially stable asymmetry in crustal construction across transform faults prevailed for more than 30 m.y. Although not fully understood, these inferences require some fundamental crustal accretion processes to take place near the RTIs. A persistent increase in fractionation toward the end of segments may indicate that delivery of magma along-axis is an important mechanism at fast spreading ridges (i.e., three-dimensional magma accretion along ridge segments).

Why is there a persistent asymmetry in crustal construction across transform faults? Our results from the left-stepping Pau and Pioneer FZs illustrate that the enhancement in fractionation can be located either on the old or young side of the FZs, respectively (Fig. 10). In fact, these two FZs confine a single spreading segment where a long-lasting enhancement prevailed at both ends of the segment. Transform fault effect (i.e., cold edge effect) should result in symmetric accretion patterns across discontinuities and consequently cannot explain the observed magnetic signature. Asymmetric morphology, geochemistry and crustal structure properties across active ridge discontinuities (e.g., Langmuir and Bender, 1984; Langmuir et al., 1986; Macdonald et al., 1988) have recently been attributed to the migration of spreading centers over the mantle (Carbotte et al., 2004) where the leading segment preferentially entrains melt while the trailing side (i.e., end of the other adjoining segment) suffers from a relative reduced melt supply. Alternatively, Toomey et al. (2007) have suggested that differences between the axes of mantle upwelling and spreading direction modulate the magmatic construction at spreading segments. The link, if any, between absolute plate motion and crustal accretion over long periods of time is still unclear. Since both the Pioneer and Pau are left-stepping transforms, there is no obvious correlation between crustal magnetization and ridge geometry, although rigorous analysis of magnetic anomalies across the Pacific FZs within and outside the Quiet Zone should provide new insights into this enigma.

The observed magnetization contrasts along the Pau and Pioneer FZs reveal oscillations over time scales of some 2 to 5 m.y. (Fig. 3). The
crust juxtaposed across these FZs (i.e., formed at the adjoining segments, north and south of the Pau and Pioneer FZs, respectively) differs in age by some ~10 m.y. Long period (longer than few hundred thousands of years) variations in geomagnetic field intensity are an unlikely source for these fluctuations as they will likely result in anomalies alternating on the north or south sides of the FZ (Fig. 9a). On the other hand, variations in the degree of shallow fractionation could theoretically produce variations in the observed magnetic contrasts but still maintain a uniform shape of anomalies. Therefore, the long period magnetic records shown here may document variations in the degree of fractionation (or possibly melting) and crustal accretion. The longest geochemical records from fast-spreading crust covers ~800 ka (Batzia et al., 1996) and indicate that temporal variability in fractionation (~2% MgO) can be of the appropriate order to explain our observed oscillations. Geophysical as well as geochemical observations from the Vema Transform fault (Bonatti et al., 2003) suggest that dynamic pulses of mantle upwelling and melting lead to variable crustal properties on a scale of millions of years. A similar mechanism may control the observed magnetic record along the studied fast spreading FZs.

The magnetization contrast across FZs can also be used to better locate the plate boundary, as opposed to the longer wavelength, topographically controlled and overprinted gravity signal. For instance, profile y–y′ (Fig. 7b and d) crosses the Pioneer FZ where no obvious topographic (measured with multi- and single beam) or gravity signature can be used to locate the fault. Yet, the narrow magnetic contrast calculated along the profile constrains the location of the fault at this particular place (Fig. 7d, the steepest gradient is indicated with star). Indeed, the predicted location aligns well with the observed trace of the FZ found to the west of the profile.

6. Conclusions

Systematic analysis of magnetic anomalies observed across the North Pacific FZs, within the Quiet Zone crust, reveals a remarkably uniform shape over 30 million years. These anomalies can be modeled with an enhanced remanent magnetization zone located mostly on one side of the FZs. The most likely cause of this zone is an increase in the degree of fractionation at one of the confining segment ends, which, in turn, implies long-lived asymmetric crustal construction. 3D magnetic forward modeling suggests that geomagnetic field intensity in the Cretaceous superchron had a typical variability of 50% or less about its average. The observed magnetization contrasts are on the order of 8 A/m for most of the Cretaceous superchron suggesting that the dipole strength remained, overall, near constant. Therefore, if the CNS field was associated with higher dipole moments, then the decrease to Cenozoic magnitudes might be discernable with additional FZ magnetic profiles near the end of the CNS and over younger crust.

The presence of long-lasting enhanced zones of remanent magnetization confined to one side of a fracture zone may provide constraints in models of melting accretion near RTIs. Oscillations of 2 to 5 m.y. in the observed magnetizations at the Pau and Pioneer FZs most likely reflect crustal accretion dynamics. The magnetic signature of FZs formed along intermediate to fast spreading axes can potentially be used to study the long-term effect of absolute plate motion on crustal construction at RTIs.

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