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Three-Dimensional Inversion of the Magnetic Field Over the Easter-Nazca Propagating Rift Near 25°S, 112°25'W

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The Easter microplate boundary configuration is being reorganized by rift propagation. A Sea Beam survey of the Easter-Nazca spreading center, which forms the eastern boundary of the microplate, has revealed the presence of a young propagating rift growing northward (Naar and Hey, 1986). The tip of the propagating rift is associated with a high-amplitude positive magnetic anomaly. We have performed a three-dimensional inversion of the magnetic field over the propagating rift tip area. The magnetization solution suggests that the western and eastern pseudofaults strike 014° and 338°, respectively, and converge near the rift tip. These orientations yield a propagation to spreading rate ratio of 1.5, slightly higher than the estimate of Naar and Hey (1986). Using the revised estimate of the full spreading rate along the Easter-Nazca spreading center near 25°S (80 mm/yr) (D. F. Naar and R. N. Hey, unpublished manuscript, 1989), we obtain a propagation rate of 120 mm/yr. Within 27–30 km of the rift tip, the propagating rift curves by about 15° to the east toward the failing rift, probably as a result of the interaction between the two offset spreading centers. As at the Galapagos propagating rift, rift propagation appears to be a very orderly process along the Easter-Nazca spreading center. The magnetization distribution that we obtain exhibits a high at the propagating rift tip. At other large ridge axis discontinuities, similar magnetization highs have been interpreted as being the result of the eruption of highly differentiated basalts enriched in iron. The origin of the high magnetization zone in the case of the Easter-Nazca propagating rift near 25°S may be more complex. Preliminary rock magnetic measurements of basalts recovered in the vicinity of the propagating rift confirm the presence of highly magnetized basalts but suggest that the relationship between high magnetization intensities and high Fe content is not straightforward.

INTRODUCTION

The existence of the Easter microplate, initially proposed by Herron [1972], was confirmed by Forsyth [1972], who showed that focal mechanisms of two strike-slip earthquakes in this region were anomalous with respect to the orientation of the Pacific-Nazca spreading center (Figure 1). Hey and Vogt [1977] and Hey *et al.* [1980] suggested that the existence of the Easter microplate could be accounted for by rift propagation and that the microplate should have a limited lifetime determined by the time required for the western spreading center to stop spreading and for the eastern spreading center to accelerate to the full Pacific-Nazca rate. Handschumacher *et al.* [1981] proposed a propagating rift model for the eastern boundary of the Easter microplate. Based on this work and on new focal mechanism solutions, Engeln and Stein [1984] proposed a tectonic model for the entire Easter microplate involving ridge propagation. Hey *et*

al. [1985] and Naar and Hey [1986] argued that these models are not consistent with available magnetic data and proposed a new propagating rift model for the eastern boundary of the Easter microplate.

Hey *et al.* [1985] suggested that the eastern boundary of the microplate is composed of several (at least two) northward propagating rifts. Using the high-resolution multibeam sonar system Sea Beam, Naar and Hey [1986] mapped a young propagating rift along the Easter-Nazca spreading center near 25°S, whose presence was confirmed by two-dimensional forward modeling of the magnetic field. We report here the results of the three-dimensional inversion of the surface magnetic field over the tip of this propagating rift. The goal of this study is to determine the source rock magnetization distribution responsible for the observed magnetic field over the rift tip and, in this way, to provide additional constraints on the nature and recent evolution of the propagating rift.

GEOLOGIC AND GEOPHYSICAL SETTING

Tectonic Setting

Naar and Hey [1986] showed that the orientation of lineations about the Easter-Nazca spreading center is not consistent with normal seafloor spreading nor with a nearby

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Fig. 1. Location of the Easter microplate [from Naar and Hey, 1986]. The bold lines indicate the location of the plate boundaries. The Easter microplate boundary is being reorganized by rift propagation.

pole of rotation but that they can be explained by a propagating rift model [Hey *et al.*, 1980]. They suggested that the tip of this propagating rift coincides with a 3300-m-deep basin located near 25°S, 112°25'W. The 020° and 330° trending lineations, which dominate the tectonic fabric in this area, appear to intersect in the immediate vicinity of this basin. These two trends correspond to the orientations of the pseudofaults associated with rift propagation. South of the rift tip, the Easter-Nazca spreading center shoals by about 1200 m to form a well-defined axial ridge at 26°30'S.

The failing rift that is being replaced is thought to lie about 45 km to the east of the propagator, near 112°W, and may correspond to a closed, N-S trending, elongate, 3200-m-deep basin, which narrows and shoals to the north (Figure 2a). It curves inward toward the propagating rift, and its western scarp is much steeper than its eastern one. This is similar to the well-mapped Galapagos 95°30'W propagating rift system [Hey *et al.*, 1986], where the failing rift segments are observed to curve toward the propagating rift and where the steepest scarps bounding these segments are always the ones nearest to the propagating rift. Although the data coverage is not as complete as it is in the Galapagos area, oblique ($\approx 330^\circ$) structures are observed between the inner pseudofault and this suspected failing rift (Figure 2a). This would correspond to the zone of transferred lithosphere described by Hey *et al.* [1986] for the Galapagos propagator. The bathymetric structures to the east of the failing rift are nearly N-S, thus marking a distinct change in trend between the west and east sides of this suspected failing rift. This type of trend change is also observed on the failing rift segments in the Galapagos area.

Magnetic Setting

Naar and Hey [1986] have compiled all available surface magnetic data in the survey area (Figure 2b). Distinct trends in the magnetic anomalies are observed and are consistent with Sea Beam bathymetric lineations. Naar and Hey [1986] have reinterpreted these different trends in terms of a new propagating rift model for the eastern boundary of the Easter microplate. They showed that the observed narrowing of the Brunhes anomaly to the north is best explained by the presence of a young propagating rift growing northward at the rate of 150 mm/yr, assuming an average spreading rate of 120 mm/yr. Magnetic anomalies north of the propagating rift tip are complex and difficult to interpret. Based on the magnetic anomaly interpretation of Naar and Hey [1986, also unpublished manuscript, 1989], the propagating rift appears to have been propagating into mostly reversely magnetized crust (Matuyama Epoch) and may be currently in the vicinity of the Jaramillo event. The overall general magnetic pattern (Figure 2b) is very similar to that of the Galapagos propagating rift system (see Figure 4 of Hey *et al.* [1986]).

The magnetic field over the Easter-Nazca propagating rift near 25°S exhibits a very pronounced positive anomaly. The peak-to-trough amplitude of this observed anomaly is in excess of 700 nT. This high-amplitude magnetic zone coincides with the northward narrowing of the Brunhes anomaly to zero width between about 26°S and 24°55'S. The anomaly, as defined by the 200-nT contour, extends as far as 50 km behind the rift tip. A significant part of this large positive anomaly could be due to the substantial topographic relief present at the propagating rift tip. However, similar

Fig. 2a. Bathymetric map of the Easter-Nazca spreading center between 24°45'S and 25°30'S (contour interval = 100 m). The bold continuous line marks the location of the spreading center. The bold dashed lines indicate the two pseudofaults associated with rift propagation. The bold dotted line marks the assumed location of the failing rift. Solid lines represent Sea Beam track lines; the lightly dotted lines represent conventional, wide-beam, echo-sounding lines. The contours are modified from Naar and Hey [1986] to include data from Marchig et al. [1987].

high-amplitude magnetic anomalies are commonly observed at propagating rifts (and overlapping spreading centers with offsets greater than a few kilometers) where they have been associated with the presence, at or near the rift tip, of highly differentiated basalts enriched in iron [e.g., Vogt and Johnson, 1973, 1974; Vogt and Byerly, 1976; Vogt, 1976, 1979; Anderson et al., 1975; Hey and Vogt, 1977; Christie and Sinton, 1981; Delaney et al., 1981; Sinton et al., 1983; Miller and Hey, 1986; Sempéré et al., 1984; Sempéré and Macdonald, 1986a; J.-C. Sempéré and D. M. Christie, manuscript in preparation, 1989]. One of the goals of the present study is to investigate the origin of this high-amplitude magnetic anomaly and its relationship to documented, geochemical variations along the Easter-Nazca spreading center in the vicinity of the propagating rift tip.

METHOD AND DATA COLLECTION

Because marine magnetic anomalies are band-passed representations of the source magnetization on the seafloor [Schouten, 1971], a contour map of the magnetic field does not allow us to map directly the propagating rift and its

tectonic boundaries. Before this can be done, the distortions induced in the observed magnetic field by the orientation of the magnetic lineations and the Earth's field and by the presence of bathymetric relief have to be taken into account. In addition, because propagating rifts are three-dimensional structures and clearly violate two-dimensional assumptions, a three-dimensional analysis of the magnetic data needs to be performed. For these reasons, in order to study the magnetic structure of the Easter-Nazca propagating rift near 25°S, 112°25'W, we have performed a three-dimensional inversion of the magnetic field in the presence of bathymetry. The inputs to the inversion are the gridded bathymetric and magnetic data sets, and the output is the source rock magnetization distribution over the propagating rift tip.

Gridding

In order to perform the inversion, we need to be able to grid the data (bathymetry and magnetic field) as accurately as possible (Figures 3a and 3b). This was done by digitizing the bathymetric and magnetic anomaly contours from Naar and Hey [1986] modified to include new data from a recent

Fig. 2b. Magnetic contour map over the Easter-Nazca spreading center [from Naar and Hey, 1986] (contour interval = 200 nT with additional 25-, 50-, and 100-nT contours in places).

German Sea Beam cruise [Gundlach *et al.*, 1987; M. Wilke, personal communication, 1986]. The gridding method used in this study uses the concept of lattice tuning [Tobler, 1979] by iterative use of the biharmonic finite difference operator and ensures at the same time the smoothness of the gridded values and the fit to the original data. The grid size used (1.5 km) corresponds to a Nyquist wavelength of 3 km, which is similar to the expected resolution of the analysis of surface magnetic data (3–4 km) [Miller, 1977].

Three-Dimensional Inversion of the Magnetic Field

Two-dimensional and three-dimensional inversions of the magnetic field in the presence of bathymetry have proven to be successful techniques in various studies along mid-ocean ridges [e.g., Sempère *et al.*, 1984, 1987; Miller and Hey, 1986]. Parker and Huestis [1974] solved the problem of the two-dimensional inversion of the magnetic field in the presence of bathymetry. Their formulation was extended to the three-dimensional case by Macdonald *et al.* [1980]. After Fourier transformation of the gridded bathymetric and magnetic data into the wave number domain, an iterative procedure is used to obtain a source magnetization which accounts for the observed magnetic field in the presence of

bathymetry. Several assumptions are made in the process. We assume that the magnetized layer follows the bathymetry and has a constant thickness of 1 km. This thickness corresponds to the sharp drop in magnetic intensity values in hole 504 B [Anderson *et al.*, 1982]. Because we are dealing with a young magnetic anomaly and young oceanic crust, the contribution of the extrusive volcanic layer is likely to be the most important one, and the assumption that the magnetized layer has a constant thickness of 1 km, although inexact, is reasonable. The choice of another magnetic layer thickness would result in different magnetization amplitudes but would not significantly affect the magnetization distribution. In addition to a constant magnetized layer thickness, we also assume that the orientation of the magnetization vector does not change within the survey area (with the exception of reversals) and is consistent with a geocentric axial dipole. The assumption of uniform magnetization through the magnetized layer is also questionable in the light of Deep Sea Drilling Project results in the Atlantic, where several reversals were recorded in a given drill hole [Johnson and Merrill, 1978]. However, a statistical analysis based on the ratio of average time of crustal formation to the average length of a magnetic polarity interval suggests that while this is true for crust

Fig. 3. (a) Gridded bathymetry of the Easter-Nazca propagating rift near 25°S, 112°25'W showing the extent of our survey area (contour interval = 100 m). The bold lines mark the location of the Easter-Nazca spreading center, the dashed lines that of the pseudofaults, as defined by the three-dimensional magnetic inversion described in this study. The propagating rift tip corresponds to a 3300-m-deep basin. South of this basin near 26°30'S, the Easter-Nazca spreading center shoals to a depth of 2100 m and forms a well-defined axial ridge [Naar and Hey, 1986]. (b) Gridded magnetic field over the Easter-Nazca spreading center near 25°S, 112°25'W (contour interval = 100 nT). The bold lines outline the location of the Easter-Nazca spreading center and the dashed lines the pseudofaults associated with the propagating rift found on this study. The tip of the propagating rift is associated with a large-amplitude surface magnetic anomaly. (c) Calculated magnetic field over the Easter-Nazca spreading center near 25°S, 112°25'W (contour interval = 50 nT). Forward modeling was performed assuming a magnetized layer with constant magnetization intensity (10 A m⁻¹), constant thickness (1 km) and constant magnetization orientation (given by an axially centered dipole). Geomagnetic reversals were not taken into account. This calculated field differs both in distribution and amplitude from the observed one (Figure 3b). (d) Inferred magnetization distribution over the Easter-Nazca propagating rift near 25°S, 112°25'W (contour interval = 5 A m⁻¹). The three-dimensional inversion was performed assuming a magnetized layer with constant thickness (1 km) and constant magnetization orientation (axially centered dipole). The nonuniqueness of the inversion is characterized by an annihilator. The amount of annihilator to be added to the solution was found by balancing the positive and negative magnetization on each side of reversal boundaries within the survey area. As adding different amounts of annihilator to the solution modifies the amplitude of the magnetization within the survey area but does not significantly modify the magnetization distribution, we believe that the magnetization distribution that we have obtained is representative of the magnetization structure of the propagating rift. A magnetization high is present at the tip of the propagating rift.

created at a slow spreading center, multiple reversals in a single hole are less likely to occur in oceanic crust created in a fast spreading environment such as the Easter-Nazca spreading center [Denham and Schouten, 1979; Schouten and Denham, 1979].

Because the inverse problem is equivalent to downward continuing the field to the seafloor, it is necessary to filter out the shorter-wavelength components of the surface magnetic data to ensure convergence. For this reason, a band-pass filter with cosine tapers was applied with cutoff

wavelengths at 3 km and 1000 km. This is not a major constraint since the nature of surface field measurements is such that the geological interpretation of marine magnetic anomalies collected at sea level is not valid for wavelengths less than about 3–4 km [Miller, 1977]. As is the case for all potential field problems, the inversion solution that we obtained is not unique, and we can find one magnetization distribution, called the annihilator, which, for the given bathymetry, yields no external field [Parker and Huestis, 1974]. The solution to the problem is then a combination of the solution derived from the inversion algorithm and a prescribed amount of the annihilator. The addition of varying amounts of the annihilator to the solution does not significantly affect the distribution of the solution but changes its average level. Geological constraints have to be used to select a reasonable amount of annihilator to be added to the solution. In this way, the family of admissible solutions is reduced.

RESULTS

Forward Modeling

For wavelengths less than 3–4 km, up to 30% or more of the spectral power of surface magnetic anomalies can be associated with bathymetric effects [Miller, 1977]. It is therefore likely that the high topographic relief present at the propagating rift tip will make a significant contribution to the observed magnetic signal at the surface. In order to evaluate the topographic contribution to the observed positive magnetic anomaly, we calculated the magnetic field due to a uniformly magnetized layer of constant thickness (1

km), constant magnetization intensity (10 A m^{-1}), and constant magnetization orientation (axially centered dipole). The effects of reversals were not taken into consideration in this formulation. The forward-calculated field differs considerably from the observed magnetic field both in amplitude and in distribution, suggesting the presence of short-wavelength magnetization variations in the source rocks (Figure 3c). These calculations indicate that bathymetric effects do not play an important role in the generation of the observed magnetic anomaly, but a rigorous interpretation of the magnetic data requires that these effects be taken into consideration.

Magnetization Distribution Over the Easter-Nazca Propagating Rift Near 25°S

Before a solution to the inversion problem can be found, the correct amount of annihilator needs to be added to the inversion solution. In this case, the amount of annihilator to be added to the solution was found by balancing the positive and negative magnetization on each side of reversal boundaries within the survey area. Although this procedure yields reasonable magnetization amplitudes, ultimately, we can never be sure that the correct solution has been obtained. As a different amount of annihilator would modify the amplitude of the magnetization within the survey area but would not significantly modify the magnetization distribution, we believe that the solution that we have obtained (annihilator added) is representative of the magnetization structure of the propagating rift tip.

The resulting magnetization distribution is dominated by the presence of a high in excess of 40 A m^{-1} about 45 km

TABLE 1. Summary of the Magnetic and Geochemical Properties of Samples Dredged in the Vicinity of the Easter-Nazca Propagating Rift Near 25°S, 112°25'W

Sample	Number of samples	FeO* ^a	TiO ₂	Mg # ^b	NRM, ^c A m ⁻¹	χ , ^c 10 ⁻³ SI	Q , ^c	M_{sat} , ^d 10 ³ A m ⁻¹	M_{rs} , 10 ³ A m ⁻¹	H_{rc} , 10 ³ A m ⁻¹	H_{c} , 10 ³ A m ⁻¹
EN 40D-1	3	10.83	1.55	57.2	27.9	5.36	212	1.62	0.70	20.8	15.0
EN 40D-2	4	—	—	—	19.6	11.03	67	—	—	—	—
EN 40D-3	3	—	—	—	13.8	6.89	93	—	—	—	—
EN 14D-1	8	10.12	1.63	60.6	7.4	3.81	78	0.59	0.32	30.0	22.3
EN 13D-11	9	13.57	2.26	48.1	32.3	7.64	171	1.44	0.73	42.5	29.7
EN 13D-12	3	9.21	1.47	64.7	1.9	1.12	63	0.37	0.21	44.7	31.3
PA 04-12-1	16	13.77	2.53	45.9	31.6	1.81	78	1.66	0.92	26.7	21.7
PA 04-12-2	23	—	—	—	30.4	1.77	2.15 71	0.50 —	8.2 —	4.7 —	—
EN 12D-10	16	14.17	2.81	44.8	8.9	20.16	22	2.13	0.72	34.9	22.7
EN 11D-11	12	15.69	3.17	38.5	23.1	8.44	107	1.89	0.76	34.9	22.7
EN 10D-1	9	13.69	2.58	46.9	18.2	13.71	65	2.72	0.87	12.4	7.4

^aEach point represents the average of three or more electron microprobe analyses on glass chips using VG2 as standard for MgO and FeO. FeO* is total Fe as Fe²⁺.

^bMg # = $\text{Mg}^{2+} / (\text{Mg}^{2+} + \text{Fe}^{2+}) \times 100$ where $\text{Fe}^{3+} / (\text{Fe}^{3+} + \text{Fe}^{2+}) = 0.14$.

^cNRM, natural remanent magnetization; χ , magnetic susceptibility; Q , Koenigsberger ratio; M_{sat} , saturation magnetization; M_{rs} , remanent saturation magnetization; H_{rc} , remanent coercive force; H_{c} , coercive force (arithmetic mean).

^d M_{sat} is the saturation magnetization measured in the presence of an external field. M_{rs} is the remanence (in zero external field) remaining after exposure to the saturating field. H_{c} is the bulk coercivity, the field required to reduce M_{rs} to zero in the presence of an external field. H_{rc} (coercivity of remanence) is the field required to reduce M_{rs} to zero in a zero external field.

south of the inferred tip of the propagating rift (Figure 3d). The average magnetization over the propagator tip is about 25 A m^{-1} . The magnetization maximum is a very prominent feature for any reasonable choice of the amount of annihilator added to the solution. The V-shaped magnetization high closely follows the pseudofaults determined by the magnetic and bathymetric analysis of *Naar and Hey* [1986] (Figure 3d). The calculated magnetization distribution is in general agreement with measured magnetization values from samples recovered from the survey area (Table 1). The location of the dredge sites is indicated in Figure 4.

Magnetic Properties of Dredged Samples

The magnetic properties of samples recovered in the vicinity of the propagating rift on the Easter-Nazca spreading center near 25°S were measured in order to constrain and interpret the solution of the three-dimensional magnetic inversion. The magnetic properties and relevant geochemical data for these basalts are summarized in Table 1.

The natural remanent magnetization (NRM) and bulk volume susceptibility (χ) were measured and the Koenigsberger ratio (Q , the ratio of remanent to induced magnetizations) calculated for all specimens. Although high magnetization values occur near and south of the propagating rift tip, the distribution of magnetization is variable (Figure 4). The minimum and maximum mean NRM intensities (1.9 and 32.3 A m^{-1}) were measured for two samples from dredge

13D, in the vicinity of the propagating rift tip as defined by the inversion solution. The magnetizations of samples from the failing rift to the northeast are also variable (7.4 and 20.3 A m^{-1}). Koenigsberger ratios range from 22 to over 200, indicating that, in all cases, the magnetization of the samples is dominated by the remanent contribution.

Selected specimens from each sample were subjected to alternating field (AF) or stepwise thermal demagnetization (Figure 5). Both techniques recover the same components of magnetization. The majority of samples exhibited approximately univectorial behavior during demagnetization, although samples EN 11D-11 and EN 12D-10 had significant, low-stability components. Median destructive fields (MDFs) varied from 1.8 to 73.9 mT and were greater than 10.0 mT for three quarters of the specimens. All samples achieved saturation isothermal remanence (SIRM) in fields of 0.2-0.3 T, indicating that no high-coercivity phases contribute significantly to the remanence.

The thermal demagnetization curves also yield valuable information on the magnetic mineralogy of the samples. Two types of behavior were noted upon progressive heating. Most of the samples showed a rapid decrease in remanence upon heating to 200°-350°C, with the remaining portion of the remanence (usually <20% of the NRM) maintaining a consistent direction until temperatures of 500°-580°C (Figures 5e and 5f). In contrast, samples EN 11D-11 and EN 13D-12 were dominated by a high blocking temperature component (540°-580°C) (Figures 5b and 5c). Based on the SIRM and blocking temperature spectra, we conclude that the

Fig. 4. Fe content, Mg # and magnetization intensities of dredge samples along the Easter-Nazca spreading center in the vicinity of the propagating rift near 25°S (see Table 1). The solid circles mark the locations of dredges. Selected bathymetric contours were drawn at a contour interval of 200 m. The stippled pattern outlines the V-shaped magnetization distribution associated with the propagating rift within our survey area. There is no good correlation between high Fe concentration, low Mg numbers, and high rock magnetizations.

Fig. 5. Demagnetization behavior of basalt samples collected in the vicinity of the Easter-Nazca propagating rift near 25°S. Vector end-point diagrams for (a) alternating field demagnetization, (b) thermal demagnetization, and (c) thermal decay curve for samples dominated by the high blocking temperature component. (d, e, f) Similar diagrams for sample with small high blocking temperature component. Asterisks and circles are projections onto the horizontal and vertical plane. M/M_0 is the ratio of the magnetization at progressive heating stages to the initial magnetization.

high stability component of magnetization is carried by a Ti-poor magnetite. Reflected light petrography and limited electron probe analyses provide further support for this interpretation. In addition to abundant grains of titanomagnetite ($\text{Fe}_{3-x}\text{Ti}_x\text{O}_4$ with $x \approx 0.65$), a second opaque phase with higher reflectivity is also present. Although the small grain size of this phase prohibited quantitative analysis, energy dispersive analysis confirmed its very low Ti content. Thus the two types of behavior observed during thermal demagnetization may be attributed to variable contributions of the titanomagnetite and Ti-poor magnetite to the remanence. Therefore the magnetic mineralogy of basalts recovered in the vicinity of the propagating rift tip appears to be more complex than that of typical mid-ocean ridge basalts, which contain primarily titanomagnetites with $x = 0.6$ [Johnson, 1979; Petersen *et al.*, 1979].

DISCUSSION

Rift Propagation Along The Easter-Nazca Spreading Center

We can gain additional insight into the evolution and history of the propagating rift by studying the trends of the contacts between crusts of markedly contrasted magnetizations within our survey area. The V-shaped structure of the propagating rift tip, as defined by the 10 A m^{-1} contour, is in excellent agreement with simple models of continuous rift propagation. The western pseudofault has an average trend of 014°, while the eastern one has an average trend of 338°. These pseudofault trends are in reasonable agreement with the trends determined in the regional bathymetric and magnetic analysis of Naar and Hey [1986] (020° for the western pseudofault, 330° for the eastern one).

In a simple model of rift propagation, the relationship between propagation rate (V) and half spreading rate (U) can be written as $U = V \tan \beta$, where β is the half angle of the wedge of propagating crust. The magnetic inversion yields a value of $\beta \approx 18^\circ$. Assuming a full spreading rate of 120 mm/yr [Naar and Hey, 1986], we obtain a propagation rate of 185 mm/yr. This estimate is similar to the one derived by Naar and Hey [1986] in their more regional magnetic study. However, a recent magnetic anomaly interpretation and an analysis of the instantaneous Pacific-Easter-Nazca plate motion (D. F. Naar and R. N. Hey, unpublished manuscript, 1989) indicate that the full spreading rate is about 80 mm/yr in this area. Using this revised spreading rate, we obtain our preferred propagation rate of 120 mm/yr.

An equivalent method of studying the relationship between the propagation rate and the full spreading rate consists of calculating their ratio R . If λ and μ represent the angles that the inner and outer pseudofaults make with the spreading center, this ratio can be expressed as $R = (\tan \lambda + \tan \mu)^{-1}$. If the spreading center bisects the pseudofault angle, this relationship becomes $R = 0.5 \cot \lambda$ and $\lambda = \mu = \beta$. Using the same angles as before, we obtain $R = 1.5$, which is only slightly larger than the 1.3 value obtained by Naar and Hey [1986] but is significantly greater than the 0.8 ratio obtained for the Galapagos 95°30'W propagator (using $\lambda = \mu = 32^\circ$ [Hey et al., 1989]).

Within approximately 27–30 km of the rift tip, the western pseudofault rotates by about 14° to a new trend of 028° , while the eastern pseudofault rotates by about 19° to a new trend of 357° . The average trend of the spreading center, determined from the locus of maximum magnetization, is 355° away from the rift tip and 10° in the immediate vicinity of the propagator tip, suggesting a rotation of about 15° of the propagating rift. These orientations, which are not well constrained by the data, correspond approximately to the orientation of the bisector of the pseudofaults. This curvature is very likely the result of the interaction of the propagating rift with the failing spreading center about 45 km to the east near 112°W [Hey et al., 1980; Sempéré and Macdonald, 1986b]. Using the propagation rate derived earlier (120 mm/yr), these distances are equivalent to 225,000–250,000 years of propagation. If we assume that the propagation rate has remained constant, the mean half spreading rate in the last 225,000–250,000 years has been on the order of 33 mm/yr. This last result suggests that it takes more than 225,000 years for crustal accretion at the propagating rift tip to accelerate to the full spreading rate.

Miller and Hey [1986] performed a three-dimensional inversion of the magnetic field in the presence of topography over the Galapagos propagating rift at $95^\circ30'\text{W}$. The Galapagos propagator and the Easter-Nazca propagator near 25°S have similar geometrical characteristics. The main differences are that the offset between the propagating and failing ridges is 25 km at $95^\circ30'\text{W}$, while it is about 45 km near 25°S , and that the propagation rate of the Galapagos propagating rift is slow compared to the Easter-Nazca propagator (52 mm/yr versus 120 mm/yr). The propagation rate corresponds to 90% of the full spreading rate for the Galapagos propagating rift, while it corresponds to about 150% of the full spreading rate in our survey area. Miller and Hey [1986] estimated that it takes 250,000 years to accelerate to the full spreading rate at the propagator tip. We

derive an approximate duration of more than 225,000 years for acceleration to the full spreading rate in our survey area. In both areas, the rift propagation process appears to be quite orderly. In contrast, Hey et al. [1986] and Miller and Hey [1986] suggest that the processes leading to the extinction of the failing rift at the Galapagos are episodic. However, as adequate bathymetric and magnetic coverages are not available over the failing rift along the Easter-Nazca spreading center to allow for an inversion of the magnetic field, we have not been able to study the processes leading to the extinction of the failing rift within our survey area.

Relationship Between Magnetic Anomalies and Geochemistry

Macdougall and Tanzer [1984] and Schilling et al. [1985] studied the geochemistry of basalt samples recovered from the Easter-Nazca spreading center. Schilling et al. [1985] found that evolved basalts with low magnesium numbers ($\text{Mg\#} = \text{Mg}^{2+}/(\text{Mg}^{2+} + \text{Fe}^{2+})$, where $\text{Fe}^{3+}/(\text{Fe}^{2+} + \text{Fe}^{3+}) = 0.14$) extend up to 100 km behind the tip of the propagating rift near 25°S (Figure 4). The characteristic dimensions of the Mg # anomaly behind the rift tip are similar to those found at other propagating rifts [Sinton et al., 1983]. Schilling et al. [1985] showed that there is a steady increase in Fe content northward up to the propagating rift tip. North of the propagating rift tip, the Fe content of the basalts recovered is markedly lower than it is at the rift tip and south of it. This progressive increase is a characteristic signal associated with many propagating rifts [Christie and Sinton, 1981; Sinton et al., 1983]. The location of the most differentiated basalts, although ill-constrained because of poor sampling density, appears to lie up to 50 km behind the rift tip at 25°S . It is only 15–20 km behind the tip of the Galapagos propagating rift [Hey et al., 1989].

Several processes may be invoked to explain the presence of the magnetization high at the tip of the propagating rift [Sempéré et al., 1984]. The assumption of a uniform magnetic crustal thickness may not be applicable in regions near propagating rifts. However, in order to obtain such a magnetization high, an increase in thickness by a factor of 2 or 3 is required, which is unlikely to occur at the tip of a propagating rift. Geomagnetic intensity fluctuations may also account for some of the magnetization intensity variations. However, these variations are not observed along the crest of the Pacific-Nazca spreading center and the East Pacific Rise, except at other large ridge axis discontinuities. Finally, short-wavelength variations in magnetization intensity may be due to short-wavelength variations in the chemical composition of the basalts. The magnetic telechemistry hypothesis [Vogt and Johnson, 1973; Vogt, 1979] addresses the relationship between variations in magnetization and geochemistry and provides a possible explanation for the presence of the magnetization high.

In its simplest form the magnetic telechemistry hypothesis suggests that an increased Fe content is reflected in higher concentrations of otherwise similar titanomagnetite and thus in higher magnetizations and magnetic anomaly amplitudes [Vogt, 1979]. Watkins [1974] argued that care should be taken in applying the magnetic telechemistry hypothesis because factors other than Fe concentration play an important role in the generation of high magnetization intensities. However, if the magnetic telechemistry hypothesis is valid, it implies that bulk

volume susceptibility (χ), NRM intensity, saturation magnetization (M_{sat}) and saturation remanence (M_{rs}) should all increase with Fe content. Therefore a comparison between the variations of these parameters and Fe concentration is required as a preliminary test of this hypothesis. Geochemical data for six of the seven dredges examined in this study are presented by Schilling *et al.* [1985]. The possibility of heterogeneity within a single dredge, however, required that we determine the major element chemistry of the actual samples used in the magnetic study. Glass chips for 8 of the 11 samples were analyzed using an electron microprobe (Table 2). With the exception of EN 40D-1, our results are similar to those of Schilling *et al.* [1985]. Small, systematic differences between the two data sets are evident but for consistency we will use the values shown in Tables 1 and 2 in the following discussion.

We observe that the susceptibility of each specimen, which is a measure of its magnetic mineral content, is not closely correlated with Fe content (correlation coefficient $R = 0.56$) (Figure 6a). NRM intensities also exhibit a poor correlation ($R = 0.51$) with FeO*, reflecting the variability of values measured both from the propagator and the failing rift to the northeast (Figure 6b). In contrast, both M_{sat} and M_{rs} are positively correlated with Fe content ($R = 0.79$ and 0.76 respectively) (Figures 6c and 6d). The higher values of saturation magnetization reflect a greater abundance of magnetic minerals but are also partly the result of a paramagnetic fraction which will not contribute to the remanence. The general increase of M_{rs} with increasing Fe content indicates that some of the additional Fe is partitioned into phases which may contribute to the remanence.

Although our magnetic measurements of samples collected near the Easter-Nazca propagating rift suggest that an increased Fe content is accompanied by higher concentrations of magnetic minerals (Figure 4), it appears that the relationship between FeO* and remanent intensity is not straightforward (Figure 6). Several factors can explain this apparent complexity. We believe that the three most likely factors in the case of this study may be crystallization history, varying Fe-Ti ratios, and magnetic mineralogy. Crystallization history, and thus pillow size, is known to

exert a strong influence on magnetization [Marshall and Cox, 1971; de Boer, 1975]. The variation of magnetization with pillow size, which is probably due to differences in effective grain size, may account, in part, for the scatter in our magnetization determinations. In addition, the unequal increases in FeO* and TiO₂ during fractionation may also result in variable Fe/Ti ratios, which may be reflected in the composition of the titanomagnetites [Watkins, 1974]. Our results suggest that both titanomagnetite and a low-Ti magnetite, perhaps controlled by varying Fe/Ti ratios, are present in the samples near 25°S. The complex magnetic mineralogy of these samples further obscures any relationship between Fe content and magnetization.

Available geochemical evidence from other large ridge axis discontinuities (propagating rifts and large overlapping spreading centers) have established that high magnetization zones are associated, in these particular cases, with the eruption of highly differentiated basalts enriched in Fe. Christie and Sinton [1981] and Sinton *et al.* [1983] have suggested that the degree of differentiation attained by magmas beneath oceanic spreading ridges depends, to a large extent, on the relative balance between cooling rate and supply rate of new magma to shallow chambers. Low supply rates and/or high cooling rates will enhance closed system crystal fractionation, while high supply rates will result in compositional buffering of the magma by constant replenishment and mixing with new magmas. Propagating rifts offer a spreading environment prone to the eruption of highly differentiated basalts because of a low supply rate and because of the cold lithosphere surrounding the wedge of new lithosphere [Christie and Sinton, 1981; Sinton *et al.*, 1983]. The highly evolved basalts near 25°S may be the product of small magma bodies with a low supply rate and a high cooling rate, which correspond to the earlier stages of the growth toward a more well-developed magma chamber as the spreading center is propagating into older and colder crust to the north. Although the general association of high magnetization zones with geochemical anomalies and FeTi basalts is well-established, the relationship between remanent magnetization, the presence of a high magnetization zone, and Fe content remains unclear. Our data from 25°S do not support a simple causal relationship

TABLE 2. Major Element Concentrations of Samples Dredged in the Vicinity of the Easter-Nazca Propagating Rift Near 25°S, 112°25'W

	EN 40D-1	EN 14D-1	EN 13D-11	EN 13D-12	PA 04-12-1	EN 12D-10
SiO ₂ ^a	51.01	51.17	50.88	49.20	51.69	51.07
Al ₂ O ₃	14.34	15.10	13.42	17.51	13.43	13.35
FeO*	10.83	10.12	13.57	9.21	13.77	14.17
MgO	6.98	7.50	6.08	8.15	5.63	5.54
CaO	11.92	12.06	10.77	11.65	10.11	9.94
Na ₂ O	2.59	2.72	2.59	3.24	3.01	2.93
K ₂ O	0.06	0.07	0.10	0.03	0.17	0.23
TiO ₂	1.55	1.63	2.25	1.47	2.53	2.81
P ₂ O ₅	0.10	0.15	0.17	0.14	0.30	0.32
MnO	0.18	0.18	0.23	0.18	0.27	0.27
Total	99.57	100.71	100.07	100.77	100.91	100.62
Mg# ^b	57.2	60.6	48.1	64.7	45.9	44.8

^aVG2 used as standard for Si, Ca, Mg, Fe, Al; Smithsonian ilmenite for Ti, Mn; Kak. hornblende for K, Na, and Smithsonian apatite for P.

^bMg # = $\text{Mg}^{2+} / (\text{Mg}^{2+} + \text{Fe}^{2+}) \times 100$, where $\text{Fe}^{3+} / (\text{Fe}^{2+} + \text{Fe}^{3+}) = 0.14$.

Fig. 6. Correlation of magnetic properties and Fe content. (a) Initial susceptibility, (b) NRM intensity, (c) saturation magnetization, and (d) saturation remanence are plotted as a function of FeO^* . Best fit lines and correlation coefficients (R) are indicated. Triangles are dredges from the failing rift, stars from the propagating rift. Note the low correlation coefficients of susceptibility and NRM versus FeO^* . All correlation coefficients were determined from linear data. Vertical bars indicate range of values for each sample.

between Fe content and remanent magnetization, as suggested by the magnetic telechemistry hypothesis, but indicate that other factors may be involved.

CONCLUSIONS

We have performed a three-dimensional inversion of the magnetic field over the Easter-Nazca propagating rift near 25°S. The inversion allows us to define the magnetization structure of the propagating rift. As at the Galapagos propagating rift, rift propagation appears to be a very orderly process in this area. The ratio of propagation to spreading rate equals 1.5, slightly greater than the previous value of 1.3 derived by Naar and Hey [1986]. Propagation occurs at the fast rate of 120 mm/yr, based on a revised estimate of the full spreading rate in this area (80 mm/yr) (D. F. Naar and R. N. Hey, unpublished manuscript, 1989). This is less than the rate of 150 mm/yr proposed by Naar and Hey [1986], which assumed a 120 mm/yr full spreading rate. Within 27–30 km of the rift tip, the propagating rift curves by about 15° to the east toward the failing rift, probably as a result of the interaction with the failing spreading center about 45 km to the east near 112°W. Acceleration to the full spreading rate may require at least 225,000 years.

The propagating rift tip is associated with a zone of high magnetization, which may reflect the eruption of highly differentiated basalts enriched in iron. The measurement of the magnetic properties of samples collected in the vicinity of the Easter-Nazca spreading center confirms the presence of a high magnetization zone, as indicated by the three-dimensional magnetic inversion. However, the detailed relationship between remanent magnetization and Fe content remains unclear, possibly as the result of the influence of other factors, such as magnetic mineralogy and pillow size, on the magnetization intensity of the samples.

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