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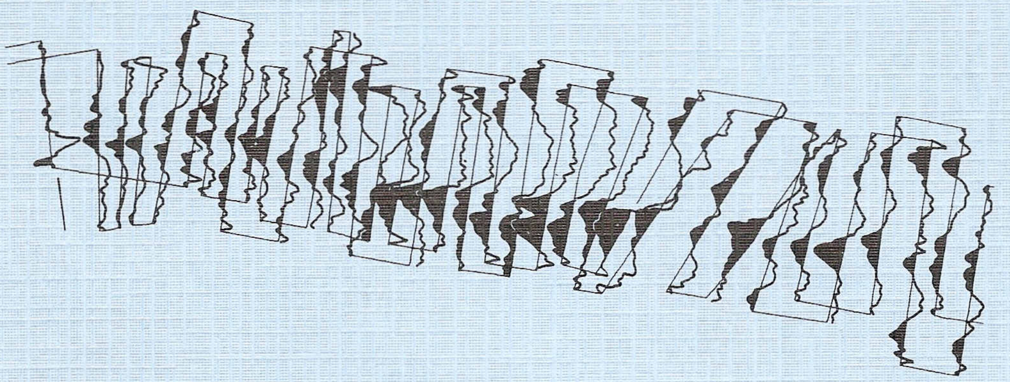
MAGNETIC ANOMALIES OVER FRACTURE ZONES IN THE CENTRAL NORTH ATLANTIC OCEAN



W. TWIGT

MAGNETIC ANOMALIES OVER FRACTURE ZONES IN THE CENTRAL NORTH ATLANTIC OCEAN

PROEFSCHRIFT

TER VERKRIJGING VAN DE GRAAD VAN DOCTOR IN DE WISKUNDE EN NATUURWETENSCHAPPEN AAN DE RIJKSUNIVERSITEIT TE UTRECHT, OP GEZAG VAN DE RECTOR MAGNIFICUS PROF. DR. M.A. BOUMAN, VOLGENS BESLUIT VAN HET COLLEGE VAN DECANEN IN HET OPENBAAR TE VERDEDIGEN OP WOENSDAG 17 DECEMBER 1980 DES NAMIDDAGS TE 2.45 UUR

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PROMOTOR: PROF. DR. B.J. COLLETTE

Aan Etta

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CONTENTS

Samenvatting

Oceanische magnetische anomalieën hebben een belangrijke rol gespeeld in de theorie van spreiding van de oceaankorst: lineaire magnetische anomalieën worden geinterpreteerd in termen van een steeds omkeren van de polariteit van het aardmagneetveld tijdens het spreiden. Correlatie van de anomalieën over de hele wereld heeft geleid tot een uitbreiding van de magnetische tijdschaal, die het mogelijk maakte grote gedeelten van de oceaankorst te dateren en een reconstructie van de spreidingsgeschiedenis op te stellen. De magnetisatie van de oceaankorst is daarom geofysisch gezien van bijzonder belang.

Het karakter van de oceaanbodem wordt sterk bepaald door de talrijke fracture zones, fossiele sporen van een transform fault op de midoceanische rug, die vanaf de rug naar de randen van de oceaan lopen. In het centrale gedeelte van de Noordatlantische Oceaan bedraagt hun onderlinge afstand 50 tot 100 km. Veel van de tectoniek en de resulterende structuur van deze verschijnselen is nog onbegrepen. De laatste jaren hebben meerdere, verschillende soorten metingen aanwijzingen gegeven, dat fracture zones geassocierd zijn met anomale oceaankorst.

Het verzet van een fracture zone leidt tot een configuratie waarbij een strook korst van een zekere leeftijd langs de as van de fracture zone ligt tegen een strook korst van een andere leeftijd. Dientengevolge kan de polariteit van de magnetische laag ter weerszijde van de fracture zone verschillend zijn. Daarnaast heeft de fracture zone een eindige breedte; in de fracture zone zelf bevindt zich een veranderde magnetisatie. In dit proefschrift concentreren we ons op de magnetische anomalieën , gemeten aan het zeeoppervlak, die geassocieerd zijn met de magnetisatie contrasten langs de fracture zone. In sommige gedeelten van de centrale Noordatlantische Oceaan overschaduwen deze zogenoemde fracture zone anomalieën zelfs de normale spreidingsanomalieën.

Hoofdstuk 1 geeft een introductie in de magnetisatie van de oceaankorst en behandelt de in de volgende hoofdstukken gebruikte technieken.

Hoofdstuk 2 geeft een drie-dimensionaal model voor enkele grote onregelmatige anomalieën over de Tydeman Fracture Zone ten zuidoosten van de Azoren. Dit hoofdstuk behandelt ook de gevoeligheid van de scheefheid ('skewness') van spreidingsanomalieën voor kleinere variaties in de strekking van de magnetisatie contrasten. Dit laatste wordt in dit proefschrift niet verder uitgewerkt. Het hoofdstuk is reeds gepubliceerd in Marine Geophysical Researches.

Hoofdstuk 3, ter publicatie aangeboden aan Journal of Geophysical Research, behandelt de variatie van de topografische en magnetische expressie van de Kane Fracture Zone in de Magnetisch Rustige Zone van het Krijt (CQZ) op de Afrikaanse plaat. Deze variatie wordt bestudeerd in relatie tot kleine veranderingen van de spreidingsrichting . In de CQZ treden geen lange magnetische omkeringen op. Dit maakt de magnetische anomalieën in de CQZ zeer geschikt om de magnetisatie in een fracture zone als zodanig te bestuderen, alsook effecten van richtingsveranderingen. De Kane FZ, die een sinistraal verzet heeft, blijkt gekarakteriseerd door een 15 tot 40 km brede zone van verhoogde magnetisatie t.o.v. de omringende normale oceaankorst. Zulks in tegenstelling tot fracture zones met een dextraal verzet, noordelijker in de CQZ, die een gereduceerde magnetisatie hebben. Het teken van de relatieve magnetisatie blijkt dus gerelateerd aan het teken van het verzet van de respectieve fracture zones. Deze conclusie is in strijd met bestaande ideeën omtrent de magnetisatie in de fracture zones (deze leiden steeds tot een reductie) en dit maakt het zoeken van een nieuw mechanisme noodzakelijk om deze magnetisatie te verklaren. De hypothese wordt geformuleerd dat het verschil in magnetisatie in fracture zones het gevolg is van spanningen die samenhangen met de schuifbeweging in het actieve gedeelte van de fracture zone. Deze beinvloeden de magnetisatie zodanig dat de magnetisatie toeneemt in de richting van samendrukking. In hoofdstuk IV wordt dit model verder uitgewerkt, vergeleken met andere modellen en verder getest aan anomalieën over andere fracture zones.

Een van de redenen van het moeilijk herkennen van fracture zones is de variatie van de topografische expressie langs de fz as. Zoals getoond in hoofdstuk III heeft de Kane FZ op enkele plaatsen in de CQZ zelfs in het geheel geen expressie, terwijl de magnetische anomalieën daar wel ononderbroken oplijnen. In hoofdstuk V worden daarom de fz anomalieën gebruikt om fracture zones te helpen identificeren. Dit wordt gedaan voor de centrale Noordatlantische Oceaan tussen 11° en 24°N. Dit hoofdstuk behandelt een gedeelte van de totale reconstructie van het fracture zone patroon tussen 10° en 37°N m.b.v. seismische reflectie en magnetische metingen van het KROONVLAG-project van het Vening Meinesz Laboratorium. Een van de uitkomsten is dat de magnetische expressie van een fracture zone sterk varieert langs de fz as, waardoor het slechts mogelijk is segmenten van fracture zones uit magnetische anomalieën te identificeren. Hoofdstukken IV en V zullen t.z.t. ook als artikelen ter publicatie worden aangeboden.

Chapter I

INTRODUCTION AND SUMMARY

Ocean Crust magnetization

Large areas of the oceanic crust are characterized by lineated magnetic anomaly patterns (Mason and Raff, 1961; Raff and Mason, 1961), which are interpreted in terms of alternating geomagnetic field polarity during seafloor spreading (Vine and Matthews, 1963). World-wide correlation of oceanic anomalies revealed a geomagnetic polarity scale, which, by comparison with radiometrically dated continental lava sequences (Cox et al., 1966) and correlation with sediment ages, allowed ages to be assigned to large parts of the ocean basins over the past 200 m.y. (Heirtzler et al., 1968); LaBrecque et al., 1977; Larson and Hilde, 1975). By matching anomalies on both sides of the spreading center at the Mid--Atlantic Ridge the relative motion of the continents bordering the Atlantic Ocean has been reconstructed (Pitman and Talwani, 1972).

The magnetization of the ocean crust is therefore of considerable geophysical interest. However, there is no unanimous agreement as to where and how the anomalies originate. The source of the magnetic anomalies has commonly been identified with basaltic layer 2A, in the upper 500-1000 meter, which is predominantly of extrusive origin. However, spectral analyses of surface magnetic anomalies (Blakeley, 1976; Cande and Kent, 1976) and direct measurement of dredged and drilled (DSDP) basalt samples indicated that the magnetic layer is much thicker. Deep penetration of layer 2A in recent DSDP holes showed a large variation of magnetization intensity and inclination and, occasionally, polarity alternations in one hole (Hall, 1976). It now appears likely that deeper layers (2B or 3A), although more weakly magnetized than layer 2A, contribute significantly to the oceanic magnetic layer. From studies of ophiolites, regarded as former oceanic crust emplaced tectonically on the continents, Levi and Banerjee (1977) concluded that the sheeted dike complex of layer 2B (between 500 and 1700 meter depth) may take a large contribution to the magnetic anomalies. Kent et al. (1978) concluded from studies of dredged samples that the sheeted dike complex probably makes no appreciable contribution, but that the second source layer would be gabbroic layer 3.

Geomagnetic polarity

From oceanic magnetic anomalies the history of reversals of the geomagnetic field has been derived since the Early Jurassic, that is in the last 180 m.y. Four distinct episodes may be identified. A continuous sequence of well-defined reversals characterizes the time interval from the present to the Late Cretaceous, the Cenozoic sequence, in which the anomalies are numbered 1 upto 34 (Heirtzler et al., 1968; LaBrecque et al., 1977). Over oceanic crust of Middle and Early Cretaceous age the anomalies have generally reduced amplitudes and are not correlatable. This is referred to as the Cretaceous Magnetic Quiet Zone and this zone is normally accepted to be associated with a long period of normal polarity (Helsley and Steiner, 1968). In the Early Cretaceous and Late Jurassic again well-defined, correlatable anomalies are found, the Mesozoic M-sequence (M0-M25, see Larson and Hilde, 1975). Over crust older than the M-sequence (older than 145 mybp) a second quiet zone is found, the Juassic Magnetic Quiet Zone.

The polarity time scale derived from oceanic magnetic anomalies by Heirtzler et al. (1968) was dated by correlation with the radiometrically dated lava sequences for the last 3.35 m.y. and by using estimated sediment ages from several cores. Analysis of subareal paleomagnetic material indicates that the geomagnetic paleofield was an essentially geocentric axial dipolar field (Wilson et al., 1972), changing polarity 2-3 times per m.y., with polarity transition periods of probably less than 10,000 years (Cox and Dalrymple, 1967; Opdyke et al., 1973). The recognition of the magnetic polarity sequence in lavas was extended to about 5 mybp with the aid of deep sea sediments data (Opdyke, 1972), beyond which age the radiometric dating method becomes limited by the lack of resolution (Cox, 1969). The reversal record in deep sea sediments was further extended to epoch 11 (Late Miocene) in a continuous long core (Foster and Opdyke, 1970), confirming the marine magnetic polarity sequence. The oceanic magnetic polarity sequence was confirmed in land sections near Gubbio, Italy (Lowrie and Alvarez, 1977), where a record of geomagnetic reversals was found to match closely the anomaly sequence 30 to 34. The age of anomaly 34 appeared to be 80 mybp and with anomaly 34 ended a long period of normal polarity which was correlated to the Cretaceous Magnetic Quiet Period. Paleomagnetic data from Moria in

Umbria (Alvarez and Lowrie, 1978) and from Cismon in the southern Alps (Channell et al., 1979) confirmed the finding that the CQ Period has been a long normal period. The latter data also revealed Mesozoic anomalies M0 to M4, placing anomaly M0 at the base of the Aptian instead of in the late Aptian as it was dated by Larson and Hilde (1975).

With regard to the Jurassic Quiet Zone various conflicting interpretations as to its nature have been suggested. One of the interpretations is based on the smoothly tapering of the amplitudes of anomalies M21 to M25 towards the magnetic quiet zone. This tapering amplitude envelope was interpreted by Larson and Hilde (1975) in terms of magnetic field intensity increasing away from an anomalously low intensity in the Jurassic Quiet Zone. Another interpretation is that the Jurassic Quiet Zone corresponds to a period of long normal magnetic polarity. The paleomagnetic data from land for this interval are too scarce for conclusions to be made regarding the predominant polarity (e.g. Irving and Pullaiah, 1976).

Fracture zones

Small to very large offsets in seafloor spreading magnetic lineations occur over the numerous fracture zones in the ocean floor. Under the term fracture zone the active transform fault between spreading centers at a mid-oceanic ridge is understood, as well as its inactive trace in older crust. A large number of fracture zones run through the ocean floor from the mid-oceanic ridges to the edges of the ocean. In the central North-Atlantic their mutual distance is between 50 and 100 km. Fracture zones thus highly determine the character of the ocean floor.

The purely geometric concept of fracture zones as transform faults (Wilson, 1965) explains the functioning of fracture zones in kinematic terms, but it does not explain their origin nor give a full understanding of the tectonics and the resulting structure of these features. Bathymetric surveys show that a trough is generally found along fracture zones (e.g. Fox et al., 1969; Van Andel et al., 1971; Collette and Rutten, 1972). The rift valley character of a fracture zone might be due to a component of tension across the active transform domain resulting from lateral thermal contraction (Turcotte, 1974; Collette, 1974). The wall which frequently accompanies a fracture zone to one side still needs explanation. At changes of spreading direction, to which the transform fault has to adjust, additional stresses act that also influence the tectonics of fracture zones (Menard and Atwater, 1968 and 1969; Van Andel et al., 1971).

Several lines of evidence indicate that abnormal crust is associated with fracture zones. Anomalously thin crust has been reported from a seismic refraction experiment in the Kane Fracture Zone (Detrick and Purdy, 1980) and in another fracture zone in the North Atlantic (White and Matthews, 1979). Either thin crust or the presence of bodies of a different mass is indicated by gravity data across the Romanche and the Vema Fracture Zones (Cochran, 1973; Robb and Kane, 1975) and across the Tamayo Fracture Zone in the Gulf of California (Kastens et al., 1979). Effective magnetization of the magnetic source layer has been reported to be very small over a narrow region associated with the fracture zone (Schouten, 1974; Twigt et al., 1979), an outcome that in its generality will be refuted in this thesis. Finally, direct sampling of rock types by dredging and from submersibles have yielded large quantities not only of basaltic and gabbroic, but also of ultramafic rocks from fracture zones (Francheteau et al., 1976).

Content of this thesis

The offset of a fracture zone leads to a configuration in which a strip of oceanic crust of one age will be juxtaposed axially to a strip of another age. Consequently, the polarity of the magnetic layer may be different on either side of the fracture zone. Next to this magnetic contrast the fracture zone may have a finite width; the magnetic source layer for oceanic crust may be altered or absent within the fracture zone. In the following chapters we will concentrate on the magnetic anomalies, measured at sea level, which are associated with the magnetic contrasts along fracture zones. In the central North-Atlantic these fracture zone anomalies even tend to overshadow seafloor spreading anomalies. Schouten (1971) showed that at low magnetic latitude magnetic contrasts along N-S planes produce much smaller anomalies than magnetic contrasts along E-W planes. This explains why the anomalies over fracture zones, which run about E-W in this area, dominate over the normal spreading anomalies, which are about N-S.

In chapter II (Twigt et al., 1979) a three-dimensional model is offered for some large irregular anomalies over the Tydeman Fracture Zone, SE of the Azores, which agrees well with the identified seafloor spreading anomalies to both sides of the fracture zone. This model describes the anomalies as end-effects of the magnetic layer to both sides of the fracture zone with a zone of zero magnetization within it. The chapter also deals with the sensitivity of the skewness of spreading anomalies to small variations in strike of the magnetic contrasts. This sensitivity is also demonstrated by a three-dimensional model for the large irregular anomalies over the Mid-Atlantic Ridge between 12° and 15°N (Twigt and Collette, 1980). The model describes the variation of the central anomaly by a succession of adjacent blocks that vary in strike. The sensitivity of magnetic anomalies to often only small strike variations is not elaborated further in this thesis.

Chapter III (Twigt et al., submitted to J.G.R.) deals with the variation of the topographic and magnetic expression of the Kane Fracture Zone in the Cretaceous Magnetic Quiet Zone (CQZ) on the African side of the Mid-Atlantic Ridge. The variation of the expression of the Kane FZ is studied in relation to the small changes in spreading direction. In the CQZ there are no long magnetic reversals. This and the circumstance that the magnetic polarity of the crust to both sides of the fracture zone is known to be normal, makes that the magnetic anomalies in the CQZ are very useful to study the magnetization in a fracture zone in general as well as effects of direction changes.

The sinistral Kane FZ (Chapter IV) appears to be characterized by a 15 to 40 km wide zone of higher than normal intensity of magnetization, in contrast to dextral fracture zones farther N in the CQZ which are characterized by a zone of reduced magnetization. The sign of the relative magnetization is thus related to the sense of the offset of the respective fracture zones. This conclusion is at variance with current ideas about the magnetization in fracture zones and necessitates the search for a new mechanism to explain this magnetization. The hypothesis is formulated that the difference in magnetization in fracture zones is due to shearing in the active section of the fracture zone, the transform fault domain, in such a way that the magnetization increases in the direction of compressive stress. In Chapter V this model is worked out and further tested on anomalies over other fracture zones.

Due to the presence of numerous fracture zones and the low geomagnetic latitude the identification of spreading anomalies with the magnetic reversal time scale is difficult in the central North Atlantic (see Pitman and Talwani, 1972). The position of the fracture zones in the central North Atlantic was not well-known, which sometimes lead to erroneous identification. One of the reasons which makes it difficult to trace a fracture zone is the variation of the topographic expression of fracture zones along their axes (Collette and Twigt, 1979). As shown in chapter III, a topographic expression of the Kane FZ is even absent at several places. However, the magnetic anomalies over the Kane FZ show a consistent alignment along the fracture zone axis, demonstrating the continuity of the Kane FZ also at these places.

Therefore, magnetic anomalies over fracture zones can be used to help to identify fossil segments of fracture zones as is done in Chapter IV for the central North Atlantic between latitudes 11° and 24°N. This chapter deals with a part of the total reconstruction of the fracture zone pattern between 10° and 37°N from the seismic profiling and magnetic data of the KROONVLAG-project of the Vening Meinesz Laboratorium. The amplitude of the magnetic expression of fracture zones appears to be highly variable along the fz axis, allowing only identification of segments of fracture zones from magnetics. The origin of this variation is studied.

Linear filtering operations on marine magnetic anomalies

When marine magnetic anomalies can be adequately modeled by two-dimensional magnetic structures within one or more plane layers, linear filtering operations are very useful (Dean, 1958; Bott, 1967; Schouten and McCamy, 1972; Parker and Huestis, 1974). Linear filters can be applied quickly and accurately by using the Fast Fourier Transform algorithm (Cooley and Tukey, 1965). We shall describe the filters used in the following chapters in some detail. The application of these filters is presented graphically insofar as possible. To illustrate the filters we consider the magnetic anomaly m(x) over a simple magnetic structure (Fig. 1, profile a). The distribution of the magnetization, alternately normal and reversed, of a plane layer model is given by j(x); the magnetization is vertically constant within the layer and two-dimensional, i.e. further only a function of distance x. The Fourier transform of j(x) is a complex function J(s) of the wavenumber $s = 2\pi/$ wavelength. To describe the anomaly at the observation level we compose the layer model of a succession of infinite rods, each with its own magnetization. The magnetic anomaly observed over the model is the superposition of the anomalies from all rods. This superposition is equivalent to multiplying the transform J(s) of the magnetization distribution in the layer by the transform K(s) of the anomaly of a rod. The product of the two transforms is the Fourier transform M(s) of the anomaly m(x). The magnetic anomaly m(x) then is the inverse Fourier transform of M(s).

The transform of the anomaly over a vertical two-dimensional tabular body of infinitesimal width with its lower and upper surface at depth a and b and uniform magnetization of $\frac{1}{2\pi}$ units, is (Schouten, 1971):

$$K(s) = c\, e^{-i\,\theta\, \mathrm{sgn}(s)}\,(e^{-a|s|} - e^{-b|s|})$$

The factor $(e^{-a|s|} - e^{-b|s|})$ is the earth filter and $e^{-i\theta\,\mathrm{sgn}(s)}$ the phase filter. Assuming vertical contrasts, the parameter θ of the phase filter is given by $\theta = I' + I'_r - 180^\circ$, where I' and I'_r are the effective inclinations (Gay, 1963) of the ambient field and remanent magnetization vectors. The effective inclination is the inclination of the vector component in a plane normal to the two-dimensional structure. The constant c is an amplitude factor: $c = (\sin I \sin I_r)/(\sin I' \sin I'_r)$.

Since the anomaly is obtained by multiplication by the filter transform in the Fourier domain, inverse filtering operations simply are divisions by the filter transform. Fourier transforming a function, multiplying or dividing its transform by a filter transform, and then inverse transforming to yield the filtered function are the steps involved in the application of the linear filters, which are discussed in the following.

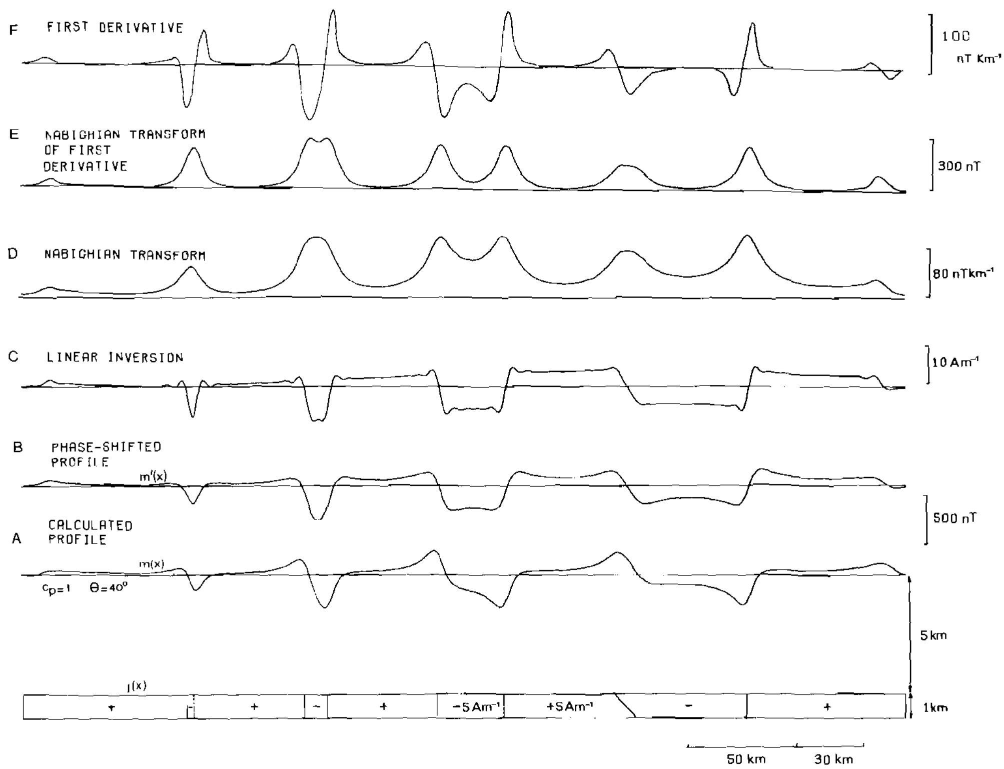

Fig. 1 *a) The calculated anomaly m(x) of a magnetization distribution of a plane layer model j(x). The magnetic polarity was taken alternately positive and negative. One of the contrast boundaries was given a dip of* 6^{o}*; the other contrast boundaries were taken vertical. b) Applying an inverse phase filter to anomaly m(x) yields a de-skewed anomaly m'(x) c) Applying an inverse earth filter to anomaly m'(x) resolves the magnetization distribution to its source. Except for the recognizable high and low wavenumber side lobes of the used bandpass filter, the filter does not introduce spurious small-scale structures in the resulting magnetization distribution. d) The result of the Nabighian transformation by taking the absolute value of the analytic signal of m(x). e) The result of the Nabighian transformation applying a high pass filter in the Fourier domain (by taking the first derivative). f) The first derivative of m(x).*

Inverse phase filter, Fig. 1, profile b

The phase filter describes the skewness of the anomalies due to the directions of the ambient field and remanent magnetization vectors. For non-vertical magnetic vectors and if the strike of the magnetic body differs from the magnetic median, the anomaly is skewed. The inverse phase filter is used to remove this skewing effect ($\theta = 40^{\circ}$ in Fig 1, profile b). This filter can also be applied to observed skew anomalies if the depth of the source is unknown, because the skewness is independent of the depth and shape of two-dimensional structures.

Inverse earth filter, Fig. 1, profile c

The inverse earth filter is used to resolve the two-dimensional magnetization distribution in a plane layer of a specified thickness and at a specified depth. Fig. 1, profile c shows the result of linear inversion of the anomaly m(x) to a layer of 1 km thickness and at a depth of 5 km to the top of the layer. This filter amplifies the high and very low wave numbers. Therefore, precautions must be taken to avoid amplifying noise by the filter, when applied to observed anomalies.

Inverse filtering can be applied to observed anomalies with skewness removed as long as the plane layer model is an adequate model for the actual magnetic structure. However, recent DSDP results (Hall, 1976) have revealed a large vertical inhomogeneity of the magnetic layer, both in intensity and inclination. The average magnetization intensity found ($4\ Am^{-1}$) is enough to place the largest part of the source of the marine magnetic anomalies in the upper 500 to 1000 m of the igneous crust. Schouten and Denham (1979) offered an explanation for the observed variation, by a spreading process at the active spreading center that is discontinuous in time and space. In their models they compose the magnetic layer of major extrusive units of about 100 m thickness by a simple two-parameter process of statistically controlled temporal and spatial emplacement of the units at the spreading center. If the horizontal dimensions of the units are not too large (also see Blakely, 1979), they only lead to short wavelength variations, which are strongly suppressed by the earth filter in the surface magnetic anomalies. Application of the inverse earth filter if combined with a suited smoothing procedure, then actually leads to a distribution of the overall magnetization. Variability in amplitude of magnetic anomaly inversions reflects the variability of the magnetic source (thickness and/or magnetization intensity). For depths of the magnetic layer of more than about 3 km only the product of the thickness of the magnetic layer and the intensity of magnetization can be determined from the surface magnetic anomalies. No absolute values of these quantities follow from such data.

Analytic signal, Fig. 1, profile d and e

Nabighian (1972) has offered another method of linear filtering to resolve the source of a magnetic anomaly. The only assumption made, beside uniform magnetization, is that the cross-sections of the horizontal causative magnetic bodies can be represented by two-dimensional polygons of finite or infinite depth extent. This technique makes use of the absolute value of the analytic signal. The analytic signal $a(x)$ of the field profile $f(x)$ is a complex function, whose real part is $f(x)$ and whose imaginary part is the Hilbert transform $F_{Hi}(x)$ of the former:

$$a(x) = f(x) - iF_{Hi}(x) \tag{2}$$

For the case of a vertical tabular body of infinitesimal width, a "dyke", the amplitude of the analytic function is represented by a symmetrical function maximizing exactly over the top of the dyke. This can easily be derived in the frequency domain. If $F(s)$ is the Fourier transform of $f(x)$, the Fourier transform $\hat{F}_{Hi}(s)$ of $F_{Hi}(x)$ is given by (Whalen, 1971, p. 62):

$$\hat{F}_{Hi}(s) = i \operatorname{sgn}(s)\ F(s) \tag{3}$$

If $A(s)$ is the Fourier transform of the analytic signal $a(x)$, it follows from (2) and (3):

$$A(s) = \begin{array}{ll} 2\,F(s) & \text{for } s > o \\ F(s) & \text{for } s = o \\ 0 & \text{for } s < o \end{array} \tag{4}$$

The transform of the anomaly of a thin dyke of infinite extent follows from (1):

$$F(s) = c\ e^{-i\theta\ \mathrm{sgn}(s)}\ e^{-a(s)} \tag{5}$$

where a is the depth to the top of the dyke.
Using (4) and (5) and inverse transforming of $A(s)$ yields for the analytic signal:

$$a(x) = 2c\ \frac{e^{-i\theta}}{a + i\ x} \tag{6}$$

The absolute value of $a(x)$ is a symmetric function with respect to $x = 0$, which does not depend on θ and thus is independent of the sign of the magnetization:

$$|a(x)| = \frac{2c}{(a^2 + x^2)^{\frac{1}{2}}} \tag{7}$$

In the case of the anomaly of a magnetic step, the first derivative of this anomaly is equal to the anomaly of the thin dyke. By taking the first derivative of a profile, the effect of magnetic steps and other two-dimensional cross sections is transformed into the equivalent of thin dykes (Fig. 1, profile e). The result of this transformation using the first derivative of the profile, are symmetric extrema, situated above the magnetic contrasts. The sharpness and depth of the magnetic contrast determines the amplitude and width of the symmetric function. However, the nature of the magnetic contrast is lost by this transformation, i.e. whether we are dealing with a +/- or -/+ contrast. Also, if we have two magnetic contrasts close by, the two related maxima in the analytic signal may merge into one peak. Generally, if the distance between two contrasts is smaller than the depth of the magnetic layer, this transformation leads to only one maximum over the two contrasts.

When not using the first derivative in taking the absolute value of the analytic signal (Fig. 1, profile d) magnetic steps correspond with maxima of the analytic signal too. In this case the extreme has a much larger width. This can be understood from a comparison of profile m(x) with its first derivative shown in Figure 6, profile f. Therefore, it on.

is a good practice to use the first derivative in applying this transformation.

Noise

The inverse earth filter amplifies the high and very low wavenumber components. Using the first derivative in applying the analytic signal also amplifies the high wavenumber components. It is important that these filters do not amplify more noise than signal. Noise in observed magnetic anomalies comes from a number of sources; diurnal variations and the definition of the regional field by the IGRF may appear as low wavenumber noise . The effect of topography may appear as noise at any wavenumber. Most important when amplifying high wavenumber components is the finite resolution of the measurements and digitalizing errors. Since the high wavenumber variations are strongly suppressed in the data be-

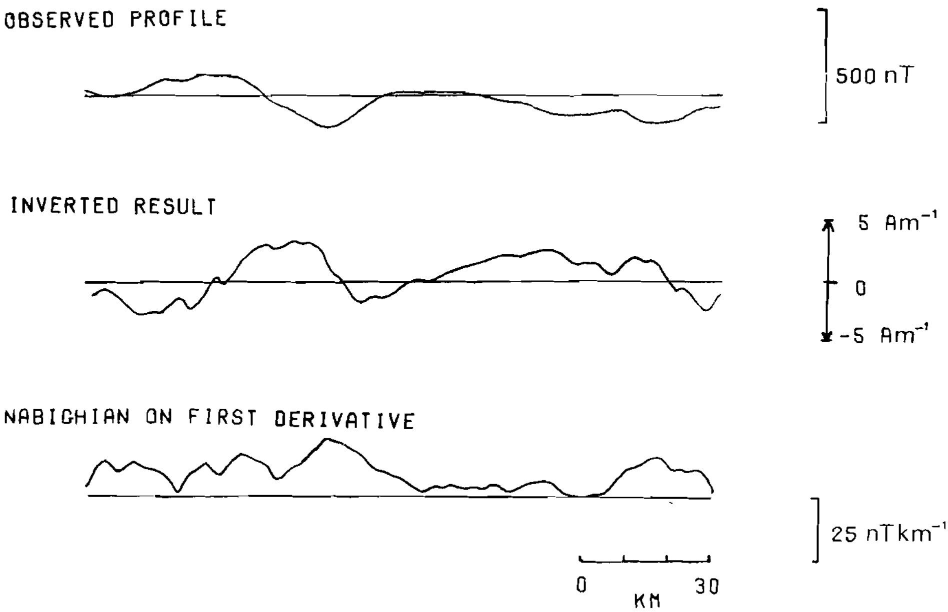

Fig. 2 The result of linear inversion and the Nabighian transformation of a profile over the Kane FZ from Chapter III. The phase-shift parameter θ was calculated using the directions of the ambient field and remanent magnetization vectors in this area and a strike of the magnetic contrasts along the fracture zone azimuth.

cause the observation is at some elevation above the source, there is a high wavenumber limit beyond which the recorded information is simply noise. This limit is estimated by noting where the power spectrum ceases to fall off and steadies at a certain level. To avoid undue amplification the inverse earth filter is truncated at high and very low wavenumbers. This is done by smoothly tapering with a double cosinus taper to avoid side lobes (Schouten and McCamy, 1972). The truncating window is, in effect, a bandpass filter. The linear inversion of real data is illustrated in Fig. 2 for a profile over the Kane FZ from Chapter III. The inversion result represents a magnetization distribution of a plane layer, with its upper and lower surface at 5 and 6 km depth, that leads to the observed anomaly. Fig. 3 shows the used inverse earth filter and the bandpass filter (low and high cut-off wavelength 5 and 225 km

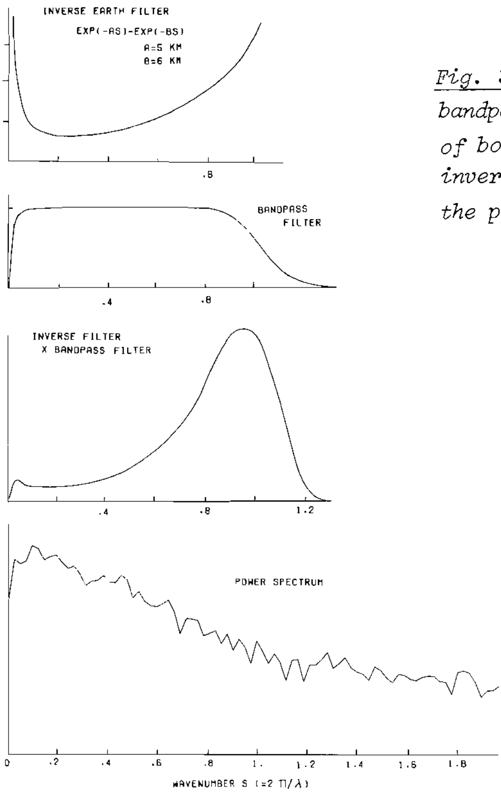

Fig. 3 Inverse earth filter, bandpass filter and the product of both filters, used in the linear inversion of Fig. 2, compared with the power spectrum of a N-S profile.

respectively), and the product of both filters, together with the power spectrum. The combination of the inverse earth filter and the band-pass filter leads to a maximum amplification at a certain wavelength (Blakely and Schouten, 1974). In Fig. 3 this is at 6 km. Though the truncating window has small enough side lobes to avoid effects of it in the inversion of calculated profiles (see Fig. 1, profile b), small ripples may still be present in the inversion of real data. These ripples are caused by a strong amplification of incoherent noise of the wavelengths mentioned above. Amplification of this noise is an inevitable consequence of the filter (Blakely and Schouten, 1974) and it leads to small wiggles of this wavelength in the inversion of real data.

Fig. 2 also shows the result of the absolute value of the analytic signal of the profile. To avoid undue enhancement of high wavenumbers by the use of the first derivative, a Gaussian filter was used (cut-off wavelength of 6 km).

Three-dimensional modeling

Near the intersection of a magnetic contrast along the fracture zone and a spreading anomaly contrast two-dimensional modeling is no longer adequate and a three-dimensional (3D) approach is needed. We shall describe the 3D-filter used in Chapter II in some detail. To illustrate the filter we consider the synthesis of a magnetic anomaly over a simple 3D-magnetic structure (Fig. 4a). The distribution of magnetization of a plane layer model, a reversely magnetized strip which undergoes an offset along a narrow zone of zero magnetization and which is flanked by regions of normal magnetization, is shown; the magnetization is vertically constant within the layer and for the rest a function of horizontal distances x and y. To obtain the anomaly at the observation level we compose the layer model of a succession of small elementary rectangular bodies, each with its own magnetization. The magnetic anomaly observed over the model can be calculated by summation of the anomalies from all the elementary bodies (linear convolution method).

The magnetic effect of a rectangular body, with its upper surface at depth a and thickness t, with magnetization $\bar{m}$ and dimensions of $h \times h$ km^2 in the x and y direction, can be written as (Bhattacharyya

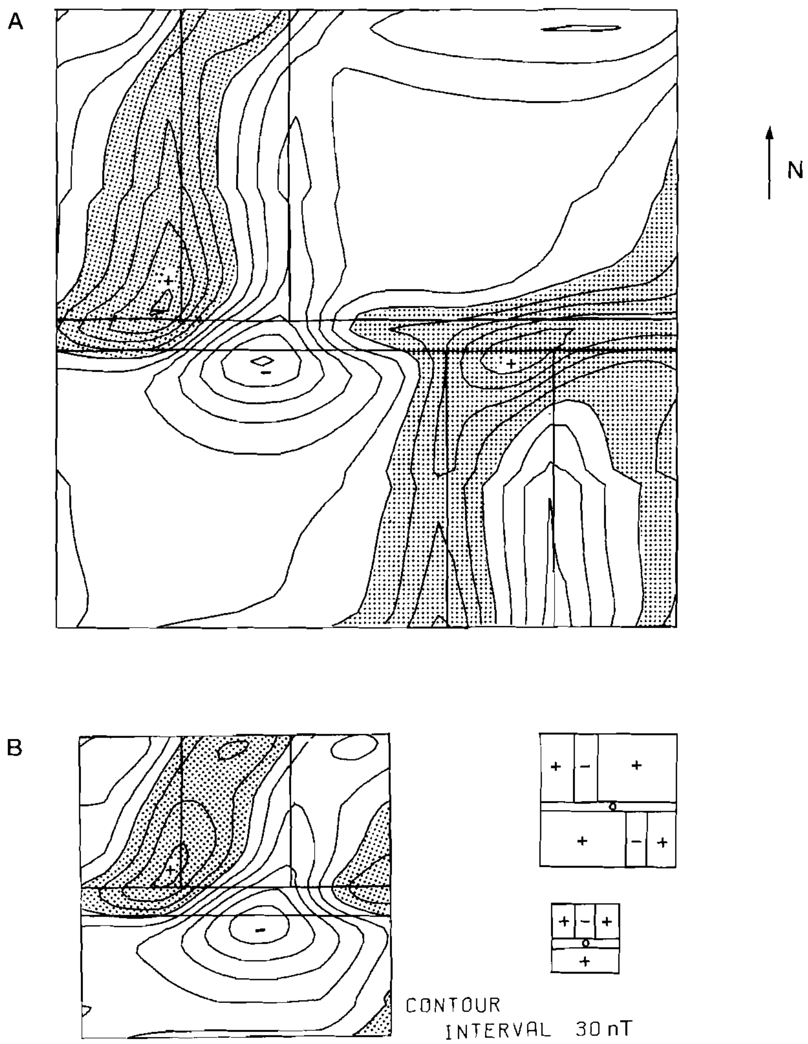

Fig. 4 *Contoured magnetic anomalies, produced by a three-dimensional plane layer model, using elementary blocks of* $2\times2\times1$ *km*^{3} *(a) and* $1\times1\times1$ *km*^{3} *(b). The anomalies were calculated for the position* 13°*N/*45°*W at the Mid-Atlantic Ridge and the upper and lower surfaces of the magnetic layer were taken at a depth of 5 and 6 km.*

and Navolio, 1975)

$$\bar{A}(\bar{r}) = - \int \text{grad } (\bar{n}.\bar{m}/_r) \text{ ds} \tag{8}$$

where

$\bar{A}$ = magnetic anomaly vector

$\bar{n}$ = vector normal to the surface

r = distance to origin

s = surface

The surface integral is composed of the contribution over the six sides of the body. Assuming that r is large with respect to the dimensions of the body, the contribution of each side is approximated by taking grad $(1/_r)$ of the center of the side. For the x-component of the contribution of the front-side of the body, at $x = -h/_2$, this gives

$$a_x = \frac{-m_x ht\ (x + h/_2)}{\left\{(x + \frac{h}{x})^2 + y^2 + (a + t/_2)^2\right\}^{3/2}} \tag{9}$$

Similar equations apply to the other components.
For the anomaly in the total intensity it follows

$$m(x,y) = \bar{A}.\bar{I} \tag{10}$$

where

$\bar{I}$ = unit vector in the direction of the ambient field.

If we assume (c_x, c_y, c_z) are the direction-cosines of $\bar{I}$, we have

$$m(x,y) = \sum a_x c_x + \sum a_y c_y + \sum a_z c_z \tag{11}$$

where

a_x = x-component of the anomaly vector from the contribution of one side of the body.

$\sum$ = summation of the contributions over the six sides of the body.

Fig. 4a shows the anomaly at sea level of a configuration of 80×80 km^2, using elementary blocks of $2 \times 2 \times 1$ km^3. The directions of the magnetic field vectors were taken as corresponding to the position at 13°N/45°W at the Ridge axis in the central North-Atlantic. The direction of the remanent magnetization was taken parallel or anti-parallel to a geocentric axial dipole field. The upper and lower surfaces of the magnetic layer were taken at a depth of 5 and 6 km respectively. The anomaly was also calculated using blocks of $1 \times 1 \times 1$ km^3 over an area of 40×40 km^2, to investigate the effect of the used dimensions of the elementary block (Fig. 4b). From a comparison of Fig. 4a and 4b it follows discrepancies upto 10 nT, i.e. 7% of the peak amplitude of the anomalies. Also note the end-effects of the magnetic layer in both figures which amount upto 5 nT at 15 km distance from the edges of the magnetic layer.

In the same way as in 2D-modeling the calculations could also have been done by way of the Fourier domain. However, to make efficiently use of the Fast Fourier Transform algorithm, the capacity of the memory of the computer that was used formed a limiting factor.

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TOPOGRAPHY AND A MAGNETIC ANALYSIS OF AN AREA SOUTH-EAST OF THE AZORES (36°N, 23°W)

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Abstract. A detailed survey of a 1° × 1°-square of seafloor 100 miles south-east of the Azores shows a strong correlation between directions of regional topographic and magnetic lineations. The area is dissected by the East Azores Fracture Zone at 36°55′N, identified as the active Eurasian–African plate boundary, and by another large, non-active fracture zone at 36°10′N. Both fracture zones strike 265° and are accompanied by large amplitude magnetic anomalies. The general strike in the area in between is 000°–015°. The skewing effect at this magnetic latitude is very sensitive to variations in strike of the magnetic contrasts. This effect was eliminated by a non-linear transformation which also gives the positions of magnetic contrasts. Some N–S contrasts were identified as sea floor spreading polarity contrasts (anomalies 31 and 32). Weak contrasts could be identified as topographic effects and gave a magnetization intensity of 5 A m^{-1}. The identified sea floor spreading anomalies to both sides of the fracture zone at 36°10′N agree very well, also quantatively, with a three-dimensional model for the fracture zone anomalies. This model describes the non-linear anomalies as end effects of the magnetic layer which is divided in blocks of alternating polarity.

Introduction

Detailed bathymetric and magnetic total intensity measurements were made of an area of $110 \times 110\,km^2$ south-east of the Azores (36°–37°M, 22°20′–23°50′W) on board HNethMS Tydeman, Spring 1977. In the north, the area is dissected by the East Azores Fracture Zone identified as the active Eurasian–African plate boundary (Laughton and Whitmarsh, 1972), and in the south by another, non-active fracture zone at 36°10′N. The magnetic anomaly pattern in the eastern North Atlantic, south of the East Azores FZ, has been identified with the standard sequence of sea floor spreading anomalies (Pitman and Talwani, 1972; Laughton and Whitmarsh, 1974; Cande and Kristoffersen, 1977). Laughton and Whitmarsh identify anomaly 30 (66 my) in this area. Lack of data makes identification of the magnetic anomalies with the magnetic polarity reversal time scale difficult in many places and this is especially true for anomalies 25 to 30. This is due to high skewness and low amplitude of the N–S anomalies at this magnetic latitude and a disturbance by numerous east-west fracture zones.

Bathymetric and magnetic contour maps are presented and a quantitative model for the magnetic pattern is given. A strong correlation between the topographic and magnetic highs and lows is apparent and we will attempt to determine quantitatively the influence of the linear topography on the magnetic

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pattern. The form of the magnetic anomaly is very sensitive to variations in strike of the linear magnetic contrasts. The influence of the 15° variation in strike is eliminated by a non-linear transformation (Nabighian, 1972). This transformation also allows us to determine magnetic contrasts caused by polarity transitions or by topographic effects. Some north-south contrasts were identified as sea floor spreading polarity contrasts. The offset over fracture zones disturbs and shifts the sea floor spreading anomaly pattern. To produce this pattern we used a three-dimensional model of adjacent blocks of alternating polarity.

Data

Figure 1 shows the location of the area surveyed with respect to the Mid-Atlantic Ridge axis and the FAMOUS area. The northernmost part of the area (36°50′N–37°10′N) has been covered by a long range side-scan sonar survey (Laughton *et al.*, 1972). Our bathymetric and magnetic total intensity data were obtained on 29 E–W tracks approximately 5 km apart (Fig. 2). The accuracy of the positions, controlled by satellite navigation, is of the order of 1 km. For the analysis we also used several seismic and magnetic NE–SW profiles that were obtained by the Vening Meinesz Laboratorium on board of scheduled freighters (unpublished data).

Figure 3 shows the bathymetry map using a method devised by Slootweg (1978). The chosen filter (low cut-off wavelength of 11 km and filter slope of 6 dB/octave) permit only delineation of major topographic trends. Seismic profiles through the area (e.g. Figure 9) reveal that the basement topography is rather irregular throughout the region. Prominent features are the E–W (265°) trending morphology at 36°55′N identified as the Gloria Fault, a section of East Azores Fracture Zone (Laughton *et al*, 1972), and the deep E–W (265°–270°) striking valley at 36°10′N of another fracture zone.[1] Between these fracture zones

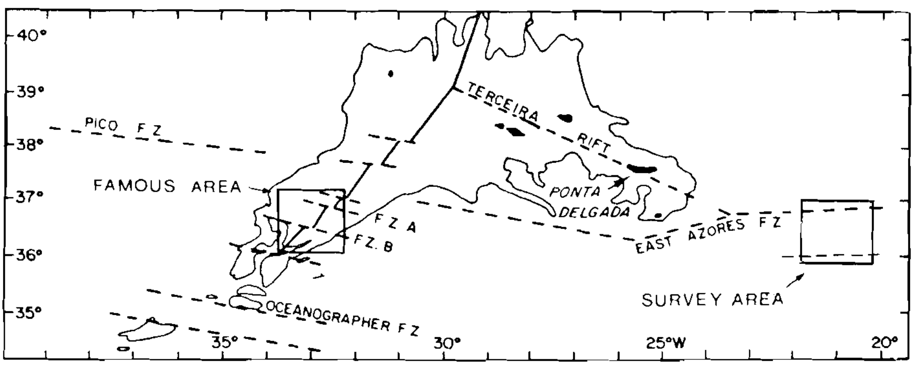

Fig. 1. Location of the survey area.

1) We propose to name this latter fracture zone the Tydeman Fracture Zone, after H.Nl.M.S. Tydeman who then made her first bathymetric survey.

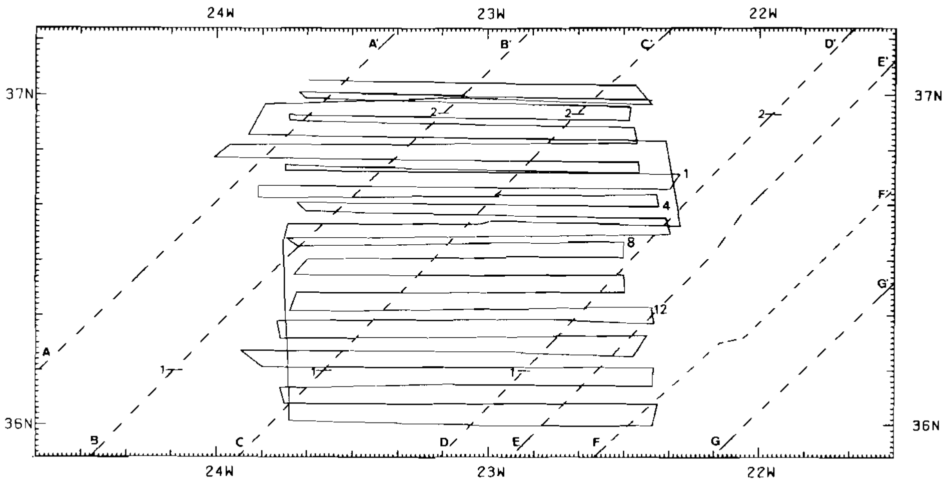

Fig. 2. Track chart. Heavy lines indicate tracks of HNethMS Tydeman. Dashed lines are tracks, obtained by the Vening Meinesz Laboratorium. Seismic reflection profiles on these last tracks were used to determine the effects of the basement topography on the magnetic anomalies (Figure 9). Magnetic profiles along these tracks on both sides of the survey area were used to help to identify the anomalies (Figure 8(a)).

the topography is aligned roughly 000°–015°. Minor features are seen in a clay model of this area (Figure 4) and are superimposed on the bathymetric contour map (Fig. 2). These minor ridges tend to be aligned more northerly (000°).

The mean topographic relief in the area between the fracture zones is about 400–600 m. The seismic records show sediment thicknesses up to approximately 650 ms (500 m).

The magnetic contour map (Figure 6) also gives only major magnetic trends (same filter as used for the bathymetry in Figure 3). The total magnetic field values were reduced by removal of the IGRF (IAGA, 1975). Both fracture zones are clearly expressed in the magnetic pattern, striking about 265°. Especially the fracture zone at 36°10′N is accompanied by large fracture zone anomalies (respectively −490 nT at 36°08′N, 23°20′W and +310 nT at 36°12′N, 22°30′W). Similar large amplitude anomalies over fracture zones were found farther south in the Atlantic (Vogt *et al.*, 1971; Schouten, 1974) and farther east over the East Azores Fracture Zone (Laughton and Whitmarsh, 1974).
The anomalies between the fracture zones are strongly linear, striking 000° at 23°30′W, 015° at 23°00′W and 000° at 22°50′W. This can also be seen in Figure 5 which shows the magnetic E–W profiles.

The peak-to-peak amplitude of these N–S anomalies reaches a value of 200 nT. The average trend direction is the same as in bathymetry. The mean distance east-west between the linear topographic ridges is about 30 km. This is also the mean distance between magnetic highs and lows. In the bathymetry (Figure 3) several north–south magnetic contours are drawn shifted 3 km to the

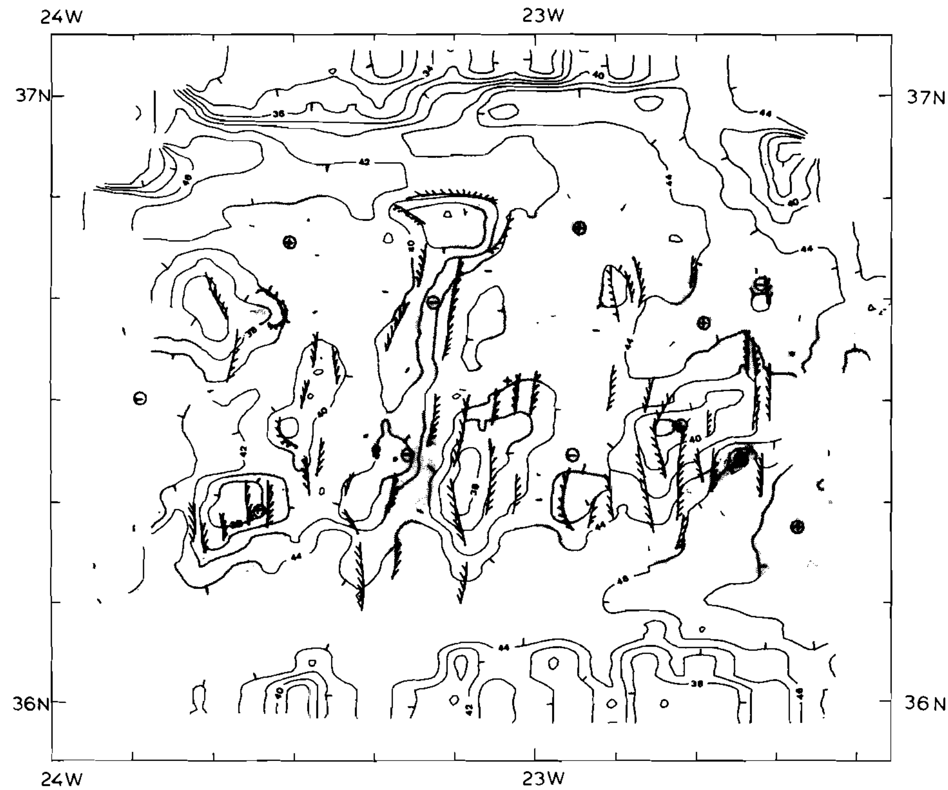

Fig. 3. Bathymetric contour chart. The contour interval is 266 ms (200 m). The dark parts indicate several magnetic contours, shifted 3 km to the west to account for the skewness effects. Superimposed are directions of minor topographic features derived from a clay model of this area (Figure 4).

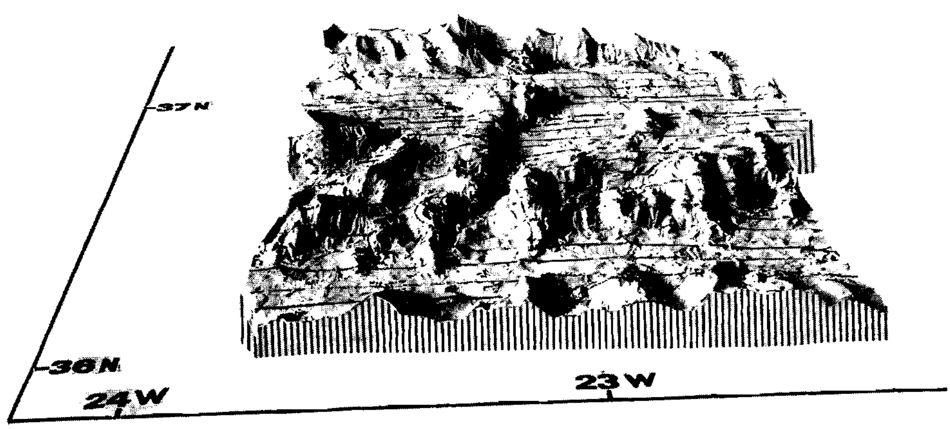

Fig. 4. A clay model of the topography. The model shows clearly minor topographic features that were lost in the contour chart by filtering.

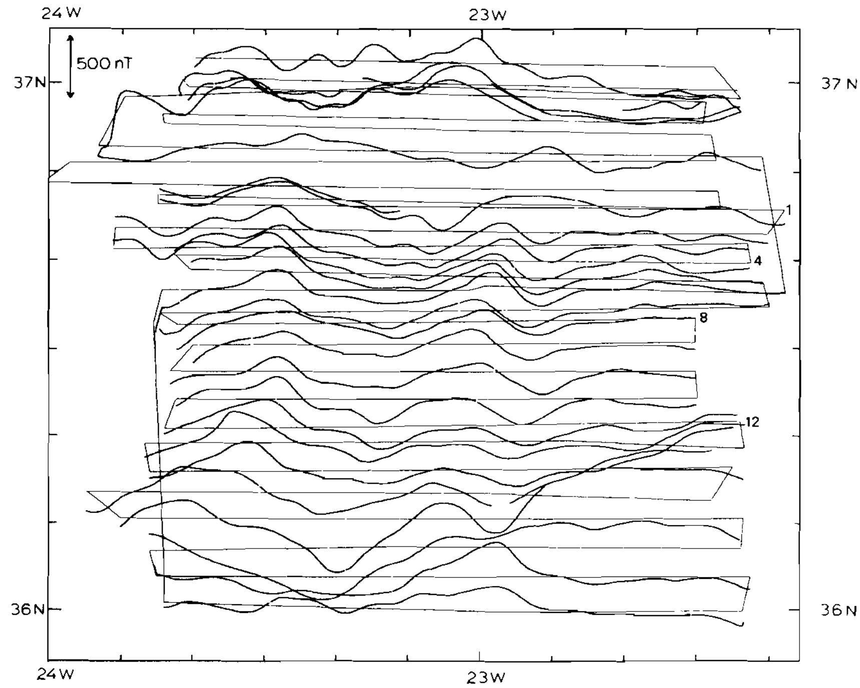

Fig. 5. Observed magnetic profiles along track, reduced to IGRF. The offset with respect to the trackline is −50 nT.

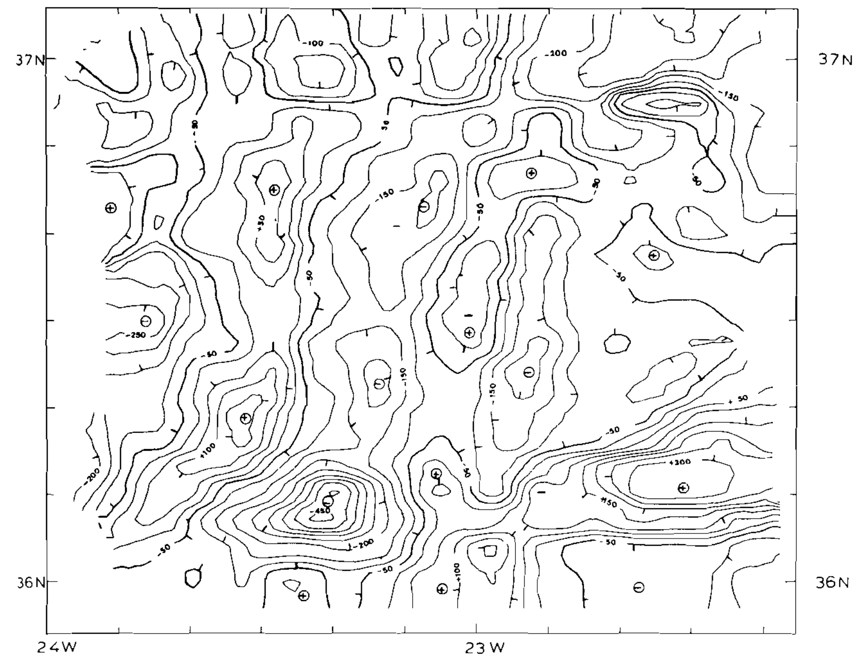

Fig. 6. Contour chart of the magnetic anomalies. (Contour interval 50 nT).

west to account for the skewness. The topographic ridges and valleys and the magnetic extremes appear to coincide, although not everywhere. This raises the question to what extent N–S anomalies are affected by topography as well as by polarity transition effects.

Fracture Zone Anomalies: Modelling

We will study the model of adjacent blocks of opposing polarity (Rea, 1972; Schouten, 1974). Rea investigated this model by comparing the observed with the calculated amplitude ratio of fracture zone anomalies to spreading anomalies. To compute this amplitude ratio the anomaly of a N–S and of an E–W striking polarity contrast was calculated. We used the 2-dimensional model of a flat magnetic layer of constant thickness and uniform magnetization. For the direction of remanent magnetization the Late Cretaceous pole of the African plate at 75.4 N, 211.7 E was used (Van der Voo and French, 1974). For comparison of the observed ratio with the calculated ratio, we applied phase shifting to both observed and calculated anomalies until the anomalies acquired a symmetric appearance over the polarity contrast (Schouten and McCamy, 1972; Schouten, 1974). This phase shifting affects the amplitudes. This operation is equal to a reduction to the pole plus a phase shift of 90°. The result gave a ratio of fracture zone anomaly amplitude to N–S anomaly amplitude of 1.5–1.7 for the observed anomalies and 1.75 for the calculated anomalies.

The changes along strike of the fracture zone anomalies are caused by the finite length in the E–W direction of the polarity contrasts over the fracture zone. The length of the part of the fracture zone over which the polarity on both sides is different will be called the polarity contrast length. To study the form of the anomaly we calculated the anomaly at sea level of a 3-dimensional model of adjacent blocks of alternating polarity which have a finite width in the E–W direction (Figure 7). This was done by calculating first the anomaly of a rectangular body of $2 \times 2 \times 1$ km^3. The anomaly of the total configuration of large blocks was composed by summing up the anomaly of such little blocks (convolution method). The magnetic layer was modelled by horizontal flat blocks of 1 km thickness and at 3.5 km depth below sea level. The magnetization was taken to be homogeneous (5 A m^{-1}) and directed parallel or antiparallel to an axial dipole field through the Late Cretaceous pole. To explain the negative anomaly at 36°10′N, 23°20′W we must assume a negative block north and a positive block south of the fracture zone. For the positive anomaly at 36°10′N, 22°30′W just the opposite situation applies. Comparing with results of calculations with a little block of $1 \times 1 \times 1$ km^3 showed discrepancies of 4 nT. Additional short reversals, say of the order of 2 km, appear to give a strong disturbance of the elliptic pattern of the anomalies. The anomalies are also influenced by the polarities of the adjacent blocks farther along the strike of the fracture zone. Taking into

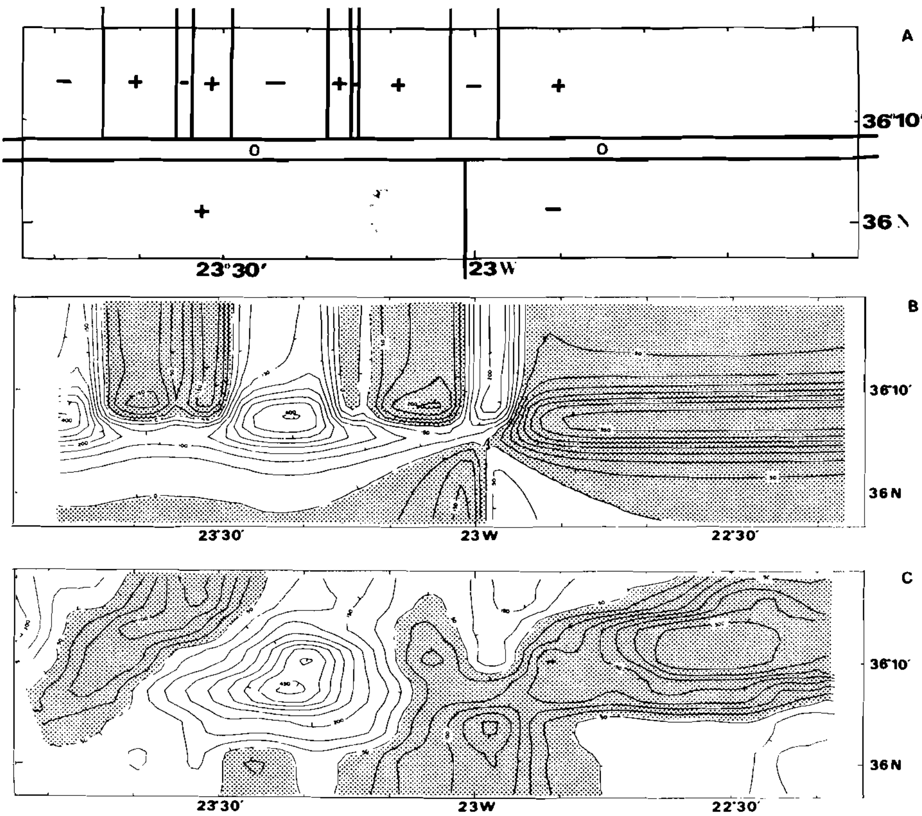

Fig. 7. Contour chart of the magnetic anomalies, produced by a 3-dimensional model of the fracture zone anomalies (b), compared to the observed anomaly pattern (c). Heavy lines mark the magnetic contrasts (a). Contour interval 50 nT. In the fracture zone a neutral zone has been assumed of 4 km width. The magnetization intensity is 5 A m^{-1}.

account the additional uncertainties arising from this circumstance, the polarity contrast length was deduced by comparing observed and calculated half width in E–W direction. For the anomaly at 36°10'N, 23°20'W a contrast length of 16–20 km was found and for the anomaly at 36°10'N, 22°30'W 30 km was the minimum value. This gives a lower limit for the fracture zone offset.

At right angles, i.e. in the N–S direction, the calculated anomalies have about half the half-width of the observed anomalies. This can be explained by either assuming a zone of zero magnetization (Collette *et al.*, 1974, p. 173) or by a deeper location of the magnetic layer.[2)]

N–S Anomalies: Modelling and Topography Effects

For a better comparison of the highly skewed N–S anomalies with theoretical models we phase shifted the profiles between the two fracture zones, until the

2) From the halfwidth of the observed anomalies of 16-19 km a width of the zone of zero magnetization would follow of 8-12 km.

anomalies acquired a square symmetric appearance (Schouten and McCamy, 1972) (Figure 8(a)). This partial normalization of the magnetic profiles removes the skewing effect of non-vertical magnetization vectors and is equal to reduction to the pole. It follows from phase shift calculations using the Late Cretaceous pole of Van der Voo and French (1974), that the phase shift parameter, θ, varies from $-27°$ to $-45°$ when the strike varies from 0° to 20°. Because of the variations in the strike direction and the sensitivity of θ to this variation, we had to content ourselves with an approximate value for θ. The average phase shift was estimated at $-45°$, although for the anomaly at 22°50′W a better estimate seems $-75°$. These values are 20°–30° higher than the calculated values.

For a better estimate of the positions of the contrasts we used a non-linear transformation on the magnetic profiles taking the absolute value of the analytic signal (Nabighian, 1972). This transformation elimates the shifting effect for an arbitrary phase shift and so corrects for the disturbing influence of the variation in strike. The transformation produces maxima that are situated above the contrast positions. It is not necessary to know the value of θ, but on the other hand the nature of the contrast is lost. We applied this transformation to the profiles between the two fracture zones (Figure 8(b)) using a Gaussian filter to suppress noise (low cut-off wavelength 6 km) and a second filter to get rid of long wave lengths. For this latter filter we used the first horizontal derivative. The resulting maxima, some of which line up clearly, can be caused both by topography and by polarity contrasts.

To investigate the effect of topography several NE–SW basement profiles through the area were used (Figure 2). For this we took as a model a homogeneous magnetized layer without polarity contrasts with the basement as the upper surface and with a flat underside. This produces anomalies and Nabighian extremes that are caused by topographic effects only. For the magnetization intensity we took 5 Am^{-1}, a value that corresponds with that of dredged basalts more than 10 km distance from the Mid-Atlantic Ridge (Johnson and Atwater, 1977). The strike is 000° and the Late Cretaceous pole of Van der Voo and French (1974) was used again. The calculated anomaly profiles were deskewed by phase shifting and the Nabighian transformation was applied on these (Figure 9). Comparing with the results of Figure 8(a) and (b), the conclusion is that only weak Nabighian maxima (e.g. at 36°20′N, 23°20′W; 36°25′N, 22°40′W; 36°40′N, 22°35′W) can be topographic effects, unless we take the magnetization to be several times greater.

With the identification of large Nabighian maxima as the position of the polarity contrasts, 2-dimensional models can be formed. The peaks at the profile ends are end effects of the Fourier transform and cannot be used. Figure 8(c) and (d) shows two models with calculated anomalies (deskewed) and the result of the Nabighian transformation on these. These results appear to compare well with the observed data at 36°22′N and 36°40′N.

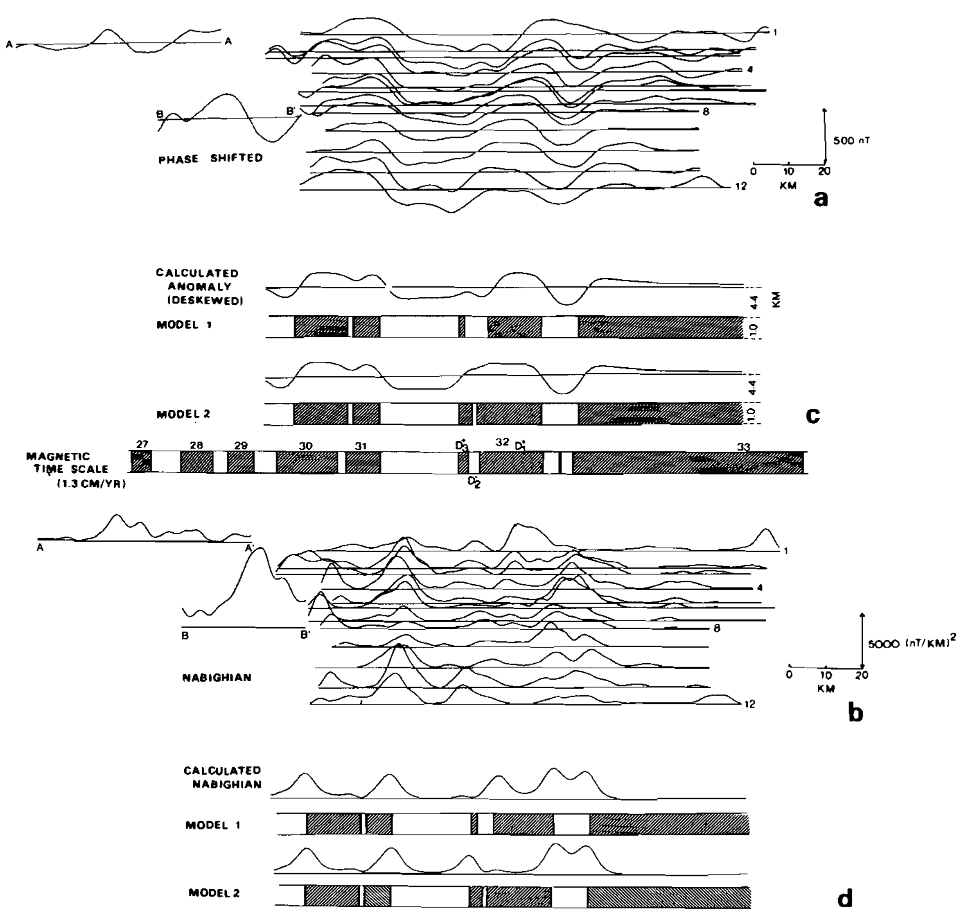

Fig. 8. (a) The magnetic profiles between 36°22′N and 36°45′N, i.e. between the two fracture zones, phase shifted for $\theta = -45°$ and projected on an E–W line through the most western point of the profile. In addition parts of sections AA′ and BB′ (Figure. 3) are shown in order to complete the picture, also −45° phase shifted and projected on an E–W line.

(b) The result of the transformation of Nabighian on the profiles of Figure 8(a). In the frequency space a high pass filter was applied (by taking the first derivative) as well as a Gaussian low pass filter (cut-off wavelength 6 km). The power spectrum showed that wavelengths shorter than 3–4 km represent noise.

(c) and (d) Two 2-dimensional models of the magnetic layer with polarity contrasts following from the large Nabighian extremes. Magnetization intensity is 5 Am^{-1}. The difference between both the models is the width of the D_2^- event (See text). The calculated anomalies (deskewed) (c) and the result of the Nabighian transformation on these (d) agree with the observed data at 36°22′N and 36°40′N, respectively. Also shown is a part of the magnetic time scale of Labrecque *et al.* (1977) with an assumed spreading rate of 1.3 cm/yr,

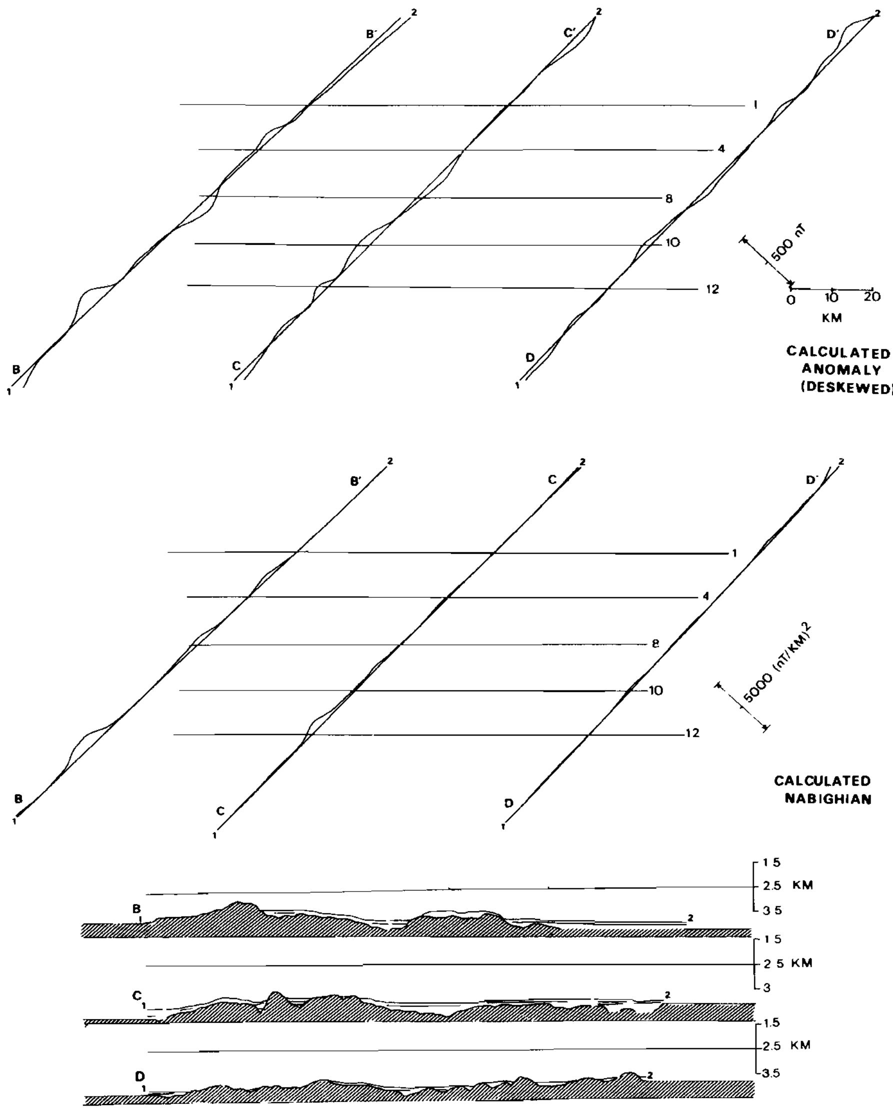

Fig. 9. Calculated anomalies (deskewed) and the corresponding Nabighian transformed curves of a homogeneously magnetized layer that follows the basement profiles of sections BB′, CC′ and DD′ of Figure 3. No polarity contrasts are taken into account to study topographic effects. The strike is 000° and the magnetization intensity is 5 A m^{-1}.

Identification

Anomaly 34 has been identified at 36°18′N, 21°30′W (Schouten, personal communication). This anomaly has an easily recognizable form. Starting from there and using the NE–SW magnetic profiles on both sides of the area (Figure 8) the sharp contrast at 23°30′W has been identified as the eastern side of anomaly 31, and the constrasts at 22°50'W and 23°00'W as the eastern side of anomaly 32 and the western side of anomaly 33, respectively (Figure 10).

For the events D1$^+$, D2$^-$ and D3$^+$ in anomaly 32 we follow Lowrie and Alvarez (1978). If the D2$^-$ event is smaller than 2–3 km, the greatest contrast will come on the western side of the D3$^+$ event. This is seen in the profile at 36°20'N (at 23°15'W) and corresponds with model 2 (Figure 8(c)). If, on the other hand, the D2$^-$ event is larger, the greatest contrast comes on the western side of D1$^+$. This occurs in the profile at 36°40'N (at 23°15'W) and is seen in model 1 (Figure 8(c)). The result is a divergence of the D2$^-$ event to the north. The anomaly at 36°00'N, 22°55'W has been identified as the eastern side of anomaly 33 by Cande and Kristoffersen (1977, their figure 1). This agrees well with our E–W profile at 36°00'N.

The anomaly identification on both sides of the fracture zone at 36°10'N (Figure 10) corresponds exceedingly well with the results of the above fracture zone anomaly model (Figure 7). The anomaly identification gives 18 km for the polarity contrast length of the fracture zone anomaly at 36°10'N, 23°20'W, while the fracture zone model gave 16–20 km.

With the positions of the polarity contrasts defined by the sharp Nabighian extremes, the spreading rate was determined, using the magnetic time scale of Labrecque *et al.*(1977) (Figure 11). Before anomaly 32 a spreading rate was found of 1.20 cm/yr at 36°43'N and 1.02 cm/yr at 36°23'N, during anomaly 32 apparent spreading rate is 1.45 cm/yr. However, the overall spreading rate

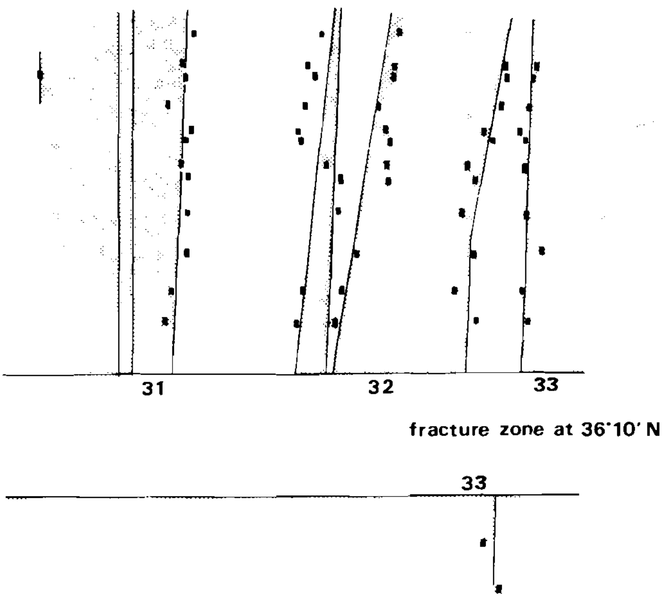

Fig. 10. Identification of the larger Nabighian extremes with the magnetic time scale. Dashes represent the positions of the larger Nabighian extremes of Figure 8(b). Note the variation in strike and the agreement with the fracture zone model of Figure 7.

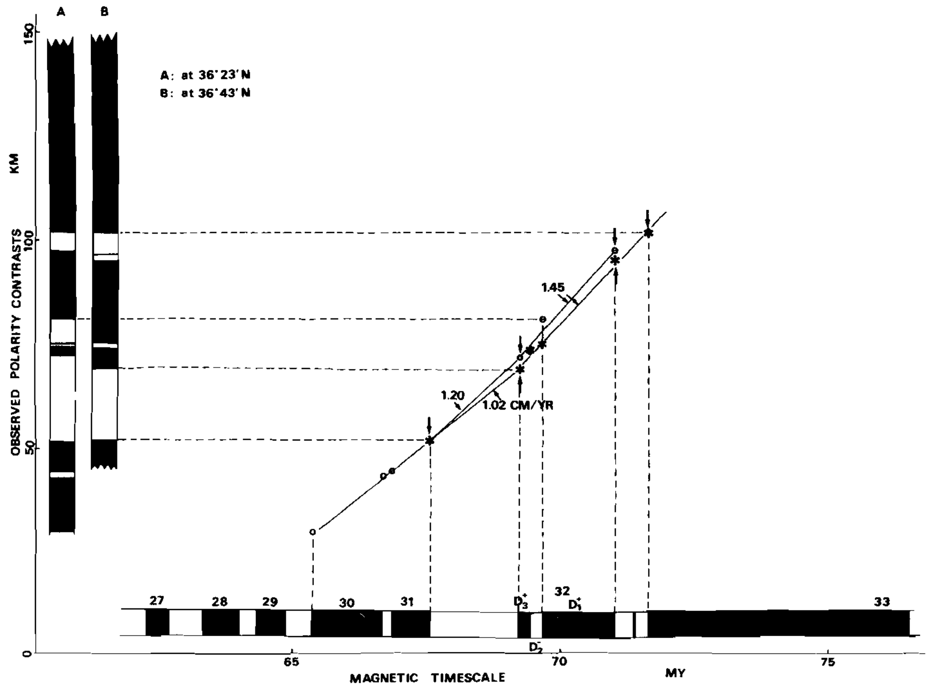

Fig. 11. Observed polarity contrast positions at 36°23'N and 36°43'N, respectively, versus the magnetic time scale of Labrecque *et al.* (1977) and the derived spreading rates. The positions with an arrow have an accuracy within 2 km.

between anomaly 31 and 33 is only 1.3 cm/yr. Earlier determinations gave 3.5 cm/yr (Laughton and Whitmarsh, 1974, Figure 7) and 0.8–1.0 cm/yr (Cande and Kristoffersen, 1977, their figure 2) for this area.

From these spreading rates, using the identification of the western side of anomaly 33 north of the fracture zone at 36°10'N and the eastern side of anomaly 33 south of this fracture zone, it follows that the offset of this fracture zone reaches a value of 60 ± 5 km.

Discussion and Conclusions

The strike of anomaly 31 is 000°–005° as compared to 010°–015° for anomaly 32. This might be interpreted as a change in spreading direction during anomaly 32, coinciding with a change of spreading rate. However, anomaly 33 strikes 000° again. Secondly, there is no distinct bending of the fracture zone at 36°10'N in this area. Further, from detailed studies over the Mid-Atlantic Ridge (Luyendijk and Macdonald, 1977; Collette *et al.*, in press) random divergences up to 10° from the average axis direction appear. Therefore a systematic change in spreading direction probably did not take place in this area but the 10° variation is associated with the statistical deviation in the direction of the spreading axis. This deviation might be caused by a a shifting of segments of the actual spreading center over distances of several kilometers. These segments then would have lengths of the order of 20 km. This process gives rise to an in echelon configuration of the topography and, incidentally, of the magnetic contrasts. The in echelon structure can be recognized from the magnetic profiles in Figure 5 and the distribution of the Nabighian maxima in Figure 10, and may form the explanation of the differences between the two models of Figure 8(c). The apparent 015° azimuth of anomaly 32 would be caused by the filtering used for the contouring. A same effect is present in the topography and accounts for the differences in strike between smaller scarps and the contoured topography in Figure 3.

Summing up, the direction of both the magnetic and bathymetric lineations between the two fracture zones, with respect to the fracture zone at 36°10′N (95° ± 5°) support perpendicular spreading in this area, although this does not follow directly from a first inspection of the contour maps. That the Gloria Fault seems to be parallel to the fracture zone in the south, may be a coincidence since the former forms an active plate boundary.

Our conclusions then are:

(1) There is a strong correlation between direction of alignment of magnetism and topography. The average trends in the topography and the magnetic anomalies reflect directions of the spreading axis at the time the crust was formed. The spreading process as such presumably is not strictly linear, but tends to give rise to in echelon structures.

(2) N–S anomalies are identified as anomaly 31 at 23°30′W and anomaly 32 at 23°00′W between the fracture zones at 36°10′N and 36°55′N. Anomaly 33 has been identified at 36°00′N, 22°55′W. From small anomalies recognized as effects of the topography a value of about $5\ \mathrm{A\ m^{-1}}$ for the magnetization intensity follows.

(3) The polarity contrast positions determined by the transformation developed by Nabighian (1972) lead to an overall spreading rate of 1.3 cm/yr. The offset of the fracture zone at 36°10′N is 60 ± 5 km.

(4) The anomaly identification agrees very well with a 3-dimensional model for the magnetic pattern over the fracture zone at 36°10′N. This model describes the fracture zone anomalies as end effects of the magnetic layer and gives an amplitude ratio of these anomalies to spreading anomalies that corresponds with the data.

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TOPOGRAPHY AND MAGNETICS OVER THE KANE FRACTURE ZONE IN THE CRETACEOUS MAGNETIC QUIET ZONE

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Abstract

The eastern limb of the Kane FZ has been surveyed between 32°W (anomaly 34) and 24°W (anomaly M4), thus comprising the Cretaceous Magnetic Quiet Zone (CQZ). Continuous reflection seismics show that the expression of the Kane FZ in the basement is very variable, from a broad zone with a central ridge to a much narrower zone. At several places a topographic expression is even absent. However, the magnetic anomalies over the Kane FZ are not interrupted, but, on the contrary, show a remarkable consistent alignment along the f.z.axis, demonstrating the continuity of the Kane FZ also at these places. The magnetic anomalies also show that the CQ Period has been a long normal period.

A model was derived based on linear inversion of the magnetic anomalies. It shows that the sinistral Kane FZ is characterized by a 15 to 40 km wide zone in which the effective magnetization intensity is *higher than normal*, about 10 to 15 Am^{-1} assuming an intensity of normal crust of 5 Am^{-1}. The dextral fracture zones farther north in the CQZ have a *reduced* magnetization. The sign of the relative magnetization is thus related to the sense of offset of the respective fracture zones. This can only be an effect of shearing, the one other directional process involved. This conclusion is at variance with current ideas about the magnetization in fracture zones. The hypothesis is formulated that shearing influences the magnetization in the active section of the fracture zone in such a way, that the resulting apparent magnetization is enhanced or reduced depending on the geometrical configuration.

The variations of the topographic and magnetic expression of the Kane FZ along its axis are related to small changes in fracture zone azimuth, resulting from changes in spreading direction. The reconstruction of what actually happened is necessarily incomplete since the

complementary oceanic lithosphere has to be found in the American plate, i.e. west of the Mid-Atlantic Ridge at longitudes 58° to 66°W. However, the total picture suggests that under the influence of changes of spreading direction the fracture zone in the transform fault area opens and a transverse ridge develops. Next a shift of the transform fault takes place adding the transverse ridge to one of the two plates involved which is then transported out of the active transform domain. At changes of spreading direction that lead to compression in the transform domain the topographic expression of a fracture zone may disappear.

Introduction

The eastern limb of the Kane Fracture Zone in the North Atlantic was surveyed in the summer of 1978. Continuous seismic, gravity and magnetic total intensity data were collected along 41 sections perpendicular to the fracture zone and situated at mutual distances of 22 to 28 km. The survey area lies N of the Cape Verde Archipelago between 32°W and 24°W. The gravity results are not dealt with in this paper.

The trace of the Kane Fracture Zone between 62°W and 32°W has been described by Rabinowitz and Purdy (1976) and Purdy, Rabinowitz and Velterop (1979). To the American side this comprises the period from the present until well into the Cretaceous Magnetic Quiet Zone (CQZ), to the African side until anomaly 34 (80 m.y.B.P.). The Kane Fracture Zone has a sinistral offset of 160 km at the Ridge axis at 24°N/45°W. At anomaly 34 the Kane FZ offset is the same. From a survey within the Mesozoic magnetic anomaly sequence S of Bermuda (Purdy and Rohr, 1979) the Kane Fracture Zone was tentatively identified W of the Ridge at 30°N and between 66° and 67°W. The offset at anomaly MO would be only 38 km.

We followed the trace of the Kane Fracture Zone on the African plate from anomaly 34 to Mesozoic anomaly M4 (113 m.y.B.P.). In doing so we followed Dr H.Schouten's advice regarding the probable course of the Kane FZ, which was based on a general reconstruction of the magnetic anomaly pattern in the central North Atlantic (H.Schouten, in preparation). This advice worked out extremely well. The survey comprises the total Cretaceous Magnetic Quiet Zone, which is characterized by the absence of identifiable sea floor spreading anomalies. At Mesozoic anomaly MO (108 m.y.B.P.) the offset of the Kane Fracture Zone appeared to be also only 38 km and at anomaly M4 15 to 25 km (see also Rohr and Twigt, 1979). This means that in the CQZ a growth of the Kane FZ offset took place of 122 km. Although it is supposed that this offset growth is related to a change or changes of the spreading direction during the Cretaceous Quiet Period, we cannot yet offer an explanation for this growth.

Due to the fact that the Cretaceous Quiet period has been a long normal period (see e.g. Lowrie, 1979) the crust N and S of the Kane FZ is normally magnetized. There are no long reversals. This and the circumstance that the magnetic polarity of the crust to both sides is known makes that magnetic anomalies over fracture zones in the CQZ are very useful to study the magnetization *in* the fracture zone. Earlier, Schouten (1974) and Twigt et al. (1979) found that in areas with magnetic reversals fracture zones are associated with a narrow region of reduced magnetization. Cochran (1973) modelled the Romanche Fracture Zone with a much wider region in which the magnetization would be induced.

To our surprise the anomalies over the Kane FZ indicate the presence of a relative positive magnetization in this fracture zone, i.e. the fracture zone has a higher than normal magnetization. This is confirmed by model studies. Fracture zones farther to the N indeed have a reduced magnetization. These fracture zones all have a dextral offset. To account for the new findings, the hypothesis is formulated that fracture zones with a sinistral offset have a higher than normal magnetization and that fracture zones with a dextral offset have a reduced magnetization. This is related to the shearing that took place in the active part of the fracture zone with respect to the magnetic meridian at the moment the anomalies were generated.

The survey provides an excellent opportunity to investigate the response of a fracture zone to changes in spreading direction. To enable spreading of the rigid plates, the transform sections of fracture zones and hence their fossil traces must be situated along small circle patterns according to the theorem of Morgan (1968). Menard and Atwater (1968, 1969) discuss the adjustment of fracture zones to changes of the spreading direction and conclude to the necessity of development of adjustment fracture zones under special circumstances. Van Andel et al.

(1971) explained the large width of the Vema fracture zone as caused by the last change of the direction of spreading. Collette and Rutten (1972) commented upon this latter idea and suggested that the transform faults have intrinsically a finite width, thus explaining the rift valley character. In the present survey both the topographic and magnetic expression of the Kane FZ appear to be rather variable along the fracture zone axis. We will try to relate changes of the Kane FZ azimuth to the topographic and magnetic character of the Kane FZ.

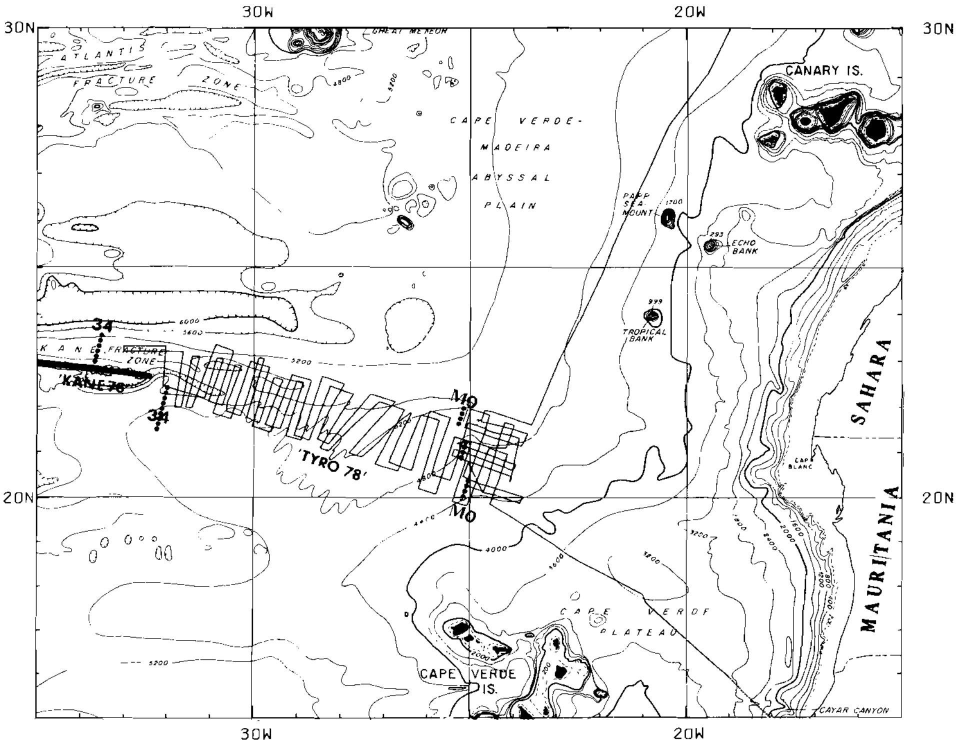


Fig. 1 Trackchart and location of the survey area. Bathymetric contours are from Uchupi et al. (1976). The heavy line shows the eastern end of the Kane Fracture Zone, as it has been followed by R.V.Knorr in 1976. Dotted lines are isochrons: identifications of magnetic anomaly 34 on the western part of the survey area and of Mesozoic anomaly MO on the eastern part.

Magnetics and continuous seismics

Figure 1 shows the survey area and the tracklines with regard to the surrounding area. H.Schouten (pers.comm.) identified magnetic anomaly 34 north of the Kane Fracture Zone at $33^{\circ}30'$W. At 32°W we identified anomaly 34 to the south of the Kane FZ and at 25°W we found anomaly MO both to the north and the south. The area in between comprises the total Cretaceous Magnetic Quiet Zone (108-80 m.y.B.P., according to Larson and Hilde, 1975 and Labrecque et al., 1977). The tracklines are about perpendicular to the fracture zone, 130-170 km in length and approximately 22 to 28 km apart. Position control was by satellite navigation with an accuracy of about 1 km. We make use of several additional profiles, obtained earlier on board of HNethMS Luymes and M.V.Aegeon Express, and of an east-west track at 22°N of HNethMS Snellius and of several tracks of the KROON-VLAG-project.

The continuous seismic profiling measurements, as shown in Figure 2, reveal the sedimentary thicknesses and the basement depths. The profiles have been projected in a direction of 290° with regard to a depth of 7000 ms (5250 meter). Since the survey area is situated at the northern slope of the Cape Verde Rise (Uchupi et al., 1976, see Figure 1) the depth along the profiles increases to the north. The eastern part of the survey area is completely covered by turbidite sedimentation, reaching thicknesses of 1.3 to 1.8 s. This corresponds with thicknesses of 1300 to 1800 meter according to the curves of Nave and Drake (1963). In the western part the turbidites, which come from the east, fill only the troughs.

The heavy lines in Figure 2, representing the oceanic basement, show the existence of the Kane Fracture Zone as a basement structure and of another fracture zone 75 km to the N. The basement in between contains some ridges and valleys trending about 020°. The northernmost fracture zone had already been found by Uchupi and Emery (1974, p.12) and then, erroneously, been identified as the Kane Fracture Zone. We will call this fracture zone the Northern fracture zone (cf. Purdy and Rohr, 1979).

The shape of the Kane Fracture Zone is highly variable in cross-section. Its course becomes only clear from a composite diagram of parallel sections. Even so, the identification could be questioned if it were

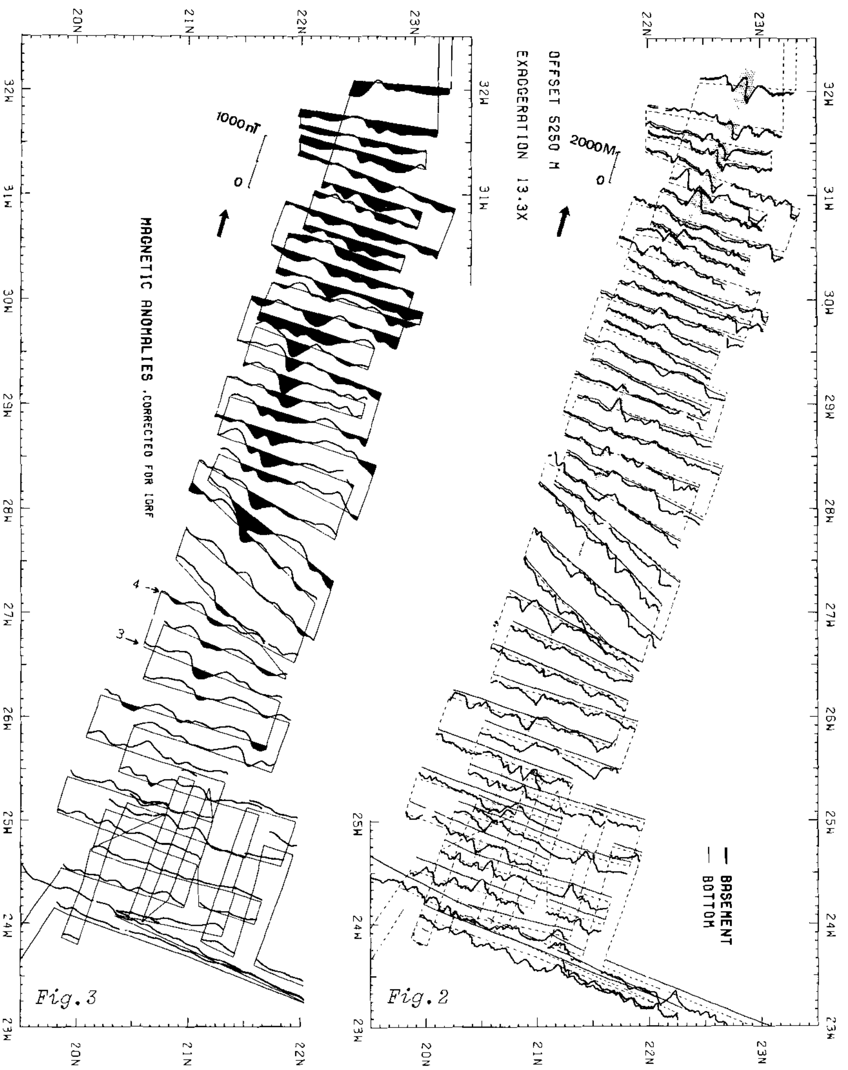
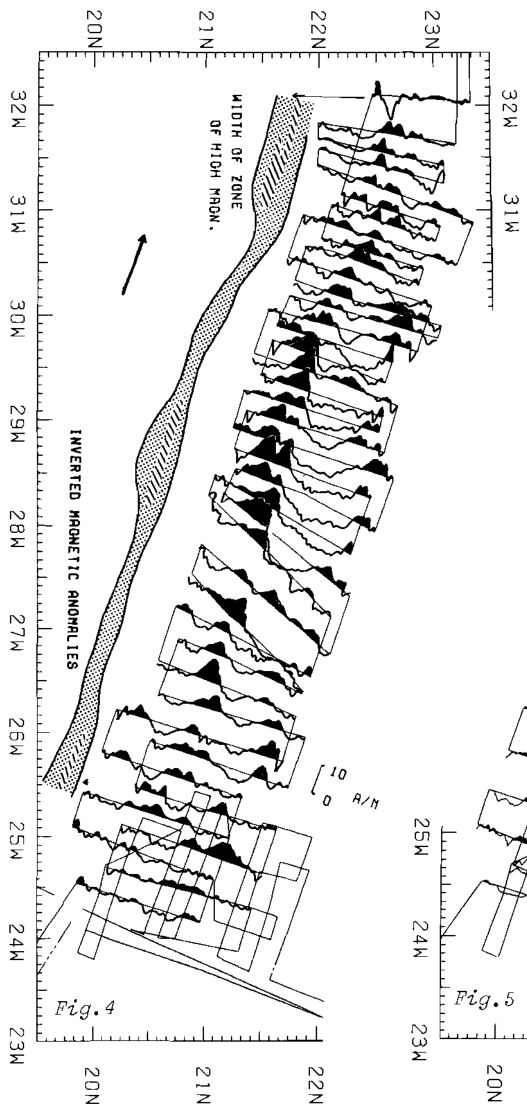


Fig. 2 A composite diagram of parallel seismic sections. The tracklines are indicated by dashed lines. Thin lines are bottom profiles, heavy lines are basement depths. The profiles have been projected in a direction of 290° with regard to a depth of 7000 ms (5250 meter). The Kane Fracture Zone can be identified as a basement structure. The dotted belt shows the axial zone, varying in width and delineating small changes of the fracture zone azimuth.

Fig. 3 Observed magnetic anomalies along track, reduced to IGRF. The offset with respect to the trackline is 100 nT. The profiles have been projected in a direction of 290°. Black areas denote negative values. For profiles 3 and 4 the results of phase-shifting are shown in Figure 6.



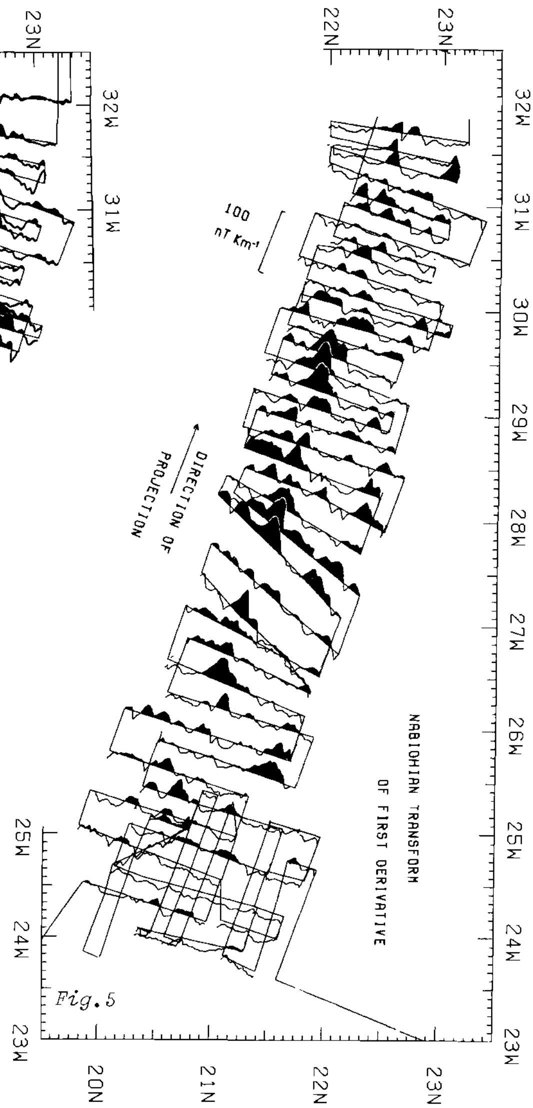


Fig. 4 The total picture for the magnetic model based on linear inversion. The phase-shift parameter θ used is -105^{o}. The level of each profile with respect to the trackline is arbitrary. The inversion results are plotted perpendicular to the tracks. Black areas denote positive values.

Fig. 5 The result of the Nabighian transformation. The offset with respect to the trackline is 15 nT km^{-1}. Black areas denote values higher than 15 nT km^{-1}. In the frequency space a high pass filter was applied (by taking the first derivative) as well as a Gaussian low pass filter (cut-off wavelength of 6 km).

not for the magnetic anomalies (Figure 3) which are remarkable consistent in character aligning along the fracture zone axis. Both fracture zones are clearly expressed in the magnetic pattern. The consistency of the magnetic anomalies is caused by the circumstance that the survey comprises the Cretaceous Magnetic Quiet Zone (CQZ). Magnetic quiet zones are regions in which the anomaly amplitudes are less than 75 nT and the anomaly wavelengths greater than 100 km (Poehls et al., 1973). In the CQZ the basement to both sides of a fracture zone has the same, normal magnetization (Helsley and Steiner, 1968). If the magnetization in the fracture zone is different, this will show as a relatively simple anomaly. Normally, by the episodically changing polarity of the Earth magnetic field, the character of the magnetic contrast also changes repeatedly along a fracture zone axis (Rea, 1972; Schouten, 1974; Collette et al., 1974). This gives rise to large irregular anomalies and no alignment is thus observed in these areas.

The magnetic profiles (Figure 3) are reduced by removal of the IGRF (IAGA, 1975). The peak-to-peak amplitude of the anomalies over the fracture zones reaches values upto 500 nT. No correction for the diurnal variation of the magnetic field has been applied. Generally, at this latitude peak-to-peak amplitude of these latter variations is less than 40 nT (e.g. see Einweich and Vogt, 1978). With periodicities of 6 to 10 hours of the diurnal variation and a ship's speed of 20 km/h (mostly the ship's speed was 11 to 12 knots) the wavelengths introduced by the diurnal variation vary between 120 and 200 km. These wavelengths are much larger than the wavelengths of the fracture zone anomalies (10 to 40 km).

The dotted belt in Figure 2 shows the axial zone, varying in width and delineating small changes in azimuth. The changes in azimuth can be related to the variations of the topographic and magnetic expression of the Kane Fracture Zone (Collette and Twigt, 1979). Topographically the Kane Fracture Zone shows as a simple asymmetric valley (at 26°W and at 27°W), as a wide valley (at 28°W) or as a wide valley with a central peak (at $28^{\circ}30'$ W). On several cross-sections a topographic expression is absent (near $29^{\circ}30'$ W). However, the magnetic anomalies here continue and are even sharper and larger in amplitude. The total picture suggests that the fracture zone expression responds to changes in the relative direction of spreading of the plates by widening and narrowing.

Magnetic modelling

In studying the magnetic anomalies we assume two-dimensionality in the fracture zone direction. We use the model of adjacent blocks of normal polarity separated by a zone of a different magnetization (Rea, 1972; Schouten, 1974). For a better comparison of the skewed anomalies with theoretical models we phase-shifted the profiles. Phase-shifting in general removes the skewing effect of the non-vertical magnetization vectors and is equal to reduction to the pole. Schouten and Cande (1976) used this linear filtering technique, developed by Schouten and McCamy (1972), for reduction to the pole of spreading anomaly profiles. They estimate the value of the phase-shift parameter θ which gives the phase-shifted profile the best resemblance with the profile of a boxcar model constructed for $\theta = 0^o$.

In a first attempt we deskewed each profile individually by making it symmetric over the fracture zone. For two profiles the results for a

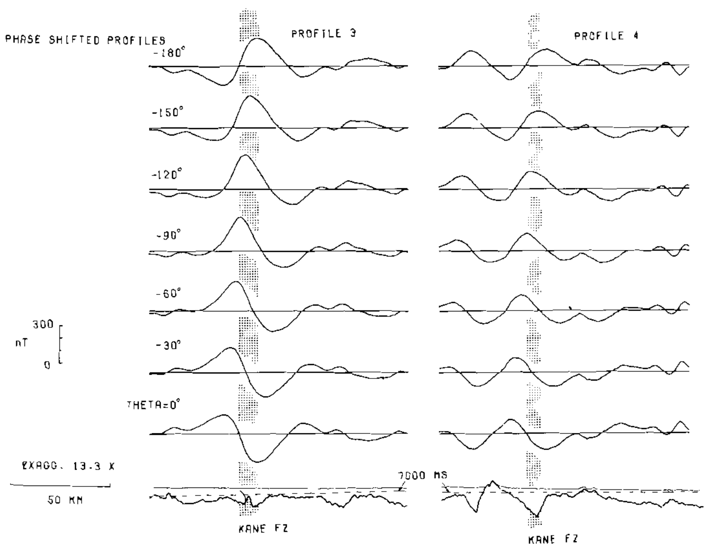


Fig. 6 The results of phase-shifting for different values of the phase shift parameter θ for profiles 3 and 4. For both profiles phase-shifting over θ=-120^o leads to a positive and symmetric result. From calculations (see Figure 7) it follows that phase-shifting over θ = - 90^o $\pm$ 15^o would lead to reduction to the pole of the anomalies.

range of different values of θ are shown in Figure 6, together with the seismic profiles. In this way we found a wide range of values of θ From a compilation of these different θ values, it followed that in half of the 34 profiles in the CQZ normally magnetized crust would be juxtaposed to reversed magnetized crust. This is in conflict with the concept that the Cretaceous Quiet Period is a long normal period. It is true that Van Hinte (1976) found a "site 263 mixed" zone (three brief reversals recorded in Upper Albian sediments at DSDP site 263). Magnetic stratigraphy of samples at Gubbio, Italy (Lowrie and Alvarez, 1977), at Moria in Umbria (Alvarez and Lowrie, 1978), and at Cismon in the Southern Alps (Channell et al., 1979) gives no evidence for further previously undetected short polarity reversals between anomaly 34 and anomaly MO. The reversals detected at Gubbio by VandenBerg and Wonders (1979), two short reversals in the Upper Albian and a mixed zone shorter than 100.000 years in the Cenomanian (Cushmani) can possibly be interpreted as the reversals of Van Hinte (1976). However, all these events are of a too short duration to lead to identifiable sea floor spreading anomalies measured at the ocean surface. Also, we did not see any correlation of the reversed blocks to the north and to the south of the fracture zone. We therefore conclude that the method of deskewing the profiles individually leads to wrong results.

Next we computed the theoretical value for θ using the Early and Late Cretaceous poles for the African plate of Van der Voo and French (1974). Figure 7 shows θ as a function of the strike for 2 different geographic positions in the area. It follows that θ is $-90^{\circ} \pm 15^{\circ}$ for the CQZ, including both the variation in strike of the fracture zone and the geographical position. This justifies the choice of one value of θ to be applied to all profiles. A phase-shift over $\theta = -105^{\circ}$ was chosen. It gave the most symmetric appearance to the anomaly and an overall coincidence of the center of the anomaly and the center of the fracture zone. We stress that this criterion is not absolute and also, that the match is not always perfect. This indicates that there are either disturbances caused, for instance, by three-dimensional effects and/or that the assumption of a symmetric magnetic arrangement is not always valid.

After the phase-shifting, we applied linear inversion to the magnetic profiles as devised by Schouten and McCamy (1972). This method

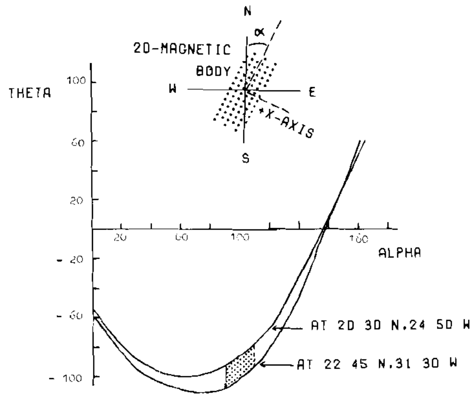


Fig. 7 The phase-shift parameter θ versus the strike for the eastern and western geographic positions in the CQZ, using the Early and Late Cretaceous pole of Van der Voo and French (1974). It follows that θ is -90° ± 15° for the CQZ, including both the variation in strike and the geographical position. For the eastern positions the inclination and declination of the present field were 37° up and 17° west, of the remanent magnetization 44° up and 16° west respectively.

implies a downward continuation of the anomalies leading to a magnetization distribution of a horizontal plane layer of a specified thickness and at a specified depth. For the thickness of the layer we took 1 km, the depth of the top of the layer was taken at 5 km below sea level. The resulting magnetization contrasts then are of the order of 8 Am^{-1} varying from 5 to 13 Am^{-1}.

From the power spectrum it appears that the contribution to the magnetic spectrum of magnetic contrasts in the crust lies in the wavenumber domain higher than 1.3 km^{-1}. A bandpass filter (a double cosinus taper with a low cut-off wavelength of 5 km and a high cut-off wavelength of 225 km, the wavelength of 5 km corresponds with a wavenumber of 1.26 km^{-1}) was used to avoid undue amplification of low and high wavelengths by the inverse earth filter. Figure 8 shows the used bandpass filter multiplied by the inverse earth filter, together with the power spectrum of a N-S profile. The sample interval of the power spectrum is 0.44 km. The total filter has a strong maximum at a wavelength of 6 km. According to Blakely and Schouten (1974) small wiggles of this

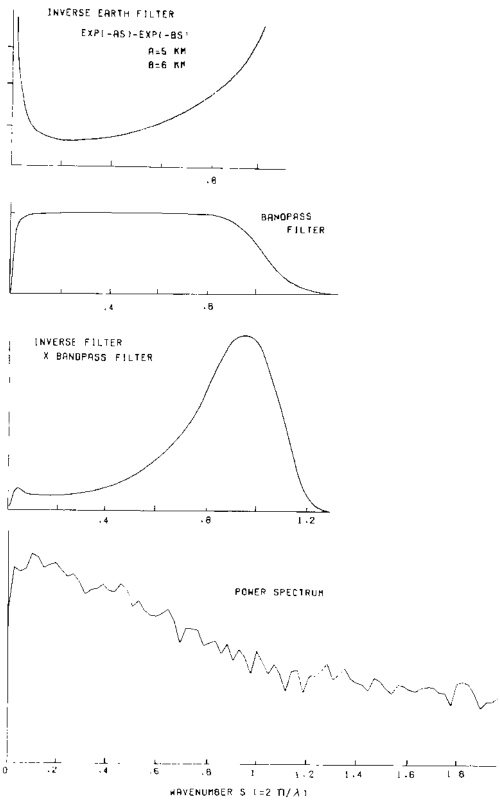


Fig. 8 Bandpass filter and inverse earth filter, used in linear inverting, in comparison with the power spectrum of a N-S profile.

wavelength in the inversion result might be caused by amplification of incoherent noise present in the real data.

The total picture for the magnetic model, based on linear inversion, is shown in Figure 4. The first thing to be noted is the outcome that the Kane FZ represents a zone of higher than normal magnetization. The width of this zone is defined badly since the magnetic contrasts are not vertical. A minimum value of 15 km seems a reasonable estimate. However, where the fracture zone valley doubles, viz. between 28° 15' and 29° 15' W the zone of positive magnetization doubles as well reaching a total width of 40 km. The ridge separating the two branches of the fracture zone has a relatively low magnetization. The magnetic contrasts are sharpest at $29^{\circ}\ 30'$ W, where we find no topographic expression. From 31° to 32° W the zone of high magnetization found over the northern branch of the fracture zone, seems to die out and another zone emerges to the S of the actual fracture zone valley. We will come back to this latter feature later.

With regard to the absolute level of magnetization (the level of the profiles with respect to the tracklines is arbitrary), the following can be said. The Mesozoic spreading anomaly sequence MO to M4 has been identified in the eastern part of the survey area (Rohr and Twigt, 1979), both to the N and to the S of the Kane FZ. These anomalies could be modelled with a horizontal magnetic layer of 1 km thickness and a magnetization intensity of plus or of minus 5 Am^{-1}. Assuming that the strength of the magnetic field in the Cretaceous Quiet Period was not essentially different, the magnetization intensity in the fracture zone in the CQZ would be about 10 to 15 Am^{-1}, again for a layer thickness of 1 km.

The analytic signal and the sharpness of the magnetic contrast

A way of estimating the positions of the magnetic contrasts is to take the absolute value of the analytic signal (Nabighian, 1972; Twigt et al., 1979). This transformation produces maxima that are situated above the contrast positions, independently of the value of the phase-shift parameter θ. In this way the skewness is eliminated. On the other hand information on the nature of the contrast is lost, i.e. whether we are dealing with a +/- or a -/+ contrast. Also, if we have two contrasts close-by, the two related maxima in the analytic signal may merge into one broad maximum. To compute the analytic signal we applied an exponential filter to suppress noise (low cut-off wavelength of 6 km). A second filter was applied to get rid of long wavelengths. For this latter filter we used the first horizontal derivative.

Figure 5 shows the result of the Nabighian transformation of the first derivative of all N-S profiles. At less than 15 km distance from the profile ends deformations take place by FFT end effects. A great resemblance between the result of the Nabighian transformation and the inversion result is apparent. To understand this, in Fig.9 both the result of linear inversion and the result of the Nabighian transformation is shown, applied

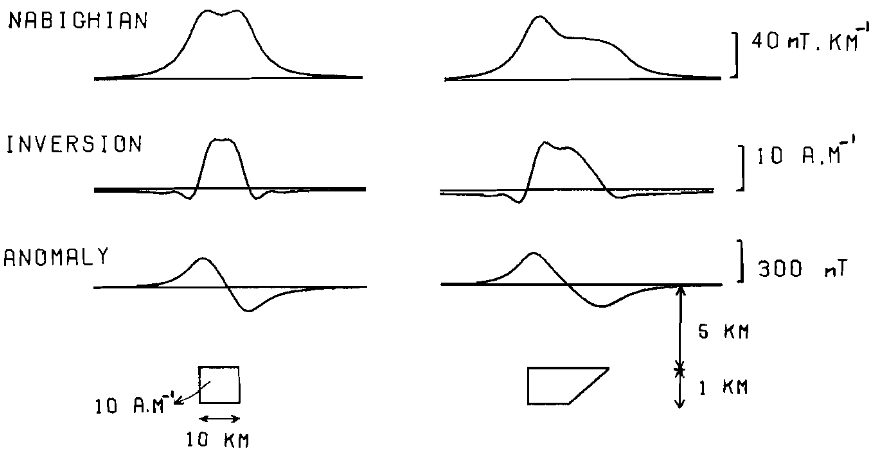


Fig. 9 The results of linear inversion and of the Nabighian transformation applied to a calculated anomaly. The models used are plane layer models, in which a positive zone is flanked by regions of zero magnetization. In the first model the magnetic boundaries were taken vertical, in the second model one boundary was given a dip of 6°.

to a calculated anomaly. The models used are plane layer models in which a positive zone is flanked by regions of zero magnetization.In the first model the magnetic boundaries were taken vertical, in the second model one boundary was given a dip of 6°. We see that the inversion results show a great resemblance with the Nabighian transform due to interference of the Nabighian extrema of the two contrasts. In the case that the magnetic contrasts are not vertical, the Nabighian transform becomes asymmetric to the side of the sharpest contrast.

A comparison of figures 4 and 5 shows that indeed the largest Nabighian maxima coincide with the sharper magnetic contrasts. This confirms the correctness of the estimate for the deskewing parameter θ of - 105°. The Nabighian transform brings out the variable character of the magnetic fracture zone contrasts. The doubling of the zone of high magnetization at 28° 30' W results into two broad Nabighian extremes. At 29° W where the zone of high magnetization is narrow, a large Nabighian maximum is found at the northern edge of the fracture zone. West of

$31^{\circ} 00'$ W the largest Nabighian maxima are situated on the southern edge of the reduced zone, which means that the sharper contrast lies on the southern side. In general it can be concluded that the analytic signal gives a fair description of the fracture zone contrasts, confirming the picture obtained with the inversion model. The analytic signal forms a ready tool to study fracture zone anomalies in areas where blocks of changing polarity are juxtaposed along the fracture zone. Such is the case as we leave the CQZ.

The Kane Fracture Zone west of 31°W

The most eastward identification of the Kane FZ by Purdy et al. (1979) is at $32^{\circ}30'$W. At this longitude the strike is 277°. In our area, at $31^{\circ}30'$W, we see a well-developed trough, striking 286° and a widening or doubling of the zone of high magnetization. The sharpest magnetic contrast lies 28 km to the south of the trough. To study the connection between both fracture zone identifications and the effect of direction change on the fracture zone expression, we plotted, by kind permission of Dr. G.M. Purdy of the Woods Hole Oceanographic Institution, seismic and magnetic profiles of the R.V. Knorr between 31°W and 35°W, together with some older data of the Vening Meinesz Laboratorium in this area (Figures 10 and 11).

West of 31°W the basement profiles show a complex character. At $32^{\circ}40'$W we can even speak of three parallel troughs. The northern trough is the western continuation of the trough at $31^{\circ}30'$W. The southernmost trough develops from the sharp magnetic contrast mentioned earlier and continues to the west to coincide with the Kane Fracture Zone identification of Purdy et al. (1979). The strikes of both ridges and troughs in the area between $31^{\circ}30'$W and 34°W are intermediary between the values mentioned before, forming a continuous transition. The northern trough is striking 288° at 31°W, 282° at 32°W, and 280° at 33°W. The strike of the southern, less well-developed trough is 283°, 283° and 280° at these longitudes, showing a slight divergence.

The continuous character of the magnetic anomalies ends at the end of the CQZ. There we find to the south of the Kane FZ anomaly 34, which is the transition to a reversed period. The other anomaly identifications in figure 10 are from H. Schouten (pers. comm.).

Figure 12 shows the analytic signal of the magnetic anomalies in the area between 30° and 34°W. The analytic signal indicates that there is a zone of major magnetic contrasts between 31° and 33°W. Here the topographic expression of the fracture zone is poor to absent. This finding suggests that the change in fracture zone direction from 298° to 270° between 30° and 34°W was realized by two discrete jumps, ending in a more southern position of the Kane FZ at 34°W than would be expected from the topographic alignments near 32°W (cf. also Rona et al., 1974, who described the northern topographic alignment).

Origin of the positive magnetization

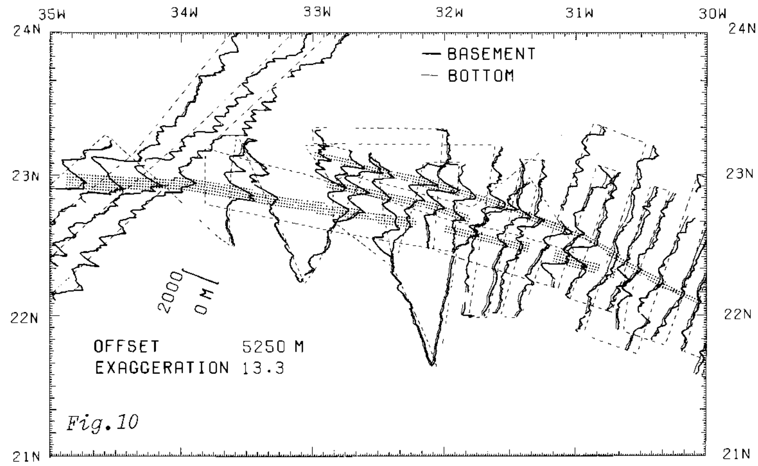
The finding that the Kane FZ in the Cretaceous Quiet Zone is characterized by a zone of higher than normal magnetization necessitated the search for a new mechanism to explain fracture zone anomalies. The reduced magnetization in fracture zones was hitherto attributed to supposed brecciation and hydrothermal action in the sheared fracture zone, leading to a reduction of the degree of magnetization whether initially positive or negative. Fracture zone anomalies were thus more or less successfully described by $\pm/0/\pm$ transitions. However, hydrothermal action cannot account for a +/++/+ transition as found in the Kane FZ.

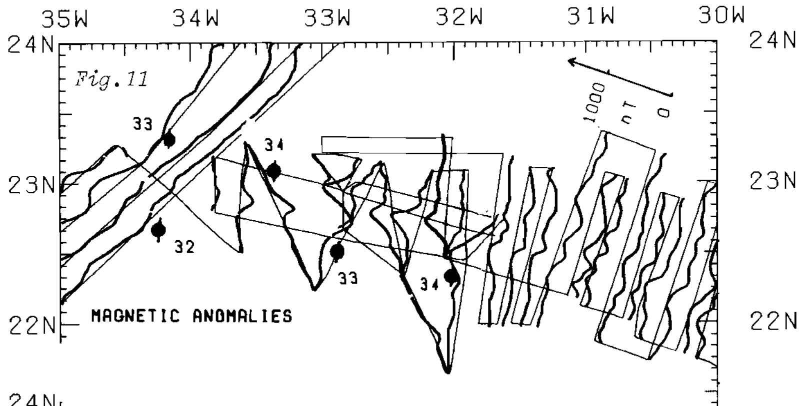
The idea arose that the sign of the magnetization in fracture zones is related to the sign of their offset. The Northern FZ, which had a sinistral offset in the beginning of the CQZ (cf. Rohr and Twigt, 1979),

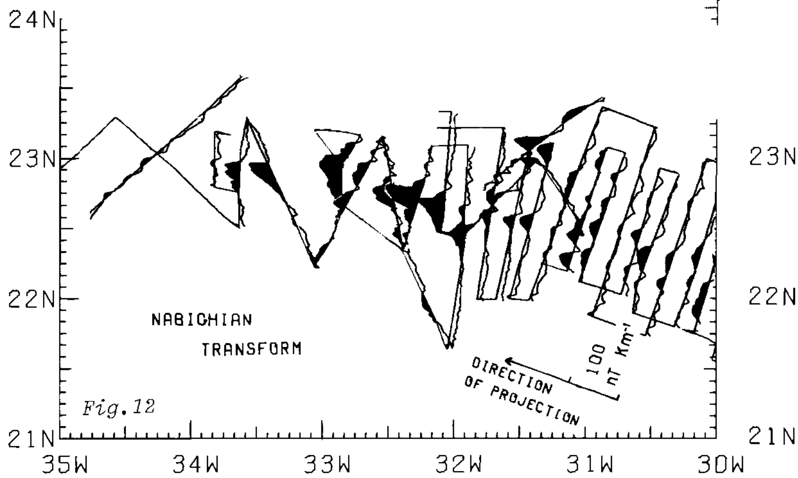
Fig. 10 *Seismic profiles of the R.V.Knorr between 31°W and 35°W, together with some older data of the Vening Meinesz Laboratorium in this area, projected in a direction of 290° with regard to a depth of 7000 ms. It shows the connection between the identification of the Kane Fracture Zone in our survey area and that of Purdy et al. (1979).*

Fig. 11 *Magnetic profiles between 31° and 35°W, projected in a direction of 290°. Dots denote magnetic anomaly 32 to 34 identifications (H.Schouten, pers.comm.).*

Fig. 12 *The result of the Nabighian transformation applied to the magnetic profiles of Figure 11 as projected in a direction of 290°. The offset with respect to the trackline is 15 nT. Values higher than 15 nT km^{-1} are denoted by black areas.*

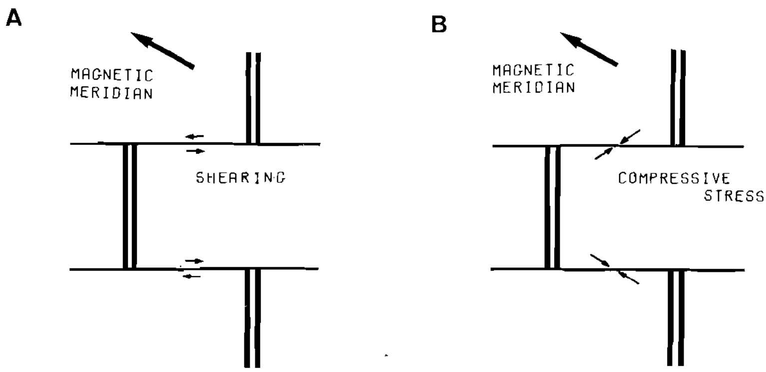

35W
34W
33W
32W
31W
30W
24N
23N
22N
21N
— BASEMENT
-- BOTTOM
2000
0 M
OFFSET 5250 M
EXAGGERATION 13.3
Fig. 10


35W
34W
33W
32W
31W
30W
24N
23N
22N
Fig. 11
1000
nT
0
33
34
32
33
34
MAGNETIC ANOMALIES


24N
23N
22N
21N
35W
34W
33W
32W
31W
30W
NABIGHIAN
TRANSFORM
100
nT Km⁻¹
DIRECTION
OF PROJECTION
Fig. 12

is indeed accompanied by a positive magnetization at these longitudes. However, further W the fracture zone has a dextral offset (H.Schouten, pers. comm.). Here the fracture zone was recognized from a topographic alignment described by Rona et al. (1974) at 23°30'N and from 30° to 31°W. From the magnetic anomalies (Rona et al.'s figure 5) it follows that the fracture zone here has a reduced magnetization. Next we made a comparative study of several dextral fracture zones in the CQZ a little farther N (between 32° and 34°N and between 23° and 26°W). All these fracture zones appeared to have a reduced magnetization.

The hypothesis was then formulated that the difference in magnetization in fracture zones is due to the effect of shearing in the active section, the transform domain. Shearing may result in two comparable although physically different effects. First, it may lead to rotation of the zone affected by the shearing. Dependent on the geometrical configuration this could lead to an enhancement or a reduction of the apparent magnetization (Figure 13a). On the other hand, the stress distribution that is related to the shearing may lead to a change of the magnetization.



<u>Fig. 13</u> a) The geometry of fracture zones in the central North Atlantic is such that rotation of the zone affected by the shearing may lead to enhancement or reduction of the apparent magnetization. b) The geometry is such that the compressive stress in sinistral transforms is parallel to the magnetic meridian and in dextral transforms more perpendicular.

Stress is known to influence the magnetization by recrystallization in such a way that compression leads to a higher magnetization in the direction of compression (Nagata and Kinoshita, 1965; Pozzi, 1979). Figure 13 b shows that the geometry of fracture zones may be such that the compressive stress in sinistral transforms is parallel to the magnetic meridian and in dextral transforms more perpendicular to the meridian. For both effects, a consequence for the resulting configuration of zones with lower or higher magnetization is that these zones are situated in the older part of lithosphere bordering the fossil transform fault trace in a fracture zone, since only this part of the lithosphere was present in the active transform domain. Such a situation might be true for the Kane FZ in the CQZ, but it is difficult to prove on account of the complex and varying character of this fracture zone. The comparative study of the four dextral fracture zones farther N mentioned before came to a same inconclusive result. The suggestion exists there that the magnetic contrasts indeed are shifted to the "older" side of the fracture zone axis, but again the fossil trace of the transform faults could not be determined. Near-bottom observations and sampling are presumably the only means to solve this aspect of the problem.

The first author (W.T., Ph.D. thesis, in prep.) studied published anomalies over several other fracture zones to check whether the generalization made indeed is valid. In addition, we report the following important result. From the symmetry in Figure 13 a/b it also might be that the transition old/young versus young/old with respect to the magnetic north would determine the sign of the anomalies. Comparison with sections over the Kane FZ W of the Mid-Atlantic Ridge (e.g. at 63^{o}W, Snellius line Golf, Anonymous, 1967) proved that such was not the case. Here too the magnetization of the Kane FZ is positive.

Fracture zone expression and change of spreading direction (discussion)

We will now investigate the suggestion made earlier that the varying topographic and magnetic expression of the Kane FZ is related to changes of sea floor spreading direction. In doing so, we confine our attention to the CQZ since there we have a clear magnetic anomaly pattern. In the CQZ the growth of the offset of the Kane FZ was realized, from 38 to

160 km.

We note three major changes in direction: an anti-clockwise change near 28°W, a clockwise change at 29°30'W and another anti-clockwise change near 30°30'W. Betweer 28°30' and 29°10'W we observe a central ridge in the Kane FZ, accompanied by a doubling of the positively magnetized zone. Between 29°15' and 29°35'W the topographic expression of the Kane FZ is poor to absent. The magnetic anomalies are very pronounced. W of 30°30'W we find the three diverging zones described in Figures 10, 11 and 12. The northernmost is best developed topographically and has a

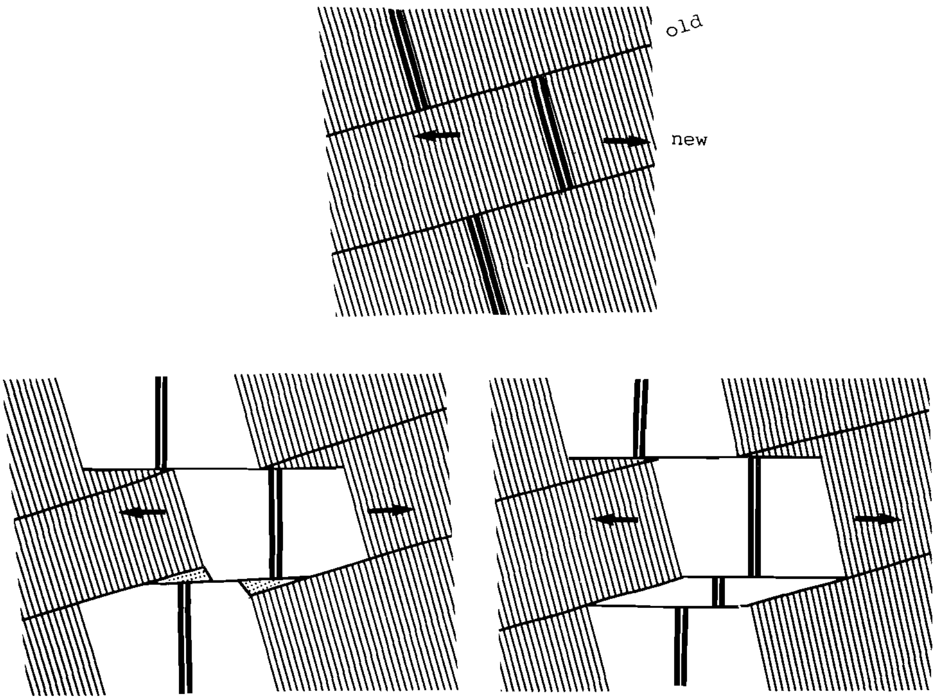
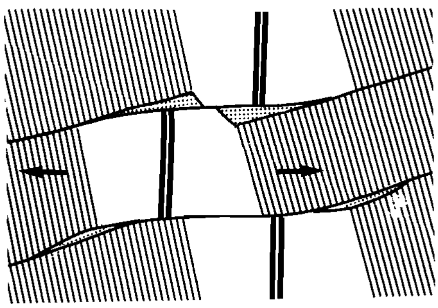


Fig. 14 *A configuration of a sinistral and a dextral fracture zone as reacting to a clockwise direction change according to the rigid approach as formulated by Menard and Atwater (1968). At the dextral fracture zone a rhombic void will develop. This void can be filled by the development of a new spreading segment or it can dissolve gradually by axial growth of the two neighbouring spreading centers. The sinistral fracture zone responds by the development of an adjustment fracture zone in both cases.*

magnetic anomaly which dies out towards the W, the southernmost has a poor topographic expression but strong magnetic anomalies and joins the Kane FZ as identified at 33°W by Purdy et al. (1979). In addition we see some minor features near 26°30'W, possibly another central ridge of smaller extent, this time buried by sediments and accompanied again by a doubling of the positive magnetic anomaly. The direction changes are more subtle here, but we note a small anti-clockwise change near 26°W and a clockwise change near 26°45'W.

When we try to interpret these phenomena, we can follow two principles. The first one is the rigid geometric or Euclidian approach as formulated by Menard and Atwater (1968, see also Fig. 14). A fracture zone with a sinistral offset which undergoes an anti-clockwise change of spreading direction (this is equivalent to a dextral fracture zone undergoing a clockwise change) will develop a rhombic void. Theoretically, this void can be filled by the development of a new spreading segment or it can dissolve gradually by axial growth of the two neighbouring spreading centers. The larger the offset is, the longer it will



<u>Fig. 15</u> The same configuration as in Figure 14, but now we allow for a non-rigid response. The fracture zone would have intrinsically a finite width in which the transform fault can adjust its direction. To this we can add a possible elastic and/or plastic deformation of the lithospheric section caught between two fracture zones with opposed offset, combined with the opening of the fossil trace of the fracture zone which is under compression. This mechanism would eventually free the imprisonned part of the oceanic lithosphere by a process that is mainly characterized by torsion.

take before a new orthogonal pattern can be realized. A sinistral fracture zone undergoing a clockwise change of spreading direction must, according to Menard and Atwater, respond by the development of an adjustment fracture zone. The second possibility is that we allow for a non-rigid response of the oceanic lithosphere. The same geometric restrictions apply but the fracture zone as such would have intrinsically a finite width in which the transform fault can adjust its direction (Collette and Rutten, 1972). To this we can add a possible elastic and/or plastic deformation of the lithospheric section caught between two fracture zones with opposed offset, combined with the opening of the fossil trace of the fracture zone which is under compression (Fig. 15). This opening of the fossil trace may give birth to a transverse ridge such as has been found e.g. in the Charlie-Gibbs FZ at 52°35'N and between 31°00' and 31°40'W (Searle, 1979, p. 288). This mechanism would eventually free the imprisoned part of the oceanic lithosphere by a process that is mainly characterized by torsion.

Can we choose between these two models for what we see in the Kane FZ? In other words, is the central ridge between 28°30' and 29°10'W the result of the anti-clockwise change of direction near 28°W (Euclidian response) or of the clockwise change at 29°30'W (non-rigid response of the fossil track)? We think we can answer this question but before doing so, we want to make an important observation, namely that we do not have a full description of all fossil evidence. All remains of the Kane FZ which were situated south of the transform fault at that time are now to be found in the American plate to the W of the Mid-Atlantic Ridge. Unfortunately, the data set at that side (Rabinowitz and Purdy, 1976) is far from complete. We note that between 60° and 61°W these authors describe a ridge to the S of the Kane FZ with an accompanying valley again to the S, but how this observation fits our data is difficult to say. A preliminary reconstruction places this ridge to the south of the complicated area W of 30°30'W at the time that this section was in the active transform domain of the Kane FZ.

Recent investigations of the Tamayo Fracture Zone in the Gulf of California (MacDonald et al, 1979; Kastens et al, 1979) may help us to understand what happens in a sinistral fracture zone which undergoes an anti-clockwise change of spreading direction. The Tamayo FZ has an offset of 75 km. The authors describe the origin of a transverse ridge of basaltic or serpentinite composition in the active transform domain. The transform fault would have adjusted its course with the result that the transverse ridge now forms part of the Pacific plate. The transverse ridge shows much resemblance with the central ridge in the Kane FZ between $28^{\circ}30'$ and $29^{\circ}10'$W.

The mechanism proposed for the Tamayo FZ implies a jumping of the transform fault. Such a jumping will leave its traces in the magnetic field in the form of a doubling of the zone of intensified or reduced magnetism. We do not see a reason why a doubling would occur if the central ridge would have developed in the fossil trace of the fracture zone as sketched in Figure 15. We, therefore, believe that the evidence we have favors the conclusion that the central ridge between $28^{\circ}30'$ and $29^{\circ}10'$W developed as a consequence of the anti-clockwise change of spreading direction at 28°W and actually is a transverse ridge of the type found in the Tamayo FZ. The same would apply to the minor event at $26^{\circ}30'$W. Note that the offset of the Kane FZ at that time presumably still was small.

To explain the disappearance of the topographic expression of a fracture zone, like we found near $29^{\circ}30'$W, we first need to understand the mechanism which produces the 'normal' cross-section of a fracture zone. On the basis of many observations in the central North Atlantic, we believe this normal cross-section to be of the type found near 26°W or at $27^{\circ}25'$W: an asymmetric valley with the steep and higher wall to the side of the *older* oceanic crust. Since no analytical models have yet been developed to account for this cross-section, it is dangerous to speculate under which circumstances the topographic expression may disappear. Compression, of course, is one possibility, accounting at the same time for the strong magnetic anomalies near $29^{\circ}30'$W, and is in line with the observation that the one clear-cut example we have of a disappearance occurred following a clockwise change of spreading direction, but that is all evidence we have.

From the structures found W of $30^{\circ}30'$W, which set in the largest change of direction recorded in the area (about 20°), we cannot say with certainty whether they represent a repeated formation of transverse ridges of the type found near 29°W, or whether, may be temporarily, the transform fault actually doubled or tripled with formation of active spreading segments in between the different branches of the Kane Fz. The facts that the troughs are longer than 160 km, the offset of the Kane FZ at the time of anomaly 34, favors the latter solution. The same would then apply for the ridge and trough found at the American side between 60° and 61°W. We feel, however, that we do not have enough detailed data to warrant a complete reconstruction of what actually happened.

In conclusion, it can be said that changes of spreading direction may lead to the formation of transverse ridges which originated in the active transform domain but later are added to one of both plates by a shifting of the transform fault, if the configuration leads to an extension of the transform fault area. Under compression the topographic expression of a fracture zone may disappear. The process by which this happens is not yet understood. Larger changes of spreading direction may possibly lead to the formation of small active spreading centers in between the two or more branches of a fracture zone. The total picture of a fossil fracture zone thus becomes one of a widening and narrowing trace even to the point that we cannot recognize a real fracture zone valley any longer, a picture that can be compared to the trace of a swerving bicyclist, who even does not hesitate to lift his forewheel from the pavement every now and then.

Changes of fracture zone offsets during the Cretaceous Quiet Period

Using anomaly 34 identifications from Purdy et al. (1979) and of H. Schouten (pers. comm.) and anomaly MO identifications from Purdy and Rohr (1979) and from Rohr and Twigt (1979), the width of the CQZ was determined between the Kane FZ and the Northern Fracture Zone and north and south of these fracture zones, both for the African and the American plate (tabel 1). Using the time scales of LaBrecque et al. (1977) and Larson and Hilde (1975) the following spreading rates were deduced (tabel 1).

tabel 1	American plate		African plate	
	width CQZ (km)	spreading rate (cm/yr)	width CQZ	s.r.
S of the Kane FZ	940	3.26	759	2.63
between the f.z.	797	2.76	875	3.03
N of the Northern FZ	872	3.02	776	2.69

The difference of the CQZ width S of the Kane FZ and between the fracture zones corresponds with the growth of 120 km of the left lateral offset over the Kane FZ. The difference in spreading rate south of the Kane FZ and between the fracture zones corresponds with a growth of 0.40 cm/yr of this left lateral offset (Schouten and Purdy, 1979). Figure 16 shows a comprehensive picture of the situation. In this figure the

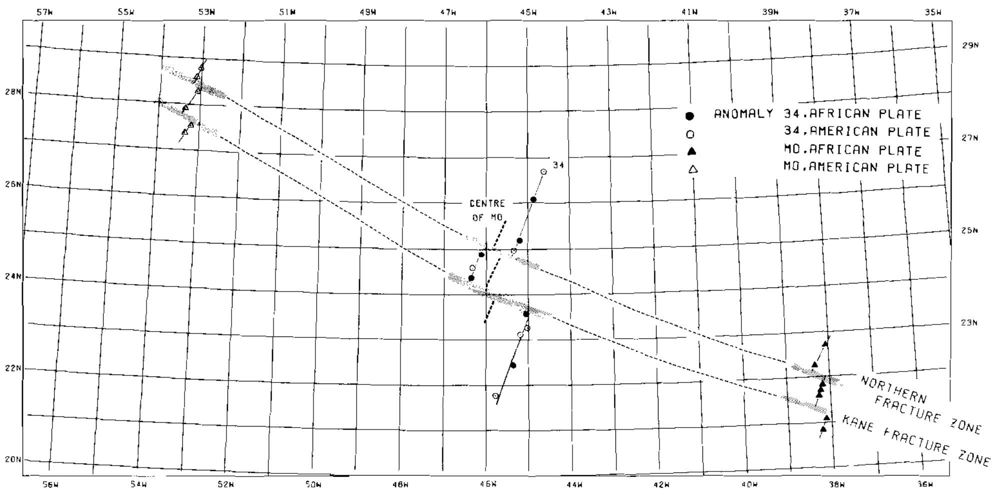


Fig. 16 Magnetic anomaly 34 and MO identifications on both the African and the American plate. Both plates have been rotated back, so that the 34 identifications coincide. For a better comparison of the distances between MO and 34 on both ridge sides, a stereographic projection was used to reduce scale variations. Dashed lines indicate the centre of the anomaly MO identification on the African plate and of the anomaly MO identification on the American plate. If there had been symmetric spreading during the Cretaceous Quiet period, these centres should have coincided with the anomaly 34 identifications.

African and the American plates have been rotated back so that the anomaly 34 identifications coincide. It follows that in addition to an average symmetric spreading of 2.9 cm/yr in the CQZ, there has been a continuous shift of the spreading axis of 0.14 cm/yr westward between the fracture zones and of 0.31 cm/yr and 0.17 cm/yr eastward S of the Kane FZ and N or the Northern FZ respectively. The asymmetry can also be described by a 39 km westward jump of the spreading axis between the fracture zones during the Cretaceous Quiet Period. S of the Kane FZ and N of the Northern FZ the jumps would be 90 km and 48 km respectively to the east. From detailed surveys over the Mid Atlantic Ridge (e.g. Collette et al., 1979) it is observed that, after subtracting the upwarping effect of the median valley walls, there is no difference between the topography within the median valley and on the ridge flanks. Thus it is not to be expected that in the slow spreading Atlantic we can recognize the topographic relicts of spreading centers which have been left. That the topographic and magnetic expression of the Kane FZ is so responsive to the direction change at $29^{\circ}30'$W is an indication that the offset over the fracture zone at that time is already larger than the 38 km which it had at anomaly MO.

Conclusions

Summarizing, we arrive at the following conclusions:

1. The fossil trace of the Kane FZ in the CQZ shows at least three major changes in azimuth: at 28°W, at $29^{\circ}30'$W and at $30^{\circ}30'$W, and two minor changes: at 26°W and at $26^{\circ}45'$W. It is remarked that fracture zones with a large offset have an integrating effect, thus small direction changes might not be recognized.

2. The topographic expression of the Kane FZ along its axis is very variable, from a broad zone with a central ridge to a much narrower zone. At several places a topographic expression is even absent. However, the magnetic anomalies over the Kane FZ show a remarkable consistent alignment, demonstrating the continuity of the Kane FZ also at these places. The magnetic anomalies also show that the CQ period has been a long normal period.

3. The Kane FZ and also another sinistral fracture zone in the

CQZ are characterized by a zone of a higher than normal magnetization, in contrast to dextral fracture zones in the CQZ which appear to have a reduced magnetization. The sign of the relative magnetization in fracture zones is related to the sense of the offset of the respective fracture zone. The hypothesis is formulated that under the influence of shearing in the transform domain of a fracture zone the magnetization is influenced in such a way, that the resulting apparent magnetization is enhanced or reduced depending on the geometrical configuration. A consequence of this would be that these zones are situated in the older part of the lithosphere bordering the fossil transform fault trace, for only this side has passed through the transform domain and has undergone shearing.

4. Changes of spreading direction may lead to the formation of transverse ridges in the fracture zone, as observed between $28^{\circ}30'$W - $29^{\circ}10'$W, which originate in the active transform domain, but later are added to one of both plates by a shift of the transform fault. At changes of spreading direction that lead to compression in the transform domain the topographic expression of the fracture zone may disappear, but the process by which this happens is not yet understood. The total picture of a fracture zone thus becomes one of a widening and narrowing trace.

5. Traces of fracture zones in the magnetic quiet zones are the best places for further study of fracture zone expressions in response to changes of the spreading direction. A comparative study of a dextral fracture zone in the CQZ may help to elucidate several points which still remain obscure in this study.

Acknowledgements

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Chapter IV

A MODEL FOR MAGNETIC ANOMALIES OVER FRACTURE ZONES: EFFECT OF STRESS ON THE MAGNETIZATION

Abstract

Magnetic anomalies over fracture zones in the cental North Atlantic in the Cretaceous Magnetic Quiet Zone (CQZ) on the African plate indicate an enhanced magnetization in fracture zones with a sinistral offset and a reduced magnetization in fracture zones with a dextral offset. The sign of the relative magnetization is thus related to the sense of offset of the respective fracture zones. This is in conflict with current ideas about the magnetization in fracture zones. The finding that the Kane FZ also has an enhanced magnetization in the CQZ on the American plate excludes the possibility that the sign of the anomalies is determined by the transition old/young with respect to the magnetic north. What remains is that the difference in magnetization is due to the effect of shearing in the transform domain of a fracture zone, the one other directional process involved. It is shown that such a left/right effect cannot be a rotation of the zone affected by the shearing, particularly not for the anomalies in the CQZ of the Equatorial Atlantic. We formulate the hypothesis that the magnetization is influenced by compressive stress in the transform domain, in such a way that the magnetization increases in the direction of compression. Depending on the geometrical configuration this will lead to an increase or a decrease of the effective magnetization. It appeared possible to apply this generalization to other fz anomalies: in the CQZ of the Equatorial Atlantic mentioned above, in the CQZ of the Indian Ocean and in the Cenozoic sequence of the central North Atlantic. With regard to the mechanism which leads to an effect of stress on the magnetization, several tentative explanations are offered. Magnetic anomalies over sinistral offset fracture zones in the Cenozoic sequence in the central North Atlantic (12^{o}-15^{o}N) indicate an enhanced magnetization too. The enhanced magnetization is thus not destroyed by the effect of alternating field directions during the time the crustal segment in question is present in the transform domain. This means that if recrystallization leads to the effect of stress on the magnetization, this process must be confined to the area close to the fracture zone/spreading center intersection.

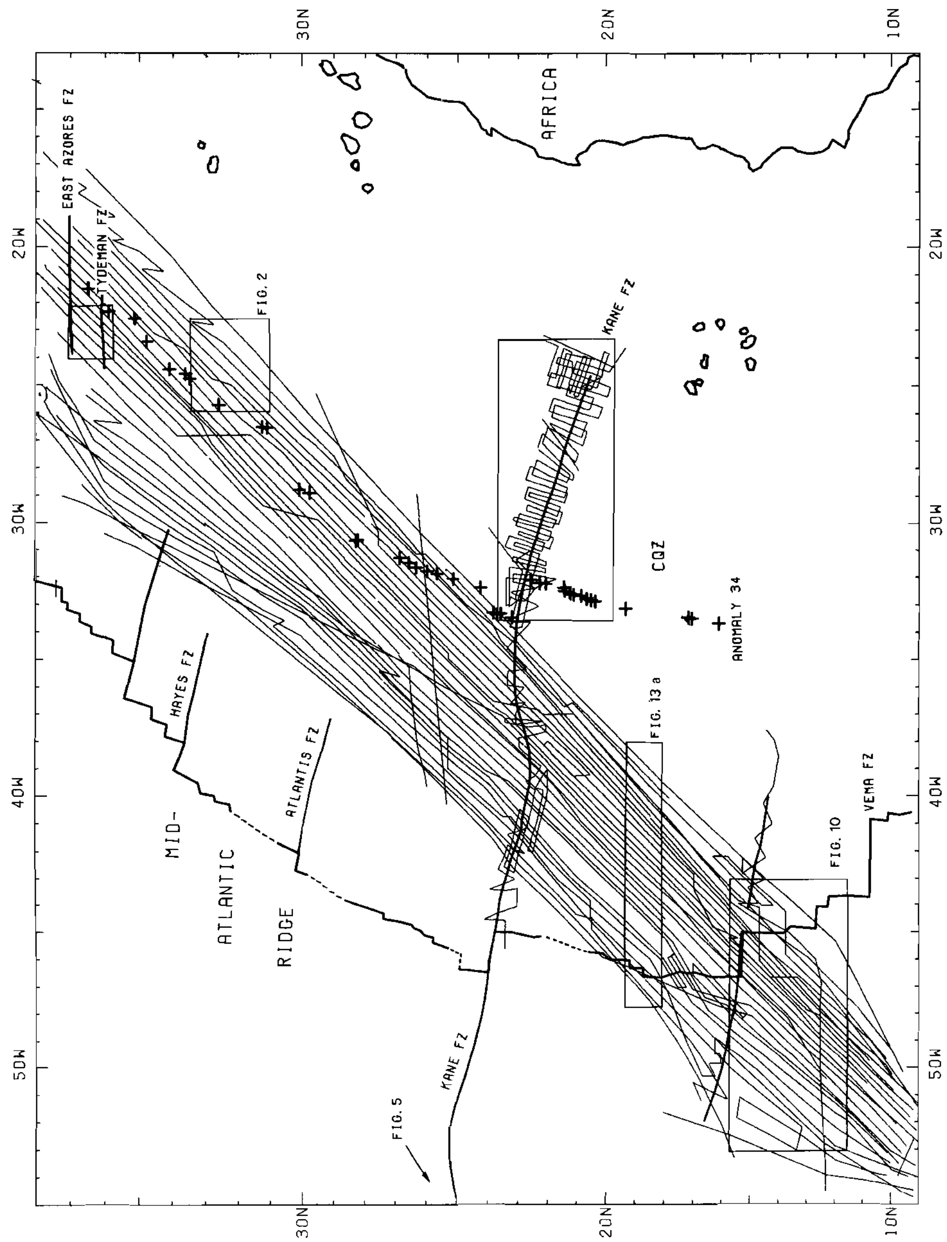


Fig. 1 Trackchart of the NE-SW profiles of the KROONVLAG-project with respect to the Mid-Atlantic Ridge and location of the areas discussed in this chapter. Identifications of magnetic anomaly 34 (Schouten, in prep.) mark the part of the bundle that is situated in the CQZ.

Introduction

The finding that the Kane FZ in the Cretaceous Magnetic Quiet Zone (CQZ) on the African plate is characterized by a zone of higher than normal magnetization (Chapter III) necessitated the search for a new mechanism to explain the magnetization in fracture zones. Until then fz anomalies were more or less successfully described by $\pm/0/\pm$ transitions, as being due end-effects of the magnetic layer and a zone of zero magnetization in the fracture zone (Collette et al., 1974; Schouten, 1974; Emery et al., 1975; Twigt et al., 1979) ; the reduced magnetization was attributed to brecciation and hydrothermal alteration by shearing within the fault zone (e.g. Matthews et al.,1965), leading to a reduction of the degree of magnetization whether initially positive or negative. However, hydrothermal action cannot account for a +/++/+ transition as found in the Kane FZ. The location of the survey area and of the other areas discussed in this chapter are shown in Figure 1.

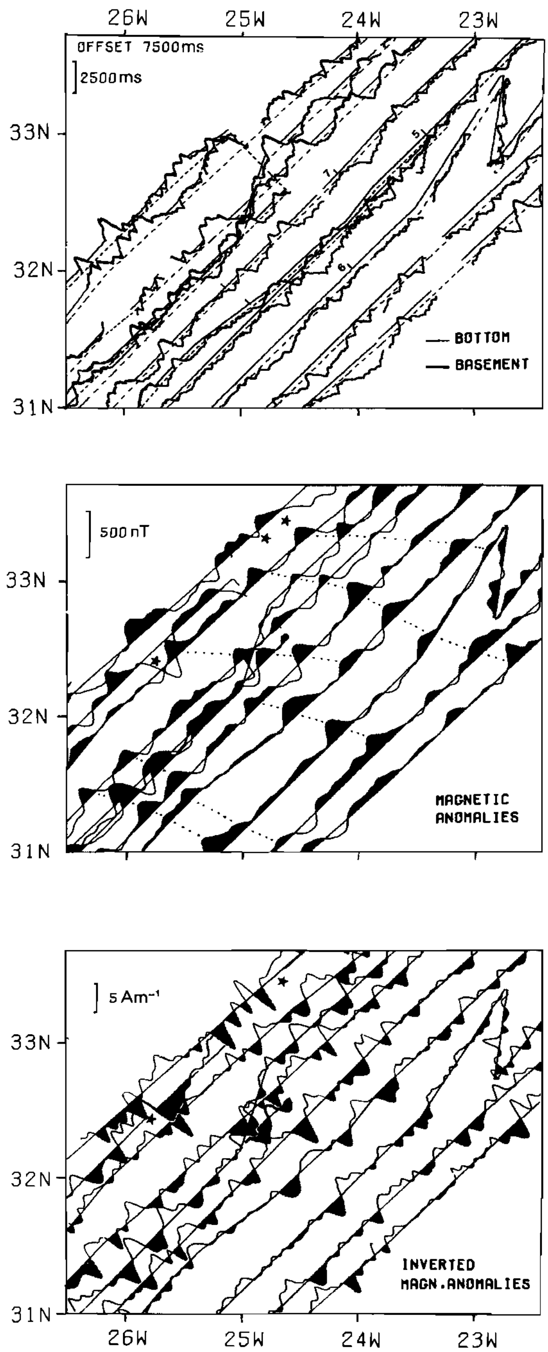
Anomalies over fracture zones to the N of the Kane FZ in the CQZ appeared to indicate a reduced magnetization (a +/0/+ transition). This is demonstrated for the area between 31° to 34°N and 23° to 26°W in Figures 2a, b and c, which show respectively seismic and magnetic profiles (KROONVLAG-project) and the result of a linear inversion solution of a magnetization distribution in a plane layer (Schouten and McCamy, 1972). The identifications of magnetic anomaly 34 (H.Schouten, pers. comm.) between 25° and 26°W show that this area is indeed situated in the CQZ. The difference in sign of the anomalies over these fracture zones and over the Kane FZ is also demonstrated in Figure 3, which shows two profiles over the Kane FZ and three profiles from the northern area. After a phase-shift of -90° (which is equal to a reduction to the pole), the anomalies over the Kane FZ become *positive* over the fracture zone as it is recognized in the basement profile, while the anomalies over the fracture zones to the N become *negative*. The Kane FZ has a sinistral offset, all these fracture zones to the N have a dextral offset. In chapter III we suggested that the sign of the anomalies is related to the sense of offset of the respective fracture zones. This idea was confirmed by a fracture zone 75 km to the N of the Kane FZ, which had a sinistral offset in the beginning of the CQZ and a dextral offset in the end.

In this chapter we search for a mechanism that can explain the difference in sign of the relative magnetization in sinistral and dextral offset fracture zones. Hydrothermal alteration as such is an isotropic process and cannot explain this difference in sign. Also serpentinization of ultramafic rocks, which

A

B

C


26W
25W
24W
23W
OFFSET 7500ms
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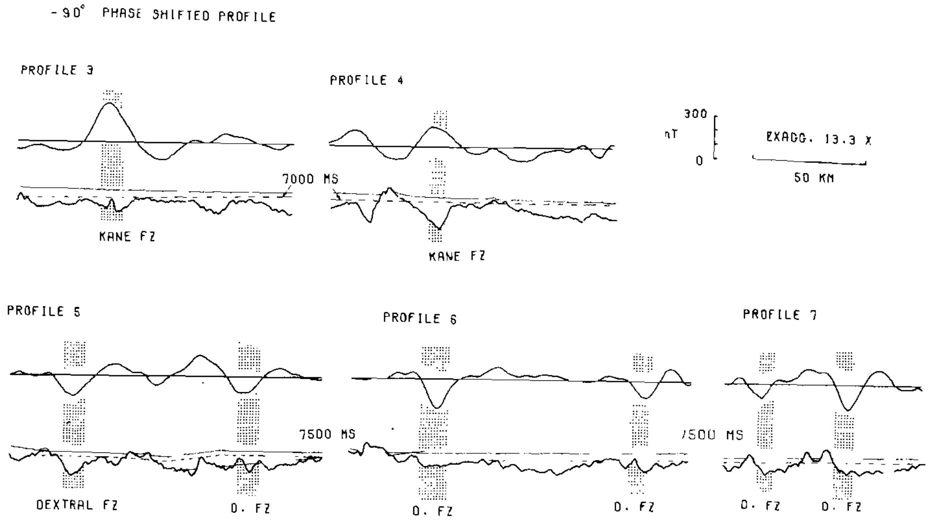

Fig. 3 The results of phase-shifting for θ is -90° of magnetic profiles 3 and 4 over the Kane FZ (see Chapter III, figure 3) and profiles 5, 6 and 7 over the fracture zones farther N (see Figure 2a), as compared to the fz positions in the seimic sections.

might be present in the fracture zone, cannot explain the difference in sign, since serpentinite magnetization is mainly induced (Saud, 1969). A process involved that is directionally dependent is the shearing in the active section of the fracture zone, the transform domain. First we discuss a possible tectonic rotation of the zone affected by the shearing, which would lead to a change of the effective magnetization. Then, as another explanation for the observed left/

← *Fig. 2 a) Seismic sections along NE-SW tracks, projected in a direction of 315° with respect to a depth of 7500 ms. Fracture zones can be recognized from east-west alignments of the basement. b) Magnetic anomalies, perpendicular to track and reduced by removal of long wavelengths. Black areas denote positive values. Stars indicate anomaly 34 identifications. c) The result of linear inversion of the magnetic profiles. The level of each profile is arbitrary. Black areas denote negative values. The used phase-shift of -90° corresponds to a strike of the fracture zones of 270° immediately east of anomaly 34 and to the Late Cretaceous pole for the African plate of Van der Voo and French (1974). The upper and lower surfaces of the magnetic layer used in inversion were taken at 5 and 6 km depth.*

right effect, we formulate the hypothesis that the difference in magnetization is due to the effect of stress on the magnetization in the transform domain. We will further test this hypothesis on several other fz anomalies: in the CQZ of the Equatorial Atlantic and of the Indian Ocean and in the Cenozoic sequence in the central North Atlantic.

The Kane FZ in the CQZ W of the Mid-Atlantic Ridge

The geometry of the fracture zones under discussion on the African plate is such that for sinistral offset fracture zones the older part of lithosphere bordering the fossil fracture zone is situated N and for dextral offset fracture zones S of the fracture zone (Figure 4). Note that also a transition young/old versus old/young with respect to the magnetic north can determine the sign of the anomalies. However, comparison with sections over the Kane FZ in the CQZ on the American plate proves that this is not the case. The position of the Kane FZ on this plate (see Figure 5) in the beginning of the CQZ is known from Purdy and Rohr (1979) and Rohr and Twigt (1979). Near anomaly 34 it is known from Rabinowitz and Purdy (1976). Its position was further confirmed by a profile of HNethMS Snellius (line Golf, Anonymous, 1967), which shows a topographic high with a topographic low to the N at 28^{0}N/63^{0}W. Comparison with the calculated anomaly of a positive zone flanked by regions of zero magnetization (see inset in Figure 5) shows that here too the magnetization is relatively positive.

The similarity between anomalies over the Kane FZ E and W of the Mid-Atlan-

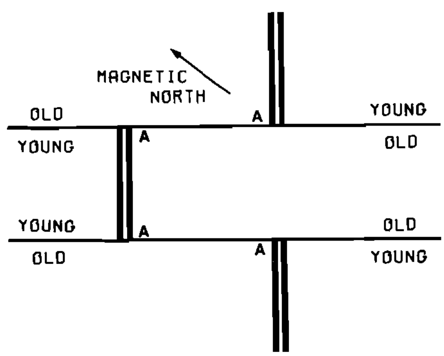

Fig. 4 The geometry of a sinistral and a dextral offset fracture zone with respect to the magnetic north for the CQZ in the central North Atlantic. For the meaning of mark A see text.

tic Ridge shows that the sign of the anomalies is not determined by the old/young effect. This outcome was confirmed by modeling studies of the anomalies in the African CQZ; it was not possible to explain the anomalies by a geometric effect such as a thinning of the magnetic layer to one side of the fracture zone and/or a thickening to the other, or by a vertical uplift of the crust on the older side leading to a change of the direction of magnetization. What indeed remains is a left/right effect, i.e. that the difference in magnetization is due to the strike-slip movement, the shearing, of the two plates involved in the active section of the fracture zone. This is the one other directionally dependent process involved.

A consequence of this will be that the zones with lower or higher magneti-

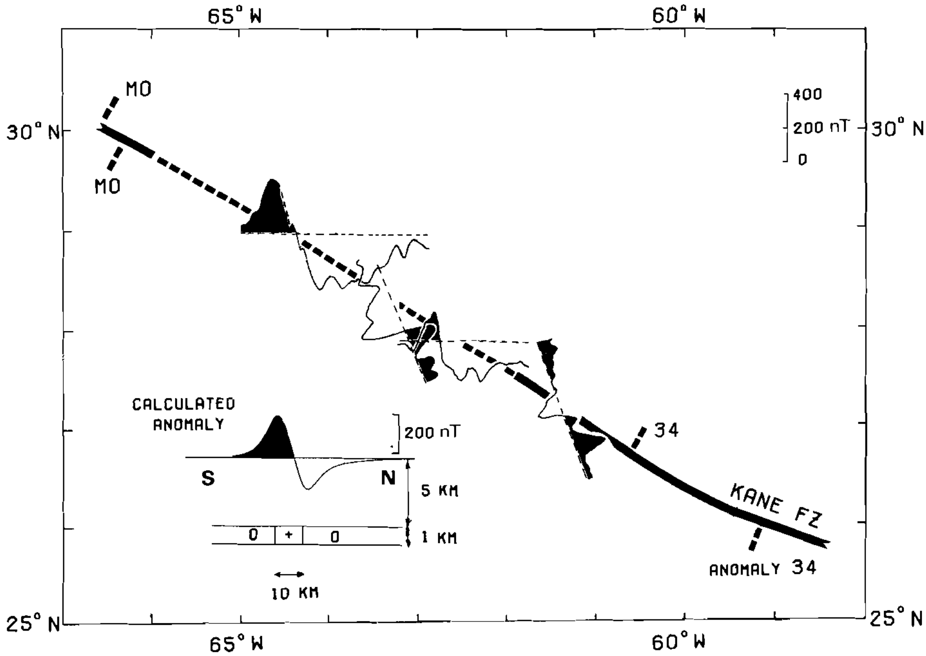

Fig. 5 Magnetic anomalies over the Kane FZ in the CQZ on the American plate, W of the Mid-Atlantic Ridge. Profiles from west to east are respectively from research vessels Vema 25, Snellius Golf, Chain 75 and Chain 44. Black areas denote positive values. The heavy line indicates the position of the Kane FZ. The inset shows the calculated anomaly of a positive zone flanked by regions of zero magnetization. The anomaly was calculated for the position at 28°N/63°W, for a strike of 300° and using the Late Cretaceous pole for the American plate of Van der Voo and French (1974).

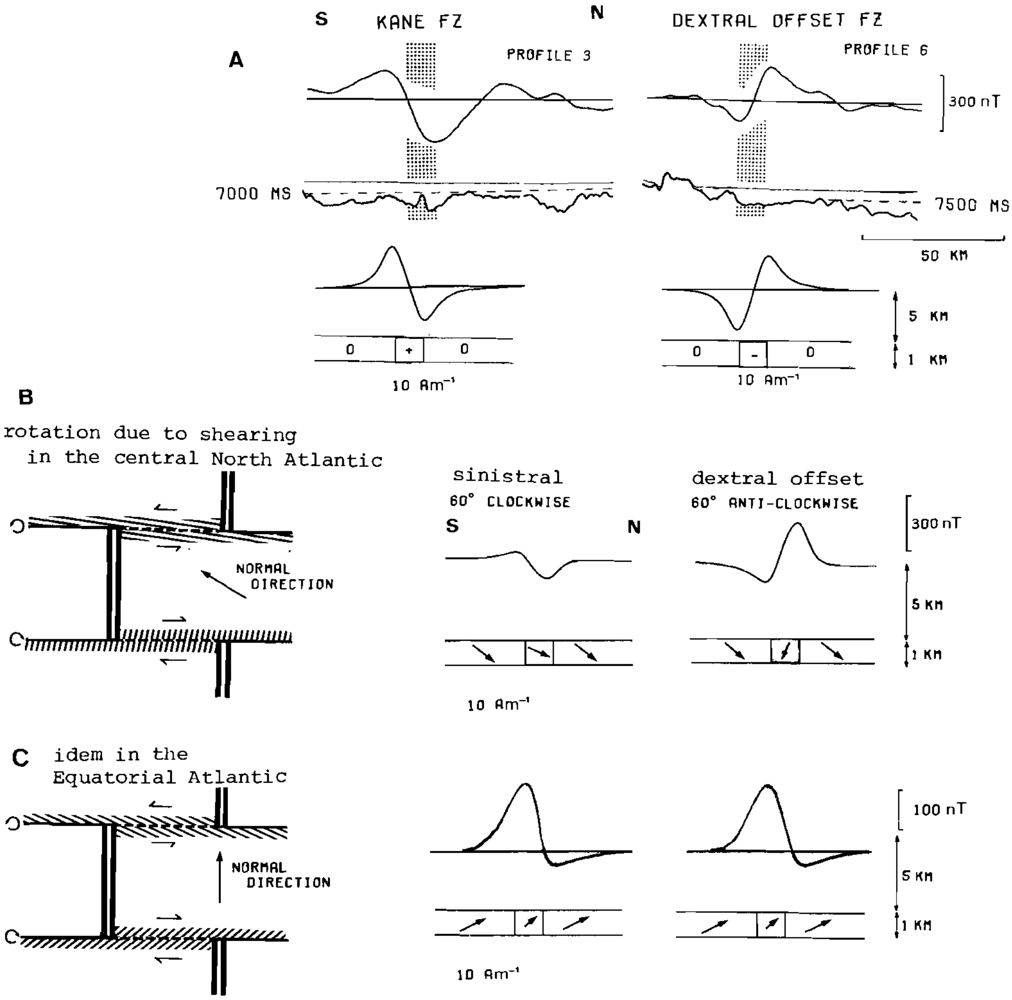

Fig. 6 a) The observed anomaly over the Kane FZ (profile 3) and over one of the fracture zones farther N (profile 5), in comparison with the calculated anomaly of a zone of respectively positive and negative magnetization flanked by regions of zero magnetization. The inclination and declination of the ambient field were 34° down/16° west and for the remanent magnetization they were 43° down/36° west using the Early Cretaceous pole for the African plate of Van der Voo and French (1974) for the position at 22°N/29°W. The strike was taken at 290°.
b) Model in which the declination of the magnetization in the fracture zone is rotated by a tectonic rotation in the active transform domain. The geometry corresponds with the CQZ in the central North Atlantic. It shows the resulting anomalies of a zone, in which the declination was rotated respectively 60° clockwise and 60° anti-clockwise, flanked by regions of normal magnetization.
c) The same model for the geometry in the CQZ of the Equatorial Atlantic and the resulting anomalies. For the used parameter values see text Figure 8b.

zation are confined to the 'older' part of lithosphere bordering the fossil transform fault trace in a fracture zone. For only this side was present in the active transform domain and underwent shearing. Such a situation might be true for the Kane FZ as well as for the fracture zones farther N, but it is difficult to prove on account of the complex and varying character of these fracture zones. This makes it difficult to determine the position of the fossil transform fault trace.

Change of the magnetization by a tectonic rotation?

Shearing may lead to a tectonic rotation of the crustal zone affected by the shearing in the transform domain. Such a rotation around the vertical axis would result in a change of the declination of the magnetization in the fracture zone, leading to a change of the effective magnetization in the fracture zone. The effective magnetization is the magnetization in the plane normal to the fz axis (Gay, 1963) and only this component of magnetization actually determines the anomaly over the fracture zone. Note from the symmetry of Figure 6b that such a rotation would be clockwise in the sinistral offset Kane FZ and anti-clockwise in the dextral offset fracture zones. The rotation would indeed be in the same direction to both sides of the Mid-Atlantic Ridge.

As indications for a possible tectonic rotation, we mention that oblique topographic trends have been observed in the active transform domain of fracture zones (Searle, 1979; Macdonald et al., 1979; Crane, 1976), although these directions are not the direct expression of the shearing in the fracture zone. In that case the sense of the trends would have been contrary to what has been found. In the Bay of Islands ophiolite complex of western Newfoundland where oceanic fracture zones have been recognized (Karson and Dewey, 1978), the dike layer of these ophiolites shows a bending of the dikes near the supposed fracture zones (Karson, pers. comm.). However, it cannot be said how this bending relates to a movement in the transform domain, since the sense of offset of the fracture zone is not known.

A comparison of the observed and the calculated anomalies of such a rotation model shows a problem. First of all, Figure 6a shows the observed anomalies over the Kane FZ in the African CQZ and over one of the fracture zones farther N, and the anomalies correspond well with the calculated anomalies of a zone of enhanced and reduced intensity of magnetization. Figure 6b shows then the calculated anomalies due to a clockwise rotation of the declination of 60°

and an anti-clockwise rotation of 60°. The general shape of the calculated anomalies of such a rotation model bears a good resemblance to the observed anomalies. However, the amplitude of the clockwise rotation model, using a magnetic layer of a thickness of 1 km and a magnetization of 10 Am^{-1}, is only one third of the observed anomaly over the Kane FZ. Further clockwise rotation again reduces the amplitude. In the given configuration the maximum positive magnetization is reached with 56° clockwise rotation, the maximum negative effect with 236° clockwise (or, of course, 124° anti-clockwise) rotation.

Another problem with this model (and this is perhaps even more meaningful) is that it cannot explain the enhanced magnetization in the fracture zones in the CQZ in the Gulf of Guinea in the Equatorial Atlantic. The direction of the magnetization is here essentially normal to the fz axis. Rotation under these circumstances will alway result in a reduction of the effective magnetization (Figure 6c). The resulting anomaly is a magnetic high and a minor magnetic low to the N. As we will see later on in this chapter, we actually find the reversed situation.

As will be discussed in the following section, an increase (or decrease for that matter) of the intensity of magnetization may be brought about by the stresses that reign in the active section of the fracture zone. It will appear that stress effects are indeed able to account for the observed left/right effects.

Change of the magnetization under the influence of stress

That the two parts of lithosphere bordering the active transform fault are not fully decoupled, is shown by the occurrence of numerous shallow earthquakes in the transform areas of fracture zones at the mid-oceanic ridges. Earthquakes occur along the total length of the transform fault, as can be observed for e.g. the Vema, the Fifteen Twenty and the Kane Fracture Zones. This means that the principal stress axes are not parallel and perpendicular to the actual fault plane. In other words, the stress trajectories are deflected in such a way that there is compressive stress over the fault plane as sketched in Figure 7a.

We formulate the hypothesis that the difference in magnetization in fracture zones is due to the effect of this stress distribution in the transform domain. Depending on the orientation of the direction of compressive stress with respect to the direction of magnetization, this will lead to an enhancement or a reduction of the effective magnetization. Figure 7a shows that the geometry of the fracture zones is such that the compressive stress in sinistral offset

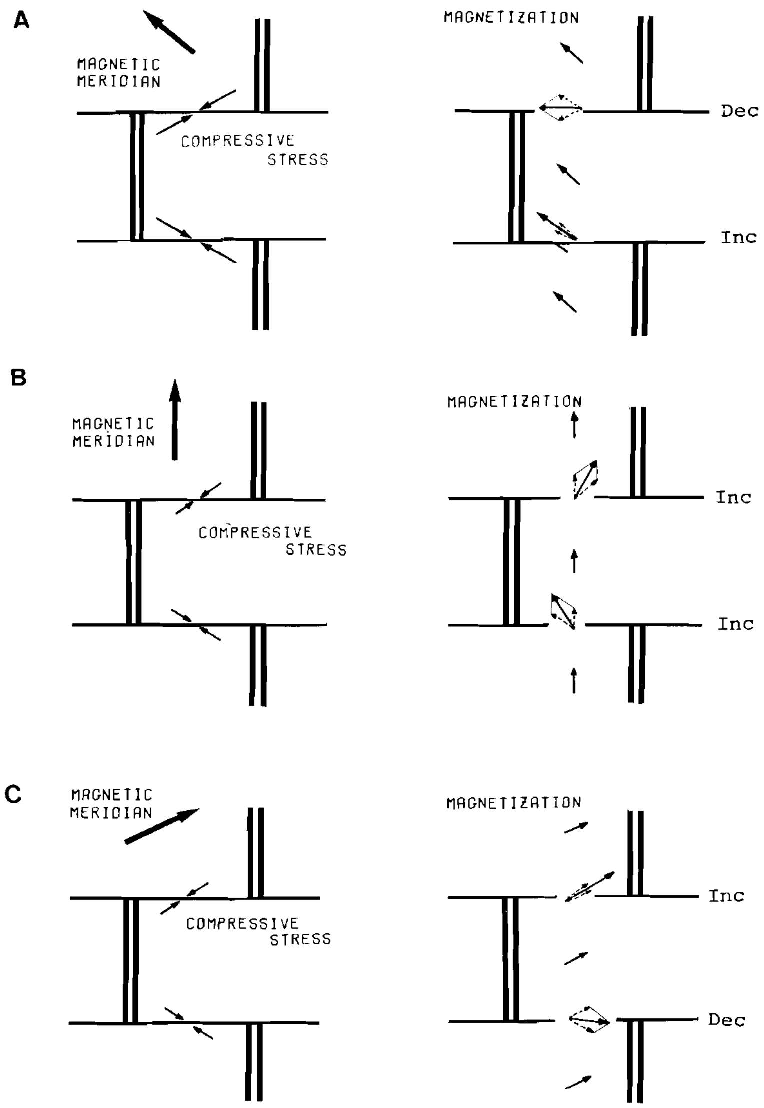

Fig. 7 a) The geometry of a dextral and sinistral fracture zone with respect to the magnetic north and the direction of compressive stress, for the fracture zones in the CQZ in the central North Atlantic. Inc and Dec indicate that the relative effective magnetization increases or decreases as resulting from an additional magnetization in the direction of compression. b) The geometry for the fracture zones in the CQZ in the Gulf of Guinea in the Equatorial Atlantic. c) The geometry for the fracture zones in the Mozambique Basin in the Indian Ocean.

transforms is parallel to the magnetic meridian and in dextral offset transforms more perpendicular to the magnetic meridian.

As a tentative explanation for an effect of stress on the magnetization we may think of a reorientation of the magnetic minerals or grains under the influence of shearing in the active transform domain. Such a reorientation might be accomplished by a rotation of non-regularly shaped grains. This mechanism leads to an orientation of the least compressible axis of the grains perpendicular to the direction of maximum stress (e.g. Collette, 1958, 1959). Reorientation of grains will lead to a magnetic anisotropy. Whether such an effect is large enough and has the proper sign, we do not know.

Reorientation may also be accomplished by a recrystallization. Irreversible effects of stress on remanent magnetization by recrystallization are generally referred to as piezoremanent magnetization (PRM). PRM is related to small local, irreversible changes of the walls of the magnetic domains. In the case of PRM compression results in an increase of the magnetization in the direction of stress in the presence of an external field (Nagata and Kinoshita, 1965). The amount of increase found for magnetite, 15% per kbar (Nagata and Kinoshita, 1967), is fairly low to explain the enhanced magnetization as found in the Kane FZ, from 10 to 15 Am^{-1} assuming an intensity of normal crust of 5 Am^{-1}. But in addition, processes like hydrothermal alteration within the sheared zone might have lead to the formation of minerals that are more stress-sensitive (titano-maghemite ?).

Cooling of the basalts in the transform domain from the Curie temperature to lower temperatures in the presence of compressive stress might be another possible candidate for an effect of stress on the magnetization. Schmidtbauer and Petersen (1968) studied the effect of heat treatment of basalts that contained homogeneous titanomagnetite upon their stress sensitivity. They found changes of plus or of minus 50% in TRM under compression of approximately 1 kbar, depending upon whether uniaxial compression and applied magnetic field were perpendicular or parallel to each other. However, in order to explain our observations, these changes would have to have the opposite sign.

The first process, a mechanical reorientation of grains, or for that matter all types of rotation, is independent of the ambient magnetic field during the time that the process would be active. In that case a magnetic anisotropy depends on the direction of the initial magnetization, i.e. the direction of the magnetic field at the time the crust in the fracture zone was generated. Recrystallization effects, on the other hand, are dependent on the direction of the ambient field (as is cooling). Let us suppose that recrystallization under hydrothermal action is the agent. The shearing in the fracture zone is active over the whole length of the transform domain. If the offset is large enough, it could then be that the recrystallization occurs under alternating field directions. The additional magnetization would then be in one direction during a normal period and in the other direction during a reversed period. The resulting magnetization would be undetermined and would depend on the whole sequence of events, possibly most on the field polarity at the moment that the crustal segment leaves the transform domain. As we will see later, the fz anomalies in the Cenozoic sequence between 12° and 15°W in the central North Atlantic show a definite pattern; the magnetization in these fracture zones shows a relation in sign with the crustal segment in question. Therefore, recrystallization as a hypothetical agent must be confined to the region close to the intersection with the spreading center and to the younger side of the transform fault (area A in Figure 4). Only in that case can we expect that the enhanced or reduced magnetization shows a relation in sign with the polarity of the crustal segment in question. As with cooling, a certain phase-lag will be present, which will result in a smearing if we are dealing with short reversals. For short reversals fz anomalies are anyhow unreadable due to disturbing three-dimensional effects.

For the time being we will assume that there is a process generating an additional magnetization in the direction of compressive stress. Figure 7a shows that for the given fracture zones in the central North Atlantic such an additional magnetization leads to an increase of the effective magnetization in sinistral offset transforms and to a decrease in dextral offset transforms.

Fz anomalies in the CQZ in the Equatorial Atlantic and in the Indian Ocean

A survey was made of published anomalies over fracture zones in other areas of the World's oceans,to check whether the generalization made is indeed valid. We are especially interested in fz anomalies in the CQZ, since there the magnetic polarity of the crust to both sides of the fracture zone is known to be normal, which makes it possible to determine the magnetization in the fracture zone. Although the CQZ is present in all the three oceans, it was difficult to find useful profiles. Many profiles intersect the fracture zones under small angles and, furthermore, the exact position of the fracture zones often is not known well enough to be able to isolate the corresponding fz anomaly.

For the Equatorial Atlantic, Sibuet and Mascle (1978, figure 10) have published magnetic profiles over fracture zones in the Gulf of Guinea in the

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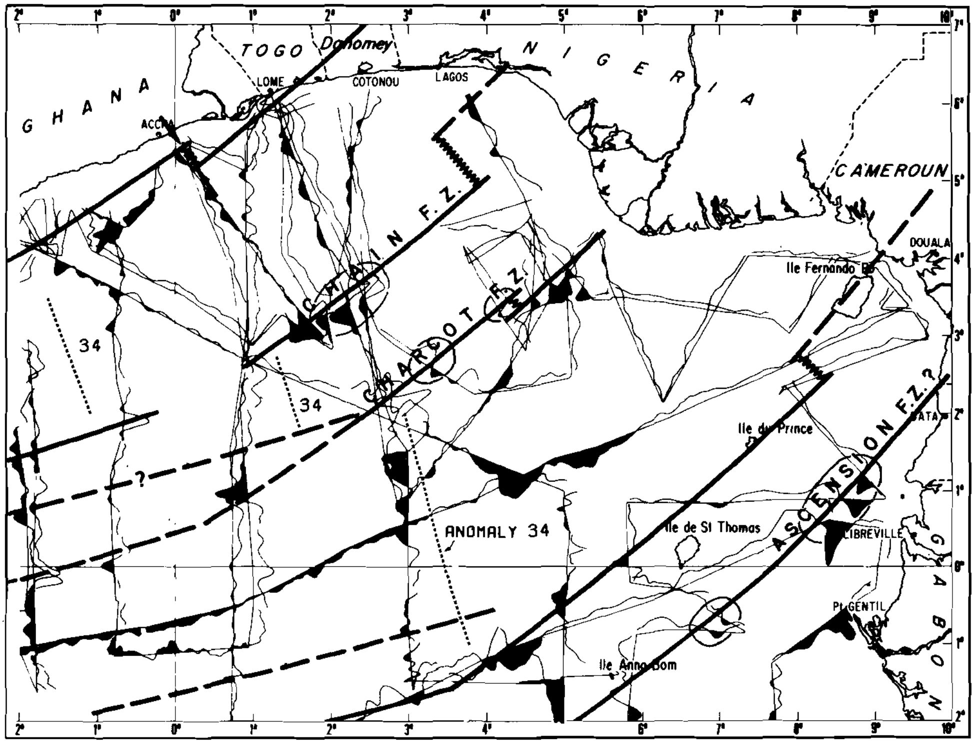

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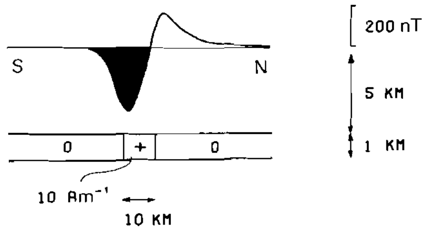


Fig. 8 a) Magnetic anomalies over fracture zones in the Gulf of Guinea in the Equatorial Atlantic (from Sibuet and Mascle, 1978). Black areas denote negative values. About N-S dashed lines indicate the magnetic anomaly 34 isochron, calculated by using the spreading pole for the South Atlantic after Ladd (1974, 1976), and mark the part of the area situated in the CQZ. Characteristic fz anomalies have been encircled. b) The calculated anomaly of a zone of positive magnetization flanked by regions of zero magnetization. The inclination and declination of the ambient field were taken as 20^{o} up/9^{o} west and for the remanent magnetization they were 28^{o} up/22^{o} west using the Late Cretaceous pole for the African plate of Van der voo and French (1974). The strike was taken as 237^{o}.

Equatorial Atlantic (Figure 8a). The opening of the Atlantic in this area started about 110 mybp. Since the CQ Period extends from 108 to 80 mybp (LaBrecque et al.,1977; Larson and Hilde, 1975), the easternmost parts of the fracture zones are thus situated in the CQZ. Since at this low magnetic latitude the roughly N-S spreading anomalies are highly subdued (see Schouten,1971) and cannot be used for dating the ocean floor, we calculated the theoretical position of anomaly 34 using the spreading pole for the South Atlantic after Ladd (1974, 1976) to define the CQZ. The general shape of the fz anomalies in the CQZ consists of a magnetic high and a magnetic low to the S. This applies both to the Chain and the Charcot Fracture Zones, which have a sinistral offset at the Mid-Atlantic Ridge, as well as to the tentatively identified Ascension FZ, which has a dextral offset at the Ridge. As follows from Figure 8b, the anomalies show a correspondence with a relatively positive magnetization in the fracture zone. In this area both sinistral and dextral offset fracture zone thus have a higher than normal magnetization. This situation is explained in Figure 7b, which shows the geometry of the fracture zones with respect to the magnetic north. For the used values of the fz azimuth and the declination of the remanent magnetization see text Figure 8b. This geometry then is such that an additional magnetization in the direction of compression leads to an increase of the effective magnetization both in sinistral and dextral offset transforms.

For the Indian Ocean, Bergh and Norton (1976, figure 21) have presented magnetic profiles over the Prince Edward FZ in the Mozambique Basin. For the location of the area see Figure 9a. Figure 9b shows the profiles at the northern part of this sinistral offset fracture zone. The authors identified magnetic anomalies 32 to 34 (called anomaly N by the authors) to the eastern side and anomaly 34 to the western, oppositely to anomaly 32. The interval between anomaly 32 and 33 was mainly a long normal period, so that the crust on either side of this part of the fracture zone is normally magnetized. As follows from Figure 9d, the anomalies over this part of the fracture zone correspond to a reduced magnetization in the fracture zone. Also across another fracture zone with a sinistral offset farther N in the Mozambique Basin magnetic profiles have been published (Ségoufin, 1978) (Figure 9c). According to this author's identification of the Mesozoic magnetic anomaly sequence, the two profiles S of 27^{o}S intersect the fracture zone in the CQZ. Again the anomalies can be explained by the model of Figure 9d. The presence of a reduced magnetization is explained in Figure 7c, which shows the geometry of the fracture zones with respect to the magnetic north. For the used values of the fz azimuth and the declination of the remanent magnetization see text Figure 9d. This geometry

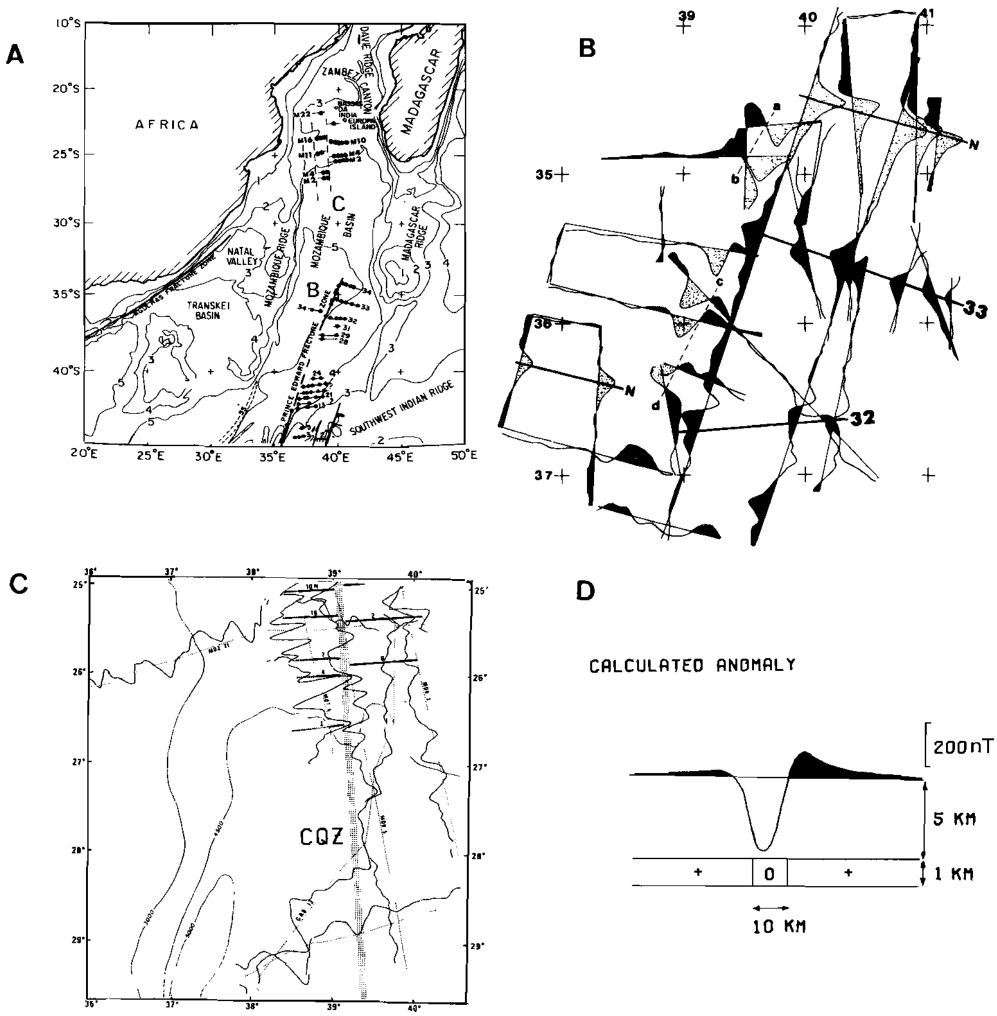


Fig. 9 a) Location of the areas of Figures 9b and 9c in the Mozambique Basin in the western Indian ocean. b) Magnetic profiles over the Prince Edward FZ (from Bergh and Norton, 1976). Black areas denote positive values. Magnetic anomaly identifications are from Bergh and Norton. (Anomaly N is anomaly 34.) c) Magnetic profiles over a fracture zone farther N (from Ségoufin, 1978). d) The calculated anomaly of a zone of zero magnetization flanked by regions of normal magnetization. The inclination and declination taken for the ambient field were 62^{o}up/25^{o}west and for the remanent magnetization they were 73^{o}up/ 4^{o}west using the Late Cretaceous pole for the African plate of Van der Voo and French (1974). The strike was taken as 020^{o}.

is such that in sinistral offset transforms the effective magnetization decreases and in dextral offset transforms it increases. This is the reverse of the situation for the studied fracture zones in the CQZ of the central North Atlantic, where in sinistral offset fracture zones enhancement takes place and in dextral offset fracture zones reduction. Unfortunately there are no data over dextral offset fracture zones in the CQZ of the Indian Ocean.

Anomalies over fossil fz sections in the Cenozoic sequence

In contrast to the CQZ, in the Cenozoic sequence the earth magnetic field may have changed polarity one or more several times during the time the crust in the fracture zone was present in the active transform domain. In order to determine whether this alternating of the magnetic field affects the magnetization in the fracture zone, so that it does not fit in the general scheme, we study magnetic anomalies over fracture zones in the Cenozoic sequence of the central north Atlantic. In this study we must realize that, while in the CQZ only one combination of magnetic end-effects occurs, viz. +/+, in the Cenozoic sequence four combinations are conceivable, viz. +/+, +/-, -/+ and -/-. In addition the fracture zone has an enhanced or reduced magnetization, resulting in a large variety of conceivable magnetic transitions over fracture zones.

Sinistral offset fracture zones in the central North Atlantic between 12^o and 15^{o}N

We studied magnetic profiles over several fracture zones S of the Fifteen Twenty FZ in the North Atlantic (KROONVLAG-project, in part published in Collette et al.,1974). In general, interference with spreading anomalies makes it difficult to isolate fz anomalies in the Cenozoic sequence. However, since at this low magnetic latitude the roughly N-S spreading anomalies are highly subdued and the roughly E-W fz anomalies are well-developed, these profiles are useful for the study of fz anomalies. Figure 10 shows the location of the tracklines with respect to the Mid-Atlantic Ridge and the traces of the 12^{o}10'N FZ, the 12^{o}40'N FZ, a fracture zone 60 km S of the 12^{o}10'N FZ and a fracture zone 60-90 km N of the 12^{o}40'N FZ. For the latter two fracture zones only segments could be identified. The 12^{o}10'N and the 12^{o}40'N FZ have a sinistral offset at the Ridge axis of 45 and 80 km respectively (Collette et al.,1979). The general course of the Ridge axis in this area makes it probable that the other two fracture zones had also sinistral offsets at the time roughly between anomaly 13 and anomaly 24.

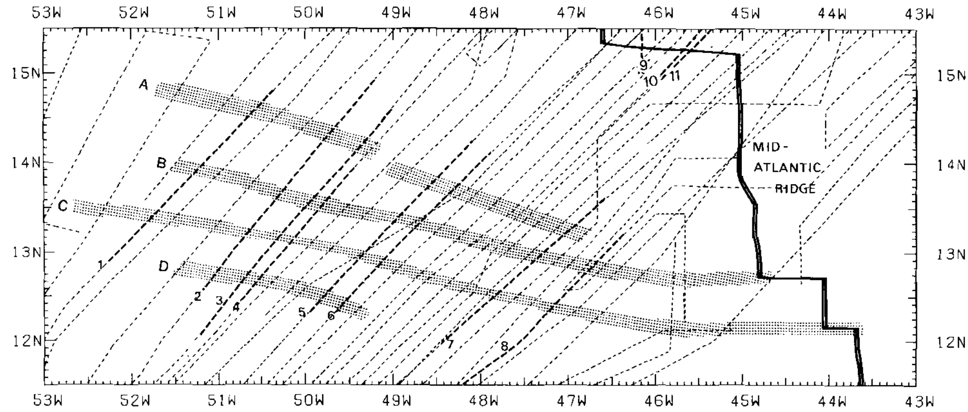


Fig. 10 *Location of NE-SW tracks (KROONVLAG-project) over fracture zones in the central North Atlantic between 12° and 15° N. Profiles along tracks indicated by heavy lines are shown in Figure 11a (numbers 1-8) and in Figure 12b (9-11). The position of the Ridge axis and the traces of fracture zones were identified from seismic and magnetic profiles of the KROONVLAG-project and from two detailed surveys over the Ridge axis (Collette et al.,1979; Collette et al., 1980).*

The declination of the remanent magnetization varies from 0° at 13°N/45°W to 11°west at 13°N/53°W, using respectively a geocentric axial dipole field at the Ridge axis and the Early Tertiary pole for the American plate (Van der Voo and French, 1974) for the westernmost position in the area. The geometry of the fracture zones with respect to the magnetic north thus resembles the geometry of the fracture zones in the Equatorial Atlantic (Figure 7b). If we were in the CQZ this geometry would give rise to enhancement of the magnetization.

Figure 11a shows the seismic and magnetic profiles along the indicated tracks (heavy lines) in Figure 10, projected on the meridian. Most of the profiles used are situated W of 48°W. E of this longitude the anomalies over the fracture zones have a much lower amplitude and were not used for this reason. As an example two profiles E of 48°W are shown in Figure 11a (profiles 7 and 8). This problem of the variation of the amplitude of fz anomalies along the fz axis will be dealt with in Chapter V. Several profiles W of 48°W could not be used, since they show data gaps. In Figure 11a the fracture zones clearly appear in the topography as a rift valley and large magnetic anomalies are present over the fracture zones. Linear inversion was applied to the magnetic anomalies. In

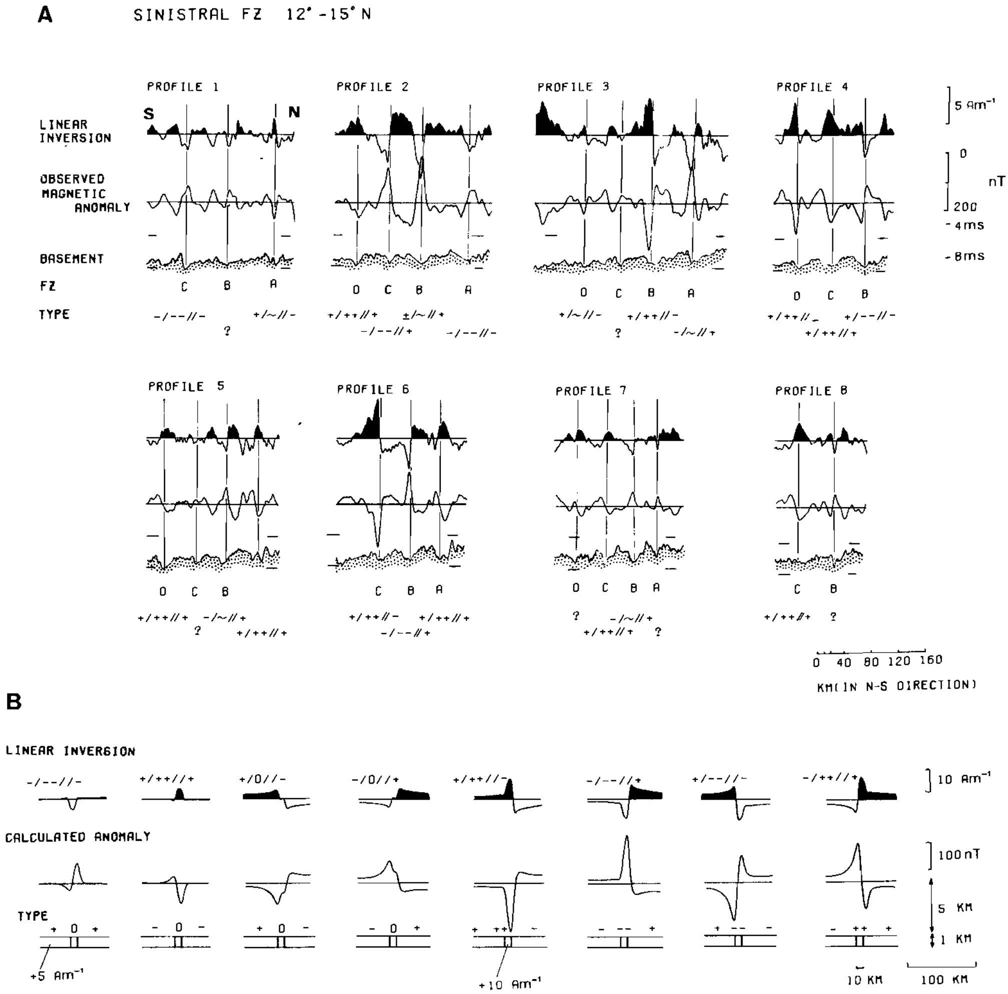


Fig. 11 *a) Seismic and magnetic profiles and the result of linear inversion along tracks 1 to 8 across the fracture zones A to D in Figure 10, projected on the meridian. The average level of the magnetic profiles and of the inversion results was taken zero. Positive values are shown in black. The used θ of -144° corresponds to a strike of 270° and to the position at 13°N/45°W using a geocentric axial dipole field for the direction of magnetization. The upper and lower surfaces used in inversion were taken at 5 and 6 km depth.*
b) Calculated anomalies and the result of linear inversion for a number of magnetic transitions as corresponding to the position at 13°N/45°W.

applying this inversion the magnetic contrasts along the fracture zone are considered to be two-dimensional. Three-dimensional modeling calculations (Chapter II, figure 3) show that the fz anomaly is disturbed by a spreading anomaly contrast to about 7 km from the fracture zone/spreading contrast intersection. However, the fz anomalies on the used profiles must be sufficiently two-dimensional, since otherwise they could not have such large amplitudes and steep gradients.

For a better recognition of the type of magnetic transition in the inverted anomalies, linear inversion was also applied to calculated anomalies over a number of magnetic transitions (Figure 11b). The inversion results of the observed anomalies show both symmetric and anti-symmetric transitions over the fracture zones. Reading old/fracture zone//young , the symmetric transitions correspond to +/++//+ and -/--//- transitions. However, since a -/0//- and a +/0//+ would give the same result, this outcome is not discriminating. Of the anti-symmetric transitions, 3 of them can be identified as a +/++//- transition, 2 as -/--//+ , 1 (profile 8, fracture zone B) as +/--//- and 5 as +/~//- or -/~//+. In the latter cases it was not possible to determine the magnetization in the fracture zone. Most of the anti-symmetric transitions thus point to the presence of an enhanced magnetization in the fracture zones. In the cases in which it was possible to determine the polarity of this enhanced zone, in five cases out of six this polarity corresponds to the polarity of the crust to the southern, i.e. the older side of the fracture zone. The latter is in agreement with our conclusion that the change of the magnetization is due to shearing, for only the older side was present in the active transform domain and underwent shearing.

This outcome has two important consequences. Firstly, the fracture zones between 12° and 15°N fit in the general scheme of enhancement or reduction depending on the direction of compression with respect to the direction of magnetization. Secondly, the enhanced magnetization is not destroyed by the effect of alternating field directions during the time the crustal segment in question is present in the active transform domain. This means that if recrystallization is involved, this process must be confined to the area close to the intersection of the fracture zone with the spreading center, i.e. the part of the fracture zone where the temperature is highest.

Tydeman Fracture Zone

Three-dimensional modeling for several large anomalies over the Tydeman

FZ, SE of the Azores (Chapter II), showed that these anomalies correspond to a +/0//- and a -/0//+ transition. The Tydeman FZ has a dextral offset. Its strike is east-west and the declination of the remanent magnetization is 24^{o} west, according to the Late Cretaceous pole for the African plate of Van der Voo and French 81974). The geometry of the fracture zone resembles the geometry of the dextral offset fracture zones in the CQZ in the central North Atlantic (Figure 7a). Reduced magnetization thus is what we can expect.

Magnetic anomalies over the active part of fracture zones

According to the stress-hypothesis the change of the magnetization in the fracture zone takes place in the active section. The difference with the fossil section is that in the active section the anomalous magnetization is present to both sides of the transform fault. Once the anomalous magnetization reaches the intersection with the spreading center, it is halved and merges with crust which was never in the transform domain, having the normal magnetization (see Figure 12a). Across the active section we can thus expect the following magnetic transitions: $\frac{+/++}{-/--}//\frac{++/+}{--/-}$ in the case of enhancement and $\pm/0//0/\pm$ in the case of reduction.

We would expect enhancement of the magnetization in the active sections of the Vema and the Fifteen Twenty FZ (Figure 7a or 7b). Robb and Kane (1975) modeled a magnetic anomaly profile over the active section of the Vema FZ with a -/0//0/- transition. This result can also be interpreted as a +/++//++/+ transition.

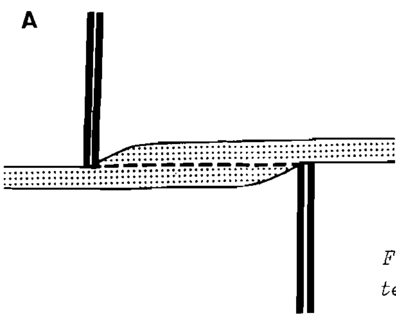
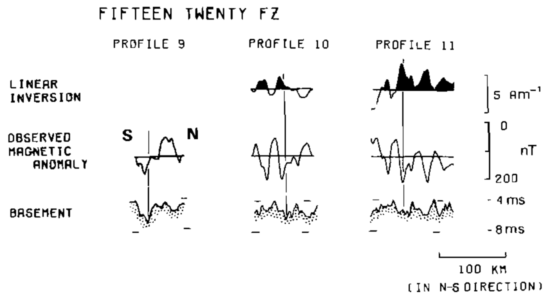


Fig. 12a
text see →



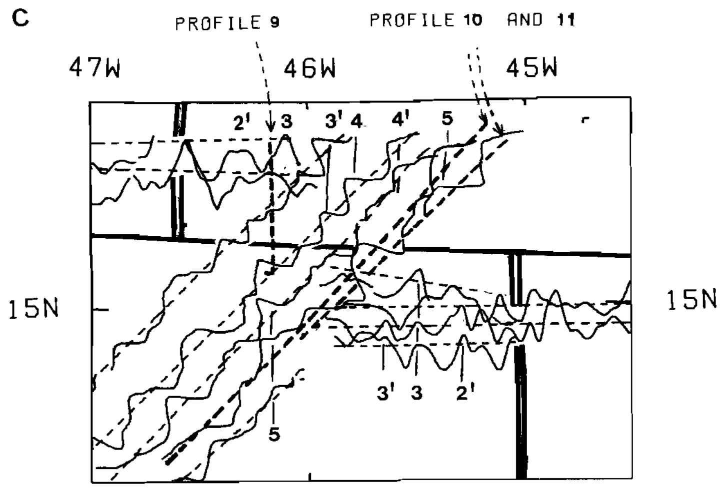


Fig. 12 a) In the active section the anomalous magnetization is present to both sides, in the fossil sections only to the older. b) Seismic and magnetic profiles and the result of linear inversion along tracks 9 to 11 over the active part of the Fifteen Twenty FZ (Figure 10), projected on the meridian. Since profile 9 is too short, no inversion could be applied to this profile. The used value of θ was -144° and the upper and lower surfaces of the magnetic layer were taken as 3.5 and 4.5 km depth. c) Identification of spreading anomalies to both sides of the Fifteen Twenty FZ, used to determine the polarity of the crust adjacent to the fracture zone at the intersections with profiles 9 to 11.

We studied several anomalies over the active part of the Fifteen Twenty FZ. Figure 10 shows the location of two NE-SW profiles (profiles 10 and 11, KROONVLAG-project) and one N-S profile (profile 9, detailed survey in 1975). Figure 12b shows the seismic and magnetic profiles and the result of linear inversion. The identification of the spreading anomalies in Figure 12c is based on the other profiles shown and on data not incorporated in this chapter (KROONVLAG-project and detailed surveys in 1975 and 1977). For profiles 10 and 11 we have the positive strip of anomaly 4' to the N and the positive strip of anomaly 3' to the S of the intersection with the fracture zone. For profile 9 the positive strip of anomaly 3 is situated to the N and the positive strip of anomaly 5 to the S. We would thus expect +/++//++/+ transitions in all three profiles. The inverted anomalies of profiles 10 and 11 agree with this model. Profile 9 is too short for inversion, but half of the expected anomaly can still be recognized. The magnetization in the transform domain of the Fifteen twenty FZ thus is indeed enhanced. The theory predicts that the enhanced zone is twice as wide in the transform domain as in the fossil part of the fracture zone. The present data are not conclusive at this point.

Conclusions

Summarizing, we arrive at the following:

1. The finding that sinistral offset fracture zones in the CQZ on the African plate in the central North Atlantic have an enhanced magnetization and dextral offset fracture zones a reduced magnetization, necessitated the search for a new mechanism to explain the magnetization in fracture zones.

2. The similarity of the magnetization in the Kane FZ in the CQZ E and W of the Mid-Atlantic Ridge excludes the possibility of an old/young effect with respect to the magnetic north. What remains is a left/right effect, i.e. that the change of the magnetization is due to shearing in the active section of the fracture zone, the transform domain.

3. A consequence of this change due to shearing is that the zones with lower or higher magnetization are confined to the 'older' side of the fracture zone, for only this side was present in the transform domain and underwent shearing.

4. Shearing may result in a tectonic rotation of the zone affected by the shearing. This would lead to a change of the effective magnetization, i.e. the magnetization normal to the fz axis. However, such a rotation cannot explain the amplitude of the anomalies over the Kane FZ in the CQZ as well as the shape of the anomalies in the CQZ of the Equatorial Atlantic.

5. As an explanation for the observed left/right effect, we formulate the hypothesis that the difference in magnetization is due to the effect of stress on the magnetization in the transform domain, in such a way that the magnetiza-

tion increases in the direction of compression. Depending on the orientation of the direction of compressive stress with respect to the direction of the magnetization , the effective magnetization will be enhanced or reduced.

6. It appeared possible to apply this generalization to other fz anomalies: in the CQZ of the Equatorial Atlantic and of the Indian Ocean and in the Cenozoic sequence of the central North Atlantic.

7. Several tentative explanations are offered for an effect of stress on the magnetization: a rotation of the magnetic grains within the sheared zone, cooling in the presence of stress and a recrystallization of minerals newly formed by hydrothermal alteration.

8. The magnetization in sinistral offset fracture zones in the central North Atlantic (12°-15°N) is found to be enhanced too. The enhanced magnetization is thus not destroyed by the effect of alternating field directions during the time the crustal segment in question is present in the active transform domain. This means that if recrystallization is involved, this process must be confined to the area close to the fracture zone/spreading center intersection.

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Appendix

In addition to the magnetic profiles over the fracture zones between 12° and 15°N, we also studied the magnetization in two *dextral offset fracture zones between 18° and 19°N in the central North Atlantic*. According to the stress model, dextral offset fracture zones have a reduced magnetization N of the Kane FZ in the CQZ in the central North Atlantic, but an enhanced magnetization in the Equatorial Atlantic. Somewhere in between there must be a region of transition from reduction to enhancement. Since the angle between the direction of compressive stress and the fz azimuth in the active transform domain is not known exactly, it is hard to predict the position of this region. Figure 13a then shows the location of the tracklines with respect to the Mid-Atlantic Ridge and the positions of the fracture zones. Figure 13b shows the seismic and magnetic profiles along the tracks, projected on the meridian, as well as the result of linear inversion. From a comparison with the inversion result of the calculated anomalies in Figure 11b it follows that 2 of the anti-symmetric transitions show the best correspondence with a -/0//+ transition, 1 with +/0//- , 1 with -/--//+ and 2 with -/∼//+ . In the latter cases it was not possible to determine the magnetization in the fracture zone. In three cases versus one the suggestion thus is that the magnetization in the fracture zone is reduced. However, the result of a comparison of observed and calculated anomalies is less convincing than over the sinistral offset fracture zones between 12° and 15°N. The explanation might be that the anomalies over zones with a reduced magnetization, e.g. a +/0//- transition, are less sharp and lower in amplitude than the anomalies over zones with an enhanced magnetization, e.g. a +/++//- transition.

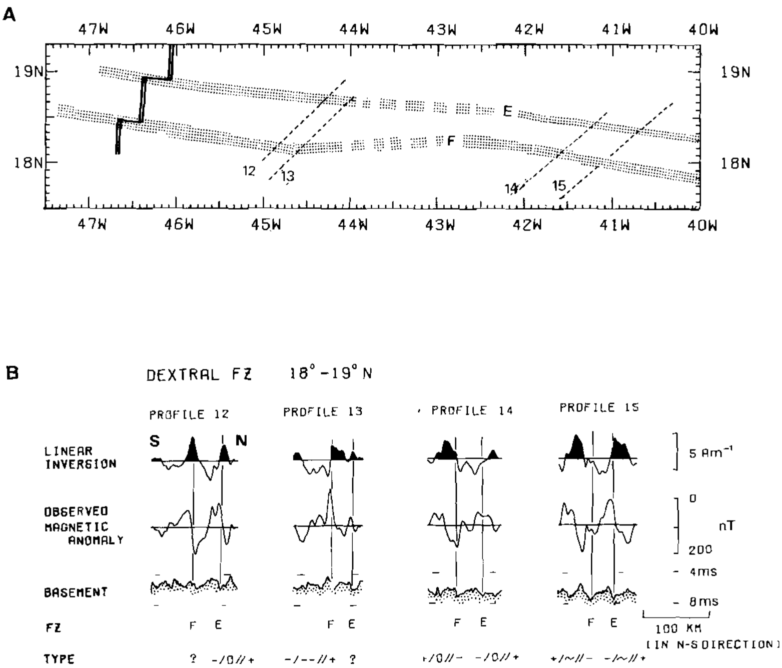


Fig. 13 a) Location of NE-SW tracks (KROONVLAG-project) over fracture zones in the central North Atlantic between 18° and 19°N. The position of the Ridge axis and the traces of the fracture zones were identified from seismic and magnetic profiles along these tracks and along a large number of tracks not shown in this figure . b) Seismic and magnetic profiles and the result of linear inversion along tracks 12 to 15 across the fracture zones E and F in Figure 13a, projected on the meridian. The used value of θ of −105° corresponds to a position at 18°N/42°W and to a strike of 275°, using the Early Tertiary pole for the African plate of Van der Voo and French (1974). The upper and lower surfaces of the magnetic layer were taken as 5 and 6 km depth.

Chapter V

IDENTIFICATION OF FRACTURE ZONES FROM MAGNETIC ANOMALIES IN THE CENTRAL NORTH ATLANTIC BETWEEN 11^{o} AND 24^{o}N

Abstract

Until recently the positions of the fracture zones in the central North Atlantic was not known sufficiently well, which in some cases has lead to erroneous identification of magnetic sea floor spreading anomalies. In this study the magnetic anomalies across fracture zones are used to help identify the fossil segments of fracture zones in the central North Atlantic between latitudes 11^{o} and 24^{o}N, using a large number of NE-SW profiles. A transformation using the analytic signal eliminates the variation of the type of anomaly along the fz axis. Having identified the fracture zones and recognized the fz anomalies, the magnetic profiles were used to date the ocean floor so far as this is possible at this lower magnetic latitude.

The amplitude of the fz anomalies varies along the fz axis, allowing identification only of segments of fracture zones from magnetics. At places a magnetic expression of the fracture zone is poor, whereas at other places the anomalies have large amplitudes. These variations seem to be related to changes in sea floor spreading direction which lead to tension and compression in the transform fault area, and can be explained by stress effects.

Introduction

A systematic survey between Europe and South America has been carried out by the Vening Meinesz Laboratorium in the years 1968-1979 (KROONVLAG-project). Continuous seismic profiling and magnetic total intensity measurements were made along 31 NE-SW tracks situated at mutual distances of 20 to 40 km (Figure 1). The bundle of tracks crosses the western limb of the Vema Fracture Zone on the American plate and the Mid-Atlantic Ridge between 12^{o} and 20^{o}N. Farther N it crosses the eastern limbs of the Kane FZ and the Atlantis FZ and subsequently it crosses the Meteor-Atlantis Seamount complex, the Oceanographer FZ and the East-Azores FZ. The latter fracture zone forms the active Eurasian-African plate boundary. The tracks cross the roughly east-west fracture zones in this area under angles of about 45^{o}. This makes them particularly useful for

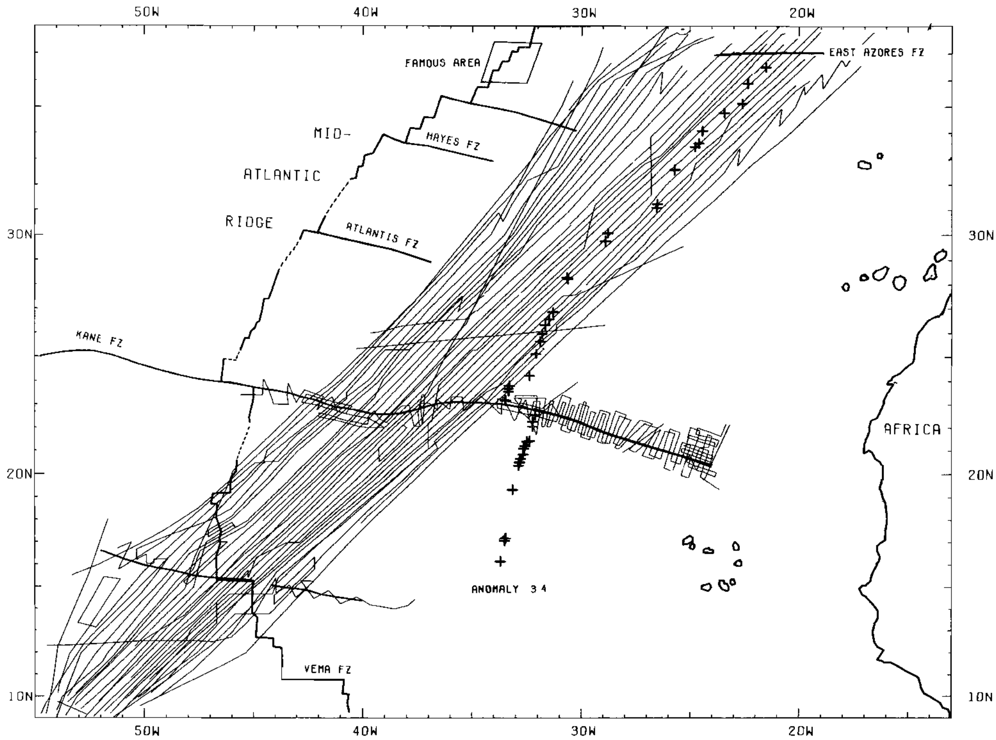


Fig. 1 Location with respect to the Mid-Atlantic Ridge of NE-SW profiles of the KROONVLAG-project, of profiles of R.V. Knorr and M.V. Tyro over the eastern limb of the Kane FZ and of HNethMS Luymes over the eastern limb of the Fifteen Twenty FZ.

the identification of fracture zones.

Due to the presence of numerous fracture zones and the low magnetic latitude the identification of the magnetic anomalies with the magnetic reversal time scale (see Pitman and Talwani, 1972)is difficult in the central North Atlantic. The positions of the fracture zones was not known sufficiently well, which sometimes has lead to erroneous identification of the magnetic anomalies (e.g. Phillips et al., 1975). One of the reasons which makes it difficult to trace a fracture zone is the variation of the topographic expression of fracture zones along their axes (Chapter III). Therefore, the magnetic anomalies over fracture zones can be used to help identify fossil segments of fracture zones. This is done in this chapter for the central North Atlantic between latitudes 11° and 24°N. This study forms part of the total reconstruction of the fracture zone pattern between 10° and 37°N from the continuous seismic and magnetic data of the KROONVLAG-project. Fracture zone anomalies in this area sometimes tend to overshadow the spreading anomalies (see Schouten, 1971).

Since outside the CQZ the crust to both sides of the fracture zone has alternately normal and reversed magnetization, which leads to different end-effects of the magnetic layer along the fz axis, a large variation of the type of anomaly occurs along the fracture zone. This means that, in general, no proper alignment is observed in these areas, as was found in the CQZ. A transformation on the magnetic profiles taking the absolute value of the analytic signal (Nabighian, 1972) eliminates this variation.

A remarkable outcome of this study is that the amplitude of the fz anomalies shows a large variation along the fz axis, allowing identification only of segments of fracture zones from magnetics. At places the magnetic expression of the fracture zones is well-developed, whereas at other places a magnetic expression is poor. This variation seems to be related to changes of spreading direction, which can be recognized from the changes of the fz azimuth. We will try to explain this variation and we make use of insights into the magnetization in fracture zones developed earlier (Chapter IV).

Survey area and details

S of the Fifteen Twenty FZ the bundle of tracks is mainly situated on the American plate. The Ridge axis here undergoes several sinistral offsets, e.g. an offset of 290 km along the Vema FZ and of 165 km along the Fifteen Twenty FZ (Van Andel et al., 1971; Collette and Rutten, 1972). Between 12° and 20°N the bundle crosses the Mid-Atlantic Ridge. The position of the Ridge axis from 12° to 18°N is based on detailed surveys (Collette et al., 1979; Collette et al., 1980). N of the Fifteen Twenty FZ the Ridge axis runs roughly N-S showing several smaller sinistral and dextral offsets. Still farther N, at 23°45'N, the Ridge axis undergoes a large sinistral offset of 160 km along the Kane FZ (Fox et al., 1969).

For the analysis we also used magnetic profiles of HNethMS Luymes, of HNethMS Snellius, and several profiles of R.V. Knorr. These latter data were kindly made available by Dr.G.M.Purdy of the Woods Hole Oceanogr. Institution.

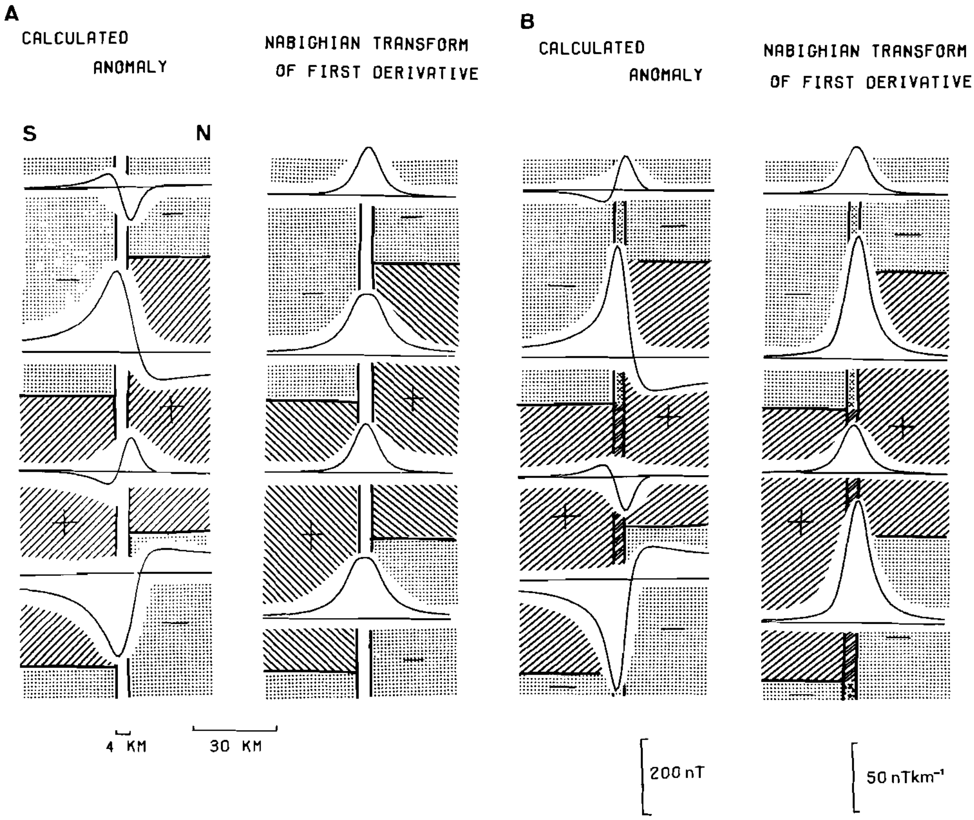


Fig. 2 *a) Calculated anomalies and the result of the Nabighian transformation over the four different magnetic contrasts that are conceivable over a fracture zone. A two-dimensional plane layer model was used with its upper and lower surfaces at depths of 5 and 6 km. In the fracture zone a zone of zero magnetization with a width of 4 km was assumed. The used parameter values for the ambient field and remanent magnetization vectors correspond to the position at* $13^{o}N/45^{o}W$ *at the Mid-Atlantic Ridge axis. In the frequency space a high pass filter was applied (by taking the first derivative) as well as a Gaussian low pass filter (cut-off wavelength 6 km). b) the same as Figure 2a, with the exception that the magnetization in the fracture zone was taken relatively enhanced corresponding in polarity with the crust bordering the fracture zone to the south. The intensity of the enhanced magnetization was taken as 10* Am^{-1} *against an intensity of normal oceanic crust of 5* Am^{-1}.

Analytic signal

In the CQZ the magnetic anomalies show an alignment along the fracture zone due to the fact that the CQ Period was a long normal period. In the Cenozoic sequence the crust bordering the fracture zone to both sides has alternately a normal and reversed magnetization leading to different end-effects of the magnetic layer along the fracture zone. A large variation of the type of anomaly is the result and no proper alignment is observed. This makes it difficult to recognize the fracture zones from the magnetic profiles outside the CQZ. We try to solve this problem by a transformation taking the absolute value of the analytic signal (Nabighian, 1972). Figures 2a and 2b illustrate this transformation for two-dimensional horizontal plane layer models. The transformation was applied to the calculated anomalies over the four different magnetic contrasts that are conceivable over a fracture zone. In addition to the end-effects of the magnetic layer, the fz anomalies are influenced by the finite width of the fracture zone; the magnetization of this zone can be enhanced or reduced (see Chapter IV). In Figure 2a a zone of zero (or reduced) magnetization with a width of 4 km was assumed. In Figure 2b the magnetization in this zone was made relatively enhanced and the polarity was taken as corresponding to the polarity of the crust bordering the fracture zone to the south. The anomalies were calculated for the position at 13^{o} N/45^{o} W at the Mid-Atlantic Ridge axis. For the direction of the remanent magnetization a geocentric axial dipole field was used. The upper and lower surfaces of the magnetic layer were taken at depths of 5 and 6 km.

The resulting maxima over the calculated magnetic transitions align clearly along the fracture zone, both in the case of reduction and of enhancement of the magnetization in the fracture zone. Application of this transformation to the real profiles may help to recognize fracture zones from magnetics in the Cenozoic sequence. However, alignment along a fracture zone in reality will only be recognizable, if the magnetic contrasts along the fracture zone are sufficiently large and two-dimensional.

The depth of the magnetic layer also influences the amplitude of the Nabighian signal. Figure 3a shows the signal for different depths of the magnetic layer, both for a +/- and a +/0/+ magnetic contrast. The shallower the magnetic layer, the smaller is the width and the larger is the amplitude of the Nabighian signal. The ratio of the amplitudes of the Nabighian extrema over a magnetic contrast at dephts of 3, 4 and 5 km to the top of the layer is 2.2 : 1.3 : 1.0.

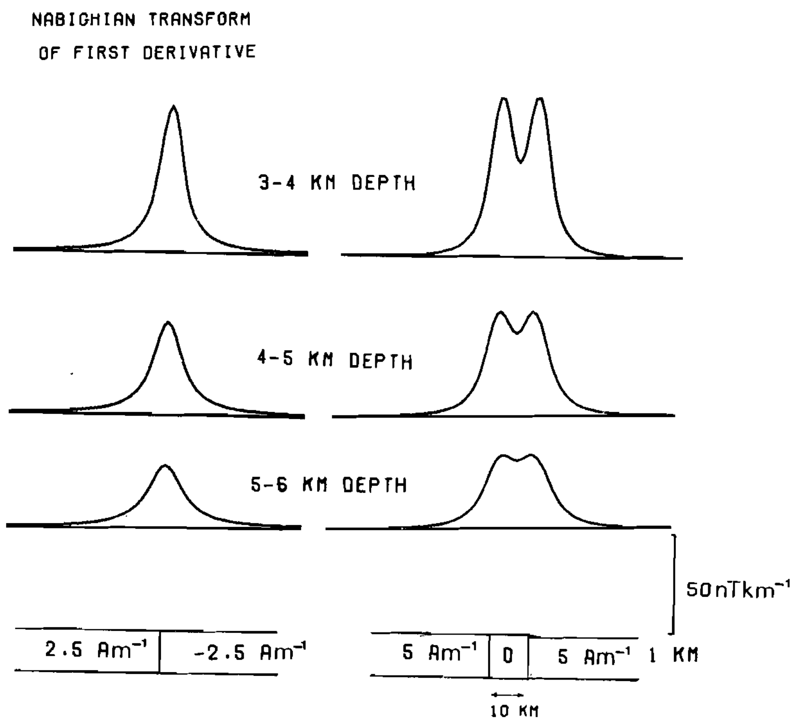


Fig. 3 *The result of the Nabighian transformation for different depths of a two-dimensional plane layer model, both for a +/- and a +/0/+ magnetic contrast.*

Identification of fracture zones between 11° and 24° N.

Figure 4 shows the seismic profiles along the NE-SW tracks in the area between 11° and 15° N, projected in a direction of 315°. The western limbs of several fracture zones can be clearly recognized as east-west topografic alignments. Figure 5 shows the magnetic anomalies along the tracks between 11° and 24° N plotted perpendicular to the track. The magnetic values were reduced by removal of the long wavelengths. The long wavelengths were determined by using a low-pass Butterworth filter (low cut-off wavelength 185 km, filter steepness 24 dB/octave; see Slootweg, 1978). The fracture zones are accompanied by large magnetic anomalies. The type of anomaly varies due to the different end-effects as mentioned above. Schouten (1971, figure 5) showed that the anomaly of a linear east-west magnetic contrast is near unit amplitude at any latitude along the Ridge axis, whereas the anomaly of a north-south magnetic contrast is zero at the magnetic equator. At this latitude the normal spreading anomalies, azimuth 0° to 20°, are small. This is one of the reasons why the fracture zone anomalies dominate the magnetic pattern off the Ridge. For a two-dimensional plane layer model of constant thickness and uniform magnetization we calculated the amplitude ratio of an E-W to a N-S striking magnetic contrast at several geographic positions in the area. The results gave a ratio respectively of 2.2 for the position at 20° N at the Ridge axis, of 2.9 for 13° N at the Ridge axis and 7.9 for 13° N/53° W in the southwestern part of the area. For the first two positions the geocentric axial dipole field was used for the direction of magnetization. For the third position we have to use the axial dipole field through the Early Tertiary pole for the American plate, for which we took the corresponding pole of Van der Voo and French (1974). To the SW the spreading anomalies thus become increasingly smaller with respect to the fracture zone anomalies.

Nabighian Transformation

Figure 6 shows the result of the Nabighian transformation on the NE-SW magnetic profiles between 11° and 24° N as well as on the profiles of HNethMS Luymes and R.V. Knorr, projected in a direction of 270°. An offset of 15 nT.km^{-1}

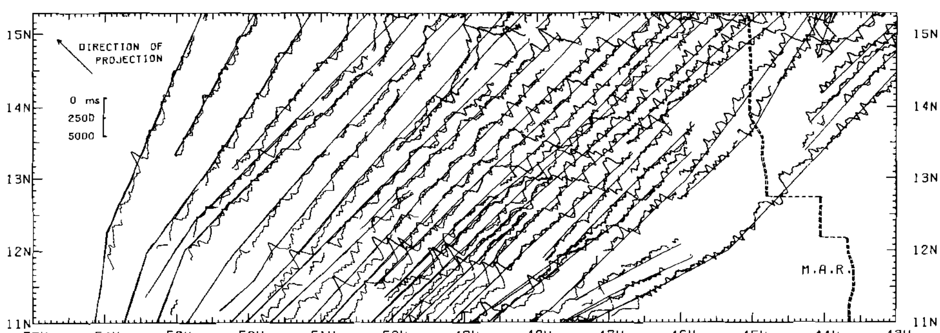


Fig. 4 Seismic reflection profiles along KROONVLAG-tracks between 11° and 15°N. The profiles have been projected in a direction of 315° with regard to a depth of 5000 ms (3750 meter). Fracture zones running about east-west in this area can be clearly recognized.

was given with respect to the trackline. Values larger than 15 $nT.km^{-1}$ are shown in black. Values above 63 $nT.km^{-1}$ were clipped to increase the readibility of the figure. In applying the Nabighian transformation the data were processed in sections of 240 minute values; 50 adjacent minute values were added on either side of the section to avoid disturbances of the section by FFT end-effects. Before the application of FFT the data were projected on the meridian and made equidistant (distances between 250 and 350 meter depending on ship's speed). A Gaussian filter (cut-off wavelength 6 km) and the first derivative filter were applied in the frequency domain. Afterwards, the results of the Nabighian transformation were brought back to the track positions. Artifacts due to digitizing errors and sharp changes of course of the ship were eliminated by hand.

The resulting extrema clearly show alignments in E-W direction. Several fracture zones come out already at a first inspection. As could be expected, the extrema over fz contrasts are larger than over spreading anomaly contrasts. A factor which also contributes to this is that the fracture zones are often crossed not exactly under 45^{o}, but at a larger angle, and the spreading anomalies at a smaller angle. The increase of the amplitude ratio of fz anomalies to spreading anomalies to the SW can be recognized from the better recognition of the fracture zones to the SW.

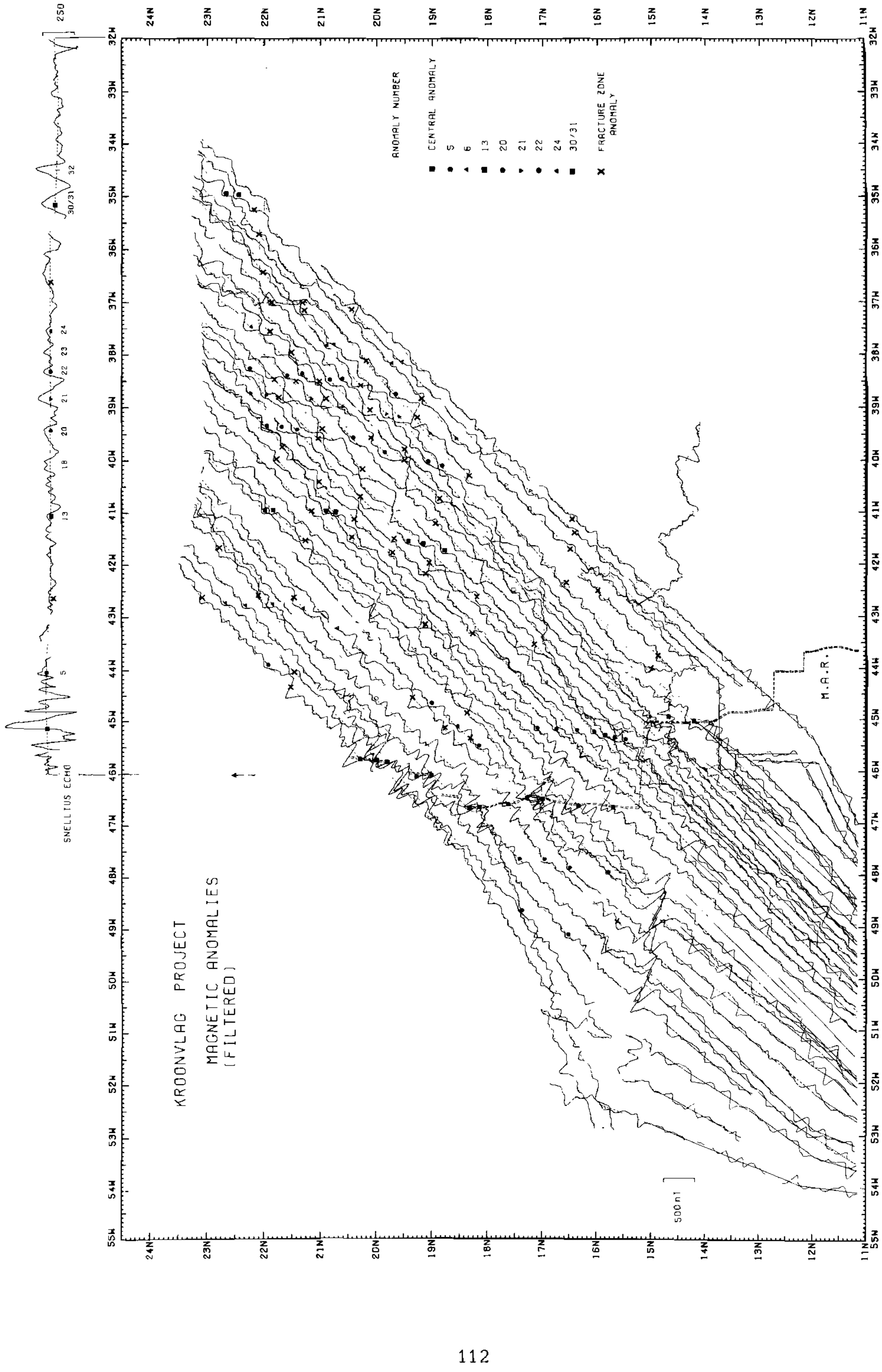
At places very large amplitudes of the Nabighian signal occur. First of all over the Mid-Atlantic Ridge axis, where we are dealing with spreading anomalies. The sinistral offset over the Fifteen Twenty FZ and the slowly bending to the east of the Ridge axis N of this fracture zone can be clearly recognized. The amplitude of the Nabighian signal decreases rapidly from the Ridge axis. However, from dredged samples in the FAMOUS area it was found that this reduction already takes place within 10 km of the Ridge axis (Johnson and Atwater, 1977). A second effect is the increase of basement depth to the ridge flanks. Between 12^{o} and 18^{o}N this depth increases from 2500 meter on the walls of the median valley to 3500-4000 meter at about 60 km distance from the median valley (see Collette et al., 1980, figure 3). Such an increase in depth can only explain a decrease of the signal by a factor of two, which is less than the observed decrease of the signal. A further effect might be an increase of the width of the magnetic polarity transition zones with oceanic crustal age as found by Blakely (1976). Very large amplitudes of the Nabighian signal also occur over the Researcher Ridge, from 14^{o}N/48^{o}W to 15^{o}N/51^{o}30'W, a structure which was first described by Peter et al. (1973). The Researcher Ridge, presumably a younger volcanic structure, is associated with very large and sharp anomalies.

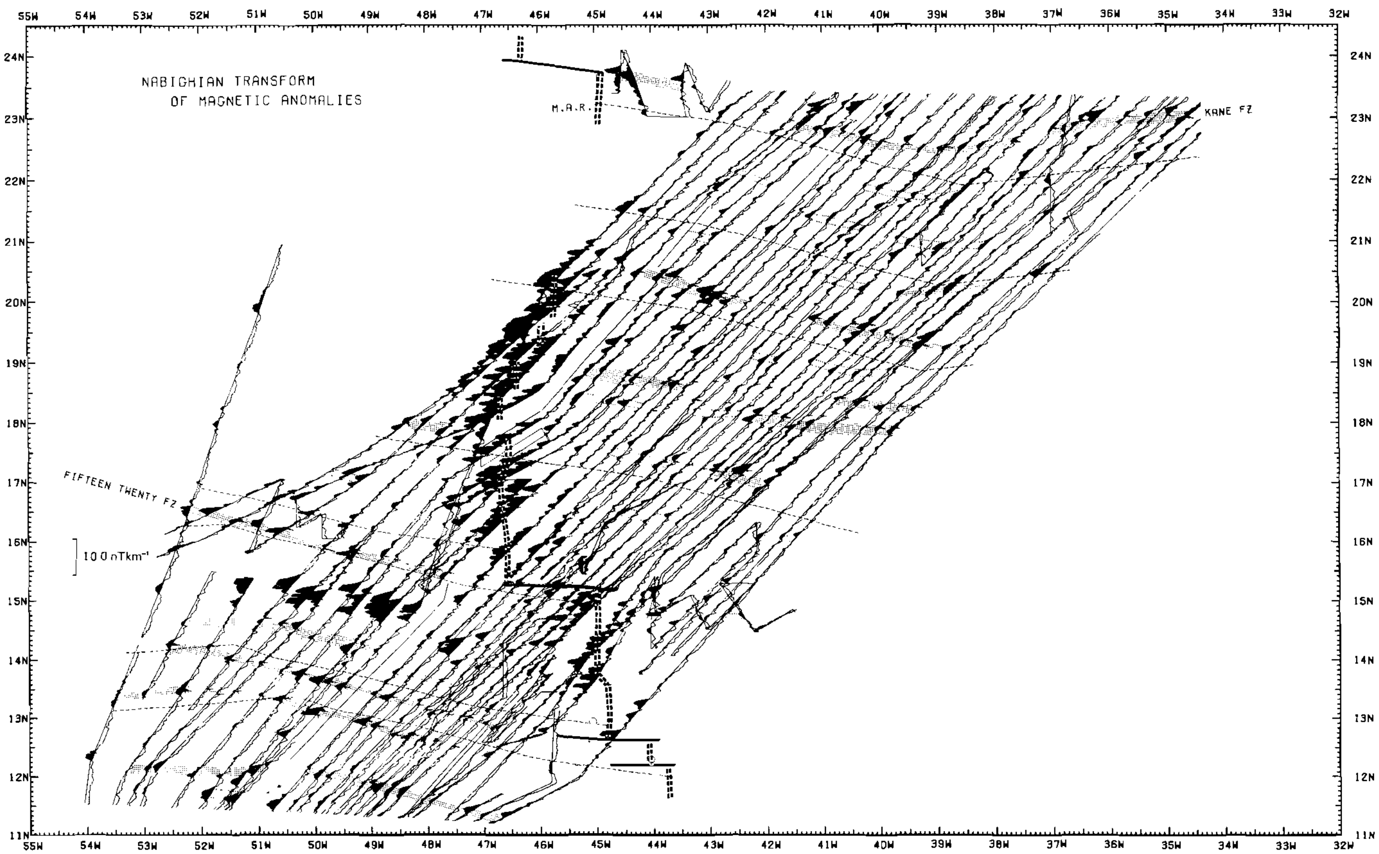
Clearly recognizable segments of fracture zones are indicated in Figure 6 by dotted zones. For labeling these identifications as reliable the criterion was used that four Nabighian maxima align roughly in an E-W direction, with at least three of them having a large amplitude with respect to the surroundings. The segments of fracture zones identified in this way were compared with synthetic flowlines, indicated by dashes in Figure 6. For these flowlines the preliminary total spreading poles of Schouten (in preparation) were used. Finite difference poles were derived for the African and American plate using the formulas of Phillips and Forsyth (1972). In addition, the rotation between anomaly 19 and 24 was decomposed into two rotations to get a better fit to the directions of fracture zones in this area.

According to the theorem of Morgan (1968), transform sections of fracture zones and hence their fossil sections are situated on small circles. The synthetic flowlines fit the fracture zones in this area only within certain limits. For example, the flowline that coincides with the 12°40'N FZ at 53°W reaches the Ridge axis 30 km north of the transform fault of this fracture zone. The degree to which the total fossil trace of a fracture zone fits an individual flowline will be determined by the reaction of a fracture zone to direction changes. The finite offset of a fracture zone will lead to a complication of

Fig. 5 *Magnetic anomalies along KROONVLAG-tracks between 11° and 24°N, plotted perpendicular to the tracks. Long wavelengths were reduced by using a low pass filter (cut-off wavelength 185 km). Crosses indicate sharp gradient magnetic anomalies that interrupt N-S spreading lineations and that were identified as fz effects. After having identified the fracture zones in this area spreading anomalies were identified in between. The top of the figure shows the anomaly identification on the east-west profile of HNethMS Snellius, line Echo, at 22°N.* →

Fig. 6 *The result of the Nabighian transformation on the KROONVLAG magnetic profiles and several other profiles between 11° and 24°N, projected in a direction of 270°. The offset with respect to the trackline is 15 nT.km^{-1}. Black areas denote values larger than 15 nT.km^{-1}. Values above 63 nT.km^{-1} were clipped. Fracture zones can be recognized as roughly east-west alignments of the resulting maxima. Dotted zones indicate clearly recognizable segments of fracture zones. Dashes indicate synthetic flowlines. Less certain traces of fracture zones that fit the synthetic flowlines have been indicated by dotted lines.* →→


KROONVLAG PROJECT
MAGNETIC ANOMALIES
(FILTERED)
ANOMALY NUMBER
CENTRAL ANOMALY
5
6
13
20
21
22
24
30/31
FRACTURE ZONE ANOMALY
SNELLIUS ECHO
250 nT
500 nT
M.A.R.


NABIGHIAN TRANSFORM
OF MAGNETIC ANOMALIES
M.A.R.
KANE FZ
FIFTEEN TWENTY FZ
100 nTkm^{-1}
55W 54W 53W 52W 51W 50W 49W 48W 47W 46W 45W 44W 43W 42W 41W 40W 39W 38W 37W 36W 35W 34W 33W 32W
24N 23N 22N 21N 20N 19N 18N 17N 16N 15N 14N 13N 12N 11N

the fossil trace. This is geometrically expressed by the circumstance that the flowline rotated from the western transform fault / Ridge axis intersection differs from the flowline rotated from the eastern intersection. Since from the magnetic anomalies the position of a change of the fz azimuth can be localized only roughly, we refrain from a further study of this point.

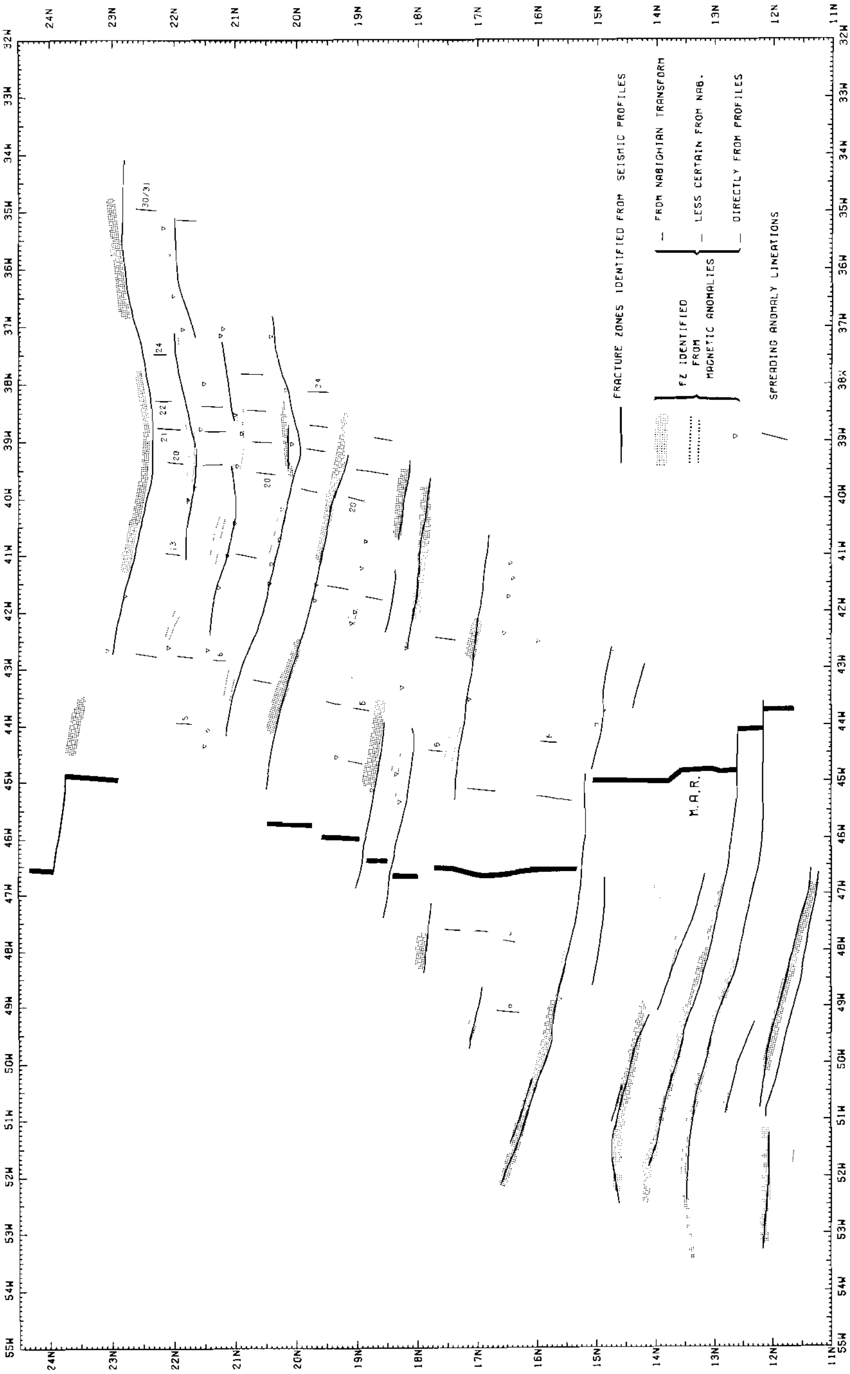
Subsequently, less certain traces of fracture zones were identified that fit the synthetic flowlines. They are indicated by dotted lines in Figure 6.

Spreading lineations of magnetic anomalies

In general, it is also possible to recognize fracture zones directly from interruptions of N-S spreading lineations in the magnetic profiles. N of the Fifteen Twenty FZ the amplitude of spreading anomalies is larger. However, the mutual track distance generally is too large for the recognition of N-S alignments from the magnetic profiles, especially if the distance between fracture zones is less than about 100 km. In places N of 20^{o}N, N-S lineations could be recognized and where the lineations are disturbed by steep gradient magnetic anomalies, these anomalies were identified as fracture zone effects (indicated by crosses in Figure 5).

Figure 7 compares the fracture zones identified from the magnetic anomalies with the fracture zones identified from the seismic profiles. The solid line indicates the southern slope of the topographic expression of a fracture zone (Collette, 1980). The overall coincidence of both identifications is good. At some places magnetics give indications (all of the category 'less certain') for the presence of fracture zones that were not recognized from the seismic profiles. Magnetically only segments of fracture zones could be identified, whereas the topographic expression of a fracture zone is only seldom interrupted. Places where the magnetic expression of a fracture zone is poor also occur along fracture zones with a large offset, such as along the Kane FZ

Fig. 7 Comparison of fracture zones identified from the seismic profiles with those identified from magnetics in Figure 6. The solid lines indicate the southern slope of the topographic expression of the fracture zone. Triangles indicate fz anomalies identified in Figure 5. N-S lineations are the anomaly identifications from Figure 5. The position of the Ridge axis between 12^{o} *and* 18^{o}*N is from detailed surveys over the Ridge axis and between* 18^{o} *and* 20^{o}*N from the KROONVLAG-profiles.*


FRACTURE ZONES IDENTIFIED FROM SEISMIC PROFILES
FZ IDENTIFIED FROM MAGNETIC ANOMALIES
FROM NABIGHIAN TRANSFORM
LESS CERTAIN FROM NAB.
DIRECTLY FROM PROFILES
SPREADING ANOMALY LINEATIONS
M.A.R.

between 47° and 49°W and the Fifteen Twenty FZ between 41° and 43°W. This indicates that the absence of a magnetic expression does not mean that the fracture zone is absent or that the offset is only small.

Variation of the amplitude of the magnetic expression along the fz axis.

While in places the amplitude of the Nabighian signal along the fracture zone is almost zero, large amplitudes of the signal occur at other places. This variation of the Nabighian amplitude along the fracture zone axis, such as along the $12^{\circ}10$'N and the $12^{\circ}40$'N FZ, cannot be attributed to a variation of the amplitude coefficient along the fracture zone. This coefficient is 0.76 to 0.63 for a variation in strike from 95° to 105° at 13°N at the Ridge axis, and it is 0.90 to 0.81 for a same variation in strike at 13°N/53°W. An explanation might be that the fracture zone contrasts are sufficiently two-dimensional only in places, whereas elsewhere the magnetic contrasts are more three-dimensional leading to a reduction of the Nabighian signal. However, this does not explain a further observation, viz. that large and small amplitudes of the Nabighian signal seem to coincide with specific direction changes. To show this, several traces of fracture zones were aligned along the spreading axis (Figure 8). The fracture zones involved are the $12^{\circ}10$'N FZ, the $12^{\circ}40$'N FZ, the Fifteen Twenty FZ, a fracture zone that intersects the Ridge axis at about $20^{\circ}55$'N, and the Kane FZ. The traces of the latter two fracture zones, which are from the African plate, have been rotated 180 degrees in order to compare them with those on the American plate. For a better illustration of changes of the fz azimuth, the positions of the deepest points of the fz valleys have been indicated by dashes. From a careful consideration of Figure 8, it follows that the large amplitudes of the Nabighian signal coincide with clockwise direction changes of sea floor spreading and the small amplitudes with anti-clockwise direction changes.

All fracture zones of Figure 8 have sinistral offsets. This means that at a clockwise direction change these fracture zones undergo compression and at an anti-clockwise direction change they undergo tension (which is equivalent to a dextral offset fracture zone at a clockwise direction change), (see Chapter III, figure 14). Since direction changes are known to be accompanied by a narrowing or widening of the fracture zone (Chapter III), we investigated whether such effects might possibly be the cause of the variations of the amplitude of the Nabighian signal. In Figure 9 the Nabighian signal was calculated for different widths of the zone of enhanced magnetization in the fracture zone.

We recall that sinistral offset fracture zones in this area have been found to be associated with a relatively enhanced magnetization in the fracture zone (Chapter IV). All parameters are the same as in Figure 2b with the exception of the width of the fracture zone. The calculations show that a widening of the enhanced zone does not lead to higher or lower amplitudes of the Nabighian signal, only to a doubling of the Nabighian extrema.

A better and more interesting explanation for the variation of the ampli-

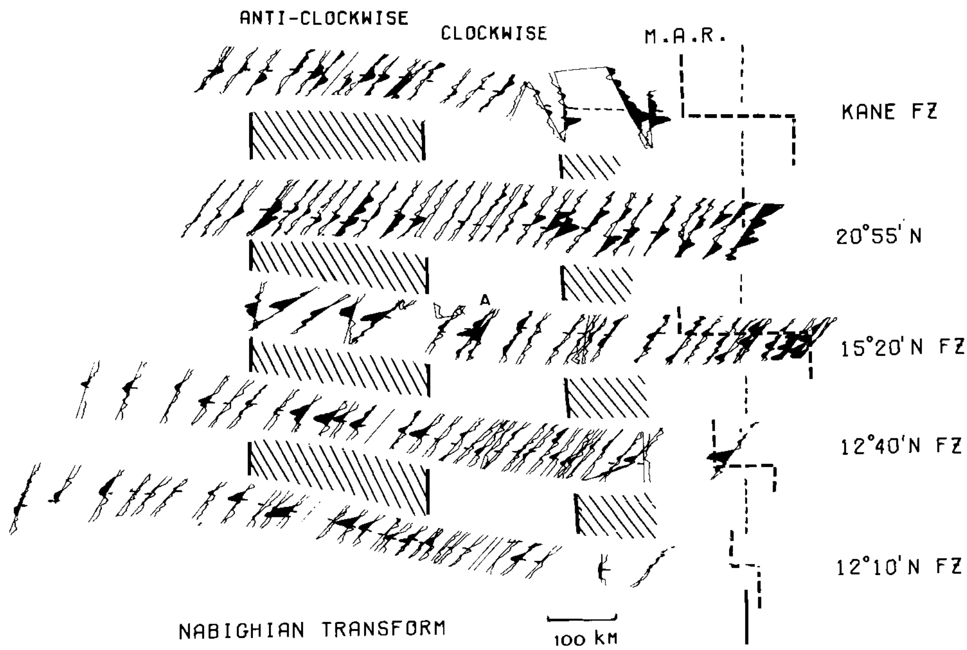


Fig. 8 Traces of fracture zones from Figure 6 aligned along the spreading axis. The traces of the upper two fracture zones, which are from the African plate, have been rotated in order to compare them with those on the African plate. Dashes indicate the position of the deepest points of the fz valleys. The segments of the fracture zones with larger and smaller amplitudes of the Nabighian signal seem to coincide with respectively clockwise and anti-clockwise direction changes of sea floor spreading. The large Nabighian marked A seems related to the nearby presence of Royal Trough (Collette et al., 1974), a structure which is not yet understood.

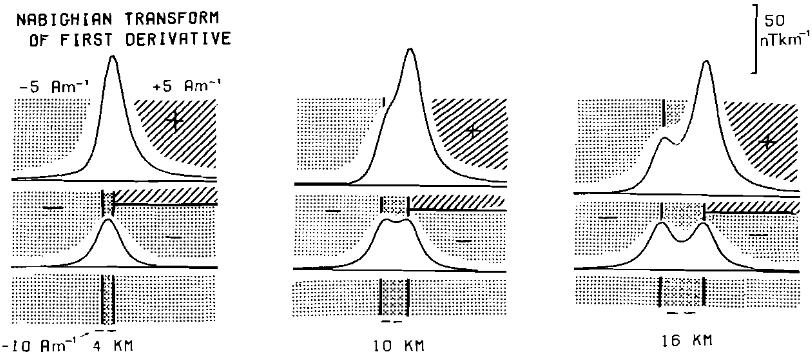


Fig. 9 *The result of the Nabighian transformation calculated for different widths of the zone of enhanced magnetization in the fracture zone. With the exception of the width of the fracture zone all parameters are the same as in Figure 2b.*

tude of the Nabighian signal is to assume a variation of the intensity of magnetization in the fracture zone. Since the amplitude of the Nabighian signal (if it is double peaked we mean the largest extreme) is proportional to the magnitude of the magnetization contrast along the fracture zone, variation of the intensity indeed results in a large variation of the amplitude of the Nabighian signal. In Chapter IV the hypothesis was formulated that the difference in magnetization in fracture zones is due to the effect of stress in the transform domain of the fracture zone. It may be imagined that with a clockwise direction change, when the compression in the transform domain increases, the stress influence on the magnetization increases too, and that with an anticlockwise direction change the stress influence decreases or even results in reduction.

Large variations of the amplitude of the Nabighian signal also occur along the Kane FZ and along other fracture zones farther N in the CQZ on the African plate (Chapter III, figure 5 and Chapter IV, figure 2). Figure 10a shows the result of the Nabighian transformation on magnetic profiles over the sinistral offset Kane FZ and over a dextral offset fracture zone N of the Kane FZ, in the CQZ immediately east of anomaly 34. Both fracture zones were aligned along the intersection with the anomaly 34 isochron (indicated by diamonds). As discussed in Chapter III several changes of spreading direction could be recognized in the CQZ from the fossil trace of the Kane FZ, e.g. a clockwise direction change at

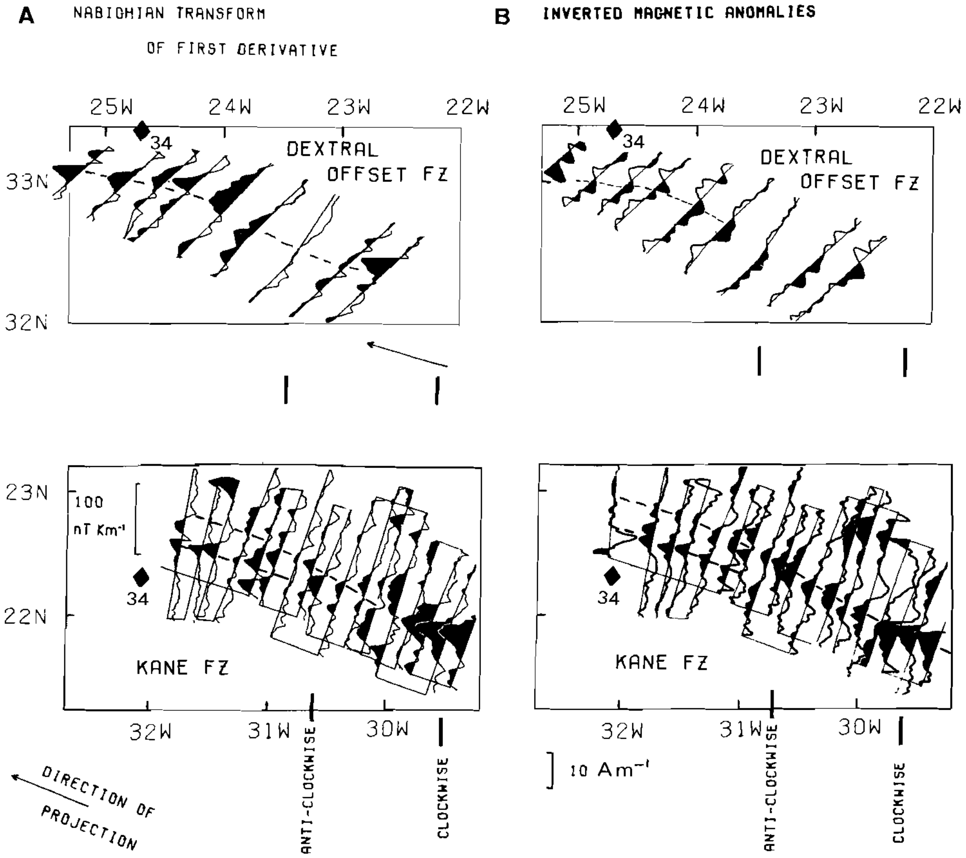


Fig. 10 a) The result of the Nabighian transformation on magnetic profiles over a dextral offset fracture zone at 33°N and over the Kane FZ, in the CQZ on the African plate immediately east of anomaly 34 (indicated by diamonds). The results were aligned along the intersection with anomaly 34. Black areas denote values larger than 15 nT.km^{-1}. b) The results of linear inversion of the magnetic profiles, plotted perpendicular to track. The level of each profile is arbitrary. For a better presentation of the magnetization in the fracture zone, black areas denote negative values in the case of the fracture zone at 33°N and positive values in the case of the Kane FZ. Dashes indicate the fz axis, as recognized from seismic profiles.

$29^{o}30$'W and an anti-clockwise change at 31^{o}W. The clockwise change corresponds to compression in the transform domain of the Kane FZ and the anti-clockwise change to tension. For the dextral offset fracture zone the changes that correspond with the two direction changes above occur at 22^{o}W and at $23^{o}40$'W. For this fracture zone the relation is just reversed: the clockwise direction change at 22^{o}W corresponds to tension and the anti-clockwise change at $23^{o}40$'W corresponds to compression. From Figure 10a we see that at the 'compressional' direction changes the amplitudes of the Nabighian extrema are large and that at the 'tensional' direction changes the amplitudes are lower. For the dextral offset fracture zone the 'tensional' direction change at 22^{o}W cannot be observed, since the profiles do not go far enough to the W.

Since we are in the CQZ, the variation of the Nabighian signal can be compared with the inverted anomalies. The crust on both sides of the fracture zone is normally magnetized and the inverted anomalies show the variation of the zone with anomalous magnetization in the fracture zone (Figure 10b); the Kane FZ has a zone with enhanced magnetization and the dextral offset fracture zone has a zone with reduced magnetization. Although the Kane FZ has an enhanced magnetization over the total width of the CQZ (see also Chapter III, figure 4), this magnetization is very high in intensity at the clockwise (= compression) direction change at $29^{o}30$'W and is much lower in intensity at the anti-clockwise (= tension) change at 31^{o}W. In the case of the dextral offset fracture zone the situation is less clear. The anti-clockwise (= compression) direction change at $23^{o}40$'W may or may not be accompanied by an increase of the difference in magnetization in the fracture zone. Further investigations will be necessary. In addition to these variations in intensity, for the Kane FZ the suggestion exists that the magnetic contrasts at the 'compressional' direction change at $29^{o}30$'W are sharper than at the 'tensional' direction change at 31^{o}W. (Sharper contrasts lead to a higher amplitude of the Nabighian signal, cf. Chapter III, figure 9.) The variation of the Nabighian signal can thus be explained by a combination of a variation in the intensity of the anomalous magnetization within the fracture zone and in the sharpness of the magnetic contrasts.

In conclusion, it can be said that changes of spreading direction seem to lead to a variation of the intensity of magnetization in the fracture zone. A direction change that leads to an increase of compression in the transform domain may result in a greater difference in magnetization. Conversely a direction change that leads to tension in the transform domain, may result in a smaller difference in magnetization. In addition, these direction changes may lead to a variation in the sharpness of the magnetic contrasts along the fracture zone. The higher and lower amplitudes of the Nabighian signal along the fracture zone can be explained by these variations.

Identifications of spreading anomalies

Having identified the traces of fracture zones, we tried to identify the magnetic anomalies in between with the magnetic reversal time scale (see Figure 5). S of the Fifteen Twenty FZ the anomalies between the fracture zones are of too low amplitude for the identifications of spreading anomalies along tracks that are not carefully arranged to be parallel to fracture zones. In this area sequences of spreading anomalies were identified by Peter et al. (1973) between 12°-18°N, 44°-56°W on a number of east-west tracks. Their spreading anomaly sequences frequently cross the fracture zones and most of the proposed anomaly identifications are actually fz anomalies.

N of the Fifteen Twenty FZ the amplitude of spreading anomalies is higher. At several places it was possible to identify spreading anomalies in between the fracture zones; in particular the anomaly sequence 20 to 24 (45 to 56 mybp, according to LaBrecque et al., 1977) could be recognized. The identification is sustained and illustrated by the anomaly identification on the east-west profile of HNethMS Snellius at 22°N (line Echo; Anonymous, 1967) which has been plotted at the top of Figure 5. Although this profile is east-west, it nevertheless crosses a fracture zone at several places. An identification of spreading anomalies in this area has been given earlier by Pitman and Talwani (1972) and later by Uchupi et al. (1976, figure 12). A number of the anomalies identified by these authors as spreading anomalies appear to be situated across fracture zones and are fz anomalies.

The anomaly identifications of Figure 5 have been reproduced in Figure 7.

Conclusions

Summarizing it can be said that, at this low magnetic latitude, magnetic anomalies are of great value for the identification of fracture zones and as such confirm and supplement identifications of fracture zones from seismic profiles. Outside the CQZ the identification of fracture zones from magnetic profiles is hindered by the variation of the type of anomaly along the fz axis and, if the tracks are not perpendicular to the fracture axes, by the presence of spreading anomalies on the profiles. Application of a transformation taking the absolute value of the analytic signal eliminates this variation and helped to identify fracture zones from magnetic profiles in the central North Atlantic between 11° and 24°N. In addition to clearly recognizable fz traces, less clear traces are reported that fit synthetic flowlines.

The amplitude of the Nabighian signal shows a large variation along the fz axis, allowing identification only of segments of fracture zones from magnetics. In places a magnetic expression is not recognized, whereas the topographic expression is not interrupted. At other places large amplitudes of the Nabighian signal occur. The large and small amplitudes of the Nabighian signal seem to be related to direction changes, which lead to respectively compression and tension in the transform domain. In Chapter IV the hypothesis was formulated that the difference in magnetization in fracture zones is due to the effect of stress in the transform domain. At direction changes the following may happen. A direction change that leads to an increase of the compressive stress in the transform domain may result in a greater difference in magnetization in the fracture zone. Conversely, a direction change that leads to tension may result in a smaller difference in magnetization. In addition, these direction changes may lead to a variation of the sharpness of the magnetic contrasts along the fracture zone. The higher and lower amplitudes of the Nabighian signal along the fracture zone can be explained by these variations.

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