along the faults paralleling the earth field vector and have very little chance to concentrate on body corners to create anomalies. Reduction-to-the-pole filtering is an amplitude- and phase-changing operation that assumes nothing about depth, body shape, or altitude (but does assume a known remanence). The weak spots in the spectrum are boosted in amplitude by the RTP filter, presenting the most sensitive part of the operation. Because noise is present in any survey, boosting parts of the spectrum by factors of 4 to 50 or more when the signal-to-noise ratio is weak will cause the catastrophic artifact of north-south striping so common to many RTP algorithms. This problem can be avoided by limiting the amount of amplification.

An occasionally applied process of "reduction-to-the-equator" only worsens a bad anomaly distortion and should be avoided. Figure 3 is the block model at the magnetic equator. Low-cut filtering or reduction part of the way to the pole has been tried unsuccessfully. They leave the resulting grid, and certainly the eventual high-pass filtered displays, with incorrect and misleading anomalies.

Once the above approaches have been followed and the grid has been extended properly and filtered with an appropriate amount of whitening, how can the interpreter be sure the map is right? Although this question can be answered by applying the same operator to 3-D theoretical models with known geology, the fact that the question is so common underlies the need to improve and standardize the low-latitude RTP filter so potential-field experts and their geologic/geophysical customers can trust and use the results.

Interpretation of Magnetic Anomalies at Low Latitudes: Potential Pitfalls

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EDITOR'S NOTE: *Many people are "afraid" of magnetics because it seems complicated by inclination and declination effects. It is very important for the magnetics interpreter to understand what to expect for the geologic and geographic setting. This paper deals with pitfalls inherent to data coverage and inclination/declination effects. Often you cannot understand the tectonics from a casual glance at a magnetic map; analysis is mandatory.*

Abstract

The vector nature of the Earth's magnetic field dictates that interpreters must take care to understand pitfalls related to the orientation of the field (i.e., magnetic inclination and declination), and the relationship of the magnetic field to a region's geology. The case history presented here demonstrates one such pitfall. Present models for the formation of the Grenada Basin vary from north-south extension to northeast-southwest extension to east-west extension. Gridded magnetic anomalies over the basin provide a picture of the Earth's field that contributes to this spectrum of possible extensional origins.

The Grenada Basin is a back-arc basin located near the eastern edge of the Caribbean Plate. The basin is bounded on the east and west by the roughly north-south-trending active Lesser Antilles and remnant Aves Ridge Island Arcs, respectively. Although this physiography, as well as gravity data, supports formation by near east-west extension, magnetic anomalies over the basin exhibit predominantly east-west trends. The crust of the Grenada Basin and of other back-arc basins forms similarly to the crusts of ocean basins. If the observed magnetic anomalies over the basin are produced by sea-floor spreading, then the orientation of extension may be complex. Extension in most back-arc basins is roughly normal to their trenches and subduction zones, but some basins appear to exhibit oblique extension. A careful interpretation of magnetic profiles reveals low-amplitude magnetic anomaly trends, oriented subparallel to the island arc, over the southern part of the Grenada Basin, which supports a model for basin development by near east-west extension.

Introduction

Theories on the development of the Grenada Basin generally agree that it was formed by sea-floor spreading in early Cenozoic time (Bouysse, 1988; Boynton et al., 1979; Donnelly, 1975; Pindell and Dewey, 1982; Shurbet, 1976; Uyeda and Kanamori, 1979; Uyeda, 1982; and Westbrook, 1975). Late Tertiary tectonic forces caused the northern half of the Lesser Antilles Island Arc to bifurcate into an older outer arc and younger, inner arc. In general, back-arc basins are formed in response to a reorganization of tectonic plates. Extensional forces resulting from this reorganization can cause an island arc to split, followed by the accretion of back-arc crust by sea-floor spreading.

The direction of extension shown in existing models for the formation of the Grenada Basin varies from north-south (Pindell and Barrett, 1990) to northeast-southwest (Bouysse, 1988) to east-west (Tomblin, 1975). The eastern Caribbean Plate boundary between the North and South American Plates is a subduction zone that is oriented generally north-south (Figure 1). Similarly, the trends of the Aves Ridge, Grenada Basin, and Lesser Antilles region are oriented north-south. East-west extension is suggested by these trends (Tomblin, 1975). However, magnetic anomalies over the Grenada Basin exhibit predominantly east-west trends, suggesting that the basin may have formed by north-south extension (Figure 2).

Magnetic anomaly patterns over some of the world's back-arc basins are organized poorly, indicating changing patterns of sea-floor spreading; however, the patterns over other back-arc basins are well defined, indicating preferred directions of sea-floor spreading. A review of back-arc basins located along the west Pacific margin demonstrates this relationship (Weissel, 1981). The orientation of most linear anomaly trends over back-arc basins is generally subparallel to their associated subduction zones.

Tomblin (1975) describes a possible scenario for east-west extension that involves a shift of the Aves Ridge westward, relative to the subduction zone, with the formation and subsequent spreading from a north-south-oriented median ridge (Figure 3a). He reports that no such ridge has been observed.

Pindell and Barrett (1990) describe a model in which the Leeward Antilles have been coupled to the northern edge of the South American Plate (Figure 3b). North-south spreading in the Grenada Basin occurs as a result of oblique convergence with the South American Plate. In this model, the Leeward Antilles was part of the Aves Ridge prior to the formation of the basin and represents fragmentation of the arc as the Caribbean Plate progressed eastward. Pindell and Barrett (1990) suggest that the general east-west orientation (i.e., perpendicular to the island arc) of magnetic anomalies over the basin supports north-south extension.

Bouysse (1988) describes a possible mechanism for extension, similar to Pindell and Barrett's, in which coupling of the southern part of the Lesser Antilles with the South American Plate also precedes opening of the basin (Figure 3c); however, the mechanism of back-arc spreading in this model is similar to a mechanism described by Poehls (1978). Bouysse (1988) further suggests that sea-floor spreading in the Grenada Basin was oriented northeast-southwest at the onset of the Cenozoic, and was segmented in a manner such as described by Tamaki (1985) for the Sea of Japan Basin. Initial spreading was in the southernmost part of the basin, gradually progressing northward as the Caribbean Plate moved eastward between the North and South American Plates.

Data

The database for this study includes gridded gravity, bathymetry, and magnetic data as well as shipborne magnetic profiles. Gravity and total-intensity magnetic anomalies were compiled in 1987 by the Geological Society of America Decade of North American Geology (DNAG) Committees on the Magnetic and Gravity Anomaly Maps of North America, and were gridded at 6 and 2 km (Figures 4 and 2), respectively. Gridded bathymetry data were extracted from the ETOPO5 data set and regridded from 5 minutes to 9 km (Figure 5). Magnetic anomaly profile locations are shown in Figure 6. All data used in this study are available from the National Geophysical Data Center (NGDC).

The Pitfall

The shape of a magnetic anomaly depends on several factors, including magnetic inclination and declination, source-body geometry, and the orientation of the source body (Sharma, 1976). The following discussion assumes that source bodies are symmetric, have stronger magnetizations than surrounding media, and have no components of remanent magnetization. These assumptions are not necessarily exactly correct, but in the absence of evidence to the contrary, they are reasonable and typical of those made by interpreters in this kind of analysis.

At either magnetic pole, a magnetized source body will produce an anomaly high centered over it. At the magnetic equator, a source body will produce a symmetric anomaly low over it. Elsewhere in the world, a source body will produce an asymmetric high-low anomaly pair. The location of the source body beneath this anomaly pair depends on the magnetic inclination (or latitude). For example, if the source body is at 45° magnetic latitude, then the center of the body would be located beneath the inflection point between the high-low anomaly pair. This anomaly would shift toward an anomaly low over the source as the latitude decreases from 45°, and would shift toward an anomaly high as the latitude increases from 45°. In the northern magnetic hemisphere, the "high" part of the high-low pair is located south of the "low" part, and in the southern magnetic hemisphere, it is located north of the "low" part. Note that magnetic latitude is not coincident with geographic latitude, except in a general way.

The relationship between magnetic inclination and source body is complicated further by source-body geometry and orientation. To illustrate this dependence, four profiles have been calculated, using two geomagnetic inclinations and two strike directions for a 2-D model (Figure 7). Most plate reconstructions place the leading edge of the Caribbean plate at approximately 12° latitude at the time the Grenada Basin formed (Duncan and Hargraves, 1984; Ghosh et al., 1984; Pindell et al., 1988; Ross and Scotese, 1988). To simulate a remanent inclination and, it is hoped, to resolve anomalies produced by this remanent field, a paleomagnetic inclination of 23° is calculated (Sharma, 1976). Present magnetic inclination in the Grenada Basin is 43°. Two profiles were oriented

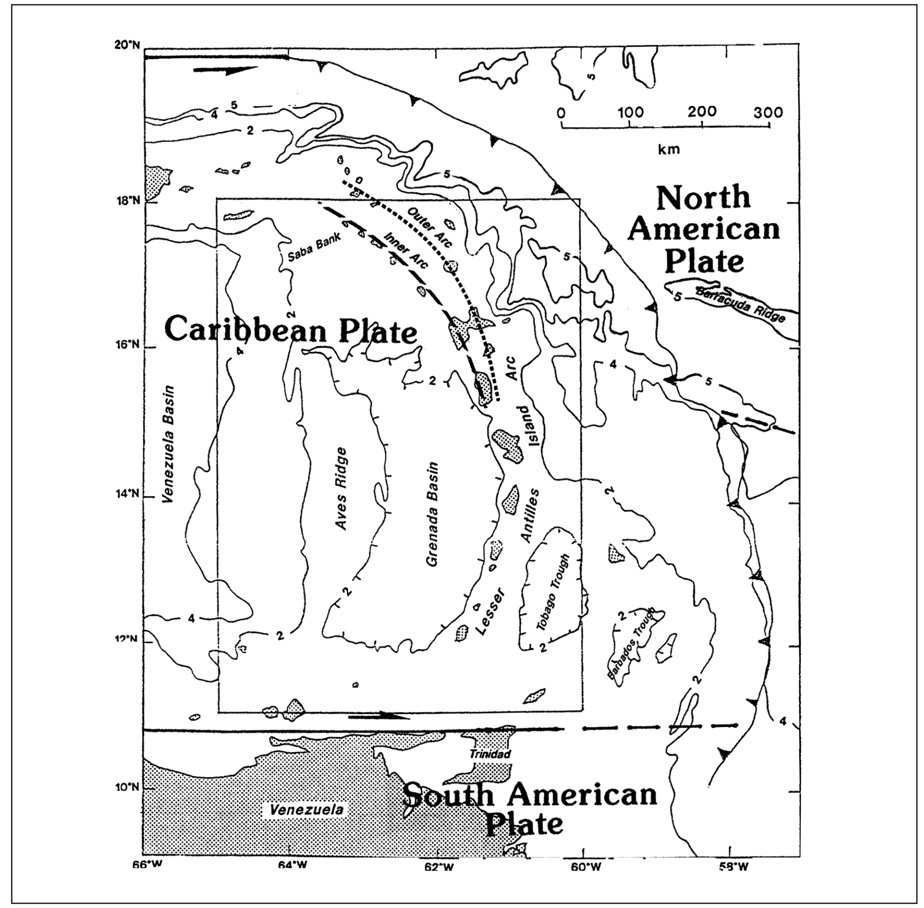

Figure 1. Physiography of the eastern Caribbean with 2-, 4-, and 5-km isobaths contoured (after Bouysse, 1984). The outline of the study area, trace of the subduction zone, and strike-slip fault zones which define the North American/Caribbean and South American/Caribbean Plate boundaries are displayed. Heavy dashed lines indicate probable locations for plate boundaries. The inner and outer arcs are represented by dashed and dotted lines, respectively.

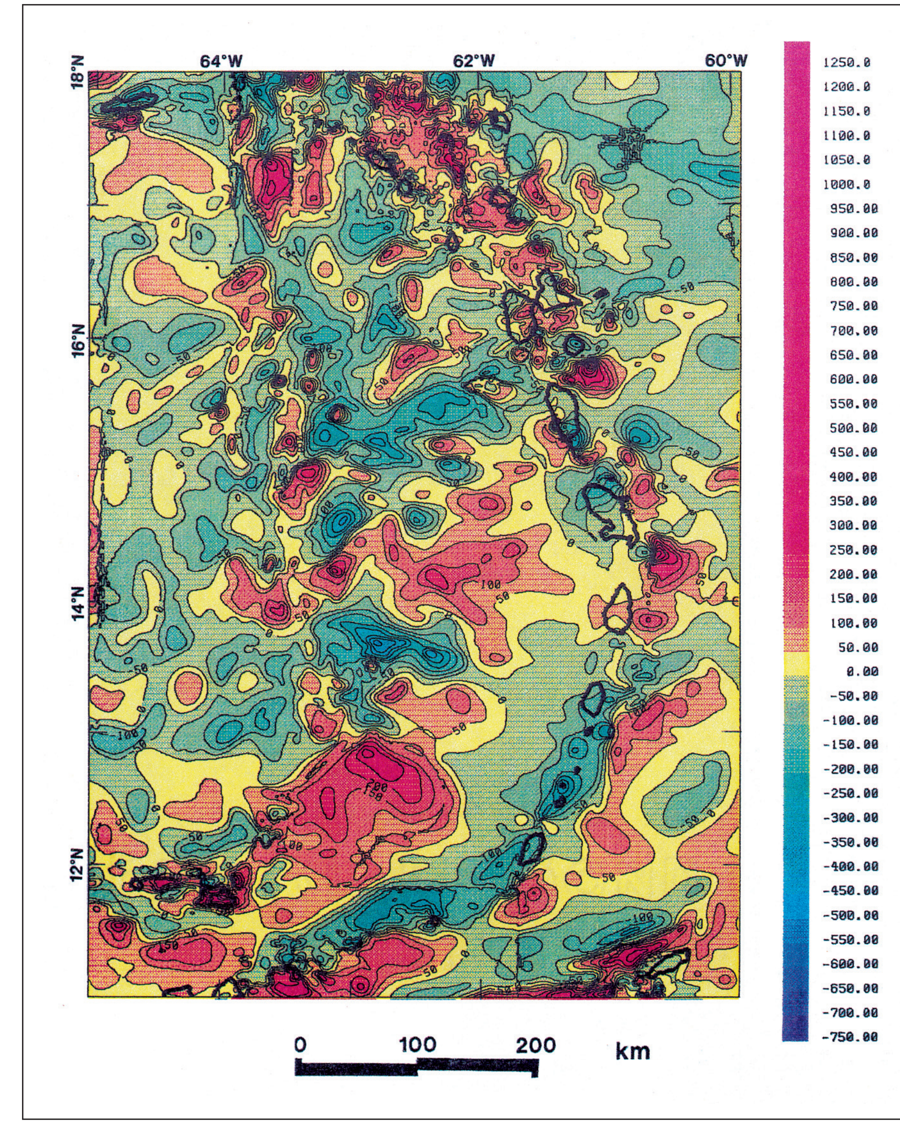

Figure 2. Total-intensity magnetic anomalies over the study area. The contour interval is 50 nT. Gridded data (2 km) were compiled in 1987 by the Geological Society of America Decade of North American Geology Committee on the Magnetic Anomaly Map of North America.

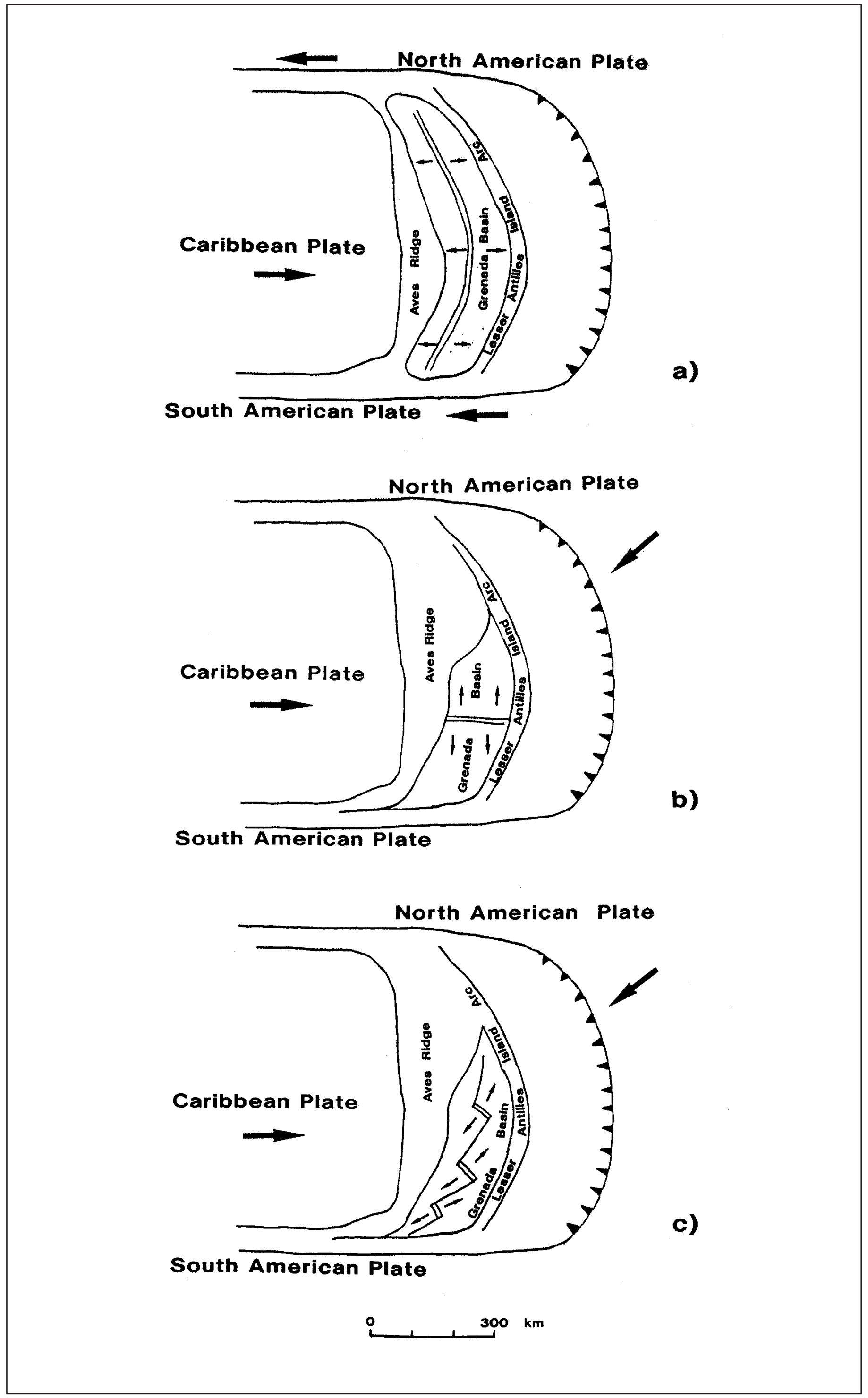

Figure 3. *(a) Possible east-west extension caused by a westward shift of the Aves Ridge for the opening of the Grenada Basin, as proposed by Tomblin (1975). Large arrows indicate the relative motions of the North American, Caribbean, and South American Plates. Small arrows indicate the directions of extension for the formation of the basin. (b) Possible north-south extension for the opening of the basin, as proposed by Pindell and Barrett (1990). (c) Possible northeast-southwest extension for the opening of the basin, as proposed by Bouysse (1988).*

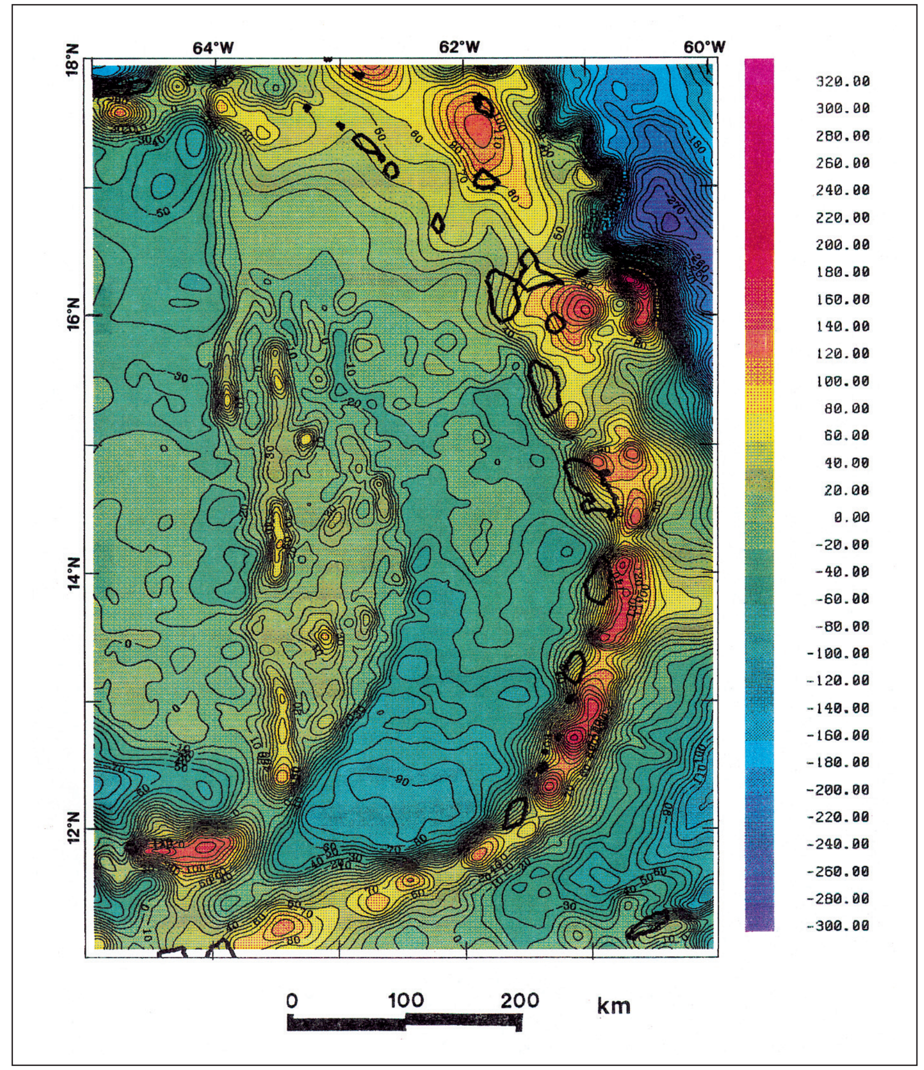

Figure 4. *Free-air gravity anomalies over the study area. The contour interval is 10 mGal. Gridded data (6 km) were compiled in 1987 by the Geological Society of America Decade of North American Geology Committee on the Gravity Map of North America.*

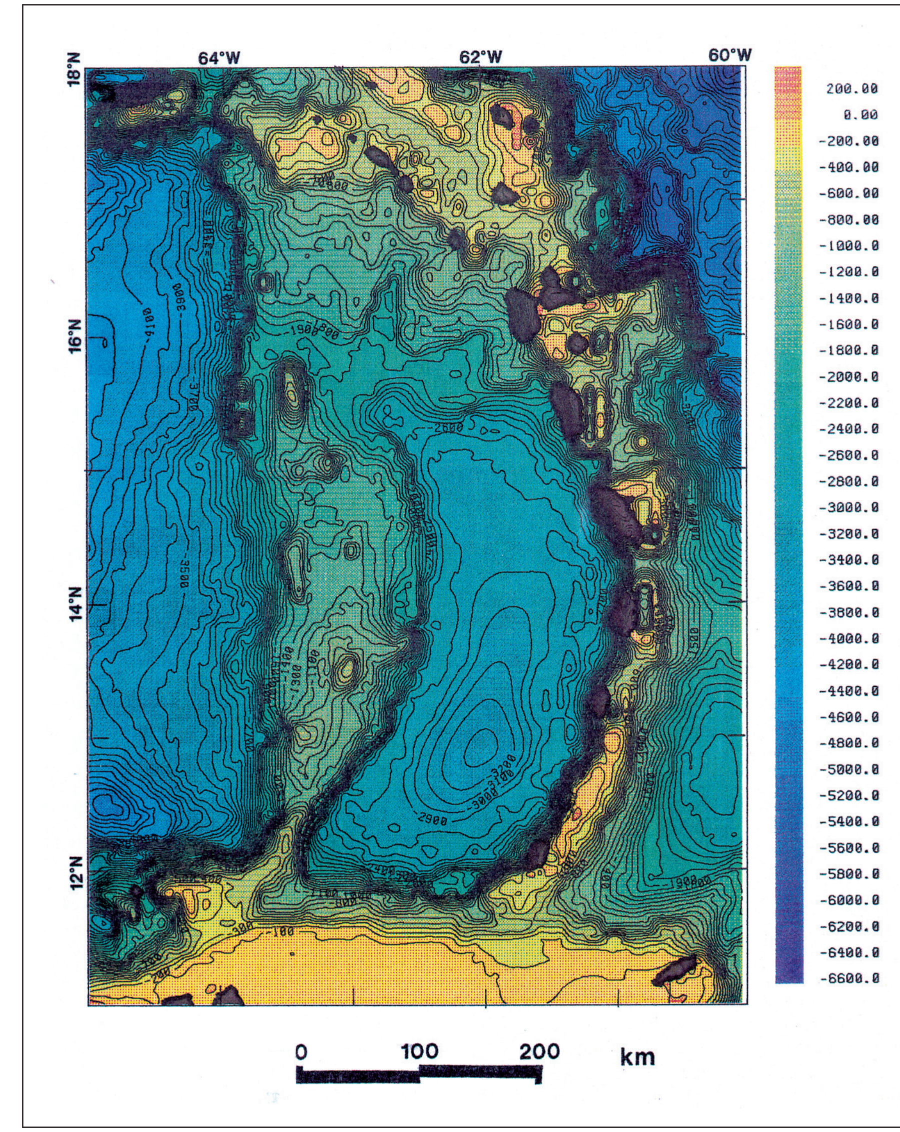

Figure 5. *Bathymetry of the study area. The contour interval is 100 m. Gridded data (5 minute) were compiled by Lamont-Doherty Geological Observatory of Columbia University.*

south-north over an east-west-trending body, and the other two were oriented west-east over a north-south-trending body.

Using an inclination of 43°, calculated amplitudes decrease about 57% (from about 300 to 130 nT) from south-north to west-east. A more dramatic decrease, and more important to this study, is observed from south-north to west-east calculations using a 23° inclination. The decrease in amplitude is about 86% (from about 290 to 40 nT).

Interpretation

Figure 8 displays selected magnetic anomaly profiles over the southern part of the basin, with some of the major anomaly trends indicated. Note that trends, although discontinuous, are oriented generally north-south, or subparallel to the island arc and the trench line of the subduction zone. Anomalies correlated from the observed magnetic profile data over the southern part of the basin exhibit amplitudes near 40 nT. There does not appear to be structural relief on the acoustic basement surface which would produce these anomalies (Speed et al., 1984). Furthermore, in this comparison of relative anomaly amplitudes, the smaller amplitude over a north-south-oriented body suggests that magnetization of the body is caused primarily by the hypothetical remanent field (or 23° inclination). That is because any effect of the inducing field would only increase the

Figure 6. Shipboard magnetics data coverage for the study area. Anomaly profiles for west-northwest-oriented ship tracks outlined by the dashed box are displayed in Figure 8.

amplitude, because the north-south-oriented body produces a larger-amplitude anomaly at 43° magnetic inclination. The effect of magnetization contrasts caused by geomagnetic polarity reversals also increases the relative amplitude of anomalies.

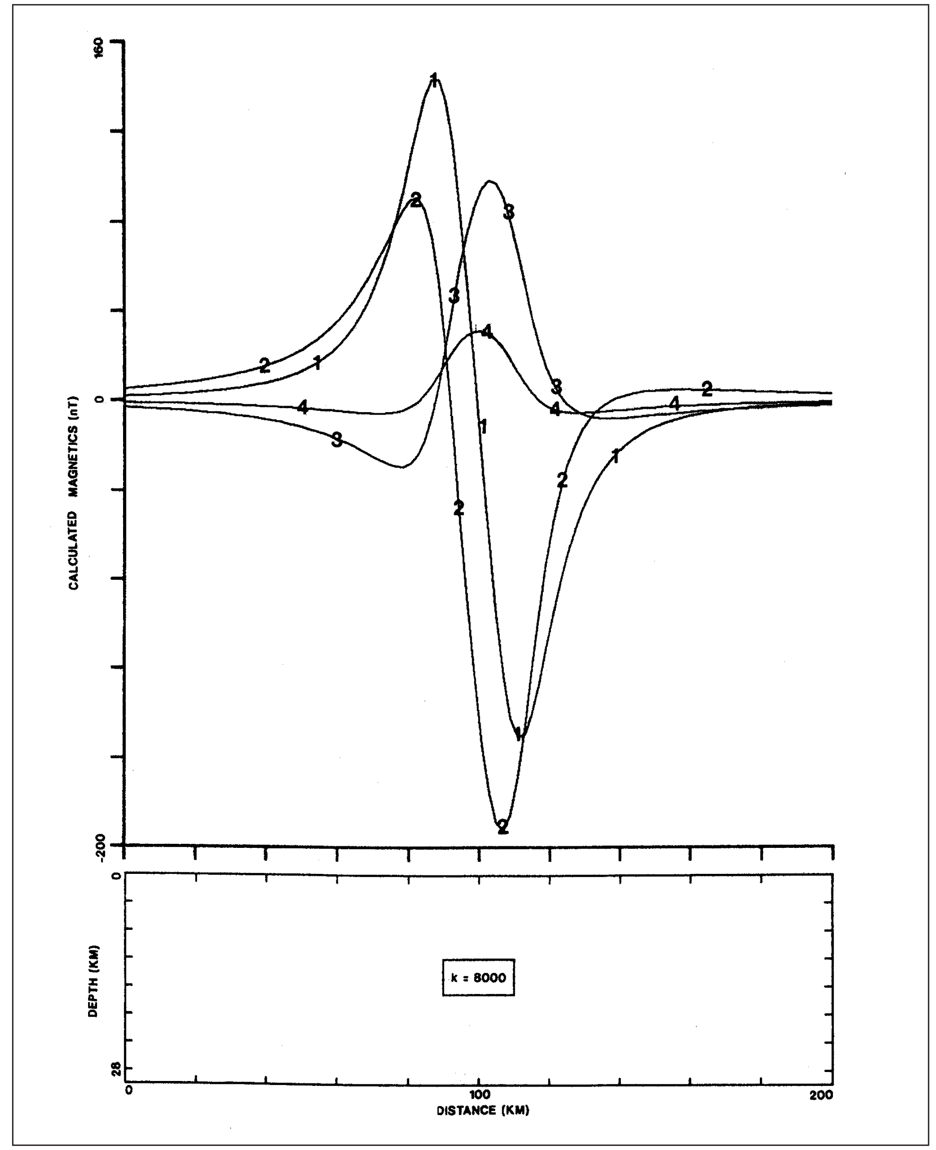

Figure 7. Magnetic anomalies calculated for two profile directions (south-north and west-east). For profiles 1 and 3, present-day magnetic inclination (43°) and declination (–11°) are used, and paleomagnetic inclination (23°) and declination (0°) are used for profiles 2 and 4. In each calculation, the same 2-D causative body is used: 5 km thick, at 12 km depth, and 8000 micro-cgs units susceptibility magnetization.

At low geomagnetic inclinations, the ends of offset-spreading ridge segments or east-west-trending features such as transform faults that have been injected with magnetized material would produce anomalies of several hundred nT. In contrast, north-south-trending ridge segments would produce anomalies of only a few tens of nT. At the magnetic equator, a north-south ridge segment would produce no anomaly if magnetization of the source body is caused solely by the inducing field.

The north-northeast to north-south orientation of anomaly trends, seen in profile data, over the basin south of 14°N are interpreted to be produced by sea-floor spreading and indicate a near east-west direction of extension and opening of the Grenada Basin. Although these anomalies exhibit amplitudes of about 40 nT, confidence in these trends is high. This confidence is supported by two aspects of the region and the magnetic field. First, the trends were correlated using data from a single cruise (U. S. Navy WI932010) with eighteen lines spaced approximately 8 km apart. Second, the acoustic basement surface in this part of the basin is relatively smooth (Speed et al., 1984), suggesting that intrabasement sources are responsible for the anomaly trends observed in profiles. Trends over the northern part of the basin may have resulted from the tectonic event responsible for the bifurcation of the northern Lesser Antilles. That is, the original magnetic signature is thought to have been disrupted by faulting and possible strike-slip motion (Bird, 1991; Bird et al., 1993).

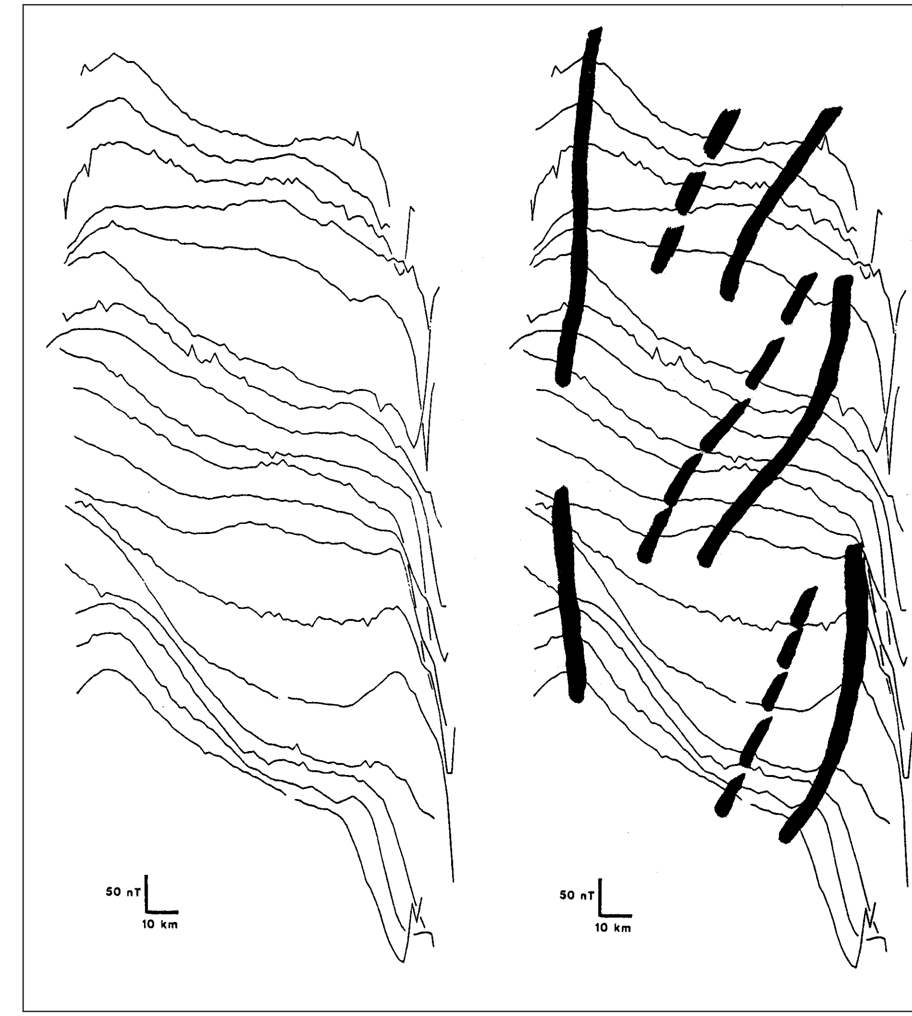

Figure 8. Magnetic anomaly trends over the study area from profile data. Anomaly highs are indicated by solid lines and anomaly lows are indicated by dashed lines.

Conclusion

After understanding the magnetic field over the Grenada Basin, it is a relatively easy task to piece together the geologic events related to its formation. In his discussion regarding the magnetic anomalies over the Grenada Basin, Bouysse (1988) points out that the great depth to the oceanic basement, combined with a possible location near the geomagnetic equator of the eastern Caribbean, may blur the original anomaly pattern. These factors are the primary reason for the confusion regarding the magnetic field over the Grenada Basin.

Interpretation of magnetic anomalies at low geomagnetic inclinations depends on the strike of the geologic features and the anomaly patterns they produce. The magnetic anomaly patterns over the Grenada Basin and our interpretation of them demonstrate this dependence. The Grenada Basin is interpreted to have formed by near east-west extension in the Early Tertiary (Figure 9). This conclusion is supported by the basin morphology, gravity data, and subtle magnetic anomaly trends over the southern part of the basin (Bird, 1991). These low-amplitude anomalies are produced by roughly north-south-oriented spreading centers near the geomagnetic equator. The chaotic, patchy anomalies over the northern part of the basin are thought to have formed by sea-floor spreading also, but they were disrupted later by the Late Tertiary event responsible for the bifurcation of the Lesser Antilles (Bird et al., 1993).

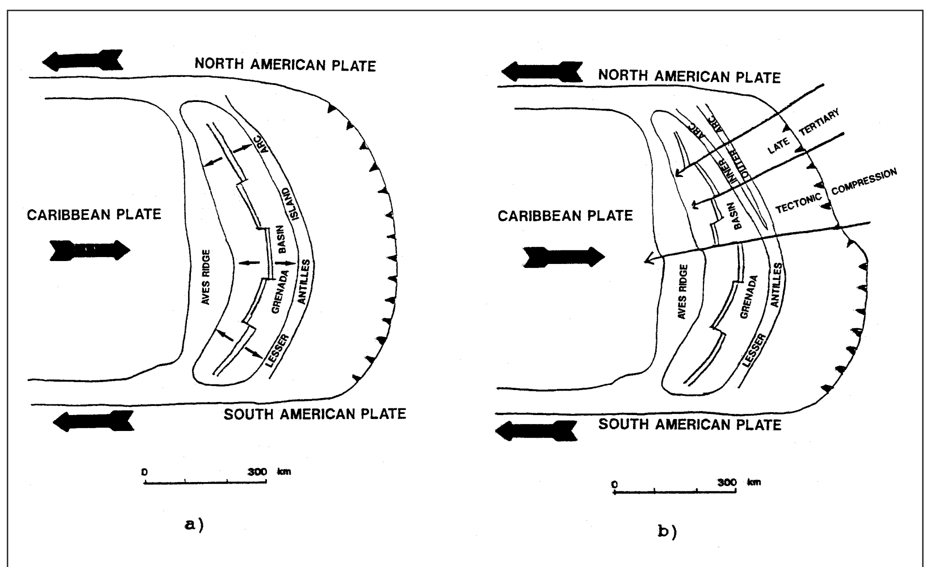

***Figure 9**. Two-step model for the formation of the Grenada Basin via east-west extension. Large arrows indicate directions of relative plate motion. Small arrows indicate directions of extension and basin formation. (a) The basin formed fairly uniformly by sea-floor spreading. (b) Late Tertiary compressional tectonism disrupted the northern portion of the basin (indicated by long, northeast-oriented arrows).*

Because many of the world's prospective basins are in regions characterized by low magnetic latitudes, the work performed here can be used as an analog for understanding the magnetic field, and the geology which produces it, in such regions.

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