Early Central Atlantic Ocean seafloor spreading history

D.E. Bird*
S.A. Hall
K. Burke
J.F. Casey
Department of Geosciences, University of Houston, 4800 Calhoun Road, Houston, Texas 77204-5007, USA

D.S. Sawyer
Department of Earth Science, Rice University, M.S. 126, 6100 South Main Street, Houston, Texas 77005-1892, USA

ABSTRACT

Twenty-three Mesozoic "Chrons" (specific time intervals) from M0 to M40, including several in the Jurassic Magnetic Quiet Zone ("Jurassic Quiet Zone"), as well as Cenozoic Chron C34, are identified and mapped between the Atlantis and Fifteen-Twenty fracture zones on the North American plate, and between the Atlantis and Kane fracture zones on the African plate. Asymmetric seafloor spreading is indicated by the distances spanned over Chron intervals for the western and eastern flanks of the Central Atlantic ocean basin: C34 to the Mid-Atlantic Ridge (84 Ma to 0 Ma), M0 to C34 (120.6 Ma to 84 Ma), and M25 to M0 (154 Ma to 120.6 Ma). Chron M40 (167.5 Ma) is mapped ~65 km outboard of the S1 magnetic anomaly over the African flank, and its conjugate, the Blake Spur Magnetic Anomaly ("Blake Spur Anomaly") over the North American flank. Another pair of conjugate anomalies, the S3 magnetic anomaly over the African flank, and the East Coast Magnetic Anomaly ("East Coast Anomaly") over the North American flank, are respectively located ~30 km and 180 km inboard of the S1-Blake Spur Magnetic Anomaly pair. Therefore, the ridge jump to the east between "Blake Spur" and "East Coast" anomalies at ~170 Ma theorized by Vogt and others in 1971 is supported by this study. Between the Atlantis and Kane fracture zones, the width of the African Jurassic Magnetic Quiet Zone is ~70 km greater (22%) than the North American Jurassic Magnetic Quiet Zone. Correlatable anomalies exist over the African plate, suggesting a second ridge jump, to the west. Modeling results indicate that this jump occurred between 164 Ma and 159 Ma (Chrons M38 and M32). The ridge jumps can be related to plate interactions as North America separated from Gondwana. However, we note that the second ridge jump occurred approximately at the time suggested for the onset of seafloor spreading in the Gulf of Mexico.

Keywords: Central Atlantic, ridge jumps, asymmetric spreading, seafloor spreading, magnetics, reconstruction.

INTRODUCTION

The overall kinematic history of the Central Atlantic Ocean between 10° N and 40° N is well understood (Fig. 1) (Klitgord and Schouten, 1986; Muller and Roest, 1992; Muller and Smith, 1993; Muller et al., 1999; Vogt, 1986; Withjack et al., 1998). Following Middle to Late Triassic rifting between North America and Africa, seafloor spreading began at ca. 185 Ma (Withjack et al., 1998). Seafloor spreading anomalies corresponding to intervals Mid-Atlantic Ridge to C34 and M0 to M25 are well documented (Klitgord and Schouten, 1986; Muller and Roest, 1992, Muller et al., 1999). Magnetic data can be divided into five major anomaly provinces that form symmetric bands along the eastern and western sides of the Central Atlantic: (1) Cenozoic Chron C34 to the Mid-Atlantic Ridge; (2) the Cretaceous Magnetic Quiet Zone; (3) Mesozoic Chrons (M-Series) M25 to M0; (4) the Jurassic Magnetic Quiet Zone consisting of Mesozoic Chrons M41 to M26; and (5) a zone of low-amplitude anomalies between the East Coast Magnetic Anomaly ("East Coast") and Blake Spur Magnetic Anomaly ("Blake Spur") over the North American flank of the ocean basin is called the Inner Magnetic Quiet Zone (Rona et al., 1970; Vogt, 1986; Vogt et al., 1971). S1 and S3, similar to the "East Coast" and "Blake Spur" anomalies, are located over the African flank inboard of Chron M40 (Roeser et al., 2002).

The age and relative rotation history between the North American and African plates have been determined by combining fracture zones identified from Geosat and Seasat altimetry data with magnetic isochrons (Klitgord and Schouten, 1986; Muller and Roest, 1992; Muller et al., 1999). We use similar methods and integrate gridded magnetic data with a recently compiled, extensive profile-based magnetic data set to: (1) identify and map eighteen M-Series Chrons (M25 to M0) in the Central Atlantic Ocean; (2) identify and map five additional M-Series Chrons within the Jurassic Magnetic Quiet Zone (M40 to M28); (3) interpret the intersections between Chrons C34, M0, and M25 with the Fifteen-Twenty, Kane, and Atlantis fracture zones to calculate finite difference Euler poles needed to reconstruct the relative plate motion between North America and Africa from 154 Ma to present (Chron M25 to Mid-Atlantic Ridge); (4) estimate asymmetric spreading rates from Chron C34 to the Mid-Atlantic Ridge, Chrons M0 to C34, and Chrons M25 to M0; (5) document a previously proposed ridge jump in the North American plate that occurred at ca. 170 Ma (Vogt et al., 1971; Vogt, 1973, 1986); and (6) propose the existence of another ridge jump between 164 Ma and 159 Ma (Chrons M38 and M32).

*Present address: Bird Geophysical, 16903 Clan Macintosh, Houston, Texas 77084, USA; dale@birdgeo.com.

Geosphere; October 2007; v. 3; no. 5; p. 282–298; doi: 10.1130/GES00047.1; 15 figures; 5 tables.

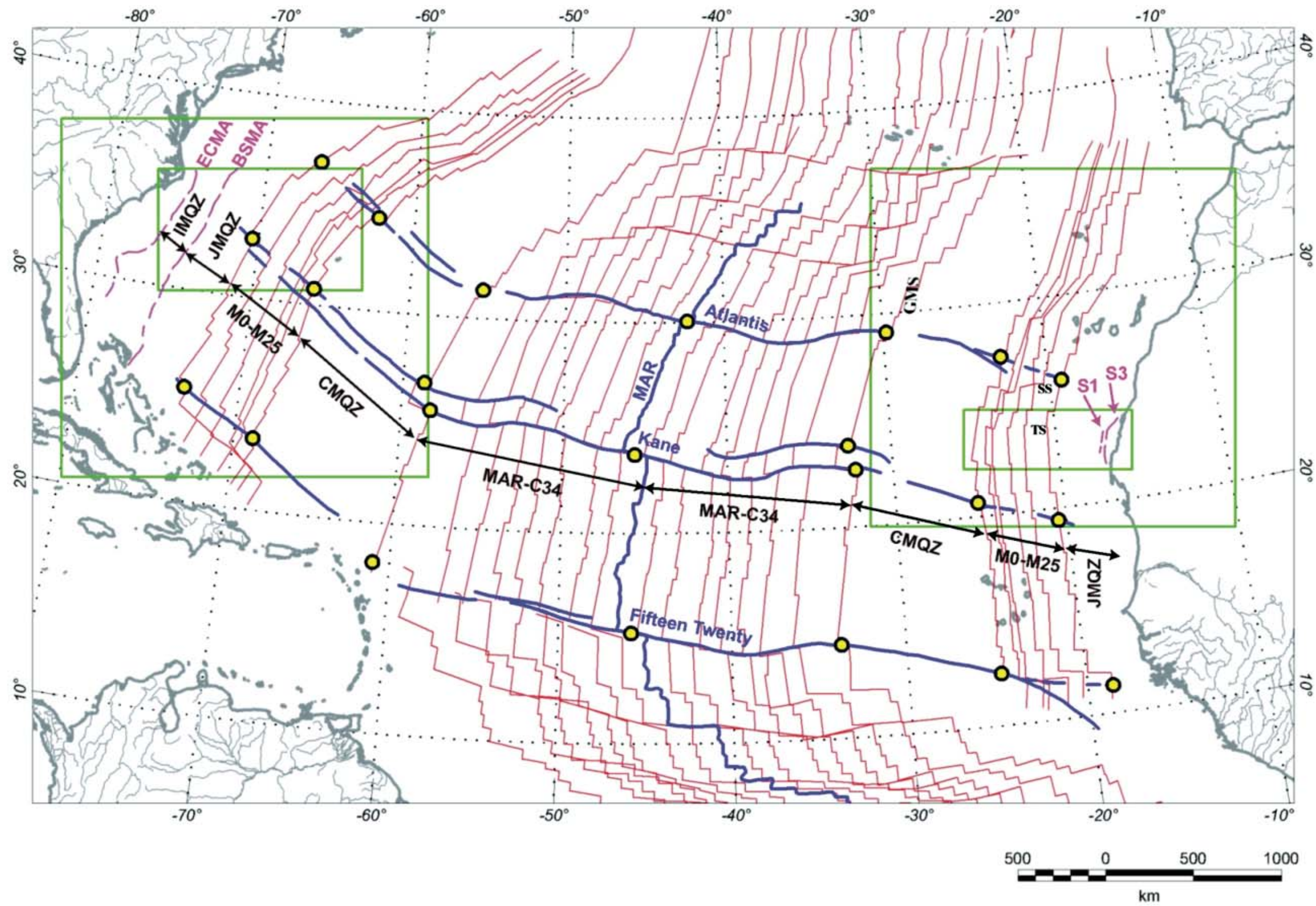

Figure 1. Fracture zones (blue) and geomagnetic isochrons (red) (Muller et al., 1997) in the Central Atlantic Ocean. Fracture zones were mapped by tracing through residual, free-air gravity minima with dashed lines representing less confidence. Magnetic anomaly provinces are Chron C34 to Mid-Atlantic Ridge (MAR), Cretaceous Magnetic Quiet Zone (CMQZ), Chrons M0 to M25, Jurassic Magnetic Quiet Zone (JMQZ) and Inner Magnetic Quiet Zone (IMQZ). Prominent anomalies include the East Coast Magnetic Anomaly (ECMA), the Blake Spur Magnetic Anomaly (BSMA), S1, and S3. Control points used for plate reconstructions located at the intersections of fracture zones and isochrons are yellow circles (Tables 2 and 3). GMS, SS, and TS are the approximate locations of the Great Meteor Seamounts, Saharan Seamounts, and the Tropic Seamount. Green boxes outline detailed maps of succeeding figures.

GEOPHYSICAL DATA

The open-file geophysical data used in this study consisted of two magnetic anomaly grids, a gravity grid, and three magnetic anomaly profile data sets. Two open-file magnetic anomaly grids partially cover the Central Atlantic Ocean (Fig. 2) (Hinze et al., 1988; Verhoef et al., 1996). Magnetic anomaly profile data sources are: the National Oceanic and Atmospheric Administration/National Geophysical Data Center GEOphysical DAta System (GEODAS) database, the Kroonvlag project data from the Geological Survey of Canada (Collette et al. 1984), and forty-two lines digitized from Vogt et al. (1971) (Fig. 3).

The satellite-derived free-air gravity anomaly grid over the Central Atlantic Ocean is a two arc-minute grid of fairly uniform coverage acquired during the Geosat Geodetic Mission and the ERS-1 Geodetic Phase along closely spaced satellite tracks (Fig. 4) (Sandwell and Smith, 1997).

METHODS

Fracture Zones and Flowlines

Flowlines describe the relative motion between two accreting plates over time. Fracture zones provide approximations of these flowlines by recording changes in seafloor spreading direction over time (Collette and Roest, 1992; Klitgord and Schouten, 1986). Fracture zones can be identified by their characteristic signatures in magnetic and gravity data. Magnetic lineations related to geomagnetic polarity reversals are often offset along fracture zones, and free-air gravity anomalies over fracture zones are typically distinct, 25–50 km wide, curvilinear minima. Therefore, we interpret fracture zones from maps of gravity and magnetic anomalies by tracing gravity minima through the transform offsets (Figs. 1, 5, and 6). From south to north, the Fifteen-Twenty, Kane, and Atlantis fracture zones span most of the Central Atlantic, or ~2000 km, and they extend west and east close to the coasts of North America and Africa, or almost 6000 km (Fig. 1).

Geomagnetic Isochrons

Distinct magnetic anomalies are produced by rocks accreted along the Mid-Atlantic Ridge during specific time intervals ("Chrons") that are associated with geomagnetic polarity reversals. Magnetic anomalies produced by sea-floor

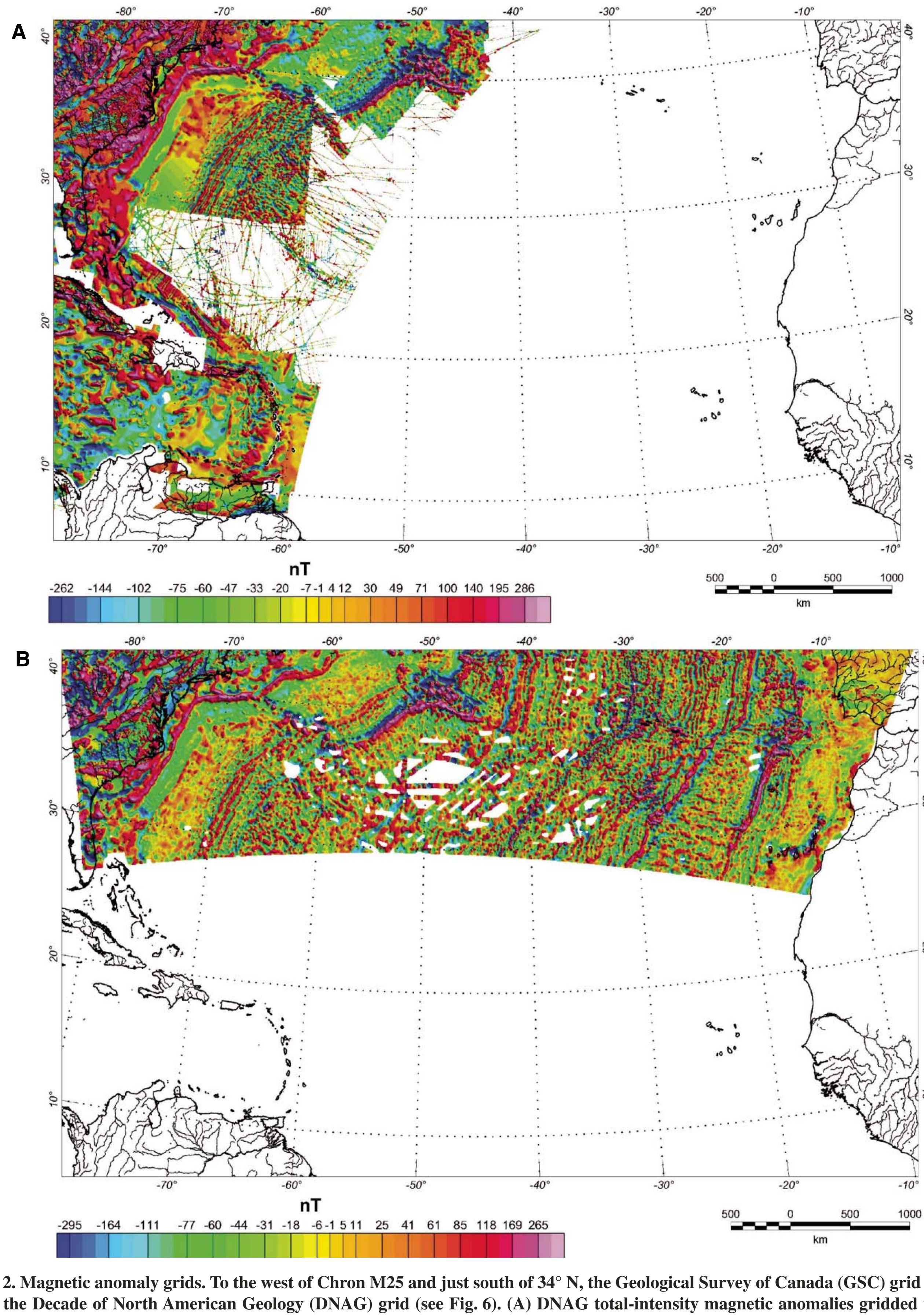

Figure 2. Magnetic anomaly grids. To the west of Chron M25 and just south of 34° N, the Geological Survey of Canada (GSC) grid is superior to the Decade of North American Geology (DNAG) grid (see Fig. 6). (A) DNAG total-intensity magnetic anomalies gridded to 2 km (Hinze et al., 1988). (B) GSC total-intensity magnetic anomalies gridded to 5 km (Verhoef et al., 1996).

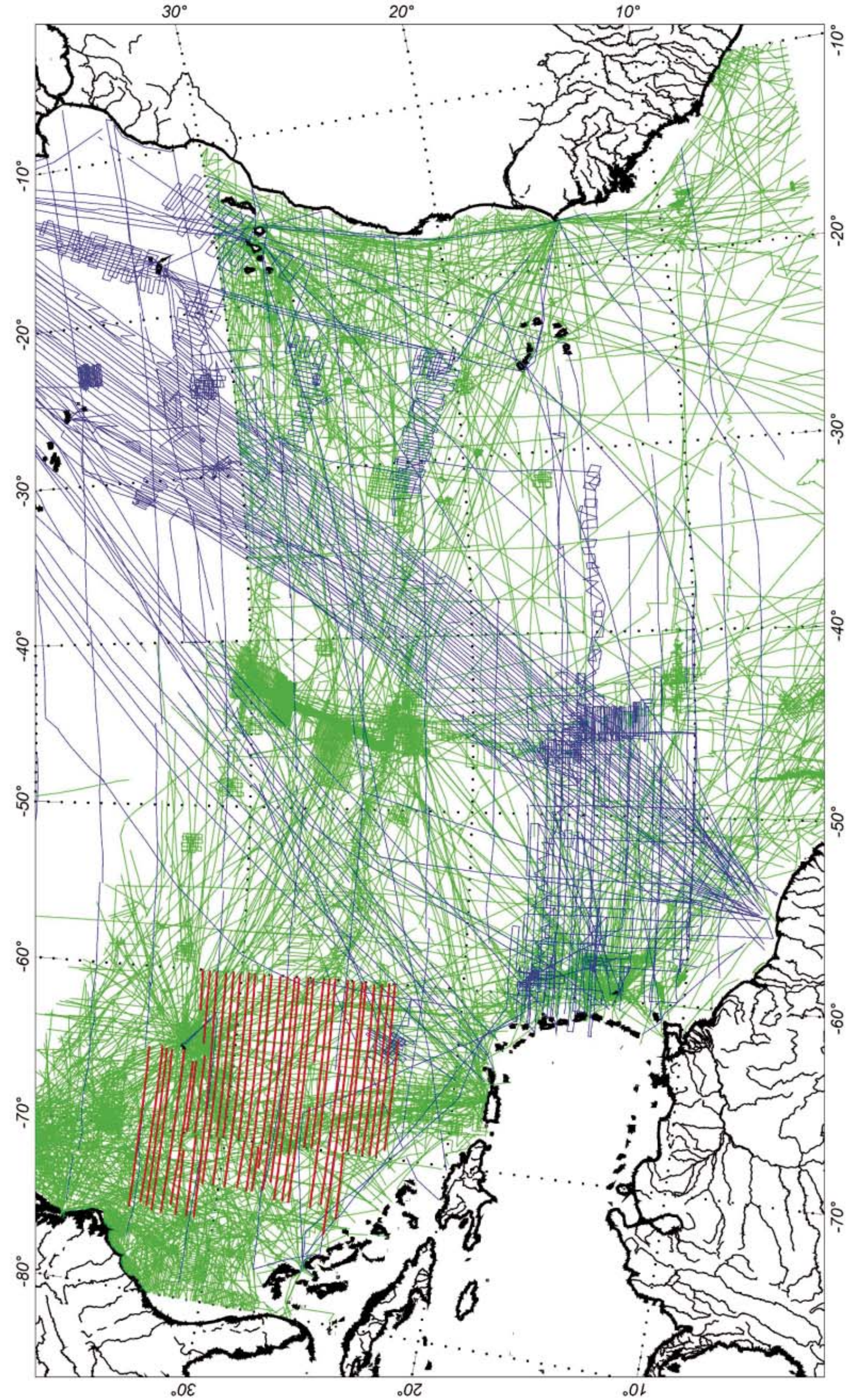

Figure 3. Magnetic anomaly profiles. GEODAS magnetic data ship-track locations (green). GSC magnetic data ship-track locations (blue) (Collette et al. 1984). Magnetic data acquired along east-west transects in 1967 and 1968 (thick red lines) (Vogt et al., 1971).

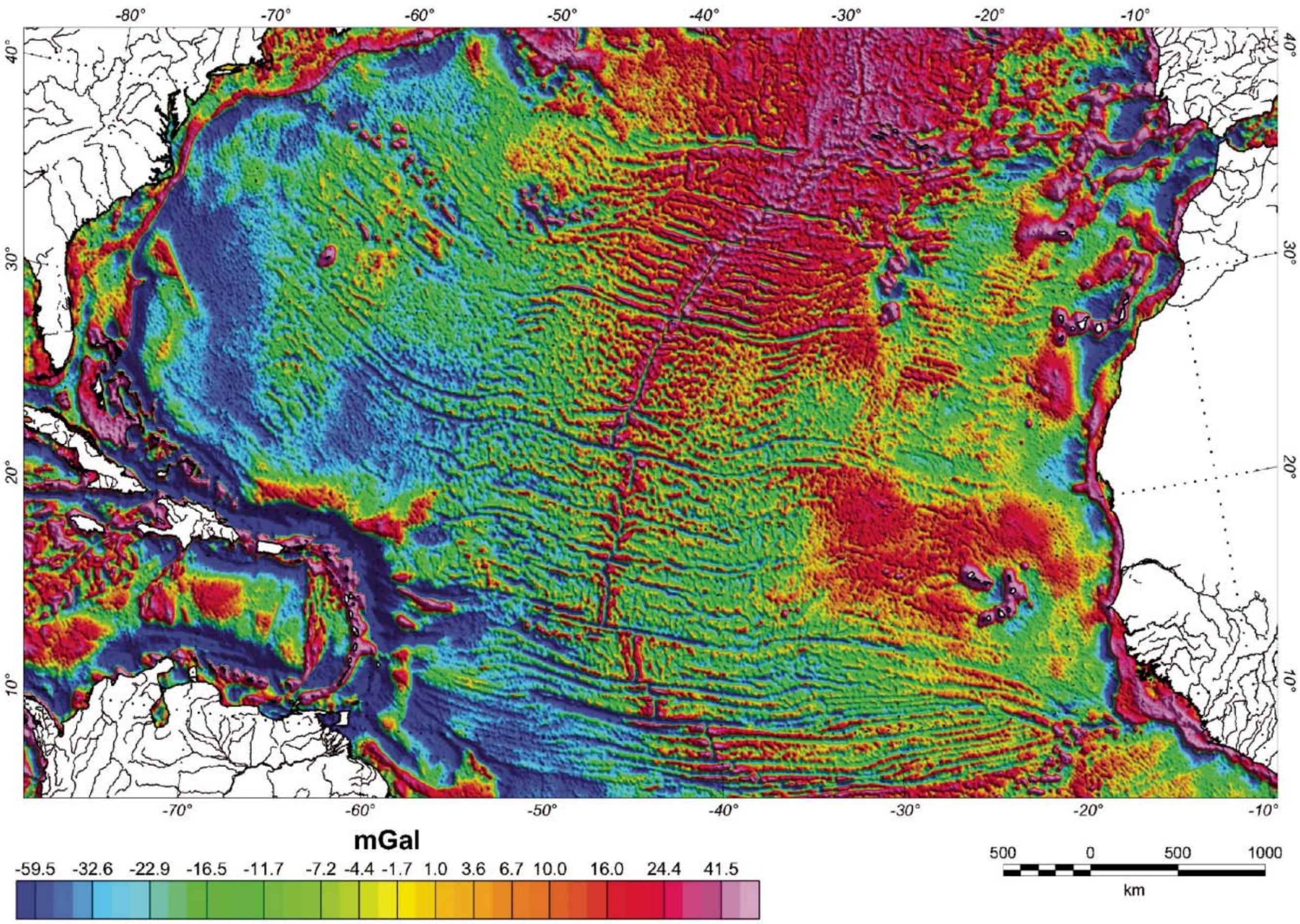

Figure 4. Satellite-derived, free-air gravity anomalies (Sandwell and Smith, 1997). The grid cell interval is 2 arc-minutes.

spreading are identified in a two-step process: (1) by simultaneous interpretation of gridded and profile magnetic anomalies to correlate significant anomaly trends, and (2) by comparison of selected anomaly profiles with synthetic anomaly profiles that are calculated from two-dimensional magnetic models based on the geomagnetic polarity reversal time scales of Channell et al. (1995) and Sager et al. (1998). The magnetic data coverage over the North American flank of the Central Atlantic ocean basin is relatively dense, including extensive ship-track coverage as well as gridded data sets (Figs. 2 and 3). The data coverage over the African flank has low ship-track data density and lacks gridded data south of 30° N. Therefore, we interpret Mesozoic Chrons from the Bahamas to just northeast of the Atlantis fracture zone on the North American flank, but only along a 200-km-wide corridor between the Atlantis and Kane fracture zones on the African flank.

We correlate magnetic anomalies in groups, or sequences of anomalies, for line-to-line coherency. Anomalies produced by geomagnetic polarity reversals should be consistent and roughly parallel to seafloor spreading centers, while anomalies produced by basement relief are typically shorter and less organized. Initially (step 1), prominent anomalies coinciding approximately with the globally mapped magnetic isochrons by Muller et al. (1997) were identified on maps: C34, M0, M4, M10N, M16, M21, and M25. Next, additional anomalies were identified between this first set of prominent anomalies by approximating distances based on time intervals defined by geomagnetic polarity reversals and anomaly character (Channell et al., 1995; Sager et al., 1998). Landward of M25 in the Jurassic Magnetic Quiet Zone, anomalies were also identified by approximating distances based on time intervals and by comparing anomaly shapes with Chrons identified by Roeser et al. (2002) and Sager et al. (1998): M28, M29, M32, M38, and M40.

Excellent examples of Jurassic Magnetic Quiet Zone anomalies, which can be used for comparison with the Central Atlantic “Jurassic Quiet Zone” anomalies, are found over the western Pacific Ocean and off the northwest shelf of Australia. Anomalies over the Jurassic Magnetic Quiet Zone in the Pigafetta Basin, just east of the Northern Mariana Basin, are produced by basement at depths of 6–6.5 km. Two deep-tow profiles were acquired over an ~8 m. y. sequence (167.5 Ma to 157.5 Ma) containing eighty-eight M41 to pre-M29 Chrons (Sager et al., 1998). After upward continuing profiles to sea level, only 44% of the Chrons were retained (Sager et al., 1998). We use similar upward continued profiles to compare and identify anomaly patterns over the Central Atlantic.

Twenty-three magnetic anomaly profiles were selected between Atlantis and Kane fracture zones over the western flank of the ocean basin, and thirteen profiles were selected between Atlantis and Kane fracture zones over the eastern flank. These were correlated with synthetic anomalies generated from a two-dimensional model based on the geomagnetic polarity reversal time scale (step 2). Anomaly profiles were

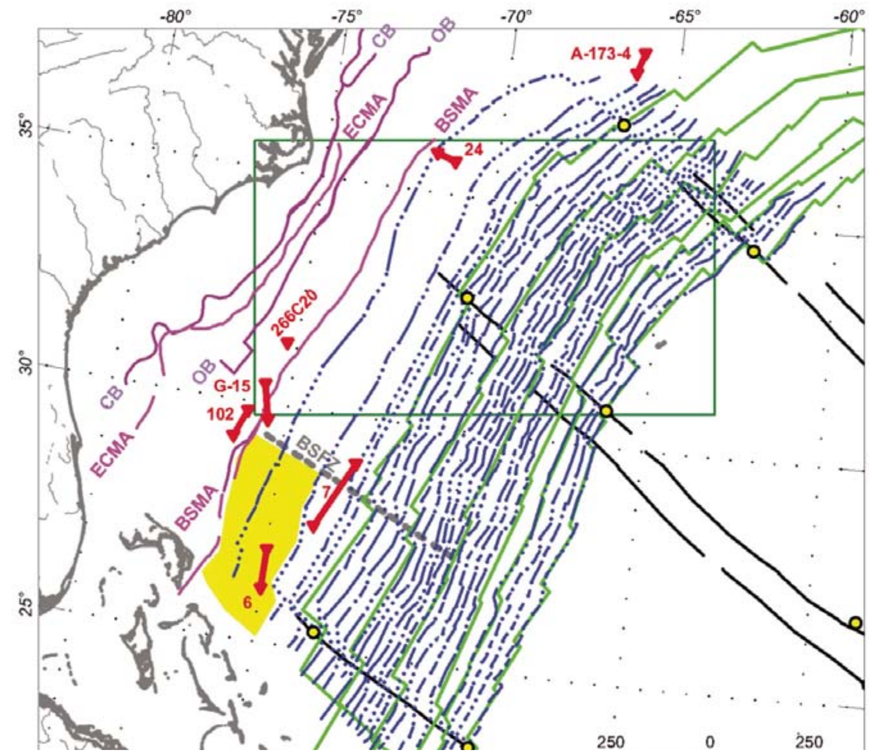

Figure 5. Fracture zones (thick black) and geomagnetic isochrons—North America. Chrons mapped in this study are blue (Table 1); global Chrons are green (M25, M21, M16, M10N, M4, and M0) (Muller et al., 1997). Control points used for plate reconstructions are located at the intersections of fracture zones, and isochrons are yellow circles. Inverted red triangles and heavy red lines are locations of refraction data that indicate oceanic crust (see Table 4 for details). The East Coast Magnetic Anomaly (ECMA) and the Blake Spur Magnetic Anomaly (BSMA) are subparallel to the coast (magenta). Dark-purple lines are the mappable limits of continental (CB) and oceanic crust (OB) (Uchupi et al., 1984a, 1984b). The Blake Spur Fracture Zone (BSFZ) is indicated by heavy, dashed, light-gray line. Yellow shaded area corresponds to continental extension of the Blake Plateau suggested by Dunbar and Sawyer (1989). The magnetic anomaly correlation example is outlined by the green box (Figs. 6 and 7).

projected to straight-line segments, approximately parallel to the flow lines and displayed at the same horizontal and vertical scales. Correlated anomalies were then identified as Chrons according to their similarity with the synthetic profiles (Table 1). Line-to-line correlations were connected with solid lines, which were, in turn, connected by dotted lines to maintain a spatial reference frame over fracture zones or areas where profile data did not exist (Figs. 5–8). Two-dimensional magnetic models were generated using 2-km-thick blocks representing constant polarity intervals of the geomagnetic polarity time scale with 2-km-wide Gaussian polarity transitions between the Chrons. Magnetic anomalies produced by these models are compared to magnetic anomaly data profiles. Basement depths in the "Jurassic Quiet Zone" off North America are ~7–9 km (Uchupi et al., 1984a, 1984b); therefore, the basement depth of our two-dimensional, magnetic anomaly model is 8 km for North America. We use 8-km basement depth for Africa as well.

Finite-Difference Poles

Stage poles were calculated for the North American and African flanks: Chron C34 to Mid-Atlantic Ridge, Chron M0 to C34, and Chron M25 to M0; and total reconstruction poles were calculated for C34 (84 Ma), M0 (120.6 Ma), and M25 (154 Ma) (Tables 2 and 3). A method similar to that described by Engebretson et al. (1984) was used to find the best-fit Euler pole for pairs of control points defined by the intersections between interpreted geomagnetic isochrons (C34, M0, and M25) and fracture zones (Atlantis, Kane, and Fifteen-Twenty). Each pair of control points is assumed to have been originally coincident so that a plate rotation exists that will restore them to a single point. A computer program minimized mismatch between one set of control points and the rotated set of control points by least-squares approximation (Bird, 2004). The program required an input geographic seed location (latitude and longitude) for the center of a scan matrix and a scan increment (in degrees); it built the scan matrix and then searched for the best-fit Euler pole. Once the best-fit pole was located, its coordinates were input into the program as the next seed location using a smaller scan increment. Convergence to a solution yielding a 90% confidence region was typically achieved in three or four iterations (Bird, 2004).

TABLE 1. INTERPRETED GEOMAGNETIC ISOCHRONS

Chron	Time interval (Ma)	Chron	Time Interval (Ma)
M0	**120.60 to 121.00**	M20	144.70 to 145.52
M1	123.19 to 123.55	**M21**	**146.56 to 147.06**
M3	124.05 to 125.67	M22	148.79 to 149.49
M4	**126.57 to 126.91**	M23	150.69 to 150.91 and 150.93 to 151.40
M10N	**130.49 to 130.84**	M24	151.72 to 151.98 and 152.00 to 152.15
M12A	133.99 to 134.08	**M25**	**154.00 to 154.31**
M14	134.81 to 135.57	M28	156.19 to 156.51
M16	**137.85 to 138.50**	M29	157.27 to 157.53
M17	138.89 to 140.51	M32	159.68 to 159.77
M18	141.22 to 141.63	M38	164.50 to 164.60
M19	143.07 to 143.36	M40	167.22 to 167.33
M20n-1	143.77 to 143.84		

Note: Isochrons M0 through M29 were classified by Channell et al. (1995) and M32–M40 were classified by Sager et al. (1998). Globally mapped isochrons are bold (Muller et al., 1997).

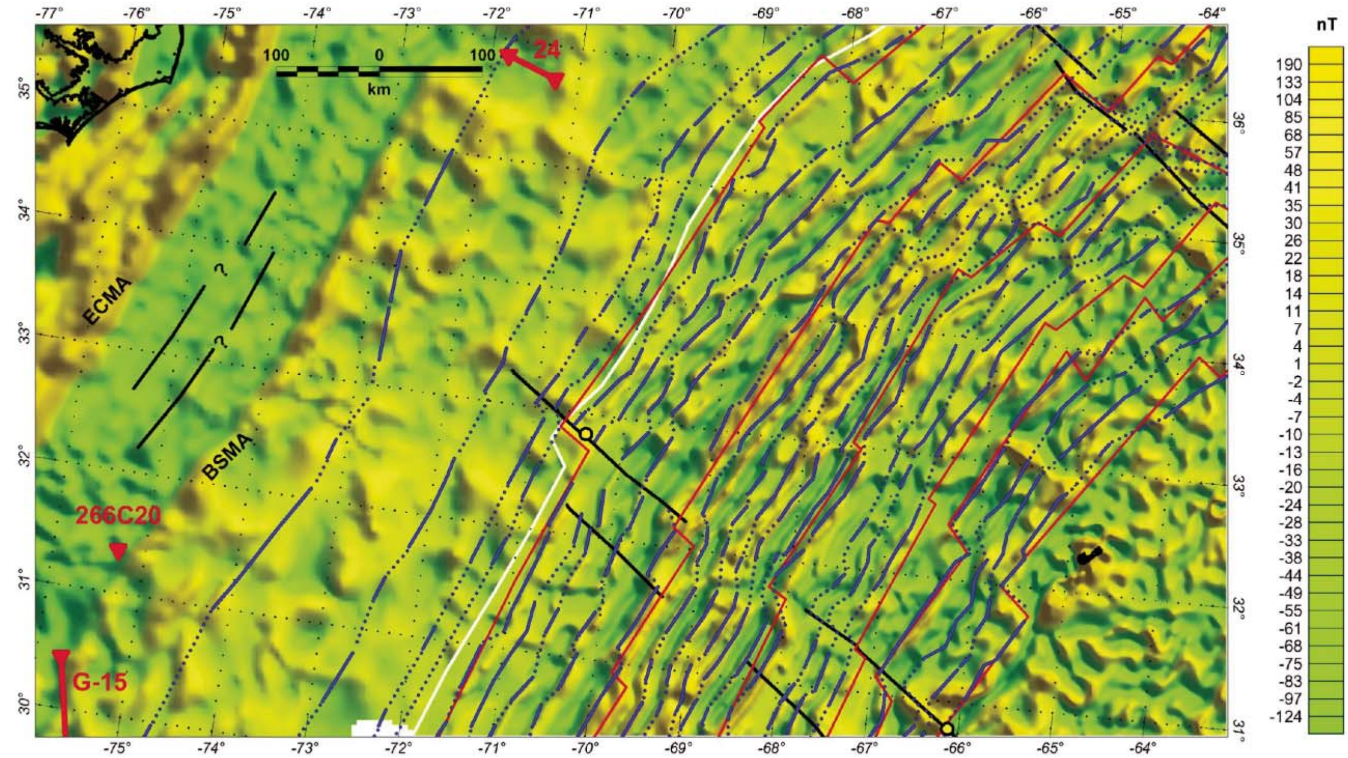

Figure 6. Total-intensity magnetic anomalies and Chron interpretation—North American plate. DNAG (east) and GSC Mag (west) total-intensity grids are separated by the thick white line. Chrons mapped in this study are blue (Table 1); global Chrons are red (M25, M21, M16, M10N, M4, and M0) (Muller et al., 1997). Fracture zones are heavy black lines, and reconstruction control points are yellow circles. Inverted red triangles and heavy red lines are locations of refraction data (Table 4). Between the East Coast Magnetic Anomaly (ECMA) and Blake Spur Magnetic Anomaly (BSMA), two linear anomaly trends support the existence of oceanic crust.

TABLE 2. TOTAL RECONSTRUCTION POLES

	Latitude	Longitude	Rotation	Rotation error
C34, this study	75.75°N	21.55°W	30.21°	0.456°
C34, Muller and Roest	76.55°N	20.73°W	29.60°	
M0, this study	66.70°N	18.55°W	54.23°	1.40°
M0, Muller and Roest	66.09°N	20.17°W	54.45°	
M25, this study	66.10°N	16.45°W	65.84°	0.76°
M25, Muller and Roest	66.70°N	15.85°W	64.90°	

Note: Total reconstruction poles calculated from North American and African sides of the central Atlantic Ocean. Error ellipsoids, and poles reported by Muller and Roest (1992), are shown in Figure 11.

TABLE 3. STAGE POLES

	Latitude	Longitude	Rotation	Rotation error
West: MAR to C34	62.65°N	36.20°W	20.00°	0.80°
East: C34 to MAR	78.85°N	127.95°E	11.81°	0.66°
West: C34 to M0	57.10°N	22.65°W	11.94°	0.88°
East: M0 to C34	55.25°N	10.00°W	12.88°	0.74°
West: M0 to M25	63.55°N	21.55°E	4.87°	0.29°
East: M25 to M0	42.10°N	13.45°W	11.82°	0.26°

Note: Stage poles calculated for North American and African sides of the central Atlantic Ocean. Error ellipsoids are shown in Figure 11. MAR—Mid-Atlantic Ridge

ANALYSIS

Oceanic Crust and Fracture Zones

Gridded magnetic data and published seismic refraction data indicate that oceanic crust exists beneath the interpreted Jurassic Magnetic Quiet Zone Chrons, or M40 to M28 (Figs. 5–7, Table 4) (Ewing and Ewing, 1959; Houtz, 1980; Katz and Ewing, 1956; Sheridan et al., 1966). Crustal boundaries mapped by Uchupi et al. (1984a, 1984b) indicate that oceanic crust extends inboard almost as far as the East Coast Magnetic Anomaly (Fig. 5). Magnetic anomalies produced by geomagnetic polarity reversals coinciding with Chrons M25 through M0, and subtle, broad linear anomalies, similar to M40 to M28 between "East Coast" and "Blake Spur" anomalies, also support this interpretation of oceanic crust (Fig. 6).

The primary difficulty associated with mapping fracture zones using satellite-derived free-air gravity data over long distances, such as from the Mid-Atlantic Ridge to the continental shelves of North America and Africa, is their variable expression. Their expression can be

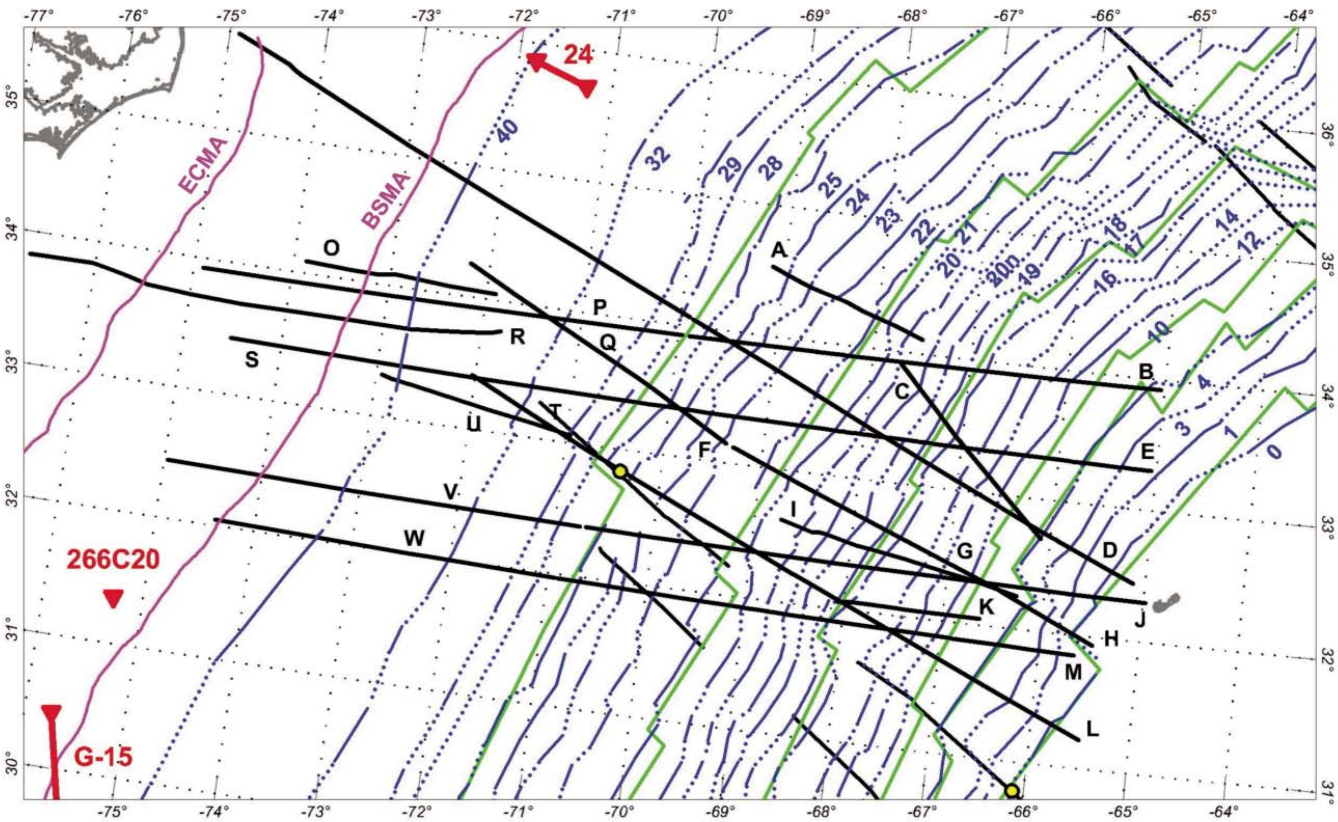

Figure 7. Interpretation and profile correlation ship tracks—North American plate. Chrons mapped in this study are blue (Table 1); global Chrons are green (M25, M21, M16, M10N, M4, and M0) (Muller et al., 1997). ECMA and BSMA magnetic anomalies are magenta. Lines selected for Chron identification are heavy black (profiles are displayed in Figs. 9 and 10). Inverted red triangles and heavy red lines are locations of refraction data (Table 4).

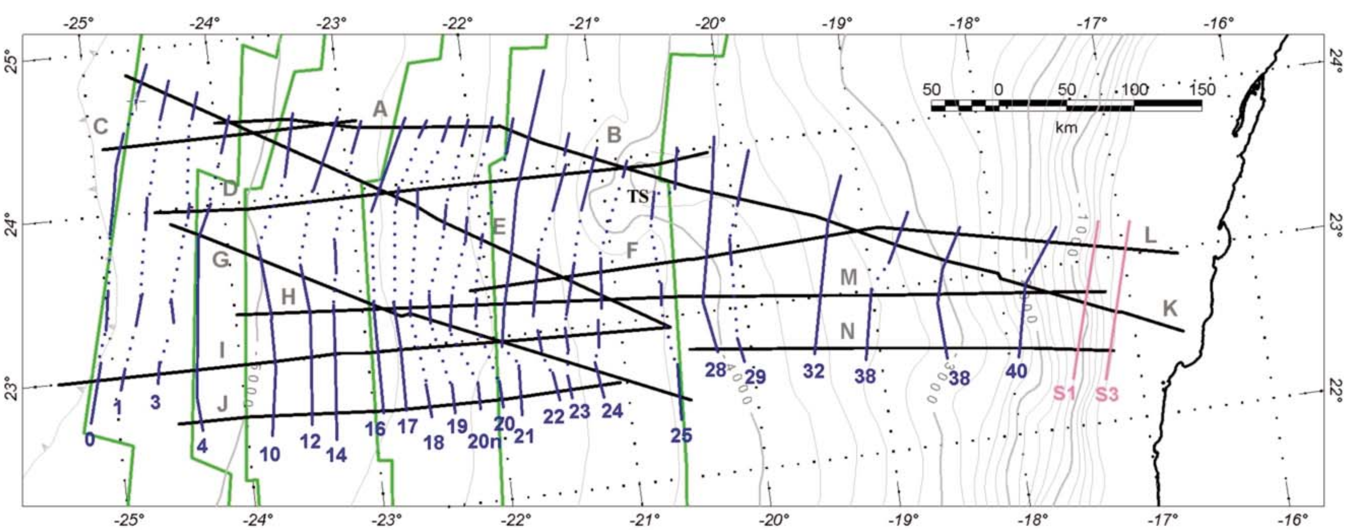

Figure 8. Interpretation and profile correlation ship tracks—African plate. Chrons mapped in this study are blue (Table 1); global Chrons are green (M25, M21, M16, M10N, M4, and M0) (Muller et al., 1997). Lines selected for Chron identification are heavy black (profiles are displayed in Figures 9 and 10). The Tropic Seamount (TS) is located on the northern end of interpreted Chron M25. The light-gray bathymetry contour interval is 200 m.

TABLE 4. SEISMIC REFRACTION DATA

Station or line no.	Basement depth (km)	Moho depth (km)	Thickness (km)	Source
A-173-4	6.6	11.0	4.4	EE
24 (west)	6.5	11.0	4.5	KE
24 (east)	6.9	13.5	6.6	KE
266C20	8.3	16.2	7.9	H
G-15	8.1	14.8	6.7	EE
102	8.5	12.1	3.6	S
7	6.8	13.5	6.7	KE
6	6.6	12.5	5.9	KE

Note: Seismic refraction data on and near the Blake Plateau (located in Figure 5). Crustal thicknesses indicate oceanic crust. Data sources: Ewing and Ewing (EE, 1959), Houtz (H, 1980), Katz and Ewing (KE, 1956), and Sheridan et al. (S, 1966).

affected by several factors including seafloor spreading rate, length of transform segment, magma supply, and sedimentation, which can result in fracture zones that seem to disappear and reappear along strike. Muller and Roest (1992) estimate the average error for identifying fracture-zone locations from satellite-derived gravity data to be 5 km.

Using satellite-derived gravity alone over the North American plate, the interpreted landward projections of the Atlantis, Kane and Fifteen-Twenty fracture zones extend to Chron 21, 75 km inboard of Chron 25, and to Chron 25, respectively (Figs. 1 and 5). The Atlantis fracture zone trace can be followed farther landward in the North American plate to over 100 km inboard of Chron M40 using the magnetic anomaly grids. M-Series Chrons are offset sinistral almost 80 km along the inboard projection of this fracture zone (Fig. 6). The landward projections of the Kane and Fifteen-Twenty fracture zones on the African plate extend to Chron M16 and Chron M25, with dashed lines indicating less confidence (Fig. 1). The volcanic Great Meteor Seamount and Saharan Seamount complexes mask parts of the Atlantis fracture zone on the African plate, where its inferred location between Chrons C34 and M25 is represented by a dashed line (Fig. 1).

Geomagnetic Isochrons

Geomagnetic Chrons M0 to M40 have been interpreted and mapped outboard of the North American and African continental slopes (Figs. 5–8). Due to their relatively high amplitudes, M25 to M0 Series anomalies are readily identified; however, "Jurassic Quiet Zone" anomalies (M28 to M40) are more difficult to interpret because: (1) anomaly amplitudes are much lower; (2) they are located over the deepest parts of the basin near the continental margins; and (3) geomagnetic polarity reversals occurred at a rapid rate during this time. All M-Series anomaly amplitudes over the eastern side of the Central Atlantic Ocean are lower than those over the western side.

The M25 to M0 province offshore North America is a region characterized by distinctive packages of anomalies (Fig. 9). M0 has a prominent

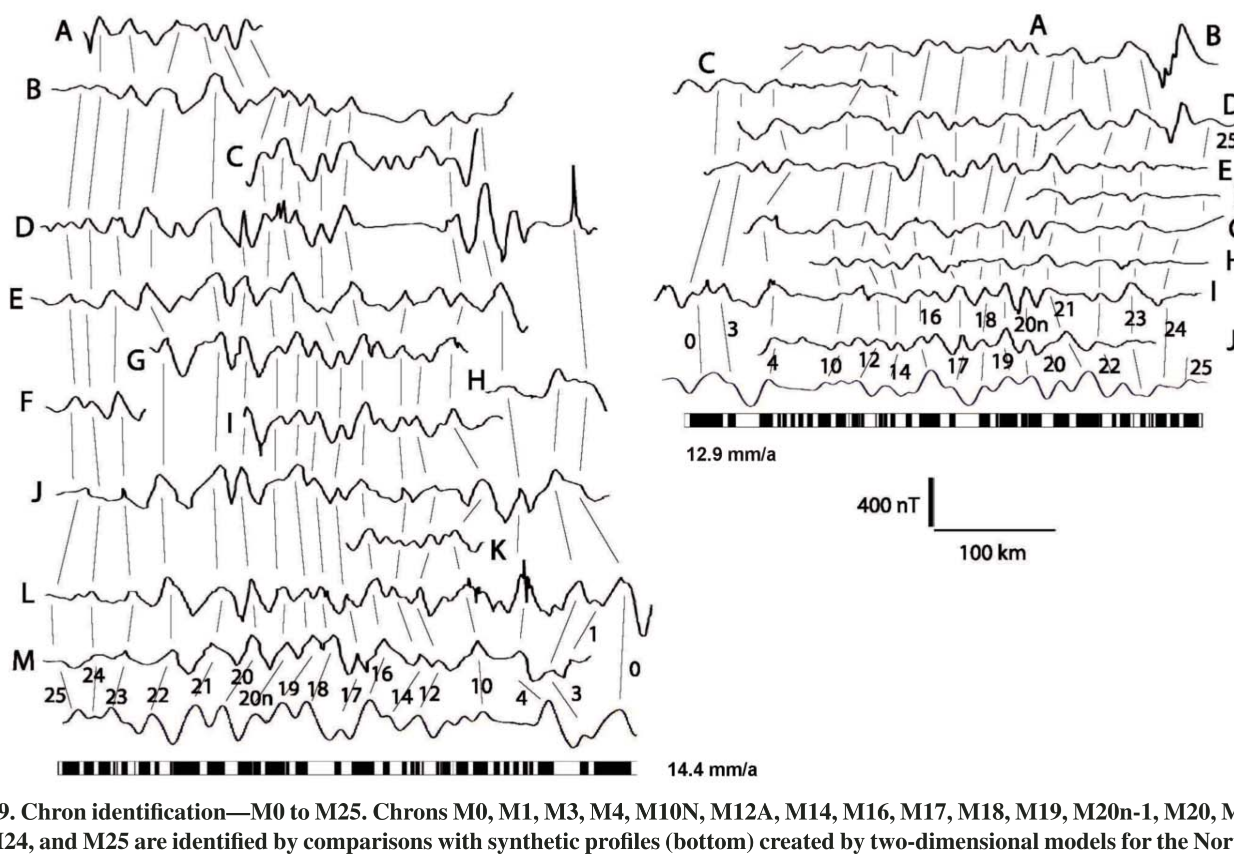

Figure 9. Chron identification—M0 to M25. Chrons M0, M1, M3, M4, M10N, M12A, M14, M16, M17, M18, M19, M20n-1, M20, M21, M22, M23, M24, and M25 are identified by comparisons with synthetic profiles (bottom) created by two-dimensional models for the North American and African flanks of the ocean basin using spreading rates of 14.4 mm/a and 12.9 mm/a, respectively. Line locations are displayed in Figures 7 and 8.

positive peak just landward of a sharp anomaly minimum; then a broad low is followed by a sequence of three peaks associated with the M1, M3, and M4 Chrons. M4 typically has the greatest amplitude of these three anomalies, similar to M0. Landward of M4, following an interval lacking coherent anomaly trends, are Chrons M10N, M12A, and M14. M10N typically coincides with a broad high-amplitude anomaly, which sometimes is expressed as two peaks and it is identified at the crest of the western flank of this anomaly. M12A and M14 are slightly lower in amplitude than M10, but coincide with distinctive peaks that, together with M10N, can be mapped with consistency from the Atlantis to the Fifteen-Twenty fracture zones. The package of anomalies bounded by M16 to M21 includes seven Chrons: M16, M17, M18, M19, M20n-1, M20, and M21. Chrons M16, M20, and M21 are the highest amplitude anomalies overall in the package, but are not well defined over the entire interval from the Atlantis to Fifteen-Twenty fracture zones. However, these Chrons are consistent with respect to their relative spatial position. Between M16 and M20, Chrons M17, M18, M19, and M20n-1 are just as consistent with respect to their position, although Anomaly M17 is often lower in amplitude. Between the Atlantis and Kane fracture zones, the next three prominent anomalies are Chrons M22, M23, and M24. M25 is more difficult to interpret. Its general character is a broad anomaly, with the Chron coinciding with highest amplitude at the crest of its eastern flank; however, often the western flank of the anomaly is much lower in amplitude and even absent at times.

M25 to M0 anomalies on the African side of the Central Atlantic do not identically mirror those on the North American side (Fig. 9). However, distinctive anomalies are correlated and interpreted such that the same Chrons are identified on both sides of the ocean basin. Similar to M0 anomalies over the North American plate, M0 anomalies over the African plate are characterized by a sharp minimum to the west followed by a relatively broad, high-amplitude peak to the east. Chron M4 is similar in shape to Chron M0. M1 and M3 anomalies are associated with anomaly peaks, and their spatial relation between M0 and M4 is consistent. Chrons M10N, M12A, and M14 are evenly spaced peaks; however, M12A is identified as the eastern peak of a pair of low-amplitude anomalies superimposed on a broad-anomaly high between M10N and M14. Chron M16 is identified as the western peak of a pair of anomalies. Chrons M17–M21 over the African plate mirror the same package of anomalies over the North American plate by an evenly spaced sequence of anomaly highs. Similar to the North American plate, Chron M17 is often a low-amplitude peak near the landward side of Chron 16. Unlike the North American plate, Chron M21 over the African plate is consistently higher in amplitude, and more prominent, than M20. This might be the result of our comparatively limited area of investigation on the African side of the basin. Chrons M22, M23, and M24 are the next landward set of peaks on the African plate, and M22 and M23 are easily mapped. However, M24 can only be mapped south of Profile D (Fig. 9). The low-amplitude Chron M25 is transitional to the

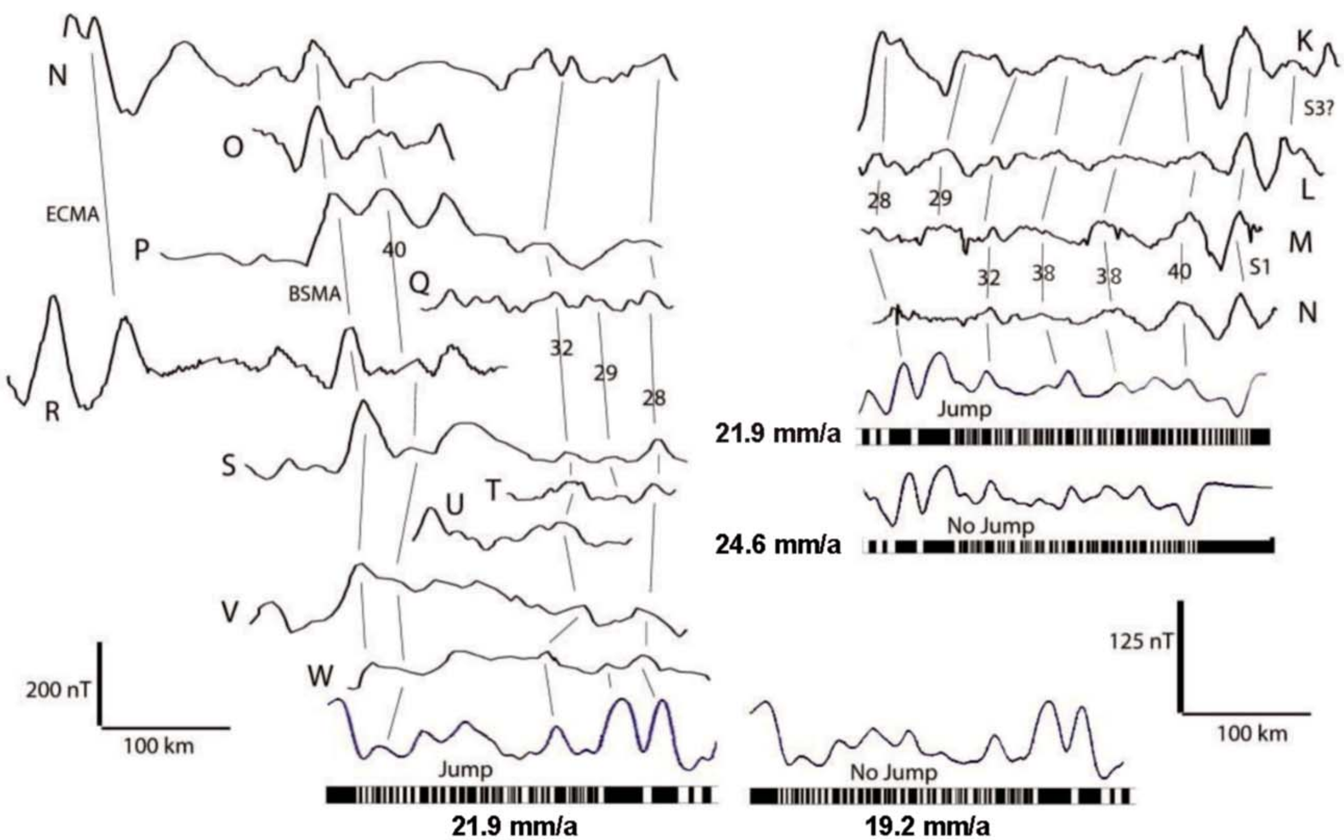

Figure 10. Chron identification—M28 to M40, Jurassic Magnetic Quiet Zone (JMQZ). Chrons M28, M29, M32, M38, and M40 are identified by comparisons with synthetic profiles (bottom) created by two-dimensional models for the North American and African flanks of the ocean basin. Two sets of synthetic models were generated: (1) assuming an asymmetric spreading rate of 19.2 mm/a for North America and 24.6 mm/a for Africa, and (2) assuming a ridge jump that left ~35 km of the North American plate on the African side between 164 Ma and 159 Ma using a symmetric spreading rate of 21.9 mm/a. Chrons M38 through M32 are reversed and repeated on the African flank. Line locations are displayed in Figures 7 and 8.

Jurassic Magnetic Quiet Zone, and it is mapped by correlating a broad, subtle, anomaly high. Also, anomaly M25, which is typically a low-amplitude anomaly, cannot be identified on profile B and only tentatively on Profile D because the Tropic Seamount produces high-amplitude (>400 nT) anomalies that interfere with Chrons along these profiles (Figs. 8 and 9).

Correlated "Jurassic Quiet Zone" anomalies over the North American plate include M28, M29, M32, and M40 (Fig. 10). M28 and M29 are similar in amplitude to M25, and, while their shapes vary somewhat from north to south, the distinct pair of relatively prominent anomalies is mapped with confidence in several locations. Chron M32 is also sometimes difficult to identify, but like M28 and M29, a distinct peak that is slightly higher in amplitude than the surrounding anomalies, similar to modeled anomalies, occurs in several locations. M40 is a persistent anomaly high that is mapped ~50–75 km outboard of the Blake Spur Magnetic Anomaly.

Mirroring the North American plate, M28 and M29 are mapped as a pair of peaks similar to and just landward of M25. M32, over the African plate, is a distinct peak that is slightly higher in amplitude than the surrounding anomalies, similar to M32 over the North American plate. The characteristic package of anomalies between Chrons M38 and M39 are superimposed on a broad, asymmetric high with a steep flank over M38 (Sager et al., 1998). M40 is a relatively high-amplitude anomaly that is mapped ~65 km outboard of S1.

Prominent, near-shore, magnetic anomalies, extending hundreds of kilometers parallel to the coasts of North America and Africa, have been identified: the "East Coast Anomaly" and "Blake Spur Anomaly" are ~180 km apart over North America (Figs. 1 and 5–7) (Klitgord and Schouten, 1986; Vogt, 1986), and the S1 and S3 anomalies over Africa are ~50 km apart (Figs. 1 and 8) (Roeser et al., 2002; Roeser, 1982; Verhoef et al., 1991). The amplitudes, trends, and lengths of "East Coast," "Blake Spur," S1, and S3 are similar to M-Series anomalies (M0 to M25). Vogt et al. (1971) and Vogt (1973; 1986) suggested that the Blake Spur Magnetic Anomaly is the result of an eastward jump of the spreading center away from the East Coast Magnetic Anomaly prior to 170 Ma.

The East Coast Magnetic Anomaly bends eastward at ~40º N, which appears to also be the northernmost extent of the Blake Spur Magnetic Anomaly. To the north of this eastward bend, Roeser et al. (2002) suggested that S1 and "East Coast" are conjugate anomalies that coincide with the oceanic-continental crustal boundary. However, Roest (1987) suggested that to the south, S1 and "Blake Spur" are conjugate anomalies. We interpret that East Coast Magnetic Anomaly-S3 and Blake Spur Magnetic Anomaly-S1 are conjugate anomalies and that East Coast Magnetic Anomaly and S3 coincide with the ocean-continent boundary.

Ridge Jumps and Asymmetric Spreading

Ninety-percent confidence regions of calculated Euler poles, are shown in Figure 11. Total reconstruction poles reported by Muller and Roest (1992) lie within the 90% confidence regions. Stage poles for the western and eastern sides of the Central Atlantic Ocean basin appear to show significant asymmetry (Table 3). However, the asymmetry suggested by stage-pole rotation angles can be misleading due to the proximity of a given pole with respect to a given plate location. That is, a small change in this distance can produce a relatively large change in the rotation angle when the plate being rotated is very close to, or even contains, the rotation pole. For example, M25 to M0 spreading rates offshore Morocco are 10 mm/a for M21 to M0, 16 mm/a for M25 to M21, and 10 mm/a for Jurassic Magnetic Quiet Zone (Roeser et al., 2002). This slow rate for the "Jurassic Quiet Zone" is reasonable when considering its close proximity to the reconstruction pole that describes the plate motion over this time ("M0-M25 SPE"; Fig. 11). Therefore, it is important to measure distances between Chrons over specific time intervals to determine relative spreading rates (Table 5).

Asymmetric spreading is characterized by excess seafloor accretion on one side of a spreading center and is typically less than 5%; however, the percentage of asymmetric spreading of the East Pacific Rise is over 10% (Muller et al., 1998). We interpret the widths of anomaly provinces C34 to Mid-Atlantic Ridge and M0 to C34 to indicate asymmetric spreading (Table 5). The spreading rate for the high-amplitude M25 through M0 Chrons in the North American plate (14.4 mm/a) is ~10.5% faster than the 12.9 mm/a spreading rate for the African plate, which indicates asymmetric spreading in this interval as well.

The spreading rate for the North American Jurassic Magnetic Quiet Zone reported by Klitgord and Schouten (1986) of 19 mm/a is close to the "Jurassic Quiet Zone" rate calculated in this analysis (19.2 mm/a); however, it differs significantly from our African "Jurassic zone" rate of 24.6 mm/a, which is ~22% greater. Figure 10 shows correlated anomalies for the low-amplitude M40 to M28 sequence compared to two-dimensional synthetic models using two different sets of spreading velocities. This large difference in spreading rates suggests that a ridge jump may have occurred in this time interval. Therefore, the magnetic data over the African side were inspected for repeated anomalies. A sequence of anomalies near M38 appears to repeat on the few profiles we analyzed and could account for an additional ~70 km of oceanic crust that seems to be absent from the North American side. The seafloor spreading models were modified by removing these Chrons from the North American model and inserting them into the African model such that correlated "Jurassic Quiet Zone" anomalies over Africa include M28, M29, M32, M38 (abandoned from the North American side), M38 (African side), and M40. The combined width of the conjugate Jurassic Magnetic Quiet Zones is 570 km, corresponding to a total symmetric spreading rate of 43.8 mm/a. We then use a half-spreading rate of 21.9 mm/a for each side of this low-amplitude sequence. Comparing "Jurassic Quiet Zone" anomalies with those calculated from our ridge-jump models suggests that a sequence of anomalies approximately between M38 and M32 could be produced by a sliver of oceanic lithosphere that was abandoned by a ridge jump.

TABLE 5. MEAN SPREADING RATES

	Distance (km)	Rate (mm/a)	Percentage of asymmetry
West: MAR to C34	1420	16.9	+10.0%
East: MAR to C34	1280	15.2	
West: C34 to M0	810	22.1	–3.5%
East: C34 to M0	837	22.9	
West: M0 to M25	480	14.4	+10.5%
East: M0 to M25	430	12.9	
West: M25 to M40	250	19.2	–22.0%
East: M25 to M40	320	24.6	
West: M40 to BSMA	65		
East: M40 to S1	65		
West: BSMA to ECMA	180		
East: S1 to S3	50		

Note: Mean spreading rates calculated from the east-west distances along the Atlantis and Kane fracture zones between the Mid-Atlantic Ridge and interpreted Chrons.

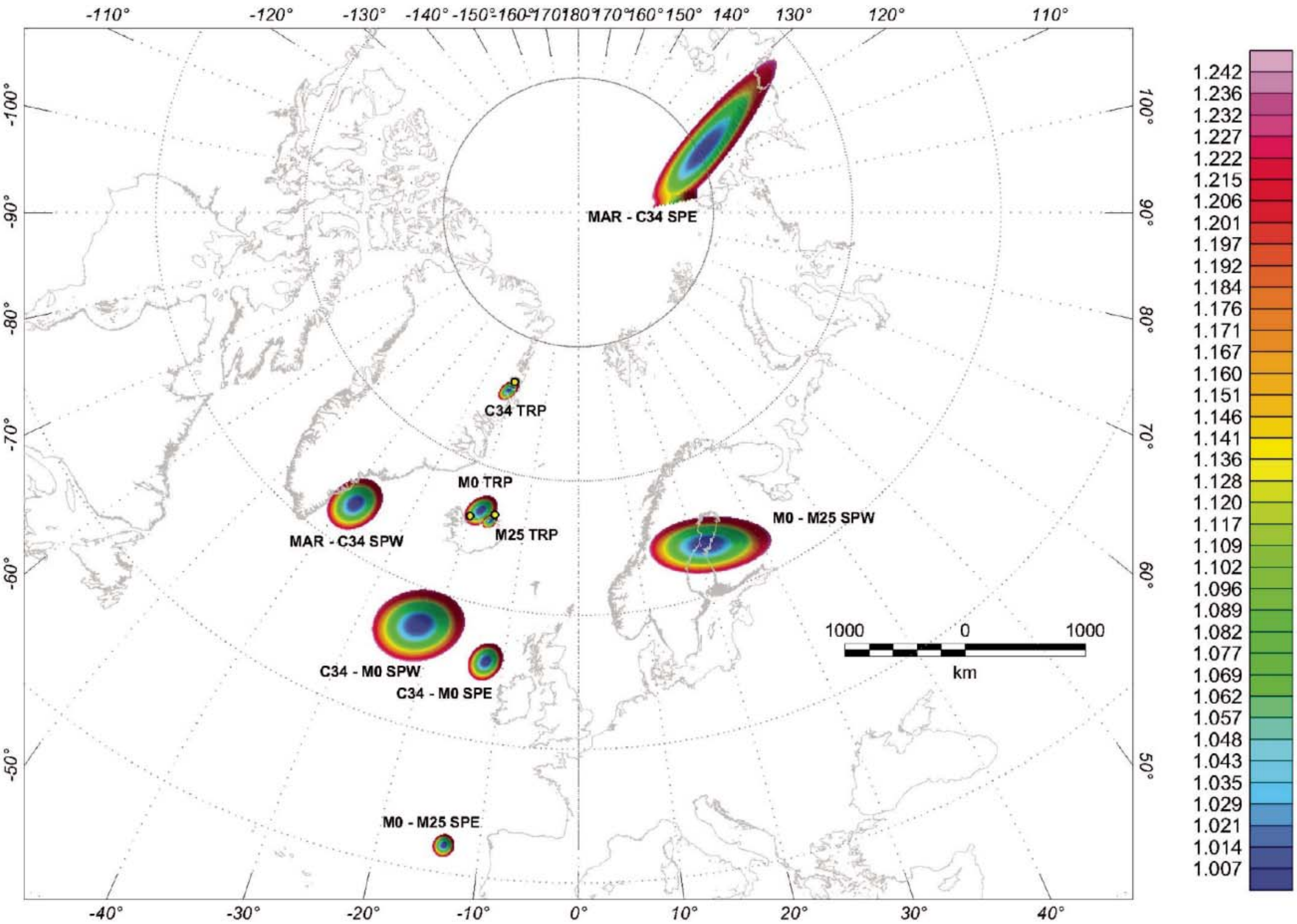

Figure 11. Finite-difference pole confidence regions. Error ellipse grids show 90% confidence regions for all calculated stage poles and total reconstruction poles. Stage poles ellipsoids for Mid-Atlantic Ridge (MAR) to Chron C34, Chrons C34 to M0, and Chrons M0 to M25 are SPW and SPE for the western and eastern flanks of the Central Atlantic ocean basin. Total reconstruction pole (TRP) ellipsoids are compared with those reported by Muller and Roest (1992) (yellow circles).

The proximity of the African Jurassic Magnetic Quiet Zone stage pole, and the fanning of North American M25 to M0 and "Jurassic Quiet Zone" anomalies to the south, indicate that this distance increases southward to 10° N. Furthermore, Roeser et al. (2002) reported that interpreted anomalies over the Seine Abyssal Plain, offshore Morocco, approach S1 northward at a 10° angle, which also reflects the close proximity to the rotation pole for this interval. We suggest that the difference in "Jurassic Quiet Zone" widths indicates that a ridge jump occurred between 164 and 159 Ma (Chrons M38 to M32), abandoning ~35 km of North American lithosphere on the African side of the Central Atlantic ocean basin, but that its extent and timing cannot be determined with precision.

Our identification of M40 along North America suggests that the high-amplitude western and eastern basin bounding anomalies, East Coast Magnetic Anomaly-S3 and Blake Spur Magnetic Anomaly-S1, are conjugate pairs. The asymmetric spreading required to create oceanic crust from "East Coast" to "Blake Spur" (180 km), and S3 to S1 (50 km), greatly exceeds the maximum asymmetry reported by Muller et al. (1998). We conclude that a ridge jump occurred within the Inner Magnetic Quiet Zone, substantiating the ridge jump hypothesized by Vogt et al. (1971) and Vogt (1973; 1986). This jump probably occurred prior to 167 Ma (M40). Roeser et al. (2002) identified Chrons M41 to M25 off the coast of Morocco, reported that Seaward Dipping Reflectors (SDR) coincide with S1, and assigned an age of 170 Ma for that anomaly. Assuming a constant spreading rate of 21.9 mm/a over the 65-km distance from "Blake Spur" to M40 and S1 to M40, the time interval would be 2.97 m.y. and indicates that this early ridge jump occurred ca.170 Ma as postulated by Vogt for the western flank, and it is consistent with the S1 age for the eastern flank (Roeser et al., 2002).

Plate Reconstructions

Figures 12, 13, and 14 show North American and African plate reconstructions for 84 Ma, 120.6 Ma, and 154 Ma, coinciding with Chrons C34, M0, and M25. Plates are rotated with respect to the trace of the Mid-Atlantic Ridge using the calculated stage poles (Table 3). Gravity anomalies over fracture zones for C34 and M0 reconstructions (Figs. 12 and 13) are continuous across the Mid-Atlantic Ridge, adding confidence to the plate reconstruction. Inspection of the M25 reconstruction (Fig. 14) illustrates the differences in distance between

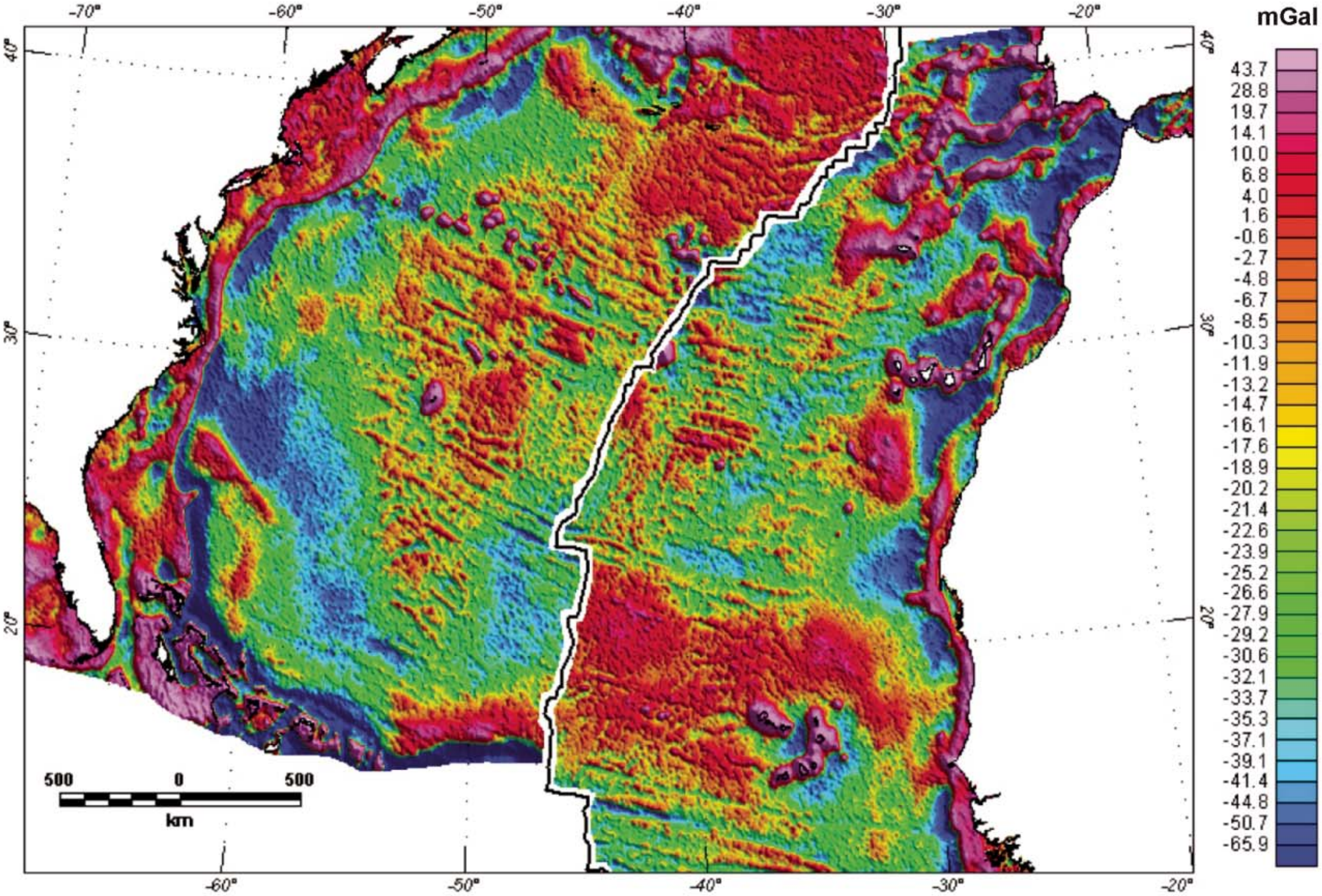

Figure 12. North America-Africa plate reconstruction by closing the Central Atlantic on both sides to Chron C34 (84 Ma). The angles of rotation are 20.00° for North America and 11.81° for Africa (Table 3). Satellite-derived, free-air gravity anomalies show continuous linear feature across the Mid-Atlantic Ridge (MAR).

"Jurassic Quiet Zone" provinces as well as the relative distance spanned by the Inner Magnetic Quiet Zone section during this time.

DISCUSSION

Blake Plateau

Seafloor spreading in the Central Atlantic is marked by the onset of post-rift sediment deposition in early Middle Jurassic, or ca. 185 Ma (Withjack et al., 1998). Dunbar and Sawyer (1989) suggested that the preexisting structural grain of the continental crust controlled the amount of continental extension prior to breakup. They concluded seafloor spreading begins first along segments that follow the structural grain, that extension prior to breakup is symmetrical, and that the amount of this extension is two to three times less than the amount of extension that crosses the preexisting structural grain. They also concluded that the total range of continental extension in the Central Atlantic is 200 km to over 600 km, and that this variability is largely controlled by the preexisting weaknesses within the structural grain and the ultimate orientation of the continental break. The largest extension along North America in the Central Atlantic is over 600 km in the region of the Blake Plateau, south of the Blake Spur fracture zone (Dunbar and Sawyer, 1989), which offsets Chrons M25 to M0 by 30–50 km (Fig. 5).

The continental boundary in the Blake Plateau suggested by Dunbar and Sawyer (1989) extends to Chron M32 mapped in this study. Inboard of this margin, we map the southernmost 280 km of Chron M40. Although Jurassic Magnetic Quiet Zone anomalies are difficult to correlate, our interpretation is consistent with the trend of the Blake Spur Magnetic Anomaly and the mapped limit of oceanic crust (Uchupi et al., 1984b), which are located ~200 km landward of Dunbar and Sawyer's (1989) proposed southeastward extent of continental crust beneath the Blake Plateau. Seismic refraction data in this part of the Blake Plateau include lines interpreted by Ewing and Ewing (1959), Katz and Ewing (1956), and Sheridan et al. (1966). Table 4 summarizes seismic refraction data in and near the Blake Plateau. Except for the crust beneath Line 102, crustal thicknesses range from 5.9 km to 6.7 km. Line 102 lies over the northwest projection of the "Blake Spur Fracture Zone," and the crustal thickness along this line is consistent with the crustal thickness of other fracture zones in the Atlantic Ocean, which is ~2–3 km (Fox and Gallo, 1984).

The Blake Plateau overlies a broad basin that is ~5–6 km deep overall, but exceeds 8 km just north of 30° N, 78° W (Crosby et al., 1984). Seismic refraction data from several profiles were combined and interpreted over an 800-km-long, east-west cross section, from the west coast of Florida at 30° N eastward to ~76° W at 29° N (Fig. 15) (Sheridan et al., 1966). Inboard of seismic refraction Line 102 they interpreted a 2-km-thick, 5.3–5.5 km/s layer overlying basement to be volcanics, and a ridge (5.7–6.1 km/s) that rises ~2.5 km along the outer edge of the Blake Plateau to be basement. The deepest horizon detected between these volcanics and the basement ridge, at 3–4 km, is defined by velocities ranging between 5.5 and 6.0 km/s. They suggested that it might be equivalent to Paleozoic basement rocks of Florida.

Dietz (1973) proposed that the Bahamas overlie the Early Jurassic mantle plume that

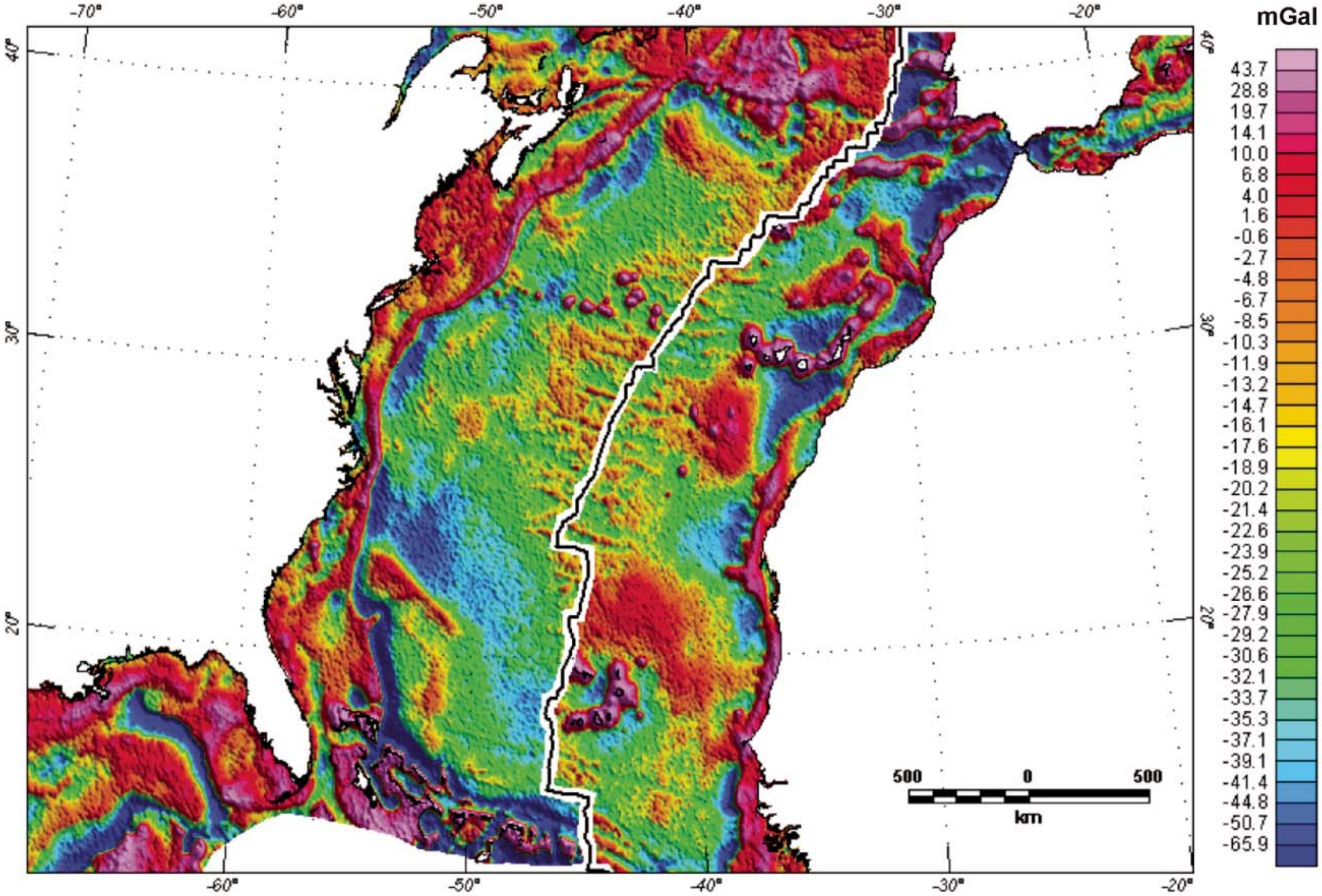

Figure 13. North America-Africa plate reconstruction by closing the Central Atlantic on both sides to Chron M0 (120.6 Ma). The angles of rotation are 31.90° for North America and 22.98° for Africa (Table 3). Satellite-derived, free-air gravity anomalies still show continuous linear feature across the Mid-Atlantic Ridge (MAR).

produced the extensive tholeiitic intrusions and flows of the Central Atlantic Magmatic Province (CAMP). Marzoli et al. (1999) reported that the total aerial extent affected by the CAMP Plume was greater than 7 million square kilometers on North America, Africa, and South America. They also reported that this volcanism occurred over just a few million years and that the peak activity was 200 Ma, or ~15 m.y. before seafloor spreading commenced in the Central Atlantic Ocean. However, if, as Dietz (1973) suggests, the Bahamas overlie seamounts produced by the CAMP Plume, then volcanic activity continued as seafloor was accreted in the Central Atlantic Ocean. Therefore, the presence of thick volcanics on the oceanic basement of the Blake Plateau seems reasonable. Although a comprehensive understanding of the history and makeup of the Blake Plateau is beyond the scope of this paper, we suggest that it is not possible to rule out the presence of oceanic crust beneath the Plateau. Therefore, based on similarities of anomalies along nine profiles, we tentatively extend Chron M40 over the Blake Plateau with dashed lines.

Refraction data support the existence of oceanic crust extending landward at least to the Blake Spur Magnetic Anomaly (Ewing and Ewing, 1959; Houtz, 1980; Katz and Ewing, 1956) (Table 4). Moho depths are not measured beneath the deep Carolina Trough and Blake Plateau. However interpretations of reflection data summarized by Withjack et al. (1998) indicate that a zone of Seaward-Dipping Reflectors (SDR) coincides with the East Coast Magnetic Anomaly from its southern end at ~30° N along the North American continental shelf to ~43° N, just south of Nova Scotia.

Chron Identification and Ridge Jumps

Unlike magnetic anomalies over M25 to M0 Chrons, "Jurassic Quiet Zone" anomalies are characterized by extremely rapid reversal rates and low amplitudes. Vogt et al. (1970) suggested that these low amplitudes could be the result of a period of rapid polar wander or that they formed at the magnetic equator. Sager et al. (1998) reported that M27 to M30 have been verified by magnetic stratigraphy, and that while magnetostratigraphic data corresponding to M38 and older are lacking, short wavelength anomalies are similar to other paleointensity variations corresponding to periods of 300–150 k.y. They noted, however, that magnetization strength data are poorly constrained and they concluded that the Jurassic geomagnetic field behavior was unusual. If the modeled polarity reversals exist, then the geomagnetic polarity reversal rate is extraordinarily high: ~12 per m.y. or 20% higher than the period between M25 and M26, which would then be the second highest reversal rate (Sager et al., 1998). They suggested that the anomalies could be produced by paleointensity fluctuations instead of geomagnetic polarity reversals.

Both ridge jumps described in this study are consistent in dimension and duration with other ridge jumps observed around the world.

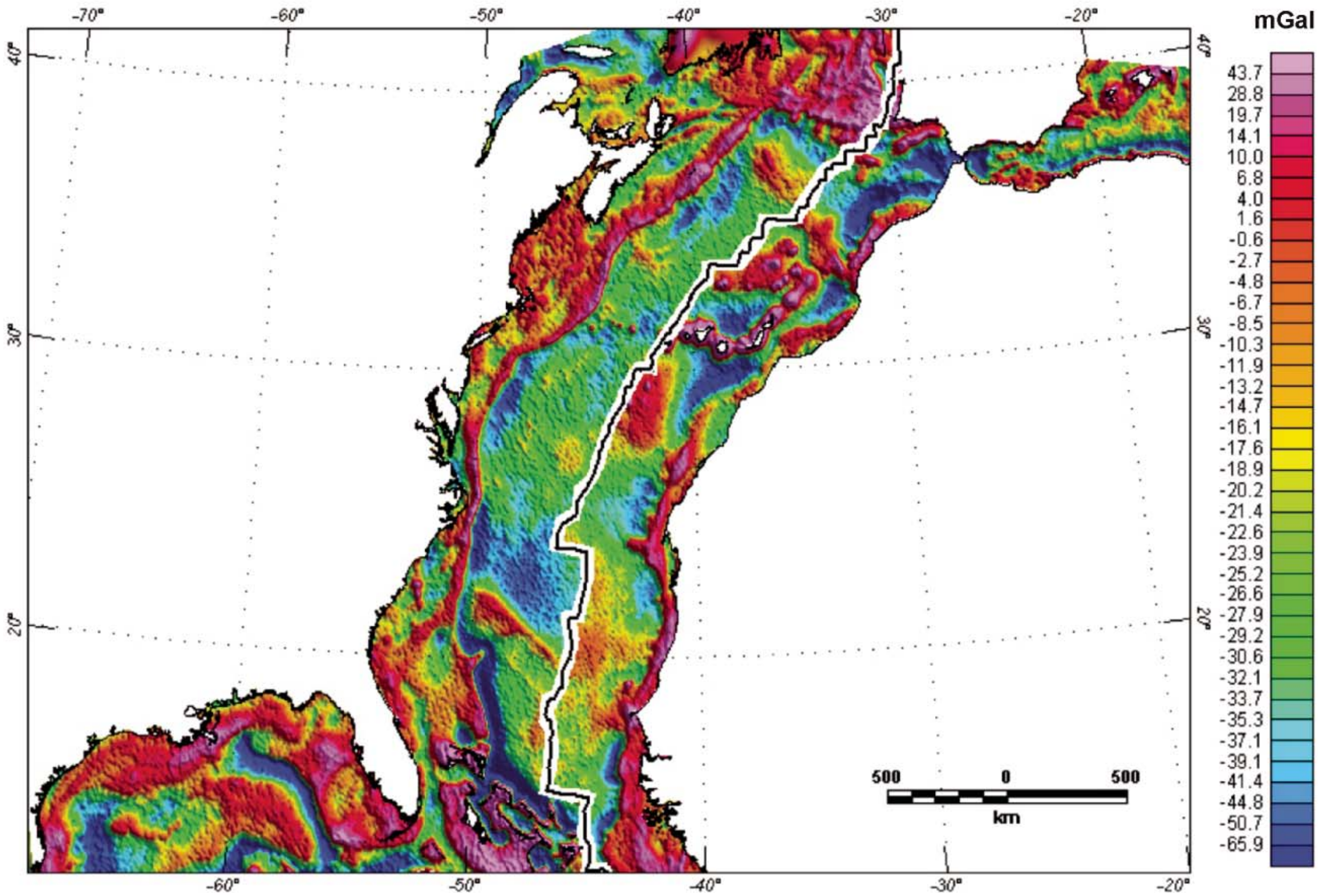

Figure 14. North America-Africa plate reconstruction by closing the Central Atlantic on both sides to Chron M25 (154 Ma). The angles of rotation are 36.34° for North America and 29.86° for Africa (Table 3). Linear correlations are difficult to interpret in the satellite-derived, free-air gravity data.

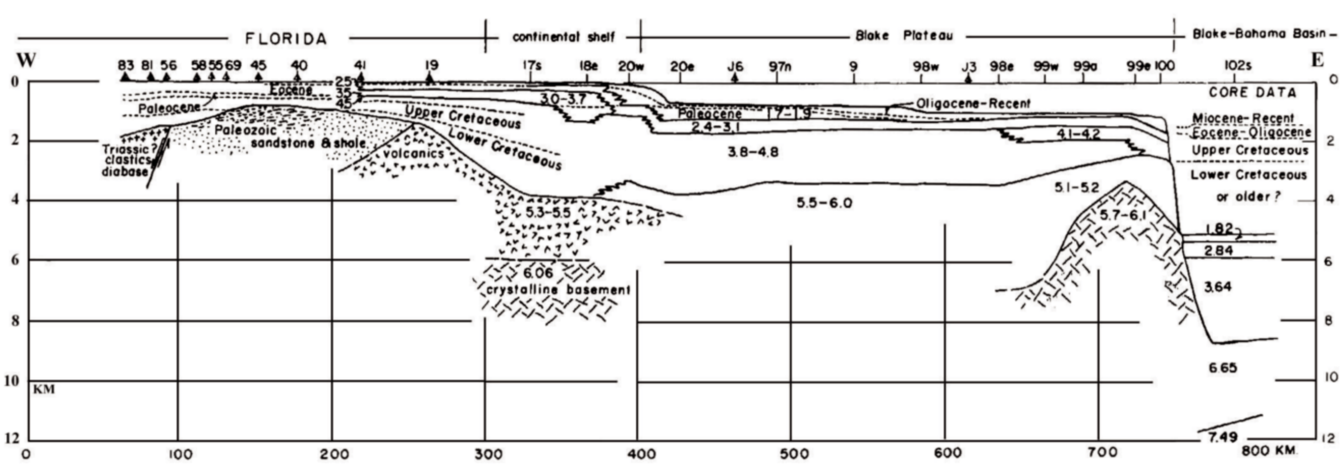

Figure 15. A west-east cross section, between 29º and 30º N across Florida and the Blake Plateau from 84º to 76º W, interpreted from seismic refraction data (Sheridan et al., 1966).

The relocation of seafloor spreading centers, or ridge jumps, has been documented along the Mid-Atlantic Ridge near the Ascension Fracture Zone (Brozena, 1986), seven locations west of the East Pacific Rise, including two ridge jumps currently under way on the East Pacific Rise (Luhr et al., 1985; Morton and Ballard, 1986; Mammerickx et al., 1988; Mammerickx and Sandwell, 1986), south of the Chilean Ridge (Mammerickx et al., 1988), and three locations in the north Pacific (Mammerickx et al., 1988). Between Mexico and the Galapagos Ridge, Luhr et al. (1985) document several ridge jumps over the past 12 Ma with jumps ranging from ~500 km to 1100 km.

CONCLUSIONS

Combining extensive magnetic data sets with satellite-derived, free-air gravity data has allowed us to map several M-Series Chrons in detail, estimate asymmetric spreading rates, and interpret two ridge jumps in previously poorly constrained swaths of the Central Atlantic Ocean. We calculate new Euler poles: stage poles for the North American and Africa sides of the basin, and total reconstruction poles for Chrons C34 (84 Ma), M0 (120.6 Ma) and M25 (154 Ma). Measured distances on the North American and African flanks between the Mid-Atlantic Ridge and Chron C34, Chrons C34 and M0, and Chrons M0 and M25 reveal asymmetric spreading (Table 5). From 154 Ma to the present, we calculate three time intervals of overall asymmetric spreading: 10.5% to the west from Chrons M25 to M0 (154 Ma to 120.6 Ma), 3.5% to the east during the Cretaceous Magnetic Quiet Zone (120.6 Ma to 84 Ma), and 10% to the west since the end of the Cretaceous Magnetic Quiet Zone (84 Ma to present).

The mapped southernmost extent of Chron M40 on the North American flank of the ocean basin, extending into the Blake Plateau, suggests that the crust beneath the plateau is oceanic and that the ocean-continent crustal boundary lies along trend with the ocean boundary interpreted by Uchupi et al. (1984a; 1984b). The second vertical derivative of total-intensity magnetic anomalies reveals subtle anomalies over the Inner Magnetic Quiet Zone that are sub-parallel to the "East Coast" and "Blake Spur" (Behrendt and Grim, 1985), further supporting the existence of oceanic crust between these two anomalies.

Newly mapped M-Series Chrons in the Jurassic Magnetic Quiet Zone, and their positions with respect to the prominent Blake Spur Magnetic Anomaly off the continental shelf of North America and S1 anomaly off the continental shelf of Africa, support the identification of two ridge jumps: (1) a previously theorized eastward jump at ca. 170 Ma (Vogt et al., 1971; Vogt, 1973; 1986), and (2) a westward jump between M32 and M38 (159 Ma and 164 Ma). These ridge jumps, especially the latter, could correspond with the opening of the Gulf of Mexico.

ACKNOWLEDGMENTS

We would like to thank Walter Roest at the Geological Survey of Canada for sending a copy of the Kroonvlag project, which is a ship-track magnetic data set (also known as the "Collette Data").

REFERENCES CITED

Behrendt, J.C., and Grim, M.S., 1985, Structure of the U.S. Atlantic continental margin from derivative and filtered maps of the magnetic field, *in* Hinze, W.J., The utility of regional gravity and magnetic anomaly maps: Tulsa, Society of Exploration Geophysicists, p. 325–338.

Bird, D.E., 2004, Jurassic tectonics of the Gulf of Mexico and Central Atlantic Ocean: University of Houston [Ph.D. thesis], 161 p.

Brozena, J.M., 1986, Temporal and spatial variability of seafloor spreading processes in the northern South Atlantic: Journal of Geophysical Research, v. 91, p. 497–510.

Channell, J.E.T., Erba, E., Nakanishi, M., and Tamaki, K., 1995, Late Jurassic-Early Cretaceous time scales and oceanic magnetic anomaly block models, *in* Geochronology, time scales and global stratigraphic correlation: SEPM Special Publication, v. 54, p. 51–63.

Collette, B.J., and Roest, W.R., 1992, Further investigations of the North Atlantic between 10° and 40°N and an analysis of spreading from 118 Ma ago to present: Amsterdam, Proceedings Koninklijke Nederlandse Akademie van Wetenschappen, Series B, v. 95, p. 159–206.

Collette, B.J., Slootweg, A.P., Verhoef, J., and Roest, W.R., 1984, Geophysical investigations of the floor of the Atlantic Ocean between 10° and 38°N (Kroonvlag-project): Amsterdam, Proceedings Koninklijke Nederlandse Akadademie van Wetenschappen, Series B, v. 87, p. 1–80.

Crosby, J.T., Uchupi, E., Manley, P.L., Bolmer, S.T., Jr., Eudsen, J.D., Jr., Gleason, R.J., and Ewing, J.I., 1984, Depth to basement, *in* Bryan, G.M., and Heirtzler, J.R., eds., Eastern North American continental margin and adjacent ocean floor, 28° to 36°N and 70° to 82°W: Woods Hole, Marine Science International, Atlas 5, p. 9.

Dietz, R.S., 1973, Morphologic fits of North America/Africa and Gondwana: A review, *in* Tarling, D.H., and Runcorn, S.K., eds., Implications of continental drift to the earth sciences, Volume 2: London, Academic Press, p. 865–872.

Dunbar, J.A., and Sawyer, D.S., 1989, Patterns of continental extension along the conjugate margins of the central and North Atlantic Oceans and Labrador Sea: Tectonics, v. 8, p. 1059–1077.

Engebretson, D.C., Cox, A., and Gordon, R.G., 1984, Relative motions between oceanic plates of the Pacific basin: Journal of Geophysical Research, v. 89, p. 10291–10310.

Ewing, J., and Ewing, M., 1959, Seismic-refraction measurements in the Atlantic Ocean basins, in the Mediterranean Sea, on the Mid-Atlantic Ridge, and in the Norwegian Sea: Geological Society of America Bulletin, v. 70, p. 291–318, doi: 10.1130/0016-7606(1959)70[291:SMITAO]2.0.CO;2.

Fox, P.J., and Gallo, D.G., 1984, A tectonic model for ridge-transform-ridge plate boundaries: Implications for the structure of oceanic lithosphere: Tectonophysics, v. 104, p. 205–242, doi: 10.1016/0040-1951(84)90124-0.

Hinze, W.J., Hood, P.J., Bonini, W.E., Case, J.E., de la Fuente, M., Godson, R.H., and Hall, S., Hanna, W.F., Heirtzler, J.R., Higgs, R.H., Kleinkopf, M.D., Meyers, H., Palmer, A.R., Peddie, N.W., Reford, M.S., Teskey, D.J., Thorning, L., and Zietz, I., 1988, Magnetic anomaly map of North America: The Leading Edge, v. 7, no. 11, p. 19–21.

Houtz, R.E., 1980, Crustal structure of the North Atlantic on the basis of large-airgun—Sonobuoy data: Geological Society of America Bulletin, v. 91, Part I, p. 406–413, doi: 10.1130/0016-7606(1980)91<406:CSOTNA>2.0.CO;2.

Katz, S., and Ewing, M., 1956, Seismic-refraction measurements in the Atlantic Ocean, part VII: Atlantic Ocean basin, west of Bermuda: Geological Society of America Bulletin, v. 67, p. 475–510, doi: 10.1130/0016-7606(1956)67[475:SMITAO]2.0.CO;2.

Klitgord, K.D., and Schouten, H., 1986, Plate kinematics of the central Atlantic, *in* Vogt, P.R., and Tucholke, B.E., eds., The geology of North America: The western North Atlantic region: Boulder, Colorado, Geological Society of America, v. M, p. 351–378.

Luhr, J.F., Nelson, S.A., Allan, J.F., and Carmichael, S.E., 1985, Active rifting in southwestern Mexico: Manifestations of an incipient eastward spreading-ridge jump: Geology, v. 13, p. 54–57, doi: 10.1130/0091-7613(1985)13<54:ARISMM>2.0.CO;2.

Mammerickx, J., Naar, D.F., and Tyce, R.L., 1988, The mathematician paleoplate: Journal of Geophysical Research, v. 93, p. 3025–3040.

Mammerickx, J., and Sandwell, D., 1986, Rifting of old oceanic lithosphere: Journal of Geophysical Research, v. 91, p. 1975–1988.

Marzoli, A., Renne, P.R., Piccirillo, E.M., Ernesto, M., Bellieni, G., and De Min, A., 1999, Extensive 200-million-year-old continental flood basalts of the central Atlantic magmatic province: Science, v. 284, p. 616–618, doi: 10.1126/science.284.5414.616.

Morton, J.L., and Ballard, R.D., 1986, East Pacific Rise at lat 19°S: Evidence for a recent ridge jump: Geology, v. 14, p. 111–114, doi: 10.1130/0091-7613(1986)14<111:EPRALS>2.0.CO;2.

Muller, R.D., and Roest, W.R., 1992, Fracture zones in the North Atlantic from combined Geosat and Seasat data: Journal of Geophysical Research, v. 97, p. 3337–3350.

Muller, R.D., Roest, W.R., and Royer, J.-Y., 1998, Asymmetric sea-floor spreading caused by ridge-plume interactions: Nature, v. 396, p. 455–459, doi: 10.1038/24850.

Muller, R.D., Roest, W.R., Royer, J.-Y., Gahagan, L.M., and Sclater, J.G., 1997, Digital isochrons of the world's ocean floor: Journal of Geophysical Research, v. 102, p. 3211–3214, doi: 10.1029/96JB01781.

Muller, R.D., Royer, J.-Y., Cande, S.C., Roest, W.R., and Maschenkov, S., 1999, New constraints on the Late Cretaceous/Tertiary plate tectonic evolution of the Caribbean, *in* Mann, P., ed. (Hsu, K.J., series editor), Caribbean basins: Sedimentary basins of the world, Volume 4: Amsterdam, Elsevier Science, p. 33–59.

Muller, R.D., and Smith, W.H.F., 1993, Deformation of the oceanic crust between the North American and South American plates: Journal of Geophysical Research, v. 98, p. 8275–8291.

Roeser, H.A., 1982, Magnetic anomalies in the magnetic quiet zone off Morocco, *in* von Rad, U., Hinz, K., Sarnthein, M., and Seibold, E., eds., Geology of the Northwest African Continental Margin: Berlin, Springer-Verlag, p. 61–68.

Roeser, H.A., Steiner, C., Schreckenberger, B., and Block, M., 2002, Structural development of the Jurassic Magnetic Quiet Zone off Morocco and identification of Middle Jurassic magnetic lineations: Journal of Geophysical Research, v. 107, p. 2207, doi: 10.1029/2000JB000094, doi: 10.1029/2000JB000094.

Roest, 1987, Seafloor spreading pattern of the North Atlantic between 10° and 40°N: Geologica Ultraiectina, 48, 121 p.

Rona, P.A., Brakl, J., and Heirtzler, J.R., 1970, Magnetic anomalies in the northeast Atlantic between the Canary and Cape Verde Islands: Journal of Geophysical Research, v. 75, p. 7412–7420.

Sager, W.W., Weiss, C.J., Tivey, M.A., and Johnson, H.P., 1998, Geomagnetic polarity reversal model of deep-tow profiles from the Pacific Jurassic Quiet Zone: Journal of Geophysical Research, v. 103, p. 5269–5286, doi: 10.1029/97JB03404.

Sandwell, D.T., and Smith, W.H.F., 1997, Marine gravity anomaly from Geosat and ERS 1 satellite altimetry: Journal of Geophysical Research, v. 102, p. 10039–10054, doi: 10.1029/96JB03223.

Sheridan, R.E., Drake, C.L., Nafe, J.E., and Hennion, J., 1966, Seismic-refraction study of continental margin east of Florida: Bulletin of the American Association of Petroleum Geologists, v. 50, p. 1972–1991.

Uchupi, E., Bolmer, S.T., Jr., Eusden, J.D., Jr., Ewing, J.I., Costain, J.K., Gleason, R.J., and Glover, L., III, 1984a, Tectonic features, *in* Ewing, J.I., and Rabinowitz, P.D., eds., Eastern North American continental margin and adjacent ocean floor, 34° to 41°N and 68° to 78°W: Woods Hole, Marine Science International, Atlas 4, p. 28.

Uchupi, E., Crosby, J.T., Bolmer, S.T., Jr., Eusden, J.D., Jr., Ewing, J.I., Costain, J.K., Gleason, R.J., and Glover, L., III, 1984b, Tectonic features, *in* Bryan, G.M., and Heirtzler, J. R., eds., Eastern North American continental margin and adjacent ocean floor, 28° to 36°N and 70° to 82°W: Woods Hole, Marine Science International, Atlas 5, p. 36.

Verhoef, J., Collette, B.J., Danobeitia, J.J., Roeser, H.A., and Roest, W.R., 1991, Magnetic anomalies off west Africa (20°-38°N): Marine Geophysical Research, v. 13, p. 81–103.

Verhoef, J., Roest, W.R., Macnab, R., Arkani-Hamed, J., and Members of the Project Team, 1996, Magnetic anomalies of the Arctic and North Atlantic Oceans and adjacent land areas: Dartmouth, Geological Survey of Canada (Atlantic), scales 1:10,000,000 and 1:6,000,000, 2 sheets.

Vogt, P.R., 1973, Early events in the opening of the North Atlantic, *in* Tarling, D.H., and Runcorn, S.K., eds., Implications of continental drift to the earth sciences: London, Academic Press, p. 693–712.

Vogt, P.R., 1986, Magnetic anomalies and crustal magnetization, *in* Vogt, P.R., and Tucholke, B.E., eds., The geology of North America: The western Atlantic region: Boulder, Geological Society of America, v. M, p. 229–256.

Vogt, P.R., Anderson, C.N., and Bracey, D.R., 1971, Mesozoic magnetic anomalies, sea-floor spreading, and geomagnetic reversals in the southwestern North Atlantic: Journal of Geophysical Research, v. 76, p. 4796–4823.

Vogt, P.R., Anderson, C.N., Bracey, D.R., and Schneider, E.D., 1970, North Atlantic magnetic smooth zones: Journal of Geophysical Research, v. 75, p. 3955–3968.

Withjack, M.O., Schlische, R.W., and Olsen, P.E., 1998, Diachronous rifting, drifting, and inversion on the passive margin of central eastern North America: An analog for other passive margins: American Association of Petroleum Geologists Bulletin, v. 82, p. 817–835.

Manuscript Received 26 March 2006
Revised Manuscript Received 8 June 2007
Manuscript Accepted 9 July 2007