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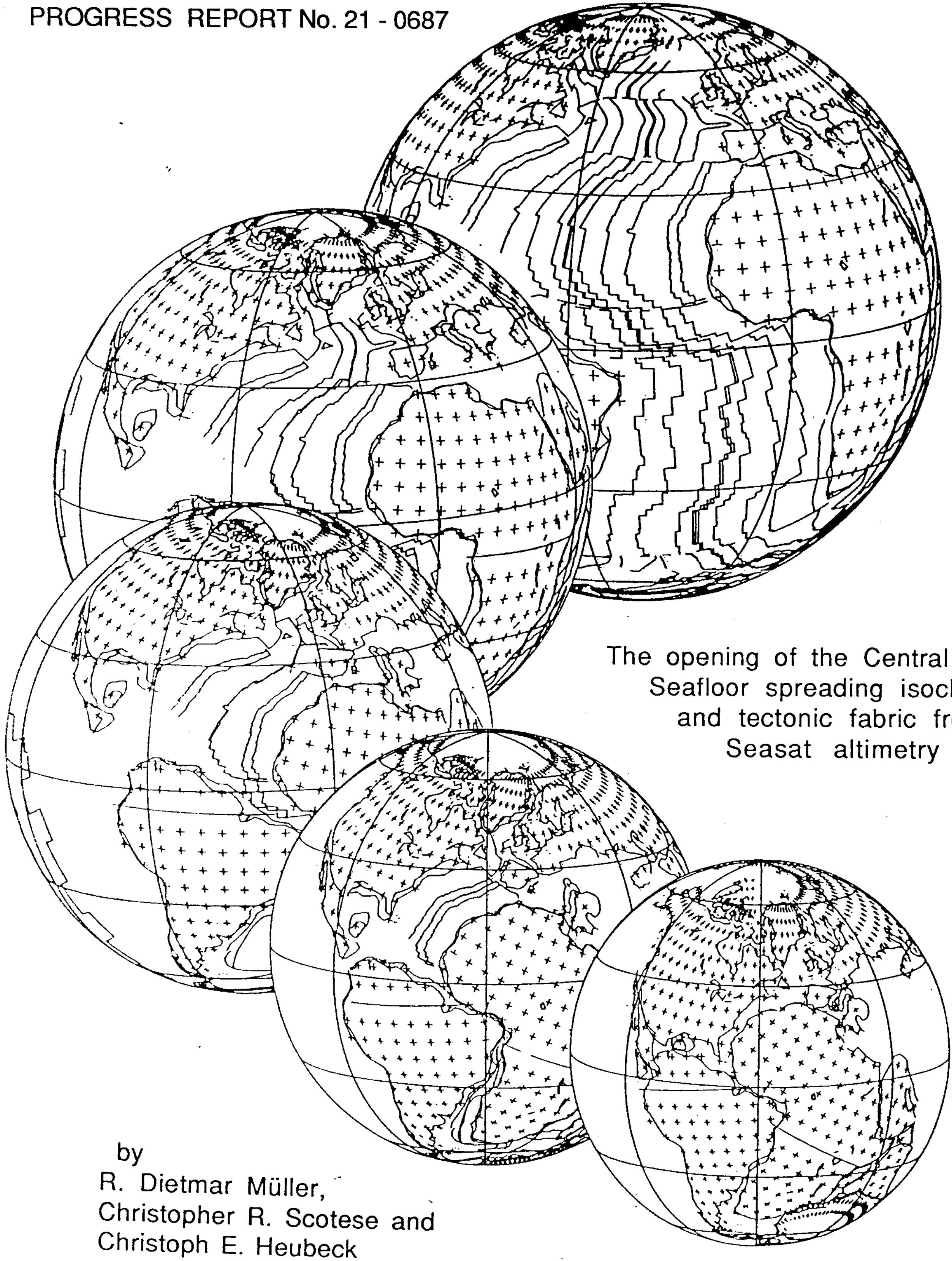

The opening of the Central Atlantic: Seafloor spreading isochrons and tectonic fabric from Seasat altimetry

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Introduction

During the last 17 years, at least 9 models for the opening history of the Central Atlantic (between the Azores Fracture zone and Fifteen Twenty Fracture zone) have been proposed (see POMP Progress Report No. 20). The increasing complexity of the plate tectonic models reflects the use of new magnetic data and improved modeling techniques. In this report we outline the procedures and data we have used to produce a revised plate tectonic model describing the opening of the Central Atlantic. Table 1 lists the finite rotation poles we have determined for 19 time slices during the Mesozoic and Cenozoic. Figures 2-5 illustrate our reconstructions for chron 21, 34, M0 and 170 Ma. (Blake Spur Magnetic Anomaly).

The essence of a plate tectonic model is a set of finite rotation poles, which can be used to calculate spreading directions and rates. From these rotation parameters synthetic flowlines describing the separation of two plates can be drawn. A flowline consists of small circle segments that describe the motion about stage poles for the time between two identified anomaly lineations (Klitgord & Schouten 1986). Ideally, the flowlines should be identical to fracture zone traces on the ocean floor.

Up to now, however, it has not been possible to evaluate the quality of predicted flowlines because the coverage and availability of fracture zone bathymetry data for different parts of the ocean floor is highly variable. Seasat altimetry data now provide broad picture of the tectonic fabric of the ocean basins. They allow a comparison between tectonic lineaments on the ocean floor and synthetic flowlines. Prominent fracture zone lineaments, as interpreted from Seasat data, provide additional constraints for determining the fit between two corresponding magnetic anomalies. Geoid signatures on the continental shelves supply new information about the structure of the basement along continental margins

We feel that by combining magnetic anomaly data (Klitgord & Schouten 1986) with the new Seasat lineations we have assembled a significantly improved tectonic database. Using the advanced 3D-graphics capabilities of an interactive Evans&Sutherland PS 300 computer, we derived a refined plate tectonic model for the Central Atlantic ocean. All ages of magnetic anomalies referred to in this study are taken from the DNAG timescale (PALMER 1983).

Data

The data base of this study includes the set of magnetic anomaly picks from Klitgord & Schouten (1986) and Seasat altimetry data in the form of the "along-track deflection of the vertical" (Sandwell 1984a). Magnetic lineations were constructed from the magnetic anomaly picks. The Seasat data, plotted on GEBCO overlays, were used to generate a tectonic fabric map of the Central Atlantic ocean floor. The techniques used to process the Seasat data are discussed in Gahagan et al. (1987) (see also POMP Progress Report # 26).

Methods

The variation in height of the geoid corresponds closely to the height of the sea surface. Thus measurements of the height of the sea surface can be used to map submarine topography, i.e. valleys, ridges, and slopes (Haxby 1985). Fig. 1 illustrates the first derivative (i.e. a gradient of a slope) of this surface. Positive slopes, as viewed to the north, are delineated by blue lines, negative slopes by red lines. Broad positive and negative slopes are represented by hatched areas.

In order to determine the location of fracture zones from these linear geoid features, the relationship between specific geoid signals and bathymetric expression of a fracture zone must be known clearly. In contrast to fracture zones in the Pacific, which are ususally characterized by a large age/depth step that often is retained even on the oldest parts of the sea floor (Sandwell 1984b), fracture zones in the Atlantic exhibit a more complex morphology (Colette 1986). In the Atlantic the expected depth/age step is commonly overprinted by the fracture zone morphology (Colette et al.1984, Roest & Colette 1986, Colette 1986, Potts et al.1986). This is due to the relatively slow spreading in the Atlantic Ocean. In addition, the morphology varies as a result of changes in spreading direction. However, a characteristic morphological feature of Atlantic fracture zones is a central valley (Van Andel 1971, Colette 1986), resulting in a prominent geoid low. This geoid low is represented by a pair of red and blue lines, as viewed from south to north (Fig. 1), locating the two slopes of the central valley.

Observation of the Seasat lineations indicate that: closely spaced pairs of red and blue lines are common, confirming that central valleys are characteristic of fracture zones in this region. Uninterrupted and continuous pairs of lineations are present only for a few large-offset fracture zones (Fifteen Twenty, Kane, Atlantis and Pico Fracture zones). Geoid lineations of small offset fracture zones commonly are interrupted and discontinuous.

Some lineations deviate from presumed tectonic flowlines. This deviation, however, does not appear to be randomly oriented. For example, a number of geoid lineations east and west of the ridge between 20°N and 35°N clearly deviate to the south, forming wide-angle, upside-down V's (Fig. 1). In the same region volcanic ridges with very similar orientation were described by Schouten et al. (1987). They attribute the V-shaped pattern of the migration of volcanic ridges from spreading centers by motion of the plate boundary over the mesospheric hot-spot reference frame. This is a consequence of the directions of absolute plate motions. This observation indicates that linear features other than tectonic flowlines only are reflected in geoid lineations and that these features may yield stronger geoid signals than small offset fracture zones.

Plate Reconstructions

Derivation of rotation poles

The method followed in this study was to use interactive computer graphics to find the finite poles of rotation that best fit a pair of corresponding magnetic anomalies and fracture zone lineations. We start with Klitgord & Schouten's (1986) reconstruction poles, evaluate the fit and, if necessary, adjust poles to achieve the best overall match of both the magnetic anomalies and fracture zones. This technique, however, only applies for reconstructions between 0 and 84 Ma because geoid lineations on older ocean floor are not pronounced enough to map distinctive fracture zones. Most of Klitgord & Schouten's (1986) poles satisfy the constraints by the data. The poles for anomalies 5, 13, 21, 25 and 30 are slightly modified, to give a better fit of major fracture zone lineations.

Defining isochrons

After the best fitting rotations were determined, finite rotation poles were calculated for every stage both for the reference frame of the North American and the African plate (Table 1). A stage is defined by the time interval between two adjacent anomaly lineations used in a reconstruction.

Subsequently reconstructions for all time slices as listed in table 1 were plotted, keeping North America fixed. These plots included superimposed magnetic lineations for the reconstruction time as well as the older anomaly lineations for both the North American and the African plate. Seasat lineations and small-circles for the stage bounded by the next older anomaly pair were plotted on the maps, too. Now continuous isochrons were drawn (which can be viewed as of "idealized ridge segments"), connected by transforms. The paleo-ridge segments were drawn by finding the best average lines for superimposed magnetic lineations. The position of transforms between paleo-ridge segments were determined by offsets in magnetic lineations and Seasat fracture zone lineations. Geoid lineations give additional constraints for the location of fracture zones, especially where magnetic data are sparse.

The fracture zone segments for different stages were drawn as synthetic flowlines, which are defined by small circles for the stage poles. This procedure yielded isochrons for the American plate, which was kept fixed for the reconstructions. A complete set of isochrons was derived by rotation of every isochron from the American plate to its corresponding position on the African plate by applying the finite reconstruction poles as shown in Table 1.

The constraints for the isochron positions, magnetic anomaly lineations and Seasat data, are displayed in Fig. 1. Both unrotated (red lines) and rotated (green lines) magnetic lineations are plotted. This was done by rotating all anomaly lineations to their corresponding positions on the opposite plate, using the finite reconstruction poles of Table 1.

Distinctive Seasat lineations permitted to draw flowlines for some fracture zones even where there appeared to be no offset of the magnetic isochrons (Fig. 1). Fracture zones which do not offset magnetic anomalies are discussed by Schouten & White (1980).

Discussion

There is a good agreement between the synthetic flowlines and geoid lineations for the time interval 0-84 Ma (A34) (Fig. 1). Jumps of fracture zones (that means breaks in the expected contineous flowline patterns), as derived from magnetic lineations, are well correlated with the observed geoid lineations.These jumps are related to changes in the direction of sea floor spreading. For example, the plate reorganization at chron 21 caused the jump of the Cruiser, Tyro and Northern Fracture zones. This can be seen in both the magnetic anomaly pattern and in discontinuous geoid lineations (Fig. 1).

Different flowline patterns have been suggested for the Cretaceous Quiet Zone (Slootweg & Colette 1985, Klitgord & Schouten 1986), where fracture zones cannot be traced by offsets in magnetic anomalies. A uniform flowline direction for this period, as proposed by Klitgord & Schouten (1986), cannot be reconciled with all Seasat lineations between anomalies M0 (118.7 Ma) and 34 (84 Ma). The lineations rather suggest that the trend in seafloor spreading between M4 (126.5 Ma) to M0 continued until about 100 Ma. Between 100 Ma and 95 Ma, we propose a clockwise change in spreading direction that was followed by an anticlockwise change and established a direction of spreading that was maintained until Klitgord and Schouten's chron 30o (80.2 Ma) Slootweg & Colette (1985) found a very similar flowline pattern for the Cretaceous Quiet Zone in the Madeira abyssal plain. Their findings, based on seismic and magnetic data (Fig. 6), confirm our interpretation.

At 100 Ma changes were also ocurring in the plate tectonic regimes in the North Atlantic, Carribean and Indian Ocean. In the North Atlantic rifting between Greenland and Labrador began about this time while spreading in the Bay of Biscay decreased (Srivastava & Tapscott 1986). At about 100 Ma, the Caribbean plate started to move into the opening gap between the North American and the South American continents, subducting proto-Caribbean crust (Ross & Scotese 1987). India also began to rift away from Madagascar at the same time (Scotese et al. 1987).

The trend of the Fifteen Twenty Fracture Zone as shown on Fig. 1 reveals that its branch on the African plate partly deveates from the flow direction to the north (Fig. 1). The clockwise shift of seafloor spreading betwen Africa and North America after about 100 Ma resulted in divergence between the Fifteen Twenty Fracture Zone and the fracture zones to the north. Despite the anticlockwise change in spreading direction in the Central Atlantic around 95 Ma, a divergent trend between the Fifteen Twenty Fracture Zone and the Central Atlantic spreading direction was maintained until chron 30. This implies that this fracture Zone acted as a plate boundary during this time.We propose that a triple junction developed at the Fifteen Twenty transform after 100 Ma, which resulted in a contineous growth of the ridge segment between the Fifteen Twenty and the Jacksonville Fracture Zone (Fig. 1).

The divergent flowline trend may have found its expression in a striking bathymetric feature consisting of a series of elongate basins along and south of the Fifteen Twenty Fracture Zone (Fig. 1). The basins are oriented parallel to the tectonic flowlines and have depths of more than 6000 m. Hence they may have formed as a result of extension in this region. For the time after chron 30, the trend of the Fifteen Twenty Fracture Zone can be correlated with the Central Atlantic spreading direction (Fig. 1). This suggests that the Fifteen Twenty Fracture Zone no longer behaved as a leaky transform after chron 30.

We show 4 reconstructions for the Central Atlantic at chrons 21 (50.3 Ma), 34 (84 Ma), M0 (118.7 Ma) and the time of the Blake Spur Magnetic Anomaly (170 Ma) with North America fixed (fig. 2 to 5). For the reconstructions for South America relative to Africa (chrons 21, 34 and M0) rotation poles from Klitgord and Schouten (1986) were used. The reconstruction pole for the fit between South America and Africa at 170 Ma is taken from Ross & Scotese (1987).

Central Atlantic Shelf Structures

In contrast to most geoid lineations in ocean basins, shelf geoid anomalies display a pattern of broad, irregular gradients, striking at various angles to the coastlines. Two different patterns of shelf anomalies are evident on Fig. 1: one set trends roughly subparallel to the coast and to the shelf break. A second set, usually better defined, trends parallel to the tectonic flowlines on the adjacent ocean floor.

In general, there is no correlation between shelf geoid signatures and shelf bathymetry. Thus it appears that the geoid variations do not reflect superficial topographic features such as submarine canyons or delta fans.

The geoid anomaly pattern off the east coast of North America strikes subparallel to the North American shelf and is very similar to free-air gravity anomalies of that region. Emery & Uchupi (1984, p. 251) interprete these anomalies by a combination of high density carbonate rocks beneath the Mesozoic shelf edge, a shallow Moho, and an oceanic crustal thickness of less than 15 km. They also may cause the observed geoid undulations.

Along the Northwest African shelf, a series of geoid anomalies are oriented subparallel to the tectonic flowlines on the adjacent oceanic crust. This may reflect a syn-rift tectonic fabric, reactivated or created during rift propagation.

Geoid anomalies off the northeastern coast of South America show structures trending subparallel to the trend of fracture zone lineations to the east. Structural and stratigraphic investigations have shown that the Amazon margin can be divided in three platforms and eight basins with sediment thicknesses varying from 2 to 10 km (Emery & Uchupi 1984). In the structural lows of this part of the Amazon basins, dominantly syn-rift sediments were deposited. The recorded geoid variations on the northern Brazilian shelf could be explained by expressions of horst and graben structures due to an extensional tectonic regime. Further to northwest, the geoid signals on the shelf partly outline volcanic features related to the Demarara Plateau.

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Legend for fig.1-5:

AB - Amazon Basin
AT - Atlantis Fracture Zone
AZ - Azores Fracture Zone
BT - Benue Trough
CF - Central Florida Fault
CR - Cruiser Fracture Zone
DP - Demarara Plateau
FT - Fifteen-Twenty Fracture Zone
GP - Guinea Plateau
JV - Jacksonville Fracture Zone
KA - Kane Fracture Zone
PI - Pico Fracture Zone
RO - Romanche Fracture Zone
SL - Sierra Leone Fracture Zone
SP - St. Paul Fracture Zone
TY - Tyro Fracture Zone

BSMA - Blake Spur Magnetic Anomaly
ECMA - East Coast Magnetic Anomaly
WACMA - West African Coast Magnetic Anomaly

A, B - stippled lines indicate flow line direction for the time-interval 100-84 Ma after KLITGORD & SCHOUTEN (1986)

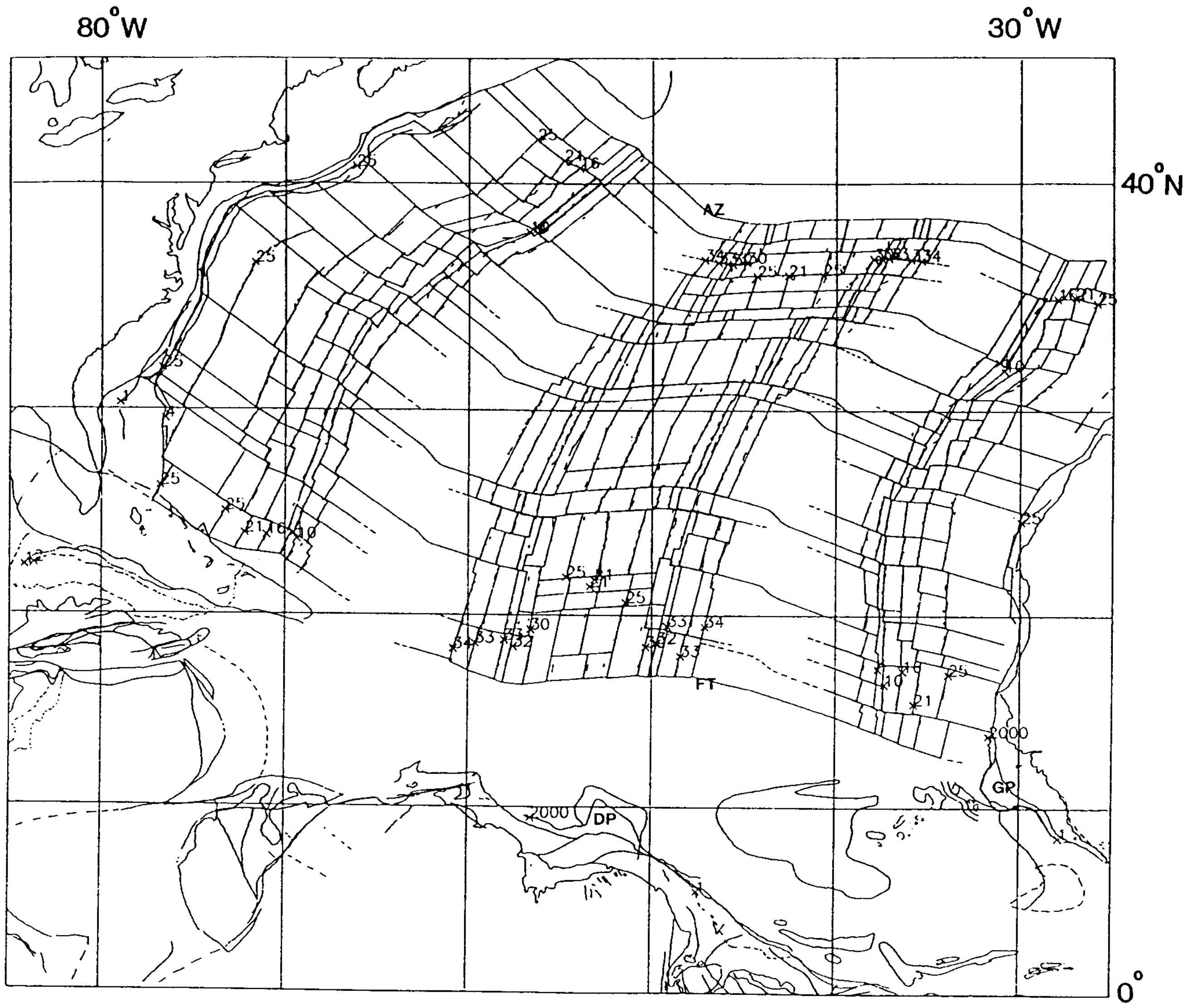

Fig.2: CHRON 21 (50.3Ma)

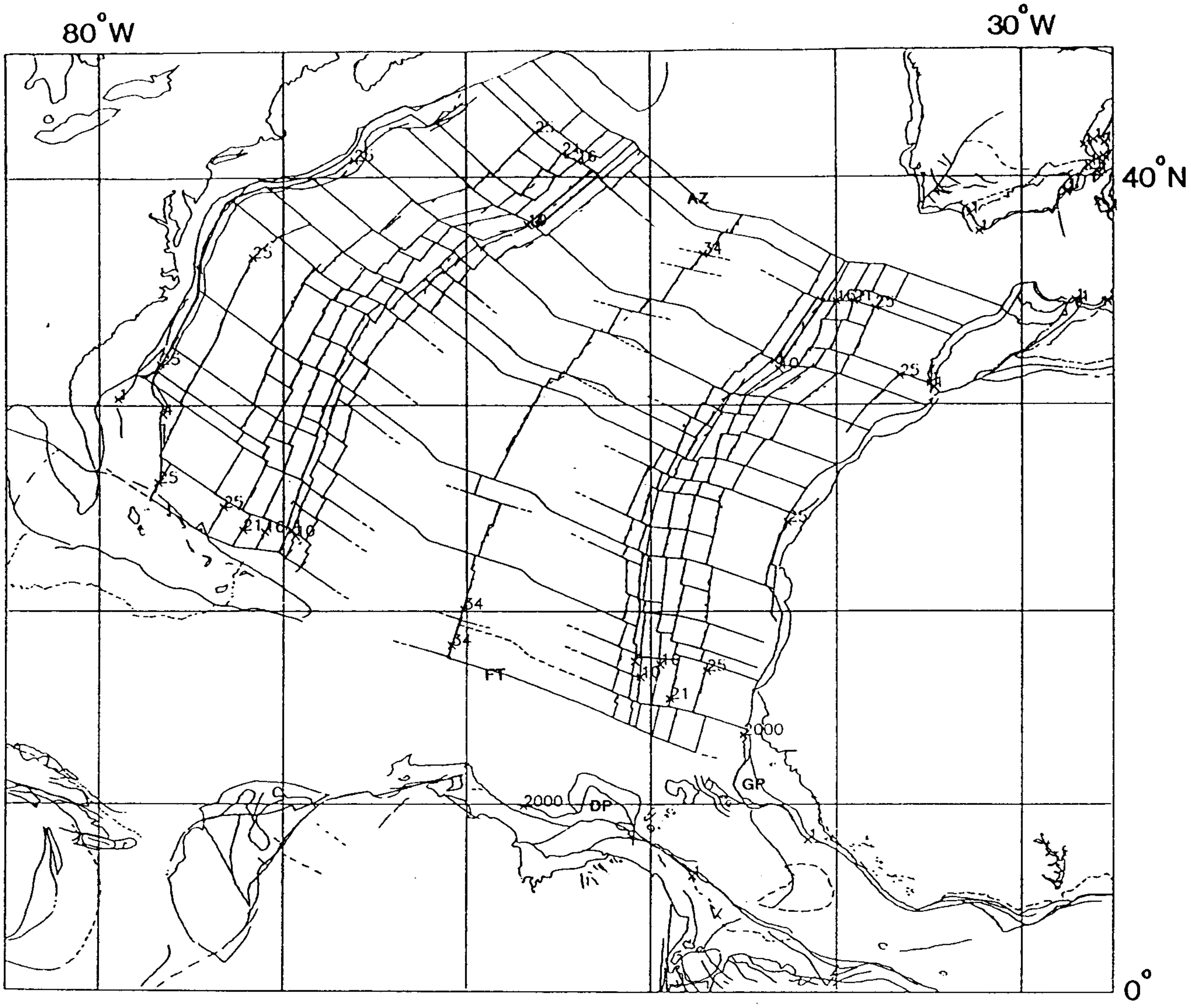

Fig.3: CHRON 34 (84 Ma)

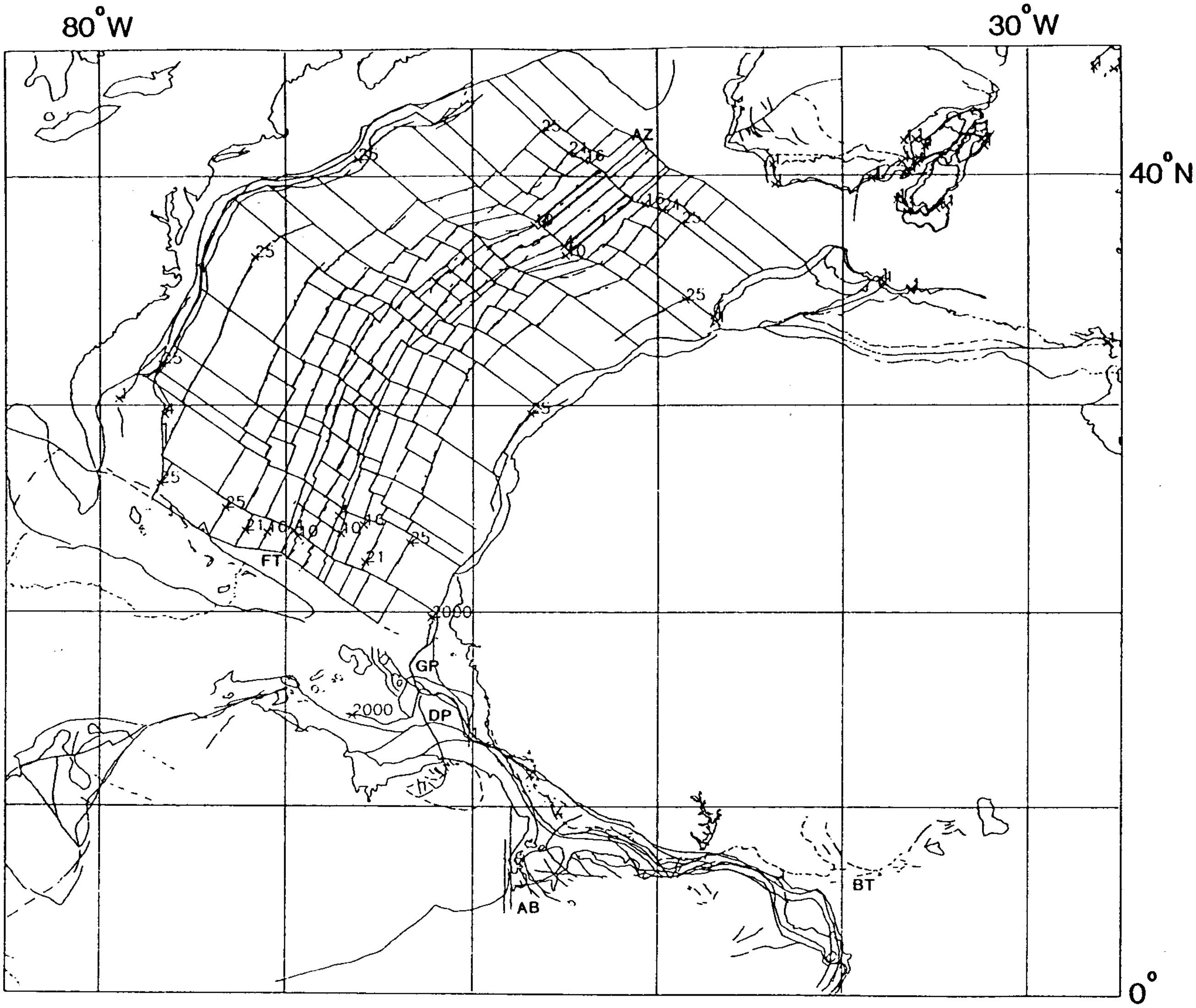

Fig.4: CHRON M0 (118.7 Ma)

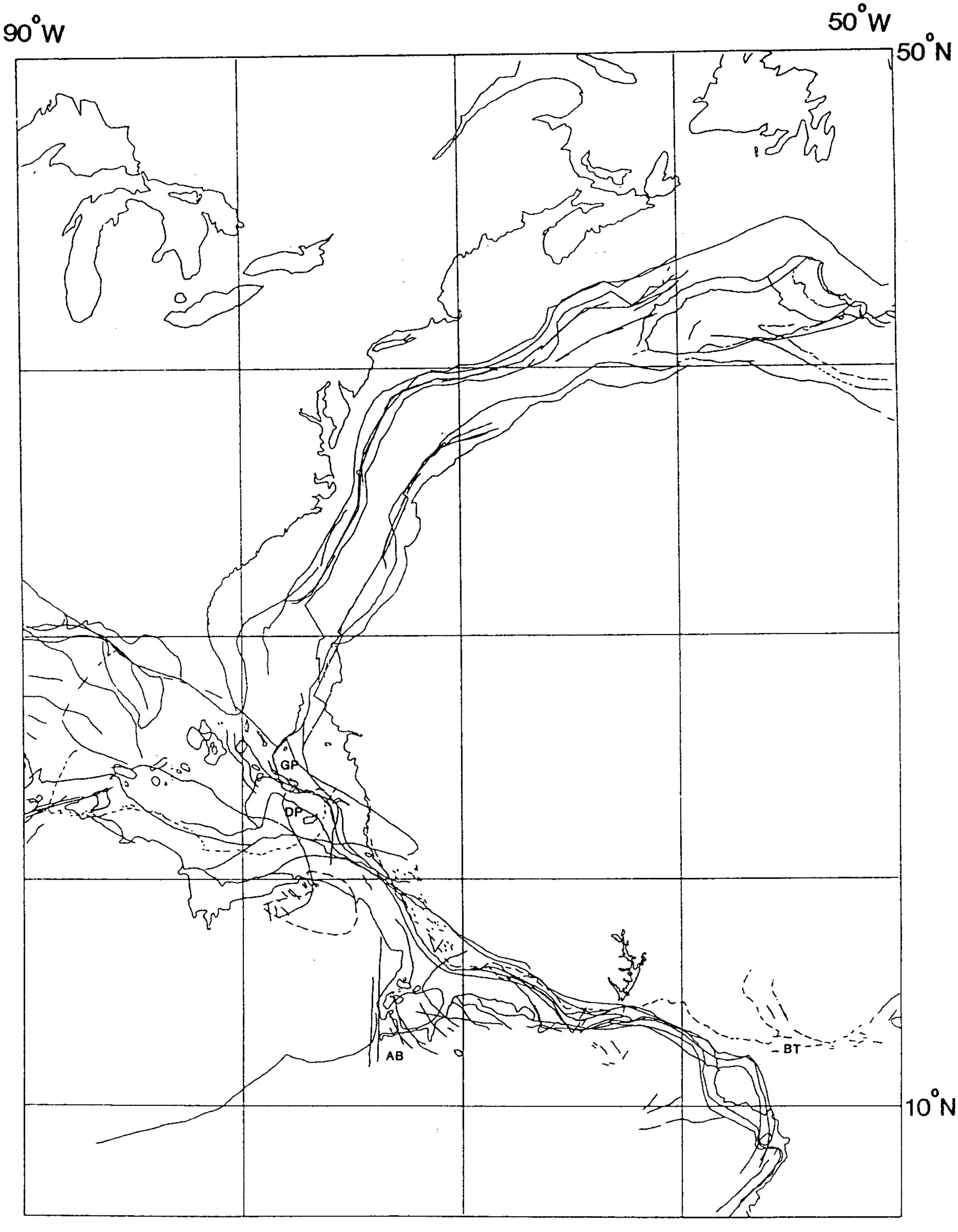

Fig.5: CHRON BSMA (170 Ma)

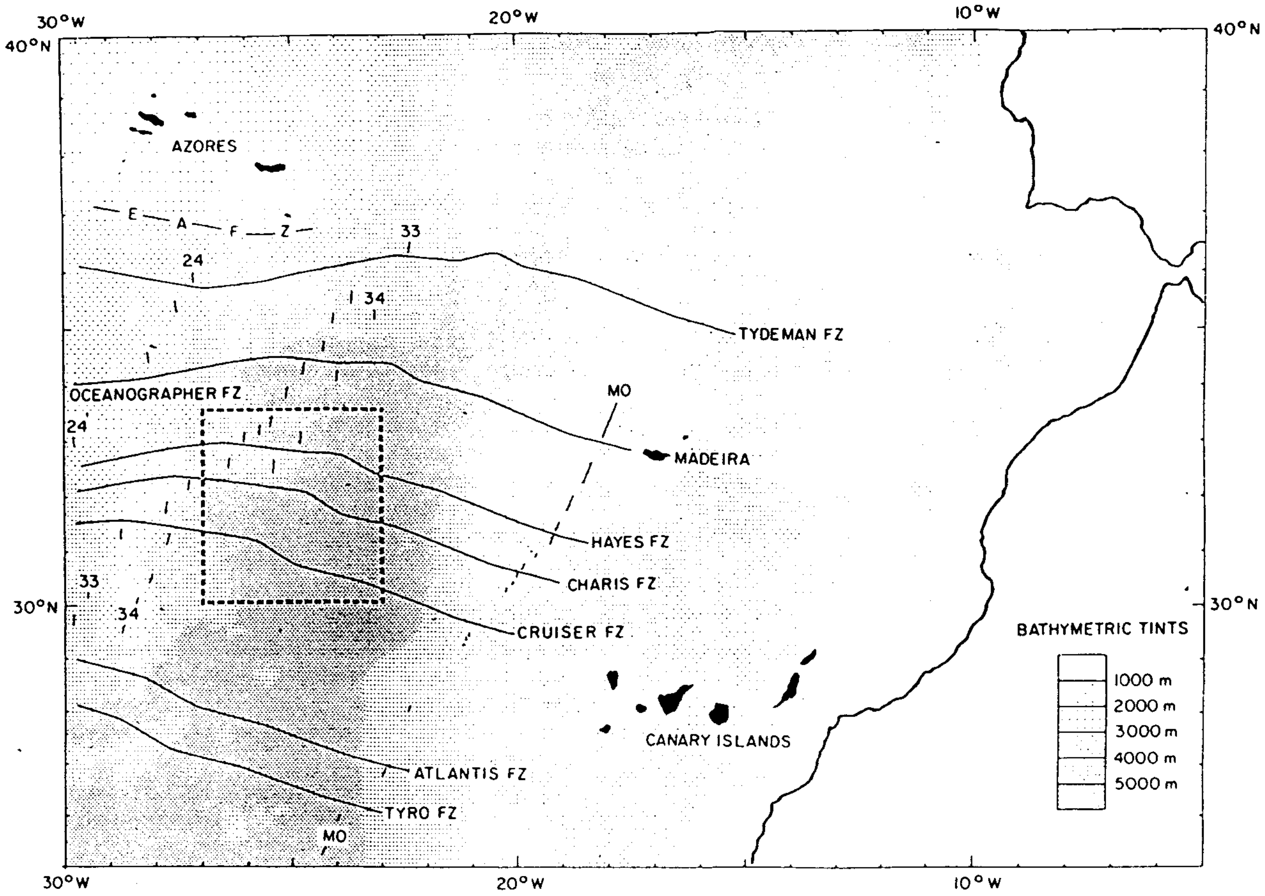

Fig. 6: Fracture Zones drawn as flowlines in the Madeira Abyssal Plain, northeast Atlantic (after Slootweg & Colette 1985). Note changes in spreading direction in the Cretaceous Magnetic Quiet Zone.

Table 1: Finite rotation poles for the Central Atlantic

Finite rotations :

	AGE	LAT	LON	Θ	
1	0.00	0.00	0.00	0.00	!NAM-AFR PRESENT-DAY
2	10.60	80.12	50.80	2.52	!NAM-AFR AN 5 MA-PICKS+SS-LIN (RDM,2-3-8
3	20.50	79.57	37.84	5.29	!NAM-AFR AN 6 Klitgord & Schouten (1987
4	35.90	75.37	1.12	10.04	!NAM-AFR AN 13 MA-PICKS+SS-LIN (RDM,2-3-
5	50.30	75.30	-3.88	15.25	!NAM-AFR AN 21 MA-PICKS+SS-LIN (RDM,2-9-
6	59.20	79.68	-0.46	18.16	!NAM-AFR AN 25 MA-PICKS+SS-LIN (RDM,2-9-
7	68.40	82.90	4.94	20.76	!NAM-AFR AN 30 MA-PICKS+SS-LIN (RDM,2-9-
8	71.70	81.35	-9.15	22.87	!NAM-AFR AN 32 KLITGORD DNAG 1986
9	74.30	80.76	-11.76	23.91	!NAM-AFR AN 33y KLITGORD DNAG 1986
10	80.20	78.30	-18.35	27.06	!NAM-AFR AN 33o KLITGORD DNAG 1986
11	84.00	76.55	-20.73	29.60	!NAM-AFR AN 34 KLITGORD DNAG 1986
12	118.70	66.30	-19.90	54.25	!NAM-AFR M-0 KLITGORD DNAG 1986
13	126.50	66.13	-19.00	56.39	!NAM-AFR M-4 KLITGORD DNAG 1986
14	131.70	65.95	-18.50	57.40	!NAM-AFR M-10N KLITGORD DNAG 1986
15	141.90	66.10	-18.40	59.79	!NAM-AFR M-16 KLIT&SCHOU (DNAG 1986)
16	149.90	66.50	-18.10	61.92	!NAM-AFR M-21 KLITGORD DNAG 1986
17	156.60	67.15	-16.00	64.70	!NAM-AFR M-25 KLITGORD & SCHOUTEN (DNAG)
18	170.00	67.02	-13.17	72.10	!NAM-AFR BSMA KLITGORD DNAG 1986
19	175.00	66.97	-12.34	74.57	!NAM-AFR ECMA KLIT & SCHOU 86 MIN CLOS
20	245.00	69.09	-7.71	76.00	!NAM-AFR MIR/CRS FIT BASED ON RESTORED C

Stage poles for plate 101 **(NAM)**

		T1	T2	LAT	LON	Θ	Spreading rates
1	2	0.00	10.60	80.1	50.8	2.52	26. mm/yr
2	3	10.60	9.90	78.7	27.3	2.77	31. mm/yr
3	4	20.50	15.40	68.0	-18.7	4.88	35. mm/yr
4	5	35.90	14.40	75.2	-13.5	5.22	40. mm/yr
5	6	50.30	8.90	77.5	143.2	3.18	40. mm/yr
6	7	59.20	9.20	74.3	146.2	2.83	34. mm/yr
7	8	68.40	3.30	61.6	-51.3	2.31	78. mm/yr
8	9	71.70	2.60	67.2	-40.7	1.08	46. mm/yr
9	10	74.30	5.90	60.2	-41.9	3.37	64. mm/yr
10	11	80.20	3.80	59.2	-38.8	2.69	79. mm/yr
11	12	84.00	34.70	55.3	-29.0	25.63	82. mm/yr
12	13	118.70	7.80	57.8	-8.2	2.17	31. mm/yr
13	14	126.50	5.20	52.2	-10.8	1.04	22. mm/yr
14	15	131.70	10.20	68.5	-11.5	2.39	26. mm/yr
15	16	141.90	8.00	72.0	9.4	2.17	30. mm/yr
16	17	149.90	6.70	60.6	31.2	2.99	50. mm/yr
17	18	156.60	13.40	60.0	0.0	7.50	62. mm/yr
18	19	170.00	5.00	59.9	0.1	2.50	56. mm/yr
19	20	175.00	70.00	26.3	82.9	3.63	6. mm/yr