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THE BENUE TROUGH AND CAMEROON LINE – A MIGRATING RIFT SYSTEM IN WEST AFRICA

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The remarkable similarity in shape between the Benue trough and the volcanic Cameroon line suggest that they are related to a common "Y"-shaped hot zone in the asthenosphere over which the African plate has moved. The required short-lived episode of clockwise rotation of Africa, 80 to ca. 70 Ma ago, interrupted the generally anticlockwise rotation implied by the South Atlantic hot spot traces. It correlates with the widespread reorganisation of plate boundaries which occurred 80 Ma ago and with a prominent offset on the Walvis Ridge.

1. Introduction

The volcanic Cameroon line and the Benue trough are two of the more important geological structures in Africa and yet there is no general consensus on the origin of either. The purpose of this paper is to present a simple model which can account for all the known geological features of both structures without the problems encountered in some of the more recent models.

2. Benue trough

The Benue trough (Fig. 1a) is a linear depression filled with up to 6000 m of Cretaceous (Albian-Maastrichtian) sediments. The earlier (Albian-Santonian) sediments in the trough are mainly marine in character and their deposition was terminated by an episode of deformation in the Santonian [1]. Following this deformation the marine sediments were eroded and deltaic sediments spread throughout the trough. Continental facies sedimentation persisted until the end of the Cretaceous, apart from a short-lived but extensive marine incursion in the Maastrichtian [1,2]. Nwachukwu [3] has described evidence for a period of slight deformation in the Cenomanian. Reviews of the geological history and theories on the origin of the Benue trough have been presented by Burke et al. [1], Olade [4] and Wright [5].

The interpretation of the Benue trough as a rift valley is supported by the recognition of a positive Bouguer anomaly [7–9], coincident with the axis of the trough and associated closely with a belt of brine springs and Cretaceous Pb-Zn and barytes mineralisation (Fig. 1a). Burke et al. [1,10] drew an analogy between the Benue trough and the Red Sea and proposed that the Benue trough formed one arm of a Cretaceous RRR triple junction which subsequently failed to develop while the other two arms gave rise ultimately to the South Atlantic Ocean. Grant [11] has presented a similar model in which the northern coast of the Gulf of Guinea developed as a transform fault rather than as a ridge.

The Benue trough is unique among rift valleys in that it is filled with sediments which have been folded along axes parallel to its length [1]. The folds are generally large but with dips rarely exceeding 30°. Burke et al. [10] explain this folding by postulating that the Benue trough underwent active sea-floor spreading during the early Cretaceous and that the new oceanic crust was subsequently consumed by subduction during the Santonian. The resulting "orogeny" was responsible for the observed folding. They cite as evidence for this subduction episode the discovery of "more than 1300 m of andesitic and basaltic lavas and tuffs" of about Santonian age in boreholes sunk into the Niger delta. These volcanic rocks, however, have not been described in the literature. Volcanic rocks underlie the earliest Albian sediments in the core of the Abakaliki anticlinorium in the lower Benue valley [12]. Olade [13] has suggested that these volcanic rocks are of alkaline affinities and were erupted during the early development of the Benue rift. Carter et al. [2] have recorded a number of very small outcrops of highly altered lavas and tuffs among the upper Cretaceous strata of the upper Benue valley.

The subduction model of Burke et al. [1,10] has little to recommend it and has been challenged by Olade [4] and Wright [5]. Freeth [14,15], however, has adopted the model in his membrane tectonics explanation for the evolution of the area.

At its northeastern end the Benue trough splits into two branches (Fig. 1a). The northern branch, the Chad rift, dies out under the Chad basin but the eastern branch, the Yola rift, can be traced geophysically as far as the Sudan border [16]. Burke and Whiteman [16] regard this bifurcation in the Benue trough as another RRR triple junction.

3. Cameroon line

The Cameroon line comprises a chain of Tertiary to Recent, generally alkaline volcanoes stretching from the Atlantic island of Annobon to the Bambouto and Oku mountains in the Cameroon Republic. North of Oku the line splits into two branches. One runs northwards into northeast Nigeria where it includes the Biu Plateau while the other runs eastwards through the Ngaoundere Plateau of eastern Cameroon. The result is a striking "Y"-shaped volcanic feature (Fig. 1a), 1600 km long, whose origin has never been satisfactorily explained.

Volcanic activity (lava flows, pyroclastic rocks and plugs) dates back to about 30 Ma ([17,18], and H.M.

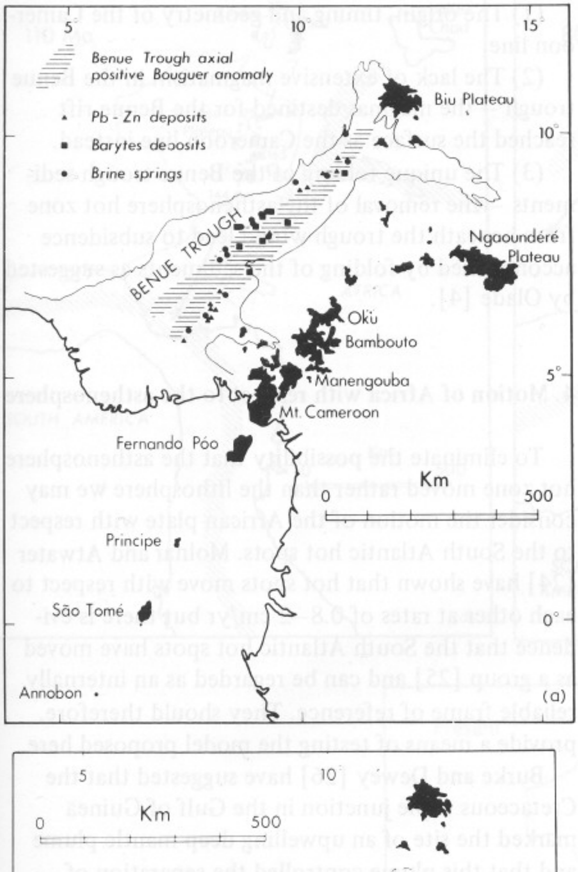

Fig. 1. (a) Cameroon line (volcanic rocks shown black) and the Benue trough. Geological data compiled from references 3, 6, 7 and 8. (b) The Cameroon line superimposed on the Benue trough by rotating the former clockwise relative to the latter by 7° about a pole at 12.2°N, 30.2°E. The Cameroon line has been brought into alignment with the Benue trough axial gravity anomaly (Fig. 1a).

Dunlop, unpublished data). The volcanism shows no consistent migration with time. Signs of recent activity can be found all along the line with the most recent (Mt. Cameroon) in the middle. The oldest Cameroon line volcanic rocks so far dated are found on the island of Principe (31 Ma) [18]. The line also includes a large number of granite and syenite ring complexes with ages ranging from 65 to 35 Ma [19, 20] which are probably the deeply eroded remnants of still older volcanoes. Thus the Cameroon line has been active since the beginning of the Tertiary and is not, as is popularly believed, entirely a Neogene and Recent feature.

Volcanism on the line has been accompanied by broad regional uplift of the Precambrian basement but there is no evidence for rift faulting. The volcanism does not seem to have been controlled by pre-existing basement fractures. The eastern branch runs obliquely to a series of large regional faults [6,21] while the northern branch cuts across the eastern branch of the Benue trough (Fig. 1a). The oceanic sector of the line is likewise unaffected by the transform faults which it crosses [22]. The Cameroon line must, therefore, be the product of mantle processes unmodified by the structure of the overlying crust.

The explanation proposed here for the origin of the Cameroon line lies in its relationship with the Benue trough. The two features are so remarkably similar in shape and size that they may be superimposed perfectly by rotating one with respect to the other by 7° about a pole at 12.1°N, 30.2°E (Fig. 1b). This geometrical coincidence cannot be accidental but probably results from a displacement of the African lithosphere relative to its underlying asthenosphere. Thus the "Y"-shaped hot zone in the asthenosphere which would have lain beneath the Benue trough in the Cretaceous became displaced (relative to the lithosphere) so that it now lies beneath Cameroon and the Gulf of Guinea. This implies that during the interval between the cessation of rifting in the Benue trough in the Santonian (ca. 80 Ma) and the initiation of igneous activity on the Cameroon line (ca. 65 Ma) Africa was rotating clockwise relative to the asthenosphere. This short-lived period of clockwise rotation, which must have interrupted the anticlockwise rotation implied by the South Atlantic hot spot traces [23], provides a simple explanation for the following features:

(1) The origin, timing and geometry of the Cameroon line.

(2) The lack of extensive magmatism in the Benue trough – the magmas destined for the Benue rift reached the surface as the Cameroon line instead.

(3) The unique folding of the Benue trough sediments – the removal of the asthenosphere hot zone from beneath the trough would lead to subsidence accompanied by folding of the sediments as suggested by Olade [4].

4. Motion of Africa with respect to the asthenosphere

To eliminate the possibility that the asthenosphere hot zone moved rather than the lithosphere we may consider the motion of the African plate with respect to the South Atlantic hot spots. Molnar and Atwater [24] have shown that hot spots move with respect to each other at rates of 0.8–2 cm/yr but there is evidence that the South Atlantic hot spots have moved as a group [25] and can be regarded as an internally reliable frame of reference. They should therefore, provide a means of testing the model proposed here.

Burke and Dewey [26] have suggested that the Cretaceous triple junction in the Gulf of Guinea marked the site of an upwelling deep mantle plume and that this plume controlled the separation of Africa from South America. Since Africa was drifting northwards throughout the Mesozoic [27] this plume should have moved southwards with respect to Africa during this period and may have been responsible for the Jurassic ring complexes on the Jos Plateau. These increase in age progressively southwards [28–30] and van Breemen and Bowden [28] have suggested that they mark the trace of a mantle plume (hot spot) which ultimately caused the rifting in the Benue trough. The Carboniferous granite bodies near Zinder in southern Niger may also be a surface expression of this hot spot. A possible hot spot trace leading to the development of the Gulf of Guinea triple junction is shown in Fig. 2a.

As the Atlantic Ocean opened the hot spot would have remained on the mid-ocean ridge and so the triple junction may have developed as depicted in Fig. 2b with extension of only a few kilometres on the Benue rift arm. This reconstruction shows the situation at the time of magnetic anomaly 34 (ca. 80

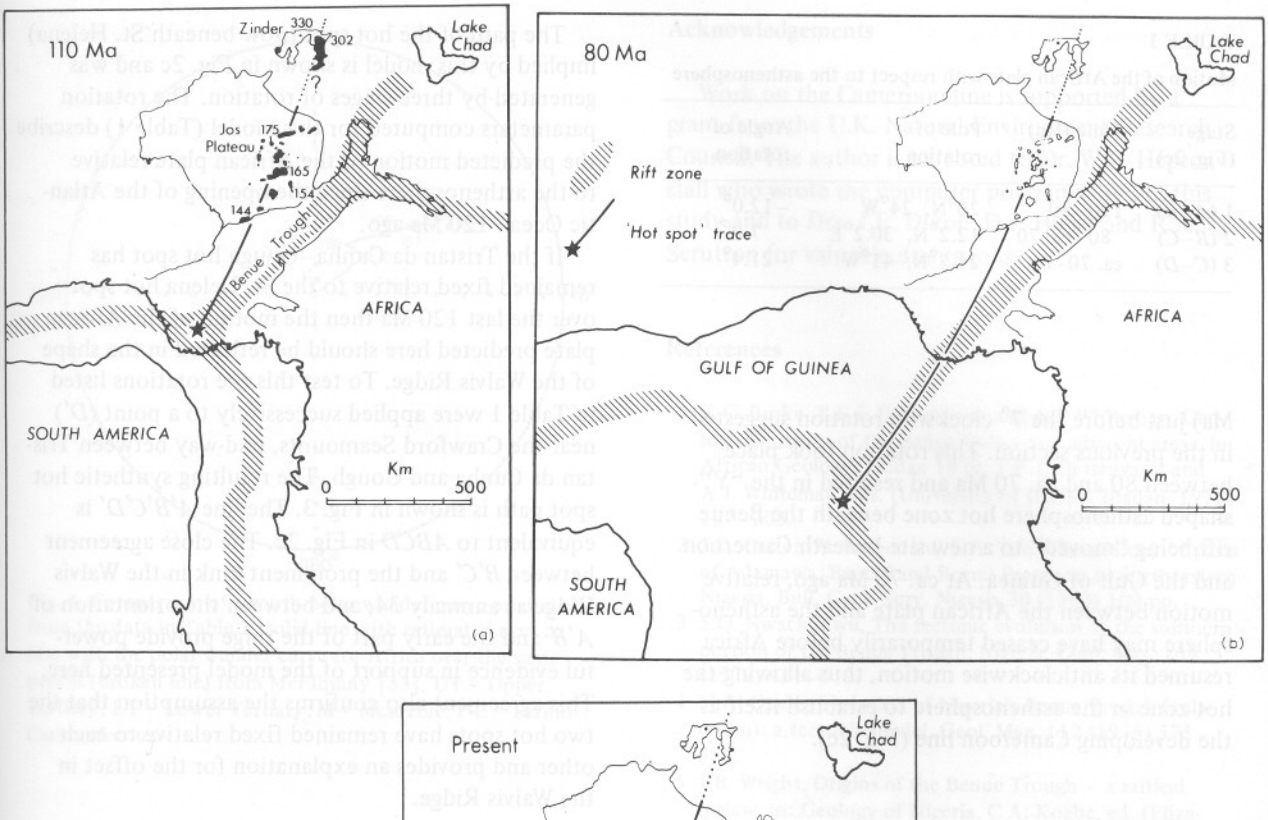

Fig. 2. Model for the evolution of the Benue trough and Cameron line. (a) The situation at 110 Ma (after Sibuet and Mascle [22]), soon after the initiation of rifting, showing the proposed relationship of the Gulf of Guinea triple junction to the Zinder–Jos Plateau hot spot. Ages of granites (black) in Ma are taken from van Breemen et al. [29] and Bowden et al. [30]. (b) Reconstruction of the Gulf of Guinea to anomaly 34 (ca. 80 Ma) (after Sibuet and Mascle [22] and Rabinowitz and LaBrecque [31]). (c) The present-day Cameroon line (black) and Benue trough. The Cameroon line has developed over the "Y"-shaped asthenosphere hot zone which originally lay beneath the Benue rift (Fig. 2b). *ABCD* is the path of the St. Helena hot spot required by the model.

TABLE 1

Motion of the African plate with respect to the asthenosphere

Stage (Fig. 2c)	Time (Ma)	Pole of rotation	Angle of rotation
1 (A–B)	120–80	20°N, 24°W	−12.0°
2 (B–C)	80–ca. 70	12.2°N, 30.2°E	7.0°
3 (C–D)	ca. 70–0	21.5°N, 41°W	−21.4°

Ma) just before the 7° clockwise rotation suggested in the previous section. This rotation took place between 80 and ca. 70 Ma and resulted in the "Y"-shaped asthenosphere hot zone beneath the Benue rift being "moved" to a new site beneath Cameroon and the Gulf of Guinea. At ca. 70 Ma ago, relative motion between the African plate and the asthenosphere may have ceased temporarily before Africa resumed its anticlockwise motion, thus allowing the hot zone in the asthenosphere to establish itself as the developing Cameroon line (Fig. 2c).

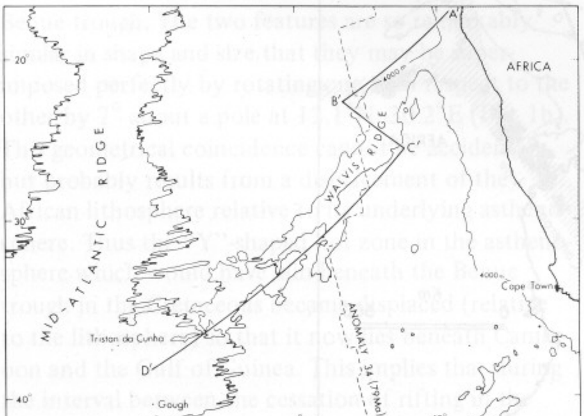

Fig. 3. Bathymetry of the South Atlantic (4-km isobath from reference 32) showing the agreement between the Walvis Ridge and a predicted hot spot path ($A'B'C'D'$) generated by applying the rotations given in Table 1 to the point D'. The points A', B', C' and D' are equivalent, respectively, to points A, B, C and D in Fig. 2c. Note the coincidence of $B'C'$, the offset in the Walvis Ridge and the estimated position of anomaly 34 (from Sibuet and Mascle [22]).

The path of the hot spot (now beneath St. Helena) implied by this model is shown in Fig. 2c and was generated by three stages of rotation. The rotation parameters computed for this model (Table 1) describe the predicted motion of the African plate relative to the asthenosphere since the opening of the Atlantic Ocean 120 Ma ago.

If the Tristan da Cunha–Gough hot spot has remained fixed relative to the St. Helena hot spot over the last 120 Ma then the motion of the African plate predicted here should be reflected in the shape of the Walvis Ridge. To test this the rotations listed in Table 1 were applied successively to a point (D') near the Crawford Seamounts, mid-way between Tristan da Cunha and Gough. The resulting synthetic hot spot path is shown in Fig. 3. The line $A'B'C'D'$ is equivalent to $ABCD$ in Fig. 2c. The close agreement between $B'C'$ and the prominent kink in the Walvis Ridge at anomaly 34, and between the orientation of $A'B'$ and the early part of the ridge provide powerful evidence in support of the model presented here. This agreement also confirms the assumption that the two hot spots have remained fixed relative to each other and provides an explanation for the offset in the Walvis Ridge.

5. Comparison with palaeomagnetic data

The 7° rotation of Africa (stage 2) is probably too small to be detected palaeomagnetically. However, the conclusion that the southern Niger granites and St. Helena are related to the same hot spot – a conclusion which requires a remarkably long life (ca. 300 Ma) for the hot spot – can be tested using palaeomagnetic data. On the assumption that the hot spots have remained fixed relative to the magnetic poles it is possible to predict a polar wander curve based on the rotations given in Table 1 and to compare this with the actual polar wander curve (cf. [23]). Such a comparison is made in Fig. 4. The *general* agreement in direction and magnitude between the two curves (which cover approximately the same 300-Ma period) lends some support to the conclusion. The differences between the two curves can be accounted for by relative motion, of the magnitude suggested by Molnar and Atwater [24], between the hot spot and the magnetic poles.

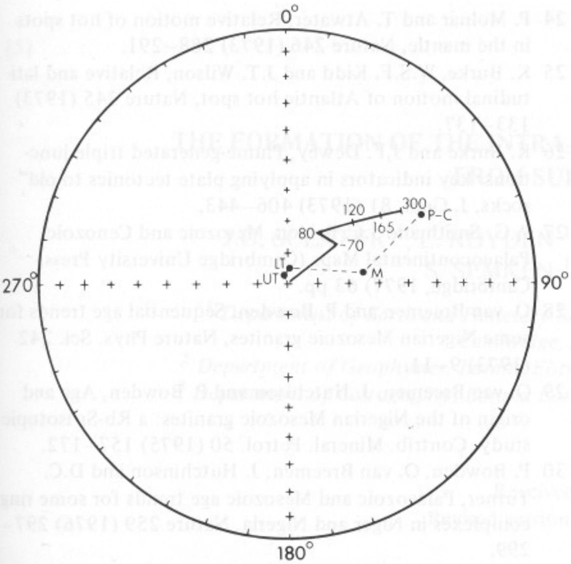

Fig. 4. Comparison of a south polar wander curve predicted from the data in Table 1 (solid line with estimated ages in Ma) with the polar wander curve for Africa over the same period (broken line) from McElhinny [33]. UT = Upper Tertiary; LT = Lower Tertiary; M = Mesozoic; P-C = Permo-Carboniferous.

6. Significance of the 80-Ma event

Why did Africa change its direction of motion 80 Ma ago? 80 Ma is a significant date in the evolution of all the major boundaries to the African plate. The change in orientation of the South Atlantic transform faults at anomaly 34 points to a change in the direction of relative motion between Africa and South America at this time [22]. Spreading in the Atlantic Ocean north of the Bay of Biscay commenced at about this time [34] and Dewey et al. [35] have shown that this resulted in the relative motion between Africa and Europe reversing direction at 80 Ma. There is, therefore, ample evidence that the events leading to the development of the Cameroon line were a manifestation of the drastic reorganisation of plate boundaries which took place 80 Ma ago. It is not possible, however, to deduce whether this reorganisation merely represents the random jostling of plates or whether it reflects some fundamental shift in the pattern of mantle convection.

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