Origin of the Cameroon Line of Volcano-Capped Swells

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ABSTRACT

Swells of the Cameroon Line, a 1000-km-long line of 10 volcano-capped swells, resemble other volcano-capped topographic and bathymetric swells on the African plate. However, individual swells of the Cameroon Line are about 10 times smaller in area and distinct in being arranged in a straight line, half on the continent and half on the ocean floor. These peculiarities are here interpreted as related to an underlying mantle plume (the "711" plume) at lat 7°N, long 11.5°E, and to the location of this plume area on the bisector of a right-angled bend in the continental margin. I suggest that circumstances that led to the development of the Cameroon Line included (1) the stress field in the neighborhood of the right-angled bend in the continental margin, which favored extension normal to the bisector, and (2) formation of a zone of extension, aligned with the bisector, that joined a point in the lithosphere over the 711 plume to the continental margin. The right-angled bend in the continental margin has existed since ca. 125 Ma, and the ages and alignment of a line of intrusions cutting the continental crust in Cameroon indicate that the 711 plume has been in its present position with respect to the continental margin for the past 65 m.yr. Nevertheless, the Cameroon Line of swells formed only at 30 Ma. Some change at 30 Ma appears to have triggered formation of the line. A new, platewide pattern of shallow-mantle convection developed under the African plate at 30 Ma. For that reason, I suggest that the trigger for formation of the Cameron Line was the establishment, as part of the new platewide convection system, of shallow-mantle convection localized under the zone of extension that joined the 711 plume to the right-angled bend in the continental margin. Changes at 30 Ma fostered rapid propagation of that zone of extension, which had been established in the continental lithosphere at 65 Ma, into the Gulf of Guinea for a horizontal distance of 650 km.

Introduction: A Platewide Swell Population

A platewide pattern of topographic and bathymetric swells set among irregularly shaped basins has long been a recognized peculiarity of the African plate (Holmes 1944; Nyblade and Robinson 1994). These swells have been interpreted as part of a shallow-mantle convection system (e.g., Burke and Wilson 1972; McKenzie and Weiss 1975; England and Houseman 1984). My own interpretation suggests that the swells are presently rising, have all originated during the past 30 m.yr., and overlie mass-deficient material in the upper mantle (Burke 1996). About 75 elliptical swells ranging from ca. 100 km to ca. 2000 km in maximum length are distinguishable (fig. 1). The exact number depends on whether some of the smaller swells are grouped or treated as separate. Some of the swells lie on the continent and others on the ocean floor, where the size and shape of active swells are hard to define (cf. Nyblade and Robinson 1994). No swells straddle the continental margin. Volcanoes, or volcanic rocks younger than 30 Ma that have been mapped on about 60% of the swells, are generally concentrated close to swell crests. In contrast, young volcanoes and volcanic rocks, apart from carbonatites, are absent from swells on Africa's cratons. Their absence is attributable to the thick, highly depleted mantle lithosphere under the cratons (Ashwal and Burke 1989). Either basalt has not been melted out of that lithosphere because it is too infertile or the top of any elevated asthenosphere under the swells is too deep to cross the basalt solidus.

The Cameroon Line (figs. 1, 2) is a line of 10 of Africa's volcano-capped swells, four of which lie on land and six in the Gulf of Guinea. Interest in the

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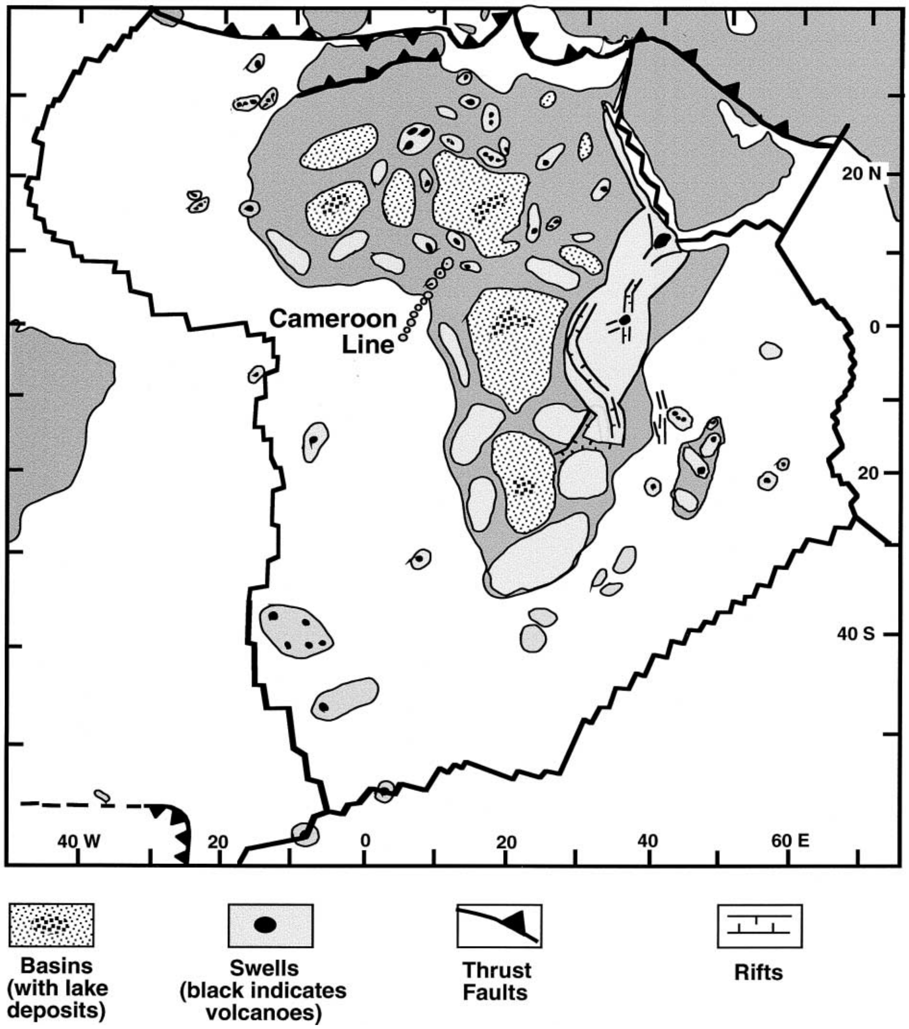


Figure 1. Basins and swells of the African plate. The Cameroon Line of 10 volcano-capped swells straddles the continental margin close to long 10°E. The line forms a distinctive part of the African plate's active swell population: (1) the swells are small, 100 km across; (2) they are arranged in a straight line; and (3) half the swells lie onshore and half offshore. The ca. 75 swells of the African plate are indicated as ellipses. Irregularly shaped basins are interspersed among the swells. Volcano-capped swells are shown with black marks indicating the locations of volcanic rocks. The three swells at the landward end of the Cameroon Line are, from west to east, the Jos, Biu, and Ngaoundere swells. Offshore swells are shown only where there is evidence of dynamic support such as active volcanism. In addition to the Cameroon Line, ca. 32 offshore and ca. 32 onshore swells are shown.

Cameroon Line, which has been episodic among solid Earth scientists during the past century, has led to numerous suggestions for its origin (summarized in Deruelle et al. 1991). The Cameroon Line swells are recognizably part of the population of <30-Ma volcano-capped swells of the African plate because they display the nine characteristic features of these swells (table 1; based mainly on Burke 1996). However, in contrast with the other swells on the plate, Cameroon swells (1) are much smaller, (2) are disposed in a 1000-km-long straight line, and (3) form the Cameroon Line, which lies half on the continent and half on ocean floor. By interpreting the ages and distributions of rocks and the structures in Nigeria, Cameroon, and the islands of the Gulf of Guinea, this article suggests a possible and testable origin for the Cameroon Line of volcano-capped swells that accounts for their unique characteristics in relation to the other African swells.

The Cameroon Line of Volcano-Capped Swells

Geometry of the Cameroon Line. The Cameroon Line has sometimes been defined to include the Ngaoundere and Biu swells (fig. 1). However, they are not here regarded as parts of the line because (1) they are much larger than the individual Cameroon Line swells and resemble in that respect the rest of the African plate's population of volcano-capped swells and (2) the long axes of the Biu and Ngaoundere swells and lines joining their crestal volcanoes have azimuths highly oblique to the trend of the Cameroon Line.

The Cameroon Line, as defined in this article, is nearly straight, with an azimuth close to N 45° E. It is ca. 1000 km long and lies half on ocean floor and half on continental crust. The six offshore swells include the four islands of Bioko (formerly Fernando Po), Principe, Sao Tome, and Pagalu (formerly Annobon). Also included are two large seamounts, one between Bioko and Principe and the other between Principe and Sao Tome. The Cameroon Line veers slightly toward the east at its southern end. Whether the undated seamounts that lie about 100 km SW of Pagalu form part of the Cameroon Line is unknown. Erosion has made the accurate location of the crests of continental volcano-capped swells more difficult than locating swell centers offshore. Cameroon Mountain with Etinde is here considered to occupy one swell, Manengouba a second, Bamboutu a third, and Oku, which is at lat 7°N, long 11.5°E, a fourth (fig. 2). Outcrops of Cretaceous sedimentary rocks between swells indicate the locations of interswell basins between the Cameroon Mountain and the Manengouba swells and between the Manengouba and Bamboutu swells. No Cretaceous sedimentary rocks define a basin separating the Oku swell from the Bamboutu swell. That distinction is here made solely on elevation and the distribution of volcanic rocks.

Distribution of Volcano-Capped Swells along the Cameroon Line. The average spacing of the swells is ca. 100 km, about 10 times closer than the average spacing of swells on the rest of the African plate. Spacing along the Cameroon Line ranges from ca. 170 km to ca. 40 km, and there is no obvious difference between swell spacing onshore and offshore (fig. 2). It has been suggested that volcanoes in the offshore part of the Cameroon Line are localized at places where the Cameroon Line crosses fracture zones (e.g., Meyers et al. 1998, fig. 5, p. 49, and references therein), but only the Ascension fracture zone has as yet been well mapped. Deruelle et al. (1991), using satellite imagery, postulated a system of oblique shear affecting the continental lithosphere in the area occupied by the onland volcanoes of the Cameroon Line and suggested that those volcanoes were localized by the shear zones.

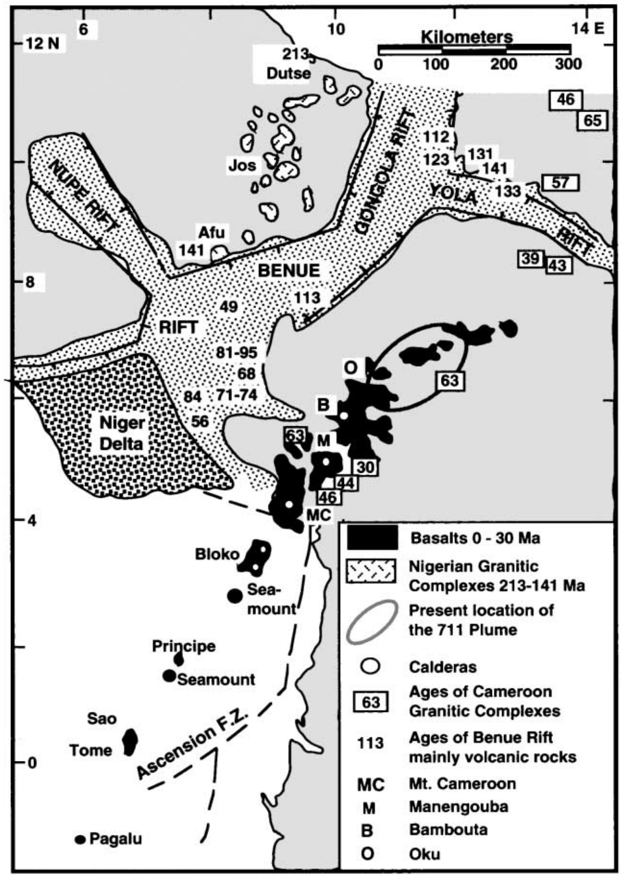


Figure 2. The Cameroon Line. The present location of the 711 plume is shown as a dashed ellipse at the landward end of the Cameroon Line of 10 volcano-capped swells. Locations of products of the 711 plume that have formed during the past ca. 210 m.yr. are shown in the Cameroon Line of granitic complexes, in the Benue rift, and in the Nigerian granites between Dutse and Afu. The Nupe, Benue, and South Atlantic rifts formed as elements of the west African rift system at a triple-rift star, close to Afu, at ca. 140 Ma. The right-angled bend of the continental margin (from Emery and Uchupi 1984) is shown, as are the locations of the Niger delta, the coastline of the continent, and the Ascension fracture zone.

A Long-Lived Plume

Plume-Generated Granites in Nigeria. Granitic complexes of latest Triassic to latest Jurassic age outcrop in a 420-km-long NNE-trending line in northern Nigeria (fig. 2). The ages of the granitic

Table 1. Characteristics of the Volcano-Capped Swells of the African Plate

	Characteristic
1.	Elliptical in shape with longer axes 100–2000 km
2.	Location on continent or ocean floor but not straddling the continental margin
3.	Dominantly the result of basement uplift that began ca. 30 Ma
4.	Basaltic volcanic rocks dominant
5.	^{3}He/^{4}He ratio of volcanic rocks less than, or similar to, that of MORB
6.	Volcanic rocks mainly derived from HIMU sources
7.	Basalt volume on any swell small compared with that of large igneous provinces
8.	Episodic eruption in the same small areas over intervals of up to 30 Ma
9.	Volcanoes on the swells show no consistent azimuth of age progression; on some swells there is a linear progression in age but azimuths differ from swell to swell

Note. Fifty swells of the African plate that share these properties are postulated to have originated as a result of shallow-mantle convection. Two swells that are different are suggested to be related to plumes of deeper origin: (1) the Ethiopian swell, generated from a deeply sourced plume at ca. 30 Ma, does not satisfy criteria 3, 5, 6, and 7, and (2) Tristan, generated from a deeply sourced plume at 130 Ma, does not satisfy criterion 6. Reunion, Shona, and Bouvet, which cap swells <2 Ma in age, do not satisfy criterion 5 because their newly risen, underlying plumes are briefly tapping a deeper-mantle helium reservoir.

complexes become steadily younger at 6 mm/yr from Dutse (213 Ma) in the north to Afu (141 Ma) in the south (Rahaman et al. 1984). Using one more data point, the line of granites can be extended farther north for another 230 km to Matsena where there is a Late Permian (258 Ma) granite (fig. 3). Adding the Matsena granite makes the line of intrusions 640 km long and distributes emplacement over 117 m.yr. The additional data point yields the same average rate of progress in age of ca. 6 mm/yr but covers a 50% longer interval.

Chemical and isotopic compositions of the rocks in the granitic complexes are consistent with an origin by partial melting of the continental crust and underlying mantle lithosphere. Because of this evidence for the presence of an underlying heat source and the evidence of a steady progression in age (fig. 3), the Nigerian granitic complexes are inferred to have originated by partial melting during rotation of the Gondwana continent over a mantle plume. The latitude and longitude of 7°N, 11.5°E, appear to have been the plume's approximate position with respect to the spin-axis for ca. 250 m.yr. A pole describing the ca. 640-km northward motion of Gondwana with respect to the plume between 258 and 141 Ma lies many tens of degrees away and close to the equator.

Formation of a Triple-Rift Junction over the Mantle Plume. Three rifts—the Benue rift, a rift system on the site of what was later to become the South Atlantic Ocean, and the Nupe (or Bida) rift—meet at a triple-rift junction ca. 100 km south of the outcrop of the southernmost of the Nigerian granitic complexes at Afu (figs. 2–4). The age of the oldest igneous rocks in the Benue rift is ca. 140 Ma (Burke 1976; Maluski et al. 1995), which is also the age of the beginning of intracontinental rifting in the South Atlantic (Burke 1976; Bate 1998; Uncini et al. 1998). The age of rifting in the Nupe rift is unknown because only the highest part of the rift's sedimentary fill, of Late Cretaceous age, is exposed. The coincidence in the timing of formation of at least two of the three rifts at the triple-rift junction with that of the emplacement of the youngest Nigerian granite at Afu, as well as the trilete pattern of the rifts (figs. 2, 4), leads to the suggestion that the 711 plume that had formed the Nigerian granites generated a topographic dome at ca. 140 Ma on which a triple-rift system developed (Burke and Dewey 1973; Houseman 1990). The slope of the dome is indicated by the exposure of deeper parts of the Jurassic granitic complexes at the southern end of the line of intrusions and by the exposure, farther north, of larger proportions of the higher parts of the granitic complexes that preserve volcanic rocks. Cassiterite-bearing greisens that developed close to the interface of the granitic and the volcanic rocks of the complexes are concentrated in an intermediate position around Jos (fig. 1). In the Jos area, the greisens have eroded to form gravels that support a tin-mining industry.

Benue Rift Evolution. Once formed, the Benue rift was dominated by extension from ca. 140 Ma (Berriasian) to ca. 84 Ma (Campanian). Some of the widely varied, small-volume, mostly alkaline igneous rocks erupted into the Benue rift during that interval likely formed as a result of pressure relief under the rift. However, plume-generated igneous rocks were forming in the Benue area before the rift began to extend at 140 Ma, and plume-generated rocks were erupted again after extension had ended at ca. 84 Ma. It therefore seems likely that plume-generated rocks are also represented among the igneous rocks erupted into the Benue rift while it was extending. Detailed geochemical and isotopic work are needed to distinguish them. The analyses in Maluski et al. (1995, table 2) represent a good beginning.

Igneous Activity in the Benue Rift between 84 Ma and

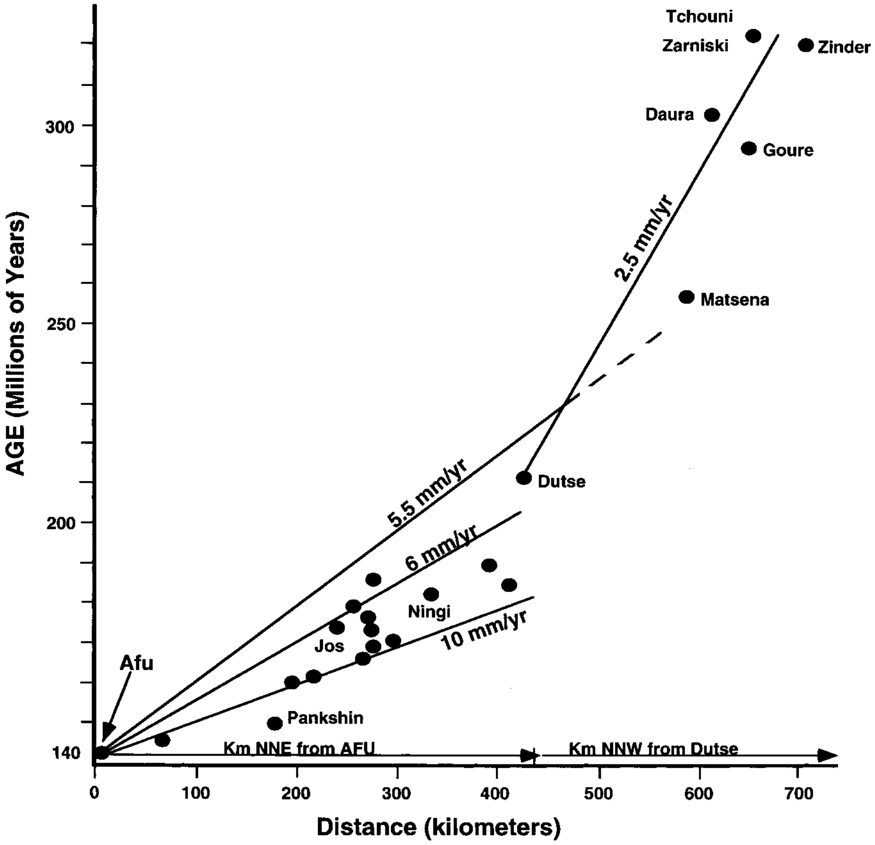


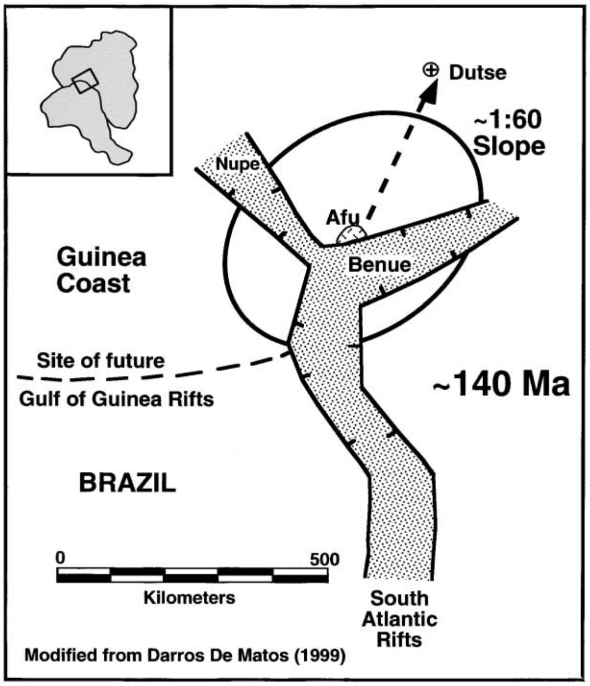
Figure 3. Rb/Sr ages of Nigerian granites plotted against distance from Afu, which lies close to the triple-rift junction of the Benue rift system (fig. 2). Progression in age is attributed to motion of the continent over the 711 plume. Based on Rahaman et al. (1984).

49 Ma. At 84 Ma, during Santonian time, an episode of locally intense compression and associated strike-slip faulting affected much of the Benue rift. This episode has long been regarded as an intraplate response to stress modification at the then northeast margin of the Afro-Arabian plate resulting from the initiation of arc-collision in Syria and Oman (Dewey and Burke 1974; Guiraud and Bosworth 1997). Propagation of stresses from a plate boundary zone in the Maghreb at the same time (Sengor and Natalin 1996, fig. 21.47) may also have contributed to the short-lived concentration of intense localized deformation in the Benue rift.

After 84 Ma, the Benue rift became tectonically quiet. Geological activity was dominated by fluvial deposition and by the progradation of deltas into the ocean at the mouth of the rift (figs. 2, 4). Marine transgressions into the Benue rift occurred during times of worldwide high sea levels (Haq et al. 1987). It is unusual for a relatively inactive rift in which the dominant processes are eustatic sea level change, deposition, and subsidence with only limited folding and faulting to experience igneous activity. However, in the southern Benue rift (Maluski et al. 1995, p. 318–320), igneous rocks in the 74–49-Ma age range exist.

Granitic Complexes of Cameroon, 65–30 Ma. Cenozoic plutonic rocks, dated at 65–30 Ma, form 75 separate 5–10-km-diameter granite-dominated igneous complexes along a ca. 1200-km line in Cameroon (fig. 5; Fitton 1987; Deruelle et al. 1991). In its southern part, the line has the same azimuth of N 45° E, as has been occupied since 30 Ma by the Cameroon Line of volcano-capped swells. The northern part of the line has an azimuth of N 20° E (fig. 5). The 10 published isotopic ages for the complexes show no age progression along the line.

Because 30% of the complexes (16 of the 51 shown in fig. 5) occur in a 100-km-diameter cluster around lat 7°N, long 11.5°E, and because this is the place where the azimuth of the line of igneous complexes changes (fig. 5; Deruelle et al. 1991, p. 303), the area is here inferred to have been the location of an underlying mantle plume for the entire du-



Modified from Darros De Matos (1999)

Figure 4. Nupe rift, Benue rift, and the northernmost rift of the south Atlantic rift system are suggested to have formed at ca. 140 Ma on the crest of a dome, shown as an ellipse, that was elevated over 711 plume. The dashed line with an arrowhead between Afu and Dutse indicates how the greater exposure of volcanic rocks in the north and plutonic rocks in the south is interpreted to have resulted from tilting of the surface of the Earth during doming.

ration of intrusive complex formation between 65 and 30 Ma. The rocks of the complexes closely resemble the Late Triassic to Late Jurassic granites of Nigeria in composition, and it seems likely that they were generated in the same way: by partial melting of underlying continental crust and lithospheric mantle. The plume at lat 7°N, long 11.5°E, could have been either the same mantle plume as the one that was responsible for generating the Nigerian granites and initiating the Benue and related rifts, or it could have been a different plume.

One Plume or Two? A single plume is more likely than two separate plumes to have produced the Nigerian and the Cameroon granites for several reasons: (1) The two sets of granitic complexes occur within 500 km of each other (fig. 2). Mantle plumes that melt overlying continental lithosphere are rare. The likelihood of two such plumes erupting independently within 500 km of each other within <100 m.yr. seems small. (2) The ca. 140–66-Ma eruptions in the Benue rift show that igneous activity continued in the area between the two periods of granitic emplacement. (3) Paleomagnetic data indicate that the African plate between 140 Ma and 30 Ma was rotating slowly about a pole in the area of Nigeria and Cameroon within which igneous rocks were being erupted (e.g., Burke 1996; fig. 4). Based on this paleomagnetic evidence, the plume that generated the Nigerian granites, if it survived, could not have moved far from the position it occupied at the end of the Jurassic (ca. 140 Ma). Movement with respect to the overlying continental crust of a single plume between 140 and 66 Ma would have been no more than 300 km in an easterly direction, yielding a rate of 4 mm/yr (fig. 2).

These three observations indicate that a single plume, the 711 plume, was involved in forming both the Nigerian and the Cameroon granites. The responsible plume is here dubbed the 711 plume because evidence will be presented that the plume now underlies a volcano-capped swell at ca. lat 7°N, long 11.5°E (fig. 2).

History of the 711 Plume. The 711 plume appears

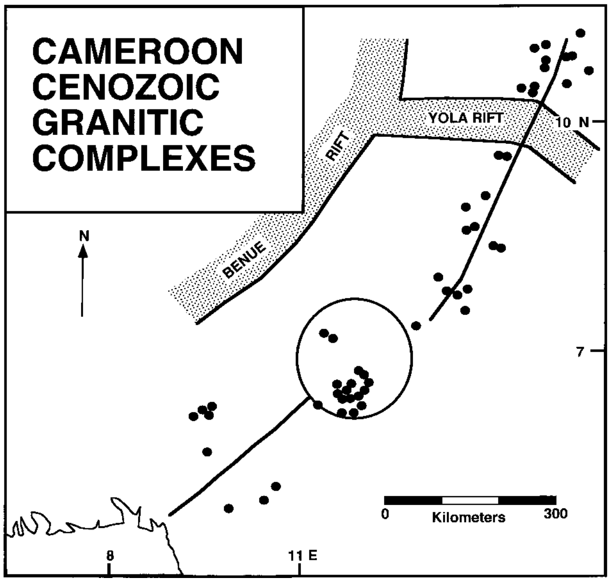


Figure 5. Distribution of Cameroon Cenozoic granitic complexes shown in relation to the postulated position of the 711 plume, which is suggested to have been at rest with respect to the overlying continental lithosphere since 65 Ma. Granitic complexes are small, 5–10 km across, and concentrated near lat 7°N, long 11.5°E. Alignments of the complexes away from the plume site toward the right-angled bend in the continental margin and across a dogleg bend in the Yola rift are indicated. Local Sh_{min} is suggested to have been normal to these alignments. Modified from Deruelle et al. (1990).

to have remained active, as indicated by the continuity of ages of igneous rocks, and to have moved only ca. 500 km with respect to overlying continental lithosphere during the past 200 m.yr. (fig. 2). Between 213 and 141 Ma (an interval of ca. 70 m.yr.), the 711 plume generated a 400-km-long line of intrusions as the continent moved over it. From 140 Ma to 66 Ma (an interval of ca. 75 m.yr.), the plume moved ca. 300 km with respect to the overlying continental lithosphere, having been caught up in the evolution of the Benue rift system (Maluski et al. 1995) rather than forming a line of intrusions. Since 66 Ma, the 711 plume appears to have been involved in a very different way with the continental lithosphere. The plume has stayed in the same place, close to lat 7°N, long 11.5°E, but has been associated with the sequential development of two geographically coincident but structurally, temporally, and compositionally different lines of igneous rocks, each of which extends away from the postulated plume site for hundreds of kilometers. Neither line shows evidence of progression in the ages of formation of its igneous rocks. The location and azimuth of the two lines along the bisector of a prominent right-angled bend in the margin of the continent (figs. 1, 2, 5) suggests that, in addition to the role of a long-lived plume, the peculiar stress distribution at a right-angled bend in the continental margin may have also played a role in the location and distribution of the two geographically coincident lines of igneous rocks.

The Role of Stress Distribution in the Formation of the Two Lines of Igneous Bodies Emplaced in Cameroon during the Past 66 m.yr.

Significance of the Colinearity of Outcrops of the Cameroon Granitic Complexes and the Cameroon Line of Volcano-Capped Swells. Paleomagnetic measurements (e.g., Burke 1996; fig. 4) have shown that the African plate rotated through ca. 45° counterclockwise about a poorly defined internal pole in the general area of lat 7°N, long 11.5°E, between ca. 140 and 30 Ma. The Cameroon granitic complexes were emplaced during that interval, and the volcano-capped swells of the Cameroon Line formed on top of the line of granitic complexes after the rotation had ceased at ca. 30 Ma. The colinearity between the line of granitic complexes and the line of volcano-capped swells indicates that both structures, although formed at different times, represent responses to a similar stress distribution.

If a single persistent stress field was responsible, it must have been in existence at 66 Ma, the age of the oldest Cameroon granitic complexes, and have persisted until 30 Ma, when the Cameroon Line formed. Furthermore, because Cameroon Line swells and volcanoes continue to be active today in the same places that they occupied at 30 Ma, the stress field presently controlling the volcano distribution appears to be the same as it was between 30 and 66 Ma. That stress field must have rotated with the plate between 66 and 30 Ma or the azimuths of the two linear trends would not coincide. These observations lead to the question, What long-lived set of forces operates in the area of the Cameroon Line and rotates with the rotation of the plate? The answer suggested here is, The forces generated as a result of the change in lithospheric structure at the continental margin (fig. 6).

A Distinctive Stress Environment at the Continental Margin. Stress distribution at the mature rifted margin of a continent is dominantly a response to the structural and compositional contrast that controls the difference in elevation between the continental surface, which typically lies close to sea level, and the ocean floor, which typically is ca. 4 km below sea level. Horizontal stress concentrations resemble those in a tall building. Extensional horizontal stresses dominate at sea level, corresponding to those in the roof, and compressional horizontal stresses dominate on the ocean floor, corresponding to those at the foot of the building (fig. 6*A*). At a right-angled bend in a continental margin, the stress distribution is modified so that Sh_{min} (the direction of minimal horizontal stress) is perpendicular to a line bisecting the right-angled bend (fig. 6*B*). The right-angled bend of the African continental margin in Cameroon (figs. 2, 3, 6) was established when South America and Africa separated at ca. 125 Ma (Austin and Uchupi 1982). As is common within plates, the interior of the African plate is presumed to have been subsequently in compression (Zoback 1992). That compressional stress-dominated regime is suggested to have prevented the continental lithosphere from rupturing in extension along the line bisecting the right-angled bend of the coast, even though substantial extensional stresses normal to that bisector would have existed. The local modified stress distribution at the right-angled bend, although extensional, was apparently insufficient to exceed the strength of the lithosphere while the lithosphere remained regionally under compression.

The 711 plume reached its present location at lat 7°N, long 11.5°E (fig. 2), at 66 Ma. Emplacement of igneous rocks and the presence of the underlying hot plume are suggested to have then elevated the overlying lithosphere. Modification of the stress field in the locally elevated lithosphere above the

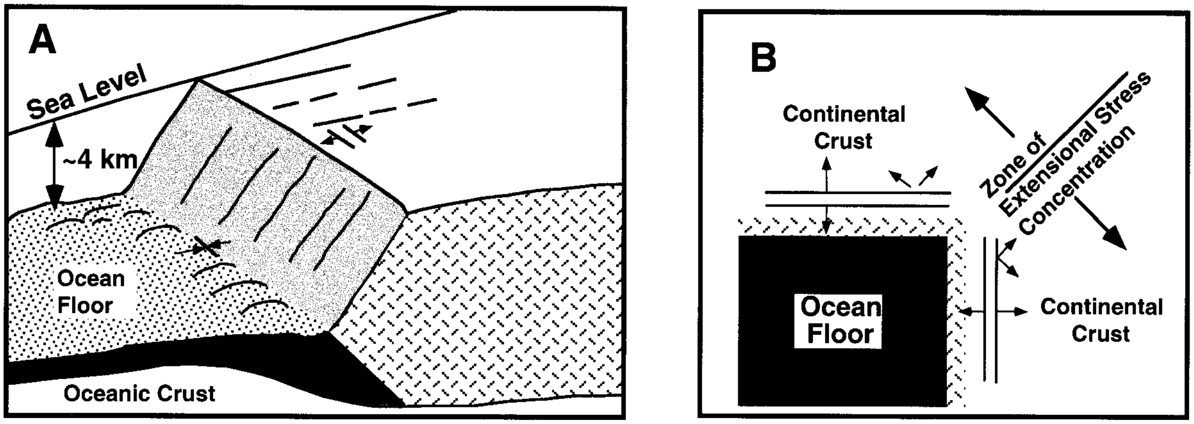


Figure 6. *A*, Concentration of extensional stress at sea level on a straight continental margin and a concentration of compressional stress at the foot of the adjacent continental slope. *B*, At a right-angled bend, such as that at Cameroon, resolution of the extensional stresses into two components at right angles indicates that a zone of extension stretches away from the right-angled bend along a line bisecting the right angle.

plume is suggested to have led at 65 Ma to development of a zone of extension between the 711 plume and the right-angled bend at the continental margin. Under a newly established regional stress field, embodying both the stresses generated at the right-angled bend and the stresses in the elevated area, extension is suggested to have developed for the first time along what would later become the Cameroon Line (figs. 1, 2).

Stress Field Control on the Cenozoic (65–30 Ma) Igneous Complexes of Cameroon. Cameroon Cenozoic granite-dominated plutonic complexes were emplaced along the bisector between 65 and 30 Ma. Complexes outcropping between the postulated area of the plume's occurrence close to lat 7°N, long 11.5°E, where many of the granites outcrop, and the coast have been mapped as occupying a broad (150-km-wide) zone. A clearer trend is not discernable because more than half of that region is buried under later Cameroon Line basalt (fig. 2). North of the area of concentration of complexes at lat 7°N, long 11.5°E, the trend of granitic complexes is along a line with an azimuth of N 20° E. That line extends across an obtuse-angled bend in the Yola arm of the Benue rift system (fig. 5). The N 20° E trend is interpreted as related to an anomalous lithospheric stress in the area of the Yola bend. A zone of extension, similar to that joining the 711 plume site to the coast, is postulated to have joined the Yola rift bend to the plume site at 65 Ma. The alternative possibility, by analogy with the progression in the ages of the Nigerian Jurassic granitic complexes (fig. 3), is that the distribution of the 65–30-Ma granitic complexes along the Cameroon trend might reflect movement of the continent over a plume. This possibility, however, is rejected because there is no progression in the 10 reported isotopic ages (fig. 2).

In summary, the granitic complexes along the 1200-km-long linear trend, outside the ca. 100-km-diameter area immediately above the postulated position of the underlying 711 mantle plume, are suggested to occupy zones of lithospheric extension. The southern zone of extension later became responsible for localization of the Cameroon Line of volcano-capped swells. A suggested cause of the two coincident alignments is a concentration of extensional stress, developed as part of the local stress field at the right-angled bend in the Cameroon continental margin (fig. 6).

Establishment and Evolution of the Cameroon Line

Establishment of the Line of Volcano-Capped Swells at ca. 30 Ma. At ca. 30 Ma, the existing shallow-mantle convection beneath Cameroon that had been dominated for ca. 100 m.yr. by the 711 plume is suggested to have become an assimilated part of a new, platewide, shallow-mantle convection system. This system had been set up at the arrest of the African plate (fig. 7; McKenzie and Weiss 1975; England and Houseman 1984). The highest present-day areas of the Cameroon Line, in the region of the Bamboutu and the Oku swells, are coincident with the location at lat 7°N, long 11.5°E, that the 711 plume is considered to have occupied between ca. 65 and 30 Ma (fig. 5). A rising plume of the new population is suggested to have taken over that site, or simply to have embodied the older plume. The ca. 30-Ma age of the circum-African regional offshore unconformity and the huge flux of sediment from Africa into the deep water around the continent within the following 10 m.yr. indicate that the swells of the African plate rose rapidly after 30 Ma and soon began to be eroded (Burke 1996, p. 392).

An ancestral Cameroon Line marked by small granitic plutonic complexes and composed of segments with two different azimuths diverging from the site of the 711 plume (fig. 5) had been established between 65 and 30 Ma. I suggest that the granitic complexes record a zone of extension and may indicate the presence of a short-wavelength, shallow-mantle convection system. The convection pattern set up at 30 Ma appears to have occupied the existing zone of extension and perhaps to have assimilated an existing convection pattern. The 30-Ma short-wavelength convection pattern is suggested to have generated today's volcano-capped swells along the same trend occupied by the earlier intrusions. Indications of greater extension normal to the trend of the bisector in association with the new Cameroon Line convection pattern are (1) that the newer igneous complexes (<30 m.yr. in age) are dominated by basalt rather than by products involving melting of continental crust and (2) that the Cameroon Line extended out to sea for 650 km from 30 Ma. The southernmost of the outcropping Cameroon granitic complexes at Koupe, emplaced at ca. 46 Ma (Fitton 1987), lies about 100 km from the coast (fig. 2), although similar complexes may be buried farther to the southwest under the voluminous young basalts of Mount Cameroon and

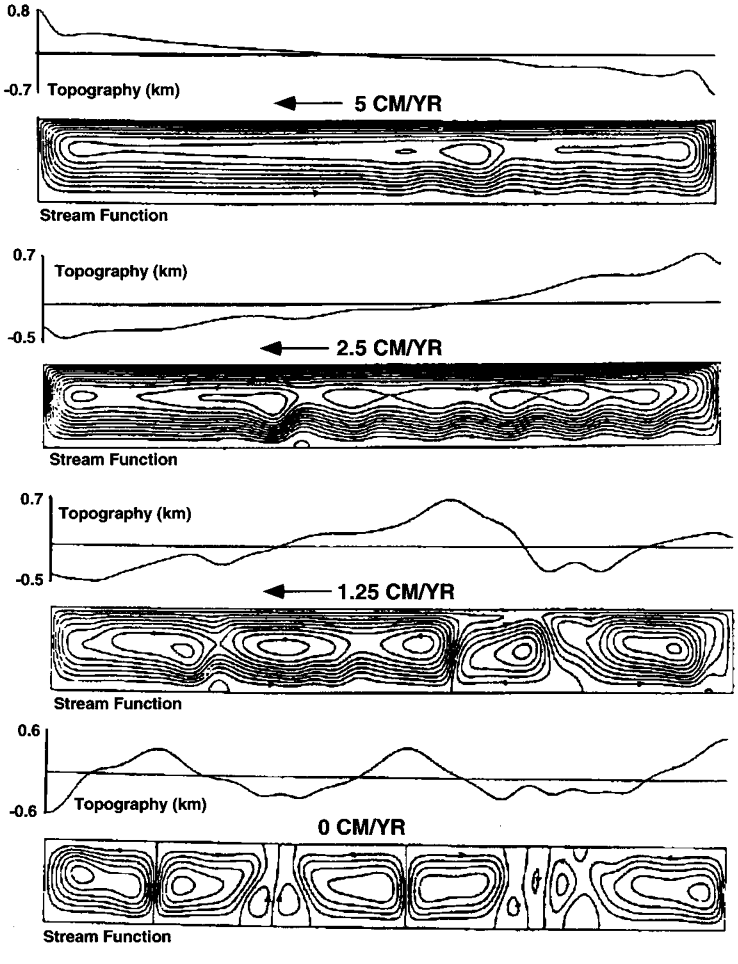


Figure 7. Cross sections illustrating the topography of a plate surface above a convecting shallow mantle. There is little relief on the surface when the plate is moving fast. At slower speeds some relief is generated, and a basin and swell pattern comparable to that of the African plate is established only when the plate is at rest. Simplified from the results of numerical experiments reported by England and Houseman (1984).

on the island of Bioko. At ca. 30 Ma, Cameroon Line swells on the ocean floor began to develop. Volcanoes on Principe have been active ever since, perhaps episodically. The azimuth of the line joining the swells of the ocean-floor segment of the Cameroon Line is also that of the bisector of the right-angled bend (fig. 2). This indicates that control of the alignment of the Cameroon Line of volcano-capped swells, both onshore and offshore, was the stress pattern at the right-angled bend in the continental margin.

The new penetration of that stress domain onto the ocean floor at 30 Ma can be considered a direct consequence of the plate coming to rest. The establishment of a platewide shallow convection pattern at 30 Ma when the plate came to rest (Burke 1996) diminished the dominance of ridge-push plate-boundary forces (Forsyth and Uyeda 1975) on the African plate. Those forces keep the interior of the plate in compression. A new buoyancy, concentrated at the numerous newly formed populations of plumes rising from shallow depths beneath the African plate, diminished the effect of the ridge-push force (cf. Meijer and Wortel 1999). The anomalous stresses at the continental margin right-angled bend that, in association with the influence of the 711 plume, had been sufficient to overcome the strength of the relatively weak continental lithosphere between 66 and 30 Ma became sufficient—with the reduction in intraplate shortening at 30 Ma—to overcome the strength of the relatively strong, old (ca. 125 Ma) oceanic lithosphere (cf. Steckler and ten Brink 1986).

The oldest igneous activity of the 30 Ma and younger Cameroon Line onshore, as distinct from the earlier igneous activity in the granitic complexes, began as "basalt and andesite flows [that] … appear to have come from fissure eruptions following the regional … trend [in] extensive areas [that lie around 5°N, 9.5°E, Mount Cameroon, and around 7°N, 11.5°E, Mount Oku]" (Piper and Richardson 1972, p. 154). Volcanism on six of the 10 swells of the Cameroon Line has been isotopically dated as beginning between 30 and 10 Ma. Because of burial by later lavas, the earlier ages are here taken to indicate the approximate timing of the beginning of eruption on all the swells. Bioko and Mount Cameroon have yielded only very young ages because the large young volcanoes on these swells have buried nearly all the older rocks. The two seamounts that form part of the line of swells have not been dated.

Evolution of the Cameroon Line over the Past 30 m.yr. The island of Principe swell is capped by volcanic rocks from which a record of episodic activity over the past 30 m.yr. has been extracted (Fitton 1987, p. 280). Less complete records on the other swells, recognizing that substantial erosion and burial by young basalt have been widespread both offshore and onshore, are consistent with similar histories. The swells are here suggested to be elevations above rising plumes of an aligned, short-wavelength (ca. 100 km), shallow-mantle, convection pattern. Hot material under the swells has formed local mass-deficient volumes of mantle material, and the elevation of the swells is primarily an isostatic response to that mass deficit (cf. Morgan et al. 1995; Meyers et al. 1998, p. 45–49). Construction on top of the swells by the eruption of relatively small volumes of volcanic rock, typically <2 km thick on the volcanic islands (Meyers et al. 1998, p. 41), and the emplacement of intrusions under the volcanoes (Meyers et al. 1998; figs. 3, 4) have made a smaller contribution to swell volume than has lithospheric uplift. Erosion has been active above sea level and has been more intense on the islands and Mount Cameroon and less intense in the drier interior. Further reduction in the elevation of the swells offshore has come from slumping off the flanks of the islands (Meyers et al. 1998; fig. 3 at field file 2000) and from the cutting of submarine canyons.

The five processes of isostatic elevation, volcanic accumulation, subaerial erosion, submarine slumping, and submarine canyon cutting along the Cameroon Line are likely to have varied in intensity since inception of the swells. By how much and on what time scales, however, cannot be discerned because relevant data are only patchily available. The oldest age of volcanic rocks of the Cameroon Line of volcano-capped swells at about 30 Ma, both offshore and onshore, is likely to be close to the time of beginning of swell elevation. Meyers et al. (1998, p. 43) identified an unconformity indicating that initial elevation of the volcanic islands was Miocene in age, between ca. 22.5 and 5 Ma. This was done by tying a prominent reflector on their seismic lines, which they designated as an "uplift unconformity" to oil wells. Onlap of reflectors, shown on their figure 3, can be interpreted as indicating more than one episode of elevation. This is consistent with their conclusion (Meyers et al. 1998, p. 43) that "crustal uplift of [the] islands and seamounts appears to have been by gradual ramping or bending of the lithosphere."

Shallow Convection under the Cameroon Line? Although the idea that shallow underlying convection in aligned cells (with the ca. 100-km spacing separating the volcanoes) is attractive (cf. Meyers et al. 1998), the evidence for such small-scale convection is as yet quite limited. Five considerations, relevant in assessing whether small-scale (ca. 100 km) convection is going on beneath the Cameroon Line of volcano-capped swells, are listed here.

1. Alignment of the volcanoes is the first consideration, although this could simply be a response to the concentration of extension normal to the Cameroon Line. Pressure relief beneath a line of extended lithosphere appears to be the cause of the volcanism. The pressure relief may be localized at 10 fairly regularly spaced locations along the line (fig. 2) for reasons unrelated to convection. Offshore, the volcanoes may be located where the Cameroon Line crosses fracture zones, as Meyers et al. (1998, p. 49) suggested. Onshore, the volcanoes may be located where structures related to Riedel-style shear have developed, as Deruelle et al. (1991, p. 302) suggested.

2. Uplift of the basement under the volcanoes, as illustrated in Meyers et al. (1998), shows that something more than a crack in the lithosphere is involved. Hot rock forming a low-density volume below the swells appears to have lifted the whole lithosphere rather than just leading to the eruption of igneous rocks through cracks.

3. The fairly regular spacing of the volcano-capped swells (fig. 2) is perhaps the strongest evidence that convection may be involved. The similarity of onshore and offshore spacing is an indication that whatever has localized the swells has operated in the same way both onshore and offshore. Convection, as illustrated in figure 7, is likely to generate regularly spaced rather than irregular patterns at the surface. The convection pattern illustrated in figure 7 was obtained with a numerical model in which the upper mantle convecting layer was about as thick as the spacing of the swells that emerged from the calculation (England and Houseman 1984). The 100-km spacing of the Cameroon swells, if it indicates the thickness of the convecting layer involved, would suggest a thin convecting layer only ca. 100 km thick immediately below the lithosphere.

4. Convection models have been used to explain irregularities with a spacing of ca. 100 km along oceanic spreading centers. As Meyers et al. (1998, p. 50) pointed out, there may be some analog in the Cameroon Line.

5. The gravity field of the Cameroon Line may be interpretable as related to convection. McKenzie and Fairhead (1997) showed that, in general, it is not possible to model the shorter-wavelength parts of the continental gravity field by comparing them with topography. This is because many elements of the short-wavelength field reflect loads added to the lithosphere over one or more billion years. The topographic response to the initial application of the load to the lithosphere has long since eroded away. The surviving load is supported by lithospheric strength. In general, only the long-wavelength parts of the field, for example, elements related to the basins and swells that extend all over the African plate (fig. 1), can be usefully modeled in estimating such parameters as elastic thickness. Uniquely, Cameroon Line basin and swell topography has a short wavelength of 100 km and every swell is capped by a volcano. The Cameroon Line may thus be an appropriate place in which to model the elastic thickness and the crustal thickness using gravity and elevation data. Poudjom Djomani et al. (1997, figs. 6, 9) have estimated crustal thickness and elastic thickness of the lithosphere for the area of the Cameroon Line. Both are thin relative to neighboring areas, but the use of overlapping grid squares 440 km on a side has meant that the 100-km-scale structures of the Cameroon Line are not well resolved.

In summary, volcano spacing, gravity, and topography indicate a thin crust and a thin elastic lithosphere in the area of the Cameroon Line of volcano-capped swells. However, there is as yet insufficient information to show whether or not the Cameroon Line is underlain by its own distinctive shallow-mantle convection system.

Discussion: Suggestions for the Origin of the Cameroon Line

Diverse but Incomplete Data Sets. As other authors have emphasized, a major problem in interpreting the Cameroon Line has been the uneven distribution of different kinds of information (see summary in Deruelle et al. 1991). For example, in some places geochemistry is well known but not geophysics and vice versa. There is a great deal of data that has been at best touched on lightly in this article. If the interpretation presented here can be shown to be incompatible with those results, it will have to be revised.

Fitton's ingenious observation (1987) that the geometry of the Cameroon Province could be reproduced by rigid rotation over the older Benue Province was a stimulus to tectonic and geophysical observation and interpretation during the 1980s (Deruelle et al. 1991). During the 1990s, tectonic and petrological studies were complemented by an abundance of geochemical data, including much that relates to the volcanic islands (Halliday et al. 1990; Lee et al. 1994). The interpretation of gravity data, including estimates of elastic thickness, has also been attempted (e.g., Poudjom Djomani et al. 1995; Hartley et al. 1996), and a splendid marine geophysical study (Meyers et al. 1998) has provided a new and important data set.

Suggestions Based on New Geochemical Results. Lee et al. (1994, p. 135–136, fig. 10) embodied several conclusions into their preferred model. (1) They distinguished a discrete modification of the mantle lithosphere on the site of the Cameroon Line at ca. 120 Ma. That is consistent with the conclusion in this article, based on quite other evidence, that the 711 plume began to interact with the continental mantle lithosphere in the Benue at ca. 140 Ma and has persisted in interacting with the lithosphere in the Benue-Cameroon area ever since. (2) They considered that only plume sources from the shallow mantle were involved in the Cameroon Line. The 711 plume is here considered a shallow-sourced plume because, at its first eruption, it did not generate a large igneous province (cf. table 1). This agrees with Lee et al.'s (1994, p. 135–136) conclusion. (3) Their conclusion that "the focus of magmatism is therefore, partly controlled tectonically; that is by preferential flow paths through the lithosphere" is compatible with the suggestion in this article that the azimuth of the Cameroon Line is controlled by the abnormal stress concentration in the lithosphere at the right-angled bend in the continental margin. (4) They considered that a HIMU source was likely to have been dominant in the formation of Cameroon swell lavas. That observation is consistent with the small volume of lava characteristic of basalt derived from the HIMU source (cf. Burke 1996, p. 358).

Suggestions Based on Recently Acquired Offshore Geophysical Data. A comprehensive marine geophysical data set from the offshore Cameroon Line allowed Meyers et al. (1998) to demonstrate that the offshore swells are dominantly the products of lithospheric uplift within the past 30 m.yr. They do not, as Hawaii does, represent thick loads of volcanic material on the top of the lithosphere. Because Cretaceous sedimentary rocks occupy the basins between the onshore swells, that interpretation can be considered valid for the entire Cameroon Line of volcano-capped swells.

Meyers et al. (1998, p. 49–50) suggested that the Cameroon Line "may relate to the geometric nature of magma penetrating the lithosphere from an underlying linear zone of hot mantle." They pointed out the possible applicability of models describing the spacing of magma chambers along spreading centers, citing papers by Nicolas (1989), Lin et al. (1990), Schouten and Whitehead (1991–1992), and Rohrman and van der Beek (1996). Suggestions about swell elevation and possible short-wavelength convection in this article follow closely those of Meyers et al. (1998, p. 49–50). The main difference is that the situation of the Cameroon Line of volcano-capped swells has been here demonstrated to be unique and to have developed as a result of location at the right-angled bend in the continental margin and over the 711 plume. Meyers et al. (1998, p. 54–58) preferred the idea, first introduced by Krenkel (1957), that the African plate is underlain by hot-lines, referring to the work of Richter and Parsons (1975) on mantle rolls, although those workers did not consider their model applicable to the African plate. Meyers et al. (1998) suggested that the Cameroon Line might be comparable to other northeast-trending lines joining volcanoes on the African plate. The contrasting suggestion here is that, if the pattern of basins and swells of figure 1 shows only one thing, it is that the Cameroon Line is very different from all of the other swells on the African plate. Lines can be drawn with various azimuths among the volcanic areas shown on figure 1, but the Cameroon Line is unique.

Suggestions from Recent Analyses of Gravity and Topographic Data Sets. In a continent-wide study based on large data sets for both gravity and topographic measurements, Hartley et al. (1996, fig. 5) estimated a particularly thin elastic thickness for the lithosphere in the general region of the Cameroon Line. Poudjom Djomani et al. (1997), in a more local study with similar data sets but using somewhat different analytical procedures, also estimated both crustal thickness and elastic thickness of the lithosphere as unusually thin in the continental part of the Cameroon Line. Their map of crustal thickness (their fig. 6) has a minimum value of 18 km at the location of the 711 plume, an exceptionally low value for a continental crust that is not obviously being rifted. The crustal thinning required to produce such a small number in the absence of rifting, of which there is no evidence, seems to require the action of an underlying thermal modifier such as a mantle plume. The methods that Poudjom Djomani and her collaborators used required extensive areas to be interpreted together, so that their crustal thickness contours for the Cameroon Line and those of the Ngaoundere (Adamawa) swell (fig. 1) run together and the Cameroon Line does not make a clear feature in contours of crustal thickness. The effective elastic thickness map of Poudjom Djomani et al. (1997, fig. 9) shows a uniformly thin value of ca. 18 km for the continental part of the Cameroon Line. Comparably low values in neighboring areas were found only on the Ngaoundere swell and at two places in the Benue rift (see figs. 1, 2). In the absence of evidence of rifting, a thermal thinning would seem to be required for the underlying structure of the Cameroon Line.

Offshore, Meyers et al. (1998, p. 47, figs. 7, 8) modeled the gravity field across the island of Principe as a response to an underlying 25-km-thick wedge of hot mantle that elevated, but did not thin, the overlying crust. Such a wedge would reduce the effective elastic thickness of the lithosphere, and the interpretation is therefore compatible with the interpretation of the onshore data by Poudjom Djomani et al. (1995). A model of the offshore gravity data that involved crustal thinning, as the onshore interpretations do, would also be compatible with the observations.

Conclusions

The Cameroon Line of volcano-capped swells is a unique feature of the Earth that is suggested in this article to owe its origin to the remarkable concatenation of three distinct phenomena: (1) a position over the 711 plume for the past ca. 140 m.yr.; (2) a location adjacent to a right-angled bend of the continental margin for ca. 125 m.yr; (3) the establishment of a new platewide pattern of shallow-mantle convection at ca. 30 Ma when the African plate came to rest.

Although the Cameroon Line of volcano-capped swells is a very unusual phenomenon, its distinctive features make it an as yet underutilized field laboratory. Many questions about mantle geochemistry, shallow-mantle circulation, mantle lithosphere interaction, plate motion, plume behavior, and structural and geochemical evolution across a continental margin can all be addressed. Only the mantle geochemistry appears to be currently under intense study (Lee et al. 1994; Ballentine et al. 1997).

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