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Giant dikes, rifts, flood basalts, and plate tectonics: A contention of mantle models

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ABSTRACT

Giant dike swarms, often hundreds of kilometers long, have produced flood basalts in large igneous provinces since the early Proterozoic. Dike patterns described as radiating from a central source are actually syntectonic swarms that curve and diverge according to lithospheric stress regimes, but they are similar in origin to smaller swarms with parallel dikes. Giant radiating patterns of dikes do not characterize most hotspots or large igneous provinces, and they are not always linked to crustal uplift swells. These mafic intrusions and the fractures they follow are essentially features of plate tectonics, not products of indeterminable deep mantle plumes. As a compelling example, the Early Jurassic central Atlantic magmatic province and its associated Pangaean rift zone are evidential products of subducted materials and convection in the upper mantle beneath the insulating Pangaean plate. Giant dike swarms were formed along lithospheric structures through plate tectonics, not by a coincidental deep mantle plume.

Keywords: giant dikes, flood basalt, LIP, plume, tectonics

INTRODUCTION

The association of giant dike swarms (GDS) and continental flood basalts (CFB) with mantle plumes (originally proposed by Morgan, 1971) is based on the observation that some flood basalt provinces seem to initiate hotspot tracks (e.g., Duncan and Richards, 1991), and also on the isotopic signatures of flood lavas (Carlson, 1991). However, many flood basalts are not associated with volcanic chains, and many volcanic chains observed within plates have no associated large igneous provinces (LIPs) or obvious plume heads. In some cases, this may be explained by the removal of the initiating LIPs by subduction, although thick-crusted regions may resist subduction. Where they do subduct, a large fertile patch is created in the mantle, which can contribute to the source for subsequent LIPs.

Seemingly radial patterns in some giant dike swarms have

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been cited as evidence for deep-plume origins and attributed to uplifts caused by mantle plume heads (e.g., Ernst et al., 1995). The amplitude of the resulting uplift may be insufficient to accommodate large dike swarms (such as the Mackenzie swarm) by simple magmatic fracturing, and some LIPs are clearly not associated with precursory uplift (Czamanske, 1998; McHone, 2000). Given large magma volumes in the source region and high fluxes during dike emplacement, it is possible that a major fraction of the observed dike thicknesses was formed via melting of the dike walls (Fialko and Rubin, 1999). The extensional stress in the crust after dike emplacement may even have been larger than it was prior to dike emplacement (Parsons and Thompson, 1991). If so, the radial or fanning patterns of large dike swarms might be due to a self-induced stress field. If a large-scale uplift was centered over the magma source, its main role was probably to provide a gravitational driving force for long-range lateral magma transport.

Dikes are self-induced magma-filled fractures, and they are the dominant mechanism by which basaltic melts are transported through the lithosphere to the surface. The class of dikes called "giant dikes" can commonly exceed 30 m in width and 100 km in length, with some examples over 100 m wide and 1000 km long. Many examples are mapped as systems or sets of en echelon, parallel, or colinear segments rather than as one continuous linear dike, but their segments must be interconnected in a vertical sense. These spectacular intrusions are likely to have fed flood basalts in LIPs, including provinces in which the surface basalts have been diminished or removed by erosion. LIPs and their dike swarms are most commonly associated with preexisting rifts or tectonic boundaries, such as sutures and the edges of cratons.

This discussion focuses on geographic patterns, magma parameters, and associated physical features that provide evidence, and support arguments, concerning the origins of giant dike swarms. We start by reviewing some of the tenets of plate tectonic and mantle plume theories that are relevant to different models. Particular tectonic and magmatic features of lithospheric plates and the upper mantle characterize flood basalt magmatism, and these are compared with ideas promoted for deep mantle plumes. The central Atlantic magmatic province (CAMP) and the early Mesozoic central rift zone of Pangaea (Fig. 1) provide important observations that have been used for and against these conflicting models. The relevant features of giant CAMP dike swarms are described in several sections. We finish with some ideas and discussions of predictable features that can help to test plate tectonic versus mantle plume models for giant dike swarms.

BACKGROUND

Plate tectonics involves the large-scale *lateral* motions of plates. Plate tectonic theory concerns itself with the formation and dynamics of plate boundaries, including the long, linear volcanic features associated with those boundaries. Plate boundaries, rifts, and the motions of plates are the results of stresses in the plate-slab system. Plume theory suggests the long-distance (~3000 km) *vertical* transport of narrow hot columns from the core-mantle boundary to volcanic provinces at the surface, including LIPs. Although not intrinsic to the plume hypothesis, recent proposals include long-distance lateral transport of plume head material as sheets within the asthenosphere (Sleep, 1990, 1997) and also long-distance transport of magma in dikes within the lithosphere. The formation of rifts and new plate boundaries is an important part of plate tectonics, and it much affects the outer layers of the Earth. Some volcanic chains form on incipient plate boundaries. The breakup of Pangaea—the opening of the central Atlantic Ocean and the Gulf of Mexico—is an especially important event in that it involved continental rifts, LIPs, giant dike swarms, a new plate boundary, and the initial production of ocean crust.

The disintegration of the supercontinent Pangaea was marked by bursts of extensive magmatism. A popular hypothesis for such expressions of magmatism is the arrival of mantle plumes. A rift-initiating mantle plume rising from a hot boundary layer, such as the core-mantle boundary, is characterized by a large mushroomlike head above and followed by a narrow cylindrical conduit. This model has been illustrated by the injection of hot fluid into a tank of colder fluid at rest. The effects of pressure are ignored in such models and in most computer simulations. The goal is to illustrate what plumes are thought to look like rather than to test the model. The plume hypothesis attributes anomalous mantle melting to thermal anomalies, concluding that warm plume heads generate tholeiitic LIPs and hot plume tails generate alkalic volcanic chains leading away from LIPs.

Plate tectonic theory is exemplified by the breakup of Pangaea and the early history of the central Atlantic Ocean (which eventually became the southern half of the North Atlantic). As a precursor to this event, several giant dike swarms fed a vast tholeiitic flood basalt province covering over 11×10^7 km^2 of central Pangaea, starting at 201 Ma during continental rifting but before the initiation of new ocean crust (Hames et al., 2003). This recently recognized LIP is known as the central Atlantic magmatic province (Marzoli et al., 1999), and it evolved into mid-ocean rift production of Atlantic Ocean crust that has remained active from the Early Jurassic to the present.

In contrast to the very widespread but brief pulse of earliest Jurassic CAMP magmatism, the events that gave rise to numerous Cretaceous and Tertiary alkalic volcanoes and seamounts in and around the central Atlantic were mainly local and independent events, with individual histories of activity. Despite the time gap of 70 m.y. and the compositional gulf between quartz tholeiites and alkali olivine basalts, some geologists have attempted to connect the CAMP LIP to a few of the younger volcanoes via a single proposed deep mantle plume (e.g., Morgan, 1983; Thompson, 1998). Their mantle plume model does not attempt to explain the geographic patterns and origins of many

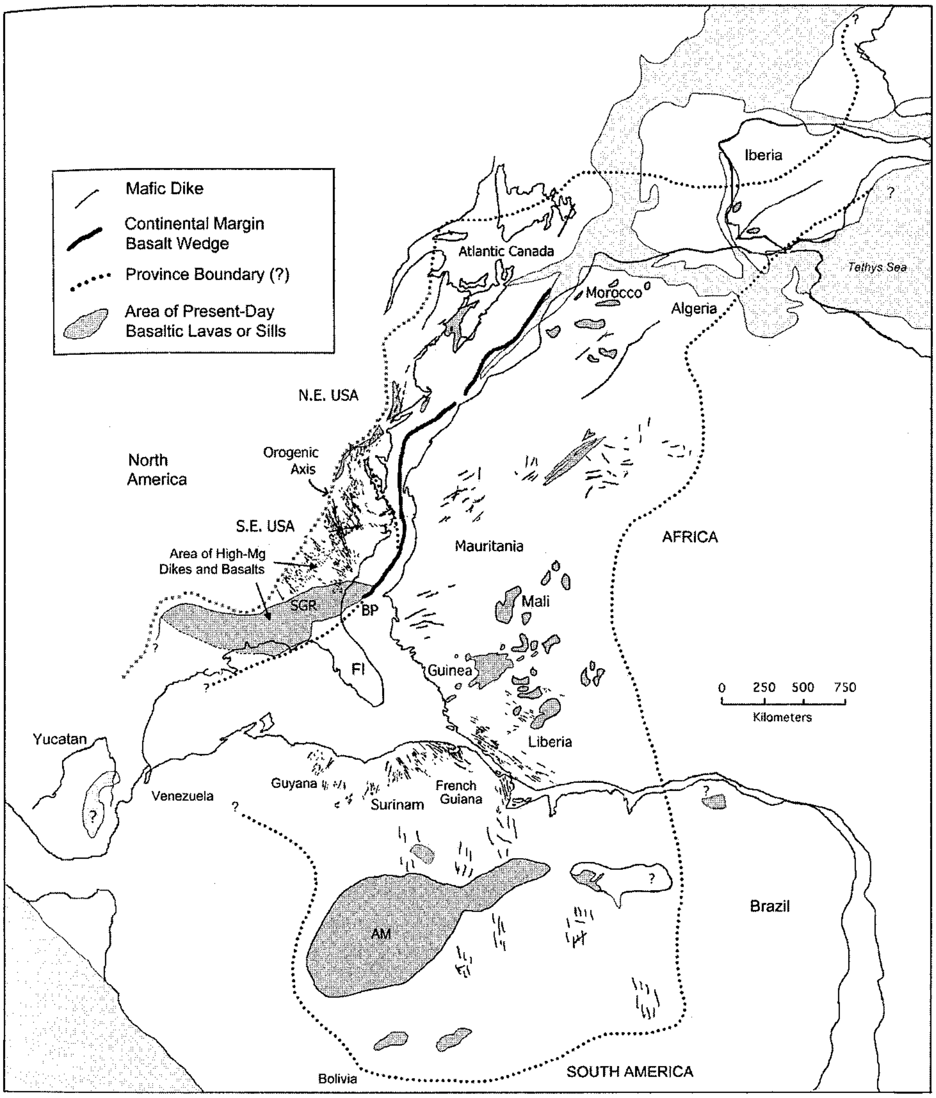


Figure 1. Sketch map of dikes, sills, and surface flows and boundaries of the central Atlantic magmatic province. After Figure 1 in McHone (2000). SGR—South Georgia Rift; BP—Blake plateau; FL—Florida; AM—Amazon.

volcanic features in and around the central Atlantic Ocean, although those features are otherwise similar to the seamounts proposed to be plume-derived (McHone, 1996, 2000).

OBSERVATIONS AND CONSTRAINTS

The defining characteristic of giant dike swarms and associated flood basalts is rapid emplacement from an enormous supply of magma from an upper-mantle source to the Earth's crust. A single dike of the Proterozoic Mackenzie swarm in Canada likely carried a volume of magma equivalent to 100 years' worth of melt production of the entire contemporary global mid-ocean ridge system. The large volumes of magma, as well as the high magma fluxes (individual giant dikes may have been emplaced on a timescale of weeks to months, and the entire magmatic episodes might have occurred on a timescale on the order of 10^5 years) imply a major thermal or compositional (or both) perturbation in the upper mantle or a perturbation in the lithospheric stress field (the stress-valve mechanism) over a relatively short time.

The inferred high rates of magma production require robust advection of hot material from the upper mantle and/or a storage mechanism (ponding, underplating), plus a release mechanism (diking? stress valve?). The delivery of melt from the mantle to the surface may not have been a single-stage process or a steady-state process. Thermomechanical and chemical arguments alone do not constrain the depth from which the hot or fertile material was supplied to the melting area (in or below the thermal boundary layer, the base of the lithosphere, or the crust). It is not certain that the source region of LIPs is strongly superheated. The smaller the holding tank (magma chamber, underplate, magma pond) and the greater the undercooling of the host rocks with respect to the solidus, the shorter the lifetime of volcanism. The stress criterion for the formation of dikes, and hence extrusion, is that the least compressive axis be horizontal. Underplating and sill formation differ from extrusion only in the orientation of the stress, yet extrusions are more dramatic and have generated separate theories.

On continents, most large igneous provinces (CFB) occur on or along suture zones adjacent to cratons. When a continent splits, there is often (but not always) a transient burst of magmatism. Mature, steady-state ridges take longer to form. Magmatic activity associated with rifting is often correlated with preexisting faults, transforms, fracture zones, and rifts (Sykes, 1978; Bailey, 1992). The association of CFB with archons (cratonic roots of Archean age), suture zones, and preexisting faults and rifts is much closer than it is with time-progressive volcanic chains. Some CFB even form during continental convergence. There is a cause and effect issue here; does a large hot buoyant mass of magma from deep in the mantle cause the split, or does continental breakup result from plate tectonic processes that then allow egress of accumulated magma? The occurrence of CFB during convergence (e.g., Deccan, Keweenawan, Siberian, Alpine/European?) and during late stages of breakup (e.g., the north Atlantic tertiary province) suggests that the association of plumes and breakup is not universal, and it may be misleading to presume a sequence of plume head impact, then extension, then CFB, and finally breakup.

Although it has been proposed that plumes and plume heads lift up and break the lithosphere, it is now generally accepted that preexisting structures, including rifts and thin spots, localize asthenospheric upwellings. The "upside down drainage" mechanism of Sleep (1997) has been used to explain the distribution of igneous rocks in Africa and elsewhere. In the plume hypothesis, the plume finds an existing rift after it hits the base of the lithosphere. The Deccan traps were erupted at 65 Ma into a Permian rift, the Tristan at 133 Ma into a Late Jurassic (145 Ma) rift, the Karoo "plume" at 180 Ma (mid-Jurassic) into a Permian rift, and the north Atlantic province into a Triassic rift. Most conjectured plumes of the past 250 m.y. were emplaced into existing rifts (Afar is an exception; Burke et al., 2003). For example, the Newark rifts of eastern North America, which were initiated ca. 230 Ma, received 201 Ma CAMP basalts as a result of within-lithosphere magmatic propagation as far as the Bay of Fundy and Maranhao in Brazil and as far as Acre in the upper Amazon rift (ca. 4000 km total distance). As we show later, the large 201 ± 1 Ma CAMP dikes in New England are clearly not radial from the CAMP center. They are products of in-lithosphere propagation of magma, no doubt responding to the local stress field in their slightly different azimuths.

"Upside down drainage" ensures LIP eruption in places where the lithosphere is thin (e.g., in intracontinental rifts), but also where preexisting lithospheric architecture thins: some rifts are localized on older suture zones (Wilson, 1976). Sleep (1997) argues that the locations of LIPs are not related to the locations of plumes, but are controlled by the lithosphere. The Deccan LIP was emplaced in a Permian rift and was followed by continental rupture. The Keweenawan (?) appears to be a collisional rift like Baikal; the convergence was to the south. Siberian Trap emplacement is associated with orogenic collapse and with huge rifts and strike-slip faults. It is apparent that the orientation of the Karoo dike swarms is controlled by preexisting structures and that the sites of initial volcanism were controlled by crustal boundaries (Bailey, 1992). Some of the dike swarms interpreted from geophysics as radiating from the supposed Karoo plume head dike are actually Proterozoic (and in some cases Archean) in age (Uken and Watkeys, 1997). These are just a few examples of LIPs localized by preexisting tectonic features. Many volcanic chains also lie along preexisting tectonic features (Favela and Anderson, 1999). The upside-down drainage mechanism is not intrinsic to the plume hypothesis; the asthenosphere itself can flow laterally in response to density variations, plate motions, and rifting. Low-melting-point and fertile portions of the asthenosphere will upwell and melt further as they rise into rifts or into thin spots of the lithosphere.

The large volumes of magma involved in flood basalt events pose several mechanical problems. If giant dike swarms were fed from an intermediate storage region in the crust, there is a problem of space for a large (thousands to millions of cubic kilometers) shallow magma chamber. If dikes ascended directly from a mantle source and spread horizontally upon reaching a level of neutral buoyancy, it is unclear how large volumes of gravitationally unstable melt might have accumulated in the source region. One possibility is that most of the melting takes place while the lithosphere is under horizontal compression, and the melt cannot readily escape via dikes until the compression is replaced by extension.

Regional uplift due to upwelling mantle generates horizontal compression in the lower lithosphere, which may result in magmatic underplating. Subsequent subvertical transport of the ponded magmas may be possible if the horizontal compression is relieved, e.g., by thermally activated creep, gravitational collapse, or tectonic extension. Regional uplift is not a prerequisite for trapping large volumes of melt at the base of the lithosphere; the latter may be accomplished in principle by any process resulting in horizontal compression in the lower lithosphere. Normal variations in lithospheric architecture also produce thin spots, toward which magma can migrate and pond. Lateral flow in the asthenosphere has been proposed for plume heads (Sleep, 1997), but normal asthenosphere can flow laterally as well.

THE PARAMETERS

Parameters controlling dike intrusion include magma density and viscosity, magmatic pressure, and magnitude and orientation of stresses in the lithosphere. Yield stress is negligible compared to typical magmatic overpressures, and host rock density affects propagation only insofar as it affects stress in the lithosphere. The tectonomagmatic history of the area is also important. A long history of ponding (in the lower crust or the upper mantle) may be essential to the formation of long diverging dikes. True radial dikes form as bladelike sheets of magma that may move laterally in the *shallow* crust. Simple gravitational stresses on elevated features such as Hawaiian volcanoes (Fiske and Jackson, 1972) or neutral buoyancy (Ryan, 1993) can control the depth of lateral dike injection, but either way, the condition of formation of radial dikes is that the difference between the intermediate and the least principal stresses is less than the magma overpressure (the difference between the magma pressure and the dike-perpendicular stress). Truly radial dikes are shallow, and their regions of lateral dike injection rise, staying at about the same depth below summits, as the volcanoes grow.

Using the Hawaiian example, volcanoes with radial dike configurations must stand in isolation and not nest against one another. Volcanoes must be high enough that the region of dike injection is *not* influenced by stresses in the ocean crust or the upper mantle. If volcanoes nest, rift zones with parallel dikes form. Bora Bora in the Society Islands is an example of a high, freestanding volcano with radial dikes. Isolated seamounts with stellate patterns of lateral rifts (Smoot, 1999) are another example; these are abundant in the far western Pacific and formed when the Pacific plate was surrounded by ridges and had minimal internal stress differences. Moreover, these are swarms of "normal"-sized dikes, not giant dikes.

By way of illustration, two of the six dikes that radiate from Ship Rock volcanic neck in New Mexico are shown in Figure 2. Ship Rock and its dikes were probably injected only 750–1000 m below the land surface at the time they formed.

Length of dike propagation is not an issue. The underlying stress field is what controls whether dikes are radial or parallel. Length is mainly controlled by magma supply and perhaps by elevation of the source volcano or magma chamber. Some Hawaiian rifts are hundreds of kilometers long, about the same length as dikes that originated at some of Hebridean intrusive centers (Thompson et al., 1983). Those dikes are subparallel, cross much of Scotland and England, and followed the direction of an aulacogen (the abandoned third arm of a continental rift system). These are examples in which underlying lithospheric stresses, not those of high volcanoes, influenced dike orientation. Afar sits at the intersection of three rift systems (Fig. 3). It is not a radial dike system, but a three-pronged "triple junction." Dikes may or may not be parallel to rift trends, but they are perpendicular to rift extension directions.

It is also apparent when comparing regional maps to local maps that dikes depicted as radial on a large scale may in fact be parallel on local maps, suggesting that scale is important in analyzing so-called radial dike swarms (Deckart et al., 1997; Edwards and Beutel, 2003). Another problem is distortion from the projection of the spherical surface onto a flat map. Some so-called radial dike swarms are actually subparallel to or subperpendicular to rifted margins. In Scotland, later-generation dikes crosscut earlier dikes. In each case, the dikes have been attributed to thermal mantle plumes.

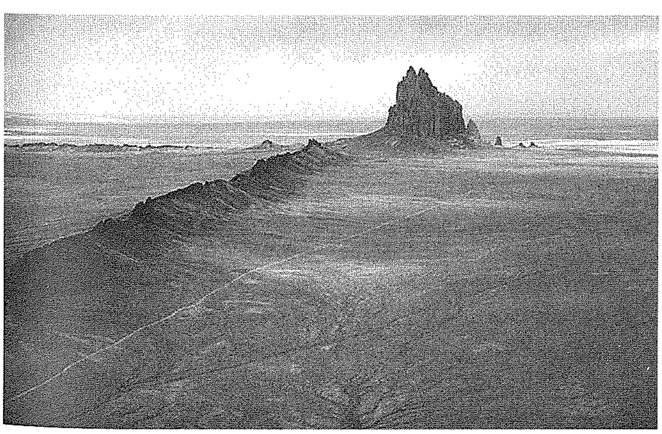


Figure 2. Aerial view of Shiprock, New Mexico, with radiating dikes. Photo © Louis Maher; image courtesy of Earth Science World Image Bank (http://www.earthscienceworld.org/imagebank).

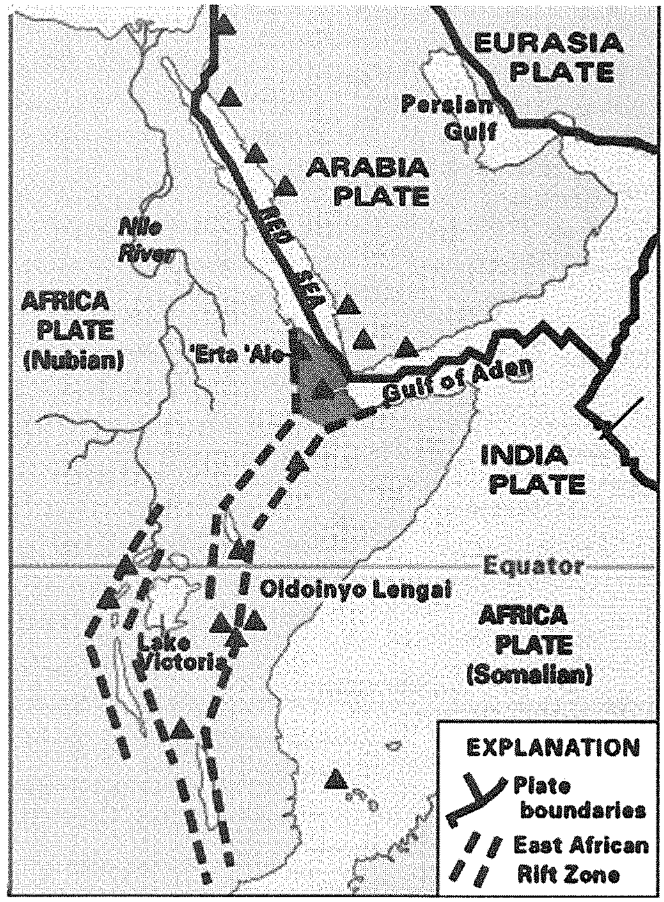


Figure 3. Rift features of the Afar Triangle region. From the United States Geological Survey hypertext book *This Dynamic Earth* (http://pubs.usgs.gov/publications/text/East_Africa.html).

Each plume head is proposed to lift up the crust and create a broad region in which intermediate and least principal stresses become equal, even in the absence of a high volcano. However, it is more likely that the stress configuration was that way originally, possibly in the absence of relative plate motion. Some diverging dike swarms, however, may have formed without a broad lithospheric uplift. Uplift is not one of the requirements for radiating dikes. For long-distance lateral injection, the main requirements are a supply of magma either at high pressure or at elevated pressure compared to the surroundings. The surface itself need not be elevated, but the magma chamber must be higher than distant parts of dikes that reach the surface (the artesian effect), if the dike is active, rather than just passively filling rifts. If there is uplift and no topographic high, the dikes will track the level of neutral buoyancy, which presumably is the same level as the magma chamber, and distant down-rift eruptions will be unlikely.

Midcontinent LIPs are sites at which large quantities of melt, or low-density asthenosphere, accumulate beneath the lithosphere in blisterlike masses that could cause uplift. Indeed some uplift, combined with tectonic stress or lithospheric weakening, may be the condition required before much magma can escape (although this apparently did not occur prior to eruption of the Siberian Traps). When the trapped magma does escape, the eruption rate is great and volume is enormous.

THE PHYSICS

The volumes associated with GDS and LIPs are indeed enormous but must be put into context. One of the largest LIPs is the Ontong-Java plateau. If the 20-km-thick ocean crust was the result of draining an area three times larger than the plateau (because of focusing to the apex of the triple junction), and if 20% melting is involved, a section of the mantle only about 30 km deep was involved. Normal mantle geotherms are well above the solidus at depths of ~30–50 km. For older GDS and LIPs, the mantle may have been hotter. A basic question, then, is this: Can magma draining by porous flow to a structural or permeability trap in or beneath the plate accumulate for a sufficient amount of time to provide ~10^6 km^3 of magma in ~10^6 years? Alternatively, can porous flow in the mantle keep pace with eruption rates?

A steady state between melting and erupting corresponding to typical CFB fluxes (~1 km^3/yr) is unlikely over geologic time. On shorter timescales on the order of ~1 m.y., such rates of melt production could conceivably be attained given advection of hot, fertile mantle material as typically envisioned in the plume theory. Problems arise if the timescale for melting is much greater than that of eruptive activity. Ponding is essential to any theory, and if ponding is possible, a plume is unnecessary.

In the source region of flood basalts, temperatures are clearly super- (or at least near-) solidus. As melt forms, it immediately escapes upward because it is gravitationally unstable. Even a "normal" melting column (say, below a mid-ocean ridge) does not contain a melt fraction of more than a few percent. Given small melt fractions, basalts may migrate upward via porous flow in a viscous matrix; the larger the melt fraction, the easier melt transport becomes. If or when melt aggregates into larger bodies, upward transport occurs through much more efficient, self-driven magma fractures (dikes). However, the picture changes once magma leaves the source region and approaches the subsolidus (by some definitions) base of the lithosphere. In the lithosphere, porous flow is impossible because melt freezes and clogs the pores. Thus flow must be accomplished via dikes. Dikes must be thicker than a certain critical width (~1 m) to avoid freezing. This implies that dikes must drain sizeable pools of magma. Correspondingly, giant dikes must be fed from *very* large reservoirs. Long-term existence of large reservoirs of melt at the base of the lithosphere (e.g., in case horizontal compression prevents diking) is unlikely if that is where it ponds, because the melt would exchange heat with the lower lithosphere and freeze. Assuming conductive cooling alone, a melt layer 1 km thick will lose most of its heat on a timescale of 10^4 years.

The surface thermal boundary layer is not the same, however, as the lithosphere, which is defined by strength or viscosity, not by a thermal gradient. Melts can conceivably pond at density and permeability interfaces, including in and below the region of high conduction gradient. In some models, the lower part of the thermal boundary layer can be close to 1400 °C (Anderson, 2000). The lithosphere is defined by long-term strength. However, for silicate rocks strength is a function of temperature. An upper mantle hotter than 900–1000 °C may not support any significant deviatoric stress, and thus cannot create the compression necessary to prevent melt from vertical propagation. If melt ponds at a density interface, it will not have any tendency for subsequent vertical propagation unless the melt density decreases as a result of fractionation. Ponding below a permeability barrier is probably the most likely option, similar to a subaxial magma lens at a fast-spreading mid-ocean ridge. In any case, precursory ponding is a process that must be better understood, because it is involved in both plume and nonplume models for basaltic as well as large silicic eruptions.

DO GIANT DIKE SWARMS RADIATE?

Some of the longest Precambrian dike sets in northern Canada both curve and diverge. Ideally, radiating means extending out from a point in many directions; it does not refer to just one or two sets that spread out and bend along their great lengths. Why are there not radiating dikes around all proposed plume-uplift centers? *Giant* dikes do not radiate around the north Atlantic tertiary province, the Columbia River basalt province, the Parana LIP, the Siberian Traps, or the Deccan Traps, although smaller dikes certainly do radiate around some single volcanic centers (such as Ship Rock). The great Precambrian dikes in Canada may have less to do with domal uplift than with extension of the spherical shell of the lithosphere, which over a great distance will not respond to stress in the same way as a flat

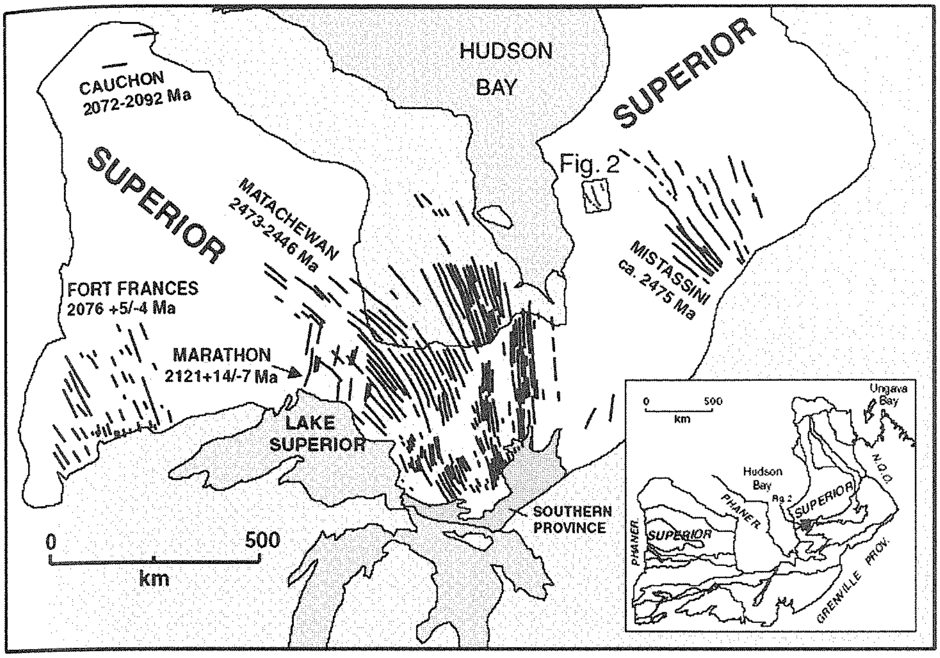


Figure 4. Proterozoic dike swarms from Superior Province, Canada. Reprinted with permission from Hamilton et al. (2001).

planar surface. Emplacement of dikes will modify the stress field and could break radial symmetry, leaving one principal swarm orientation that reflects far-field plate stresses.

Paleoproterozoic giant dike swarms exposed in the Canadian Shield have a variety of geometries (Fig. 4). Dike sets may remain subparallel within great sweeping curves or branches (e.g., the Matachewan dikes), form straight sets of roughly parallel dikes (e.g., the Fort Frances dikes), or diverge from a hypothetical focus point that they do not actually reach (e.g., the Mackenzie and Mistassini dikes). Dikes far apart and with different orientations may be similar in age (Fig. 4). Throughout Canada, there are no "hotspot tracks"; that is, no chains of volcanoes progress from a focus suggested for any of the giant dike swarms.

Large-scale dike swarms associated with rifting may represent the "third arm" of continental uplift and rifting (Burke, 1976). The association of LIPs and their attendant dike swarms with continental margins is apparent from the earliest dike swarms in the Superior Province of Canada (Fig. 4) to the Karoo flood basalts in South Africa. These swarms are characterized by point-specific, subparallel intrusion of dikes over long distances adjacent to areas of continental rifting. Present-day rifting in East Africa (Fig. 3) as well as early magnetic lineations from the western Atlantic (Fig. 5) indicate that, unlike oceanic rifts, continental rifts are not parallel and tend to form a series of linear features connected at 120° angles (Burke, 1976, and Fig. 4).

Whether a third rifting arm is formed at the junction of the two rifts is uncertain. However, the junction between two arms is predicted to be an area of extensional stress that may increase in area with distance from the junction. This would represent the third arm of a triple junction but would be a tectonic rather than a plume feature (Fig. 3). For the Red Sea area (Burke et al.,

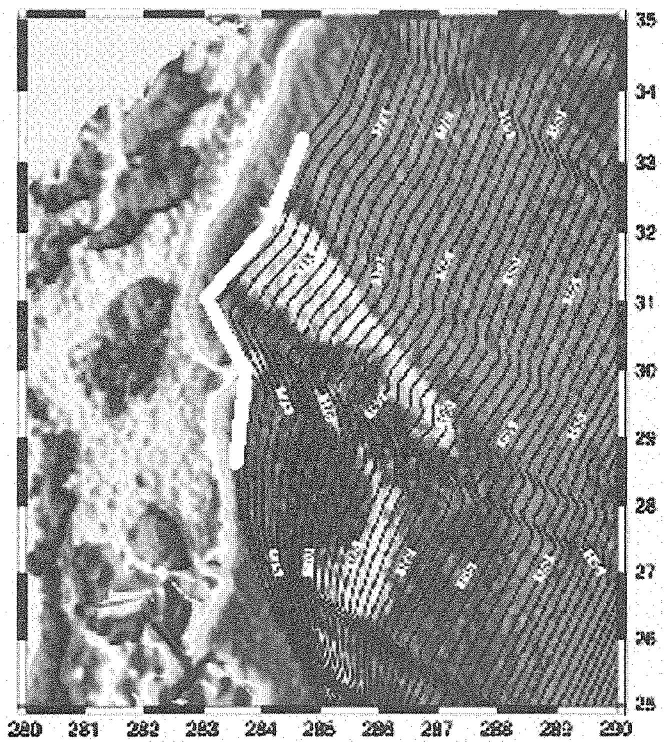


Figure 5. Magnetic lineations in the western Atlantic off the southeast coast of North America. White lines highlight 180 Ma oceanic crust: note the nonparallel nature of the magnetic lineation, which indicates a nonparallel rift sequence during the initial opening of the Atlantic. Background gray shades show free air gravity from Sandwell and Smith (1997), plotted using Generic Mapping Tools (GMT) software.

2003), the beginning of Ethiopian trap eruption, elevation, rifting, and dike emplacement are all within the temporal resolution at 31 +/- 2 Ma. Dikes were emplaced along cracks that propagated from sites of some small elevation to relieve the stress induced by that small perturbation in elevation. Dikes propagated toward the Levant corner because the stress field is conducive to diagonal extension at a 90° bend in the continental margin at the Levant corner. The Gulf of Aden cracks extended toward a smaller embayment, but never arrived and turned south inland of Socotra. The Ethiopian cracks propagated to the site of southern Ethiopian igneous activity from 45 Ma (George et al., 1998). The opening of the Red Sea and the Gulf of Aden are consequences of plate tectonics that, together with the East African Rift, constitute a classical triple junction. The Afar region is underlain by one of the most pronounced low-velocity zones in the upper mantle, but the low velocities terminate in the transition region (Ritsema and Allen, 2003).

DOES AN RRR TRIPLE JUNCTION IMPLY A PLUME?

Traditionally, the formation of a ridge-ridge-ridge (RRR) triple junction in previously contiguous crust has been attributed to domal uplift from a plume (e.g., Figs. 5.15 and 5.32 *in* Moores and Twiss, 1995). However, the need for domal uplift to explain the formation of triple junctions is negated when the prevalence of 120° angles between fractures in Earth materials at all scales, from mudcracks to basalt columns to plate boundaries, is taken into account (Fig. 6). Although Hartman's rule suggests that σ_1 bisects the angle between conjugate fractures, the actual angle between conjugate planes is more likely to be 60° than 90° due to the material properties of crustal rocks. If we assume that stress-strain relationships observed in rocks are viable on all scales, the formation of 120° angles between rift zones is not only likely, but expected (Oertel, 1965; Reches and Dieterich, 1983). The formation of the third arm of triple junction rift zones is a likely consequence of this configuration once ridge-push forces are enacted (Fig. 5). The subsequent failure of third arms probably depends on when ridge segments reorganize to become parallel.

PLATE MIGRATION VECTORS AND DIKE PATTERNS

Dikes form perpendicular to the direction of extension, but they also lie in planes that contain the direction of maximum compression. Compression is created by plate collisions, but across the plate interiors it is probably related to drag on the base of the lithosphere by the mantle. Dikes may form in those directions as a consequence of the plate motions, as has been proposed for widespread Early Cretaceous dikes in New England (McHone, 1988).

A map of plate motion vectors in southern Asia, obtained by very precise Global Positioning System (GPS) measurements, has recently been presented by Burchfiel (2004, his Fig. 3, reproduced by permission here as Fig. 7). Because terranes converge and rotate along the thrusts and suture zones of this region,

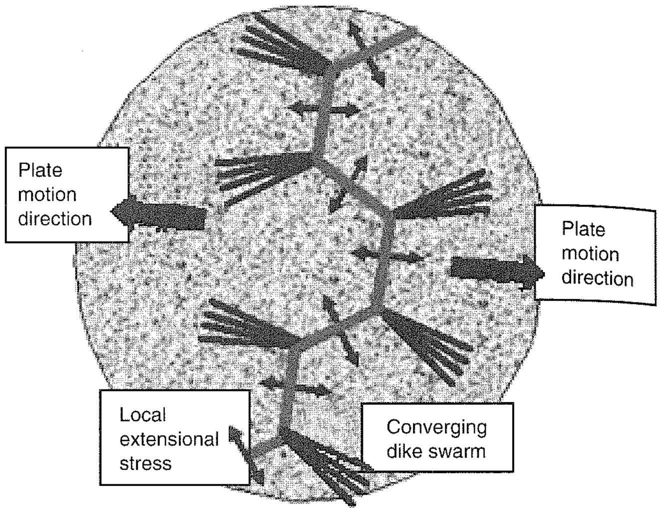


Figure 6. Cartoon of dike swarms created at the outside corners of rifts meeting at 120°. Thin, double-headed arrows represent local extensional forces ("ridge-push") perpendicular to rifting. Note that the extensional stresses perpendicular to the individual rift segments result in an extensional field at the outside ridge-ridge corner. The initial response to this extension would likely be large dike swarms (shown as thick black lines), with the size of the dike swarms dependent on the size of the rift segments. One would also expect the injection of rift-parallel dikes around the same time as the divergent swarms. Overall plate motion is indicated by the large black arrows, and rifts are represented by the thick gray line.

motion vectors are not uniform across the continent but instead form sprays or fans within tectonic domains. These may also be directions of maximum compression, analogous to the propagating fracture planes of dikes. The patterns clearly have no relationship to deep mantle plumes impinging on the base of the lithosphere, although dike swarms following these vectors (similar to the New England dikes) might be called radiating.

Dike swarms that follow absolute plate motion vectors might be the result of extensional stresses generated due to collisions, such that σ_3 is perpendicular to plate motion, resulting in extensional fractures parallel to plate motion. Given the degree of radiation associated with convergent plate motion (as illustrated in Fig. 7), any magma injected into the radiating fracture system as a dike set would appear to radiate from a point (Fig. 8). Previous work on Lake Baikal suggests that extensional stresses perpendicular to collision belts may extend thousands of kilometers into continental crust (e.g., Polyanksy, 2002). Using Lake Baikal as a model, we must bear in mind that regional extensional features, such as large radiating dike swarms, might be the result of compression and the resultant formation of fractures perpendicular to s_3 (Schlische, 2003).

THE CENTRAL ATLANTIC MAGMATIC PROVINCE (CAMP)

May (1971) first suggested a radial pattern of dikes around the nascent rift zone of central Pangaea, along which the Atlantic

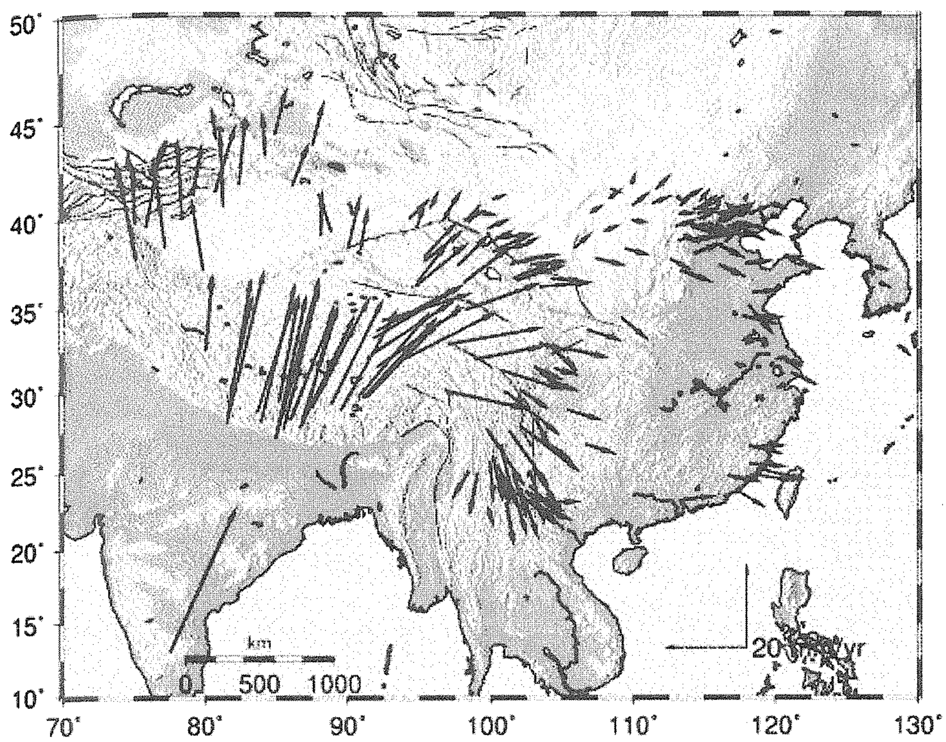


Figure 7. Absolute plate motion vectors in southern Asia, from Global Positioning System measurements. Figure 3 *in* Burchfiel (2004); reproduced by permission.

Ocean crust was first initiated in Early Jurassic time. This apparent pattern, with a focus somewhere east of Florida (perhaps the Blake plateau), has been repeatedly used as evidence that a deep mantle plume produced the tholeiitic dikes and basalts, as well as the continental rifts of central Pangaea (e.g., Morgan, 1971, 1981, 1983; Ernst et al., 1995; Wilson, 1997; Thompson, 1998). Other studies have supported a nonplume plate tectonic origin (e.g., Le Pichon and Fox, 1971; Sykes, 1978; Lameyre et al., 1984; Hames et al., 2000; McHone, 2000). Much new work on this LIP, now called the CAMP (Fig. 1), has been published in a recent monograph by Hames et al. (2003). Many papers in that volume do not support a deep mantle plume model for the CAMP.

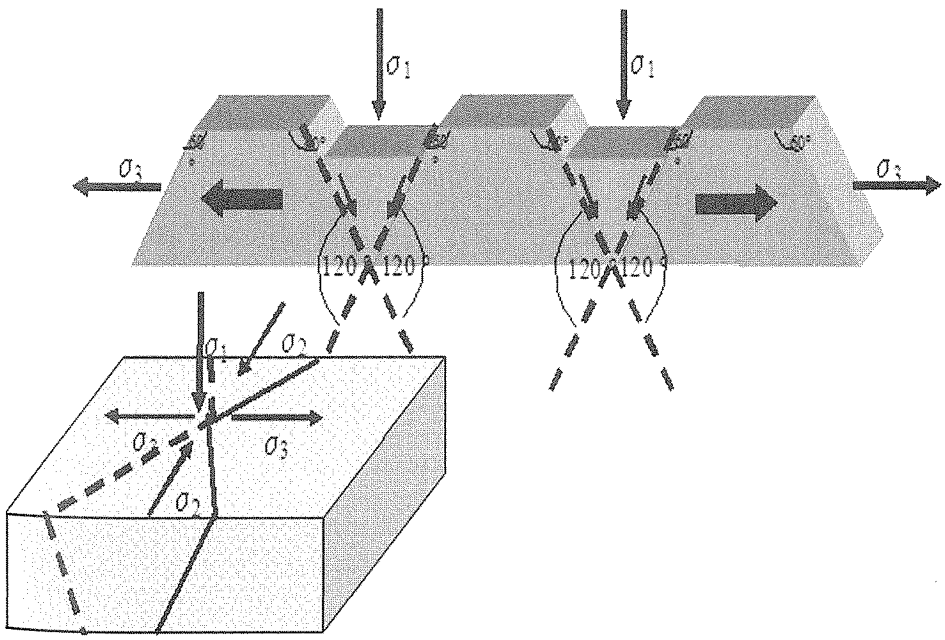


Figure 8. Top: Series of normal faults with a 60° dip created by a vertical σ_1 and a horizontal σ_3 (Twiss and Moores, 1992). The dotted lines represent the continuation of the faults at depth. Note that the intersection angle between the faults is 120°. Bottom: Extensional stress in σ_3 perpendicular directions results in orthorhombic faulting and the formation of 120° angles between faults in a map view. Conjugate pairs are dashed and may or may not coexist with solid faults (Oertel, 1965; Reches and Dieterich, 1983).

Cartoon maps of CAMP dikes reproduced in papers that advocate a plume origin oversimplify and exaggerate their radial geometry. This distortion may be partly due to poor-quality maps for some areas of dikes in Africa and South America. In fact, as discussed by McHone (2000), CAMP dikes occur in separate regions with distinct magma types, and also in numerous overlapping trend groups that do not radiate toward a common point. Even the largest dikes within the regional groups do not physically extend to a common focus at the Blake plateau (Fig. 1). In addition, most large dikes tend to be discontinuous along strike, with en echelon patterns or segments that are offset up to several kilometers. The magmas of such dikes must interconnect in mainly vertical to oblique directions. More commonly, swarms of many smaller dikes of the same magma type do not interconnect in any lateral sense with dikes closer to the proposed plume center. The compositional correlations among dikes within groups, the trend and compositional differences between groups, and the mainly vertical flow required by dike structures indicate that each dike group is derived from its own mantle source and that each group was subject to its own regional tectonic control.

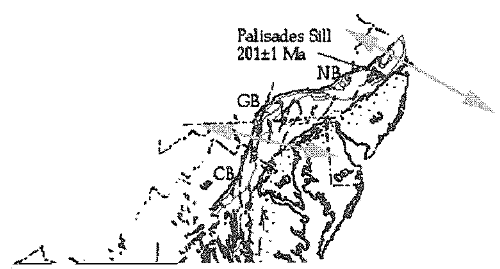
However, like the giant dikes of northern Canada, some of the very long dike systems in eastern North America do not remain parallel along their entire length: a great north-south group diverges from Charleston, South Carolina (not a "plume center"), northward into Virginia (Fig. 9). This narrow dike set crosscuts older high-Mg NW-SE dikes and rift basins in North Carolina (Fig. 10). These juxtaposed north-south and NW-SE dike sets are formed independently and from different magmas (Ragland et al., 1983). The shorter NW-SE dikes in the southern USA are numerous and occur in a very wide belt from Virginia to Alabama (and beyond under the coastal plain), and they remain subparallel from one end to the other—because they are in separate short fractures rather than long single ones.

In northeastern North America, huge but widespread dikes in Canada and New England diverge to the northeast and the east-northeast from a focus point east of New Jersey, but that is also not a plume center. The dikes change their trends across the "New England salient," which is a curve toward the continent by terrane suture zones and primary structures of this section of the Appalachian orogen. In addition, the giant dikes did not form together in a fanning pattern, but instead decrease systematically in age from southeast to northwest (Fig. 11).

"Plume Uplift" of the Early Mesozoic Rift Zone in Eastern North America

Rainbird and Ernst (2001, p. 237) asserted that the sedimentation record in the CAMP rift zone indicates uplift from a plume at the location of a giant radial dike focus ~20–25 m.y. before the magmatism. Their description of "a progressive north-to-south change in the age of sedimentation" and their claim that "sedimentation in the basins within ~1000 km of the plume center ceased between 225 and 220 Ma" are not correct. Furthermore, they attribute the cessation of sedimentation in the northern basins between 200 and 190 Ma to continued spreading of a plume head, despite the fact that magmatism attributed to the plume head occurred near 200 +/– 1 Ma in all areas (Hames et al., 2000).

Sediment accumulation in the rift basins of southeastern North America started around 225 Ma in the southern *and* northern sections of the Pangaean rift zone, along and within the Appalachian orogen and contiguous areas now in Africa and Europe. The clastic sedimentation into linear basins reflects subsidence of the rift zone along the orogenic belt as Pangaea be-



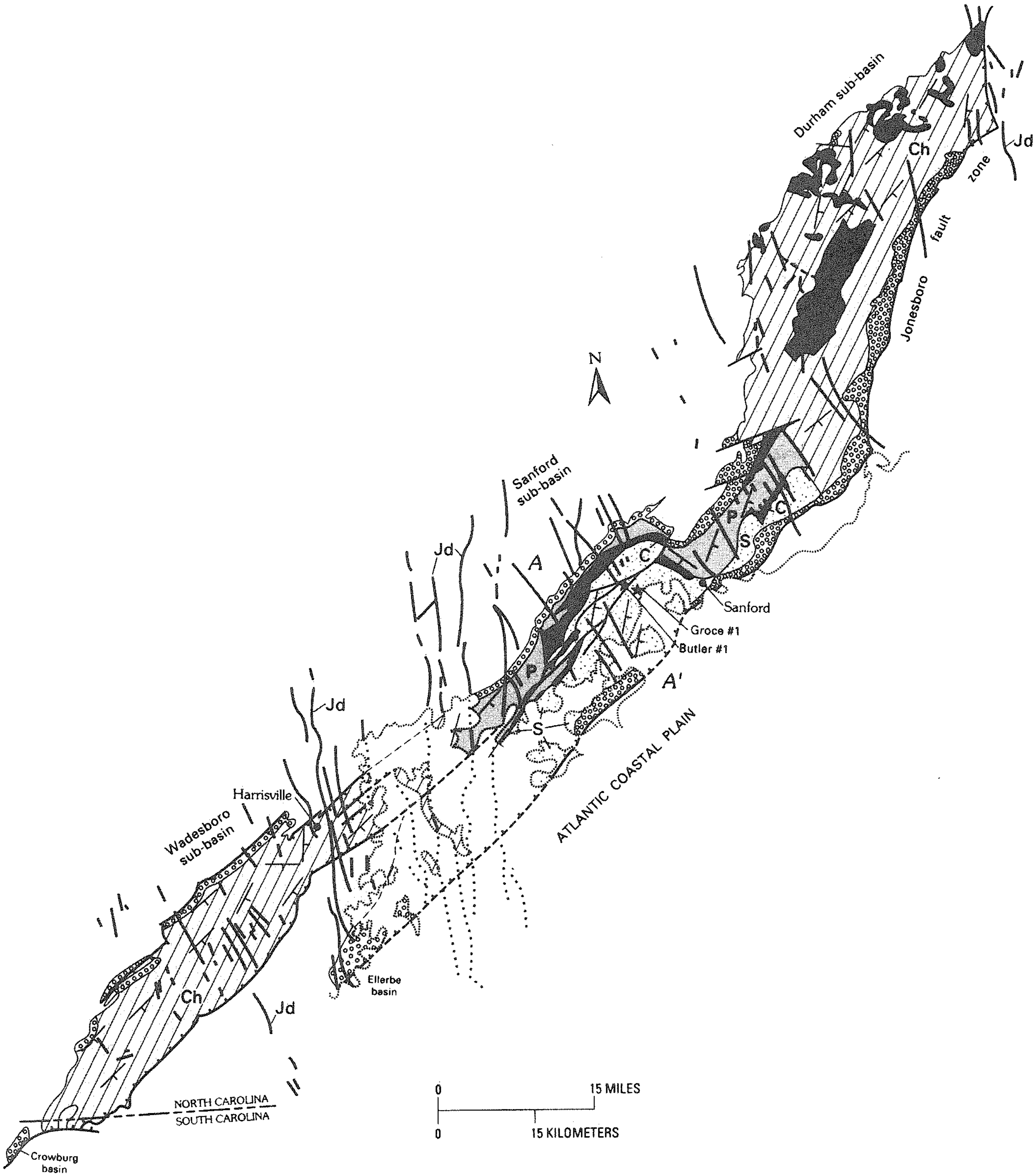


Figure 10. Separate north-south and northwest-southeast dike swarms crossing Mesozoic basins in North Carolina. From Figure 9–3 *in* Olsen et al. (1991). See Olsen et al. (1991) for abbreviations.

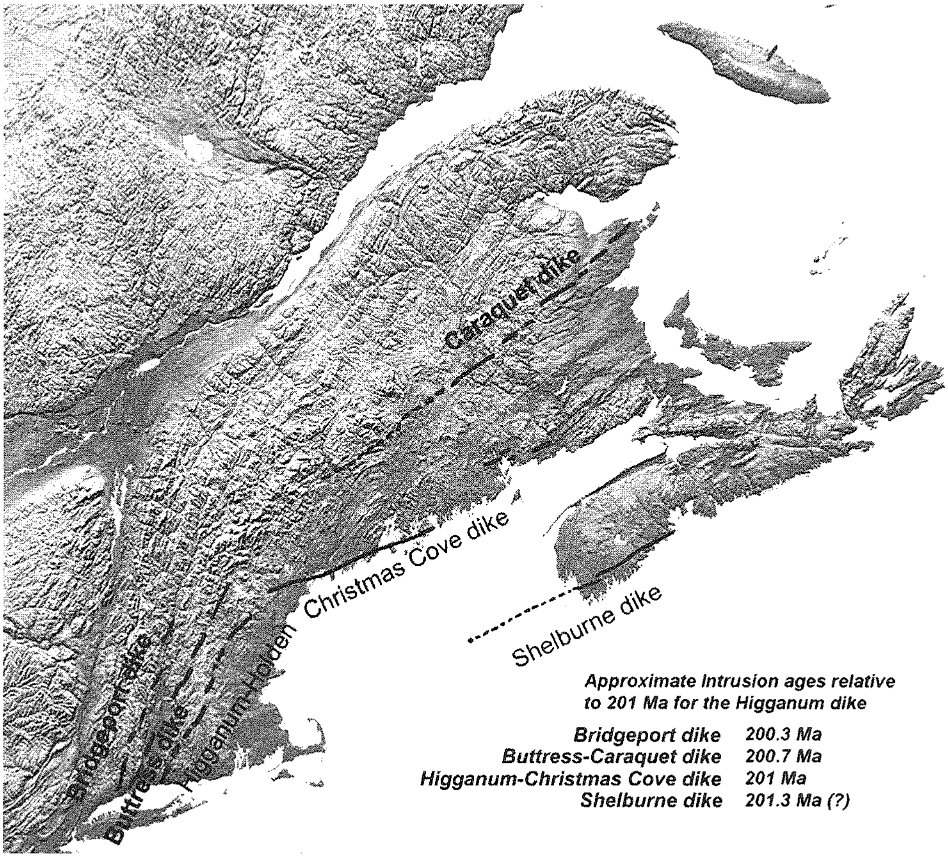


Figure 11. Giant early Mesozoic dikes in northeastern North America (this paper).

event near 201 Ma, not at 220–225 Ma (Fig. 12). Through this same Triassic-Jurassic time span, sediments continued to pile up within the northern rift zone, long before fault activity had broken that region up into its separate basins. The deposition of sediments in the northern basins continued for at least 10 Ma after magmatism commenced; how much longer it continued is not known because Jurassic and Cretaceous erosion has removed much, possibly several kilometers, of the younger rift strata.

Rifting of Pangaea, then, started with subsidence adjacent to the entire Appalachian-Hercynian orogenic belt ~20 m.y. before any uplift. Subsequent uplift was regional and linear, not a single large domal swelling. Uplift along the rift zone occurred in stages that were quite separate from magmatism in both time and space. The pattern of uplift was the response of the upper mantle upwelling into the thinning continental lithosphere, and it was precursory to the initial formation of ocean crust and the mid-ocean divergent boundary. Furthermore, throughout the 30 m.y. period of Pangaean rifting, the entire supercontinent continued to drift northward (Olsen et al., 1991), and a deep mantle plume would not have remained beneath the same southern portion of the rift zone. Late Triassic rifting near the new triple junction was clearly the cause, not the consequence, of end-Triassic uplift in that region. The evidence is clear that the rifting of Pangaea was a plate tectonic event with physical controls by orogenic lithospheric structures, and not due to domal uplift above a random deep mantle plume.

Despite the big differences in timing of the end (but not the start) of basin sedimentation, as well as of faulting and uplift, basaltic magmatism began around 201 Ma everywhere in eastern North America, as well as throughout the enormous CAMP area (Hames et al., 2000). In addition, there are distinct populations of dikes of different basaltic parentage and swarm orientations in the southern versus the northern rift zones (McHone, 2000), which are not very different in age (probably less than 1 Ma). The magmatism apparently lasted less than a million years in eastern North America, after which time sedimentation continued in the north, but not in the south. Sometime after the magmatism—possibly soon afterward, but there are good arguments for up to 25 million years later—the Atlantic Ocean crust began forming between eastern North America and northwestern Africa. As discussed later, each of these events also marked a dramatic change in stress configurations in eastern North America.

Completely absent in the Mesozoic Atlantic Ocean crust are any seamounts, ocean plateau basalts, cross ridges extending from the continent, or other independent igneous features with ages that span the gap between the Early Jurassic CAMP event and the formation of the Middle Cretaceous to Tertiary

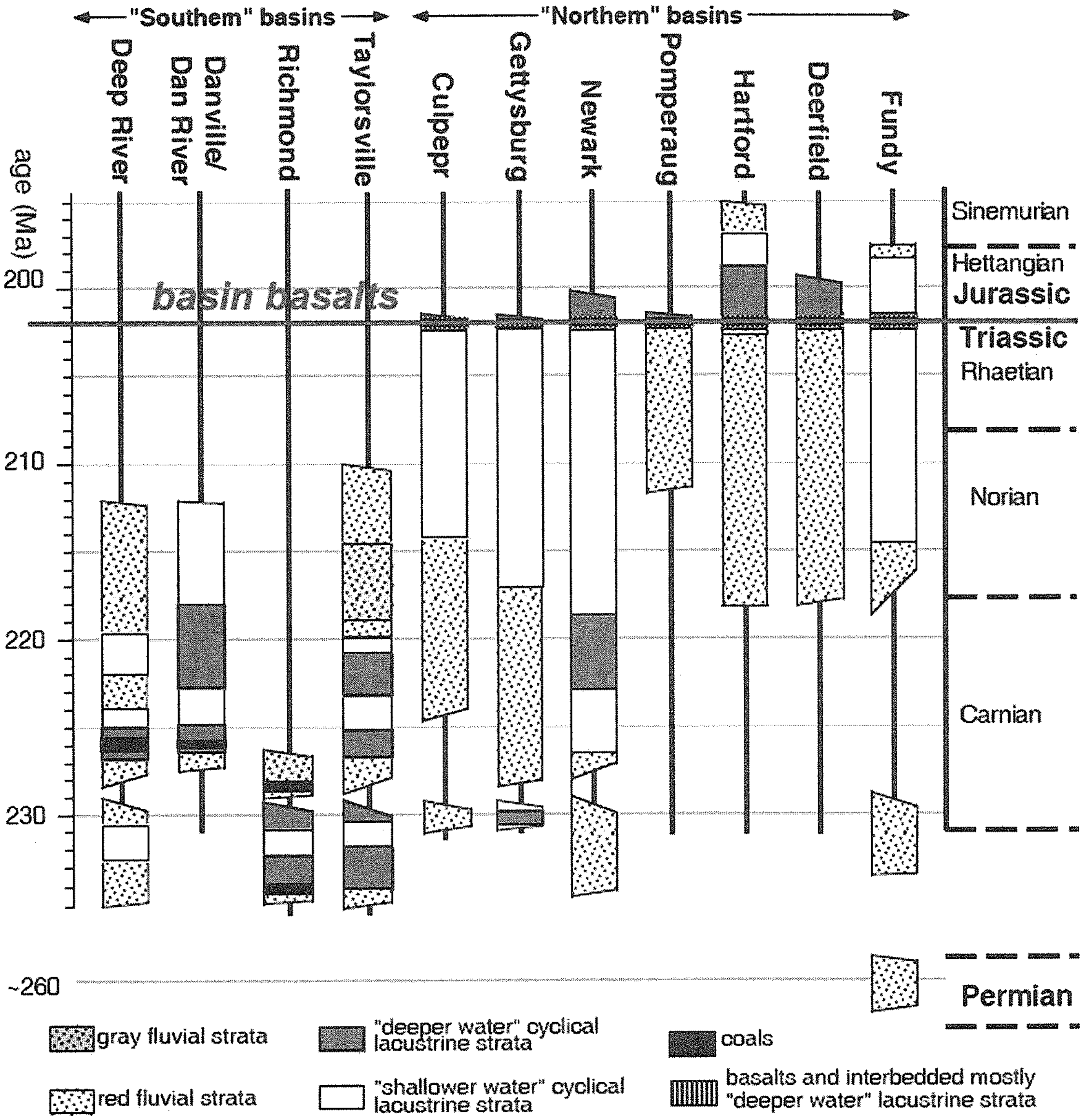


Figure 12. Rift basins and basalt correlations in eastern North America. After Figure 12 *in* Schlische (2002); reproduced by permission. Tholeiitic dikes, sills, and flows in all of the basins are close to 201 Ma in age, unlike the range in sediment ages.

alkaline volcanoes that now mark the Atlantic sea floor. That is, there is plainly no "plume track" from the initial flood basalt event, and in fact, no present-day Atlantic seamount or volcanic ocean island shows any genetic relationship whatsoever to the CAMP event. On the other hand, the limited chemical studies made of the oldest ocean crust indicate that CAMP tholeiites were the progenitors of Atlantic ocean-crust basalt (Bryan et al., 1977; Janney and Castillo, 2001). Note the title of the paper by Janney and Castillo (2001); like many geologists, they assumed that the CAMP flood basalt must be derived from a mantle plume, even though the ocean crust that is linked to the CAMP neither requires nor indicates such a production mechanism.

Upper-Mantle Sources of CAMP Basalts

In addition to accounting for the radial component of giant dike swarms, we must also account for the magma source. In the case of many of the more prominent Proterozoic swarms, much of the potential evidence for their plate tectonic setting has been lost. In the case of the CAMP, however, the overall tectonic regime of the time is better known.

The CAMP was created in a continental extensional setting that resulted from a series of conditions much like the multiple sources of the Basin and Range province today. At the end of the Permian, the supercontinent Pangaea was mostly surrounded by

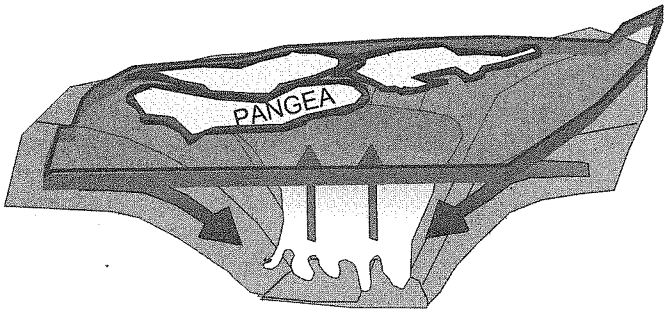


Figure 13. Schematic cartoon showing the continental lid of Pangaea surrounded by subduction zones. Material from the subduction zones is collecting beneath the continental lid and beginning to rise due to the constant influx of new material. The rising material is more fertile than the surrounding mantle.

subduction zones dipping under the massive continent (Fig. 13; Scotese, 1997; Golonka and Ford, 2001). This configuration is reflected in the supply of excess fertile magma for the CAMP. Convergent wedge materials around Pangaea were inserted into a system that is essentially closed, in that it is surrounded by subducting ocean slabs and capped by a thick continent. The new subducted material would likely be enriched or fertile relative to older material in the mantle. Thus, a large volume of enriched material collected in a closed upper-mantle system under a continental lid in one area and under oceanic crust in another (note that the reconstruction of Scotese [1997] for 195 Ma includes a ridge south of Tibet). Because the enriched material would be buoyant under the continent, it would be expected to rise and pond beneath the highest point (Sleep, 1990). We do not postulate that this material comes from long-lived, stable, hot sources or that it comes from below the 660 km discontinuity, as in the plume model. Rather it seems likely that slabs stacked up over the 660 discontinuity and contributed material from that depth.

The highest or thinnest continental crust beneath Pangaea would have lain along the edges of the suture zones between the cratonic roots, and the thinnest of these areas would have been the triple junction among North America, Africa, and South America. As the material rose and pooled between the cratons, it underwent decompression to form reservoirs of magma that maintained its heat because of the thick continental lid. Thus, a large volume of relatively enriched and hot magma accumulated under central Pangaea. The reservoir was likely widespread, and it was shaped as a sheet, not as a cylindrical central plug.

Further, the continents could move no closer together. Subsequent roll-back of subduction zones could then initiate strong slab suction forces on the edges of the continent, essentially pulling it apart. According to Schlische (2003), rifting began in southeastern North America around 230 Ma (Fig. 12). In our model, this Triassic rifting was the result of a combination of slab roll-back that was pulling North America to the northeast and upwelling mantle between the continental roots that was pushing the continents apart (Silver et al., 1998). The upwelling resulted in extension of the lithosphere in the weakest areas near the triple junction among North America, South America, and Africa, and also along the Appalachian-Hercynian orogen (the cratonic margin). The extension of the lithosphere increased decompression melting of the upper mantle, which had been enriched with wedge materials from the subducting slabs. Large volumes of basaltic magmas were ready to rise and follow propagating lithospheric fractures in dikes, many of which reached the surface to extrude basalts across a very wide area in a short period of time.

The great volume and brief time span of CAMP magmatism are characteristics shared by other flood basalt provinces, but the enormous area of the CAMP event is unmatched. The largest supercontinents may be required to form the largest continental LIPs.

Emplacement of CAMP Dikes

As stated earlier, CAMP dikes are nonradial, and the three largest swarms (northwest-trending, north-trending, and northeast-trending) evolved from separate magma sources. Further, recent work in southeastern North America suggests that several smaller dike swarms approximately parallel to the geographically confined larger swarms may cross-cut throughout the Carolinas (Fig. 14). Geochemical analysis of these smaller swarms relative to the larger swarms confirms the results of Salters et al. (2003): the northeast-trending dikes are olivine-normative, while the north-trending dikes are quartz-normative and the northwest-trending dikes display a wide variation in magma types (Ellin et al., 2004). This is significant because, although it is not a large dataset, it does suggest that the dikes in the Carolinas are related to the larger swarms to the north and that the magmatism related to each diking event was not as geographically contained as previously thought. It also makes almost impossible the idea of a giant radiating dike set (Ernst et al., 1995), because dikes with multiple orientations were injected into a given area from multiple sources in a very short period of time (Hames et al., 2000). What, then, could account for three distinct dike orientations that are generally geographically contained, but also exist contemporaneously and cross-cut in the Carolinas (Beutel et al., 2002)?

Schlische (2003) proposed that CAMP dikes were the result of compression during initial formation of oceanic crust (northwest-trending dikes) followed by rift-parallel diking to the north (north- and northeast-trending dikes). However, the presence of cross-cutting northwest-, north-, and northeast-trending dikes in South Carolina suggests a more complicated stress field evolution that resulted in three distinct stress fields and separate magmatic events in the same general area. Adding to the complication are a series of sparse but consistent cross-cutting relationships that suggest an age relationship between the dikes such that the northwest-trending dikes were injected first, followed by the north-trending dikes and finally the northeast-trending dikes (Ragland et al., 1983; Beutel et al., 2002). Because dikes are generally intruded perpendicular to the least compressive stress field (σ_3), the Carolina swarms indicate an extensional

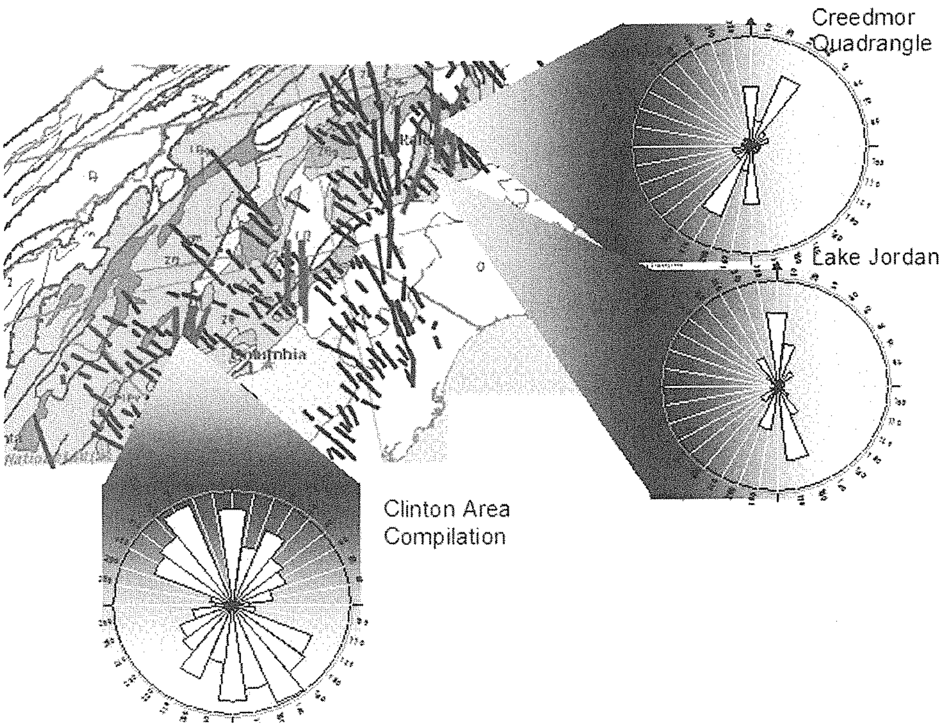


Figure 14. Rose diagrams of mapped dike orientations at three locations in North and South Carolina. The background map is from the National Atlas Web site of the United States Geological Survey (http://nationalatlas.gov). The Clinton area compilation is composed of dikes from eleven quadrangles. The dike orientations were taken from open-file South Carolina Geological Survey reports and mapped by the authors. The Lake Jordan dikes were mapped by the authors, and the Creedmor quadrangle dikes were mapped by the authors from an advance copy of the open-file map for that quadrangle (T. Clark, personal commun.).

stress field in southeastern North America that rotated 90° from NE-SW to NW-SE in less than 4 m.y. (Hames et al., 2000). Three different models can be suggested to explain the apparent rotation of stress field in southeastern North America. Each of these models may work in combination with any of the other models, and each relies on the theory described earlier for the magma source and the breakup of Pangaea. Once again, the models demonstrate that radial or divergent dike swarms associated with continental breakup and LIPs can be created by mechanisms other than plumes.

Model 1. In this model we propose that upwelling magma generated by subducting slabs was the initial cause of magmatism around the North America, South America, and Africa triple junction. Upwelling mantle beneath the triple junction resulted in overall extension across the region between 230 and 200 Ma. Around 200 Ma the upper mantle underwent massive decompression, generating a large body of magma that rose into the thinned triple junction, elevating it into an oblong amoeba-shaped circle (Fig. 15). This concurs with the previous discussion about CAMP uplift in that uplift occurs after extension and is the result of decompression, not the impingement of a mantle plume. Magma was then injected into the amoeba-perpendicular cracks in the form of dikes. These dikes trend northwest in Georgia and South Carolina, north-northwest in Alabama and Mississippi (McBride et al. 1989), and northwest in northern South America and range in orientation between northeast and northwest in Africa (Fig. 16). After this initial period of magmatism, tectonic loci developed such that rifting for a given area was

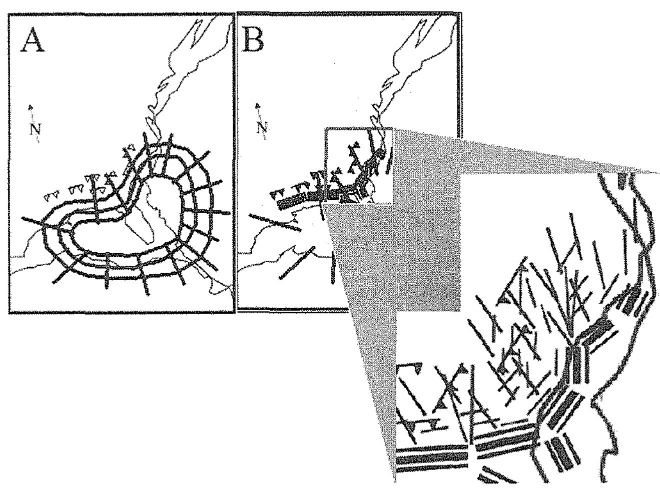


Figure 15. Schematic of stress dike injection for southeastern North America. Panel A shows the area of thinned and uplifted crust as outlined by the solid amoeba-shaped circles. The solid lines emanating from the amoeba-shaped circles indicate the lines of maximum compressive stress and are perpendicular to the lines of least compressive stress. These lines will become the NW-trending dikes in southeastern North America. Panel B shows the development of a series of continental or oceanic rift zones and the dikes (in red) that would be injected parallel to them and at their intersections. See Panel A for a comparison with the magnetic anomalies at the time of original ocean crust formation.

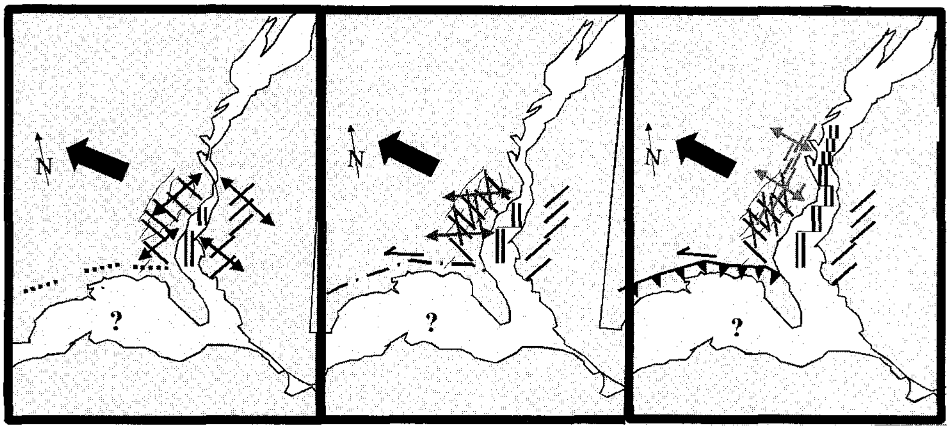


Figure 16. Progressive rotation of a stress field in southeastern North America as the boundary with South America was developing. The double-headed arrows indicate the local stress field associated with dike injection; the large black arrow indicates the motion of North America.

accommodated by faulting along subsiding continental basins. The central rift basins later coalesced into a linear zone of new oceanic crust. The initial rifts were not necessarily parallel to each other, as shown in the initial magnetic lineations in the western Atlantic (Fig. 5). Dikes were then injected parallel to the initial rift zones over the previously injected northwest-trending dike.

Based on our limited observations of how the dike sets cross-cut each other, it appears that the region was originally dominated by north-trending rift basins, and later by northeast-trending rift basins. However, as shown in Figure 16, multiple orientations can occur within a very small area, making it difficult to discern true injection order. The geographic prevalence of northwest-trending dikes in the southeast most likely indicates the earlier timing of their injection, whereas dikes in northeastern North America were formed during the subsequent rifting event. The differences in magma compositions between the northeast- and the north-trending dikes may be explained either by different source rocks for different dike events or by the next model.

Model 2. The geographic relationship between North America and South America during the breakup of Pangaea is unclear. North and South America began to separate sometime around or after 200 Ma, and this separation must have involved a mixture of strike-slip and normal faulting as North America moved off to the northwest (Klitgord and Schouten, 1986). It is this ambiguous relationship that may explain how the multiple dike orientations of southeastern North America were created. The dike orientations were controlled by fields of stress that varied as plate connections changed between North America and South America.

After the local northeast-trending fault grabens had formed and North America had begun to separate from Africa, the local stress field began to swing from NW-SE extensional to NE-SW extensional. This swing was caused by a change in the locus of rifting from the already weakened and thinned lithosphere along the southeast coast of North America to the still-attached boundary between North America and South America (Fig. 16). The resistance to the northwest motion of North America swung the extensional stress field by 90° in this region and led to the formation of northwest-trending fractures that were filled with magma from rapidly decompressing mantle beneath the suture zones (Fig. 16). As both normal and strike-slip faults began to form, the resistance to motion lessened and the stress field rotated, resulting in the formation of the north-trending dikes. The southern boundary of North America became better developed along a series of strike-slip and normal faults, which effectively reduced the resistance to plate motion and caused the extensional stress field to swing back to NW-SE extensional. With this change, the majority of magmatism moved to the northeast within Pangaea (northeastern North America), where the stress system created northeast-trending dikes.

Model 3. The third model does not really stand on its own but rather is an explanation for multiple orientations in a small area, irrespective of the origin of the dike magmas. Similar to cracks forming at any scale, continental rifts tend to initially intersect at 120° angles, as seen in the present-day Afar Rift. The very formation of several rifts at 120° angles lends itself to multiple dike sets of different orientations (Fig. 6). The junction between two rifts also creates an area of extensional stress that could lead to the injection of a divergent dike swarm emanating from the intersection (Fig. 6). This mechanism could be applied to either of the two other models we have described to account for the multiply oriented dikes in areas of the southeastern USA, and perhaps to the north-trending dike swarm that cuts across North Carolina.

Dike Models. Dike swarms that have been lumped together as "radiating" within the CAMP were not formed in a single magmatic episode and tectonic event. CAMP dike orientations varied according to stages and regions of lithospheric tectonism during the breakup of Pangaea. Dike compositions varied, with clear expressions of chemical enrichment across regions created by the fossil convergent zones between cratons, as well as by subduction around Pangaea after it was assembled. A deep mantle plume fails to explain the CAMP dike patterns and LIP as well as the breakup of Pangaea, while models based on plate tectonics fit the older data as well as new information from geochemical, radiometric, and field studies.

HORIZONTAL FLOW IN DIKES

A last area of contention concerns the evidence that magmas of giant dikes flow horizontally away from plume centers, possibly for hundreds or thousands of kilometers. Long-distance horizontal flow is required in this model, because giant dikes can extend far beyond the radius of proposed plume heads, and thus have no sources for vertical flow along their great lengths. The evidence cited for horizontal flow is often based on AMS (anisotropy of magnetic susceptibility), as measured from oriented drill cores. Although their magmas follow the propagating transcrustal fractures, the dikes themselves may not breach the surface along their entire lengths because their magma density is relatively high.

The AMS of dikes often includes a principal axis in a horizontal plane, which has been cited as definitive evidence for horizontal dike flow (Tarling and Hrouda, 1993). Exactly why this should be so remains somewhat mysterious. AMS is mainly caused by small magnetite grains that crystallize late in the cooling history of basalts (probably after magma flow has ceased). The magnetic anisotropy of basalt appears to be controlled by plagioclase laths around which the magnetite grains collect in layers along the planar feldspar faces. In addition to alignment by the primary magma flow, plagioclase crystals and resultant AMS fabrics may become oriented by other mechanisms. As basaltic magmas crystallize, a 3D plagioclase network forms (Philpotts and Dickson, 2000), then eventually collapses and flattens if the magma body is large enough (as in many sills and large dikes). A subhorizontal preferred crystal orientation results, which must affect the observed magnetic anisotropy (usually a very subtle fabric). This AMS from gravitational collapse will overprint whatever AMS direction of magma flow is preserved by the original crystal orientations.

Plagioclase crystal reorientations can also be due to backflow after fluid pressure diminishes in the later stages of dike activity. Magma movement back down into dike fissures has been observed in volcanic lava pools, and it could reorient the dike phenocrysts (commonly feldspars) and surrounding magnetite-rich planes away from their initial upward or oblique directions.

Other features such as contact rip-ups, oriented phenocrysts in glassy contact zones, wisps of melted country rock, and elongate contact cusps can show initial dike flow directions, but the directions of even these may differ from those of later main-phase magma movements. AMS measurements by themselves are not sufficient to demonstrate long-distance horizontal flow.

The many factors that might prevent the final imprint of the dominant flow direction in the AMS and other petrologic or structural indicators make it surprising that a horizontal AMS is sometimes actually backed up by other horizontal flow indicators. (This is not always the case. Many giant dikes in South Africa do not have any consistent AMS orientation; in this respect, the Mackenzie swarm appears to be an exception rather than a rule.) For "thin" dikes (those with thicknesses on the order of a few meters or less) the chilled margins may indeed be informative of the initial flow directions, and the AMS generally works well. For giant dikes, it is questionable even whether chilled margins are representative of the main magma flow, so the interpretation of the primary flow direction is less certain. The likelihood of long-range lateral magma transport in the shallow lithosphere has more to do with the mechanics of buoyant magma ascent from the source region (in particular, the problem of much-extended magma accumulation regions in the mantle), and flow in whatever directions the fractures propagate, than it has with the (often noisy and inconsistent) AMS measurements.

PLUMES AND RADIATING DIKES: PREDICTIONS

In the plume hypothesis, a large plume head rises through the mantle, flattens out below the lithosphere, pushes it up by 1–2 km, and provides the magma for LIPs and radiating dikes. Ideally, radial cracks should initially form in a symmetric 360° pattern. As the plate moves off the plume, a volcanic track forms another arm to the radial structure. The uplift and the stress pattern that allows the dikes to form are caused by the plume itself. The magnitude of the uplift, the radial symmetry, the 60° rift angles, and a subsequent age-progressive chain of volcanoes are predictions and tests of the plume hypothesis. The plume head and underlying deep mantle columns are major thermal features, and long-lived volcanism is expected.

Lateral dikes can also propagate away from regions of thin lithosphere or crustal magma chambers where ponded melts have accumulated. Rifts and dikes are likely to take advantage of preexisting boundaries, discontinuities, and weak zones and to be controlled by the tectonics of the region rather than the geometry of a plume head. In this plate tectonic world, perfect radial propagation and 360° radiation are not expected, and a large amount of uplift is not required. The lithosphere acts as a stress valve, and the stress can change quickly. Therefore, short-lived magmatism is expected unless the region experiences long, continuing extension. The orientations of dikes should settle down ultimately to a rather tight distribution of azimuths. A long-lived trend ("hotspot track") is likely to lie along a structural weakness. If magmatic zones appear to converge or radiate, it is likely because preexisting tectonic structures also converge or appear to radiate. In some cases, the tectonic stress is more important than fabric, and dikes can apparently propagate across the landscape without following any obvious structural grain.

The Pacific Northwest (www.mantleplumes.org/radvolc migrations.html) is a confluence of tectonic structures: the Wyoming craton, the Idaho batholith, the ancestral Cascades, the Rocky Mountains, the Basin and Range, and so on. It also experiences a variety of forces: slab pull, suction, ridge push, back-arc opening, rotation of the continent by the Pacific plate, edge convection on the border of the craton, cooling from below, and perhaps others. Some of these forces are extensional. In general, the mantle near cratons and slabs is expected to be cold. This does not mean it is well below the melting point. We expect dikes, sills, and extrusions in an environment that has been fluxed by volatiles and is undergoing extension. We do not expect, except as a rare coincidence, a deep mantle plume to arrive at a particularly unique time and place in the tectonic evolution of this part of North America. The close association of slabs, ridges, microplates, back-arc basins, cratons, batholiths, and a variety of tectonic processes and ages encourages one to think of tectonic, rather than core-mantle boundary, processes in trying to unravel the magmatic history of the Pacific Northwest.

If a plume did arrive (punching through the down-going slab!), the predictions we have stated would have to be modified, but the plume head effects would have to be distinguished from the tectonic controls. Many of the modifications required to make the plume head hypothesis match the unexpected observations are already intrinsic to alternative explanations, such as lithospheric stress, fabric, and architecture control. High temperatures and a large amount of uplift may be the only remaining testable predictions. Dikes radiating over a limited azimuth range may be intrinsic to the plate and dike hypotheses. Rapidity of eruption is favored by the stress hypothesis, as plume head eruptions and precursory uplifts are predicted to occur over 10–20 m.y. (e.g., Campbell and Griffiths, 1990; Cordery et al., 1997).

SUMMARY

Giant dikes and flood basalts, along with new plate boundaries, are a natural consequence of plate tectonics. Preexisting tectonic fabrics control the locations of many magmatic features. The stresses associated with ponded magmas and plate tectonics control the propagation of dikes. Eruptions take advantage of rifts and incipient plate boundaries. In particular:

1. Huge volumes of tholeiitic magmas were generated in upper mantle source regions of giant dikes and may have caused regional uplift or domal swells in the crust. Giant dikes propagated from these magma ponds and do not imply the presence of deep mantle plumes.
2. Nonradial patterns of fissure dikes are more common for flood basalt provinces than are radiating giant dikes. True radiating dikes are smaller and reflect local stress fields around volcanoes or shallow magma chambers, not regional extension of the lithosphere.
3. Most giant Proterozoic dike swarms in Canada are more accurately described as diverging, arcuate, or synparallel rather than as radiating.
4. Rather than remaining parallel, very long sets of dikes might diverge as they propagate regardless of their origin, because extensional stress orientations vary across large distances in the spherical shell of the lithosphere. There may be dike stress relationships with continental rifting, plate divergence, and mid-ocean ridges.
5. Chains of volcanoes (plume tracks) with progressive ages do not lead away from the Proterozoic giant dike swarm centers of Canada or from any dike centers of the CAMP, despite the assumption of such features in the plume model.
6. Giant dikes are not known to cause large surface rifts (Gudmundsson, 2003), and regardless of the interesting ideas of Ernst et al. (1995), radiating patterns of rifts on other planets are poorly related to magmatic intrusions on Earth.
7. As shown by recent GPS motion vectors in southern Asia, terranes can migrate and rotate along compressional sutures, terrane boundaries, or fault zones. Concordant dike swarms generated within active tectonic domains may have curving to subradial patterns because of variable stress domains.
8. The dike swarms of the CAMP are tectonic features clearly associated in geometry and location with continental cratons and rift margins, and they occur in independent but juxtaposed sets that are not synmagmatic or radiating.
9. Although the CAMP is an important reference example, many other LIPs are also observed along preexisting continental rifts, and they are often adjacent to thick cratonic keels.
10. Deep mantle plumes are unnecessary to explain either LIPs or radiating dike swarms.

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