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Revisiting hotspots and continental breakup—Updating the classical three-arm model

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ABSTRACT

Classic models proposed that continental rifting begins at hotspots—domal uplifts with associated magmatism—from which three rift arms extend. Rift arms from different hotspots link up to form new plate boundaries, along which the continent breaks up, generating a new ocean basin and leaving failed arms, termed aulacogens, within the continent. In subsequent studies, hotspots became increasingly viewed as manifestations of deeper upwellings or plumes, which were the primary cause of continental rifting. We revisited this conceptual model and found that it remains useful, though some aspects require updates based on subsequent results. First, the rift arms are often parts of boundaries of transient microplates accommodating motion between the major plates. The microplates form as continents break up, and they are ultimately incorporated into one of the major plates, leaving identifiable fossil features on land and/or offshore. Second, much of the magmatism associated with rifting is preserved either at depth, in underplated layers, or offshore. Third, many structures formed during rifting survive at the resulting passive continental margins, so study of one can yield insight into the other. Fourth, hotspots play at most a secondary role in continental breakup, because most of the associated volcanism reflects plate divergence, so three-arm junction points may not reflect localized upwelling of a deep mantle plume.

INTRODUCTION

Warren Hamilton long argued that mantle plumes—narrow columns of hot material upwelling from the deep mantle—do not exist, so that alternative models must explain geological processes attributed to plumes (Hamilton, 2011). One such process is continental rifting, leading to continental breakup and the formation of passive (i.e., not plate boundary) continental margins and new oceans. In a classic paper in the recognition of plate tectonics, Wilson (1966) proposed that "the present Atlantic Ocean started to open … by breaking open a continent which was then continuous from West Spitzbergen to Florida." The resulting view of the cycle of ocean formation and destruction, fittingly termed the Wilson cycle, underlies our current understanding of the evolution of continents and oceans.

The Wilson cycle model does not, however, explain why and how continents break up. Breakup is often explained in general terms by a model (Fig. 1) developed in two classic papers by

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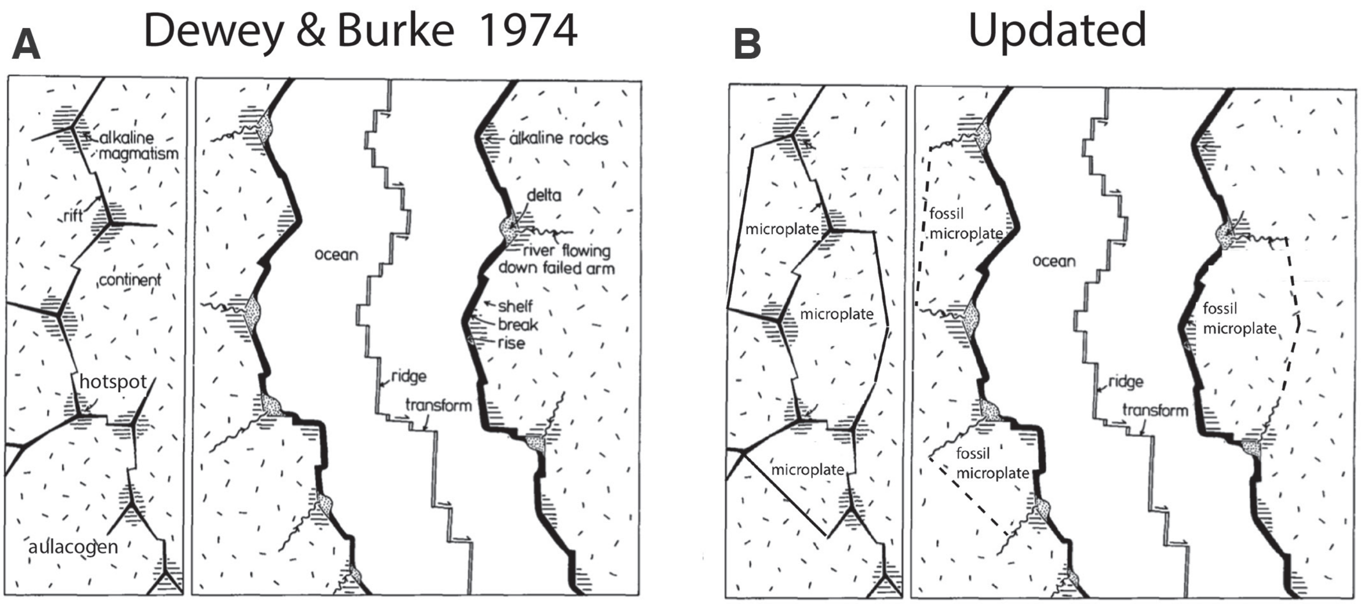

Figure 1. Left: Three-arm model of hotspots and continental rifting. Rift arms from different hotspots link up to form new plate boundaries along which the continent breaks up (A), generating a new ocean basin and leaving failed arms, termed aulacogens, within the continent (B). Right: Updated model in which the rift arms function as boundaries of microplates accommodating motion between the major plates (A). Some microplate boundaries become major plate boundaries, whereas others fail, leaving fossil microplates within the major plates (B).

Burke and Dewey (1973) and Dewey and Burke (1974). These papers proposed that continental rifting begins at "thermal domes or hot spots," commonly with associated magmatism, which are junctions from which three rift arms extend. Rift arms from different hotspots link up to form new plate boundaries, along which the continent breaks up, generating a new ocean basin bordered by continental margins that were the loci of the rifting. Some arms do not evolve to seafloor spreading, leaving failed arms, termed aulacogens, within the continent. Thus, the "junctions" they described are locations where rift arms, rather than distinct plates, meet. This usage contrasts to the present usage in which "triple junctions" are kinematically defined as sites where the boundaries between three plates meet.

The three-arm model gave important insights. First, the rifting process has two major possible outcomes (Fig. 2; Stein et al., 2018). In one outcome, a rift successfully evolves into seafloor spreading, leaving the rift structures buried beneath thick sediments at a passive continental margin. Alternatively, the rift fails and is left within a continent as a fossil feature. Often, the failed rift is inverted by regional compression, such that rocks within the failed rift are uplifted. Hence, presently active and failed continental rifts, and rifted passive continental margins are related and give insight into each other.

A second insight arose as hotspots became increasingly viewed as manifestations of mantle plumes, and hence plumes would be the primary cause of continental rifting. Thus, the three-arm model corresponds to "active" rifting, one of two end-member models of rifting (Sengör and Burke, 1978; Ruppel, 1995). "Active" rifting results from melting in the asthenosphere or deeper mantle due to mantle plumes or shallower thermal or compositional anomalies, as often proposed for the East African Rift system (Ebinger and Sleep, 1998). "Passive" rifting results from stresses within the lithosphere, as proposed for the Baikal Rift, where the Amurian plate diverges from Eurasia (Calais et al., 2003).

In this paper, we revisit the three-arm conceptual model, to see how it looks some 45 yr after it was proposed in light of new ideas and data. Given the extensive relevant literature and the length limitations of this volume, we restrict this paper to briefly discussing four questions that have arisen in our work:

1. How do rift arms function and fail?
2. How does volcanism seen at the surface relate to that at depth and offshore?
3. How does rifting control resulting passive-margin structure?
4. How important are hotspots in this process?

As discussed next, we find that the classic model remains useful, though some aspects require updates based on subsequent results.

THREE-ARM GEOMETRY AND MICROPLATES

In the three-arm model, some rifts join to form a discrete plate boundary, whereas others fail. How this occurs was not explicitly discussed in the original papers, because little relevant data existed at the time. As discussed next, subsequent

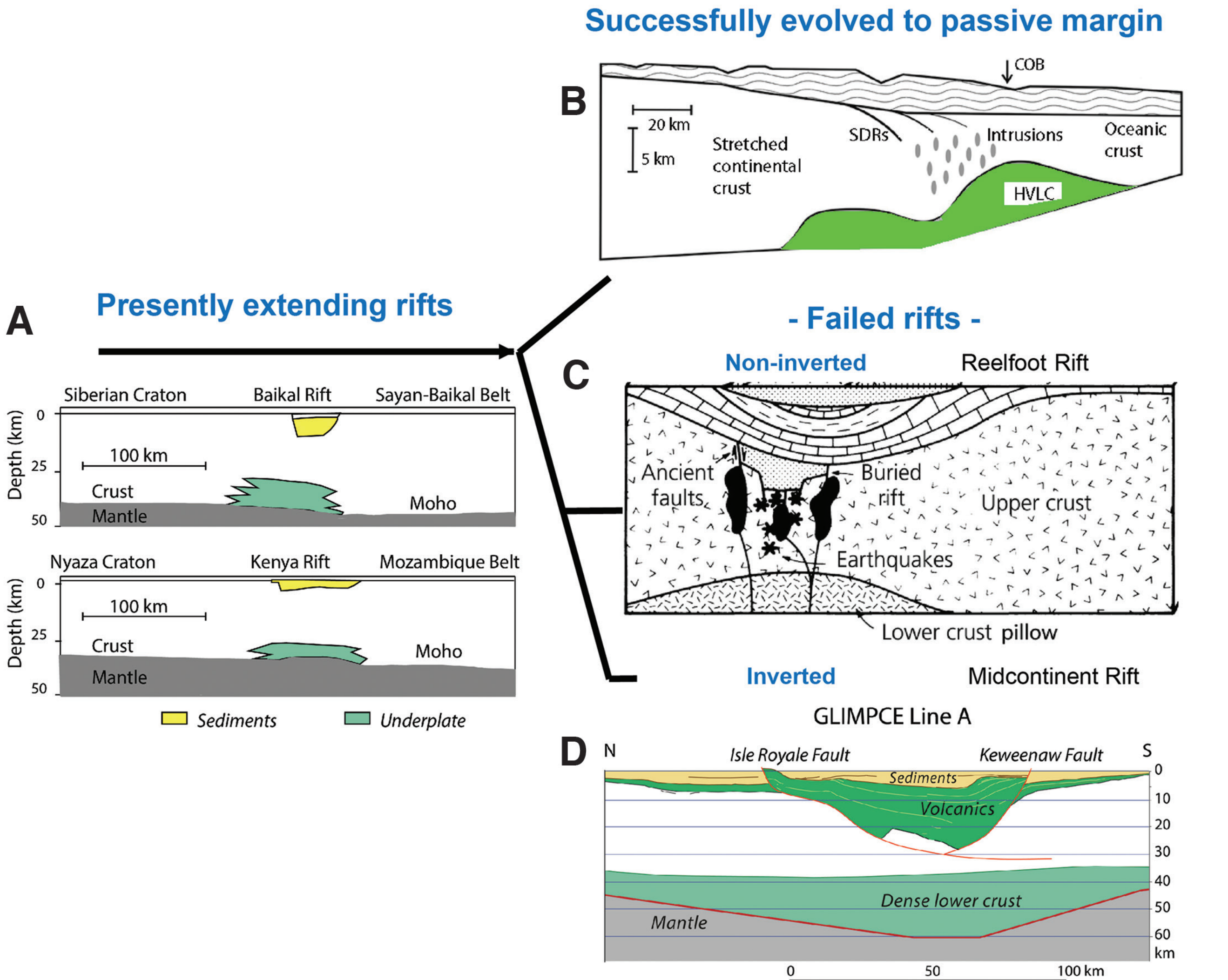

Figure 2. Schematic sequence of rift evolution illustrated by various rifts from: (A) Thybo and Artemieva (2013), (B) Schnabel et al. (2008), (C) Braile et al. (1986), and (D) Stein et al. (2015) modified from Green et al. (1989). COB—continent-ocean boundary, SDRs—seaward-dipping reflectors, and HVLC—high-velocity lower-crustal bodies. GLIMPCE—Great Lakes International Multidisciplinary Program on Crustal Evolution seismic reflection program. In D, dark green denotes rift-filling volcanics, and light green denotes underplate/dense lower crust. From Stein et al. (2018).

observations from past and present rifting have shown that the process often occurs via the rift arms functioning as boundaries of microplates accommodating motion between the major plates (Fig. 1). Some of the microplate boundaries become major plate boundaries, whereas others fail, leaving fossil microplates within major plates.

Microplates

Subsequent to formulation of the three-arm model, it became clear that microplates are a common and important feature of plate tectonics. Recognition of the importance of microplates has clarified many long-standing issues of plate kinematics (e.g., Stein and Sella, 2002). Although the term "microplate" has no formal definition, most have common general characteristics:

1. They are small (typical dimensions of approximately hundreds of kilometers) compared to major plates, which have dimensions of thousands of kilometers. Small microplates are sometimes termed "blocks."
2. They are typically in a boundary zone between major plates.
3. They are often transient, forming in response to changes in the motion between major plates and ultimately being incorporated into one of them.
4. Their boundaries generally have topographic and/or structural expressions.

5. They are kinematically distinct from the neighboring plates, in that their motions can be resolved separately.
6. They generally behave like rigid plates, i.e., a region moving coherently with little internal deformation, such that most deformation, often shown by seismicity, occurs at their boundaries. An interesting exception arises for the stretching and thinning of continental crust associated with rifting, which is sometimes modeled as deformable. In some other cases, microplates seem to break up.
7. They generally obey standard rigid plate kinematics, so Euler vectors describing rotations about a pole can be derived or inferred from relative motion data and used to describe the motions in an internally consistent fashion. Thus, motion on different parts of their boundaries can be predicted, and motion with respect to a major plate can be found by summing Euler vectors involving another major plate.

Hence, despite their small size, microplates act like larger plates and can be treated similarly. This is clearest for oceanic microplates, where magnetic anomalies record the microplate's history and associated changes in spreading center geometry. Figure 3 illustrates these features for the Easter microplate, one of several present and past microplates along the East Pacific Rise, separating the major Pacific and Nazca plates. Bathymetric, magnetic, and earthquake location data showed twinned spreading centers. Earthquakes occur on these ridges, but not between them (Fig. 3A), suggesting that the area between is an essentially rigid microplate (Herron, 1972; Anderson et al., 1974). Inversion of marine magnetic data and earthquake focal

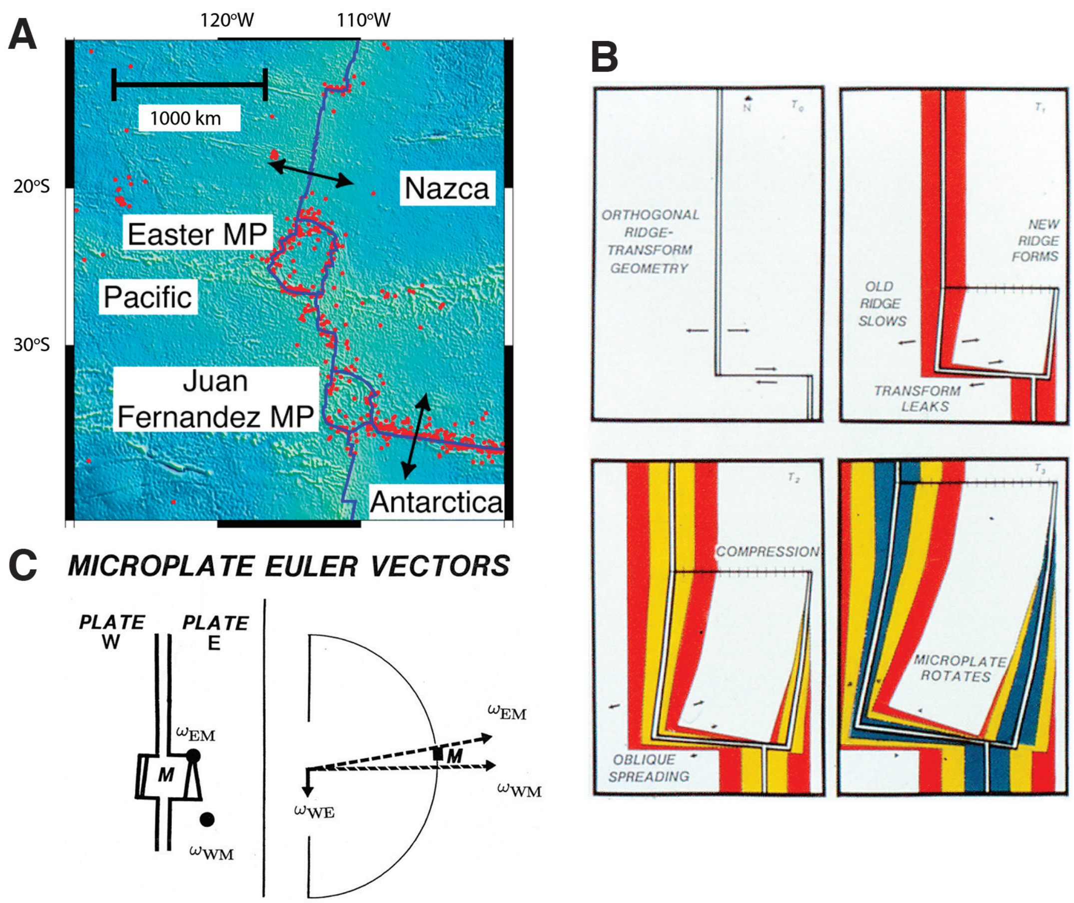

Figure 3. Aspects of microplate (MP) evolution at an oceanic spreading center. (A) Locations of the Easter and Juan Fernandez microplates along the East Pacific Rise. Red dots show earthquake epicenters. (B) Model for evolution of a microplate between major plates. Isochrons show rift propagation, ridge reorientation, microplate rotation, and conversion of a transform into a slow spreading ridge. (C) Euler vectors for a microplate ("M") between eastern ("E") and western ("W") plates. The Euler vector for the east plate relative to the microplate, ω_{EM}, is near the rift tip, and that for the west plate relative to the east one, ω_{WE}, is far away, so the magnitude of the former must be much greater to yield a spreading rate on the southernmost portion of the propagating rift comparable to that between the major plates. Hence, the sum of the other two Euler vectors, ω_{WM}, is similar in direction and magnitude to ω_{EM}. Because both microplate poles are nearby, relative velocities vary rapidly along the microplate's boundaries (Engeln et al., 1988).

mechanisms yields Euler vectors for the relative motion between the microplate and major plates (Engeln and Stein, 1984). Magnetic anomalies show that the east ridge segment is propagating northward (Hey, 1977; Hey et al., 1985) and taking over from the old (west) ridge segment.

Figure 3B shows a simplified model of the evolution of the Easter microplate (Engeln et al., 1988). Because finite time is required for the new ridge to transfer spreading from the old ridge, both ridges are active at the same time, and the spreading rate on the growing ridge is slow at its northern tip and increases southward. Spreading on the dying ridge slows accordingly, conserving motion between the major plates. As a result, the microplate rotates, causing compression (thrust faulting) and extension (normal faulting) at its north and south boundaries, respectively. Sets of anomalies formed on the growing and dying ridges "fan" in opposite directions. Ultimately, the old ridge dies (ceases spreading), transferring lithosphere originally on the Nazca plate to the Pacific plate. Fossil microplates indicated by fanned magnetic anomalies and bathymetric highs indicating fossil ridges are widely found in the ocean basins (e.g., Mammerickx et al., 1980; Cande et al., 1982; Anderson-Fontana et al., 1986; Tamaki and Larson, 1988), showing that spreading centers often reorganize this way.

The success of the Euler vector approach at describing the focal mechanisms and magnetic anomalies illustrates that the microplate is essentially rigid, because summation of the Euler vectors requires rigidity. Hence, the presence of rotated features within the microplate does not require shearing within it, as proposed initially for analogous rift propagation geometry (McKenzie, 1986).

Consideration of the Euler vectors illustrates the general features of such three-plate systems, shown schematically in Figure 3C. The Euler vectors lie in a plane, because they sum to zero as required for a system of three rigid plates (triple junction closure). The pole for motion between major plates is far away, because motion between them (which varies as the sine of the angle between a site and the pole) varies slowly in rate and direction along their boundary. In contrast, the poles for motion between the microplate and major plates are nearby, because motion varies rapidly in rate and direction along the microplate boundaries. For example, in a situation like the Easter microplate, the spreading rate changes from essentially zero to the full spreading rate between the major plates over a length comparable to the microplate dimensions. Because the poles are nearby, the magnitudes of the microplate's Euler vectors (rotation rate) are greater than that for the motion between the major plates, so as to yield rates of motion comparable to that between the major plates. These pole positions change as the microplate evolves. Similar geometries can occur in other situations where plate motions vary rapidly over short distances.

Without the benefit of marine magnetic anomalies, it is more difficult to identify microplates in continental plate boundary zones and study their evolution, but they are studied using paleomagnetic, structural, seismological, and space geodetic data (e.g., Garfunkel and Ron, 1985; McClusky et al., 2000; Stein et al., 2002; Stein and Sella, 2005; Saria et al., 2013). For example, the western U.S. plate boundary zone includes the Sierra Nevada microplate east of the San Andreas fault system (Wright, 1976; Argus and Gordon, 1991; Dixon et al., 2000; Miller et al., 2001) and a discrete Western Oregon microplate moving relative to both the North American and the Juan de Fuca plates (McCaffrey, 2002).

Microplates are important for continental rifting and hence for the history and geometry of rifted continental margins (Courtillot, 1982; Vink, 1982; Dunbar and Sawyer, 1989a). A schematic illustration of some key features is shown in Figure 4. As the major plates and stretched crust diverge, transient microplates form as continents break up and seafloor spreading begins, often by rift propagation. As a result, blocks of continental crust, now termed microcontinents, sometimes survive between regions of oceanic lithosphere. Both these blocks and oceanic portions of the microplates are ultimately incorporated into one of the major plates, leaving identifiable fossil features. Because the final location of the rift axis does not always occur at the center of the zone between the major rifted plates, the resulting passive margins are often asymmetric in width and structure, and they may have abrupt as well as gradual along-strike variations. Hence, asymmetry between opposing margins can persist even if subsequent seafloor spreading was symmetric. Additional along-axis structural variations will result if the rates of rift propagation are not uniform. Such variations may also reflect variations in the mechanical properties of the lithosphere due to compositional and topographic variations, thermal anomalies, and preexisting structural fabrics (e.g., Vink et al., 1984; Steckler and ten Brink, 1986; Dunbar and Sawyer, 1989a, 1989b). These complexities, such as propagating rifts and microplates, are often recorded in the marine magnetic record (e.g., Franke, 2013; Greene et al., 2017) and thus provide key information on the rifting history. In particular, rifting sometimes leaves microcontinents outboard of passive margins (Müller et al., 2001; Gaina et al., 2009; Péron-Pinvidic and Manatschal, 2010; Schiffer et al., 2018, 2019; Molnar et al., 2018; Peace and Welford, 2020). Some analyses include the stretching and thinning of continental crust, which is modeled as deformable (e.g., Peace et al., 2019).

Microplate and Three-Arm Junction Examples

Many three-arm systems identified by Burke and Dewey (1973) are now recognized to be microplate boundaries. To illustrate this, we briefly consider several areas they discussed, noting their microplate aspects without going into their specifics. Many of the junctions they described are now recognized to be triple junctions between kinematically distinct present or past plates.

Present Day

The clearest present-day examples involve ongoing rifting, where motions can be observed with structural, earthquake, and

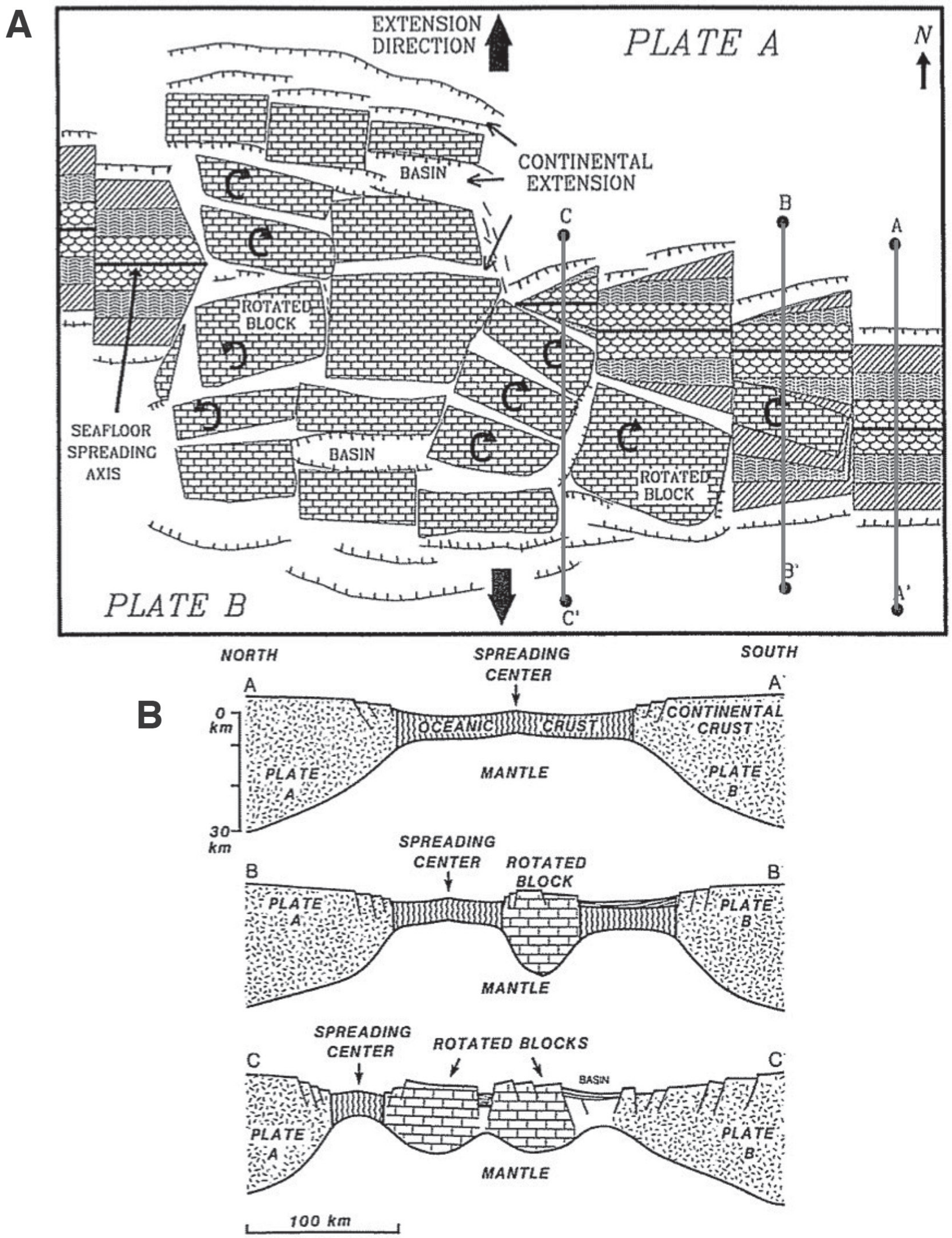

Figure 4. Illustration of possible effects of microplates for continental rifting and rifted margin geometry. (A) Schematic map view of extensional region between continental plates, in which rift propagation rate and geometry, final location of the spreading axis, and size and shape of microplates vary. (B) Schematic cross sections through the region, illustrating various possible geometries (Acton et al., 1991).

geodetic data. One case is the East African Rift system, where Burke and Dewey identified four junctions (Fig. 5A). Although they recognized some of the rift system's complexities, subsequent data demonstrated that three of these junctions are triple junctions (in current usage) between major plates and microplates in the broad boundary zone between the diverging Somalian and Nubian plates. Seafloor spreading in the Red Sea and Gulf of Aden, and continental extension in the East African Rift form a classic three-arm rift geometry as Africa splits into Arabia, Somalia, and Nubia. Topographic, earthquake, and global

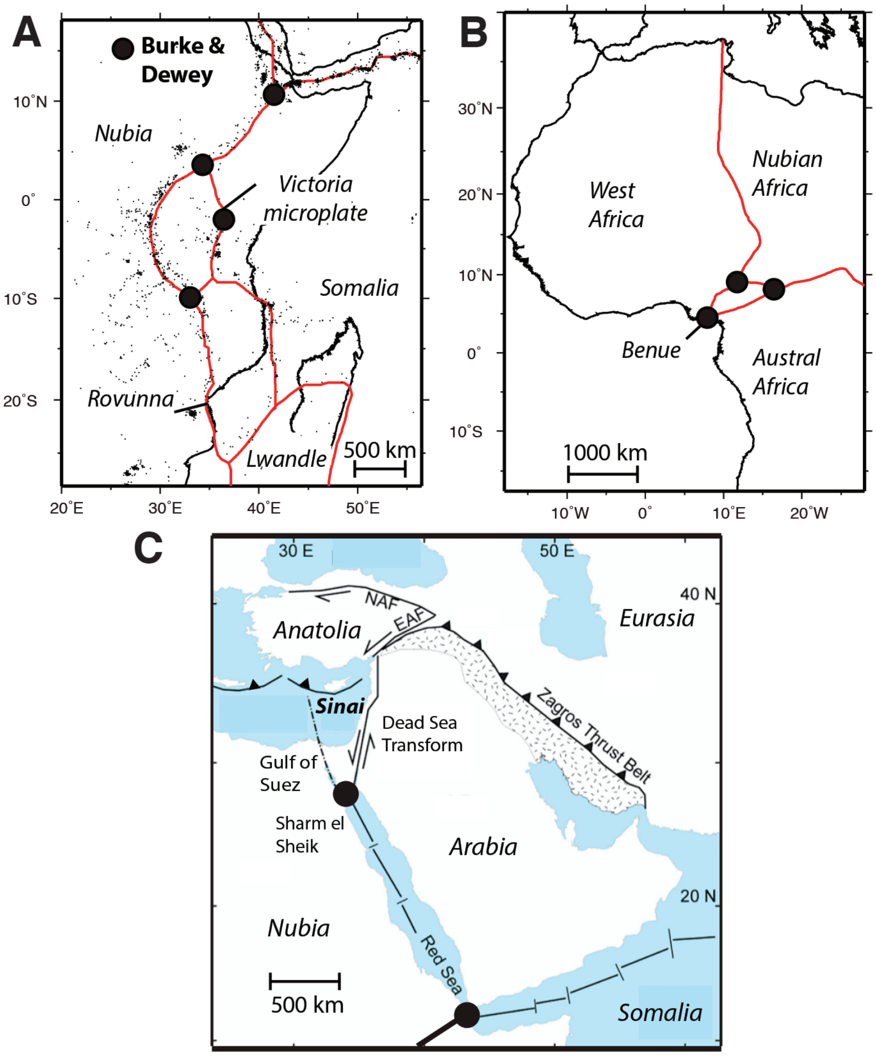

Figure 5. Microplates involved in continental rifting. Dots denote three-arm junctions identified by Burke and Dewey (1973), most of which are now recognized to be triple junctions where discrete plates meet. (A) Present rifting of Africa into three major plates and three microplates, after Saria et al. (2013). (B) Four-microplate geometry of the West Central African Rift system, formed during the Mesozoic opening of the South Atlantic Ocean, after Moulin et al. (2010). (C) Sinai microplate between Nubia, Arabia, and Anatolia, after Gomez et al. (2007, 2020). NAF—North Anatolian fault; EAF—East Anatolian fault.

positioning system (GPS) data show that much of the motion in the three-arm system actually occurs via microplates (e.g., Saria et al., 2013).

Consideration of the East African Rift's future gives insight into how failed rifts would be preserved in the geologic record. If the rift evolves to full seafloor spreading, some of the microplate boundaries would evolve into a spreading center, leaving fossil microplates along the margins of the continents, like those shown in Figure 1B. Conversely, if the rift system does not evolve to seafloor spreading and instead dies, it would appear over geologic time as a long and isolated intracontinental failed rift.

A second present-day example involves the Sinai microplate (Fig. 5C). Burke and Dewey identified Sharm-el-Sheik, at the southern tip of the Sinai Peninsula, as a junction, but they assumed that the Gulf of Suez on the western side of the Sinai Peninsula is a failed arm. Subsequent GPS and earthquake data showed the presence of a kinematically distinct Sinai microplate between Nubia and Arabia (e.g., Salamon et al., 2003; Schettino et al., 2016; Gomez et al., 2020). The Gulf of Suez is one of its boundaries, and Sharm-el-Sheik is the Nubia-Sinai-Arabia triple junction.

200–0 Ma

In other areas, rifting within the past 200 m.y., generally associated with the breakup of Pangea, can be identified and studied using marine magnetic data and geologic data on land. One case is the West Central African Rift system, where Burke and Dewey identified three junctions (Fig. 5B). Subsequent marine magnetic data showed the relation between the intracontinental rifting and opening of the South Atlantic Ocean in the Mesozoic. Reconstruction of the fit between South America and Africa without gaps and overlaps, and matching magnetic anomalies, requires extension within continents via microplate motion (e.g., Moulin et al., 2010; Seton et al., 2012). These rifts failed when seafloor spreading initiated along the whole boundary between Africa and South America, showing that continental breakup can involve extension within a continent that ends once full seafloor spreading is established.

Similar analyses have been done for the opening of the northern Atlantic Ocean over the last 200 m.y. (Figs. 6A and 6B). Burke and Dewey's reconstruction identified 16 junctions. Subsequent detailed studies showed that many of these junctions were triple junctions during the region's complex evolution, involving large and small plates, continental blocks, and deformation within boundary zones, often controlled by preexisting structures (e.g., Barnett-Moore et al., 2018; Peace et al., 2019; Foulger et al., 2020; King et al., 2020; Schiffer et al., 2019). Eventually, the microplates/blocks were incorporated into the major plates. For example, although Greenland is now part of the North American plate, it was a distinct plate from ca. 80 to 36 Ma (Barnett-Moore et al., 2018; Peace et al., 2019; Foulger et al., 2020), with a now-failed western boundary extending northwestward of Cape Farewell.

Prior to 200 Ma

Rifting within continents prior to the availability of marine magnetic data is more difficult to study. In many cases, much of the record is lost due to later tectonic events. However, some information can be derived from geological, potential field, and seismological data. An example is the Midcontinent Rift in

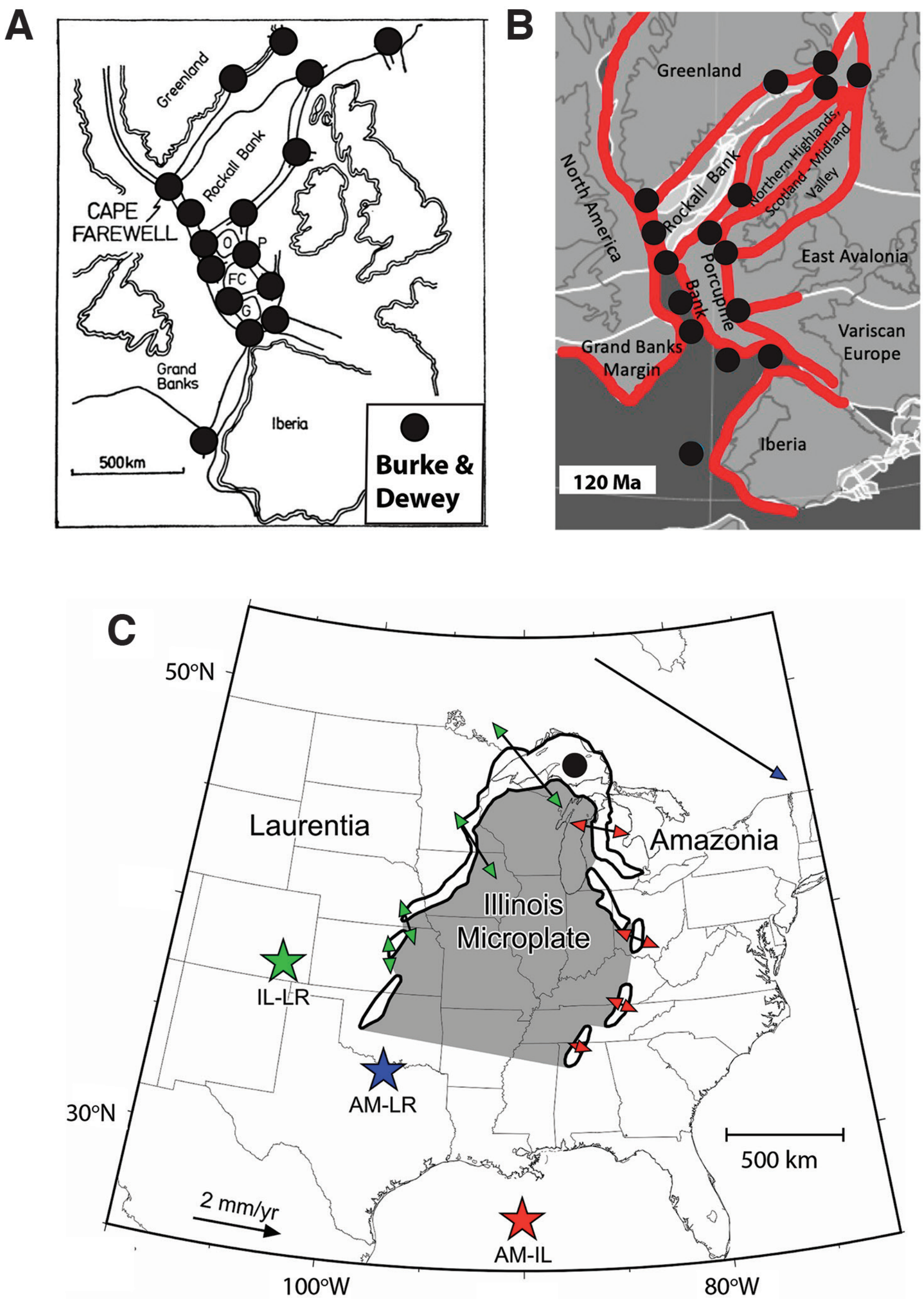

Figure 6. (A) Junctions proposed by Burke and Dewey (1973) as involved in the opening of the northern Atlantic Ocean. (B) Junction locations and proposed microplate boundaries, from GPlates reconstruction at 120 Ma (Scotese, 2016; Müller et al., 2018). (C) Schematic kinematic model of an "Illinois" (IL) microplate for which the Midcontinent Rift (MCR) arms are plate boundaries. Euler poles are shown by stars, with first plate listed rotating clockwise with respect to the second. Double-headed arrows show relative motion across Midcontinent Rift arms; single-headed arrow shows Amazonia (AM) motion relative to Laurentia (LR). Rate scale is shown by 2 mm/yr arrow (Stein et al., 2018).

North America, one of the world's most impressive failed rifts (e.g., Stein et al., 2018). The rift is a 3000-km-long, U-shaped band of buried sedimentary and igneous rocks that outcrop near Lake Superior (Fig. 6C). It is buried by younger sediments further south, but it is indicated by gravity and magnetic data showing the dense and highly magnetized igneous rocks. Burke and Dewey identified the Lake Superior area as a junction. Subsequent data showed that the Midcontinent Rift likely records the rifting of the Amazonia craton from Laurentia, the Precambrian core of the North American continent, ca. 1.1 Ga during an extensional phase of the Grenville orogeny, with the ca. 1.3–0.98 Ga sequence of events culminating in the assembly of a number of continental blocks into the supercontinent Rodinia (Stein et al., 2014; Malone et al., 2016). Rather than evolving into full seafloor spreading, the Midcontinent Rift failed when full seafloor spreading between the major plates was established. Later regional compression inverted the rift, uplifting the volcanic rocks, some of which are now exposed at the surface. The formation and cessation of the Midcontinent Rift were likely part of the evolution of the plate boundaries between Laurentia and neighboring plates. It seems likely that the rift's arms were boundaries of a transient microplate, as in the model shown, although we lack information about the southern microplate boundary due to subsequent collisions and a later rifting event.

Other Possible Microplates

Additional junctions identified by Burke and Dewey seem likely to have been associated with microplates. During the breakup of Gondwanaland, India's west coast formed by rifting from Africa and Madagascar, and its east coast formed by rifting from Antarctica and Australia. At this time, a number of intracontinental rifts formed within India, starting at the coastlines, and then subsided and accumulated thick sediments (e.g., Chakraborty et al., 2019). Some sites identified by Burke and Dewey as junctions (Fig. 7A) are on these rifts. These rifts seem likely to have been microplate boundaries active during the continental breakup. Many of these rifts remain zones of weakness

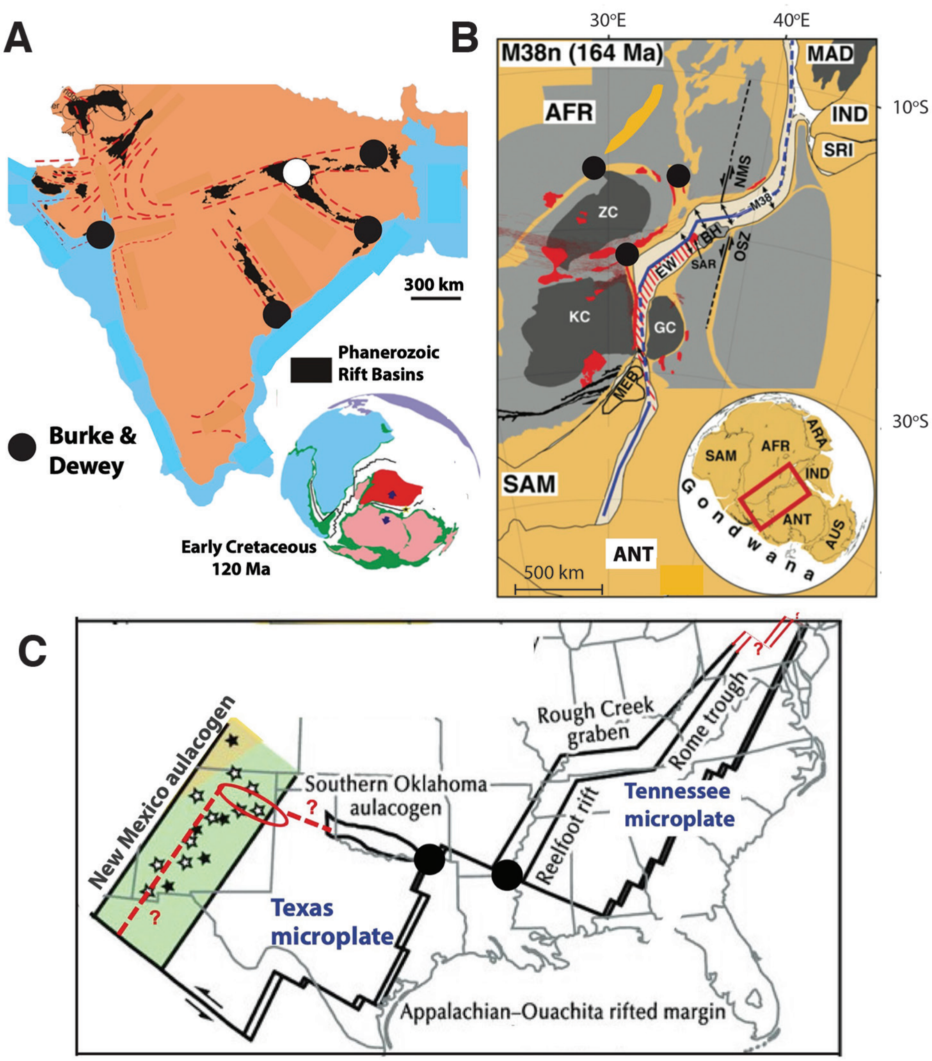

Figure 7. Three areas with junctions identified by Burke and Dewey (1973) where failed microplates may have formed during rifting. (A) Five junctions in India, with rifts after Chakraborty et al. (2019). (B) Three junctions in southeast Africa, on borders of Zimbabwe craton after Davison and Steel (2018) and Mueller and Jokat (2019). Red areas—Karoo-age volcanism. AFR—Africa; ARA—Arabia; ANT—Antarctica; AUS—Australia; BH—Beira High; EW—Explora Wedge; GC—Grunehogna craton; IND—India; KC—Kaapvaal craton; MAD—Madagascar; MEB—Maurice Ewing Bank; M38n—Mesozoic magnetic chron 38 n (normal) at about 164 Ma; NMS—Namama shear zone; OSZ—Orvin shear zone; SAM—South America; SAR—Southern Astrid Ridge; SRI—Sri Lanka; ZC—Zimbabwe craton. The latitudes and longitudes are for present-day Africa. (C) Two junctions in southern United States associated with possible microplates. In the northeast United States, the red lines mark the approximate location of the continuation of the Rome trough and the Scranton rift (Benoit et al., 2014). Filled stars are known Cambrian–Ordovician igneous rocks and open stars are suspected ones (after McMillan and McLemore, 2004).

today, and some large earthquakes in India are associated with these weak zones (Stein et al., 2002; Khan et al., 2016).

In addition to those on the East Africa Rift (Fig. 5A), Burke and Dewey identified other junctions in southeast Africa (Fig. 7B). These are associated with Karoo-age (ca. 180 Ma) volcanic rocks in rifts that border the Zimbabwe craton (e.g., Hastie et al., 2014; Davison and Steel, 2018; Peace et al., 2020). The rifts seem to have been the boundaries of microplates, composed of cratonic fragments, that were active during the breakup of Africa and Antarctica (Mueller and Jokat, 2019). We suggest that motion between the microplates in both Africa and India may have contributed to known gaps and overlaps in reconstructions of Gondwanaland (Thompson et al., 2019), and as noted for the West Central African Rift system (Fig. 5B).

Burke and Dewey also identified two junctions in the southern United States (Fig. 7C). These appear to have been associated with the final breakup of Rodinia, which involved rifting of the Argentine Precordillera block from Laurentia and formation of two rifts, the Reelfoot Rift and the Southern Oklahoma aulacogen (Thomas et al., 2004). These rifts seem to have been part of the boundaries of microplates formed during the rifting, which subsequently failed, and now they are part of the North America plate. The "Tennessee" microplate is bounded by the Reelfoot Rift, continuing northeastward into the Rough Creek graben, through the Rome trough (McMillan and McLemore, 2004; Marshak and van der Pluijm, 2021), and perhaps with a slight offset to the Scranton rift (Benoit et al., 2014). The breakup in latest Neoproterozoic–Cambrian time (Thomas, 1991) is thought to have been located slightly east of the Scranton rift, but the subsequent Appalachian orogeny obscured features at the northeastern end of this proposed microplate. The southern end of this spreading center is the Alabama-Oklahoma transform fault, connecting the Reelfoot Rift to the Southern Oklahoma aulacogen. The western boundaries of the "Texas" microplate may have been the New Mexico aulacogen proposed by McMillan and McLemore (2004) based on ages of igneous rocks. Hence, some old deformation zones within the North American craton may be fossil microplate boundaries from past episodes of rifting (Marshak and Paulsen, 1996; Marshak et al., 2017).

In many cases, the boundaries of microplates during continental breakup are located on preexisting zones of weakness and are influenced by preexisting fabric, including older collisional zones (e.g., Misra and Mukherjee, 2015). For example, some parts of the East African Rift occur in presumably weak areas associated with the Pan-African orogenic belt rather than the presumably stronger parts of the Archean Tanzania craton (e.g., Ebinger et al., 1997; Corti, 2012). At many other sites, preexisting lithospheric fabric produced by orogenic events influences the location of rifting (Vauchez et al., 1997), and rift propagation often follows the trend of orogenic belts (Tommasi and Vauchez, 2001). For example, the orogenic belt between the Zimbabwe and Kaapvaal cratons (Fig. 7B) had a significant control on the locations of dike injection (Jourdan et al., 2006). Preexisting structures and variations in lithospheric strength may allow rifts to propagate and join with other rifts (Heilman et al., 2019). Today's continents are composed of many terranes that have collided and sutured to form large landmasses. In particular, India and Africa (Figs. 7A and 7B) may have had many active microplates during the different rifting events that occurred during the breakup of Gondwanaland. Thus, it is not surprising that when continents rift, transient microplates form during the extensional phase, and triple junctions involving the microplates look like the three-arm junctions of Burke and Dewey.

LOCATION OF MAGMATISM

In 1974, little was known about the structure of rifts, so Dewey and Burke considered igneous rocks only at the hotspots, noting that they used the term "hotspot" in a purely descriptive sense for the junctions of "three-armed rift-valley" complexes.

Subsequent studies found that extensive volcanism occurs along the full length of many rifts. A consequence is that, although crustal thinning occurs in the early stages of rifting, the crust is rethickened as rifting progresses. For example, crust beneath the Midcontinent Rift is thicker than that beneath its surroundings (French et al., 2009; Moidaki et al., 2013; Shen et al., 2013; Zhang et al., 2016). Some of this thickening seems to have occurred via formation of an "underplate" layer or "rift pillow." The underplate is thought to form via a process in which low-density melt rises, leaving a high-density residue ("restite") at the base of the crust (Fig. 8; Vervoort et al., 2007). Underplating first returned the thinned crust to its original thickness, as seen in presently extending rifts, and then further thickened the crust (Stein et al., 2018). Although the specifics of this "magma-compensated" process vary, it has been observed in the Baikal, Kenya, and other rifts (Thybo and Nielsen, 2009; Thybo and Artemieva, 2013).

The net effect of these processes is that many rifts contain large volumes of igneous material, both filling the rift and in the corresponding underplate (Fig. 9). Moreover, as discussed next, large volumes of igneous rocks occur at most passive continental margins. How rifting processes give rise to these large volumes of igneous rocks is crucial for the long-standing debate over the role of mantle plumes in continental breakup.

RIFTING CONTROLS PASSIVE-MARGIN STRUCTURE

In 1974, little was known about the structure of continental margins, so Dewey and Burke did not explore the relation between continental rifting and the resulting passive continental margins. As discussed next, subsequent studies showed that many structures observed at continental margins were formed initially by the rifting.

Most passive continental margins, termed volcanic or magma-rich margins, arise where continental breakup is/was associated with the eruption of flood basalts, dikes, and sills during prerift and/or synrift stages of continental separation. The large-scale melting gives rise to thick igneous crust (Menzies et al., 2002; Geoffroy, 2005; Geoffroy et al., 2015). Hence, volca-

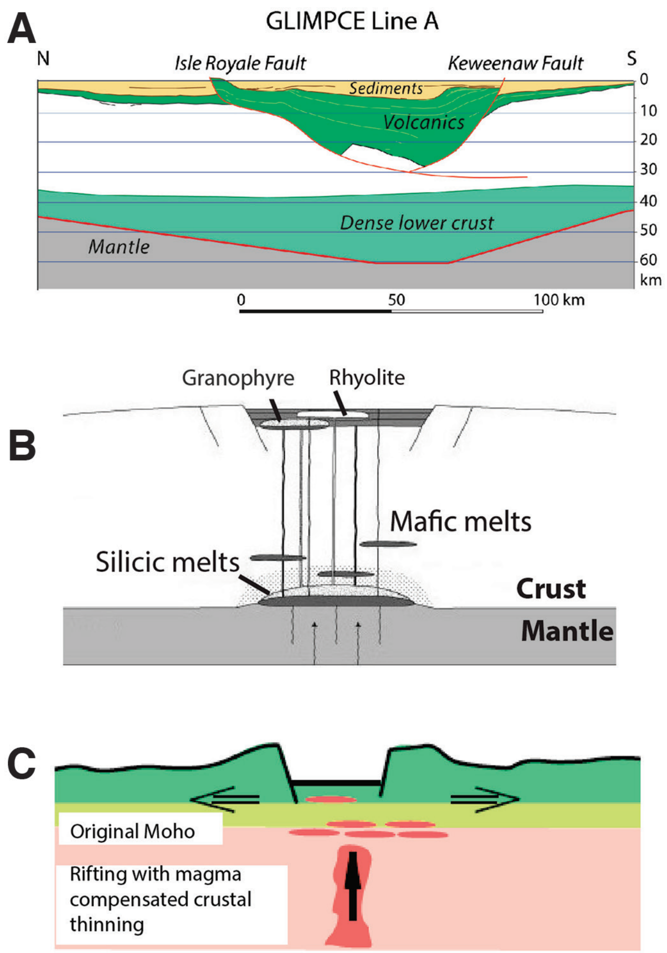

Figure 8. Volcanism and underplating associated with rifting. (A) Crustal structure model beneath Lake Superior for Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE) seismic reflection program line A showing volcanics and underplating (Green et al., 1989; Stein et al., 2015). Dark green denotes rift-filling volcanics, and light green denotes underplate/dense lower crust. (B) Model for Midcontinent Rift magmatism (modified from Vervoort et al., 2007). (C) Model for magma-compensated rifting (Thybo and Artemieva, 2013). From Stein et al. (2018).

nic passive margins are generally considered to be large igneous provinces (Eldholm and Grue, 1994).

These margins have a characteristic architecture (Fig. 2B), characterized by a transition from thinned and intruded continental crust to oceanic crust. The igneous rocks form two units. The shallower units are packages of seaward-dipping reflectors, volcanic flows interbedded with volcaniclastic sediments and tuffs (e.g., McDermott et al., 2018), which cause large magnetic anomalies landward of the oldest spreading anomalies. The deeper units, termed high-velocity lower crust, occur beneath the transitional crust and in some cases oldest oceanic crust (e.g., Blaich et al., 2011; Franke, 2013; Eddy et al., 2014). Seaward-dipping reflector volumes measured on margin-crossing profiles typically are approximately one third of the high-velocity lower-crust volumes. This consistency implies that formation of these units is related during continental rifting and breakup.

Because the architecture of the margin is the final result of rifting and early seafloor spreading, the volume and geometry of the volcanic units can give insight into the rifting process. For example, we have been considering similarities with the Midcontinent Rift. Surface exposures, gravity data, and seismic data indicate a rift basin filled by inward-dipping flood basalt layers, underlain by thinned and underplated crust, recording a history of extension, volcanism, sedimentation, subsidence, and inversion (Fig. 10A). The Midcontinent Rift began as a half graben with initial, largely nonvolcanic, extension and motion occurring on a master normal fault on one side of the rift, which was later filled by synrift and postrift flood basalts (Stein et al., 2015).

The Midcontinent Rift is thus a preserved piece of what might have evolved to a volcanic margin had it not failed. The rift-filling volcanics, which are analogous to seaward-dipping reflectors, cause large magnetic anomalies that are analogous to those observed on rifted margins. The Midcontinent Rift underplate is analogous to the high-velocity lower-crust units on rifted margins. Hence, many key features at passive margins likely formed this way, though they would have been modified thereafter. The structural reconstruction from Stein et al. (2015, 2018) suggests how the Midcontinent Rift would have evolved (Fig. 10B). As extension continued, flows dipping toward the center of the rift would have evolved into seaward-dipping reflector packages, the final geometry of which could also reflect further normal faulting, flexure, and other effects (Buck, 2017; Morgan and Watts, 2018; Tian and Buck, 2019). Additional seaward-dipping reflectors may have been deposited as seafloor spreading started (Koopmann et al., 2014).

This analogy suggests a cause for the asymmetric features often observed on opposite sides of conjugate margins, where the seaward-dipping reflector zone is wider on one side than the other (e.g., Blaich et al., 2011; Reuber et al., 2019). If the basin split at its deepest point, symmetric passive margins would result. If the basin split elsewhere, perhaps along the master fault as illustrated in Figure 10B, it would have yielded asymmetric margins.

This comparison illustrates the importance of viewing rifting structures remaining on land and those in the corresponding offshore passive margin as closely related. Study of one can yield insight into the other. For example, discussions of rift-related volcanic provinces on land, such as the Central Atlantic magmatic province associated with the breakup of Pangea (Marzoli et al., 2018), should incorporate the offshore volcanics (McHone, 2003).

HOTSPOTS PLAY AT MOST A SECONDARY ROLE IN CONTINENTAL BREAKUP

In the classic three-arm model, hotspots—subsequently viewed as the surface manifestations of mantle plumes—are the primary cause of continental rifting. However, it is still unclear whether large-scale magmatism is a cause (“active rifting”) or

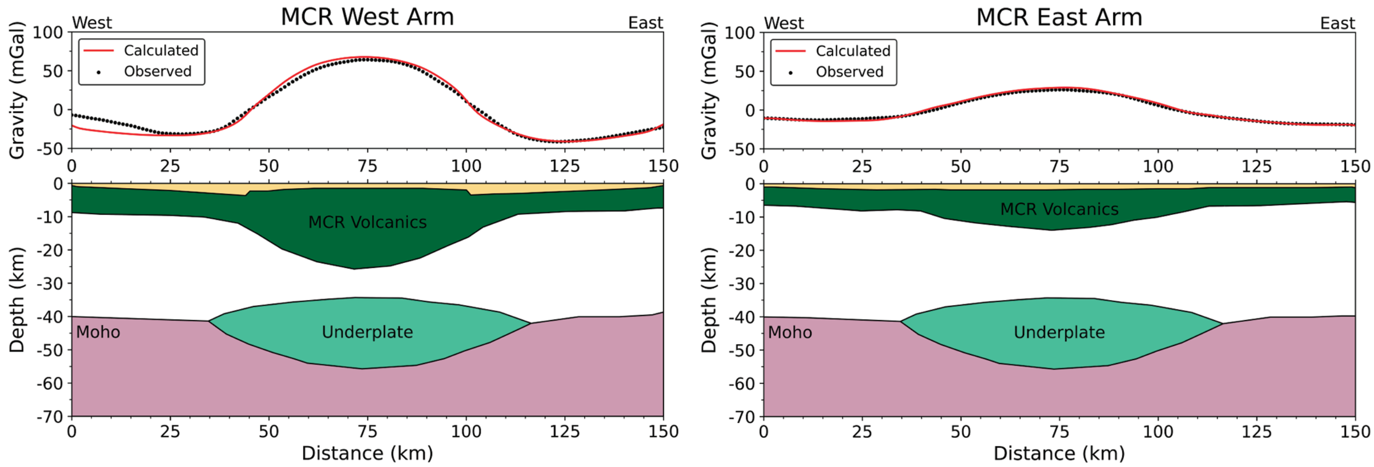

Figure 9. Gravity models matching the mean anomalies across the west and east arms of the Midcontinent Rift (MCR; Elling et al., 2020).

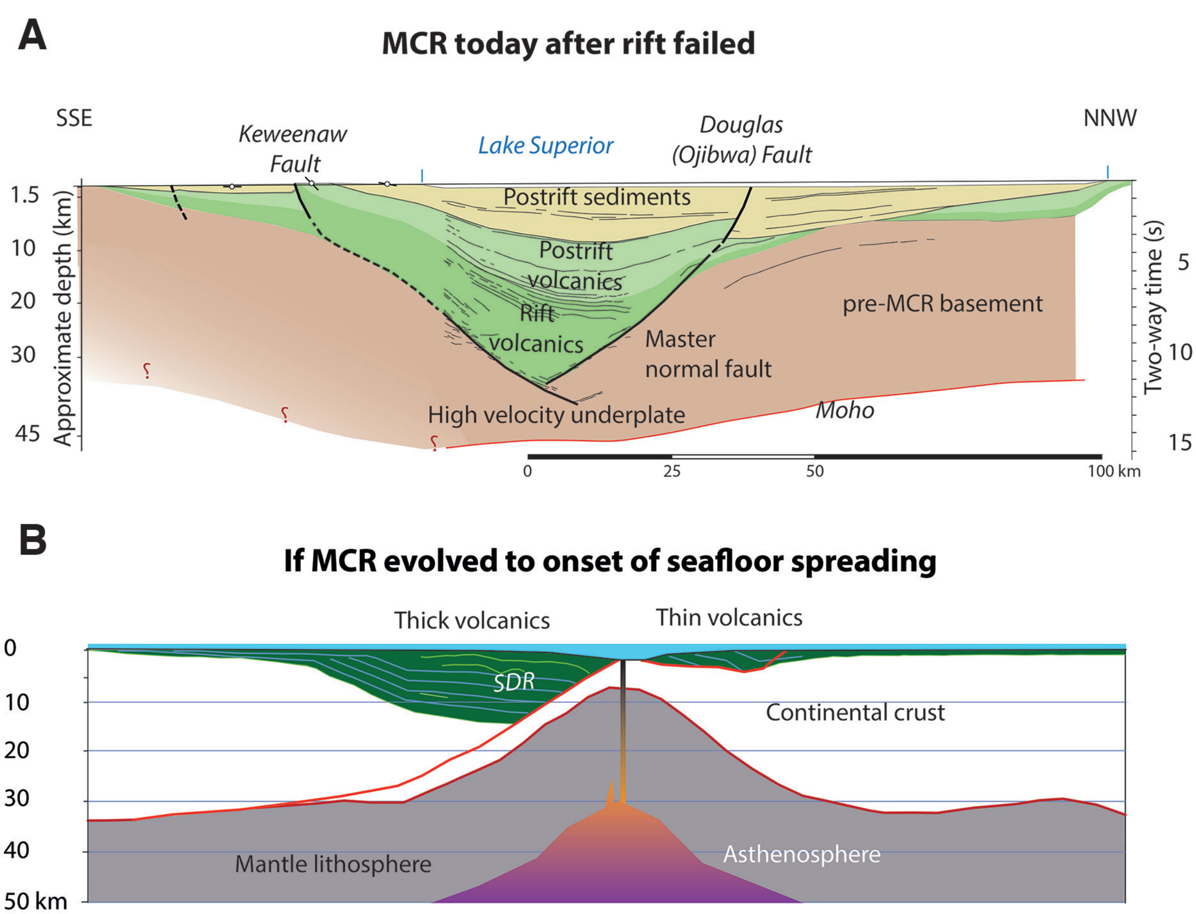

Figure 10. (A) Present Midcontinent Rift (MCR) structure, generalized by combining seismic profiles across Lake Superior with land geology. (B) Scenario by which the Midcontinent Rift could have yielded an asymmetric passive margin after continued half-graben rifting. Postrift volcanics and sediments would not have been deposited in the subsiding basin. Instead, they would have been deposited over a larger area as extension continued, splitting the continent, and evolving into seafloor spreading (Stein et al., 2018). SDR—seaward-dipping reflector.

an effect ("passive rifting") of rifting. Much of the debate has focused on the ways in which the large volumes of igneous rocks at passive margins are generated. Numerical modeling has been used to support either possibility. It has long been proposed that excess temperatures associated with hotspots/plumes and the resulting weakening of the lithosphere are required to rift continents, given the large volumes of igneous rocks at most passive margins (e.g., Burke and Whiteman, 1973; Morgan, 1981, 1983; Richards et al., 1989; Buck and Karner, 2004; Armitage and Collier, 2017). However, invoking plumes for all large igneous provinces and rifted margins has been questioned (Kelemen and Holbrook, 1995), and alternatives have been proposed (King and Anderson, 1995; McHone, 2000; King, 2007; Foulger and Jurdy, 2007; Foulger, 2011). van Wijk et al. (2001, 2004) favored generation of volcanic margins by decompression melting alone without plumes.

To explore this issue, Gallahue et al. (2020) used existing seismic reflection and refraction data to compile a data set of igneous rock volumes and geometries at volcanic passive continental margins. The VOLMIR (volcanic passive margin igneous rocks) data set is based on margin-crossing profiles, from which the volumes and geometries of both shallow seaward-dipping reflectors and deeper, high-velocity lower-crustal units can be measured. It also includes information about the corresponding ages of rifting and initiation of seafloor spreading and distances from the Euler pole associated with rifting and from hotspots that may have been involved in the rifting.

As shown in Figure 11A, more magma should be generated at locations further from the Euler pole, where spreading rates are faster and thus net extension is greater (Lundin et al., 2014), and more melt should be generated closer to a hotspot. Gallahue et al. (2020) found that the volume of igneous rocks is moderately

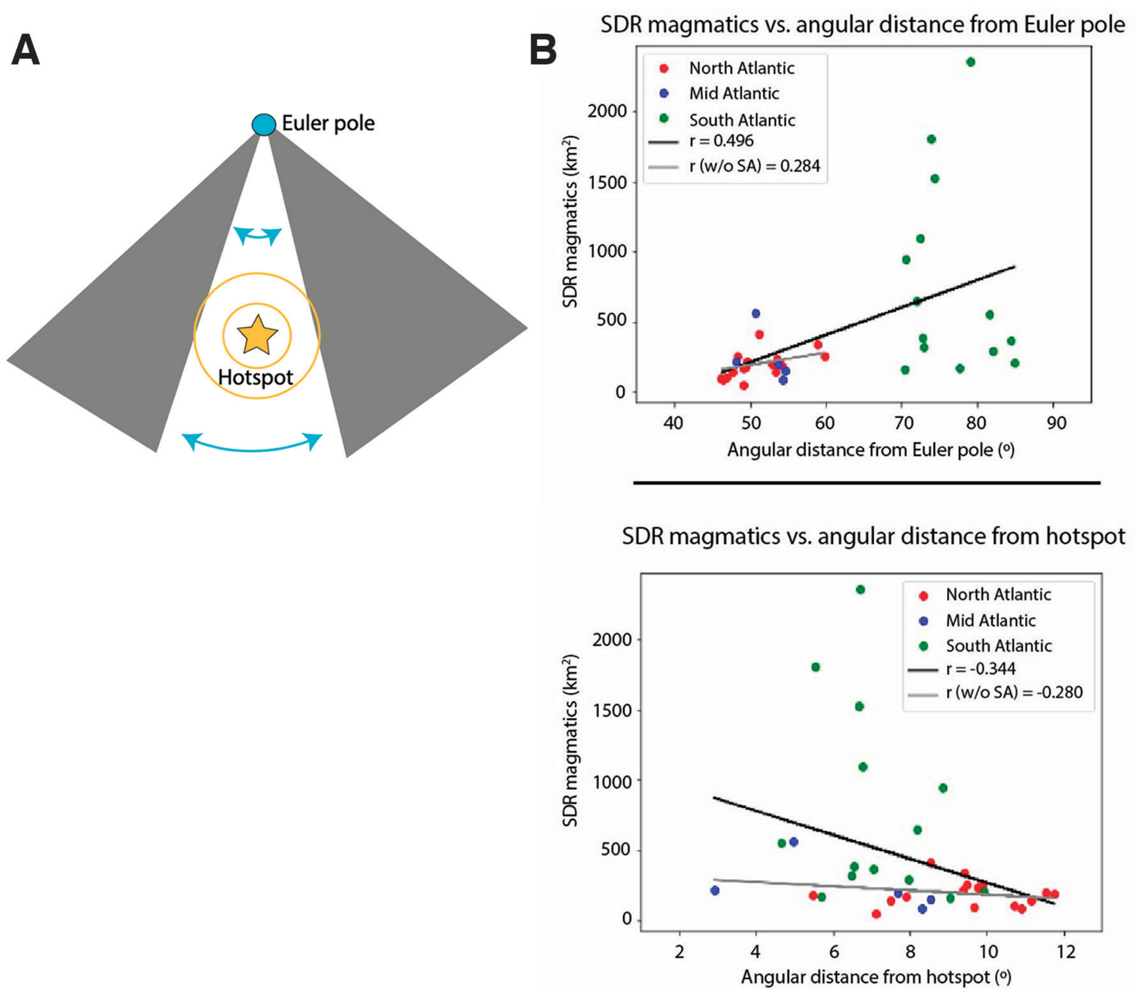

Figure 11. (A) Expected trends for volcanic volumes with angular distance along a rifted margin. For active rifting, more melt should be generated closer to a hotspot. For passive rifting, more magma should be generated further from the Euler pole, where spreading rates are faster and thus net extension is greater. (B) Seaward-dipping reflector (SDR) volcanic volumes vs. angular distance from the Euler pole (top) and hotspot (bottom) at the time of margin formation for profiles across margins from the Atlantic Ocean. Least-square fits and correlation coefficients both with and without the South Atlantic (SA) data are shown (Gallahue et al., 2020).

positively correlated with angular distance from the Euler pole, but it is only weakly negatively correlated with distance from the nearest hotspot (Fig. 11B). Although neither correlation is strong, the relative strengths of the correlations suggest that in continental breakup, lithospheric processes (passive rifting) have greater effects than hotspots (active rifting).

It is possible that hotspots initiate breakup, even if most of the igneous rocks reflect plate divergence. However, in the South Atlantic Ocean, Franke (2013) and Peace et al. (2020) found that rifting propagates toward "hotspots" and not away from them—opposite the direction expected for a mantle plume model. Hence, the inferred hotspot locations (the three-arm junction points) may not reflect localized upwelling of a deep mantle plume and thus may not have special significance for volcanism that extended along the entire rift length.

CONCLUSIONS

The classic three-arm model of continental rifting (Burke and Dewey, 1973) has stood the test of time. Although 45+ yr of data have clarified many aspects of the ways in which the proposed processes actually occur, the basic model remains useful. However, some aspects require updates based on subsequent results. First, the rift arms are often boundaries of microplates between the major diverging plates. Second, much of the rift-related magmatism is preserved at depth, in underplated layers, or offshore. Third, many structures formed during rifting survive at the resulting passive continental margins. Fourth, hotspots play at most a secondary role in continental breakup. Moreover, the model still raises crucial questions for ongoing research.

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