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Magmatic rifting of Pangaea linked to onset of South American plate motion

Erin K. Beutel *

Department of Geology and Environmental Geosciences, College of Charleston, 66 George St., Charleston, SC 29424, United States

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ABSTRACT

The causes of the transition from amagmatic to magmatic rifting during continental break-up are not always clear and have been often linked to the break-through of a plume. However, stress fields recorded in the crust may offer new insights into the relationship between changes in the stress field and the onset of magmatism. In this paper stress fields recorded in the crust of North America are used to test possible causes of the break-up of Pangaea and the transition from amagmatic to magmatic rifting. Finite element models reveal that the most likely scenario for the break-up involves the initial northwest motion of North America at 230 Ma, followed by a south-southeast motion of South America at 200 Ma with the initiation of magmatism, and finally a weakened area between North and South America sometime soon after 200 Ma which resulted in North America being dominated by northwest motion once again. It was also determined that plate boundary structure and orientation play a large part in the recorded stress fields and must be taken into consideration when modeling continental break-ups and rifting.

1. Background

Continental rifting and the transition from pure continental rifting to seafloor spreading may be investigated from both present day activity, such as rifting in East Africa—the Red Sea, and from past rifting events, such as the break-up of Pangaea. Present day studies, such as those on the East African rift and Red Sea rift have the advantage of real-time measurements and observations, while studies of the past rifting events have the advantage of a completed timeline rather than a snapshot waiting to develop. However, because of the amount of time that has passed, investigations of past rifting events sometimes smooth over the details such as rift orientation and propagation because of a lack of data or because of scale issues. In this paper I use these details to understand the stress field in North America at the time of the break-up of Pangaea, specifically the time when the rifting went from amagmatic to magmatic. The possible causes of these stress fields, and therefore the break-up of Pangaea, are then determined using finite element models.

The break-up of Pangaea began around 230 Ma with the initial rifting of the southeastern portion of North America (Schlische, 2002). These early rifts can be found in both North and South Carolina (Schlische, 2002) and generally trend Northeast with regional variations, however, it is unclear if this initial rifting also occurred along the southern margin of North America as the few Mesozoic rift basins from Georgia, Northern Florida, and Alabama are not precisely dated. Around 200 Ma+/−2 Ma (Nomade et al., 2007) magmatic injection in the form of a giant dike swarm began approximately synchronously with the progression of rifting to the North-Northeast (Hames et al., 2000; McHone, 2000; Salters et al., 2003; Schlische et al., 2003; Beutel et al., 2005). Because most of the dikes and the exposed flows are dated to around 200 Ma, it is assumed that the majority of the voluminous mafic magmas along the North American margin from Florida to New England were emplaced within a 2–3 million time period (Nomade et al., 2007). Initial maps combined with new field work indicate that the southeastern margin of North America is dominated by NW trending dikes cross-cut by infrequent to frequent N and NE trending dikes, however, as the swarm progresses to the northeast the overall dike trend slowly rotates to become predominantly NE (May, 1971; Ragland et al., 1983; McHone, 1988; Marzoli et al., 1999; Salters et al., 2003; Beutel et al., 2005). Cross-cutting relationships and geochemistry suggest that the NW trending dikes were emplaced first, followed by the N and finally the NE trending dikes (Ragland et al., 1983; Beutel et al., 2005). Because of sedimentation and logistical issues, it is not clear what the relationship between these 200 Ma dikes and the formation of the first oceanic crust around 180 Ma. However, it is clear that they represent the transition between the amagmatic phase of rifting and magmatic rifting phase. This information can be used in conjunction with a finite element model to determine the stress field during the break-up of Pangaea and the possible causes of this stress field as the rifting progresses from magmatic to amagmatic. Because the regional stresses recorded in the rock represent snapshots of what was occurring at the time, finding the sources of these stresses should clarify possible causes for the break-up of the Pangaea by indicating what was occurring prior to and during the break-up and transition from amagmatic to magmatic.

* Tel.: +1 843 953 5591; fax: +1 843 953 5446.
E-mail address: beutele@cofc.edu.

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1.1. Dikes and stress

Dikes record the stress field during their emplacement and thus the stress field during the change from amagmatic to magmatic rifting during the break-up of Pangaea. In general dikes are injected perpendicular to the least least-compressive regional stress field, however, pre-existing fractures, local stress fields, and basement structures can cause deviation from the regional (state-wide) stress field (de Boer and Snider, 1979; Mchone et al., 1987; Fialko and Rubin, 1999; Ziv et al., 2000; Jourdan et al., 2006). According to Ziv et al. (2000), one of three criteria must be met for dikes to follow pre-existing fractures; one, that the fractures are close to perpendicular to the least least-compressive stress field (which means that the dikes will still give us a general view of the stress field at the time of their emplacement); two, that the magma pressure is so high that it creates a scenario where the shear to the opening of the dike walls is small; and three, the effective dike-normal stress is small compared to the rock tensile strength. Because these conditions are difficult to maintain over long distances and/or depths, most dikes affected by fractures rotate within a short distance to become parallel to the ambient compressive stress field (Ziv et al., 2000). Local stress fields that affect dikes can be caused by the injection of the dike itself and/or the magma body, the classic example of magma bodies affecting dike orientation is seen at volcanoes where dikes are injected radially about the domal uplift (Johnson, 1961). The best evidence for basement control of dike orientation comes from the Karoo swarm in South Africa where Jourdan et al. (2006) recognized that the Karoo swarm consists of both Proterozoic and Mesozoic dikes, both of which follow the cratonic margin. This suggests that cratonic margins and basement structures may strongly affect dike orientation.

1.1.1. Can CAMP dikes be used to reveal a regional (eastern North America) stress history or are they affected by local (10's of km) structures and stress fields?

The dikes and other Mesozoic igneous features of the east coast of North America have been collectively grouped into the Central Atlantic Magmatic Province (CAMP) and have been used as evidence both for a plume and against a plume (May, 1971; de Boer and Snider, 1979; McHone et al., 1987; Ernst and Buchan, 1997; King and Anderson, 1998; Marzoli et al., 1999; Courtillot et al., 1999; Dalziel et al., 2000; McHone, 2000; Janney and Castillo, 2001; Beutel et al., 2005). In this study I will use the dike patterns to understand the least-compressive stress regime during the transition from amagmatic to magmatic in the break-up of Pangaea, however, this will only be possible if none of the previously discussed outside influences have has affected their orientation. Because the conditions under which dikes follow pre-existing fractures cannot be maintained over long distances unless the fractures are extensional stress perpendicular to begin with, it is unlikely that the giant dike swarms of CAMP are overly influenced by any non-stress responsive fractures. While the influence of a large magma chamber due to a plume has been proposed to explain the CAMP dikes, the dikes are not radial and in fact cross-cut. Further, unless the plume was a moving target, the regional stress field would have exerted some influence on the dikes at a distance and no evidence of a change in orientation along the strike of the dikes is seen, suggesting that any magma chamber influence was extremely localized (10s of km) and not visible. The other possibility, that pre-existing basement structures could have influenced dike orientation, is also unlikely given the multiple orientation of dikes within the Carolinas, and because many of the dikes cross-cut or stop against the

Fig. 1. Sketch map of 200 my Pangaea with pre-South Carolina regional studies dike orientations (e.g. Marzoli et al., 1999), continental boundaries, and normal faults. Previously mapped dikes are shown as short thick black lines (e.g. Marzoli et al., 1999), rough sketches of major normal faults in North America are shown as thin lines. Rose diagram in corner shows true orientation of dikes in South Carolina and parts of North Carolina based on new fieldwork and map compilations, while the adjacent grey box illustrates how the all the mapped dikes and faults would overlie each other in the region indicated by the connecting lines. Light gray shading of 3 states along the southeastern portion of North America indicates from North to South, the locations of North Carolina, South Carolina, and Georgia. The stippled area between the major continental outlines indicates both the continental shelves, which we do not have good data for and missing continental pieces from the time of the suture—it is assumed that all three continents were acting as one at this time.

pre-existing structures (Ragland et al., 1983; Beutel et al., 2005). Thus, it appears that the CAMP dikes were most likely influenced by regional least-compressive stress fields rather than either pre-existing stress fields or a magma body.

1.1.2. What do the dikes tell us?

Previous interpretations of the dike orientations have focused on an explanation for the NW trending dikes that dominate South Carolina and parts of Georgia and North Carolina because based on sketch maps of the region they are both at a high angle to the expected regional least-compressive stress field during rifting and to the pre-existing crustal structures (e.g. Schlische et al., 2003). Further, when presented as a group on a sketch map, the CAMP dikes are often mistaken as being regionally separate swarms of NW, N, and NE trending dikes (Fig. 1). However, detailed mapping in South and North Carolina suggests that the swarms overlap and cross-cut indicating a non-radial source and a change in local conditions during emplacement (Fig. 1). While only general maps of dike locations are available for Georgia and Alabama, detailed fieldwork and consolidation of USGS quadrangle information indicates that a series of 200 Ma NW, N, and NE trending igneous dikes are found throughout the Carolinas (Beutel et al., 2005). Cross-cutting relationships indicate that the oldest dikes are NW trending and the NE trending dikes are the youngest with the N trending dikes coming in between. Though all dike trends can be found in the Carolinas, the NW trending dikes dominate in the south, while the NE trending dikes are more dominant from Virginia north and N trending dikes are more dominant in the middle. This indicates that the least-compressive stress field during emplacement of the dikes was rotating from NE extensional, to E extensional, to NW extensional in the southeastern United States as rifting progressed northward (Fig. 2).

Therefore based on field evidence from dikes and rifts I reconstructed the following stress changes along the east coast of North America from ~230 Ma to 190 Ma and conclude based on these changes that a plume as the cause of them is unlikely. Between 230 Ma and ~200 Ma the southeastern edge of North America was slowly rifting and undergoing a NW extensional stress while the rest of the continental edge appears to be quiescent (though a lack of data from the southern margin does not preclude early rifting here) (Fig. 2). Around 200 Ma east–west rifts started to develop along the southern margin of North America and northeast trending rifts began appearing along the present day northeastern United States, this indicates that the extensional stress field was N–S along the southern margin of North America, NW–SE along the southeastern margin of North America, and NNW–SSE along the eastern margin of North America (Fig. 2). However, based on the dike orientations, there existed at the same time a NE–SW extensional stress field in the southeast that rapidly (~2 Ma) rotated to NW–SE. Dikes along the eastern margin of North America north of Virginia are parallel to the rifts and therefore apparently emplaced by the same least-compressive stress field that generated the rifts, indicating that unlike in the south the extensional stress that created the rifts was likely responsible for the dike orientation as well. This stress story, as summarized below, is used to determine the viability of the finite element models via stress field orientation comparison.

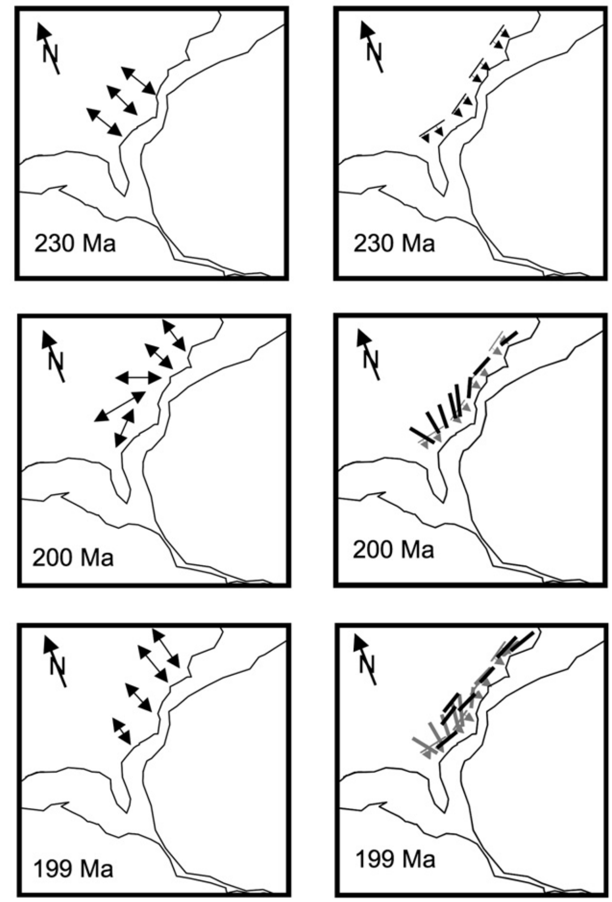

Fig. 2. From top to bottom the left column shows the estimated stress directions per time period based on the faults and dikes of that age. The right column is a series of cartoons illustrating the general orientation of the resultant extensional stress features (dikes and faults) created at that time, these are underlain by the dikes and faults created at the previous time and shown in grey. Double headed arrows indicate tensional stress directions, shorter arrows indicate estimated smaller magnitude stresses based on the prevalence of faulting or diking in that area, in the right-hand column the thick bars indicate dikes while the lines with arrows indicate normal faults. *Stress Field Summary* Time 1: NW trending extensional stress concentrated along the southeast coast of North America. Time 2: N trending extensional stress along the south margin of North America, NE trending stress along the southeast coast of North America decreasing and/or rotating to NW extensional as you move northeast along the present day coast of North America. Time 3: NW extensional stress along the eastern margin of North America, concentrated along the present day northeast coast of the United States portion of North America.

2. Model

A quadrilateral plane strain finite element grid using Gobalt and Atkinson's (1996) FElt model was constructed to determine the possible causes of the rotating stress fields during the transition from amagmatic to magmatic rifting of Pangaea. These static elastic models are essentially solutions to Hooke's law, which describes the deformation of elastic solids. If we view the models as simple grids of elastic springs and nodes, we provide the construction of the grids, the properties of the springs, and the initial forces. The program solves for the propagation of these forces across the grid, taking into account the neighboring springs. Overall, the grid is isotropic and composed of plane stress quadrilateral elements, except at the plate boundary zones between the continents and the South Georgia Rift, which feature elements specially aligned and shaped to represent these boundaries. The finite element code requires thickness for the z-direction, Poisson's ratio, Young's Modulus, and densities for all materials in the program. Strength of the continents is given based on the elastic moduli and an input thickness. The following parameters were input; continental and rift mechanical properties and locations, stress/force properties and locations, and motion constraints. Essentially the model started with the outline of the continental shelves input into the finite strain grid with a one order of magnitude weaker elastic moduli and 3 times thinner than the surrounding continents (original continental material properties: Young's Modulus 40 GPa, Poisson's ratio .2, density of 2650 kg/m^3). As an elastic model the results show only the instantaneous stress and do not take into account viscous flow.

Applied forces were calculated based on a general rate of motion and mass for continents, because I am examining relative stress orientation and strength rather than absolute numbers within an order of magnitude will give the same results. Constraints on motion were simplified into able to move in all directions or fixed in space and unable to move at all. Several models were constructed to test numerous possibilities including a radial slab suction/rollback, a vertical plume with radial compressional stress, and different applied stresses to the continents. The radial slab pull model is constructed based on the reconstructions of Pangaea that show it completely surrounded by inward dipping slabs (Golonka, 2007). Approximate slab-suction forces were based on the average rates of continental motion, which was then translated into an outward force applied to the margin. Vertical loading and topographic doming with radial compression were combined to determine the approximate magnitude of the radial compressive force that might have been caused by the intrusion of a plume. The other possible force tested was the motion of the continents as driven by a mantle basal drag force. This was also approximated based on the approximate rate and direction of motion of the continents. The assumption being that the continents are more likely to be driven by mantle flow against a continental keel and not asthenospheric flow along the bottom of an oceanic plate, the relative importance of this force is highlighted in Conrad and Lithgow-Bertelloni (2006).

Model tests within four orders of magnitude were conducted for all applied forces and the relative strength and orientation of the resulting stresses did not change. Therefore, the forces chosen for the models were based on the approximate relative strength of the forces in general and on the approximate magnitude of those stresses as listed in Fowler (1997).

Constraints on the motion of continents was limited to the end-members of either free to move in three-dimensions or fixed in space. When constraints on motion were applied they were applied to all of the nodes in the center of a continent assuming that the mechanism holding the continent in place would be a lack of forces moving it and a resistance to motion along the base of the cratonic portions of the continent as a whole.

Given the scale of the elements in the model the only pre-existing crustal elements portrayed are the plate boundary zones (or zones where the continents meet) and the South Georgia Rift, which was

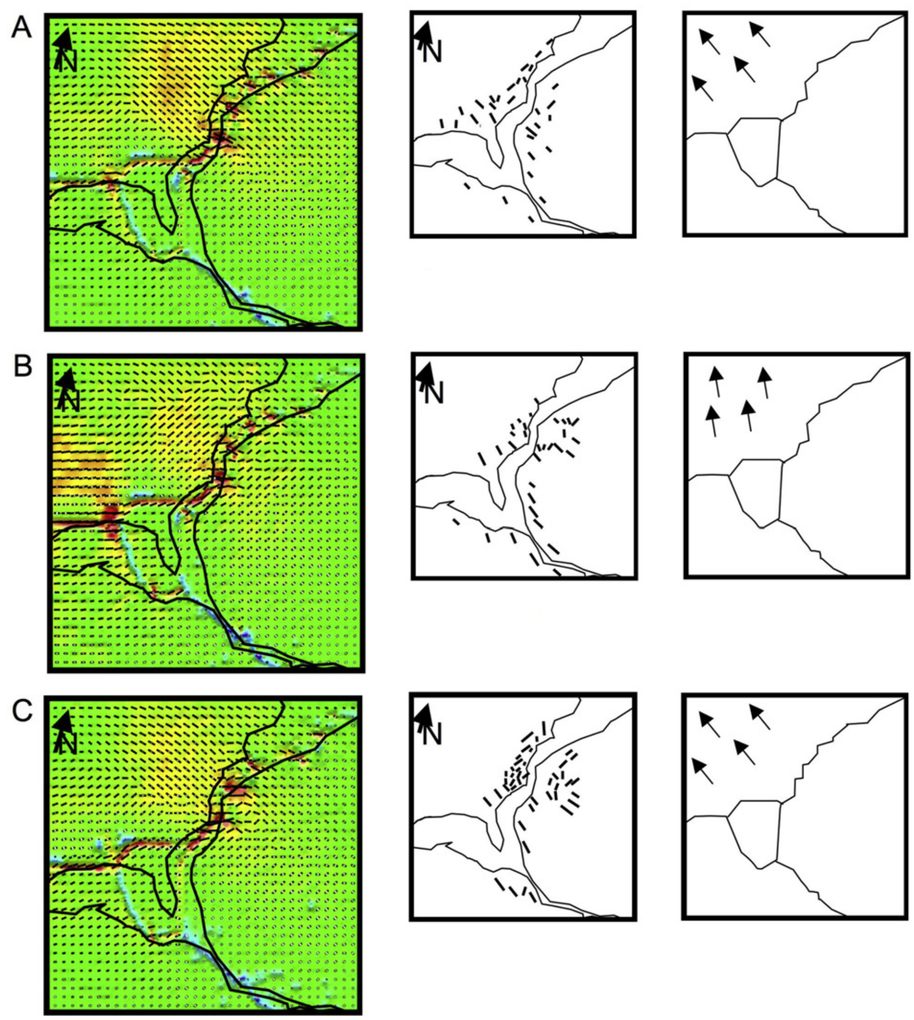

Fig. 3. A–J: Each figure A–J is divided into three boxes. The first box to the far left is the result of the finite element model and shows the maximum stress intensity as background colors, blue is compressional and red is extensional, and the maximum and minimum stress vectors, black is extensional and white is compressional. The north arrow indicates present day north while the orientation of the continents reflects their approximate position at 230 Ma. The second box shows possible rift and/or dike orientations given the stress orientations shown in the first box. Dikes and faults are only indicated for the margins of the North American continent despite stresses being transmitted throughout the continent because field work suggests that the dikes stop at the Brevard fault, a major Appalachian plate boundary zone that runs parallel to the east coast. The fault is not in the model, but any stresses behind its approximate location on the model should be viewed with suspicion. And the third box shows a cartoon of model parameters, plate boundary lines are shown (note that a plate boundary line is shown between Florida and the red of North America, this actually represents the South Georgia rift and a possible plate boundary attachment of Florida, models run without it are mildly different), as are the applied stresses (shown as arrows), and the constraints on movement (fixed areas are shown with black dots). Finally, areas of extreme weakness (areas of crust 3-orders of magnitude weaker than the surrounding crust) are shown as shaded grey.

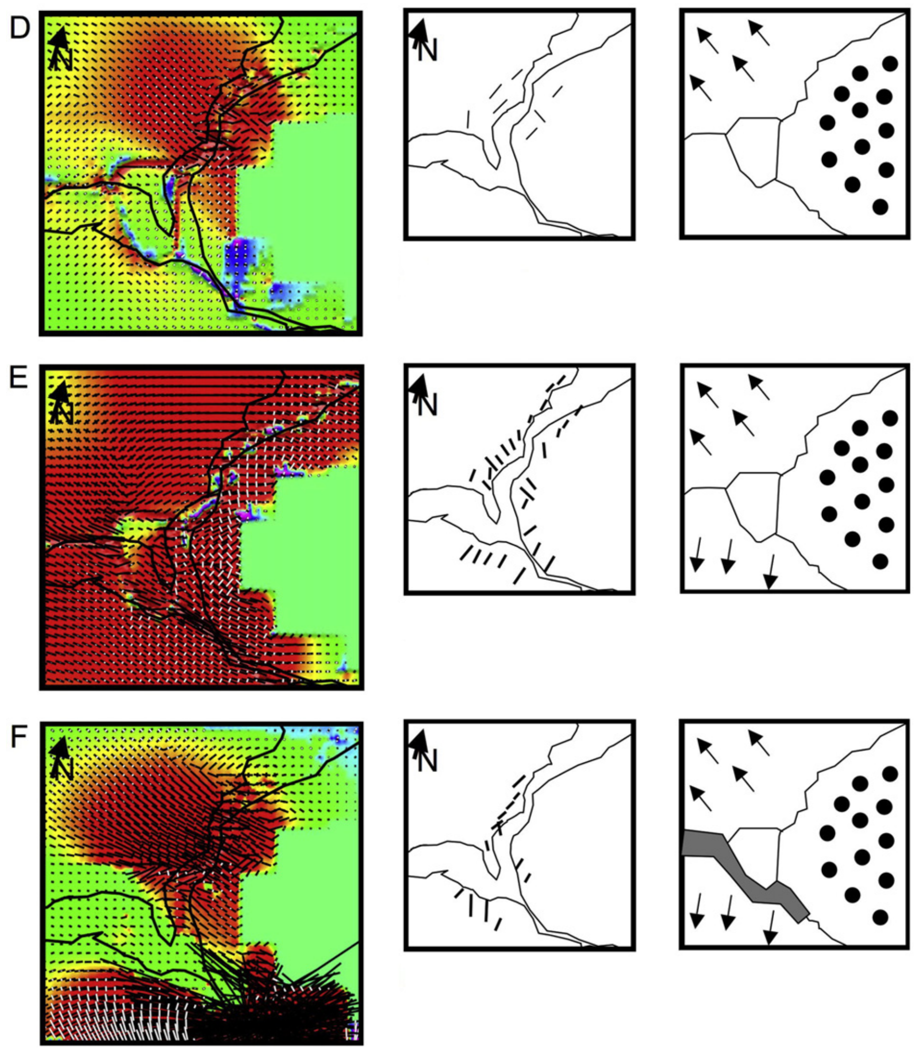

Fig. 3 (*continued*).

believed to be active during this time. For this reason the only interpretations of stress results that will be analyzed are those on the margins as other, non-modeled crustal zones would affect stress distribution in the interior.

The locations and shapes of the plate boundaries or margins of the continents are based on reconstructions of Pangaea and current continental crust outlines (e.g. Torsvik and Van der Voo, 2002). The addition of a boundary between Florida and the rest of North America is based on multiple lines of evidence that there was a zone of thinning there. Several researchers have pointed out that Florida does not appear to be North American in origin and it is often not even depicted as attached until during/after the break-up of Pangaea and it is separated from North America by the Brunswick Magnetic anomaly (e.g. Heatherington and Mueller, 1999; Heatherington et al., 1999; Ford and Golonka, 2003). The Brunswick Magnetic anomaly also marks the South Georgia Rift system, which appears to cut parallel to the probable suture between the Suwanee Terrane (Florida) and the rest of North America (McBride, 1991).

3. Results (Table 1)

Fig. 3 shows several example model results, the postulated dike fields, and the applied forces and Table 1 is a verbal summary of Fig. 3. Postulated dike and fault orientations are only modeled for the South and Eastern margins of North America despite the transmissions of stresses into the continent because the model does not take into account faults and plate boundaries within the continent known to have halted the progression fractures. For example, the CAMP dikes along the southeastern margin of North America all cease (except one) at the Brevard fault zone in the Appalachians. Because these barriers and crustal features were not taken into account the stresses from the interior of the continent are less likely to be accurate.

In the first set of three models there are no fixed continents, the plate boundary between the continents is modeled as one order of magnitude lower strength than the surrounding crust, and the only force is a force applied to the North American craton. In the first column the results of the models are displayed as a background maximum stress intensity with the maximum and minimum stresses plotted on top. Fig. 3A shows the results of a NW stress on the North American continent, which results in a relatively uniform magnitude stress field with the correct distribution of stresses to have produced NW trending dikes in the far southern United States and northeast trending stresses along the east coast. By changing the applied stress to more northerly the assumed dike orientation (perpendicular to the least least-compressive stress) becomes predominantly NW trending along the east coast of North America, once again the stress magnitude is relatively uniform. Finally, in Fig. 3C the actual areas of weakness are changed to become much sharper with defined strong transform

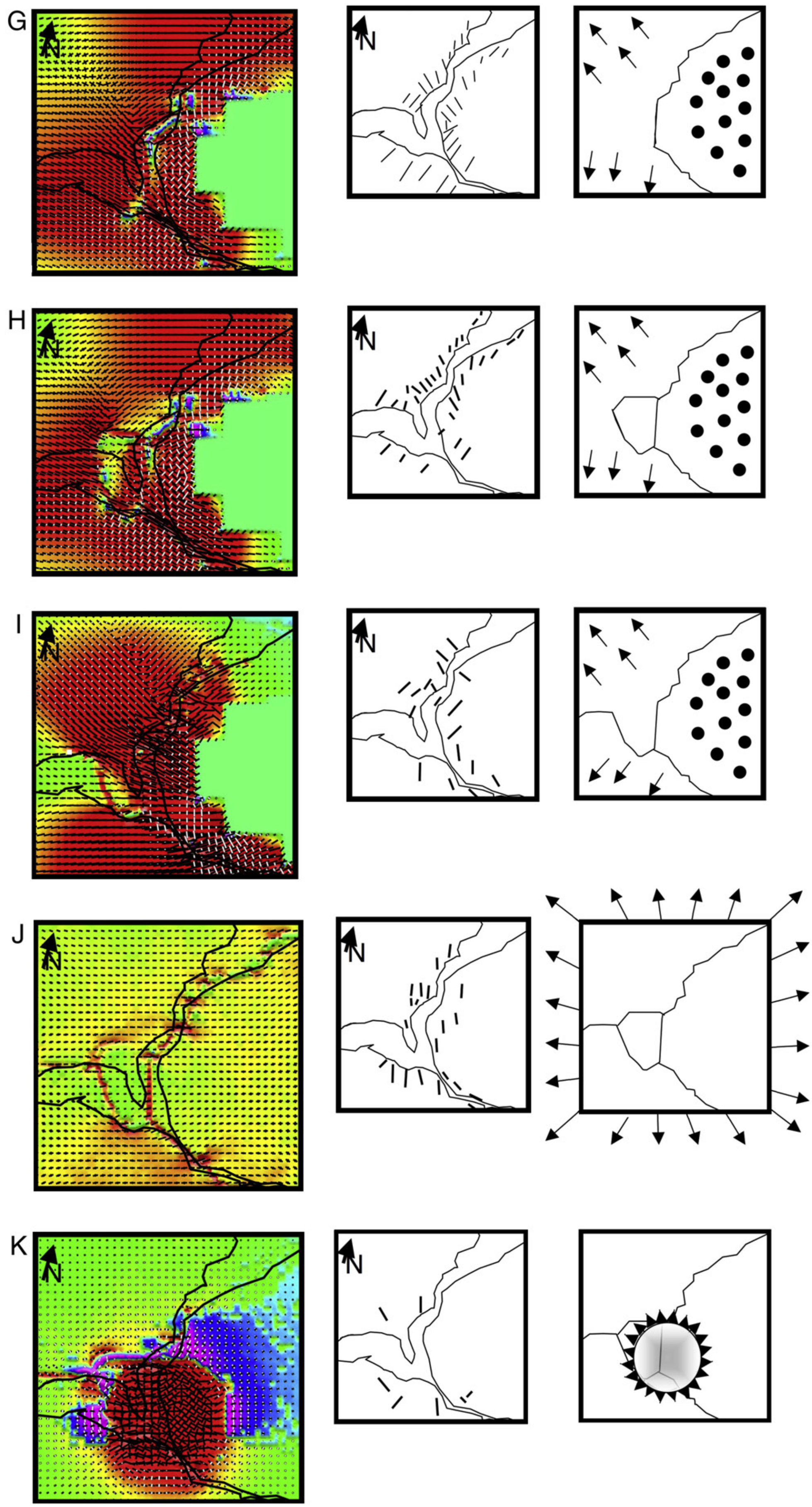

Fig. 3 (*continued*).

Table 1

Refers to Fig. 3	Results: Listed as probable dike and normal fault trends along the south and eastern coasts of North America	Model parameters: Unless otherwise specified suture zones between continents are modeled as one order of magnitude weaker and thinner than surrounding continental crust. The South Georgia Rift is modeled in the same manner.
A	N to NW trending along the Southern margin of North America, abrupt change in trend around Georgia/South Carolina border to NE trending.	NW trending motion for North America—no motion or resistance to motion for Africa or South America.
B	NW trending along South and Southeastern margin of North America.	NNW trending motion of North America—no motion or resistance to motion for Africa or South America
C	N to NW trending along the Southern and Southeastern margin of North America, change in trend around Georgia/South Carolina border to NE trending, trend change is marked by an area of highly variable stress direction coinciding with the area of most defined rift basins.	NW trending motion for North America—no motion or resistance to motion for Africa or South America. Suture zones along east coast made to resemble rift basins with north–south trending rift basins of one order of magnitude weaker and thinner crust separated by strong (same as the rest of the continent) areas of continent with structures at right angles to the rift zones.
D	Generally NE trending along the Southeastern margin of North America with possible N trending along the Southern margin.	NW trending motion for North America—no motion or resistance to motion for South America. Africa is held fixed' 'fixed' in place so it cannot move in response to North America's motion.
E	NE trending along the Southern margin of North America changing to NW trending along the Southeastern margin and finally changing to NE trending along the Northeastern margin of North America.	NW trending motion for North America and a SSW trending motion for South America. Africa is held 'fixed' in place so it cannot move in response to North America's motion.
F	Generally NE trending along the entire Eastern margin of North America.	NW trending motion for North America and a SSW trending motion for South America. Africa is held 'fixed'fixed' in place so it cannot move in response to North America's motion. The area between South and North America is modeled as 3 orders of magnitude lower strength than the continental crust.
G	NE trending along the Southern margin of North America abruptly switching to NW trending along the Eastern margin of North America.	Applied continental motions are the same As in Fig. 3F, North America is moving to the NW, South America is moving to the SSW, and Africa is held fixed. The suture between South America and North America is removed as a zone of weakness to see the effect this suture had on the distribution of stress along the coast.
H	NE trending along the Southern margin of North America, switching gradual to NW trending along the Eastern margin of North America.	As in Fig. 3F, North America is moving to the NW, South America is moving to the SSW, and Africa is held fixed. The suture between South America and North America is only modeled as weak around Florida and through the South Georgia Rift.

Table 1 (*continued*)

Refers to Fig. 3	Results: Listed as probable dike and normal fault trends along the south and eastern coasts of North America	Model parameters: Unless otherwise specified suture zones between continents are modeled as one order of magnitude weaker and thinner than surrounding continental crust. The South Georgia Rift is modeled in the same manner.
I	NE trending along the Southern and Southeastern margins of North America, switching to NW trending in the mid-section of the Eastern margin.	As in Fig. 3F, North America is moving to the NW, South America is moving to the SSW, and Africa is held fixed. In this model the suture between North and South America is simplified and the South Georgia Rift is removed from the zones of weakness.
J	N trending dikes throughout the North American Eastern margin.	All of the continents are subject to an outward motion (radial about the triple junction) applied to their outer boundaries due to a likely slab-suction force.
K	Small stresses in the continents result in small N trending dikes along the Southeastern margin and NW trending dikes along the Southern Margin.	A negative vertical loading is applied to an area around the triple junction and a radial outward force modeled on expected topographic expression is emplaced around the vertical load.

zones between them and the stress applied to North America is once again northeast and an increase in NW trending dikes along the southeastern North American continent is observed.

In Fig. 3D–F a northeastern trending force is applied to North America, Africa is fixed and the stress on South America and the strength and the width of the plate boundary area is changed. In Fig. 3D Africa is fixed, North America is pushed to the northeast, and the plate boundary zones remain linear and one order of magnitude lower strength than the surrounding crust. This results in a concentration of stress along the east coast of North America, including northwest trending tensional stress along the southeastern coast, which would create northeast trending dikes or rifts, and decreasing and more varied tensional stress along the northeastern coast of North America. In Fig. 3E the applied force to North America remains northeast and an applied south-southeasterly force is applied to South America, the plate boundary remains the same. This results in an almost radial stress pattern around the three continents with northeastern trending tensional stresses along the southeast coast of North America changing to northwestern trending tensional stresses northward along the coast. It is inferred that the results would be dominantly northwest trending dikes or rifts in the southeastern United States and northeast trending dikes or rifts in the northeastern United States. Finally, in Fig. 3F the applied forces to North and South America remain the same, but an area of significantly weakened crust is placed along the northern edge of South America. This results in the east coast of North America being subject to a northwesterly tensional stress that would result in northeast trending dikes or rifts mostly concentrated along the northeast margin of the present day United States.

In Fig. 3G and H the effect of weak plate boundary zones is examined for the scenario of a fixed Africa, a northeast trending North America, and a south-southeast trending South America. While there is some small-scale variation along the rifts, strengthening (but not removing the changes in the grid shape) the South Georgia Rift or the other plate boundaries, has little effect on the overall stress field. In Fig. 3I the force applied to South America is changed from south-southeast to southeast, this dramatically changes the stress field in

North America including northwest trending stresses in the southeastern United States and northeast trending tensional stresses in the northeastern United States.

In Fig. 3J and K two other possible scenarios are examined. In Fig. 3J the results of a slab-rollback force applied to the edge of the model such that a radial tensional stress was applied to the margins of the supercontinent is examined. This results in a non-radial stress pattern with east–west stresses dominating along the coast of North America. In Fig. 3K the results of a plume model are examined. A large area of radial stress around the triple junction between North America, South America, and Africa, was applied similar to what might be expected from a plume dome. Interestingly, though this creates extremely large tensional stress at the triple junction, there is very little stress transmitted through the continents, though some east–west tensional stresses were located along the east coast of North America. This would result in north–south trending rifts or dikes.

4. Analysis

Given the results of the models, it appears that the most likely scenario for the creation of initial northeast trending rifts along the southeastern United States followed by northwest trending dikes in the southeast with northeast trending dikes and rifts in the northeastern United States is the following: Africa is fixed (or resistant to movement); North America begins to move to the northwest around 230 Ma creating northeast trending rifts in the southeastern United States (Fig. 3D); Around 200 Ma South America begins to move to the south-southwest, this creates enough of a stretch in the crust to cause decompression melting which leads to the injection of northwest trending dikes in the southeastern United States and northeastern trending rifts and dikes along the northeastern coast of the United States (Fig. 3E); Finally, as South America pulls away from North America an area of weakened crust decouples South America's influence on North America's stress field and results in a concentration of northwestern trending tensional stress along the east coast of North America, this results in the injection of northeast trending dikes along the east coast, but predominantly in the northeast (Fig. 3F). The generation of the melt volumes generally associated with volcanic margins via stretching of the continental crust has been shown to be viable and is influenced by lithospheric architecture, mantle temperature, and the rate of spreading (Van Wijk et al., 2001). Given these parameters it appears that continental thinning could produce the melt volumes seen in the CAMP province. Further, because the CAMP dike swarms consist of the three geochemically distinct sources, with probable depth constraints on their origin (e.g. McHone, 2000), it is more likely that decompression melting at various depths and of a heterogeneous mantle would result in the observed geochemical variabilities observed in the North American Central Atlantic Magmatic Province volcanics associated with the break-up of Pangaea.

This model explains the apparently rapidly changing stress field in southeastern North America (from NW tensional to NE tensional and back to NW tensional) and why the northeastern coast of North America has a different stress history (dominantly NW tensional). These finite element model results suggest that the initial northeastern motion of North America resulted in the opening of rifts along the southeast coast and not the northeast coast because of the orientation of the weakened plate boundary, which acted as a stress guide. Further the models suggest that the initiation of the movement of South America to the south-southeast not only acted as a catalyst for magmatism, but also rotated only the southern stresses in North America to northeast tensional. This suggests that the stress field generated by South America's motion was diminished with distance from the source and by the trend of the weakened plate boundary zones. Finally, it appears that continued magmatism and stretching in the Gulf of Mexico would have essentially detached South America from North America. This would have resulted in the stress field in North America changing back to what it was before South America began to move (hence beginning with NE trending normal faulting and ending with NE trending dikes with NW trending dikes in between while South America was exerting some influence). Because the exerted stress field along the southern portion of North America decreased dramatically with the complete separation of South America from North America, it appears that tensional stress in the crust is most amplified when there is resistance to the tension.

4.1. Other scenarios

It is also clear from the models that while plate boundary orientation may be important in affecting where stress fields change, the plate boundary zone does not have to be weak and areas of fixed crust or applied force that mimic the plate boundary zone shape have the same effect (Fig. 3G and H). The effect of the shape of the plate boundary zone is also seen in Fig. 3C where transforms were inserted between the rifts, this causes localized (directly adjacent to the margin —probably 10s10's of km) changes in the stress field, but does not significantly deviate the regional (eastern North America) stress field. Two non-craton driven scenarios were also examined, that of a radial slab-retreat tensional force applied to the supercontinent and a radial stress pattern caused by a plume. While the radial slab retreat did not create the stress fields preserved in the rocks, it is also clear that slab retreat can affect the stress field within the continent and it likely was similar in orientation to the modeled craton driven forces in models 3D–F during the break-up of Pangaea. The plume scenario has been given much credence as a cause of the break-up of Pangaea and the radial' 'radial' dike swarm in the southeastern United States (May, 1971; de Boer and Snider, 1979; Wilson, 1997; Ernst and Buchan, 1997; Courtillot et al., 1999; Marzoli et al., 1999; McHone, 2000; Dalziel et al., 2000; Janney and Castillo, 2001; Storey et al., 2001), however, model results suggest that the stress generated by a plume would not be transmitted very far in a continent and that the orientation of that stress is incompatible with the observed dikes and rifts. Certainly the presence of zones of weakness between the continents may have affected the ability of stresses to propagate into continent. However, the orientation of the stresses around a domal plume feature would not result in the multiple stress fields indicated by the overlapping dike swarms in Southeastern North America and there must have been some zone of thinning or weakness prior to rifting or doming for the continents to break as they did.

5. Conclusions

The break-up of Pangaea and the transition from amagmatic rifting to magmatic rifting was likely driven by the craton driven motion of North and South America. Finite element models indicate that the complicated stress regime recorded along North Americas east coast is best recreated by assuming a structural boundary between the continents and an initial northwestern motion of North America followed by a south-southwest motion of South America and the initiation of magmatic rifting. The final changes in the stress field appear to have been caused by the separation of North America and South America by an area of weakness. The onset of magmatic rifting is clearly associated with a change in the stress field in the southeastern United States (going from Northeast rifting to Northwest trending dikes) and therefore the initiation of the movement of South America. This suggests that magmatism is a result of lithospheric thinning rather than a particular upwelling, as an upwelling would have initiated motion in North America and South America at the same time, whereas a combination of slab retreat and mantle flow might allow for the 30 million year delay in onset of South America's movement. It is also clear that magmatism and weakened crust strongly affect the regional continental stress field as shown by the period of weakened crust north of South America and its effective decoupling of the South

American continent. Thus it is apparent that the complicated stress fields preserved in amagmatic and magmatic features can illustrate the importance of continental motion, boundary shape, and coupling when considering the break-up of Pangaea and the transition from amagmatic to magmatic rifting. The results also suggest that a plume is an unlikely source of the CAMP magmatic province and the break-up of Pangaea.

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