Crustal magnetism, tectonic inheritance, and continental rifting in the southeastern United States

E.H. Parker, Jr., *University of Georgia, Department of Geology, 210 Field St., Athens, Georgia, 30602, USA, ehparker@uga.edu*

ABSTRACT

The Brunswick magnetic anomaly (BMA) in southern Georgia is coincident with seismic reflectivity marking the deep crustal suture between Laurentia and a crustal block of Gondwanan affinity. The source of the BMA remains enigmatic because of its apparent relationship with both the Permo-Carboniferous Alleghanian orogeny (ca. 315–270 Ma) and the emplacement of the Central Atlantic Magmatic Province (ca. 200 Ma). In this paper, the BMA is modeled using relatively weak (<0.5 A/m) reversed-polarity remanent magnetization in lower crustal rocks (16–24 km depth) outboard of the Laurentian margin. The acquisition of this magnetic signature is consistent with transpression and strike-slip motion along the margin during the initial stage of Alleghanian convergence, which overlaps with the Kiaman Reversed Superchron (ca. 320–263 Ma). Simple magnetic models show that the onshore segment of the BMA can be explained as an effect of continental collision rather than voluminous magmatism along the suture zone. If Central Atlantic Magmatic Province intrusions were not focused along the suture zone, then evidence for tectonic wedging at the crust-mantle boundary associated with Alleghanian convergence may be preserved along the onshore segment of the BMA, rather than over-printed by Mesozoic magmatism.

INTRODUCTION

The Brunswick magnetic anomaly (BMA) coincides with deep seismic reflectivity marking the Late Paleozoic Suwannee-Wiggins suture zone (SWS) between Laurentia and a crustal block of Gondwanan origin (McBride et al., 2005). In southern Georgia, prominent, south-dipping reflectors on Consortium for Continental Reflection Profiling (COCORP) lines crossing the BMA define the lower crustal suture (Figs. 1 and 2) (McBride and Nelson, 1988). The reflectivity is interpreted as a mylonitic zone between Grenville-age North American basement and a Gondwanan crustal block accreted during the Permo-Carboniferous Alleghanian orogeny (Thomas, 2010). Drilling data across the Atlantic Coastal Plain show that the BMA is roughly coincident with the boundary between accreted peri-Gondwanan terranes and the Gondwanan Suwannee terrane (Chowns and Williams, 1983; Dallmeyer et al., 1987). However, rocks related to the Suwannee terrane are found north of the BMA (Tauvers and Muehlberger, 1987), suggesting the magnetic anomaly is more closely associated with the deep crustal suture than the upper-crustal terrane boundary.

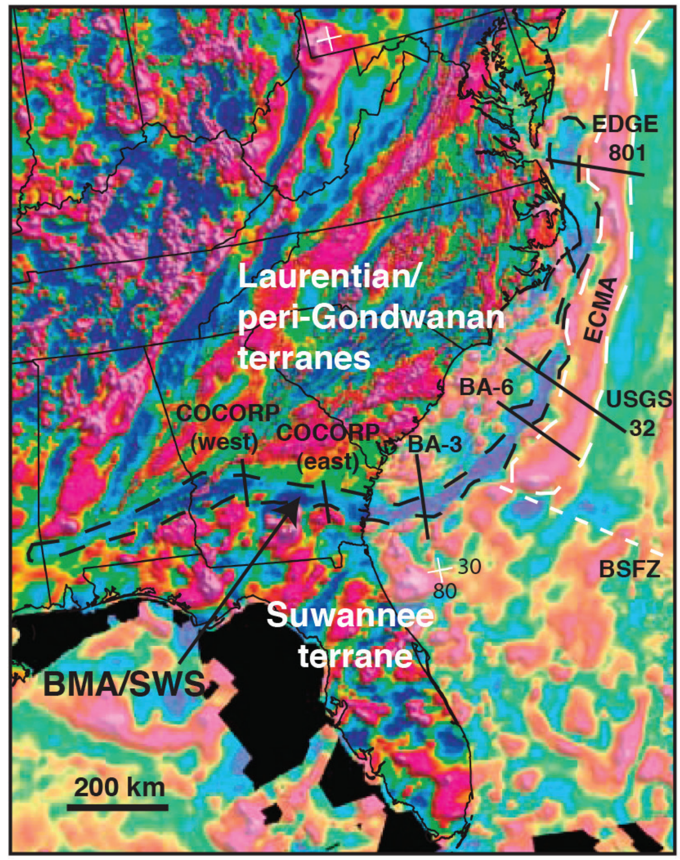

Figure 1. Aeromagnetic map (red = high; blue = low) of the eastern margin of North America showing the approximate locations of existing seismic profiles crossing the Brunswick magnetic anomaly (BMA) and East Coast magnetic anomaly (ECMA). Seismic profiles from EDGE 801, USGS 32, and BA-6 indicate relatively abrupt crustal thinning from ~35 km to ~15 km across the ECMA. Inboard of the ocean-continent transition, crustal thickness estimates range from 35 to 40 km on line BA-3 and 33–36 km for both Consortium for Continental Reflection Profiling (COCORP) transects. Strong dipping reflectivity marking the Suwannee-Wiggins suture (SWS) is evident on EDGE 801, BA-6, and both COCORP transects. The dipping reflectivity and change in crustal structure as the BMA diverges from the ECMA suggest the magnetic low is related to continental collision. BA—Brunswick anomaly; BSFZ—Blake Spur fracture zone. (Map modified from Tréhu et al., 1989; Austin et al., 1990; Sheridan et al., 1993; Lizarralde et al., 1994; North American Magnetic Anomaly Group, 2002; Bartholomew and Hatcher, 2010.)

Mesozoic rifting and emplacement of the Central Atlantic Magmatic Province (CAMP) overprint Alleghanian structure across the southeastern United States. The Triassic–Jurassic South Georgia basin cuts across the BMA (McBride, 1991), and rift basin formation was followed by extensive magmatism across the

GSA Today, v. 24, no. 4–5, doi: 10.1130/GSAT-G192A.1.

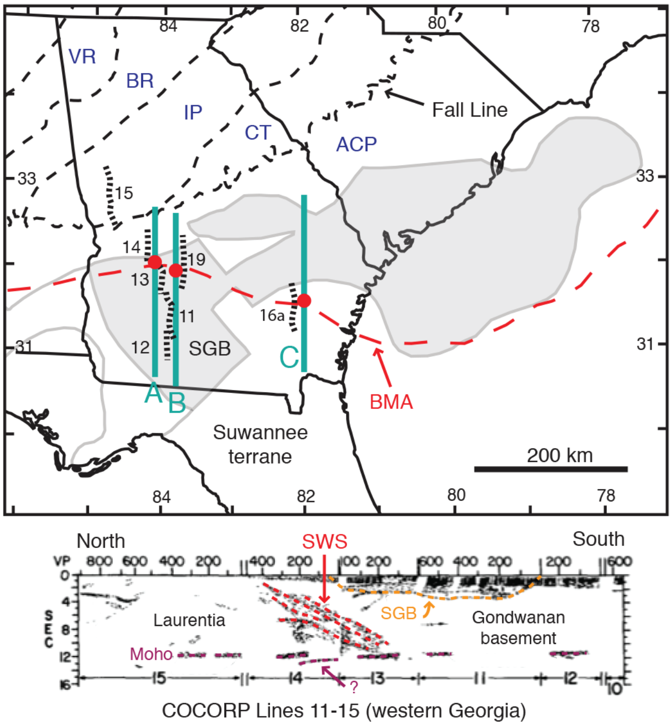

Figure 2. Top: Regional map showing the locations of magnetic profiles (A–C) with respect to selected Consortium for Continental Reflection Profiling (COCORP) lines. The red circle on each profile marks the location of the magnetic minimum within the Brunswick magnetic anomaly (BMA) (dashed line). Dipping seismic reflectors are evident on lines 13, 14, 16a, and 19. The Fall Line marks the onlap of Atlantic Coastal Plain (ACP) sediments onto the exposed terranes of the southern Appalachians. The shaded area defines the inferred extent of mafic magmatism across the South Georgia basin (SGB) and offshore South Carolina. CT—Carolina terrane; IP—Inner Piedmont; BR—Blue Ridge; VR—Valley and Ridge. (Map modified from Dallmeyer, 1988; McBride et al., 1989; Lizarralde et al., 1994) Bottom: Seismic section for COCORP lines 11–15 showing strong dipping reflectivity coincident with the BMA (after McBride and Nelson, 1988).

southeastern United States prior to Atlantic seafloor spreading (McBride et al., 1989). Approximately 1–2 km of Atlantic Coastal Plain sediments now cover the basin and suture zone, and it is unknown whether the origin of the BMA is ultimately related to continental collision or rift-related mafic intrusions concentrated along the suture (Fig. 2). Lower crustal seismic reflectors coincident with the magnetic low in southern Georgia (McBride and Nelson, 1988), offshore South Carolina (Austin et al., 1990), and offshore Virginia (Sheridan et al., 1993) suggest the source of the anomaly is related to continental collision (Fig. 1). On the other hand, the BMA appears to merge with the East Coast magnetic anomaly (ECMA), a prominent magnetic high interpreted to result from rift-related mafic underplating and magmatism along the ocean-continent transition (Fig. 1) (Holbrook et al., 1994). Discontinuous magnetic highs south of the BMA, extension across the South Georgia basin, and flood basalts/sills within rift basin strata suggest the BMA may represent a continuation of the ECMA (McBride and Nelson, 1988; McBride et al., 1989). Distinguishing between these alternatives is important for understanding the role of inherited structure during continental rifting and emplacement of CAMP intrusions in the southeastern United States.

In this paper, the BMA is modeled using reversed-polarity remanent magnetization in lower crustal rocks (16–24 km depth) along the SWS and outboard of the Laurentian margin. Strong remanent magnetization (>3.0 A/m) of exhumed granulites in other collision zones (e.g., Australia, Adirondacks, Sweden) suggests that remanence may be the source of long-wavelength magnetic anomalies in the deep crust (McEnroe et al., 2004, and references therein). The reversed-polarity remanent magnetization of Gondwanan basement blocks may have been acquired during the Kiaman Reversed Superchron (ca. 320–263 Ma), the longest reversed polarity event in Earth's history (Garcia et al., 2006). New magnetic models assuming relatively weak remanence (<0.5 A/m) provide a simple explanation for the long-wavelength character of the BMA and the coincidence with seismic reflectors along its entire length.

ALLEGHANIAN OROGENY

The Permo-Carboniferous Alleghanian orogeny in the southern Appalachians involved transpression and dextral strike-slip motion along the North American margin followed by terrane transport over Grenville-age continental crust along the Blue Ridge–Piedmont megathrust (Hatcher, 2010). Sub-horizontal reflections on COCORP profiles crossing the orogenic belt suggest that a major detachment underlies the Blue Ridge and Inner Piedmont and possibly extends eastward beneath the Atlantic Coastal Plain (Fig. 2) (Cook and Vasudevan, 2006). In southern Georgia, the detachment is interpreted to merge with seismic reflectors marking the Suwannee-Wiggins suture (McBride et al., 2005; Steltenpohl et al., 2008), but it may also cross over the suture and merge with a proposed Alleghanian suture marked by the Gulf Coast–East Coast magnetic anomalies (Hall, 1990). Alternatively, the detachment may terminate near the Central Piedmont suture zone, and the peri-Gondwanan Carolina terrane may underlie much of the Atlantic Coastal Plain in the southeastern United States (Fig. 2) (Hibbard et al., 2010).

In southern Georgia, the deep crustal suture is interpreted to separate Grenville-age Laurentian crust from Gondwanan basement (McBride et al., 2005). The collision of the crustal block underlying the Suwannee terrane is generally considered a Permo-Carboniferous event, though accretion may have occurred during the Late Devonian (Hibbard et al., 2010).

MESOZOIC CONTINENTAL RIFTING

The Atlantic and Gulf of Mexico rifts developed outboard of the Suwannee-Wiggins suture during the Mesozoic, leaving Gondwanan lower crust and the Suwannee terrane attached to North America. Alleghanian faults and post-orogenic collapse structures were reactivated during Mesozoic extension (Steltenpohl et al., 2013), and the Suwannee terrane was possibly down-dropped from higher crustal levels (Steltenpohl et al., 2008). The Triassic-Jurassic South Georgia basin formed along the boundary between accreted peri-Gondwanan terranes and the Suwannee terrane (McBride et al., 1989; McBride, 1991). Beneath the Coastal Plain, the basin separates the Suwannee terrane from the buried Brunswick-Charleston terrane for most of the length of the BMA (Hatcher, 2010).

Drilling data show that an extensive network of mafic dikes and sills is present beneath the Atlantic Coastal Plain (Chowns and Williams, 1983). Geochronological constraints indicate that the magmatism is closely related to the emplacement of the Central Atlantic Magmatic Province at ca. 200 Ma (Heatherington and Mueller, 2003). The J-reflector on regional seismic reflection profiles across the basin and offshore South Carolina was initially interpreted as an extensive subsurface basalt flow or diabase sill beneath the Coastal Plain (shaded area, Fig. 2) (McBride et al., 1989). However, Heffner et al. (2012) recently interpreted the J-reflector as simply the base of the Coastal Plain based on re-analysis of well data and seismic reflection profiles. In general, the relationship between dike and sill complexes emplaced within the South Georgia rift strata and lower crustal intrusion and underplating along the suture remains uncertain.

CRUSTAL STRUCTURE ACROSS THE BMA AND ECMA

In the eastern United States, the transition from largely unmodified crust beneath the Coastal Plain to highly stretched, transitional crust across the continental margin occurs over a distance of ~75 km (Lizarralde and Holbrook, 1997). On EDGE line 801 (Fig. 1), crustal thickness decreases from 35 to 15 km across the ECMA (Sheridan et al., 1993). On lines USGS 32 and BA-6 across the Carolina trough (Fig. 1), elevated velocities (6.5–7.5 km/s) indicative of mafic underplating are largely restricted to thinned crust along the ECMA, while 35-km-thick continental crust inboard of the ECMA with Vp of 6.4–6.8 km/s appears unmodified by rift magmatism (Tréhu et al., 1989; Holbrook et al., 1994). In general, crustal thinning and underplating appear to be highly focused along the ocean-continent transition (Lizarralde and Holbrook, 1997).

As the BMA diverges from the ECMA, evidence for crustal thinning and magmatic underplating becomes limited. A velocity model for Line BA-3 (Fig. 1), which crosses the BMA offshore, indicates that crustal thickness is ~35–40 km across the entire profile (Lizarralde et al., 1994). Middle and lower crustal velocities are 6.4–6.75 km/s, and there is a thin, poorly resolved 7.2 km/s layer at the base of the crust. On the eastern and western COCORP transects crossing the onshore segment of the BMA (Figs. 1 and 2), discontinuous Moho reflectors indicate uniform crustal thickness of 33–36 km with little relief at the crust-mantle boundary (McBride and Nelson, 1988). Truncation of dipping reflectors marking the SWS suggests that the Moho formed as a result of Mesozoic extension (McBride and Nelson, 1988), though this interpretation is not unique.

PREVIOUS MAGNETIC MODELS

McBride and Nelson (1988) modeled the source of the onshore segment of the BMA as a tabular mafic intrusive complex outboard of the suture zone beneath the South Georgia basin. They make two important assumptions: (1) induced magnetization of high susceptibility mafic rocks dominates the magnetic signature; and (2) the discontinuous magnetic highs that flank the south side of the BMA are paired with the continuous magnetic low (Fig. 1). In their model, the high-low pair is generated by a south-dipping block outboard of the suture. As the trend of the BMA changes from E-W to N-S off the Georgia coast, the disappearance of the magnetic low is related to the azimuthal

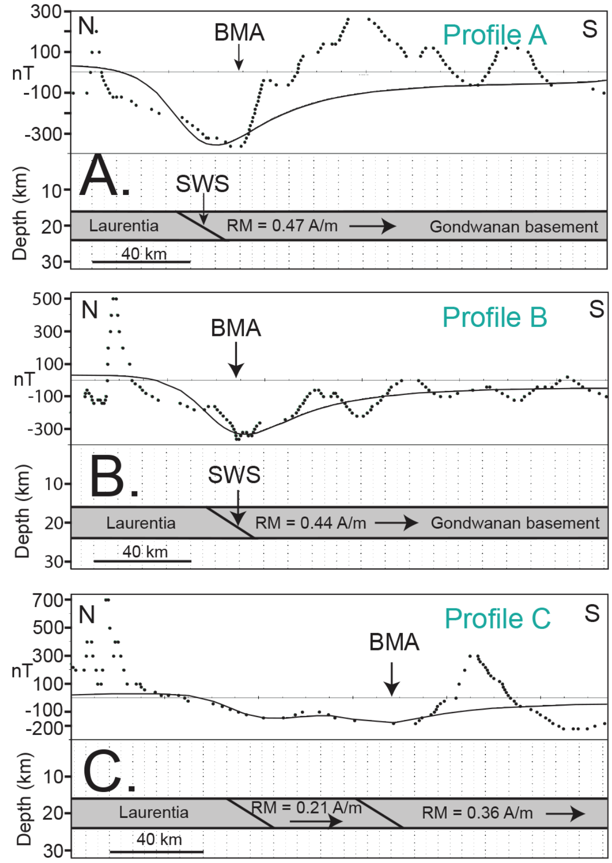

Figure 3. Observed total magnetic intensity (dots) and magnetic models (solid line) for profiles A–C. Magnetic profiles were obtained from Zietz et al. (1980) and then shifted to the datum of Daniels (2001). The present field is modeled using a magnetic declination of 0°, inclination of −63°, and total field intensity of 52,500 nT, based on 1977 values when the surveys were flown. The continuous magnetic low is modeled using remanent magnetization oriented toward the south (arrow). All lower crustal blocks are modeled with a susceptibility of $k = 0.01$ SI. The position of the Suwannee-Wiggins suture (SWS) is based on Consortium for Continental Reflection Profiling (COCORP) seismic reflectivity. (A) Model for profile A showing general agreement with the magnetic low. The flanking magnetic high to the south is interpreted as a separate anomaly. (B) Model for profile B showing close agreement with the long-wavelength signature of the magnetic low. (C) Model for profile C using two crustal blocks with slightly different remanent magnetizations (RM). BMA— Brunswick magnetic anomaly.

dependence of the anomaly. The major implication of this model is that the ECMA and BMA have a common source related to mafic magmatism.

REMANENT MAGNETIZATION OF LOWER CRUSTAL ROCKS

Remanent magnetization of lower crustal granulites is a possible source of long-wavelength magnetic anomalies originating in the deep crust (McEnroe et al., 2004), and the common assumption of induced magnetization of magnetite-bearing rocks for analysis of crustal-scale anomalies may not be completely justified (McEnroe et al., 2001). Rock magnetism and petrologic studies show that magnetite-bearing rocks can retain a strong remanent component over long periods of geologic time (Kelso et al., 1993; McEnroe and Brown, 2000). In the Arunta Block of Australia, felsic-to-mafic granulites possess a median remanent magnetization of 4.1 A/m, compared with induced magnetization of <1.0 A/m (Kelso et al. 1993).

The recognition of strong magnetism associated with the hematite-ilmenite solid solution series is also an important consideration in crustal magnetism studies (Robinson et al., 2002). Magnetization of hematite-ilmenite exsolution microstructures is thermally stable (demagnetization occurs between 530 and 650 °C) and resistant to alternating field demagnetization (McEnroe et al., 2004). These properties suggest that magnetite (Curie temperature = 580 °C) is not the only important magnetic phase at lower crustal depths (McEnroe et al., 2004). Exhumed granulites in Sweden containing hematite-ilmenite exsolution lamellae and minor magnetite are characterized by strong remanent magnetization of ~9.2 A/m (McEnroe et al., 2001).

NEW MAGNETIC MODELS

The magnetic models presented here are based on thin-skinned tectonic models of the southern Appalachians (Cook and Vasudevan, 2006) and the interpretation that deep crustal reflectivity marks the suture between Grenville-age Laurentian basement and Gondwanan lower crust (McBride et al., 2005). The BMA is modeled as the juxtaposition of lower crustal blocks with differing magnetic character (e.g., Daniels et al., 1983). Gondwanan crustal blocks may have acquired a localized remanent magnetic signature during Alleghanian transpression focused in deep crustal levels outboard of the Laurentian margin. Inboard of the suture, the thin-skinned nature of the orogen suggests that Grenville lower crust behaved as a stable block and escaped pervasive lower crustal metamorphism. The presence of Alleghanian granitoids north of the suture (Heatherington et al., 2010) is attributed to westward over-thrusting of rocks onto the Laurentian margin during the final stages of continental collision (e.g., Hatcher, 2010), rather than heating and metamorphism of Grenville lower crust by ductile thickening.

The primary goal of this study is to model the continuous long-wavelength magnetic low. Although the anomaly is often considered a high-low pair, there is no direct evidence indicating that the onshore flanking highs are related to the long-wavelength magnetic low. Because the overall magnetic character of the Suwannee terrane can be characterized by random magnetic highs (Fig. 1), these discontinuous anomalies are interpreted as separate features. No attempt has been made to model the short-wavelength features because of the variability of the flanking magnetic signature along strike.

In the model for profile A (Figs. 2 and 3A), Laurentian and Gondwanan lower crust possess the same magnetic susceptibility ($k = 0.01$) typical of granulite-facies assemblages (Kelso et al., 1993), but the lower crust outboard of the Laurentian margin is modeled with relatively weak remanence of 0.47 A/m oriented toward the south (opposite the present magnetic field). The assumed horizontal inclination of the remanent vector is supported by paleomagnetic reconstructions that show the southern margin of North America at equatorial latitudes during the formation of Pangea (van der Voo and Torsvik, 2001). The position of the SWS is based on seismic reflectivity on COCORP lines 13 and 14 (Fig. 2). In the model, the lower crustal blocks extend from 16 to 24 km depth. Assuming a relatively low geothermal gradient of 22 °C/km (e.g., Arthur, 1982), the depth to the 550 °C isotherm is ~25 km. Above this depth, remanent magnetization of rocks containing magnetite and/or hematite-ilmenite will be stable (McEnroe et al., 2004). The slightly different magnetic signature between the two blocks produces the prominent magnetic low coincident with suture zone reflectivity on the western COCORP transect. The magnetic high is interpreted as a separate feature of unknown origin.

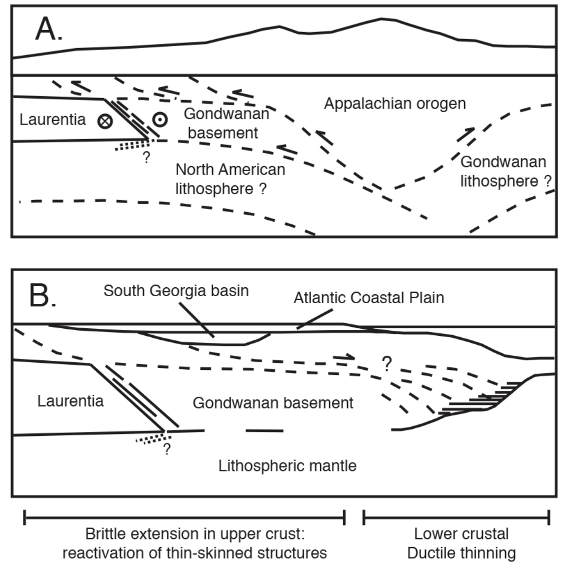

Figure 4. Conceptual tectonic model for the southeastern United States. (A) Strike-slip motion along the deep crustal suture followed by the initiation of Alleghanian thin-skinned thrusting on the eastern flank of accreted Gondwanan basement. (B) Simple shear extension along the Atlantic margin controlled by reactivation of thin-skinned structures (after Lister et al., 1991). Localized ductile thinning along the margin suggests that complex structure (tectonic wedging) may be preserved along the Suwannee-Wiggins suture zone.

The contrast between profiles A and B is intended to show that the flanking magnetic highs are localized, while the long-wavelength magnetic low is a continuous anomaly. In Figure 3B, the Gondwanan basement is modeled with a remanence of 0.44 A/m. Again, the position of the suture zone is based on seismic reflectivity on COCORP lines 13, 14, and 19 (Fig. 2). The long-wavelength magnetic low (~300 nT) generated by the two blocks closely matches the observed profile.

The BMA along profile C in southeastern Georgia is relatively broad (80 km wide) and lower in amplitude (~200 nT) compared with profiles A and B (Fig. 3C). A slight contrast of 0.15 A/m between two blocks outboard of the margin accounts for the broad anomaly on this profile. In the model, the edge of the Laurentian margin is roughly coincident with dipping reflectivity imaged on line 16a of the eastern COCORP transect (Fig. 2).

DISCUSSION

The long-wavelength aeromagnetic low associated with the BMA can be modeled using contrasts in remanent magnetization between Laurentian basement and Gondwanan crustal blocks underlying the Suwannee terrane. The magnetic models are consistent with tectonic models for the southern Appalachians involving transpression along the continental margin followed by foreland-directed thrusting of terranes over Grenville basement along a major detachment fault (Fig. 4A). The presence of African rocks north of the Brunswick magnetic anomaly is interpreted to result from thin-skinned thrusting of the Suwannee terrane across the trace of the deep crustal suture in the final stage of the Alleghanian orogeny (Fig. 4A) (e.g., Hall, 1990).

The models require that Mesozoic extension and magmatism did not overprint the magnetic signature inherited from convergence. The development of the South Georgia rift basin in the upper crust without extensive lower crustal modification along the suture is consistent with simple shear extension along the Atlantic margin (Fig. 4B) (Lister et al., 1991). In this model, focused magmatism is laterally offset toward the main Atlantic rift, and basin formation in the upper crust is accommodated by extension above a mid-crustal detachment. Lower crustal stretching is interpreted to be minimal.

If the suture zone beneath the South Georgia basin was not completely overprinted by extension and magmatism, then structure related to Alleghanian transpression and collision may be preserved along the inboard section of the suture. The truncation of crustal-scale dipping reflectors by relatively flat Moho reflectors on COCORP line 13 may be indicative of under-thrusting of crustal material beneath the Laurentian margin during collision (Figs. 2 and 4). Though speculative, the sub-Moho reflector on Line 14 (Fig. 2) may be related to tectonic wedging or transpression along the suture. This feature appears similar to Moho structure imaged on high-resolution seismic reflection profiles from the ALCUDIA transect in Spain (Martínez Poyatos et al., 2012). The preservation of convergent structures would provide insight into the nature of continental collision during the accretion of Gondwanan basement.

CONCLUSIONS

The new magnetic models presented here suggest that the source of the BMA resides in lower crustal metamorphic rocks outboard of the Laurentian margin. The acquisition of reversed-polarity remanent magnetization along the suture and within Gondwanan lower crustal blocks is consistent with transpression along the North American margin during the Kiaman Superchron. The preservation of this signature at depths of 16–24 km is consistent with simple shear extension involving limited lower crustal stretching and a lack of focused magmatism beneath the South Georgia basin.

The main implications of the magnetic modeling are as follows: (1) relatively weak reversed-polarity remanence (0.21–0.47 A/m) in lower crustal rocks outboard of the Laurentian margin provides a simple explanation for the BMA; (2) CAMP intrusions in the lower crust were not highly concentrated along the Suwannee-Wiggins suture zone; and (3) evidence for Alleghanian convergent structure at the crust-mantle boundary or within the mantle lithosphere may be preserved along the suture, rather than overprinted by Mesozoic extension.

The analysis provides an alternative to rift-related models assuming induced magnetization of mafic intrusions concentrated along the Suwannee-Wiggins suture zone. Additional geophysical constraints on crustal structure from the EarthScope Southeastern Suture of the Appalachian Margin Experiment (SESAME) broadband array (Fischer et al., 2012) and the Suwannee Suture and Georgia Rift basin (SUGAR) active-source seismic experiment (Shillington et al., 2013) targeting the suture and CAMP will help differentiate between tectonic models. Integration of seismic data with new perspectives on crustal magnetism will provide a better understanding of terrane accretion, rifting processes, and passive margin formation in the southeastern United States.

ACKNOWLEDGMENTS

I would like to thank Rob Hawman for his encouragement, advice, and assistance with magnetic modeling. Reviews by Paul Mueller and an anonymous reviewer greatly improved the manuscript. Alberto Patiño-Douce, Mike Roden, Alex Brown, and Jacqui Maleski also provided helpful comments on an earlier version of this manuscript. This work was supported by U.S. National Science Foundation Grant EAR-0844154 and the University of Georgia Department of Geology.

REFERENCES CITED

Arthur, M.A., 1982, Thermal history of the Georges Bank basin, *in* Scholle, P.A., and Wenkham, C.R., eds., Geological studies of the COST Nos. G-1 and G-2 wells, United States North Atlantic outer continental shelf: U.S. Geological Survey Circular 861, p. 143–152.

Austin, J.A., Jr., Stoffa, P.L., Phillips, J.D., Oh, J., Sawyer, D.S., Purdy, G.M., Reiter, E., and Makris, J., 1990, Crustal structure of the Southeast Georgia embayment–Carolina trough: Preliminary results of a composite seismic image of a continental suture(?) and a volcanic passive margin: Geology, v. 18, p. 1023–1027, doi: 10.1130/0091-7613(1990)018<1023:CSOTSG>2.3.CO;2.

Bartholomew, M.J., and Hatcher, R.D., Jr., 2010, The Grenville orogenic cycle of southern Laurentia: Unraveling sutures, rifts, and shear zones as potential piercing points for Amazonia: Journal of South American Earth Sciences, v. 29, p. 4–20, doi: 10.1016/j.jsames.2009.08.007.

Chowns, T.M., and Williams, C.T., 1983, Pre-Cretaceous rocks beneath the Georgia Coastal Plain—Regional implications, *in* Gohn, G.S., ed., Studies related to the Charleston, South Carolina, earthquake of 1886—Tectonics and seismicity: U.S. Geological Survey Professional Paper 1313-L, p. L1–L42.

Cook, F.A., and Vasudevan, K., 2006, Reprocessing and enhanced interpretation of the initial COCORP Southern Appalachian traverse: Tectonophysics, v. 420, p. 161–174, doi: 10.1016/j.tecto.2006.01.022.

Dallmeyer, R.D., 1988, Late Paleozoic tectonothermal evolution of the western Piedmont and eastern Blue Ridge, Georgia: Controls on the chronology of terrane accretion and transport in the southern Appalachian orogen: GSA Bulletin, v. 100, p. 702–713, doi: 10.1130/0016-7606(1988)100<0702:LPTEOT>2.3.CO;2.

Dallmeyer, R.D., Caen-Vachette, M., and Villeneuve, M., 1987, Emplacement age of post-tectonic granites in southern Guinea (West Africa) and the peninsular Florida subsurface: Implications for origins of southern Appalachian exotic terranes: GSA Bulletin, v. 99, p. 87–93, doi: 10.1130/0016-7606(1987)99<87:EAOPGI>2.0.CO;2.

Daniels, D.L., 2001, Georgia aeromagnetic and gravity maps and data: A website for distribution of data: U.S. Geological Survey Open-File Report 01-0106, http://pubs.usgs.gov/of/2001/of01-106/ (last accessed December 2012).

Daniels, D.L., Zietz, I., and Popenoe, P., 1983, Distribution of subsurface lower Mesozoic rocks in the southeastern United States as interpreted from regional aeromagnetic and gravity maps, *in* Gohn, G.S., ed., Studies related to the Charleston, South Carolina, earthquake of 1886—Tectonics and seismicity: U.S. Geological Survey Professional Paper 1313-K, p. K1–K24.

Fischer, K.M., MacDougall, J.G., Hawman, R.B., Parker, E.H., and Wagner, L.S., 2012, The lithosphere of the Appalachian orogen and Atlantic passive margin: San Francisco, Calif., AGU 2012 Fall Meeting, 3–7 Dec. 2012, abstract T43G-03.

Garcia, A.S., Thomas, D.N., Liss, D., and Shaw, J., 2006, Low geomagnetic field intensity during the Kiaman superchron: Thellier and microwave results from the Great Whin Sill intrusive complex, northern United Kingdom: Geophysical Research Letters, v. 33, L16308, doi: 10.1029/2006GL026729.

Hall, D.J., 1990, Gulf Coast–East Coast magnetic anomaly 1: Root of the main crustal décollement for the Appalachian-Ouachita orogen: Geology, v. 18, p. 862–865, doi: 10.1130/0091-7613(1990)018<0862:GCECMA>2.3.CO;2.

Hatcher, R.D., Jr., 2010, The Appalachian orogen: A brief summary, *in* Tollo, R.P., Bartholomew, M.J., Hibbard, J.P., and Karabinos, P.M., eds., From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region: Geological Society of America Memoir 206, p. 1–19, doi: 10.1130/2010.1206(01).

Heatherington, A.L., and Mueller, P.A., 2003, Mesozoic igneous activity in the Suwannee terrane, southeastern USA: Petrogenesis and Gondwanan affinities: Gondwana Research, v. 6, p. 296–311, doi: 10.1016/S1342-937X(05)70979-5.

Heatherington, A.L., Mueller, P.A., and Wooden, J.L., 2010, Alleghanian plutonism in the Suwannee terrane, USA: Implications for late Paleozoic tectonic models, *in* Tollo, R.P., Bartholomew, M.J., Hibbard, J.P., and Karabinos, P.M., eds., From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region: Geological Society of America Memoir 206, p. 607–620, doi: 10.1130/2010.1206(24).

Heffner, D.M., Knapp, J.H., Akintunde, O.M., and Knapp, C.C., 2012, Preserved extent of Jurassic flood basalt in the South Georgia Rift: A new interpretation of the J horizon: Geology, v. 40, p. 167–170, doi: 10.1130/G32638.1.

Hibbard, J.P., van Staal, C.R., and Rankin, D.W., 2010, Comparative analysis of the geological evolution of the northern and southern Appalachian orogen: Late Ordovician–Permian, *in* Tollo, R.P., Bartholomew, M.J., Hibbard, J.P., and Karabinos, P.M., eds., From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region: Geological Society of America Memoir 206, p. 51–69, doi: 10.1130/2010.1206(03).

Holbrook, W.S., Reiter, E.C., Purdy, G.M., Sawyer, D., Stoffa, P.L., Austin, J.A., Jr., Oh, J., and Makris, J., 1994, Deep structure of the U.S. Atlantic continental margin, offshore South Carolina, from coincident ocean bottom and multichannel seismic data: Journal of Geophysical Research, v. 99, p. 9155–9178, doi: 10.1029/93JB01821.

Kelso, P.R., Banerjee, S.K., and Teyssier, C., 1993, Rock magnetic properties of the Arunta block, central Australia, and their implication for the interpretation of long-wavelength magnetic anomalies: Journal of Geophysical Research, v. 98, p. 15,987–15,999, doi: 10.1029/93JB01158.

Lister, G.S., Etheridge, M.A., and Symonds, P.A., 1991, Detachment models for the formation of passive continental margins: Tectonics, v. 10, p. 1038–1064, doi: 10.1029/90TC01007.

Lizarralde, D., and Holbrook, W.S., 1997, U.S. mid-Atlantic margin structure and early thermal evolution: Journal of Geophysical Research, v. 102, p. 22,855–22,875, doi: 10.1029/96JB03805.

Lizarralde, D., Holbrook, W.S., and Oh, J., 1994, Crustal structure across the Brunswick magnetic anomaly, offshore Georgia, from coincident ocean bottom and multi-channel seismic data: Journal of Geophysical Research, v. 99, p. 21,741–21,757, doi: 10.1029/94JB01550.

Martínez Poyatos, D., Carbonell, R., Palomeras, I., Simancas, J.F., Ayarza, P., Martí, D., Azor, A., Jabaloy, A., González Cuadra, P., Tejero, R., Martín Parra, L.M., Matas, J., González Lodeiro, F., Pérez-Estaún, A., García Lobón, J.L., and Mansilla, L., 2012, Imaging the crustal structure of the Central Iberian Zone (Variscan Belt): The ALCUDIA deep seismic reflection transect: Tectonics, v. 31, TC3017, doi: 10.1029/2011TC002995.

McBride, J.H., 1991, Constraints on the structure and tectonic development of the early Mesozoic south Georgia rift, southeastern United States; seismic reflection data processing and interpretation: Tectonics, v. 10, p. 1065–1083, doi: 10.1029/90TC02682.

McBride, J.H., and Nelson, K.D., 1988, Integration of COCORP deep reflection and magnetic anomaly analysis in the southeastern United States: Implications for origin of the Brunswick and East Coast magnetic anomalies: GSA Bulletin, v. 100, p. 436–445, doi: 10.1130/0016-7606(1988)100<0436:IOCDRA>2.3.CO;2.

McBride, J.H., Nelson, K.D., and Brown, L.D., 1989, Evidence and implications of an extensive early Mesozoic rift basin and basalt/diabase sequence beneath the southeast Coastal Plain: GSA Bulletin, v. 101, p. 512–520, doi: 10.1130/0016-7606(1989)101<0512:EAIOAE>2.3.CO;2.

McBride, J.H., Hatcher, R.D., Jr., Stephenson, W.J., and Hooper, R.J., 2005, Integrating seismic reflection and geological data and interpretations across an internal basement massif: The southern Appalachian Pine Mountain window, USA: GSA Bulletin, v. 117, p. 669–686, doi: 10.1130/B25313.1.

McEnroe, S.A., and Brown, L.L., 2000, A closer look at remanence-dominated aeromagnetic anomalies: Rock magnetic properties and magnetic mineralogy of the Russell Belt microcline-sillimanite gneiss, northwest Adirondack Mountains, New York: Journal of Geophysical Research, v. 105, p. 16,437–16,456, doi: 10.1029/2000JB900051.

McEnroe, S.A., Harrison, R.J., Robinson, P., Golla, U., and Jercinovic, M.J., 2001, Effect of fine-scale microstructures in titanohematite on the acquisition and stability of natural remanent magnetization in granulite facies metamorphic rocks, southwest Sweden: Implications for crustal magnetism: Journal of Geophysical Research, v. 106, p. 30,523–30,546, doi: 10.1029/2001JB000180.

McEnroe, S.A., Langenhorst, F., Robinson, P., Bromiley, G.D., and Shaw, C.S.J., 2004, What is magnetic in the lower crust?: Earth and Planetary Science Letters, v. 226, p. 175–192, doi: 10.1016/j.epsl.2004.07.020.

North American Magnetic Anomaly Group (NAMAG), 2002, Magnetic anomaly map of North America: U.S. Geological Survey, scale 1:10,000,000, 1 sheet.

Robinson, P., Harrison, R.J., McEnroe, S.A., and Hargraves, R.B., 2002, Lamellar magnetism in the haematite-ilmenite series as an explanation for strong remanent magnetization: Nature, v. 418, p. 517–520, doi: 10.1038/nature00942.

Sheridan, R.E., Musser, D.L., Glover, L., III, Talwani, M., Ewing, J.I., Holbrook, W.S., Purdy, G.M., Hawman, R., and Smithson, S., 1993, Deep seismic reflection data of EDGE U.S. mid-Atlantic continental-margin experiment: Implications for Appalachian sutures and Mesozoic rifting and magmatic underplating: Geology, v. 21, p. 563–567, doi: 10.1130/0091-7613(1993)021<0563:DSRDOE>2.3.CO;2.

Shillington, D.J., Lizarralde, D., and Harder, S., 2013, The SUGAR experiment: An upcoming active-source seismic experiment of the South Georgia Basin to examine the relationship between extension, magmatism, and pre-existing structures: EarthScope National Meeting, Raleigh, NC, 13–15 May 2013.

Steltenpohl, M.G., Mueller, P.M., Heatherington, A.L., Hanley, T.B., and Wooden, J.L., 2008, Gondwanan/peri-Gondwanan origin for the Uchee terrane, Alabama and Georgia: Carolina zone or Suwannee terrane(?) and its suture with Grenvillian basement of the Pine Mountain window: Geosphere, v. 4, p. 131–144, doi: 10.1130/GES00079.1.

Steltenpohl, M.G., Schwartz, J.J., and Miller, B.V., 2013, Late to post-Appalachian strain partitioning and extension in the Blue Ridge of Alabama and Georgia: Geosphere, v. 9, p. 647–666, doi: 10.1130/GES00738.1.

Tauvers, P.R., and Muehlberger, W.R., 1987, Is the Brunswick magnetic anomaly really the Alleghanian suture?: Tectonics, v. 6, p. 331–342, doi: 10.1029/TC006i003p00331.

Thomas, W.A., 2010, Interactions between the southern Appalachian-Ouachita orogenic belt and basement faults in the orogenic footwall and foreland, *in* Tollo, R.P., Bartholomew, M.J., Hibbard, J.P., and Karabinos, P.M., eds., From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region: Geological Society of America Memoir 206, p. 897–916, doi: 10.1130/2010.1206(34).

Tréhu, A.M., Ballard, A., Dorman, L.M., Gettrust, J.F., Klitgord, K.D., and Schreiner, A., 1989, Structure of the lower crust beneath the Carolina trough, U.S. Atlantic continental margin: Journal of Geophysical Research, v. 94, p. 10,585–10,600, doi: 10.1029/JB094iB08p10585.

van der Voo, R., and Torsvik, T.H., 2001, Evidence for Late Paleozoic and Mesozoic non-dipole fields provides an explanation for the Pangea reconstruction problems: Earth and Planetary Science Letters, v. 187, p. 71–81, doi: 10.1016/S0012-821X(01)00285-0.

Zietz, I., Riggle, F.E., and Gilbert, F.P., 1980, Aeromagnetic map of Georgia: U.S. Geological Survey Geophysical Investigations Map GP-940, scale 1:500,000, 1 sheet.

Manuscript received 4 June 2013; accepted 5 Sept. 2013. ▲