Grenville basement structure associated with the Eastern Tennessee seismic zone, southeastern USA

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ABSTRACT

The Eastern Tennessee seismic zone extends more than 300 km from as far north as southeastern Kentucky southward into Alabama, southeastern United States. We propose that a large-scale shear zone, which originated as a continental transform fault during the Grenville orogeny and assembly of supercontinent Rodinia, constitutes the framework for earthquake activity in the Eastern Tennessee seismic zone. This new seismotectonic model is based on a diverse set of geophysical and geological observations, including paleomagnetic and isotopic constraints on the growth of southeastern Laurentia during the Grenville orogeny.

INTRODUCTION

Concentrated zones of seismic activity far from plate boundaries can provide valuable information about ancient tectonic events. The general interpretation is that intraplate earthquakes are associated with passive rifted margins, intracratonic rifts, and the edges of Archean cratons (Johnston and Kanter, 1990; Mooney et al., 2012). An exception is the Eastern Tennessee seismic zone (ETSZ), an elongate northeast-trending band of seismicity stretching from as far north as southeastern Kentucky (Carpenter et al., 2014) southward into northern Alabama, southeastern United States (Fig. 1). Earthquakes in the ETSZ occur below the décollement that separates Paleozoic sedimentary rocks of the Appalachian thrust belt from the underlying Grenville basement. Tectonic reconstructions indicate that the basement within the seismic zone was not rifted during the openings of either the Iapetus or Atlantic Oceans (Thomas, 2006). Association of the seismic zone with ancient basement structure is suggested by a remarkable correlation of ETSZ seismicity with potential-field anomalies; the most concentrated seismic activity is bounded on the northwest by the prominent New York–Alabama magnetic lineament and associated Bouguer gravity lows (Fig. 2). This 1600-km-long magnetic lineament is interpreted to represent a basement structure beneath sedimentary strata of the Appalachian foreland basin and thin-skinned thrust belt (King and Zietz, 1978).

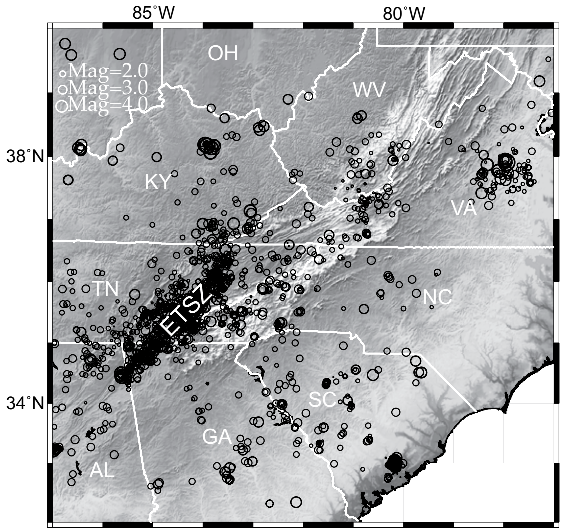

Figure 1. Location of Eastern Tennessee seismic zone (ETSZ), southeastern United States. Epicenters (circles) are shown for the time period A.D. 1984 to present. Abbreviations: Mag.—magnitude; AL—Alabama; GA—Georgia; KY—Kentucky; NC—North Carolina; OH—Ohio; SC—South Carolina; TN—Tennessee; VA—Virginia; WV—West Virginia.

New insights into the basement structure associated with the ETSZ are provided by a local earthquake tomography investigation of crustal velocities (Powell et al., 2014). P-wave and S-wave velocity (Vp and Vs) models and earthquake relocations, combined with potential-field anomalies and basement exposures in the Blue Ridge province in western North Carolina, support construction of a seismotectonic model that relates present-day seismicity to the framework of ancient basement structures formed during the Grenville orogeny.

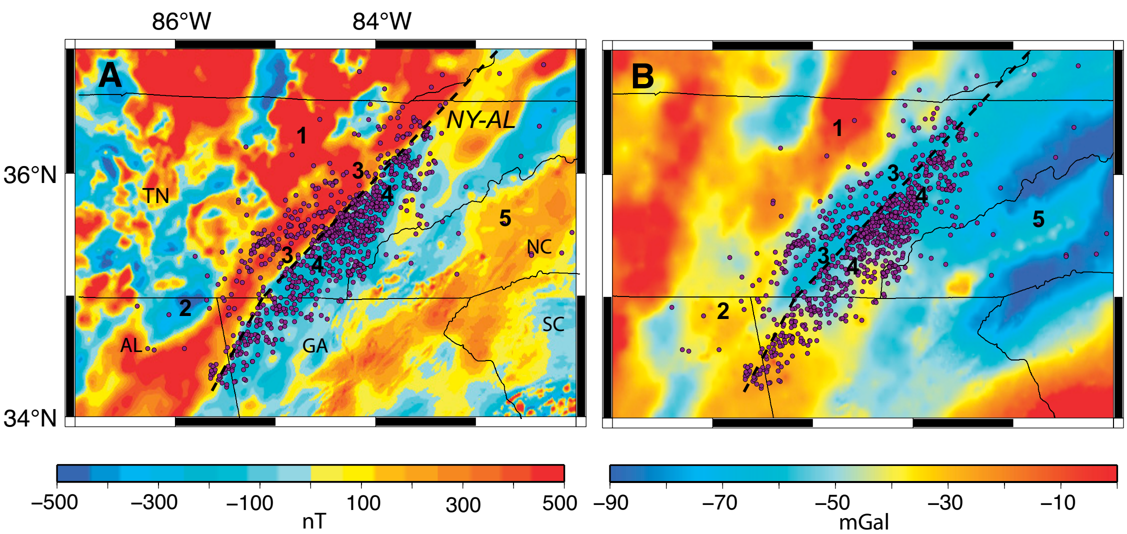

Figure 2. Potential-field maps for region around the Eastern Tennessee seismic zone (ETSZ), southeastern United States. A: Aeromagnetic anomalies. B: Bouguer gravity anomalies. Earthquakes are shown as purple dots. Numbers refer to rock types identified in Table DR1 (see footnote 1). Dashed line marks trace of New York–Alabama (NY-AL) magnetic lineament. Refer to Figure 1 for state abbreviations.

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VELOCITY INVERSION

The inversion methodology, resolution tests, and results are discussed in detail in Powell et al. (2014) and are summarized here. The data set of Powell et al. (2014), consisting of 1039 earthquakes recorded from A.D. 1984 to 2009, is augmented for this article by the addition of 211 earthquakes recorded from 2009 to 2014. Addition of these earthquakes does not change the velocity inversion results but adds information about the distribution of hypocenters. The starting, one-dimensional (1-D) velocity model is taken from Vlahovic et al. (1998), and a nonlinear traveltime tomography method is used to calculate 3-D Vp and Vs models and hypocenter locations. The inversion volume is divided into blocks with dimensions of 12 × 12 km horizontally × 4 km vertically. Resolution is adequate to a depth of 24 km, as indicated by recovery of synthetic checkerboard models. The Vp solution for the layer in the depth range 8–12 km is shown in Figure 3. Vp and Vs solutions for all layers and additional cross sections are described in Powell et al. (2014).

SEISMOTECTONIC MODEL

The primary objective of the velocity inversion is to associate prominent velocity anomalies with specific rock types in the basement. This requires knowledge of the absolute Vp and Vs values so that a comparison can be made to laboratory measurements of rock velocities (e.g., Christensen, 1996). Estimates of absolute velocity that are not influenced by smoothing used in the inversion solution are obtained by using a forward-modeling technique in which input velocity for a specified volume representing a prominent anomaly is varied until a good match is obtained with the inversion results for the real data. The plausible set of rock types associated with each major velocity anomaly is restricted further by considering the associated Bouguer gravity and magnetic anomalies. Rock types that meet all criteria for the depth range 4–20 km are listed in Table DR1 in the GSA Data Repository[1] and are used to develop the seismotectonic model (Fig. 3). Further description of the interpretation procedure and results are given by Powell et al. (2014).

A prominent feature in the velocity models is a narrow zone of low velocity that trends northeast-southwest and extends to a depth of at least 24 km. The low-velocity zone (LVZ) is associated with a low Bouguer gravity anomaly and with the vertical projection of the New York–Alabama magnetic lineament. The low Vp and Vs values are compatible with mylonites (Table DR1) (Jones and Nur, 1982), and we interpret the LVZ as a major fault zone (labeled in Fig. 3) containing highly sheared rocks. Earthquakes are not concentrated along the fault. Rather, the fault forms the northwest boundary of the most seismogenic basement (labeled "reactivated sheared basement rocks" in Fig. 3). The Mesoproterozoic (Grenville) basement rocks exposed in Blue Ridge (southern Appalachian) basement massifs include granite gneisses, felsic to mafic granulite gneisses, and paragneisses (Carrigan et al., 2003; Ownby et al., 2004). The range of Blue Ridge rock types accounts for a range in velocity anomalies like those southeast of the LVZ, suggesting that rocks southeast of the LVZ are similar to those in the Blue Ridge. The moderate to low potential-field anomalies are also compatible with these rock types (Table DR1). The high-velocity area labeled "mafic intrusion" (Fig. 3) is along a Keweenawan-age rift identified in Kentucky on the basis of potential-field, seismic, and petrologic data (Keller et al., 1982), and in Tennessee using receiver functions (Owens et al., 1984). The area labeled "anorthosite" (Fig. 3) has high velocity but low magnetic and moderate gravity anomalies, similar to anorthosite bodies exposed in Canada (e.g., Hayward et al., 2001).

[1]GSA Data Repository item 2016009, Table DR1 (rock types that are compatible with the computed velocities and the observed potential-field data), is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

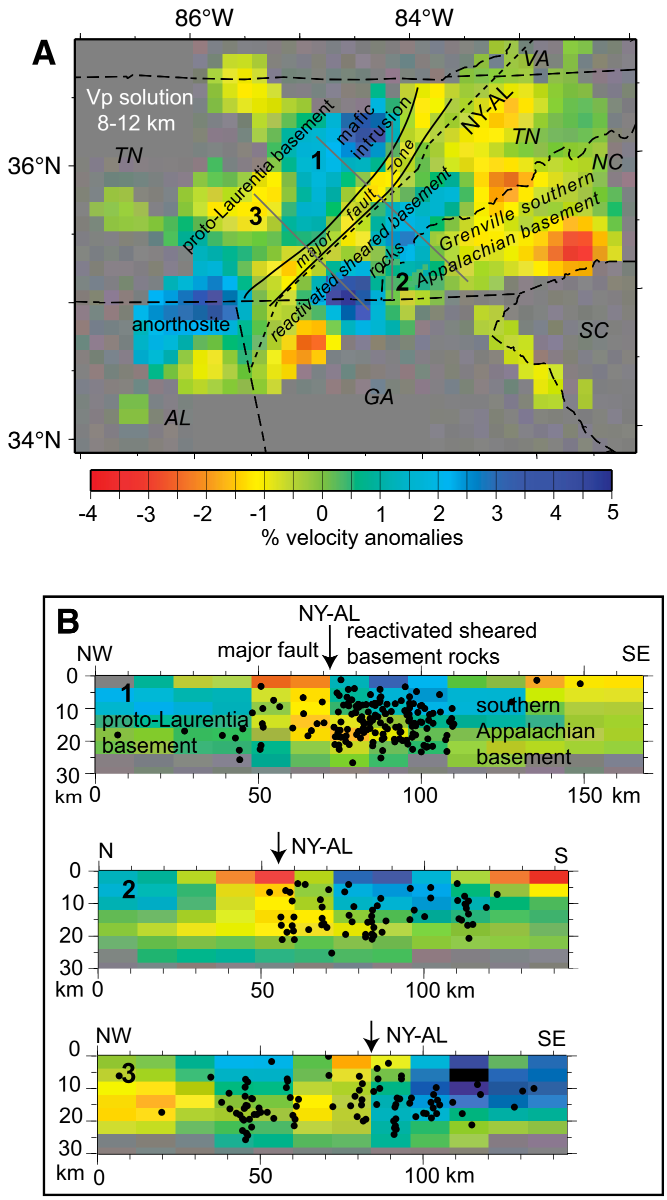

Figure 3. Interpreted velocity solution for the Eastern Tennessee seismic zone, southeastern United States (modified from Powell et al., 2014). Same velocity anomaly scale for all plots. A: Map of P-wave velocity (Vp) anomalies for 8–12 km depth slice. Refer to Figure 1 for state abbreviations. B: Profiles 1, 2, and 3; locations shown in A. Earthquake hypocenters are shown as dots. Hypocenters within 12 km of profiles 1 and 3, and within 3 km of profile 2, are plotted. Major basement fault zone follows trace of the New York–Alabama magnetic lineament (dashed line) and extends to a depth of at least 24 km. Southern Appalachian Grenville basement includes all crust southeast of the New York–Alabama magnetic lineament.

Relocated ETSZ hypocenters generally are aligned in vertical planes that trend northeast-southwest and east-southeast–west-northwest (Fig. 3). Focal-mechanism solutions for the seismic zone are dominated by consistent strike-slip motion on two sets of steeply dipping nodal planes that are oriented in the approximate ranges 80°–110° and 30°–50° (Chapman et al., 1997; Cooley, 2015). The compatible alignments of hypocenters and nodal planes suggest that the hypocenters delineate steeply dipping fault planes in the basement. The orientations suggest a conjugate set of faults, a characteristic of major strike-slip faults in continental crust (Fossen and Tikoff, 1998).

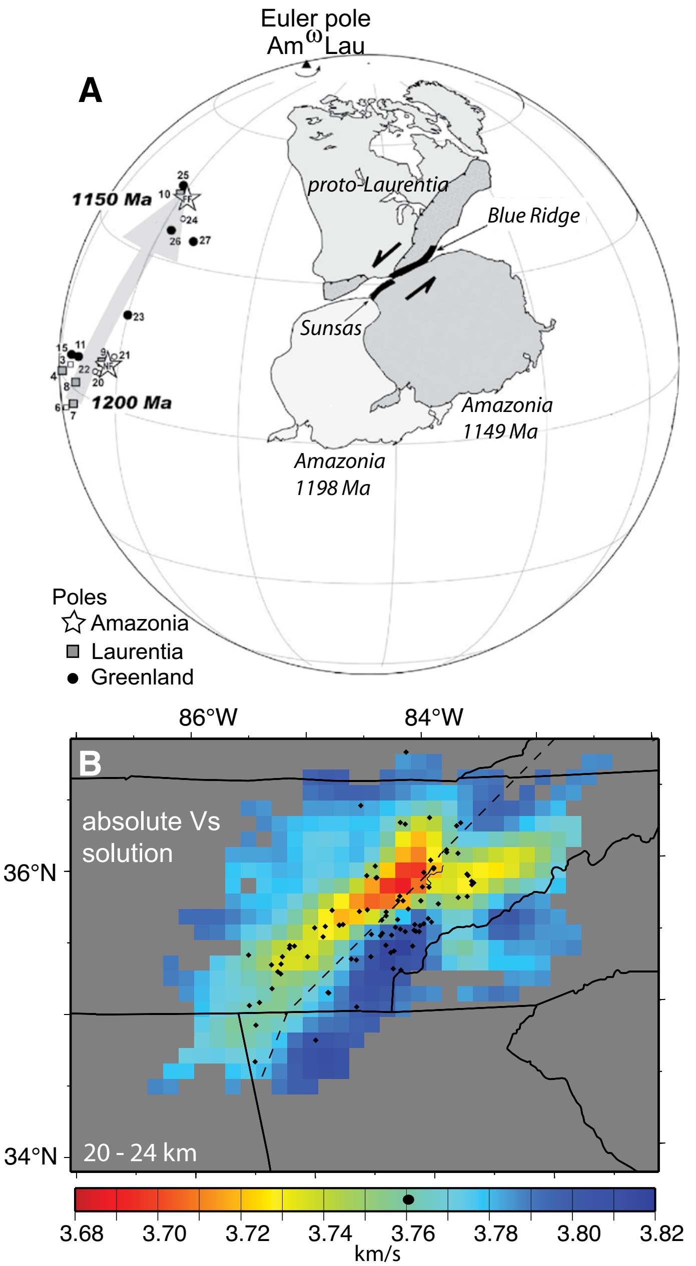

Figure 4. A: Apparent polar-wander curves document a 2000-km along-strike migration of Amazonia (Am) relative to proto-Laurentia (Lau) during the Grenville orogeny (adapted from D'Agrella-Filho et al., 2008). B: Absolute S-wave velocity (Vs) values determined for the depth range 20–24 km in the velocity inversion. Earthquakes are indicated by small dots. Large dot on velocity scale indicates starting velocity value for the layer. Note the sharp velocity contrast across the vertical projection of the New York–Alabama magnetic lineament (dashed black line) even at the limit of the depth resolution in the Vs model. Low-velocity zone is interpreted as a preserved segment of the sinistral transform fault between Amazonia and proto-Laurentia.

SUPPORTING EVIDENCE

Polar-wander curves indicate a 2000-km along-strike migration of Amazonia relative to proto-Laurentia during assembly of supercontinent Rodinia (Fig. 4) (D'Agrella-Filho et al., 2008). Large-scale, sinistral strike-slip shear zones in southwest Amazonia support this reconstruction (Tohver et al., 2004). In particular, the Sunsas orogeny (ca. 1100–900 Ma) formed the Sunsas province of Bolivia and southern Brazil during the assembly of Rodinia; extensive, linear mylonitic shear zones with sinistral strike-slip motion characterize the deformation (Teixeira et al., 2010). The major basement shear zone (marked by the New York–Alabama magnetic lineament), which bounds the most concentrated seismicity in the ETSZ, is interpreted to represent a transform fault between Amazonia and proto-Laurentia in the assembly of Rodinia, and to have been left attached to Laurentia following the breakup of Rodinia and opening of the Iapetus Ocean (Figs. 3 and 4). The Alpine fault in New Zealand (Davey et al., 1998), representing transform motion between two continental plates, may serve as a modern analogue.

Isotopic data indicate the growth of southeastern Laurentia during Grenville orogenesis. Whole-rock Pb and Sm-Nd isotopic data indicate that Grenville basement east of the New York–Alabama magnetic lineament originally was part of Amazonia and was added to proto-Laurentia during the Grenville orogeny (e.g., Loewy et al., 2003; Ownby et al., 2004; Tohver et al., 2004). In addition, southern and central Appalachian basement Pb isotopic data are strikingly similar to Pb data from ca. 1 Ga rocks in the Sunsas province (e.g., Carrigan et al., 2003). On the basis of these similarities, Loewy et al. (2003) and Tohver et al. (2004) proposed that Amazonia is the parent craton for the central and southern Appalachian basement, a suggestion further supported by isotopic analysis of a larger suite of rocks by Fisher et al. (2010). Given the location of their samples, Fisher et al. (2010) agreed with sinistral displacement of Amazonia along the proto-Laurentian margin and suggested that the boundary in the upper crust is coincident with the New York–Alabama magnetic lineament.

Shear-wave (SKS) splitting results support the hypothesis that the basement in the region of the ETSZ was affected by extensive shearing. Wagner et al. (2012) presented SKS splitting results for the southeastern United States and observed that many fast directions within the southern Appalachians are approximately parallel to the trend of the New York–Alabama magnetic lineament and do not correspond to absolute plate motion (APM) vectors. The magnitude of splitting generally exceeds 1 s, arguing for a coherent deformation fabric in the crust and mantle because the contribution from the crust alone would probably not exceed a few tenths of a second (Long and Silver, 2009). As stated by Wagner et al. (2012), the alignment of the splitting measurements with the New York–Alabama magnetic lineament implies thick, sheared mantle lithosphere in which the deformation-induced anisotropy is strong enough to overprint the APM anisotropy and is aligned with the crustal structures that generated the magnetic lineament. This interpretation is consistent with paleomagnetic evidence suggesting continent-continent strike-slip motion of Amazonia relative to proto-Laurentia during the assembly of Rodinia (Fig. 4) (D'Agrella-Filho et al., 2008). In this scenario, the entire lithosphere would have been subjected to ductile shearing along the transform boundary.

CONCLUSIONS

A new seismotectonic model for earthquakes of the ETSZ involves reactivation of sheared basement rocks, which are bounded by a large-scale transform fault between Amazonia and proto-Laurentia in the Mesoproterozoic assembly of Rodinia. Paleomagnetic polar-wander curves for the assembly of Rodinia are compatible with a transform fault between Amazonia and proto-Laurentia (Fig. 4) (D'Agrella-Filho et al., 2008). Isotopic data for the growth of southeastern Laurentia during the Grenville orogeny indicate Amazonian crust that remained attached to Laurentia. SKS splitting results support the presence of a lithospheric-scale shear zone.

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