A Seismotectonic Model for the 300-Kilometer-Long Eastern Tennessee Seismic Zone

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Ten years of monitoring microearthquakes with a regional seismic network has revealed the presence of a well-defined, linear zone of seismic activity in eastern Tennessee. This zone produced the second highest release of seismic strain energy in the United States east of the Rocky Mountains during the last decade, when normalized by crustal area. The data indicate that seismicity produced by regional, intraplate stresses is now concentrating near the boundary between relatively strong and weak basement crustal blocks.

Unlike the western United States, the tectonic origin for seismic activity in the eastern United States is unclear. This uncertainty arises from several factors including inadequate seismograph network coverage, a sparsity of large earthquakes, and a lack of earthquakes associated with recognized geological structures. Eastern United States earthquakes have the potential to cause widespread damage in heavily populated areas. In general, the area containing structural damage in the eastern United States is five times the damage area in the western United States for an earthquake of comparable magnitude (*1*). Prominent seismogenic zones east of the Rocky Mountains include New Madrid in the central Mississippi River valley, New England, and Charleston, South Carolina. Two other zones of concentrated seismic activity have been detected in the Southeast after ten years of instrumental monitoring in the southern Appalachian Mountains. The zones are located in Giles County, southwestern Virginia (*2*), and eastern Tennessee (*3*). The Giles County zone is 40 km long by 10 km wide and produced a damaging earthquake (body wave magnitude of 5.8) in 1897 (*2*). The zone in eastern Tennessee is 300 km long by 50 km wide and has not produced a damaging earthquake in historical time; the largest recorded magnitude is 4.6 (*4*).

The eastern Tennessee seismic zone (ETSZ) is a pronounced seismic feature in the central and southeastern United States (Fig. 1) (*3*, *4*). With the seismic moment release per unit crustal volume (25,000 km^2 by 20 km depth) over the last decade as a basis of comparison, the ETSZ has produced the second highest release of seismic strain energy in the United States east of the Rocky Mountains. Only the New Madrid zone has been more seismogenic. New England has experienced more earthquakes than has Tennessee, but events in eastern Tennessee occur in a more concentrated zone. Contained within the ETSZ are numerous nuclear power reactors and hydroelectric projects, Oak Ridge National Laboratory, and population centers including Knoxville and Chattanooga. In this report, we describe some of the unusual characteristics of this seismic zone and develop a tectonic model to account for the seismicity. The model indicates that the potential for a large, damaging earthquake in the ETSZ may be higher than the available historical record suggests.

The ETSZ traverses eastern Tennessee and parts of North Carolina and Georgia (Fig. 2). Seismicity has been monitored by the Southern Appalachian Regional Seismic Network (SARSN) since 1981. Stations in this network are spaced 45 to 80 km apart throughout eastern Tennessee and western North Carolina (*3*), and station locations have not varied. Event locations are accurate and relatively unbiased (*3*). Except for the southernmost part in Georgia, the ETSZ lies within the network. Thus, the clustered nature of seismicity within the ETSZ for the time period illustrated in Fig. 2 cannot be attributed to nonuniform station distribution, an inadequate crustal velocity model, or variable detection capabilities.

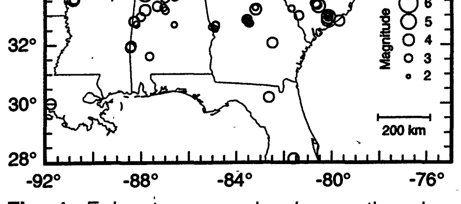

Fig. 1. Epicenter map showing earthquakes with magnitudes ≥2 occurring in the central and southeastern United States for the period 1965 to 1985 (*18*).

The Valley and Ridge and Blue Ridge provinces (outlined in Fig. 2) are thrust and fold complexes underlain by a master décollement (*5*). The maximum depth to the décollement within the ETSZ is approximately 5 km (*5*); in contrast, the mean focal depth within the ETSZ is 15 km (*3*, *4*, *6*). Thus, most of the earthquakes occurred in crystalline basement rocks of inferred Grenville age and are evidently not associated with the decollemont or the overlying, detached rocks.

Instrumentally located epicenters in the ETSZ generally lie close to and east of the New York–Alabama (NY–AL) aeromagnetic lineament between latitudes 34.3° and 36.5°N (Fig. 2). No other seismic zone in eastern North America exhibits such a clear spatial association with a major geophysical anomaly. Epicenters also lie west of the Clingman aeromagnetic lineament (Fig. 2). Both lineaments trend to the northeast; the NY–AL lineament extends for more than 1600 km from the northeast corner of Alabama to Albany, New York, while the Clingman lineament extends for roughly 1000 km from northwest Georgia to Maryland. The long wavelengths of the NY–AL and Clingman lineaments suggest that they are associated with structural or mineralogical variations in basement rocks (*7*, *8*). These lineaments define a basement block with a distinctly different aeromagnetic signature (*8*, *9*). Between the lineaments, the signature is characterized by relatively low intensities and numerous gradients trending roughly N15°E. Outside of the block, magnetic features have higher amplitudes and trend roughly northeast-southwest.

The basement bounded by the NY–AL and Clingman lineaments has been named the Ocoee block (*3*), and the association of ETSZ seismicity with this block is shown in Fig. 3. Epicenters for the largest events are shown and, thus, represent the most reliable epicenter distribution. The northwest boundary of the zone of dense seismicity is particularly distinct and parallels the NY–AL lineament. The largest events concentrate near the lineament (Fig. 3).

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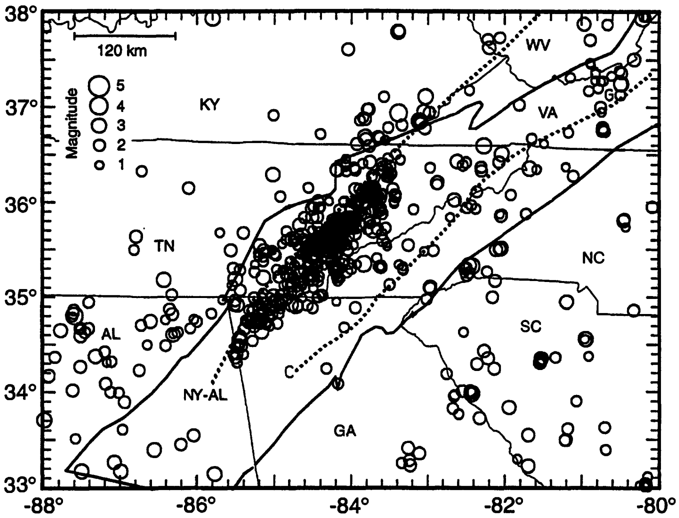

Fig. 2. Seismicity in eastern Tennessee and surrounding regions for 1981 to 1992. The ETSZ covers eastern Tennessee and parts of North Carolina and Georgia. The Valley and Ridge and Blue Ridge physiographic provinces are enclosed by the heavy line. The dotted lines indicate the NY–AL and Clingman (C) magnetic lineaments. The location of the Giles County, Virginia, seismic zone is indicated by the letter G.

the regional northeast-southwest–oriented, midplate stress field. These fault orientations differ from the northeast-southwest trend of the seismic zone because this trend is controlled by the subsurface geometry of the Ocoee block. The concentration of seismicity along the NY–AL magnetic lineament is also controlled by the geometry of the Ocoee block. Thus, we suggest that the ETSZ represents seismic activity that results from the regional stress field and is coalescing near the juncture between a relatively weak, seismogenic block (Ocoee block) and the relatively strong crust to the northwest.

Seismicity levels may be high in eastern Tennessee because this portion of the Ocoee block contains preexisting faults, foliations, or compositional layerings that are oriented favorably for failure in the present-day, regional stress field. Faults within the Ocoee block may date from rifting associated with the formation of the Iapetos Ocean (*3*) and may have been modified by Paleozoic compression or Mesozoic extension. Similarly, earthquake activity in the adjacent Giles County, Virginia, seismic zone (Fig. 2), which is remarkably similar to the ETSZ in focal depths, focal mechanism solutions, and association with the Ocoee block, has been attributed to the compressional reactivation of Iapetan normal faults (*2, 6*).

Eastern Tennessee also corresponds to the portion of the NY–AL lineament with the steepest gradient and the most distinct separation of magnetic basements. Basement crust northwest of the lineament may be strengthened by the presence of mafic rocks associated with an inferred Keweenawan-age (1100 million years old) rift (*16*). The presence of mafic rocks is suggested by magnetic, gravity, and seismic (*17*) data, and the inferred rift runs parallel to and just northwest of the NY–AL lineament in Tennessee (*16*). The proposed rift does not appear to be seismogenic, although a few earthquakes have been associated with its western boundary (*16*).

Deformation within the ETSZ may evolve eventually into a throughgoing, strike-slip fault running along or near the entire northwest boundary of the Ocoee block in eastern Tennessee. This evolution is suggested by several observations. First, seismic strain energy release is highest along this boundary, as evidenced by the concentration of the largest events near the NY–AL magnetic lineament. Second, the aeromagnetic signature associated with the NY–AL lineament suggests that this feature is a sharp (vertical?) boundary separating two distinct rock types and, thus, that it may facilitate strike-slip motion. Third, the orientation of the boundary is more north-south than the orientation of s_1; a shear couple exists along this boundary facilitating right-lateral strike-slip motion. Fourth, seismicity appears to have concentrated near the boundary recently. The specification of a me-

Earthquakes within the ETSZ cannot be attributed to known faults. Focal mechanism solutions indicate subvertical strike-slip faulting with either right-lateral motion along north-south striking planes or left-lateral motion along east-west striking planes (*3, 4, 6*), consistent with the regional stress field (*10*). The axis of maximum horizontal compressive stress (s_1) is oriented roughly northeast-southwest in eastern Tennessee (*10–12*). A similar orientation (N50°E) was determined for s_1 by an inversion of ETSZ focal mechanism solutions (*13*). Neither set of fault planes strikes parallel to the trend of the ETSZ; fault planes are oriented roughly 45° to the overall northeasterly trend of the seismic zone. Most strike-slip fault zones trend at large angles to s_1. For example, the low stress-bearing San Andreas fault system trends almost 90° to s_1 (*14*) and the southwest trending branch of the New Madrid seismic zone trends roughly 30° to 40° to s_1 (*15*). In contrast, the ETSZ trends at a small angle (5° to 15°) to s_1.

The ETSZ appears to have narrowed to its present horizontal dimensions within the last 15 to 20 years [figures 2 and 3 in (*4*)]. Seismicity for the years 1698 to 1977 was equally distributed between eastern Tennessee and western North Carolina, whereas after 1977 seismicity was concentrated in eastern Tennessee. One possibility for this change is that the apparent narrowing of the zone is due to increased earthquake detection and location capabilities provided since 1981 by SARSN. We investigated this possibility by considering the spatial and temporal distribution of felt earthquakes, because such intensity reports are independent of seismic station operation and can be extended to the period before instrument observations. Seismic activity appears to have narrowed over the last 20 years on the basis of the felt earthquake distribution, despite the large errors associated with events. Event relocations, now in progress, will help clarify this issue.

We propose that the ETSZ is an evolving seismic zone in which slip on north- and east-striking surfaces is slowly coalescing into a northeast-trending zone. Whether the associated faults are new or represent a reactivation of ancient faults that were partially healed during prolonged past inactivity is uncertain. Seismicity has occurred most recently in the Ocoee basement block. Orientations of focal planes within the block are appropriate for failure in

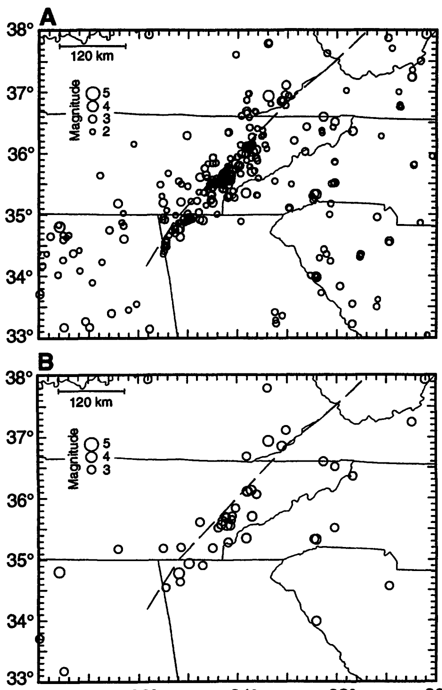

Fig. 3. Instrumentally located epicenters for 1981 to 1992. The NY–AL magnetic lineament is shown as a dashed line. (**A**) magnitudes ≥2, (**B**) magnitudes ≥3.

chanical model for a throughgoing fault may be possible after event relocation analysis. Relocated events may reveal en echelon strike-slip movement in agreement with wrench-zone models or tabular zones striking parallel to the northwest boundary of the Ocoee block, suggesting general weakening of the crust leading to possible failure.

Our model for seismicity in the ETSZ has implications for seismic hazard assessment. If a throughgoing fault is developing along the northwest boundary of the Ocoee block, the potential for a future large earthquake may be higher than the historical record suggests. However, the estimation of when a potentially damaging event may occur is speculative.

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Detection of Large Prehistoric Earthquakes in the Pacific Northwest by Microfossil Analysis

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Geologic and palynological evidence for rapid sea level change ~3400 and ~2000 carbon-14 years ago (3600 and 1900 calendar years ago) has been found at sites up to 110 kilometers apart in southwestern British Columbia. Submergence on southern Vancouver Island and slight emergence on the mainland during the older event are consistent with a great (magnitude $M \geq 8$) earthquake on the Cascadia subduction zone. The younger event is characterized by submergence throughout the region and may also record a plate-boundary earthquake or a very large crustal or intraplate earthquake. Microfossil analysis can detect small amounts of coseismic uplift and subsidence that leave little or no lithostratigraphic signature.

There is mounting concern that coastal areas of the Pacific Northwest of the United States and Canada could experience an earthquake much larger than any of the historical period (*1*). Geodetic data and geophysical modeling (*2, 3*) indicate that converging plates within the Cascadia subduction zone (Fig. 1) are locked and accumulating strain, portending a great ($M \geq 8$) plate-boundary earthquake in the future.

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There is also compelling geologic evidence for large prehistoric earthquakes, both on the Cascadia subduction zone (*4, 5*) and at relatively shallow depth within the North American plate (*6*).

Geophysical models (*3*) and crustal deformation patterns of historical plate-boundary earthquakes in Alaska and Chile (*7*) suggest that part of the Pacific coast between northern California and central Vancouver Island would subside during an earthquake on the Cascadia subduction zone. The amount of subsidence would decrease eastward, approaching zero several tens of kilometers east of the outer coast. A large earthquake within the North American or Juan de Fuca plate might also cause uplift or subsidence, although the affected area probably would be smaller.

We present evidence for two large earthquakes that affected sites in south-coastal British Columbia up to 110 km apart. Much of the evidence comes from an analysis of fossil pollen, spores, and other microfossils in Holocene peat deposits. Small amounts of emergence and submergence, even with little or no lithologic expression, can be detected from such records.

The study area includes southern Vancouver Island and the British Columbia mainland in the vicinity of the Fraser and Serpentine rivers (Fig. 1). Peaty wetlands at or near the upper limit of tides were selected for study because plants growing there are strongly influenced by small differences in elevation and salinity (*8*) and are thus potentially sensitive indicators of coseismic subsidence or uplift. Subsidence might transform freshwater shrublands or marshes into tidal marshes, whereas uplift might convert herbaceous, salt-tolerant plant communities into supratidal vegetation.

Holocene vegetation changes in Fraser delta wetlands have previously been attributed to natural succession or river flooding (*9*). While these processes are undeniably important, our results indicate that earthquakes may be implicated in at least two instances of rapid vegetation change at ~3400 and ~2000 ^{14}C years B.P. (radiocarbon years before present, taken as A.D. 1950; 3600 and 1900 calendar years ago).

These events are most clearly recorded on the coast of southern Vancouver Island and along the Serpentine River, south of Vancouver. Rooted stumps, logs, branches, cones, and peaty forest soil are exposed at low tide at the mouth of Muir Creek (Fig. 1). Nearby, the fossil forest is abruptly overlain by silt and sand containing brackish water diatoms. Wood from the peat bed has been dated at 3280 ± 50 and 3530 ± 60 ^{14}C years B.P., suggesting that the forest was submerged and killed at about that time (Table 1). Farther east, at Island View Beach, in situ fossil stumps 1.0 to 1.5 m below the upper limit of tides indicate another transgression. One of the stumps yielded a radiocarbon age of 2040 ± 130 ^{14}C years B.P. Finally, numerous stumps are exposed in the banks of the Serpentine River about 1 m below high tide level. The stumps are rooted near the top of a widespread peat that is abruptly overlain by intertidal mud. A radiocarbon age of 2290 ± 60 ^{14}C years B.P. on one of the stumps is a maximum for submergence and mud deposition.

On the basis of these observations alone, it is not possible to determine whether the transgressions at Muir Creek, Island View Beach, and Serpentine River were the result of subsidence during earthquakes, aseismic subsidence, or eustatic sea level rise