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The 2011 Virginia M_w 5.8 earthquake: Insights from seismic reflection imaging into the influence of older structures on eastern U.S. seismicity

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ABSTRACT

The Mineral, Virginia (USA), earthquake of 23 August 2011 occurred at 6–8 km depth within the allochthonous terranes of the Appalachian Piedmont Province, rupturing an ~N36°E striking reverse fault dipping ~50° southeast. This study used the Interstate Highway 64 seismic reflection profile acquired ~6 km southwest of the hypocenter to examine the structural setting of the earthquake. The profile shows that the 2011 earthquake and its aftershocks are almost entirely within the early Paleozoic Chopawamsic volcanic arc terrane, which is bounded by listric thrust faults dipping 30°–40° southeast that sole out into an ~2-km-thick, strongly reflective zone at 7–12 km depth. Reflectors above and below the southward projection of the 2011 earthquake focal plane do not show evidence for large displacement, and the updip projection of the fault plane does not match either the location or trend of a previously mapped fault or lithologic boundary. The 2011 earthquake thus does not appear to be a simple reactivation of a known Paleozoic thrust fault or a major Mesozoic rift basin-boundary fault. The fault that ruptured appears to be a new fault, a fault with only minor displacement, or to not extend the ~3 km from the aftershock zone to the seismic profile. Although the Paleozoic structures appear to influence the general distribution of seismicity in the area, Central Virginia seismic zone earthquakes have yet to be tied directly to specific fault systems mapped at the surface or imaged on seismic profiles.

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INTRODUCTION

The moment magnitude M_w 5.8 Mineral, Virginia, earthquake of 23 August 2011 was felt over a wide area by perhaps more people than any other earthquake in the United States (Horton and Williams, 2012; Hough, 2012). The earthquake occurred at 6–8 km depth within the Central Virginia seismic zone (CVSZ) (Chapman, 2013; Hartzell et al., 2013; McNamara et al., 2014), a zone of dispersed seismicity within the central Appalachian Piedmont and Blue Ridge Provinces (Fig. 1A; Bollinger and Sibol, 1985; Kim and Chapman, 2005). The focal mechanism and aftershock locations show that the 2011 earthquake ruptured a fault plane oriented ~N36°E and dipping ~50° southeast (Fig. 1B; McNamara et al., 2014). The main cluster of aftershocks defines a fault plane, or several planes, with dimensions of nearly 10 km along strike and 8 km downdip (McNamara et al., 2014). The earthquake and its aftershocks are one of the few well-documented earthquake sequences in the eastern United States, and one of the few sets of well-located earthquakes within the CVSZ. Documenting the structural setting of the earthquake is therefore important for trying to understand long-standing questions such as the relationship of CVSZ seismicity to Appalachian structures and the reactivation of older structures in the modern stress regime.

The Mineral earthquake occurred ~6 km northeast of a U.S. Geological Survey (USGS) seismic reflection profile acquired in 1981 along Interstate Highway 64 (I-64; Fig. 1A) (Harris et al., 1986; Pratt et al., 1988; Çoruh et al., 1988). To better understand the tectonic setting and try to identify the fault responsible for the earthquake, we projected the rupture plane defined by the 2011 main shock and aftershock sequence onto a reprocessed version of the I-64 seismic profile to investigate how the rupture plane relates to preexisting (Paleozoic and Mesozoic) structures.

DATA

The I-64 seismic reflection profile extends from the Appalachian Valley and Ridge Province to the coast, crossing the Blue Ridge and Piedmont Provinces and the Atlantic coastal plain province (Fig. 1). During acquisition three large vibrators were centered in a 48 channel receiver array, with a 134 m source spacing and 67 m geophone spacing producing a nominal 12-fold stacked section (Pratt et al., 1988). We reprocessed the profile, which was last processed in the mid-1980s, to improve the imaging. Although the basic structure is imaged on both the original (1980s processing) and reprocessed profiles, the reprocessing brought out the higher frequencies better and slightly improved the imaging of dipping reflectors in the shallow portions of the profile. More aggressive deconvolution parameters were used to retain higher frequencies, and faster computers allowed for improved residual statics calculations (Ronen and Claerbout, 1985). The short receiver distances (1800 m maximum offset) prevented accurate velocity determinations below ~2 km depth, however, and thus limited the effectiveness of pre-stack processing. We therefore used a standard processing sequence (Yilmaz, 2001), but during interpretation we also examined versions of the profile made with a range of high stacking velocities that accentuated steeply dipping reflectors.

There was little lateral variation in the shallow (upper ~2 km) stacking velocities within the Piedmont Province. For post-stack migration and depth conversion we used a velocity model based on the shallow stacking velocities and on the regional velocity model developed for locating earthquakes (Kim and Chapman, 2005; Chapman, 2013). Our velocity model had a surface velocity of 5600 m/s, increasing in the upper 3 km to 5900 m/s and then gradually increasing to 6100 m/s at ~9 km depth. The upper 3 km of this velocity function is slightly lower (~3%–8%) than the 6.09 km/s upper crustal (to 15 km depth) velocity used for earthquake locations (Kim and Chapman, 2005), but this difference is likely similar to the accuracy of the velocity determinations and results in differences in depth estimates of <~300 m. During interpretation the profile was also migrated with a range of velocities to examine how the imaging of structure is influenced by changes in the migration velocity.

The acquisition parameters did not change along the seismic profile, but between stations 2700 and 2900 the reflection amplitudes gradually fade to the east, so that there are only scattered reflections below shallow Mesozoic and younger Atlantic coastal plain strata on the eastern third of the profile (Fig. 2; Pratt et al., 1988). This lack of reflections appears to be an energy penetration problem associated with the eastern portion of the Atlantic coastal plain strata rather than a problem with processing, as the reflections on the unprocessed shot records also fade in amplitude across this area.

Locations for 394 aftershocks that were mostly recorded on a dense temporary array were computed using a multiple event location method based on the hypocentroidal decomposition algorithm (McNamara et al., 2014), which belongs to a class of algorithms used to obtain high-precision relative earthquake locations through multiple event analysis (Jordan and Sverdrup, 1981). Focal mechanisms for 16 of the larger aftershocks were computed using the methods of Herrmann et al. (2011).

Earthquakes were projected onto the seismic profile along the trend of the rupture plane defined by the main shock focal mechanism and the aftershock distribution, both of which are consistent with a common rupture plane. The profile is ~6 km south of the main shock and ~3 km south of the southernmost aftershocks. The projection of the fault plane on the seismic profile assumes that if the 2011 earthquakes were on a fault or faults with a substantial history of displacement, this fault or faults would extend the 3 km distance from the aftershocks to the seismic profile. Neither existing geologic maps nor newer mapping shows a tear fault or other structure cutting the fault systems at a high angle between the earthquake and the seismic profile that would indicate termination of the fault.

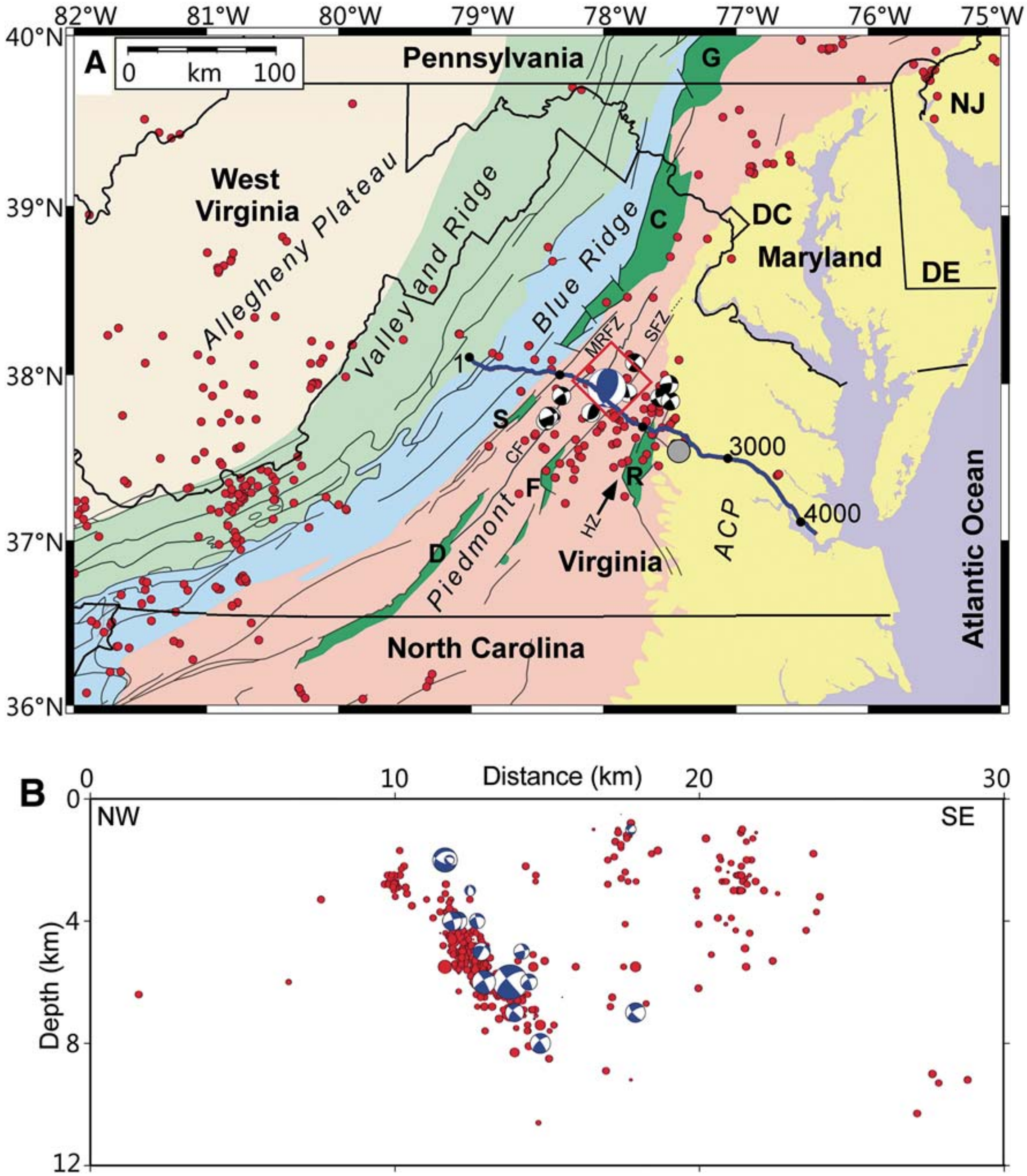
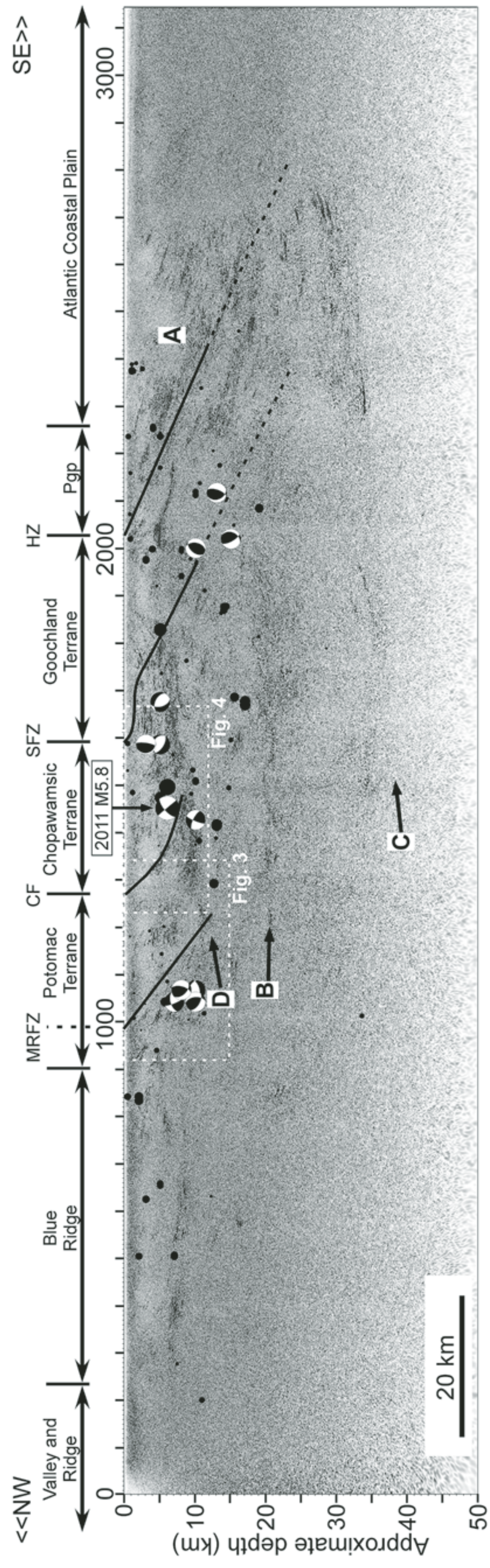


Figure 1. (A) Generalized map of the major Appalachian geologic features showing the setting of the moment magnitude, M_w 5.8 Mineral, Virginia, earthquake of 23 August 2011 (blue focal mechanism) and the Interstate Highway 64 seismic profile (blue line; every thousandth station shown as a black dot). Red dots are earthquakes (all plotted the same size) obtained from the U.S. Geological Survey Preliminary Determination of Epicenters (PDE) catalog (earthquake.usgs.gov/data/pde.php; the 2011 aftershock sequence was excluded for clarity). Black focal mechanisms are from Munsey and Bollinger (1985) and Kim and Chapman (2005) plotted at the same size regardless of magnitude. The cluster of earthquakes in central Virginia forms the Central Virginia seismic zone; the cluster of earthquakes in southwest Virginia forms the Giles County seismic zone. Gray circle is the city of Richmond. Mesozoic rift basins are depicted in green: C—Culpeper; D—Danville; F—Farmville; G—Gettysburg; R—Richmond; S—Scottsville (the Taylorsville basin is beneath the focal mechanisms just north of the Richmond basin). Major faults: MRFZ—Mountain Run fault zone; CF—Chopawamsic fault; SFZ—Spotsylvania fault zone; HZ—Hylas zone. ACP—Atlantic coastal plain province. (B) Cross section of the Mineral sequence and focal mechanisms; the circle diameter is scaled by magnitude (main shock is M_w 5.8), projected onto a vertical profile oriented 120° (approximately perpendicular to the strike of the main shock focal plane). Focal mechanisms are plotted with their diameters at twice the scale of the other earthquakes. Hypocenter locations and magnitudes are from McNamara et al. (2014).



CRUSTAL STRUCTURE OF THE CVSZ

The Mineral earthquake occurred within allochthonous Piedmont terranes that were accreted to North America during the Paleozoic Taconic (Ordovician–Silurian), Neo-acadian (Devonian–Early Mississippian) and Alleghanian (Mississippian–Permian) orogenies (Horton et al., 1989; Hibbard et al., 2007; Thomas, 2006; Hatcher, 2010; Sinha et al., 2012). The earthquake was located in the northeastern part of the CVSZ, which is a diffuse set of earthquakes in a west-trending zone ~150 km by 80 km in extent (Fig. 1; Munsey and Bollinger, 1985; Kim and Chapman, 2005). The CVSZ earthquakes are predominantly in the upper crust within the Paleozoic accreted terranes (Fig. 2; Çoruh et al., 1988), and have focal mechanisms with a variety of orientations (Fig. 1). Past earthquake locations have not been accurate enough to identify specific faults on which the earthquakes occurred. Thus, CVSZ earthquakes generally correspond with the allochthonous thrust sheets (Çoruh et al., 1988), but to date the earthquakes have not been definitively tied to individual fault systems. Central Virginia also is an area of eastward-thinning crust of the Atlantic rifted margin. Distinct lower crustal and Moho reflectors on the I-64 profile (Fig. 2) indicate a crustal thickness of ~38 km near stations 1400–1600 beneath the Chopawamsic terrane and ~32 km near stations 2700–2900 beneath the Atlantic coastal plain. This Mesozoic rifting caused normal motion along some of the major Paleozoic fault zones (Lindholm, 1978; Swanson, 1986; Schlische, 1993; Withjack et al., 2012) with Mesozoic rift basins within the Piedmont terranes to the north and south of the profile (Fig. 1). The profile crossed the northern tip of the Richmond basin (Fig. 1). The region is now under compression, with the principal axis of horizontal compression being oriented west to northwest (Kim and Chapman, 2005; Mazzotti and Townend, 2010).

The seismic profile shows southeast-dipping reflectors interpreted to be the major Paleozoic thrust faults separating reflector packages of various orientations within the Piedmont terranes (Figs. 2–4). Some of the southeast-dipping reflectors project to

Figure 2. Western part of the migrated Interstate 64 seismic reflection profile as reprocessed for this study and displayed using the envelope function (Taner et al., 1979) to enhance large-amplitude reflectors. Black dots are earthquakes within a 50-km-wide swath (excluding the Mineral aftershocks) and the large focal mechanism is the Mineral main shock. Smaller focal mechanisms from Munsey and Bollinger (1985) and Kim and Chapman (2005) are plotted at the same size regardless of magnitude. Black lines show the major fault zones (dashed where inferred). White dashed rectangles show locations of Figures 3 and 4. Labels across the top show station numbers, major geologic provinces, and fault zones. Pgp—Petersburg Granite; MRFZ—Mountain Run fault zone; CF—Chopawamsic fault; SFZ—Spotsylvania fault zone; HZ—Hylas fault zone. A—southeast-dipping reflectors east of the Spotsylvania fault zone; B—mid-crustal zone of enhanced reflectivity; C—Moho at base of lower crustal reflectors; D—west-dipping reflective zone beneath the western Piedmont (Chopawamsic and Potomac terranes). No vertical exaggeration.

the surface at the mapped locations of the major thrust faults and appear to separate coherent reflector packages; both observations are consistent with the dipping reflectors being fault zones. The 2011 earthquake and aftershock sequence were located almost entirely within the Chopawamsic terrane (Fig. 4), which consists of volcanic arc rocks thrust westward over metaclastic rocks (Mine Run Complex) of the Potomac composite terrane (Horton et al., 1989; Hibbard et al., 2007). The northwest edge of the Piedmont Province and Potomac composite terrane in this area is formed by the Mountain Run fault zone (MRFZ), which the seismic profile shows to be part of a wide (~8 km) zone of southeast-dipping, nearly planar reflectors extending to at least 10 km depth (Fig. 3). Below ~10 km it is not clear whether the MRFZ continues deeper or becomes listric and merges with the subhorizontal band of reflectors at ~20 km depth (B in Fig. 2). Substantial Mesozoic normal motion near and along the MRFZ is indicated by the ~400-m-thick Scottsville rift basin to the south (Quinlan, 2012) and the 4–5-km-thick Culpeper rift basin to the north (Fig. 1; Schlische, 1993; Ryan et al., 2006). The MRFZ marks the northwest end of an ~2-km-thick strongly reflective band (D in Fig. 2), the base of which dips westward from ~7.5 to 12 km depth and appears to form the root zone for the overlying southeast-dipping thrust faults of the Potomac and Chopawamsic terranes. The slightly west-dipping reflective strata have been interpreted as volcanic rocks of the Catoctin Formation (Harris et al., 1986; Pratt et al., 1988; Çoruh et al., 1988), but if the thrust faults root at the base of this sequence, as interpreted here (Fig. 4), the reflective strata are more likely the lower part of the Chopawamsic and Potomac terranes that were thrust over the Catoctin rocks. The westward tilt of the reflective strata could be caused by duplexing by underlying thrust faults (e.g., Harris et al., 1986; Pratt et al., 1988; Çoruh et al., 1988) and/or by normal motion on the MRFZ during Mesozoic extension.

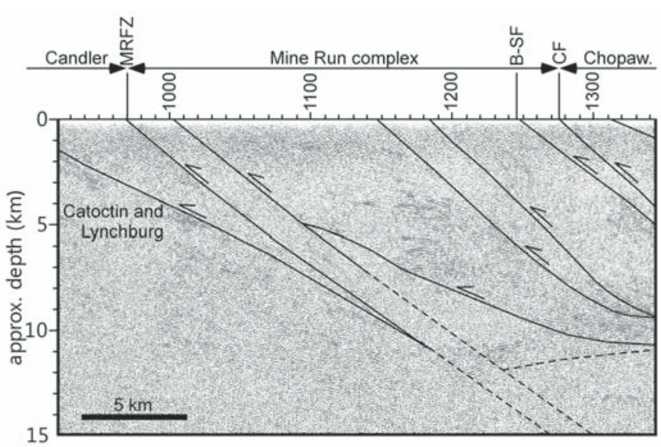


Figure 3. Seismic reflection profile showing the Mountain Run fault zone (MRFZ) at the west edge of the Piedmont and east edge of the Blue Ridge Province (Candler Formation). The MRFZ is expressed on the seismic profile as part of a broad zone of nearly planar, southeast-dipping reflectors that truncate reflectors of the Mine Run Complex and extend to ~10 km depth, below which their geometry is not clear. The MRFZ also forms the west end of the reflective sequence at 10–12 km depth. The southwest-dipping reflectors crossing the MRFZ at 7–8 km depth likely indicate three-dimensional effects that are not properly resolved on the two-dimensional seismic profile. B-SF—Brookneal-Shores fault; CF—Chopawamsic fault. Numbers across the top are station numbers. No vertical exaggeration.

The Chopawamsic fault (CF), which forms the boundary between the Potomac terrane and the west edge of the Chopawamsic terrane, is well defined on the seismic profile by southeast-dipping (40º–45º) reflectors extending from ~3–9 km depth, above which more shallowly dipping reflectors are truncated (Figs. 2 and 4). The reflectors interpreted to be the fault flatten with depth and appear to merge into the base of the west-dipping reflective band described here, or possibly to cut through the reflective band at a nearly horizontal angle. The latest significant motion on the CF in this area predates the crosscutting Ellisville pluton and is constrained to an ~10 m.y. interval in the Late Ordovician between 453 and 444 Ma (Hughes et al., 2013). Southwest of this area the CF may have been reactivated as part of the Alleghanian Brookneal ductile shear zone (Gates et al., 1988; Bailey et al., 2004), which subsequently localized deposits of the Danville rift basin during Mesozoic extensional faulting.

The Spotsylvania fault zone forms the eastern edge of the Chopawamsic terrane and west edge of the Goochland terrane, and can be traced to ~1.5 km depth as a curved reflector that becomes subhorizontal for ~7 km before curving downward to the southeast (Figs. 2 and 4). The basal reflective band beneath the western Piedmont terranes appears to be truncated at its east end by the Spotsylvania fault zone (Fig. 2). Substantial dextral strike slip is interpreted on the Spotsylvania fault zone, with the Proterozoic Goochland terrane possibly being transported hundreds of kilometers from the northeast during the transpressional Alleghanian orogeny (Bobyarchick, 1981; Gates et al., 1988; Gates and Glover, 1989; Bailey et al., 2004; Bartholomew and Tollo, 2004). The Spotsylvania fault and adjacent Lakeside fault immediately to the west extend southward to form border faults of the Farmville Mesozoic basin (Wilkes, 1982), suggesting that at least portions of these faults were reactivated in the Mesozoic with normal motion.

The reflectors marking the Hylas zone at the east edge of the Goochland terrane (Gates and Glover, 1989) dip southeast. The Hylas zone reflectors are near the west edge of a broad zone of prominent, crustal-penetrating, southeast-dipping reflectors interpreted to include a Paleozoic suture at the east edge of Proterozoic (Grenville) North American crust (Fig. 2; Pratt et al., 1988; Çoruh et al., 1988; Sheridan et al., 1993). Mesozoic normal motion on the Hylas zone formed the west edges of the 2–3-km-deep Richmond and Taylorsville rift basins (Fig. 1; Schlische, 1993; Withjack et al., 2012).

STRUCTURE OF THE EPICENTRAL AREA

Focal mechanisms of the Mineral earthquake and larger aftershocks indicate reverse slip along a northeast-southwest–striking

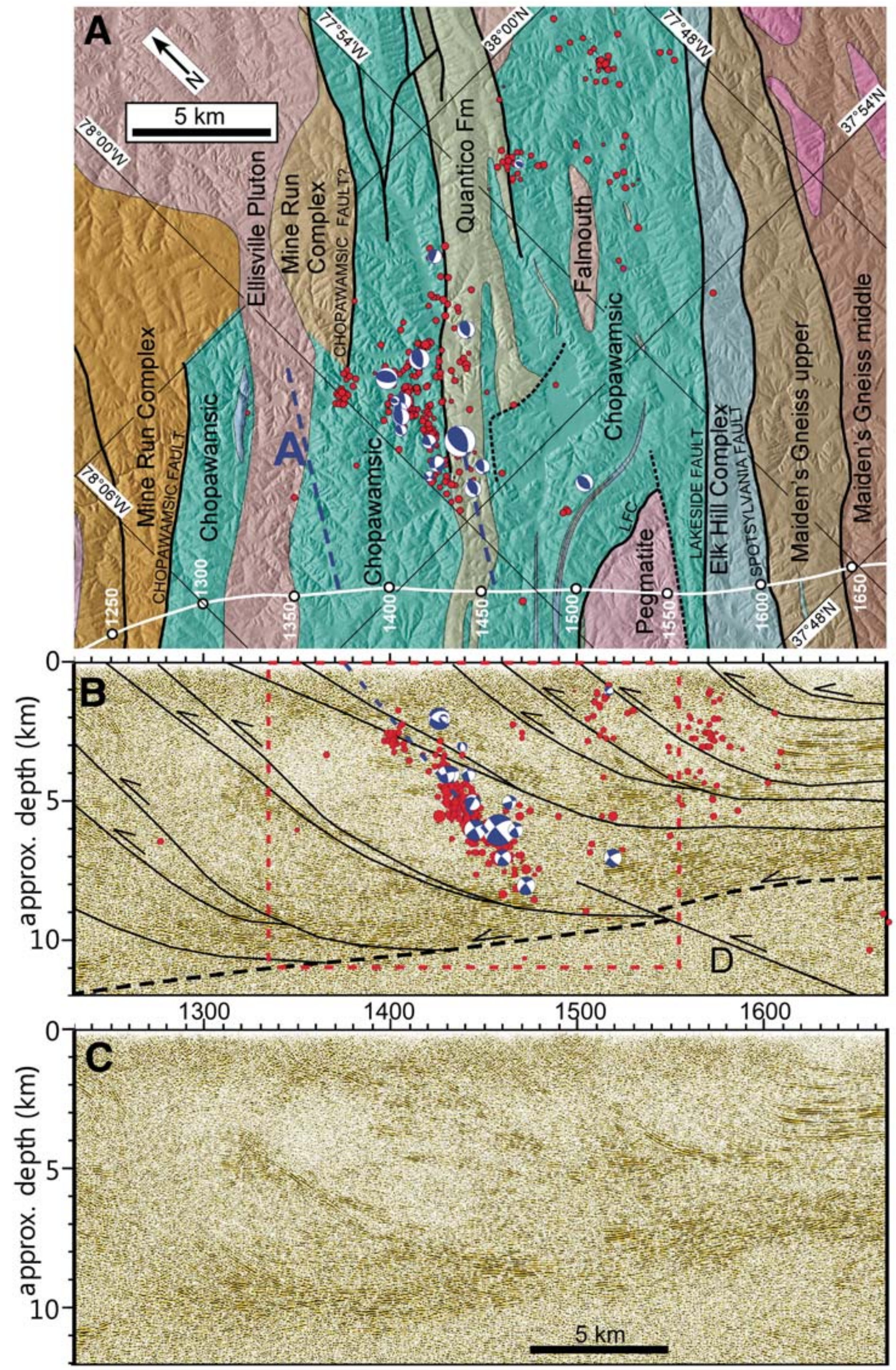


Figure 4. (A) Geologic map of the epicentral area, rotated 45° so that geologic strike is approximately perpendicular to the seismic profile (white line with every 50th station labeled). Blue dashed line labeled A is the approximate surface projection of the focal plane. LFC—Little Fork Church fault. (B) Interpreted seismic reflection profile across the Chopawamsic terrane with the 2011 earthquakes projected onto the seismic profile along the trend of the focal plane. Black lines show interpreted faults. The aftershocks, as projected, are largely within a single thrust sheet. The hypocenter is near a small-displacement thrust fault cutting the reflective zone below the thrust sheets (D), but the 2011 rupture plane has a steeper dip. Dashed red rectangle shows area in Figure 5. (C) Uninterpreted seismic reflection profile. The map and seismic profiles are at the same scale, with no vertical exaggeration.

and southeast-dipping fault plane (McNamara et al., 2014). Subsequent aftershocks define a fault plane that extends from ~2–8 km in depth and is 8–10 km in length (McNamara et al., 2014). The aftershock dimensions are consistent with the Wells and Coppersmith (1994) empirical source scaling relationships expected for the subsurface rupture of a moment magnitude, M_w 5.8 earthquake in the eastern United States. The main shock and its aftershocks are located almost entirely within metavolcanic and associated rocks of the Chopawamsic terrane, structurally below the Spotsylvania fault zone and above the CF (Fig. 4). The dominant reflectors near the hypocenter dip ~30° southeast and likely include reflections from faults bounding the Paleozoic thrust sheets.

The projection of the main shock onto the profile is 2–3 km west of a gently southeast dipping thrust fault that cuts the reflective strata at 8 km depth beneath station 1525 (fault D in Figs. 4 and 5). This deep fault does not obviously displace reflectors in the overlying thrust sheets and cannot be traced clearly to the epicentral area. The CF meets this deeper fault near the base of the reflective zone, and could merge with it. The dip of the 2011 focal plane and associated aftershocks is steeper than the relatively shallow dip of either the underlying portion of the CF or the deeper thrust fault (D) cutting the reflective sequence. Therefore, the fault on which the main shock and its aftershocks occurred does not appear to be a simple rupture of this deeper fault, and the relationship between the two faults is not clear.

The main fault plane of the Mineral earthquakes does not correlate with an obvious reflection on the seismic profile or with a previously mapped surface fault. In map view, the surface projection of the fault plane crosses the neck of the Ellisville pluton with an ~10°–20° more northward trend than the mapped strike of lithologic contacts, but there does not appear to be a displacement of these lithologic units at the surface (blue dashed line A in Fig. 4A). A series of reflectors dipping ~30° southeast from the Ellisville pluton may delineate lithologic boundaries and/or listric thrust faults that turn horizontal at ~6 km depth (Fig. 4B). These reflectors approximately coincide with the upper limit of the main aftershock sequence, suggesting that the main shock fault plane is concentrated within a single Paleozoic thrust sheet bounded below by the CF and above by the base of a thrust sheet containing most of the Ellisville pluton. A more steeply dipping reflector corresponding to possible projections of the 2011 rupture plane is not obvious on the seismic profile (Figs. 4 and 5). Even on sections processed with a range of high stacking velocities to accentuate steeply dipping reflectors, there is not a clear fault-plane reflection on the seismic profile near the location and with a dip similar to that of the focal plane. This does not appear to be an imaging limitation because reflectors with similar dips to the focal plane are imaged elsewhere on the profile. The fault plane therefore either does not produce a reflection strong enough to see clearly above the background noise, or it does not extend as far south as the seismic profile. Either of these alternatives, plus the lack of a clear surface expression, suggest that the fault has not had a large amount of displacement.

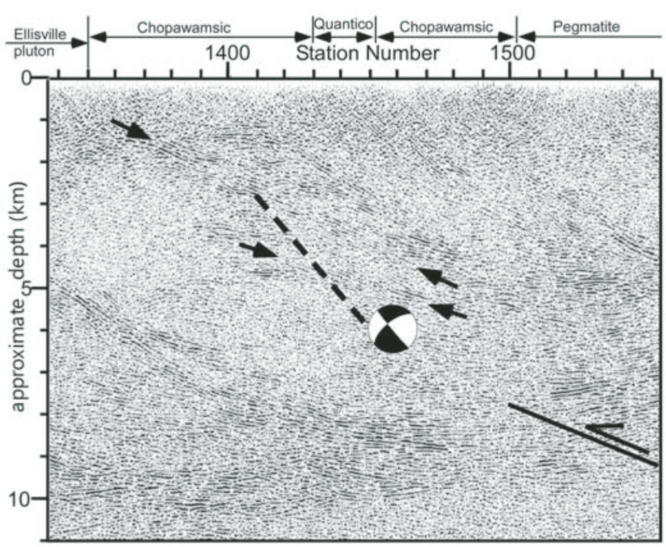


Figure 5. Enlarged view of seismic reflection profile in the hypocentral area (focal mechanism) with dashed line showing the approximate projected location of the aftershock sequence as defined by the blue dashed line in Figure 4A. The black arrows show southeast-dipping sets of reflectors that appear to extend across the projected location of the steeper inferred 2011 fault rupture plane, but do not show obvious displacements. No vertical exaggeration.

Reflectors crossing the projection of the fault plane of the Mineral earthquake do not appear to have been displaced, consistent with the earthquake rupturing a fault that does not have a history of substantial displacement. The main shock fault plane does not noticeably displace the shallower southeast-dipping reflectors that project to the surface near the Ellisville pluton (Figs. 4 and 5), although displacement of <~30 m could be below the resolution of the seismic profile. Small amounts of displacement (<~100 m) also could be interpreted if the focal plane were projected onto the profile along a slightly different trend to areas where the reflectors are not well imaged, but reflector sets that appear to cross the focal plane prevent interpretation of a fault with large displacement (Fig. 5). There also is no obvious displacement of the highly reflective sequence at the downdip projection of the fault plane, as some individual reflectors appear to be continuous beneath the focal plane (Fig. 5). Small displacements (~100 m or less) would be difficult to identify on the seismic profile because there are not strong, individual reflectors that can be traced across the epicentral area. However, the southeast-dipping reflector packages (arrows in Fig. 5) do not appear to be obviously displaced across the fault plane defined by the focal mechanism and aftershocks. The lack of an obvious fault on the seismic profile and the lack to date of an identified surface scarp from lidar (light detection and ranging) or geologic mapping argue against a history of large displacement on the fault or faults responsible for the 2011 earthquake.

One possibility for the focal plane appearing to cross Paleozoic thrust faults is that the earthquake reactivated with opposite motion a Mesozoic normal fault that dips more steeply than the Paleozoic thrust faults. If so, the fault that ruptured in the 23 August 2011 Virginia earthquake must have had only minor displacement (~100 m or less?) under Mesozoic extension and, more recently, little reverse displacement in the modern east to east-southeast compressional regime estimated from earthquake focal mechanisms (Kim and Chapman, 2005; Mazzotti and Townend, 2010). A suite of Jurassic dikes was emplaced within extensional fractures that show little net displacement, indicating that Mesozoic fractures with only minor displacement are found within the area (e.g., Ragland et al., 1983; McHone et al., 1987; Bartholomew and Van Arsdale, 2012).

Another possibility is that the fault on which the 2011 earthquake occurred does not extend far enough south to intersect the seismic profile. The dimensions of a rupture corresponding to an M_w 5.8 earthquake, and the extent of the aftershock sequence, would not require that the rupture reach as far south as the profile. If the fault terminates in the 3–4 km distance between the aftershocks and the seismic profile, it suggests that the fault has not had substantial displacement, as a fault with large displacement would not be expected to abruptly terminate within a few kilometers. There are no mapped faults crossing the area at a high angle to the 2011 fault plane that might cause a termination.

A final possibility is that the earthquake occurred on an older fault formed in the Paleozoic and subsequently truncated above and below by thrust faults. If the fault juxtaposes rocks with similar properties, it may cause only a weak reflection that is not visible on the seismic profile. Such a fault could have had substantial motion in the Paleozoic, but little motion since emplacement within the thrust sheets.

DISCUSSION

The Mineral earthquake within the CVSZ exposes gaps in our understanding of seismicity along passive margins. A fundamental question is why there are areas of increased seismicity like the CVSZ along passive margins. Most of the eastern United States is dominated by a northeast-directed principal horizontal compressive stress, but the central Appalachian Piedmont is a localized area of west to northwest compressive stress of unknown cause (Zoback, 1992; Kim and Chapman, 2005; Mazzotti and Townend, 2010). This area of anomalous stress orientation extends over a larger area than the CVSZ, however, so there is not a direct correspondence between the areas of increased seismicity and the anomalous stress orientation. Forces associated with glacial rebound (Sella et al., 2007) or dynamic topography of the Appalachians (Pazzaglia and Gardner, 1994; Pazzaglia and Brandon, 1996) are not obvious causes of the CVSZ seismicity because their effects also should extend over much larger areas unless somehow concentrated by other factors (e.g., Grollimund and Zoback, 2001).

Another fundamental question is why this earthquake, and perhaps other seismicity in the CVSZ, is not directly on the major Piedmont fault systems. Earthquakes along passive margins are generally assumed to occur on margin-parallel faults inherited from previous orogenic events (e.g., Wolin et al., 2012), and the CVSZ earthquakes are within upper crustal allochthonous Paleozoic thrust sheets (Fig. 2; Munsey and Bollinger, 1985; Çoruh et al., 1988). The 2011 earthquake sequence appears to be constrained by Paleozoic thrust sheets or resulting lithologic contrasts, with the seismicity predominantly within a single thrust sheet (Fig. 4), but CVSZ seismicity is not obviously concentrated along linear trends coincident with the MRFZ, CF, Spotsylvania fault zone, or Hylas zone. The orientations of CVSZ focal mechanisms also do not uniformly match the trends and dips of specific Paleozoic and Mesozoic faults (Fig. 2; Munsey and Bollinger, 1985; Bollinger and Sibol, 1985; Çoruh et al., 1988). The major faults in the region extend into the middle crust, bound disparate terranes, and exhibit both Paleozoic transpression and Mesozoic normal motion (Lindholm, 1978; Swanson, 1986; Gates et al., 1988; Bartholomew and Tollo, 2001; Bailey et al., 2004; Withjack et al., 2012). These major fault zones therefore would be expected to form weaknesses in the crust with orientations well suited for motion in the present west to northwest compression within the central Virginia Piedmont (Zoback, 1992; Kim and Chapman, 2005; Mazzotti and Townend, 2010). Despite this, the 2011 earthquake appears to have ruptured a fault that is slightly oblique to the Piedmont fault systems as mapped at the surface. The dispersed CVSZ seismicity also seems inconsistent with an interpretation as an aftershock sequence from a large prehistoric earthquake (e.g., Wolin et al., 2012), because such an aftershock sequence should be localized along a single fault system or set of faults, for example, as has been speculated for the New Madrid seismic zone (e.g., Ebel et al., 2000; Stein and Liu, 2009; Wolin et al., 2012; also see Page and Hough, 2014).

The apparent lack of a spatial correlation between historical seismicity and major preexisting fault zones could be in part an artifact of the limited number of well-located earthquakes within the CVSZ (with the exception of the well-located 2011 sequence), rather than a fundamental structural property. In addition to the major fault systems, there may also be secondary sets of fractures within individual crustal blocks between the major fault zones (e.g., Bartholomew and Van Arsdale, 2012). CVSZ earthquakes thus may be reactivating minor related faults or fractures with a variety of trends. Given the small number of earthquakes and relatively large earthquake location errors in the CVSZ, a complex three-dimensional pattern of active faults may exist but not yet be adequately illuminated. As an analog, if one were looking at only a few dozen earthquakes spread across the New Madrid seismic zone, the complex fault pattern (e.g., Pratt, 2012) might also be difficult to discern.

The results presented here highlight the complexity of relations between CVSZ seismicity and regional geologic structure, but the well-located sequence of 2011 earthquakes fails to resolve the scientific uncertainty about the influence of inherited structure on modern seismicity. Having a well-located earthquake in the eastern United States is unusual, and detailed studies of the event are therefore important for the improvement of probabilistic assessments of seismic hazard. In order to better understand the relationship between CVSZ seismicity and regional geologic structure, additional data collection and analysis are required using a multidisciplinary approach. In addition to already completed studies, such an effort should include improved earthquake monitoring to accurately discern the relationship between older structures and modern seismicity, paleoseismic studies, and seismic reflection profiles directly over the earthquake source zone. Such an effort to study important earthquakes in the central and eastern United States may be the best way to improve our understanding of the enigmatic nature of seismicity in the eastern United States.

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