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Extraordinary Distance Limits of Landslides Triggered by the 2011 Mineral, Virginia, Earthquake

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Abstract The 23 August 2011 Mineral, Virginia, earthquake (M_w 5.8) was the largest to strike the eastern U.S. since 1897 and was felt over an extraordinarily large area. Although no large landslides occurred, the shaking did trigger many rock and soil falls from steep river banks and natural cliffs in the epicentral area and from steep road cuts along, and northwest of, the Blue Ridge Parkway. We mapped the occurrence of rock falls to determine distance limits that could be compared with those from other documented earthquakes. Studies of previous earthquakes indicated a maximum epicentral distance limit for landsliding of ~60 km for an M 5.8 earthquake; the maximum distance limit for the 2011 earthquake was 245 km, the largest exceedance of the historical limit ever recorded. Likewise, the previous maximum area affected by landslides for this magnitude was 1500 km^2; the area affected by landslides in the 2011 earthquake was 33,400 km^2. These observations provide physical evidence that attenuation of strong shaking for eastern U.S. earthquakes is significantly lower than for plate-boundary earthquakes. Also, distance limits parallel to the regional structural trend are greater than those that transect the structure, which suggests anisotropic attenuation related to the regional geologic structure. Peak ground acceleration (PGA) at the landslide distance limits is estimated to have been about 0.02–0.04g.

Introduction

On 23 August 2011, an M_w 5.8 earthquake occurred near Mineral, Virginia, about 60 km northwest of Richmond (Fig. 1). This was the largest earthquake in the eastern U.S. since the 1897 Giles County, Virginia, earthquake (~M 5.9). We conducted extensive field work to locate landslides triggered by the 2011 earthquake and to determine the maximum distance limits of landsliding for comparison with similar limits from other earthquakes worldwide. We determined that the landslide limits from this earthquake far exceed worldwide norms for earthquakes of similar magnitude; this provides observational confirmation that attenuation of seismic shaking in the eastern U.S. is significantly lower than in the western U.S. and other plate-boundary regions. The overall distribution of landslides also suggests that the regional geologic structure significantly affects attenuation.

In this paper, we briefly describe the earthquake, provide background on previous studies of landslide distance limits, describe our field investigation and its results, and then compare those results with similar published results from other earthquakes. We relate landslide limits to observed measurements of ground shaking and conclude with a discussion of the ramifications of this investigation with respect to strong-shaking attenuation in the eastern U.S.

The 23 August 2011 Earthquake

The 23 August 2011 earthquake was centered about 8 km south-southwest of Mineral, Virginia (37.936° N, 77.933° W). The focal-mechanism solution indicated reverse motion on a fault that lies within the broad area included in the Central Virginia Seismic Zone; focal depth was 6 km (U.S. Geological Survey; see Data and Resources). Aftershock studies indicated that the seismogenic fault strikes N28°E and dips 45° E (Ellsworth *et al.*, 2012). The maximum Modified Mercalli Intensity estimated from the U.S. Geological Survey's Did You Feel It? map was VIII, which indicates very strong shaking and moderately heavy damage. The earthquake was felt from Canada to Florida and westward as far as Texas and Wisconsin. The maximum distance of a felt report was 1673 km, an extraordinary distance for an earthquake of this magnitude (U.S. Geological Survey; see Data and Resources).

Seven seismic stations recorded ground motion within 325 km of the epicenter, the area within which we investigated landslides (Table 1). The maximum recorded peak ground acceleration (PGA) was 0.26g at the North Anna nuclear power plant (NAP), ~18 km from the epicenter. Figure 2 shows PGA as a function of epicentral distance and compares

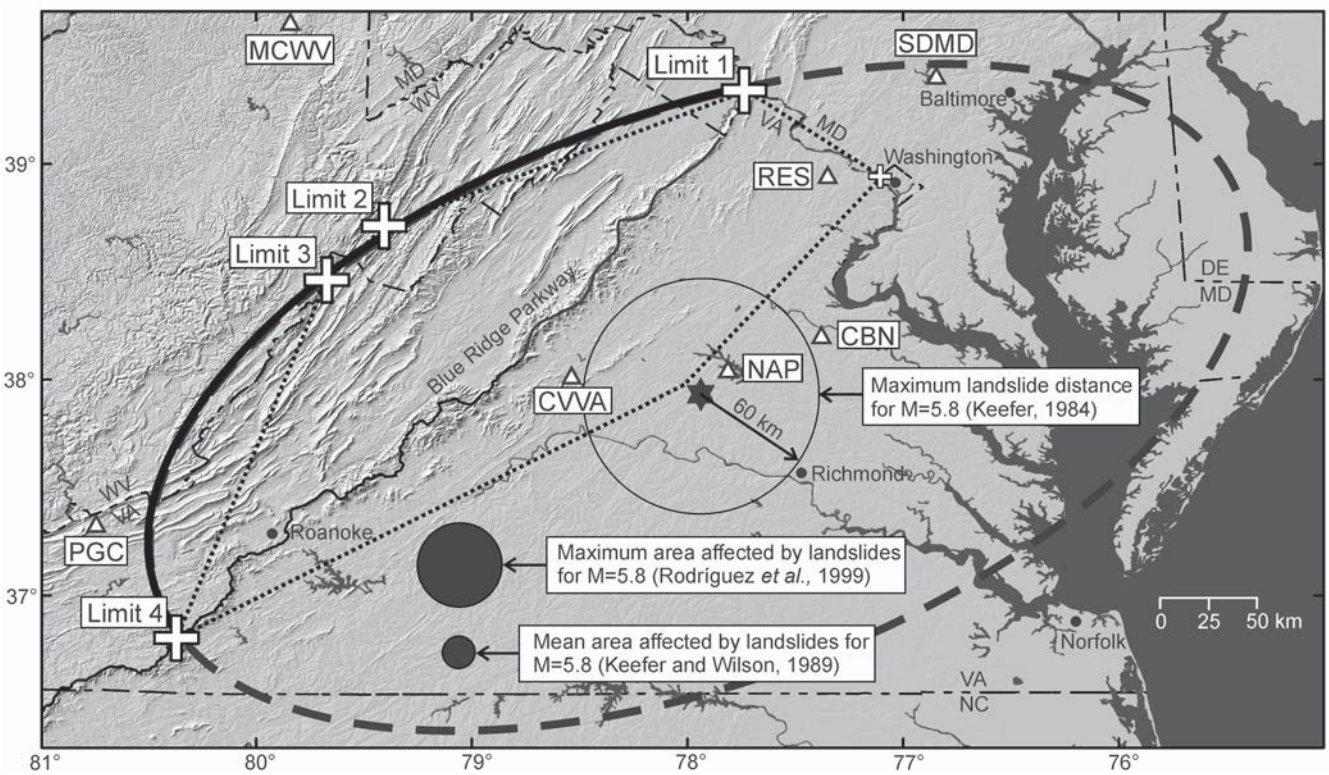

Figure 1. Map showing epicentral region of the 23 August 2011 Mineral, Virginia, earthquake. The star indicates the epicenter; large crosses are landslide limits; the small cross represents the largest landslide observed; triangles represent seismic recording stations with station codes indicated (see Table 1 for station names and codes); and dash-double-dot lines are state boundaries. The bold line shows a best-fit ellipse centered at the epicenter and passing through the observed limits (dashed where inferred beyond limits); the dotted line shows a polygon enclosing the observed landslides; the circle around the epicenter indicates the previous maximum distance limit for *M* 5.8 earthquake (Keefer, 1984); filled circles show maximum (1500 km^2) and average (219 km^2) areas expected to experience landslides for an *M* 5.8 earthquake based on previous studies (Keefer, 1984, 2002; Rodríguez *et al.*, 1999). Sinuous solid line shows Blue Ridge Parkway, which extends along the crest of the Blue Ridge. Abundant susceptible slopes exist from the Blue Ridge to the west and north; few susceptible slopes are present to the south and east.

the observed values from the 2011 Virginia earthquake with values predicted for earthquakes in California (Abrahamson and Silva, 2008) and eastern North America (Campbell, 2003). As expected, ground motions were significantly higher than would have been predicted for California, but they also exceeded predictions for eastern North America in the distance range of ~20–200 km. Figure 3 shows observed Arias (1970) intensity (I_a) as a function of epicentral distance. With one exception, I_a values observed from the 2011 earthquake significantly exceeded values predicted for plate-boundary earthquakes (Travasarou *et al.*, 2003). The station having a lower-than-predicted I_a (Fig. 1, station PGC) is the only station southeast of the epicenter and suggests possible shaking directivity.

Table 1
Strong-Motion Stations

Station	Map ID	Epicentral Distance (km)	PGA* (*g*)	I_a† (m/s)	I_h‡ (m/s)
North Anna Power Plant, Virginia	NAP	18	0.260		
Charlottesville, Virginia	CVVA	54	0.121	0.177	0.350
Corbin, Fredericksburg Observatory, Virginia	CBN	58	0.135	0.143	0.236
Reston Fire Station, Virginia	RES	122	0.092	0.076	0.095
Soldier's Delight Natural Environmental Area, Maryland	SDMD	189	0.021	0.037	0.064
Mont Chateau, West Virginia	MCWV	253	0.006	0.002	0.003
Pearisburg, Giles County, Virginia	PGC	254	0.003	0.0001	0.0002

*Peak horizontal ground acceleration.
†Maximum Arias intensity of the two horizontal strong-motion components.
‡Sum of the Arias intensities of the two horizontal strong-motion components.

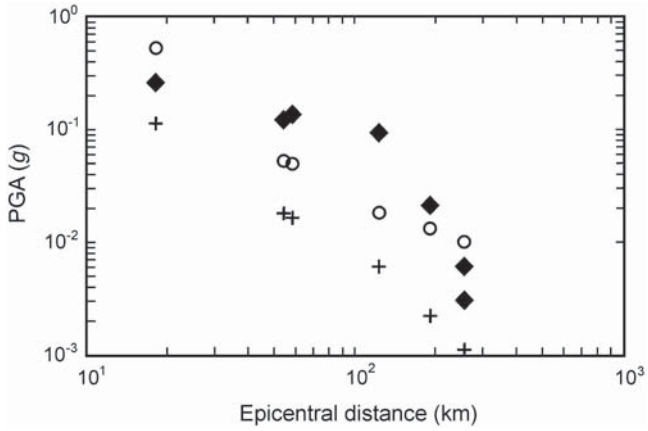

Figure 2. Peak ground acceleration (PGA, diamonds) plotted as a function of epicentral distance for the seven stations listed in Table 1. Crosses represent ground motions predicted for California earthquakes (Abrahamson and Silva, 2008); circles indicate ground motions predicted for eastern North American earthquakes (Campbell, 2003).

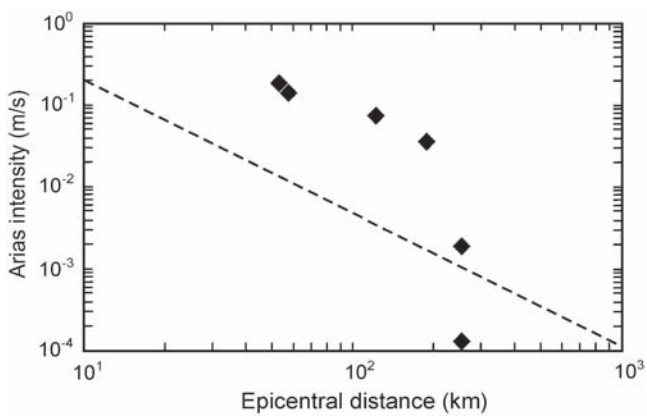

Figure 3. Arias (1970) intensity (diamonds) plotted as a function of epicentral distance for the seven stations listed in Table 1. The dashed line represents predicted Arias intensity for California earthquakes (Travasarou *et al.*, 2003).

Background on Landslide Limits from Earthquakes

Documentation of distance limits for landslides triggered by earthquakes provides a physical basis to relate strong shaking to landslide triggering. Keefer (1984) compiled landslide reports from 40 worldwide earthquakes and related the maximum epicentral and fault-rupture distances of various categories of triggered landslides to earthquake magnitude; he drew upper-bound curves to define maximum distance as a function of magnitude (Fig. 4). He also measured areas enclosed by reported landslides and constructed an upper-bound area curve as a function of magnitude (Fig. 5). Keefer and Wilson (1989) supplemented the 1984 data set with additional data points and calculated a regression curve relating earthquake magnitude to average area affected by landslides. Rodríguez *et al.* (1999) and Keefer (2002) updated the original 1984 data set with more recent observations and

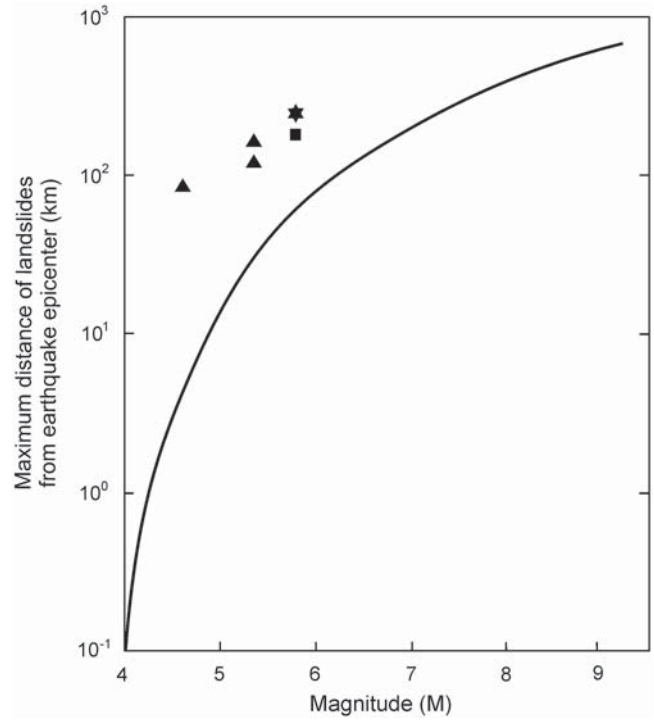

Figure 4. Curve showing maximum epicentral distance limit of disrupted landslides from 40 historical earthquakes as a function of earthquake magnitude (modified from Keefer, 1984). Earthquake-triggered landslides that exceeded previous historical distance limits are shown as follows: triangles are earthquakes from the Colorado Plateau region (Keefer, 2002); square is the 1988 Saguenay, Canada, earthquake (Lefebvre *et al.*, 1992); star is the 2011 Virginia earthquake.

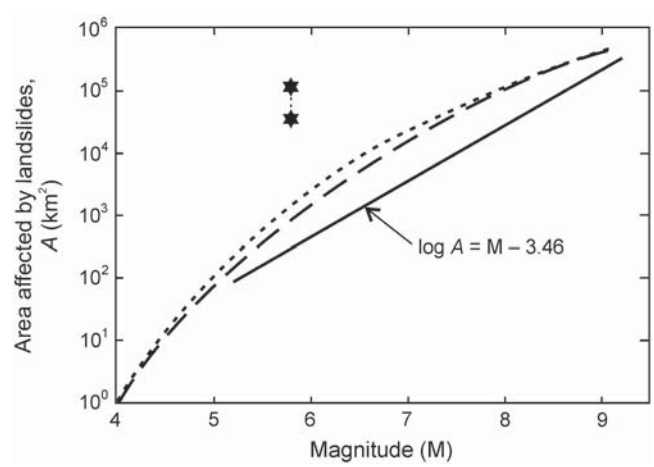

Figure 5. Curves showing areas affected by landslides in historical earthquakes as a function of earthquake magnitude (modified from Keefer, 2002). The solid line indicates the best-fit regression line from Keefer and Wilson (1989) indicating the average area affected; the long-dashed line is approximate upper bound from Keefer (1984); the short-dashed line is upper bound from Rodríguez *et al.*, (1999); the lower star is area enclosed by observed landslide limits from the 2011 Virginia earthquake; the upper star indicates the area of best-fit ellipse shown in Figure 1.

replotted the distance and area curves (Fig. 5). A few earthquakes exceeded the 1984 distance limits, and upper-bound curves were adjusted accordingly. These studies provide a reliable baseline for expected landslide distances and affected areas during earthquakes.

Keefer (1984) observed no differences in areas affected by landslides that could be related to regional differences in seismic attenuation. His data set, however, contained only two earthquakes from the stable continental interior of the central and eastern U.S.: the 1811–12 New Madrid, Missouri, and 1886 Charleston, South Carolina, earthquakes. Landslides from earthquakes in those times and places, however, were not documented rigorously, and these two events do not provide a statistically significant characterization of landslides limits in the eastern and central U.S. Keefer's (2002) later work added data points from landslides triggered by earthquakes in the Colorado Plateau (e.g., Jibson and Harp, 1996) and eastern Canada (Lefebvre *et al.*, 1992) that exceeded his previous upper bounds. These additional observations suggest that attenuation differences do lead to greater landslide distances and areas in non-plate-boundary earthquakes.

Wilson and Keefer (1985) and Keefer and Wilson (1989) related magnitude–distance limits for landslides to a magnitude–distance relationship for I_a to estimate the threshold level of shaking needed to trigger the smallest landslides. Harp and Wilson (1995) quantified the relation between landslide limits and instrumentally recorded strong ground shaking using observations from the 1987 Whittier Narrows and Superstition Hills earthquakes in Southern California. While further research still is needed on this subject, these studies laid the groundwork for the quantification of threshold ground motions required to trigger landslides.

Field Investigation

From 25 August through 3 September 2011, we conducted field reconnaissance to map limits of triggered landslides. This work involved driving outward from the epicentral area in transects of various directions and inspecting highly susceptible slopes, mainly steep road cuts in fractured or weathered rock and soil. For a given transect, we plotted locations of landslides until an apparent limit was reached; we continued each transect until we observed several highly susceptible outcrops that lacked landslides and were convinced we were beyond the limit. Locations of landslides were plotted on paper maps, and global positioning system coordinates of their locations were recorded. Results were later transferred to a digital database to facilitate analysis and publication.

Determining limits of landslides in this geographic region was challenging because of the paucity of highly susceptible slopes in much of the area. The epicenter and areas to the south and east are in the piedmont and coastal plain provinces and contain few highly susceptible slopes. Although we did find some small soil and rock falls along stream banks and rock cliffs near the epicenter, our field investigation primarily was confined to more steeply sloping areas west and north of the Blue Ridge Front, the boundary of the Appalachian Mountains (see Fig. 1). Our principal traverses included inspecting the length of the crest of the Blue Ridge from Maryland to North Carolina and making several transects through the Appalachian Mountains into West Virginia.

Landslides Triggered by the Earthquake

The earthquake triggered no large, damaging landslides. The largest triggered landslide had a volume of perhaps 100 m^3; other triggered landslides ranged in volume from ~5 m^3 down to small rock fragments a few centimeters across. This is not surprising given the moderate magnitude of the earthquake. Strong shaking from shallow earthquakes of moderate magnitude is brief and tends to be concentrated in the higher frequency range; such shaking tends to trigger small, shallow landslides in brittle, weathered surficial material and is unlikely to trigger large, deep landslides.

Most triggered landslides we observed were small rock and soil falls from steep, highly susceptible slopes, most commonly road cuts (Fig. 6). Because landslides can occur without earthquake shaking, determining a seismic origin for these small features required evidence of recency; we generally attributed an earthquake origin if (1) rocks were resting on vegetation that was still green beneath the landslide material (Fig. 7) or (2) we could see a fresh source area in the slope above the deposit.

Hurricane Irene passed along the Atlantic coastal area a few days after the earthquake. Rainfall in the Appalachian region was only moderate: records for 27–28 August 2011 indicate about 13 mm of rainfall along the Blue Ridge in central Virginia (Weather Underground; see Data and Resources). This amount of rainfall is indistinguishable from what normally occurs in this area: in the previous two weeks, 19 mm of rain fell, mostly during a thunderstorm that produced 14 mm of rainfall. We saw some very small (<1 m^3) debris flows from soil-covered outcrops that were probably triggered by the hurricane-induced rainfall; these features were quite distinct from the rock falls triggered by the earthquake, and we feel confident in distinguishing between failures triggered by the earthquake and by rainfall from Hurricane Irene.

Landslide Limits

Four landslide limits were determined as a result of our field investigation (Fig. 1). The northeastern limit was in southern Maryland just north of Harpers Ferry, West Virginia. Small rock fragments were present on top of green vegetation along slopes of the diminishing Blue Ridge; inspection of nearby slopes revealed no additional landslides farther to the northeast. In Harpers Ferry, just 2 km south of the limit, a boulder several decimeters across was shaken loose by the

Figure 6. Example of earthquake-triggered rock fall from a road cut along the Blue Ridge Parkway. The color version of this figure is available only in the electronic edition.

earthquake and rested on green vegetation. The unequivocal failure in Harpers Ferry that is a short distance from the much smaller rocks in Maryland provides confidence that the northeastern limit, 158 km from the epicenter, is well located.

The southwestern limit is well constrained by observed small rock falls on road cuts along the Blue Ridge Parkway. We mapped rock falls southwestward until they no longer were present on steep, highly susceptible slopes similar to those that produced observed rock falls. The consistency of steep road cuts along the parkway gives a high degree of confidence that the observed limit is reliable. This limit is 245 km from the epicenter, the farthest of the limits.

Two northwestern limits were determined by making traverses both outward and inward through the Appalachian Mountains. This allowed us to look for the last occurrence of landslides on the outbound traverse and the first occurrence of landslides on that of the inbound. The two limits, having epicentral distances of 151 and 158 km, were remarkably concordant and provided confidence in our ability to identify earthquake-triggered features.

As indicated above, the lack of highly susceptible slopes to the east and south of the Blue Ridge made it impossible to identify landslide limits in those directions; thus, the limit is well constrained only in the directions previously described. To get an idea of what a perfectly constrained limit might look like if equally susceptible slopes were present everywhere, we fit an ellipse to the observed limits, which was constrained to be centered at the epicenter and to pass through or near the four observed limits (Fig. 1). The ellipse encloses Washington, D.C., which is reasonable considering the observed building damage there. A rock fall along the Potomac River near the western edge of the District of Columbia (Fig. 8) also suggests that the estimated ellipse is realistic. This was the largest observed triggered landslide and had a volume of $\sim$100 m^3.

Comparison of Landslide Limits with Historical Data

The landslide limits from the Virginia earthquake are remarkable when compared to historical landslide limits from worldwide earthquakes. Figure 4 shows Keefer's (1984, 2002) historical distance limit for disrupted landslides as a function of magnitude for 40 worldwide earthquakes; subsequent earthquakes that have triggered landslides well beyond this limit also are shown. The curve indicates a distance limit of about 60 km for an M 5.8 earthquake. The farthest landslide from the 2011 Virginia earthquake was 245 km from the epicenter. The 1988 Saguenay, Canada, earthquake (also

Figure 7. Rock falls triggered by the earthquake were identified, in part, by looking for green vegetation under fallen rocks, which indicated very recent deposition. The color version of this figure is available only in the electronic edition.

an M 5.8) triggered landslides at about 180 km, which also exceeded the historical distance limit. These slides occurred in highly sensitive glacial clays and are considered a special case (Rodríguez *et al.*, 1999). The landslide limit for the 2011 Virginia earthquake represents the largest exceedance of historical landslide distance limits ever recorded.

Even more remarkable is the total area affected by landslides. Areas of landsliding in historical studies are defined simply as the area of a polygon enclosing all observed landslides. Figure 5 shows data from Keefer (1984, 2002) and Rodríguez *et al.* (1999), including an upper bound curve for observed areas of landsliding from historical earthquakes. Again, the 1988 Saguenay earthquake exceeded the historical limit, but it is a special case. Bommer and Rodríguez (2002) also reported two earthquakes in Guatemala of slightly smaller magnitude than the Virginia earthquake that had areas affected by landslides of ~6000 km^2, which exceeds the Rodríguez *et al.* (1999) limit. The upper-bound curve indicates an area of ~1500 km^2 for an M 5.8 earthquake. A polygon enclosing all observed landslides from the 2011 Virginia earthquake (see Fig. 1) has an area of about 33,400 km^2, more than 20 times greater than observed previously. The best-fit ellipse shown in Figure 1 has an area of about 135,000 km^2 and would exceed the historical norms by almost two orders of magnitude. Keefer and Wilson (1989) calculated a regression line to predict average area affected as a function of magnitude; the average area for an M 5.8 is 219 km^2. The observed area in 2011 is more than 150 times as large as the average area, and the projected area of the ellipse is more than 600 times as large.

Relation of Landslide Limits to Ground Shaking

Relating landslide limits to measured or inferred ground-shaking levels provides direct observational evidence of the threshold ground shaking needed to trigger the smallest landslides. Identifying such a threshold then provides a tool for interpretation of landslide limits in future earthquakes. PGA values from the 2011 Virginia earthquake in the study area ranged from a high of 0.26g at the NAP, 18 km from the epicenter, down to 0.003g in Giles County, Virginia (PGC), 254 km from the epicenter (Table 1). I_a was calculated where seismic records were accessible. Values of I_a (the larger I_a of the two horizontal components) ranged from 0.177 m/s in Charlottesville (CVVA) down to 0.0001 m/s in Giles County (no I_a value is available for the NAP). Values of I_h (the sum of the I_a values of the two

Figure 8. Rock fall along the Potomac Heritage Trail in the District of Columbia. This was the largest observed landslide and had a volume of perhaps 100 m^3. (Photograph by Greg Bayens, used with permission.) The color version of this figure is available only in the electronic edition.

horizontal components) ranged from 0.350 m/s in CVVA to 0.0002 m/s in Giles County.

One strong-motion recording (SDMD) was located fortuitously near the inferred landslide limit (see Fig. 1); at that location, $\text{PGA} = 0.021g$, $I_a = 0.037$ m/s, and $I_h = 0.064$ m/s. This station, located in the Soldiers Delight Natural Environmental Area in Maryland, rests on thin soil over hard bedrock, site conditions that should not produce significant amplification. Figure 9 shows horizontal-to-vertical spectral ratios (HVSRs) of three seismic stations; the SDMD record shows no significant site amplification. Thus, station SDMD provides the best instrumental observation of the threshold ground shaking for the triggering of landslides in this earthquake.

The U.S. Geological Survey's *ShakeMap* for the earthquake used both the sparse instrumental readings and a large number of intensity observations to produce a map that estimates ground motion throughout the epicentral region (U.S. Geological Survey; see Data and Resources). Table 2 shows the inferred *ShakeMap* ground accelerations at the four observed landslide limits; PGA values are ~0.02–0.04g. These *ShakeMap* values at the landslide limits are consistent with the instrumental reading of 0.021g on the inferred limit at station SDMD, as previously discussed.

Previous studies that related ground motion to landslide limits commonly used I_a as the measure of ground motion. Wilson and Keefer (1985) related the landslide distance limits from Keefer (1984) to a rather poorly constrained magnitude–distance relation for I_a to estimate a threshold I_a value of 0.15 m/s for the triggering of disrupted landslides such as the rock falls observed in the Virginia earthquake. Keefer and Wilson (1989) updated this analysis and proposed a slightly lower threshold of 0.11 m/s. These values are 3–4 times greater than the observed value of 0.037 m/s at the SDMD site.

Harp and Wilson (1995) provided a much better constrained study relating landslide limits to instrumentally recorded ground motions from the 1987 Superstition Hills and Whittier Narrows, California, earthquakes. Their study developed thresholds in terms of I_h, the sum of the two

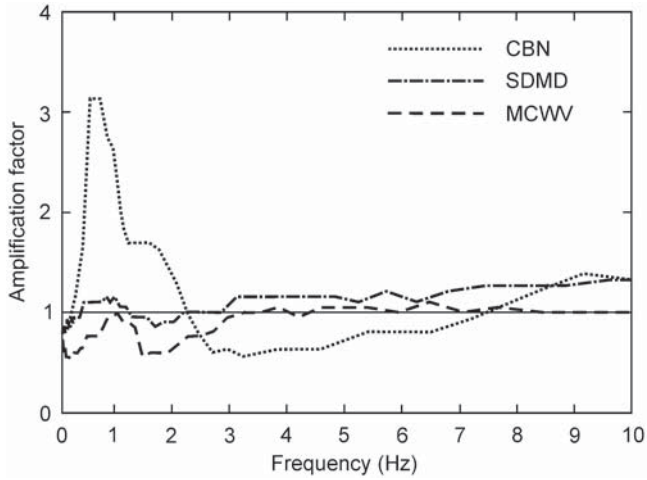

Figure 9. Horizontal-to-vertical spectral ratios (Nakamura, 1989) of three seismic recordings from the 2011 Virginia earthquake (See Table 1 for station list). Station CBN had an amplification spike at ~1 Hz; no other significant amplification occurred at any station, including strong-motion recording (SDMD), which lies near the inferred landslide limit.

horizontal I_a values from strong-motion records. They determined different threshold ranges for the two predominant rock types in the region: $I_h = 0.08 - 0.60$ m/s for Tertiary and younger rocks and $I_h = 0.01 - 0.07$ m/s for Mesozoic and older rocks. The observed I_h of 0.064 m/s at the SDMD site falls within the range for older rocks in Southern California, which is reasonable because the rock falls from the Virginia earthquake occurred overwhelmingly in Paleozoic and Proterozoic rock formations.

Discussion

The landslide limits from the 2011 Virginia earthquake exceeded historical distance limits by a greater amount than in any other documented earthquake. At least two reasons for this can be considered. First, very few earthquakes in stable continental interiors, where ground-motion attenuation is known to be lower than in plate-boundary regions, have had thorough documentations of triggered landslides. As stated previously, earlier studies of landslide limits (Keefer, 1984, 2002; Rodríguez *et al.*, 1999) included only three earthquakes from stable continental interiors: the 1811–12 New Madrid, Missouri; 1886 Charleston, South Carolina; and 1988 Saguenay, Canada, earthquakes. Landslide limits for the first two of those earthquakes fell within the normal range established by other worldwide earthquakes, but neither of those earthquakes had thorough investigations of triggered landslides, and it is possible that smaller, more distant landslides were triggered but not reported. The landslide limit from the 1988 Saguenay earthquake exceeded previously published limits (Rodríguez *et al.*, 1999; Keefer, 2002), but the landslides at the far limit were a special case: they occurred in highly sensitive clays that responded to low-frequency, low-amplitude, long-duration shaking. Thus, the paucity of data on landslides triggered in stable-continental-interior earthquakes is one probable reason that previously published landslide limits were exceeded in 2011.

Table 2
Estimated Ground-Motion Values at Landslide Limits

Location	Latitude	Longitude	Epicentral distance (km)	*ShakeMap* PGA* (*g*)
Limit 1	39.3398°	−77.7310°	158	0.039
Limit 2	38.7101°	−79.4032°	151	0.021
Limit 3	38.4601°	−79.6662°	158	0.021
Limit 4	36.8047°	−80.3630°	245	0.015

*Peak horizontal ground acceleration.

A second possible reason for the exceedance of previous limits is the different level of investigation that contemporary earthquakes receive relative to historical earthquakes. Most of Keefer's (1984) data were from published reports of general observations of the effects of each earthquake. In few of those investigations (noted in the paper) were landslides the specific target of the investigation; therefore, it is likely that some smaller, more distant landslides were not reported. By contrast, in many contemporary earthquakes thorough and detailed field investigations of landslides are conducted to find and map the very smallest, most distant landslides to establish limits (Harp *et al.*, 2011). In some earthquakes that triggered large or damaging landslides, however, the focus of the investigations has been primarily on these larger landslides (e.g., Jibson *et al.*, 2006). Also, many investigations have focused more on the area of concentrated landsliding rather than the extreme limits of very small slides (e.g., Bommer and Rodríguez, 2002). Thus, extreme limits from recent, rigorous investigations are perhaps not directly comparable to limits estimated from older generic reports of landslides from historical earthquakes or from other types of contemporary landslide investigations.

Even taking differential landslide reporting into account, the landslide limits from the 2011 Virginia earthquake are extraordinary. This significant exceedance of previous limits, along with other documented cases of exceedance from non-plate-boundary earthquakes, suggests the need to establish different upper bounds for landslide occurrence for different tectonic environments. Gathering sufficient data from non-plate-boundary earthquakes might take a long period of time because of their relative infrequency, but we now have enough data points from such earthquakes to suggest a significant difference in landslide limits, which presumably relates to different levels of ground-shaking attenuation in these regions.

The southwestern limit (Fig. 1, Limit 4) is much farther from the epicenter than that of the northeastern limit (Fig. 1, Limit 1). The northeastern limit was observed where the Blue Ridge is diminishing in height and where highly susceptible slopes became much more sparse. Thus, it is unclear if this limit represents a shaking threshold or simply an end to highly susceptible slopes. The inferred elliptical landslide

limit (Fig. 1) extends northeastward well beyond the observed northeastern limit.

The limits to the northwest (Fig. 1, Limits 2 and 3), which lie perpendicular to the regional structural trend, are much closer to the epicenter than are the observed southwestern limit and the inferred limit to the northeast, which lie sub-parallel to the structural trend and to the fault plane defined by aftershock studies (Ellsworth *et al.*, 2012). This suggests that strong-motion attenuation perpendicular to the regional structure is significantly greater than attenuation parallel to the structure. This same pattern is visible in the U.S. Geological Survey Did You Feel It? and *ShakeMap* plots (U.S. Geological Survey; see Data and Resources). Thus, the observed landslide distribution is fully consistent with other sources of intensity information. Azimuthally dependent attenuation in the Appalachians also was observed by Jones *et al.* (1977) in a study of ground motions generated by 72 earthquakes of M 1.9–4.7 that occurred in the southeastern U.S. from 1963 through 1975. Observations from the 2011 earthquake, which appear to corroborate the earlier study just cited, suggest that azimuthal differences in attenuation might be significant enough in this region that attenuation equations should be adjusted to account for it.

The good agreement of estimated ground-shaking levels at the landslide limits in Virginia as compared with those from previous studies suggests that $I_h = 0.01$–0.07 m/s (for pre-Cenozoic rocks) and PGA $= 0.02$–$0.04g$ are reasonable values for the threshold ground shaking necessary to trigger the smallest landslides from the most susceptible slopes. Determining landslide limits in future poorly recorded earthquakes thus could help constrain some characteristics of regional ground motions.

Conclusion

Shaking from the 2011 Virginia earthquake triggered small rock falls from steep road cuts and natural slopes at extraordinary epicentral distances as compared with limits determined from historical earthquakes, most of which occurred in plate-boundary regions. The previous historical limit for an M 5.8 earthquake was ~60 km; the 2011 earthquake triggered landslides 245 km from the epicenter. Previous studies indicated that the maximum area expected to experience landslides in an M 5.8 earthquake is about 1500 km^2; the 2011 earthquake triggered landslides over an area of about 33,400 km^2. PGA values at the landslide limits were 0.02–$0.04g$, which provides a reasonable threshold value for the triggering of small landslides from the most susceptible slopes. These observations constitute a physical confirmation of the observation that strong-motion attenuation in the eastern U.S. is significantly lower than in plate-boundary regions. The inferred elliptical distribution of landslides, elongated sub-parallel to the regional geologic structure, also suggests anisotropic attenuation that is lower parallel to the geologic structure and higher perpendicular to the structure.

Data and Resources

Seismic records used in this study came from the Center for Engineering Strong Motion Data (CESMD) website (www.strongmotioncenter.org; last accessed July 2012) or from the U.S. Geological Survey NEIC archives. Data on the 2011 Virginia earthquake is from the following U.S. Geological Survey earthquake website: http://earthquake.usgs.gov/earthquakes/recenteqsww/Quakes/se082311a.php (last accessed July 2012). Did You Feel It? information for the 2011 Virginia earthquake is from the following U.S. Geological Survey website: http://earthquake.usgs.gov/earthquakes/dyfi/events/se/082311a/us/index.html (last accessed July 2012). *ShakeMap* information for the 2011 Virginia earthquake is from the following U.S. Geological Survey website: http://earthquake.usgs.gov/earthquakes/shakemap/global/shake/082311a/ (last accessed July 2012). Rainfall data came from the following Weather Underground websites: http://www.wunderground.com/history/airport/KOKV/2011/8/27/DailyHistory.html?req_city=NA&req_state=NA&req_statename=NA, and http://www.wunderground.com/history/airport/KOKV/2011/8/28/DailyHistory.html?req_city=NA&req_state=NA&req_statename=NA (last accessed July 2012). All other data used in this paper were collected by the authors or came from published sources listed in the references.

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