UNITED STATES OF AMERICA
NUCLEAR REGULATORY COMMISSION

BEFORE THE ATOMIC SAFETY AND LICENSING BOARD

Ronald M. Spritzer, Chair
Dr. Richard F. Cole
Dr. Alice C. Mignerey
Alan S. Rosenthal

In the Matter of Virginia Electric and Power Company d/b/a Dominion Virginia Power and Old Dominion Electric Cooperative North Anna Unit 3 Combined License	Docket Nos. 52-017 ASLBP No. 08-863-01-COL March 7, 2014

MOTION TO REOPEN AND ADMIT NEW CONTENTION

Pursuant to 10 C.F.R. § 2.326, and in accord with the Atomic Safety and Licensing Board (ñASLBò) orders issued July 23, 2013[1], July 26, 2012[2] and September 1, 2011,[3] the Blue Ridge Environmental Defense League and its chapter Peoples Alliance for Clean Energy (ñBREDLò or ñIntervenorò) hereby request to reopen this proceeding and to file a new contention based on new information. The Intervenorôs contention is that Dominion-Virginia Power (ñApplicantò) has not presented a sound probabilistic basis for

[1] ASLB Order Holding Motion to Reopen the Proceeding in Abeyance: ñBREDL asserts that the petition was timely filed following the April 26, 2013 announcement by the applicants...that they will amend their combined operating license (COL) application to utilize a new reactor design. [citation omitted]

[2] ASLB Order Setting Time for Filing Motion to Reopen the Proceeding: ñIn consideration of the significant revisions that Dominion will make in its application, and the strict procedural requirements of a section 2.326 motion to reopen, we adopt BREDLôs suggestion and will grant a period of 60 days for BREDL to submit a motion to reopen the proceeding.ò

[3] LBP-11-22 states: ñ[W]e have already found that BREDL demonstrated standing pursuant to 10 C.F.R. § 2.309(d), and that it proffered one admissible contention as required by 10 C.F.R. § 2.309(f). Therefore, BREDL met the criteria for intervention and, as explained in the Commissionôs hearing notice, it became a party to the licensing proceeding and entitled to participate fully in the conduct of the hearing.ò

the magnitude of the possible adverse consequences and the likelihood of occurrence of each consequence for issuing a license to construct and operate North Anna Unit 3.

Background

On October 2, 2010 Blue Ridge Environmental Defense League filed a contention, which the ASLB declined to admit, regarding earthquake factors at North Anna.[4] LBP-11-10.

On August 23, 2011, an alert was declared under Emergency Action Level EAL HA6.1 at the North Anna Power Station which was caused by seismic activity onsite. Both units underwent automatic reactor trips of 100% power and all offsite electrical power to the site was lost. On September 22, 2011, pursuant to 10 C.F.R. § 2.309 and in accordance with the ASLB order issued September 1, 2011,[5] BREDL sought to file a new contention based on the earthquake of August 23, 2011. Subsequently, parties to the proceeding agreed that the proposed contention be held in abeyance until Dominion completed its reassessment of the Unit 3 application.[6] On June 7, 2012 the Commission ordered that the record of the proceeding be closed. *See* CLI-12-14 at 15. Subsequently, the Board issued an order allowing sixty days for the Intervenor to move for reopening the proceeding for seismic issues.[7]

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[4] In Contention 13, ñUnit 3 Seismic Spectra Exceedance,ò Intervenor argued that Dominion improperly requested a site-specific exemption from the APWR Design Control Document for proposed North Anna Unit 3. in violation of 10 C.F.R. §§ 52.7, 52.93, and 100.23.

[5] LBP-11-22 states: ñ[W]e have already found that BREDL demonstrated standing pursuant to 10 C.F.R. § 2.309(d), and that it proffered one admissible contention as required by 10 C.F.R. § 2.309(f). Therefore, BREDL met the criteria for intervention and, as explained in the Commissionôs hearing notice, it became a party to the licensing proceeding and entitled to participate fully in the conduct of the hearing.ò

[6] *Consent Motion to Hold BREDL's New Contention in Abeyance* (Oct. 12, 2011)

[7] *ORDER (Setting Time for Filing Motion to Reopen the Proceeding)* July 26, 2012. At that time, the seismic assessment was expected to be completed in May 2013.

Motion to Reopen: Satisfaction of 10 C.F.R. § 2.326:

(a.1) The motion is timely. On January 6, 2014, an email from the Commission Secretary notified the Intervenor of the availability of a document entitled ñDominion Ltr re Completion of Seismic Assessment.ò The deadline set forth in the letter for submitting a motion to reopen was today, March 7, 2014.

(a.2) The motion addresses a significant issue. The NRC must make a determination under the Atomic Energy Act that it has a reasonable assurance that the facility will be constructed and will operate in conformity with the provisions of the Act and the Commissionôs rules and regulations. Under NEPA, the NRC must also evaluate the environmental impacts of the plant. As presented in detail *infra*, the proposed design of Unit 3 is unsuitable for the North Anna site.

(a.3) Demonstration that a materially different result would be likely. The contention is within the scope of this proceeding and material to the findings the NRC must make to support Dominionôs request to build and operate a third reactor at North Anna. If standards cannot be met and a license is altered, a modified power plant would be substituted; alternatively, if the license is denied, no reactor will be constructed.

(b) Attached to this motion is an assessment of quake impacts on North Anna by Christopher M. Bailey, Ph.D., Professor and Chair of the Geology Department at The College of William and Mary.[8]

[8] ñAll Shook Up! The 2011 Virginia Earthquake,ò Christopher M. Bailey, December 22, 2011

Admissibility: Satisfaction of 10 C.F.R. § 2.309(f)(1)

Case Law Cited

Private Fuel Storage, L.L.C. (Independent Spent Fuel Storage Installation), CLI-0603, 63 NRC 19, 24 (2006). Intervenor moved to allow litigation of a new version of a previously rejected contention.

In general, a new contention must satisfy the timeliness requirement of either 10 C.F.R. §§ 2.309(f)(2) or 2.309(c), and the admissibility requirements of Section 2.309(f)(1). See Entergy Nuclear Vermont Yankee, LLC & Entergy Nuclear Operations, Inc. (Vermont Yankee Nuclear Power Station), LBP-06-14, 63 NRC 568, 571-76 (2006).

ñBREDL has established its right to a hearing on óall material factors bearing on the licensing decision.ôò LBP-11-22 at 13, f.n. 58, citing *Union of Concerned Scientists*, 735 F.2d at 1443.

(i) Provide a specific statement of the issue of law or fact to be raised

Geologic and seismic criteria are found in 10 CFR § 100.23 and detail the requirements for determining whether a proposed site is acceptable for a nuclear power plant. The rule states that geological, seismological, and engineering characteristics of a site and its surrounding area environs must be investigated in sufficient detail to provide sufficient information to arrive at estimates of the Safe Shutdown Earthquake Ground Motion. The area to be investigated must be based on the nature of the region surrounding the proposed site. The August 23, 2011 earthquake is now, according to this rule, part of the ñnatureò of the site which must be investigated.

Under in 10 CFR § 100.23, this data would include vibratory ground motion, tectonic surface deformation, nontectonic deformation, earthquake recurrence rates, fault

geometry and slip rates, site foundation material, and seismically induced floods and water waves. However, gathering of these data may have been hampered. For example, the August 2011 quake apparently generated horizontal acceleration 100% over the existing North Anna standard, causing numerous problems such as an electronic sensor failure of eight seconds before power was restored. In order to comply with 10 CFR § 100.23, these data were essential to the determination of the geological, seismological, and engineering characteristics of the North Anna Unit 3 site.

Pursuant to 10 CFR §52.47, Contents of applications, the COL application must contain a level of design information sufficient to enable the Commission to reach a conclusion on all safety questions. Specifically, the North Anna Unit 3 COLA ñmust contain a final safety analysis report (FSAR) that describes the facility, presents the design bases and the limits on its operation, and presents a safety analysis of the structures, systems, and components and of the facility as a whole.ò This includes an assessment of site itself.

(ii) Provide a brief explanation of the basis for the contention

The principal objective of the Nuclear Regulatory Commissionôs adjudicatory process is to produce an informed record which supports sound decision making for the protection of public health and safety and the environment. *Hydro Resources Inc*. CLI-01-4, 52 NRC 31, 38 (2001). Before a COL may be issued, the new information triggered by the central precipitating events of August 23, 2011 and developed and revealed in subsequent investigations must be assessed and integrated into the FSAR, ER, FEIS and other required documents.

(iii) Demonstrate that the issue raised in the contention is within the scope of the proceeding

Before licensing the proposed North Anna nuclear power plant, the NRC must make a determination under the Atomic Energy Act that it has a reasonable assurance that the facility will be constructed and will operate in conformity with the provisions of the Act and the Commissionôs rules and regulations. Under NEPA, the NRC must also evaluate the environmental impacts of the plant. The contention is within the scope of this proceeding and material to the findings the NRC must make to support Dominionôs request to build and operate a third reactor at North Anna. Each reactor is designed for a different ground motion that is determined on a site-specific basis:

> New reactors are designed using probabilistic techniques that characterize both the ground motion levels and uncertainty at the proposed site. These probabilistic techniques account for the ground motions that may result from all potential seismic sources in the region around the site. Technically speaking, this is the ground motion with an annual frequency of occurrence of $1x10^{-4}$/year, but this can be thought of as the ground motion that occurs every 10,000 years on average.[9]

The contention is within the scope of the proceeding because it seeks to ensure compliance with AEA, NEPA and NRC implementing regulations.

(iv) Demonstrate that the issue raised in the contention is material to the findings the NRC must make to support the action that is involved in the proceeding

NRC must show that licensing of North Anna 3 reactors would not be ñinimical to public health and safety.ò 42 U.S.C. § 2133. Further, the technical issues raised by the August 2011 quake are central to the safety determinations which NRC must make. Under Section 182a of the Atomic Energy Act, technical specifications have the statutory function of allowing the Commission to make its operational safety finding. Section

[9] NRC frequently asked questions related to the March 11, 2011 Japanese Earthquake and Tsunami, available at http://www.nrc.gov/japan/faqs-related-to-japan.pdf

182a also requires the issued license to include technical specifications. Section 185b of the Atomic Energy Act governs the issuance of combined licenses and requires the Commission to find, before issuing the license that ñthe facility will be constructed and will operate in conformity with the license, the provisions of this Act, and the Commissionôs rules and regulations.[10]

Technical specifications include *inter alia* SCDF: Seismic core damage frequency. SCDF is the probability of damage to the core resulting from a seismic initiating event. ñIn nuclear power plant seismic risk assessment, the site earthquake-induced vibratory ground motion is usually expressed in terms of the peak ground acceleration (PGA).ò Appendix A Seismic Core-Damage Frequency Estimates.

The National Environmental Policy Act requires federal agencies to supplement environmental documents when ñthere are significant new circumstances or information relevant to environmental concerns and bearing on the proposed action or its impacts.ò 40 C.F.R. § 1509(c)(1)(ii). As a federal agency, it is clearly the NRCôs continuing duty to assess environmental impacts of their actions, to determine the significance of the new data and prepare supplemental documentation. *Warm Springs Task Force v. Gribble*, 621 F.2d at 1023-24; *Stop H-3 Association v. Dole,* 740 F.2d 1442, 1463-64 (9th Cir. 1984). A materially different result can be based on different conclusions of the EIS; e.g., environmental impacts identified as SMALL would instead be classified as MODERATE or LARGE. A supplemental EIS is required when ñthere are substantial changes in the proposed action that are relevant to environmental concerns; or there are new and significant circumstances or information relevant to environmental concerns and bearing on the proposed action or its impacts.ò 10 C.F.R. § 51.92

[10] SECY-08-0142, September 25, 2008

(v) Provide a concise statement of the alleged facts or expert opinions which support the requestor's/petitioner's position on the issue and on which the petitioner intends to rely at hearing, together with references to the specific sources and documents on which the requestor/petitioner intends to rely to support its position on the issue

First, in 2010, the NRC itself rated the North Anna plant as the seventh riskiest of all nuclear reactors in the U.S.

Second, in a seismic hazard analysis conducted for Generic Issue 199, in four ESP submittalsð North Anna, Grand Gulf, Vogtle, and Clintonð the seismic hazard was found to be higher over most frequency ranges compared to an earlier Electric Power Research Institute/Seismicity Owners Group (EPRI-SOG) study.[11]

Third, probabilistic risk assessments conducted for the North Anna 3 COLA and other documents do not account for unexpected failure modes:

> The lesson from the Fukushima, Chernobyl, and Three Mile Island accidents is simply that nuclear power comes with the inevitability of catastrophic accidents. While these may not be frequent in an absolute sense, there are good reasons to believe that they will be far more frequent than quantitative tools such as probabilistic risk assessments predict. Any discussion about the future of nuclear power ought to start with that realization.[12]

Also,

> [A]s a 1978 Risk Assessment Review Group Report to the NRC pointed out, it is "conceptually impossible to be complete in a mathematical sense in the construction of event-trees and fault-trees é This inherent limitation means that any calculation using this methodology is always subject to revision and to doubt as to its completeness.[13]

Further,

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[11] GI-199 Implications of Updates Probabilistic Seismic Hazard Estimates in Central and Eastern United States on Existing Plants, August 2010, http://pbadupws.nrc.gov/docs/ML1002/ML100270639.pdf

[12] Ramana, NV, ñBeyond our imagination: Fukushima and the problem of assessing risk,ò *Bulletin of the Atomic Scientists*, April 19, 2011. M. V. Ramana, a physicist, is currently appointed jointly with the Nuclear Futures Laboratory and the Program on Science and Global Security, both at Princeton University, and works on the future of nuclear energy in the context of climate change and nuclear disarmament. He is the author of *The Power of Promise: Examining Nuclear Energy in India*, to be published later this year by Penguin Books. Ramana is a member of the Bulletin of Atomic Scientists Science and Security Board.

[13] *Id.*

> When it comes to future safety, nuclear designers and operators often assume that they know what is likely to happen, which is what allows them to assert that they have planned for all possible contingencies. Yet there is one weakness of the probabilistic risk assessment method that has been emphatically demonstrated with the Fukushima I nuclear accidents -- the difficulty of modeling common-cause or common-mode failures.[14]

Finally, attached to this motion is an assessment of quake impacts on North Anna by a geologist at The College of William and Mary which states:[15]

> At the North Anna Nuclear Power Station, 21 km from the epicenter, peak ground accelerations reached ~250 cm/sec^2, more than sufficient to damage unreinforced masonry structures in the epicentral region.
>
> During the quake the southeastern side of the fault (hanging wall) was shoved upward with a maximum displacement of about 1 meter. The total rupture length along the fault was likely 5 to 10 kilometers. There was no rupture at the surface because displacement across the fault did not propagate all the way to the Earthôs surface. The 2011 earthquake occurred along a blind, and previously unrecognized, reverse fault in the Virginia Piedmont.
>
> What makes this quake special is that it was the largest quake to rock the eastern United States in over a century and was felt by more people than any other quake in U.S. history. At the recent American Geophysical Union meeting, Shao and others report a seismic moment of 5.75 x 10^{17} Newton meters for the quake, which translates into ~35 terajoules of energy released (for comparison, World War II-era atomic bombs packed an energy punch of 50 to 90 terajoules).

The region referred to in this analysis is the Central Virginia Seismic Zone and the epicenter was the one near Mineral, Virginia on August 23, 2011.

In addition, the Intervenor will rely on the expertise of Arnold Gundersen who has reviewed this submittal but is unable to provide an affidavit because he is traveling.

(vi) provide sufficient information to show that a genuine dispute exists with the applicant/licensee on a material issue of law or fact

Intervenor has raised contentions regarding seismicity factorsô environmental impacts and plant safety issues at North Anna since 2010, and for almost that long DVP

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[14] *Id.*

[15] ñAll Shook Up! The 2011 Virginia Earthquake,ò Christopher Bailey, December 22, 2011

and NRC staff have opposed them. For example, in Intervenorôs Contention 13, not admitted, Dominion alleged the contention was vague and unsupported. However, it was Dominion which provided evidence that earth movements would exceed the regulatory requirements. Dominion said that it is the Commission which determines if a requested exemption is granted and whether *special circumstances* ñoutweigh any decrease in safety that may result from the reduction in standardization caused by the exemption.ò Intervenorôs Reply to Dominion and NRC Staff Answers, November 4, 2010.

Discussion

The Blue Ridge Environmental Defense League seeks to reopen the proceeding to bring a new contention because events at the North Anna nuclear power site indicate that the design of North Anna Unit 3 is unsuitable for the site. The August 2011 quake registered 5.8 Richter and horizontal acceleration caused earth to move 4½ inches under the 115-ton steel casks storing highly radioactive nuclear waste. The quake was felt by residents from Georgia to Maine and Illinois. Moreover, the basis for the COL, the early site permit completed before these events occurred, is outdated. Nevertheless, the applicant again seeks numerous departures, exceptions and variances in order to gain approval for an NRC license.

Indeed, the August 23, 2011 earthquake has opened a new line of inquiry to determine the risks associated with the construction of a nuclear power plant in the Central Virginia Seismic Zone. The following findings are from an assessment of the impact of the quake on the North Anna plant by the US Geological Survey:[16]

- Decades of study have been unable to link earthquakes in CVSZ to a causative fault.

[16] ñLearning from the 2011 Virginia Earthquake,ò Wright Horton, Geologist, U.S. Geological Survey, March 29, 2012

- Mapped lengths of old faults suggest that, if reactivated, earthquakes larger than M5.8 are possible.
- 2011 quake occurred in a gap in detailed geologic map coverage
- Geologic mapping by VGDMR [*sic*, Virginia Division of Geology and Mineral Resources] and USGS is in progress.

The USGS analysis continues:

> ñBased on evaluation of the U.S. Geological Survey (USGS) data and plant specific data analysis, Dominion has confirmed that the August 23, 2011 **earthquake exceeded the spectral and peak ground accelerations for the Operating Basis and Design Basis earthquakes** (OBE and DBE respectively) for North Anna Units 1 and 2.ò - Operator report to USNRC.[17]

Emphasis in the original. Seismic Shaking Records gathered by USGS comparing the Design Basis Earthquake to data gathered from instruments at the plant on 8/23/11 indicated exceedance of DBE acceleration in all three planes: eastï west, northï south and vertical. From the same report, a photograph of the damage at the Washington National Cathedral illustrates the potential damage. Describing the future situation at North Anna, the USGS assessment lamented: ñFundamentally, we donôt know the cause of earthquakes in this part of the country.ò[18]

Nevertheless, the Applicant seeks departures, exceptions and variances similar to the following:

> Because the SSE is also defined in DCD Tier 1, Table 5.1-1, the changes to the site-specific definition requires a departure from DCD Tier 1 information. Therefore, a request for exemption from DCD Tier 1 information is provided in Exemption 3.

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[17] ñLearning from the 2011 Virginia Earthquake,ò Wright Horton, Geologist, U.S. Geological Survey, March 29, 2012, Slide 9

[18] ñLearning from the 2011 Virginia Earthquake,ò Wright Horton, Geologist, U.S. Geological Survey, March 29, 2012, Slide 20

North Anna 3, Combined License Application, December 2013.[19] According to the updated COLA, the Certified Seismic Design Response Spectra (CSDRS) is 135% of that in the DCD.

Conclusion

The Applicant has tried two different designs for Unit 3. Neither one has been able to meet the standards of the DCDs. Is the geology of the North Anna site unsuitable for construction of a new nuclear power reactor?

Intervenor requests to have the North Anna Unit 3 license application process reopened pending new contentions to be submitted by BREDL to the Atomic Safety and Licensing Board. Intervenor notes that, as of this date, the ESBWR DCD is not yet finalized and still under review. At a minimum, the Commission should conduct the COL licensing proceeding for the North Anna Unit 3 including the final design certification rule, completing the ESBWR rulemaking before proceeding with the COLA.

Respectfully submitted,

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Pursuant to 10 C.F.R. § 2.323, the movant has made a sincere effort to contact counsel for the Applicant and NRC to resolve the issues raised in the motion, but the effort was unsuccessful.

[19] COLA Revision 6, Part 7: Departures Report ñDeparture: NAPS DEP 3.7-1, Ground Response Spectra for Seismic Structural Loads and Floor Response Spectra,ò page 1-2

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CERTIFICATE OF SERVICE

I hereby certify that the
MOTION TO REOPEN AND ADMIT NEW CONTENTION
has been filed through the Electronic Information Exchange system
this 7th day of March, 2014.

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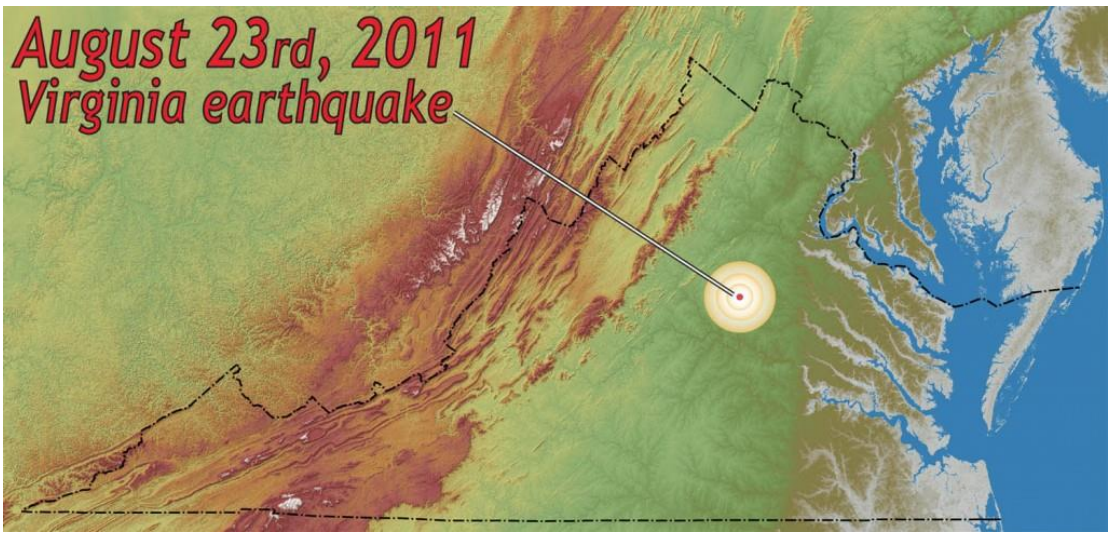
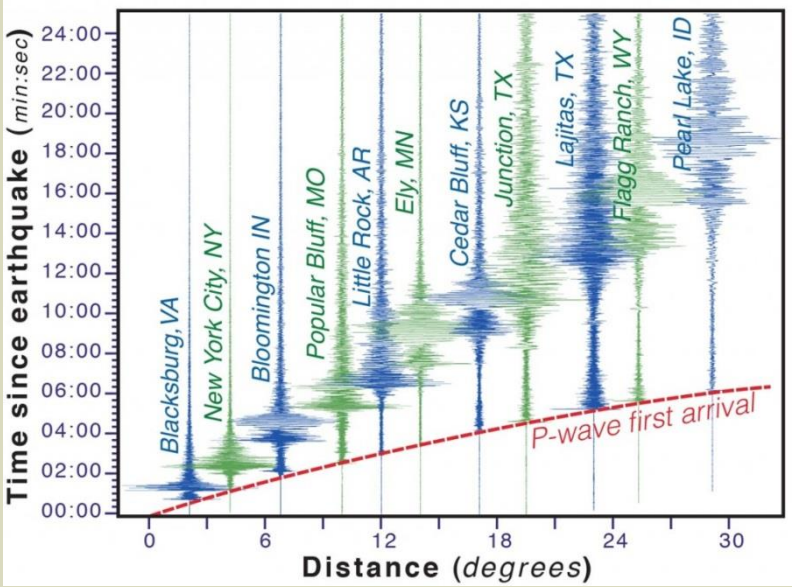
All Shook Up! The 2011 Virginia Earthquake

December 22, 2011

As the year comes to a close it is a fine time to reflect on the 2011 Virginia earthquake. Itôs been four months since the Virginia earthquake jolted eastern North America, and we now know more about what happened. This moderate-size (M_w=5.8) quakeï felt by millions of people from Alabama to Quebecï caused significant damage in Louisa County, cracked both buildings and nerves in Washington D.C., and served notice that there is still some kick left in these ancient rocks.



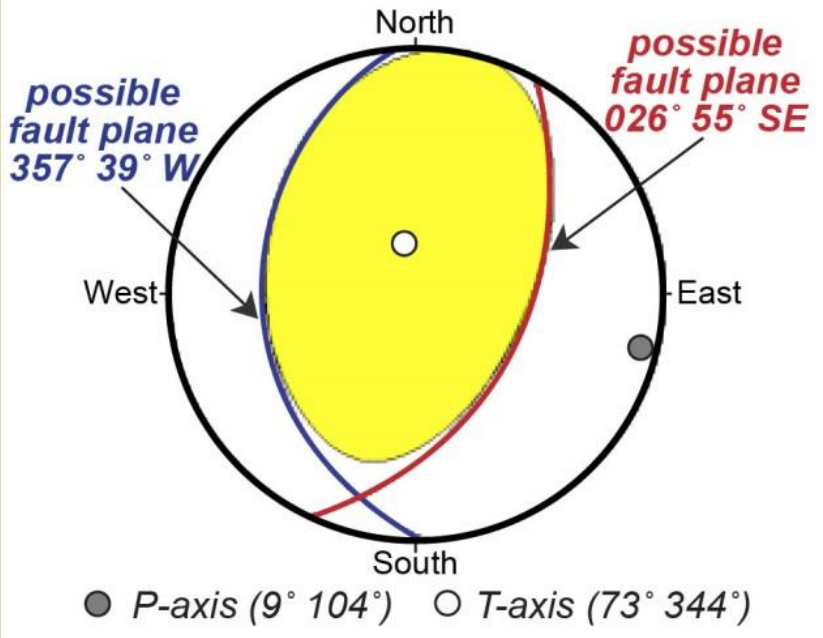


Seisomograms generated from the Virginia earthquake. Modified from-
http://rev.seis.sc.edu/earthquakes/2011/08/23/17/51/03

What Happened on August 23rd?

At 1:51:04 p.m. (EDT) a fault ruptured at a point some 4 to 5 km (2.5 to 3 miles) below the Earthôs surface in Louisa County, Virginia (~60 km northwest of Richmond). As one side of the fault slid past the other, seismic waves radiated outward from the source area. The primary waves (P-waves) raced away at nearly 6 km/second: sweeping through Richmond 11 seconds after the quake, passing through Williamsburg in 20 seconds, and arriving at the West Coast in about 5 minutes. The primary waves were followed by shear waves and salvos of surface waves, these were the jolts that people felt. On the William & Mary campus; shaking perceptible to humans lasted about 20 seconds. At the North Anna Nuclear Power Station, 21 km from the epicenter, peak ground accelerations reached ~250 cm/sec^2, more than sufficient to damage unreinforced masonry structures in the epicentral region.

The Virginia temblor was a moderate earthquake. Worldwide there have been 344 earthquakes of magnitude 5.8 or greater this year, which averages out to about one quake of this size (or larger) per day somewhere in the world. What makes this quake special is that it was the largest quake to rock the eastern United States in over a century and was felt by more people than any other quake in U.S. history. At the recent American Geophysical Union meeting, Shao and others report a seismic moment of 5.75 x 10^{17} Newton meters for the quake, which translates into ~35 terajoules of energy released (for comparison, World War II-era atomic bombs packed an energy punch of 50 to 90 terajoules).

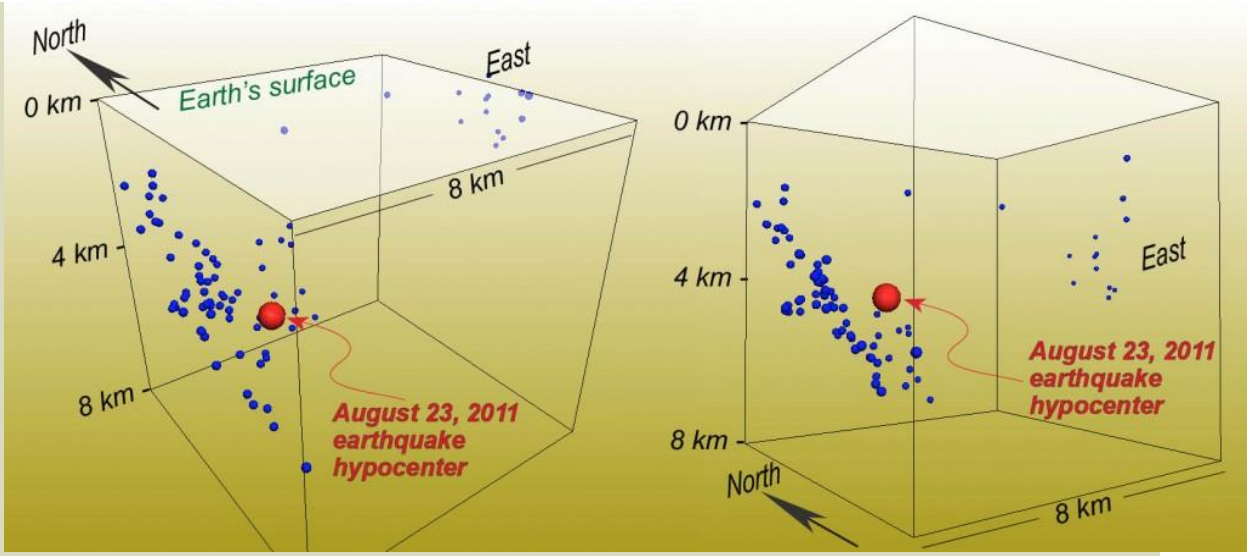


Beachball diagram from USGS/SLU Regional Moment Solution. Modified from- http://earthquake.usgs.gov/earthquakes/ eqarchives/fm/se082311a_rmt.php

The nature of seismic wave first arrivals at seismic stations helped define both the geometry and type of fault that slipped. The diagram to the right is a first motion diagram, in essence a stereographic projection that forms a visual representation of the fault style and defines two possible fault orientations for the Virginia earthquake. For the uninitiated these diagrams are confusing, geologists commonly refer to these diagrams as *beachball diagrams*.

Based on the pattern of first arrivals, the fault that slipped was a ***reverse fault*** striking to the north or northeast and dipping moderately either to the west or southeast. With these data alone the fault cannot be uniquely determined- it could be either plane. The P- and T- axes represent the axes of maximum contraction and extension respectively; in essence the Earthôs crust in central Virginia was shortened in an approximately east/west direction from the quake movement.

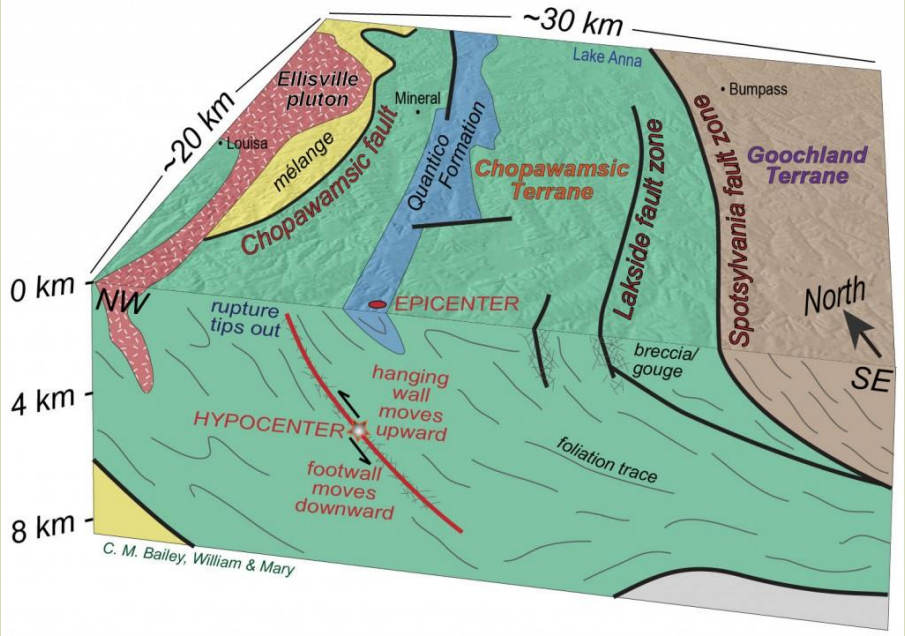
Within a day or so after the earthquake, seismologists from Virginia Tech and the U.S. Geological Survey had an array of portable seismometers installed in central Virginia. This equipment recorded hundreds of aftershocks. Most of these aftershocks were small (M= 1-3), but Louisa County residents certainly felt them.



Block diagrams illustrating Virginia earthquake hypocenter (red) and aftershocks (blue). Left- Oblique downward view to the northeast. Right- Oblique view to northeast from below the Earth's surface. Note- planar alignment of many aftershocks. Aftershock locations from- http://www.geol.vt.edu/outreach/vtso/2011/0823-louisa/

The aftershock pattern clearly reveals the fault geometry: the earthquake occurred on a northeastð striking fault that dips about 50 to 55ęto the southeast. Click on the link below to watch a short animation. The aftershocks are blue spheres, notice how they mostly line up neatly along a planeð that is the fault that slipped. The big red sphere (the August 23rd quake) plots off the plane, that quake was located by a regional network of seismometers and is not as accurately located as the aftershocks pinpointed by the locally deployed array of seismometers.

Watch aftershock animation



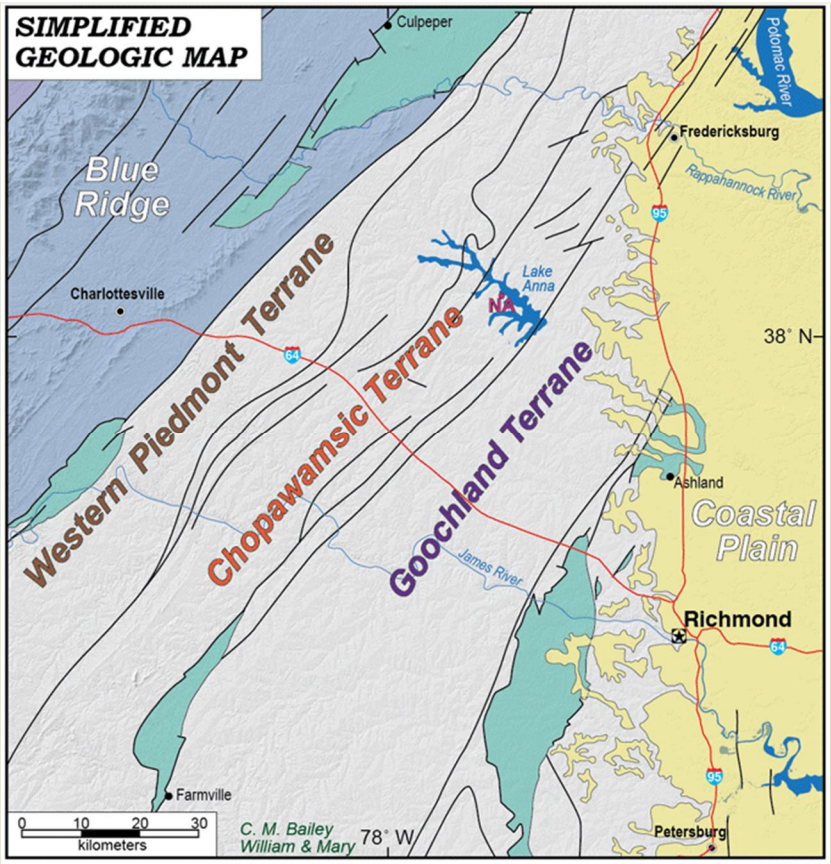
Block diagram of the central Virginia Piedmont illustrating 2011 earthquake hypocenter on a southeast dipping reverse fault. Note- rupture did not reach the surface. Oblique view to the northeast.

During the quake the southeastern side of the fault (hanging wall) was shoved upward with a maximum displacement of about 1 meter. The total rupture length along the fault was likely 5 to 10 kilometers. There was no rupture at the surface because displacement across the fault did not propagate all the way to the Earthôs surface. The 2011 earthquake occurred along a blind, and previously unrecognized, reverse fault in the Virginia Piedmont.

Geology of the Piedmont

The earthquake occurred in the Piedmont, a region of complex geology that is the metamorphic core of the Appalachian Mountain system. Some of these rocks originated far from North America and were later crushed against the continental margin during tectonic collision and faulted to their current location. In the past twenty years geologists have distinguished many different *terranes* in the Piedmont: terranes are blocks of crust with distinct geologic histories and are bound by major faults or tectonic sutures. The difference between terranes is well illustrated on the aeromagnetic map displayed in the animated map sequence below.

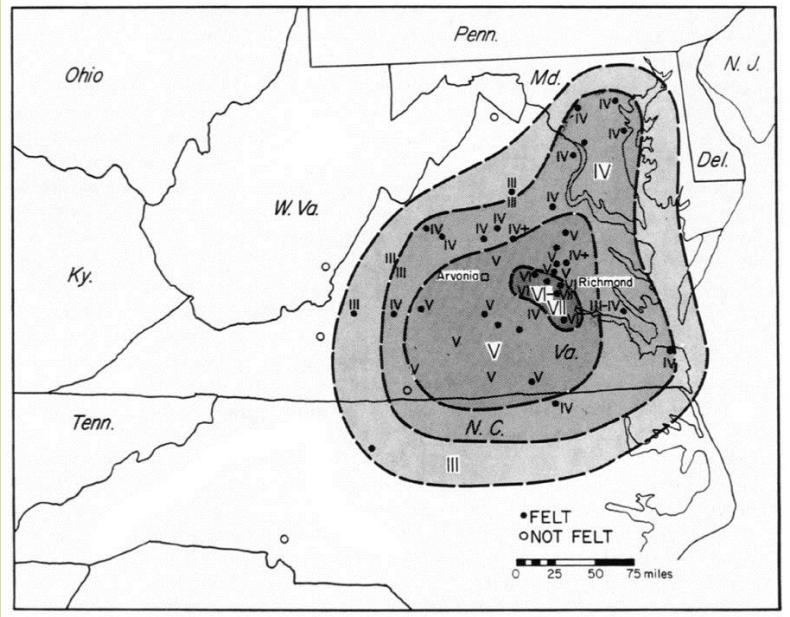
The 2011 Virginia earthquake occurred in the ***Chopawamsic terrane***. Rocks in this terrane formed as volcanic and plutonic rocks in a continental arc during the Ordovician Period (~470 to 450 million years ago). This arc was likely outboard of ancient North America and was later accreted to the continent. In the late Paleozoic (300 to 280 million years ago), during the massive tectonic collision that created Pangaea, these rocks were squeezed and baked (deformed and metamorphosed) into gneisses and schists. The Chopawamsic terrane is bound on the northwest by the Brookneal/Shores fault zone and on the southeast by the Spotsylvania fault zone. Our kinematic studies of these fault zones indicate that they experienced simultaneous right-lateral wrenching and shortening when they were active in the Paleozoic. In essence, the Spotsylvania fault zone moved the Goochland terrane to the southwest and the Brookneal/Shores fault zone moved the Chopawamsic terrane to the southwest relative to the western Piedmont.



Animated map of the central Virginia Seismic Zone illustrating geography, geologic terranes, basins, faults, aeromagnetic patterns, and earthquake epicenters (1774-2011). Frames flash in every 4 seconds. Earthquake data from the Virginia Tech Seismological Observatory. Geologic data from numerous sources. NA- North Anna Nuclear Power Station.

In the Triassic Period (220 to 195 million years ago) Piedmont terranes were fractured and broken during rifting which created sedimentary basins, such as the Culpeper and Richmond basins. This rifting ultimately opened the Atlantic Ocean. Traditionally, geologists have viewed the Piedmont as a relatively static region whose tectonic heyday was long past. Today, it is a gently rolling landscape mantled by thick soils, the product of slow erosion for millions of years and a seeming dearth of tectonic activity.

But as my colleague David Spears at the Virginia Division of Geology and Mineral Resources has pointed out, there are subtle clues in the rock structure of the central Piedmont that suggest recent tectonic activity. The 2011 quake was a not so subtle reminder that David is correct and we need to get our boots on the ground and eyes on the outcrop to study the region in more detail.



Isoseismal map for the December 23, 1875 earthquake. Map from Bollinger and Hopper, 1971, Seismological Society of America Bulletin, v. 61, p. 1033-1039.

The Central Virginia Seismic Zone

The Central Virginia seismic zone is a region of moderate but persistent seismic activity. The first recorded quake occurred in 1774 near Petersburg and was felt throughout Virginia and North Carolina. The largest historical quake (prior to the 2011 temblor) in the central Virginia region took place in 1875 and is estimated to have been a magnitude 5.0. Estimating both the size and exact location of historic earthquakes is difficult. Geologists use the *Modified Mercalli Intensity Scale* to estimate the size of historical earthquakes based on eyewitness accounts and damage reports. This is a 12-

point scale that employs roman numerals, with a II being a quake so small that only few people felt it, a IV being felt by many people indoors, a VI being felt by all with some damage to plaster and masonry, a VIII causes considerable damage to structures, a X destroys most structures and the ground is thoroughly cracked, and a XII equals total damage. The intensity of damage decreases away from the epicenter. The 1875 quake reached an intensity of VI to VII in central Virginia; the 2011 quake had a maximum intensity of VIII in Louisa County whereas in Williamsburg the quakeôs intensity was a IV.

Damage from the 2011 earthquake in Louisa County, Virginia. Source- http://www.dmme.virginia.gov/DMR3/5.8_earthquake_album.shtml

By the late 1970s a regional array of permanent seismic monitoring stations helped better locate and measure earthquakes in the southeastern United States. Over the past three decades there have been 47 quakes with a MÓ2 in central Virginia (22 of those are aftershocks from the 2011 quake). These quakes are widely distributed and rarely correlate to mapped faults (see the animated map above). The focal mechanisms are consistent with slip on reverse faults at depths between 4 to 10 kilometers. At these depths, the rock is warm (70ę to 200ę C or 160ę to 400ę F), but solid and behaves in a brittle fashion when placed under stress.

There is more to tell, but my research students counseled me to curb my enthusiasm, as blog posts should not be too long. In the next post Iõll discuss the possible causes of the 2011 earthquake and tell the lurid history of finding fault at the North Anna Nuclear Power station.