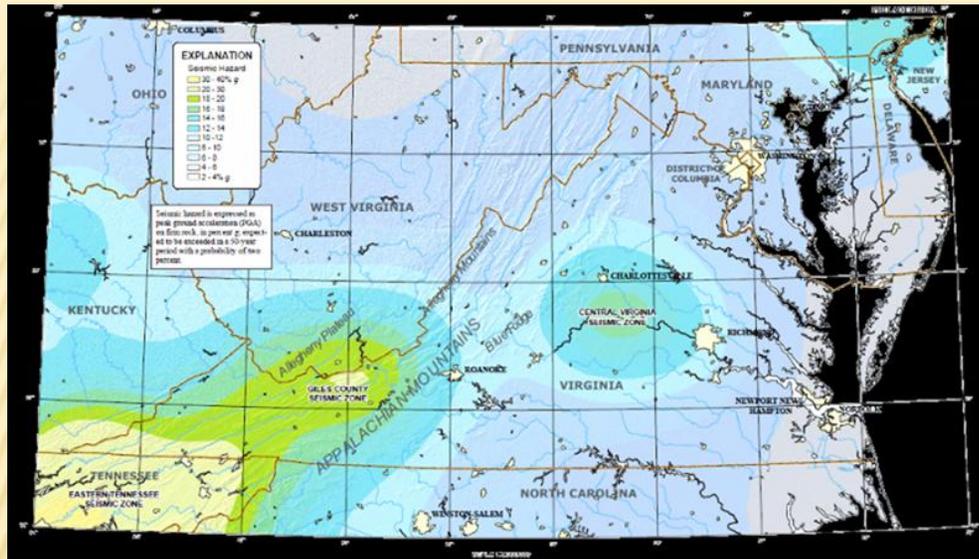


**Virginia Geological Research
Symposium 2013
*Charlottesville, April 11, 2013***

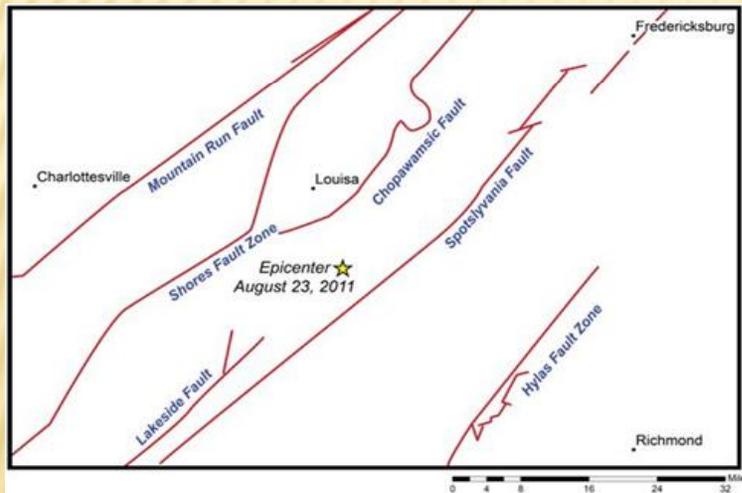
**"ARE THE EARTHQUAKES
OF CENTRAL VIRGINIA
SEISMIC ZONE
CONNECTED WITH
PRECIPITATION?"**

Dr. Betim Muço



There are two seismic zones in Virginia: Central Virginia Seismic Zone (CVSZ) and Jilles zone.

Virginia is far away from plate boundaries .

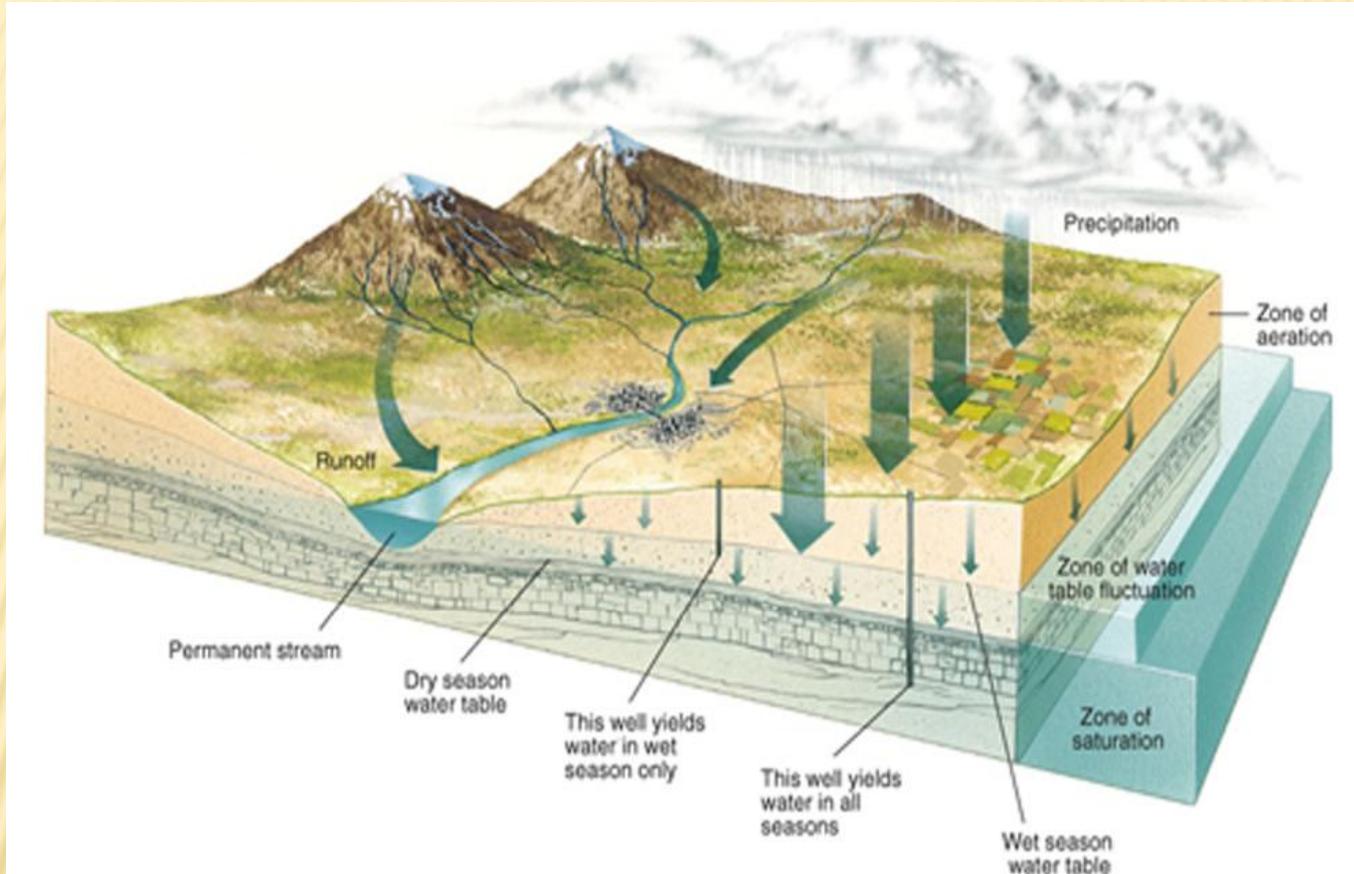


CVSZ is populated with known faults but many other blind and deeply buried faults remain undetected.



Then who is the trigger that gives the last push to earthquake generation in CVSZ? 2

It's underground water!!



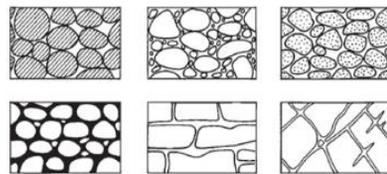
- The development in the second half of 20th century of a new direction in seismology, that is induced seismicity by large man-made reservoirs and fluid injection in the deep, shed a new light on the underground water as an important factor in the geodynamics processes of earth crust.
- Despite the growing evidence of earthquake occurrence under the influence of hydrological factors, the role fluids play in crustal processes is still underestimated in earth science studies.

How present is the water in the earth's depth?

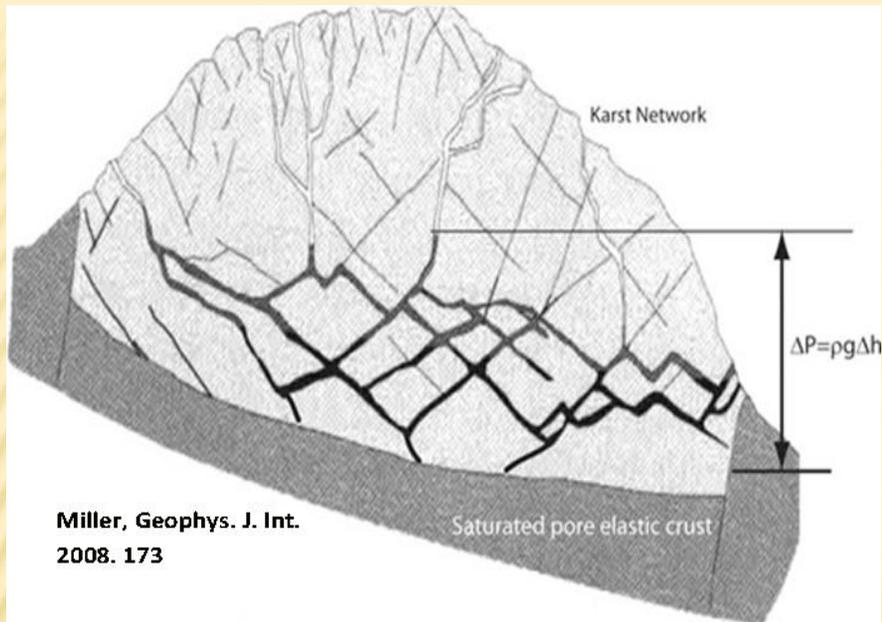
The humans with their exploration have only scratched the big earth we have under our feet.



- The results from deep drilling challenged the traditional idea that geological data obtained from the surface can be directly correlated with geological materials in the deep crust.
- Drilling at Kola, Russia, at 4.5 km encountered a sudden decrease in density, presumably due to increased porosity.
- Drilling at Oberpfälz, Germany, discovered hot fluids in open fractures at 3.4 km.



Rocks contain cracks and pores. Most of these voids within rocks are interconnected and, hence, subject to penetration by fluids migrating through the crust.

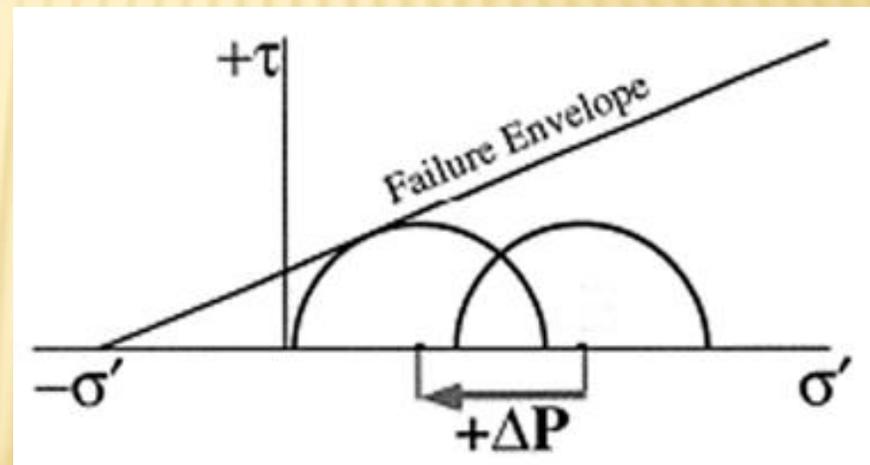


$$\sigma' = \sigma - P_p$$

The abundant rainfall raises the level of water-table which induces the pressure transient, increases pore-fluid pressure and reduce effective stress.

The mean earthquake depth for earthquakes of CVSZ since 1960 is 6.7km.

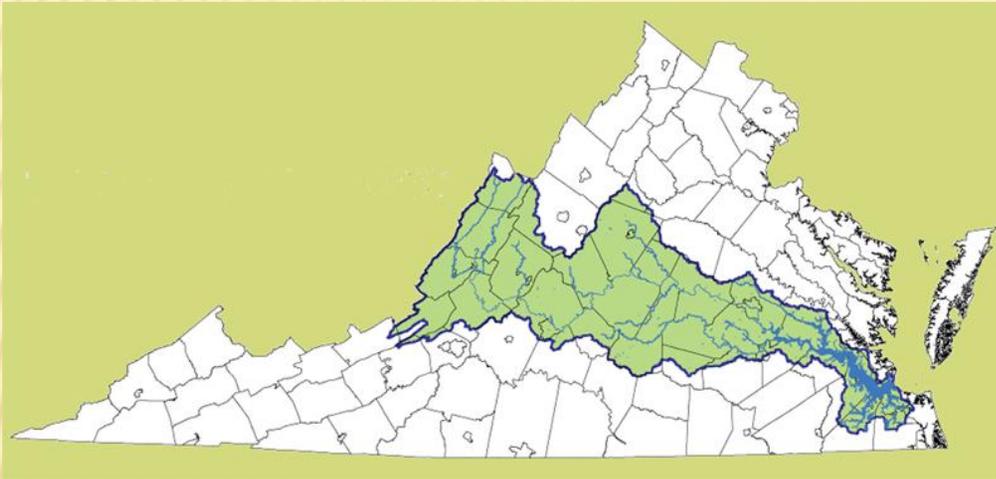
But what is important in the earthquake generation is pressure transient response in stress-sensitive formations. Through this pressure transient, or water-hammer effect, in a fractured and permeable crust, a higher water table or river stage means an increase in pore-fluid pressure at depths where earthquakes can be generated.



Studies have shown that the occurrence of earthquakes can be effected even by small stress changes of as little as 0.1 bar

What makes Virginia special that helps the penetration of surface water underground ?

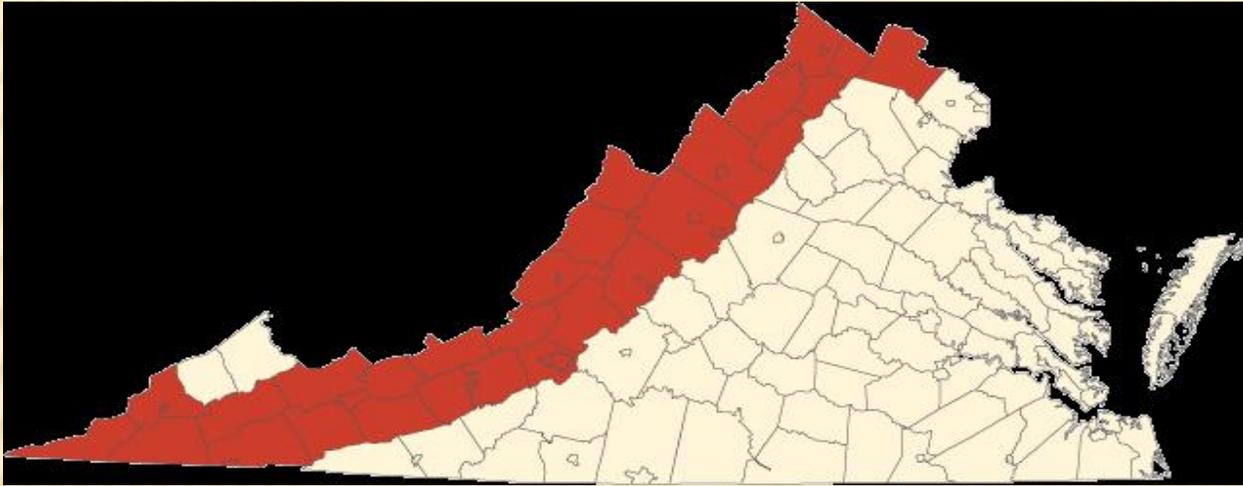
1. A big James River watershed (25 percent of the entire state of Virginia).



- Annual discharge of the James River at Richmond is about 213 cubic meters/ sec or about four time than at its origin.

- Total length of the river from the sources to southern Chesapeake Bay is about 540 km and its total basin area is 26,164 square km.

2. Presence of karst



Karst comprises the Valley and Ridge Province, which is one third of the state

(Virginia Department of Mines Minerals and Energy)

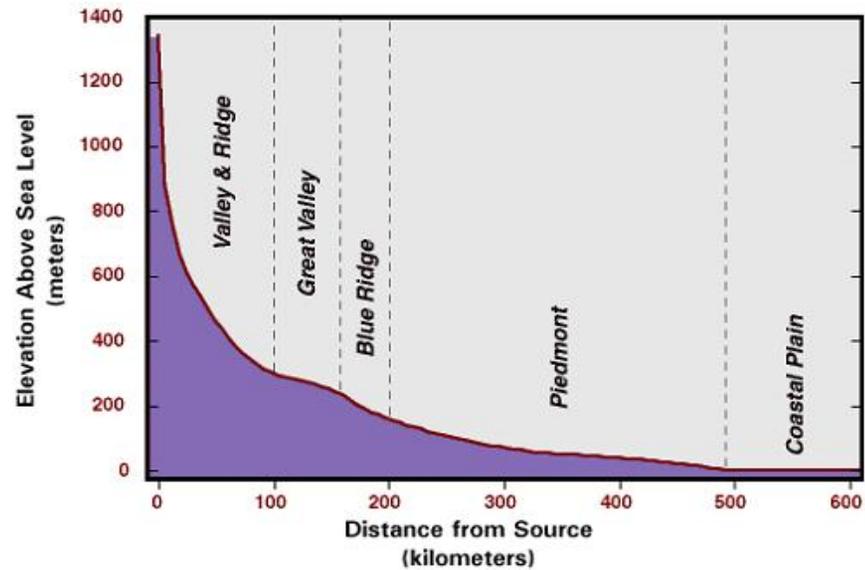


3. Topography

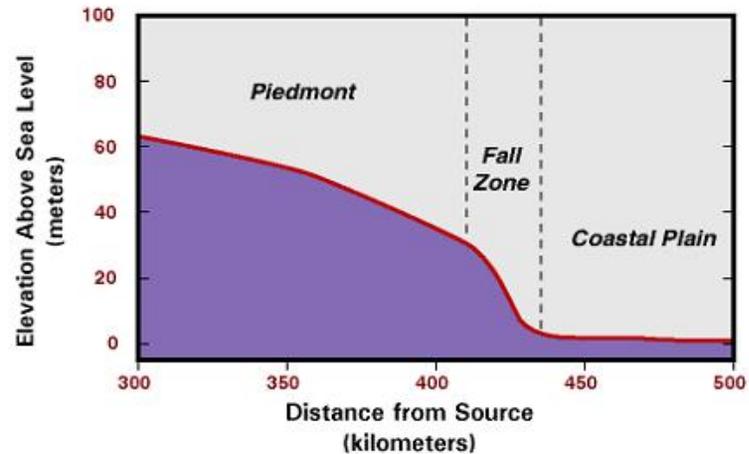
- From Blue Ridge to the end of Fall Zone the gradient is 0.7 m per 1 km and for 70 km through Coastal Plain the river is tidal.
- The river topography decreases the amount of runoff and let more water to penetrate underground.

K. Davis & C.M. Bailey, College of William & Mary, 1999

Profile of the James River across Virginia

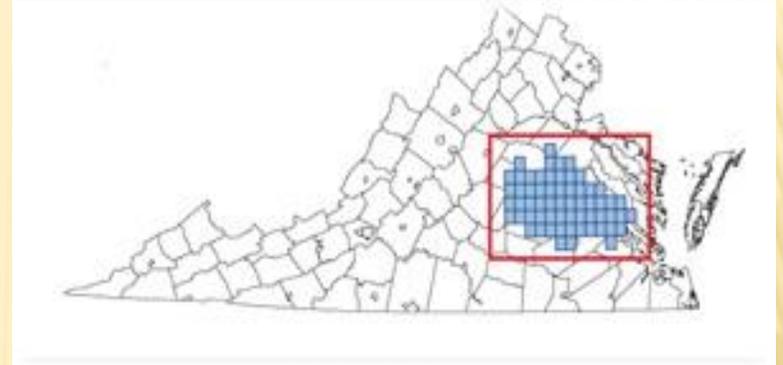


Profile of the James River across the Fall Zone

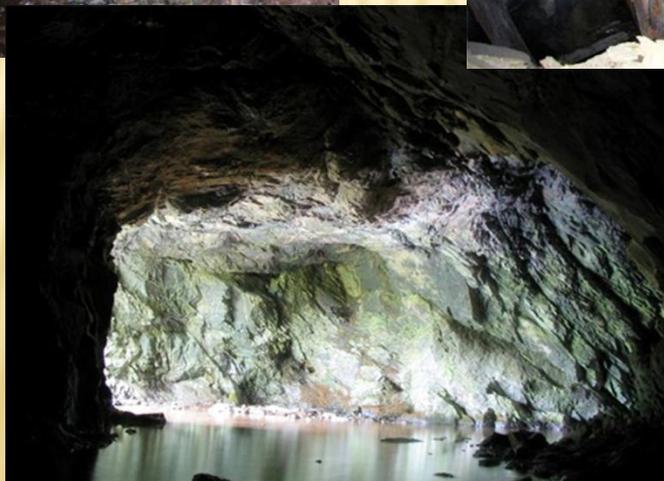


4. Mines

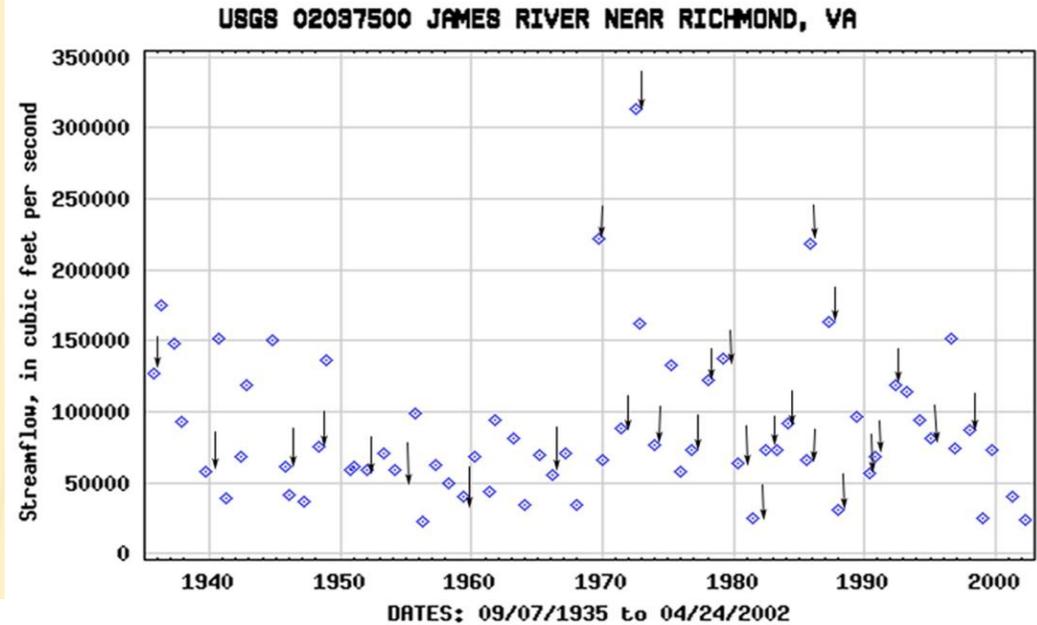
According to the Virginia Department of Mines/Minerals and Energy approximately 2,000 abandoned mine lands sites exist in the state. Vertical shafts of abandoned mines can be hundreds of feet deep.



They can intercept and convey surface water and groundwater.



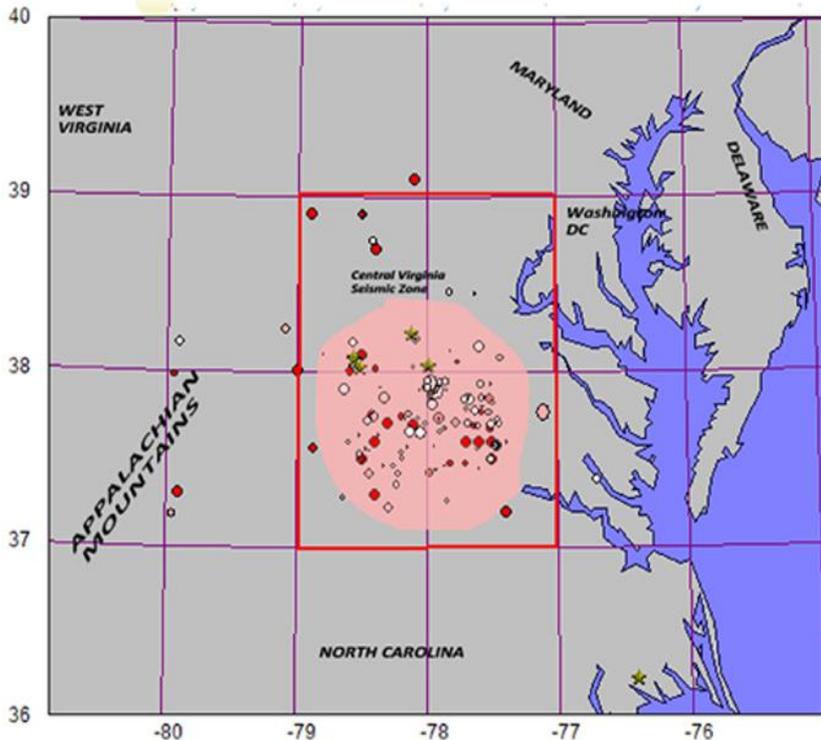
- The possibility of a causal relationship between climate and intraplate seismicity in the case CVSZ has been suggested time ago by Costain and Bollinger (1991,1996).
- They observed common periodicities between residual streamflow and earthquake strain energy in this zone.

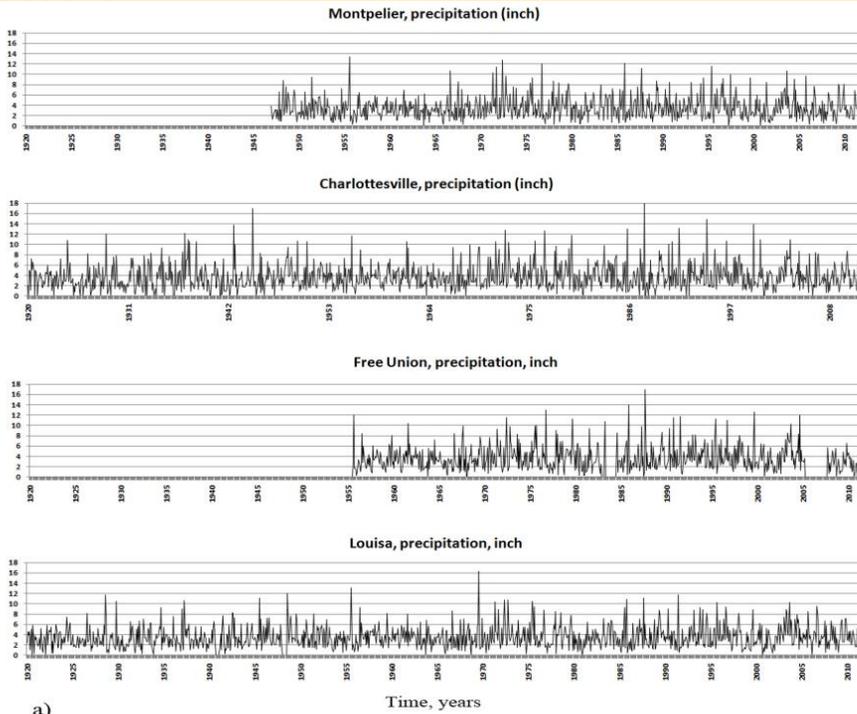


Average streamflow for James River near Richmond is about 5,000 cub-ft/sec on summer and 20,000 cub-ft/sec at March. With black arrows are noted the time when earthquakes occurred in CVSZ.

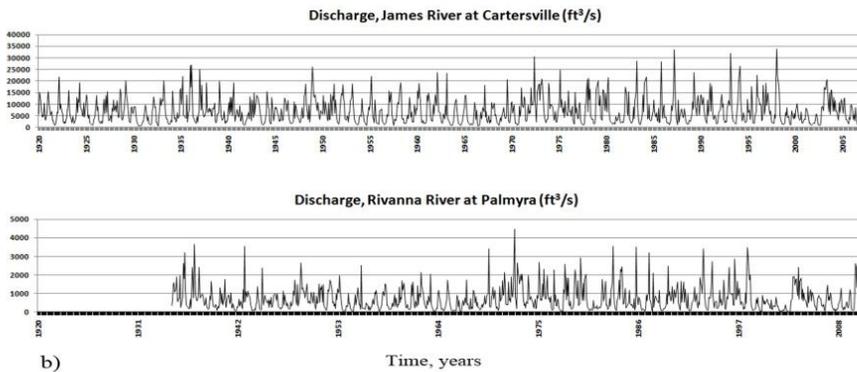
The flooding of James River following by earthquakes gave the first hint for seeking a deeper correlation between rainfall and discharge and earthquakes for CVSZ.

- Some time series with rainfall data from four hydrometeorological stations for rainfall and two other ones for discharge of James and Rivanna River, were constructed.
- A time series for earthquakes of this zone has been constructed too.

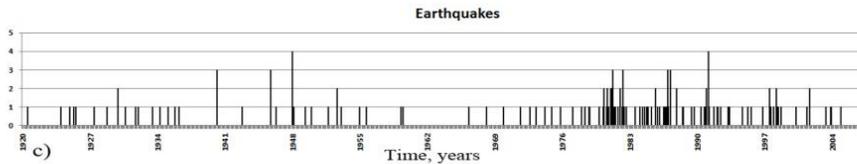




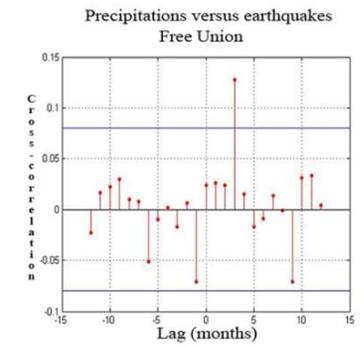
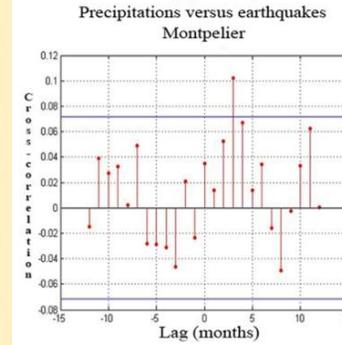
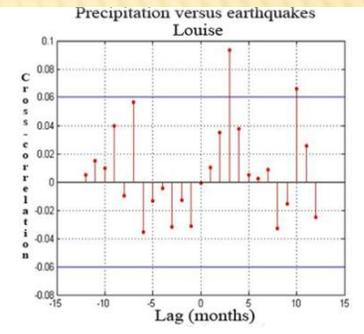
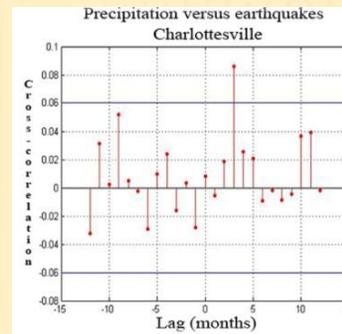
a)



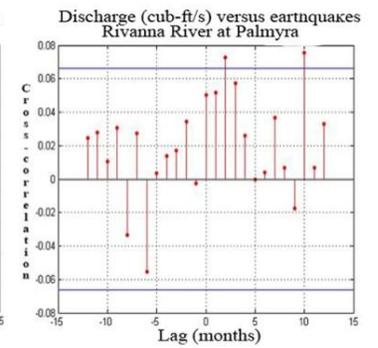
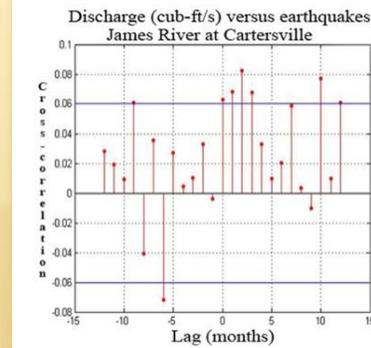
b)



c)



The time-lag for all precipitation series is three months.

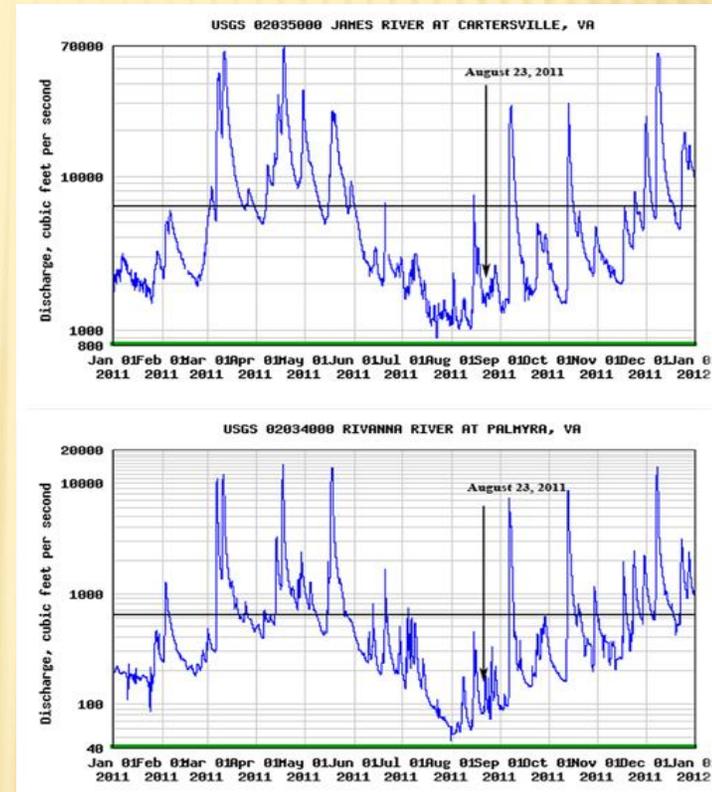


Kendall's tau b		Charlottesville	Earthquakes
Charlottesville	Correlation Coefficient	1.000	.051*
	Sig. (1-tailed)	.	.019
	N	1102	1099
Earthquakes	Correlation Coefficient	.051*	1.000
	Sig. (1-tailed)	.019	.
	N	1099	1099
<i>*. Correlation is significant at the 0.05 level (1-tailed).</i>			
Kendall's tau b		Montpelier	Earthquakes
Montpelier	Correlation Coefficient	1.000	.050*
	Sig. (1-tailed)	.	.045
	N	778	778
Earthquakes	Correlation Coefficient	.050*	1.000
	Sig. (1-tailed)	.045	.
	N	778	778
<i>*. Correlation is significant at the 0.05 level (1-tailed).</i>			
Kendall's tau b		Louisa	Earthquakes
Louisa	Correlation Coefficient	1.000	.048*
	Sig. (1-tailed)	.	.024
	N	1102	1096
Earthquakes	Correlation Coefficient	.048*	1.000
	Sig. (1-tailed)	.024	.
	N	1096	1096
<i>*. Correlation is significant at the 0.05 level (1-tailed).</i>			
Kendall's tau b		Free Union	Earthquakes
Free Union	Correlation Coefficient	1.000	.055*
	Sig. (1-tailed)	.	.042
	N	677	673
Earthquakes	Correlation Coefficient	.055*	1.000
	Sig. (1-tailed)	.042	.
	N	673	673
<i>*. Correlation is significant at the 0.05 level (1-tailed).</i>			
Kendall's tau b		James River	Earthquakes
James River	Correlation Coefficient	1.000	.042*
	Sig. (1-tailed)	.	.046
	N	1102	1102
Earthquakes	Correlation Coefficient	.042*	1.000
	Sig. (1-tailed)	.046	.
	N	1102	1102
<i>*. Correlation is significant at the 0.05 level (1-tailed).</i>			
Kendall's tau b		Rivanna River	Earthquakes
Rivanna River	Correlation Coefficient	1.000	.013
	Sig. (1-tailed)	.	.334
	N	912	912
Earthquakes	Correlation Coefficient	.013	1.000
	Sig. (1-tailed)	.334	.
	N	912	920

- The significance of these results is controlled using Kendall test.
- Except of discharge for Rivanna River, all other cross-correlations are significant at the 0.05 probability level.

Date and location	Intensity or magnitude	Preceded month with high precipitation	Precipitation, inch	Ratio of precipitation to monthly mean
Dec. 26, 1929 Charlottesville	VI	Oct. 1929	10.5	3.3 at Louise stn.
Apr. 9, 1936 Charlottesville	III	Jan. 1936	7.56	2.3 at Louise stn.
Oct. 6, 1942 Charlottesville	III	July, 1942 Aug. 1942 Aug. 1942	8.32 8.18 13.7	2.3 at Louise stn. 2.1 at Louise stn. 3.3 at Charlott. stn.
Oct. 10, 1946 Goodland County	III	July, 1945	11.1	2.5 at Louise stn.
Jan. 4, 1948 Buckingham County	IV	Nov., 1947	6.55	2 at Montpelier stn.
Nov. 26, 1950 Buckingham County	V	Sept. 1950	10.57	2.6 at Charlott. stn.
Dec. 11, 1969 Louisa County	IV, M=3.5	Aug. 1968	16.38	4 at Louise stn.
Feb., 27, 1977 Hanover County	IV, M=2.4	Oct., 1976	13.05 12.77	3.3 at Louise stn. 3.4 at Charlott. stn.
May, 5, 1978 Goodland County	M=3.8	Jan., 1978	8.71	2.9 at Montpel. stn.
Aug., 8, 1983 Goodland County	M=3.4	Apr., 1983	10.88	3.2 at Free Union stn.
March, 15, 1991 Louisa County	M=3.8	Oct. 1990	11.5	2.8 at Free Union stn.
May, 5, 2003 Goodland County	M=3.8	Feb., 2003	7.35 7.64	2.5 at Louise stn. 2.3 at Charlott. stn.
Dec., 9, 2003 Goodland County	M=4.5	Sept., 2003	10.91 7.64	2.3 at Charlott. stn. 2.2 at Montpel. stn.

The cross-correlation can be demonstrated also going after some rainfall-earthquake pairs during the years.



As for the earthquake of August 23, 2011, we can see that it happened after 2-3 months of high discharge at James River.

Conclusions:

- 1. Central Virginia Seismic Zone is very rich in surface waters and its terrain is very favorable for penetration of large amounts of these waters deep underground.**
- 2. A strong correlation has been found between rainfall and earthquakes and consequently between James River discharge and earthquakes.**
- 3. The earthquakes of CVSZ are generally generated approximately three months after abundant precipitation that surpasses 2-3 times the precipitation monthly mean.**