Geomorphic paleogeodesy and intraplate deformation associated with the Mineral, VA earthquake and surrounding Central Virginia Seismic Zone (CVSZ)

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Claudio Berti, Anne Meltzer, Tammy Rittenour,
and in Louisa County, VA:
Mark Carter (USGS), Richard Harrison (USGS), and David Spears (VA DMME)

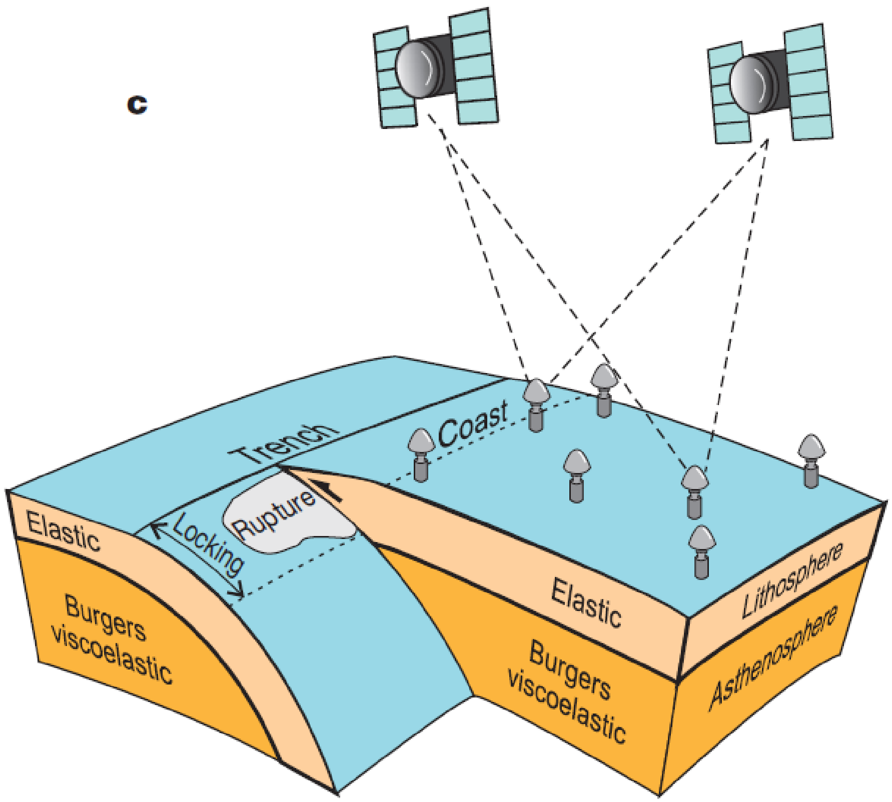
In the past two decades, geodesy and geochronology have endeavored to quantify crustal strain and paleoseismology in the central and eastern U.S (CEUS). We have learned that:

- **Seismic zones have little to no measurable crustal strains when using GPS geodesy.**
- **Seismic zones have measurable crustal strains when using geomorphic and stratigraphic markers.**
- **Seismic zones have clear evidence of past earthquakes.**
- **We know virtually nothing about the potential for earthquakes in between seismic zones.**

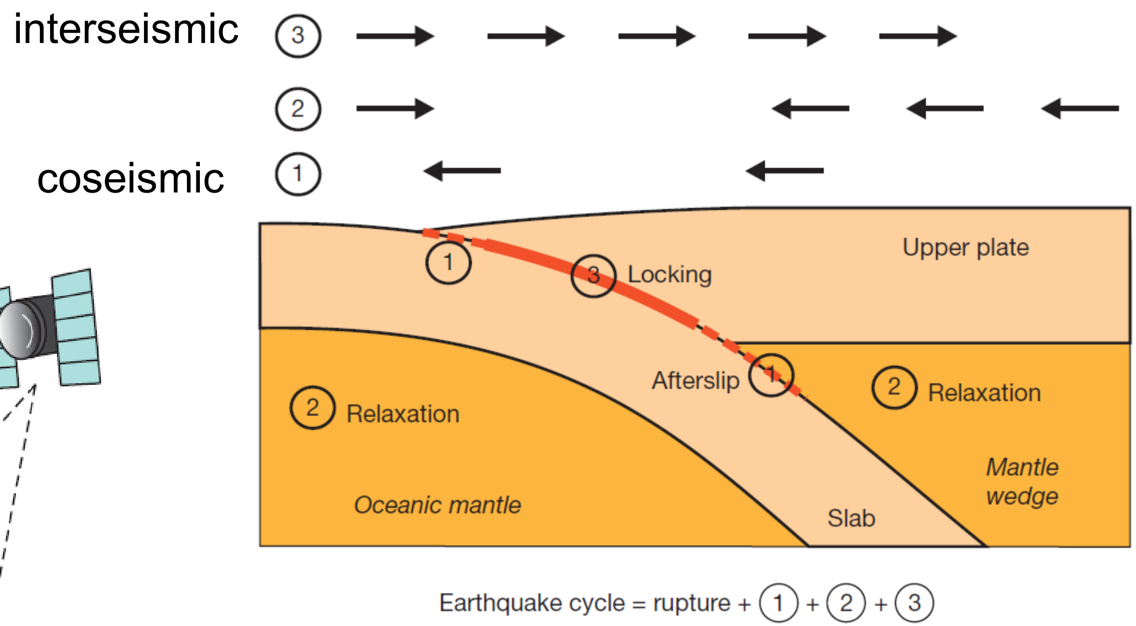
1 = now at Colorado School of Mines

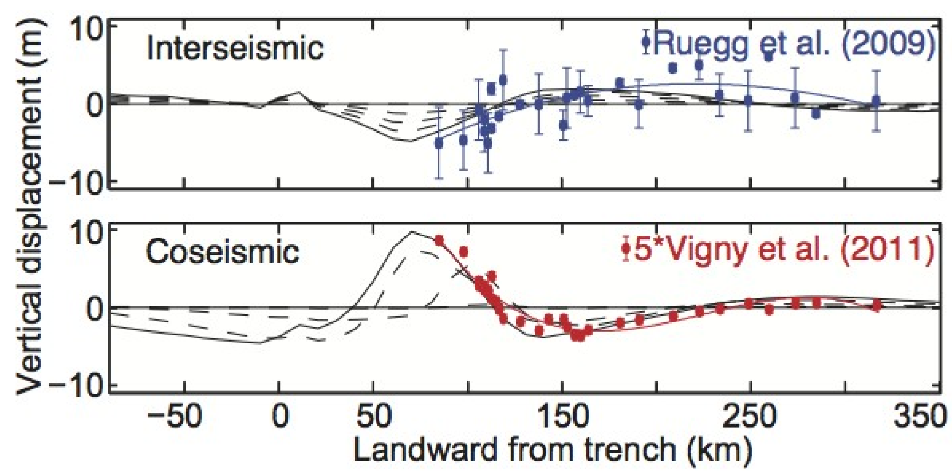
NSF EAR-9909393; 1202798 (EarthScope RAPID) and USGS EDMAP - G13AC00115

Plate boundary earthquake cycle and crustal strain measured geodetically



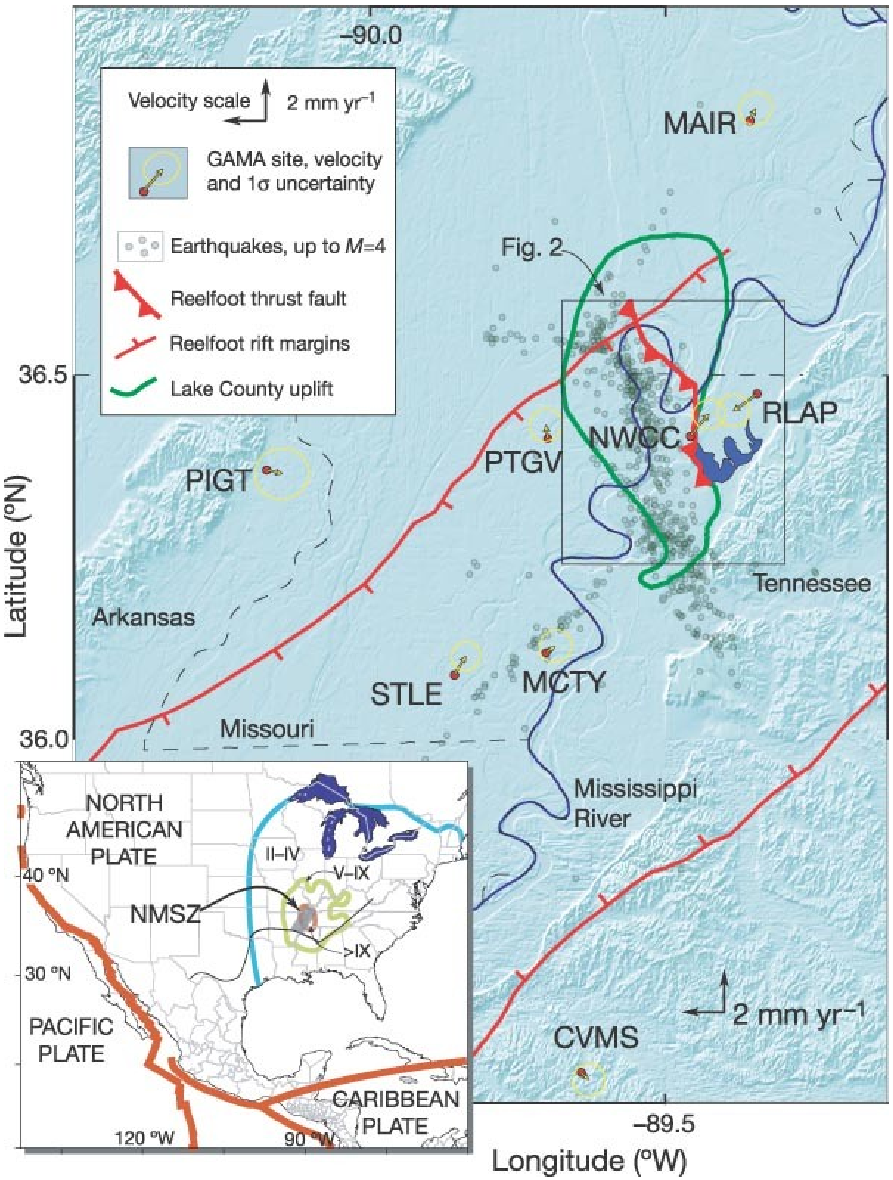
Wang et al., 2012, Nature



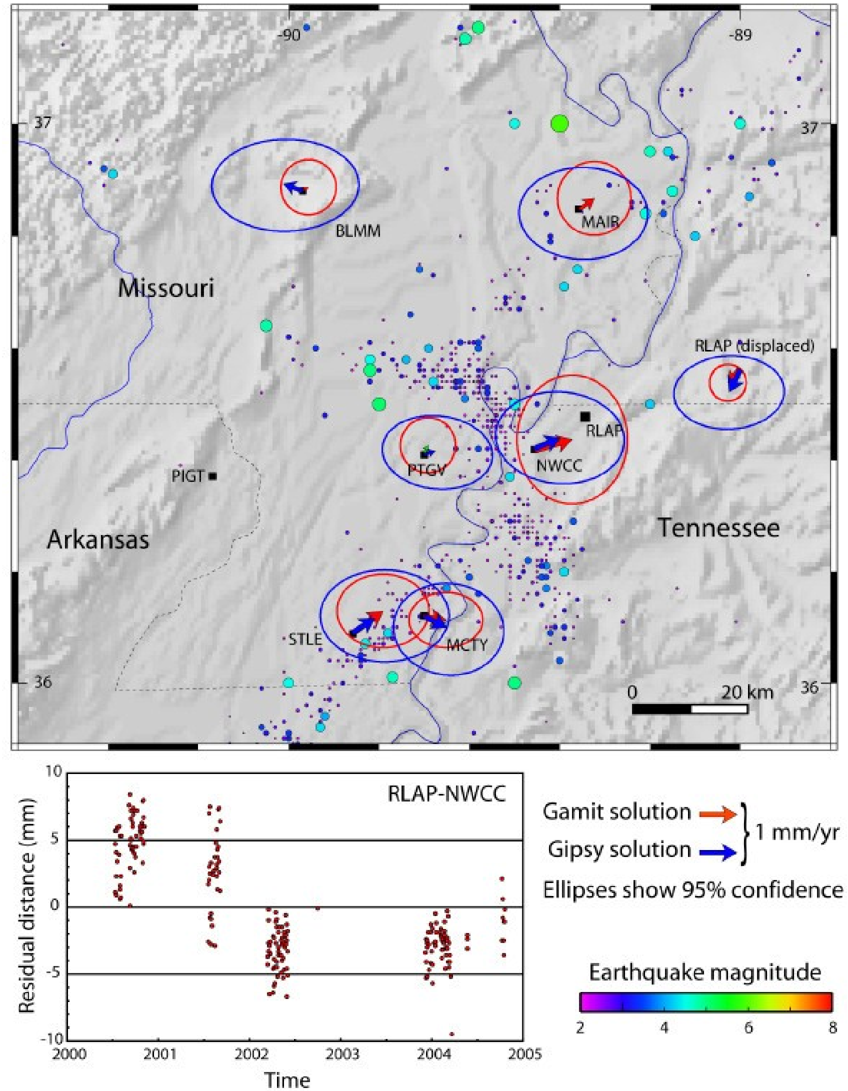


http://www.cos.ethz.ch/research/earthquake-physics.html

No GPS geodetically measurable crustal strains at New Madrid

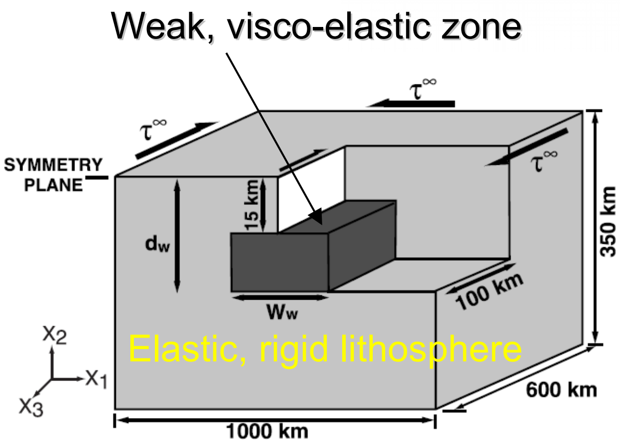


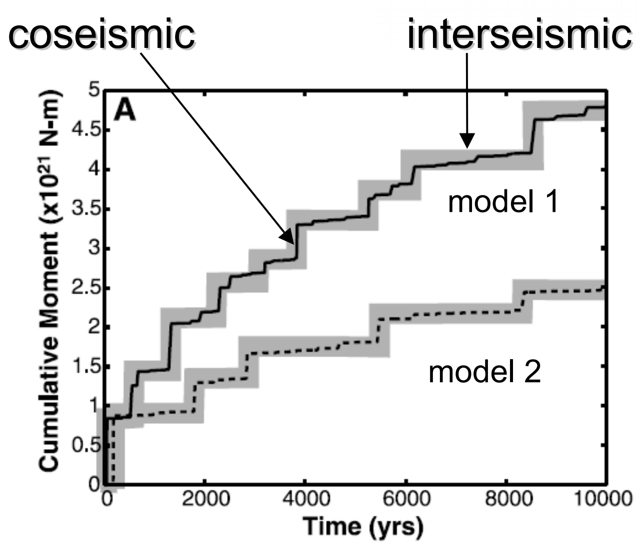
Smalley et al., 2005, Nature



Calais et al., 2005, Nature
Calais and Stein, 2009, Science
Craig and Calais, 2014, JGR-SE
Boyd et al., 2015, JGR-SE

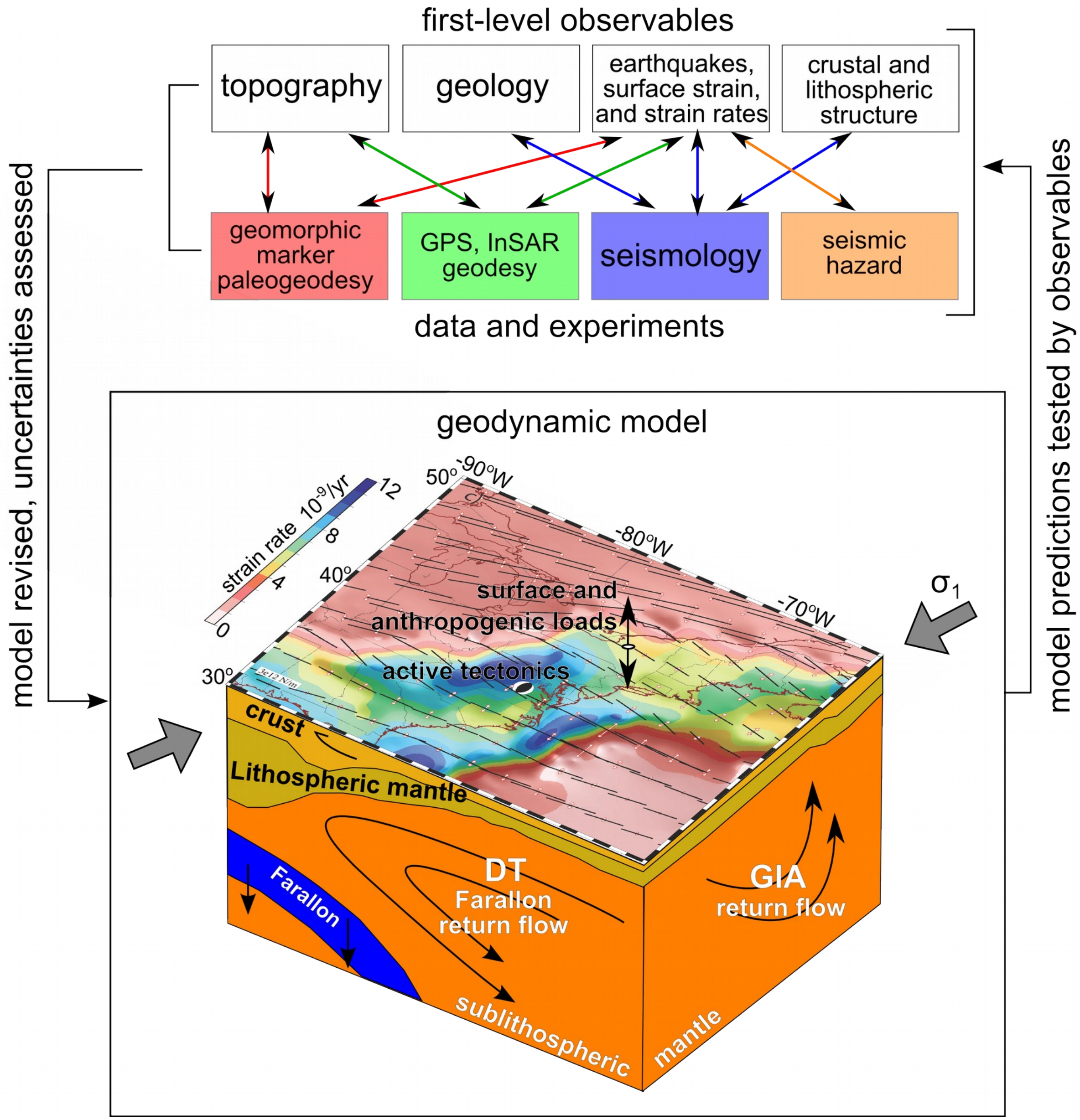
Visco-elastic oscillator



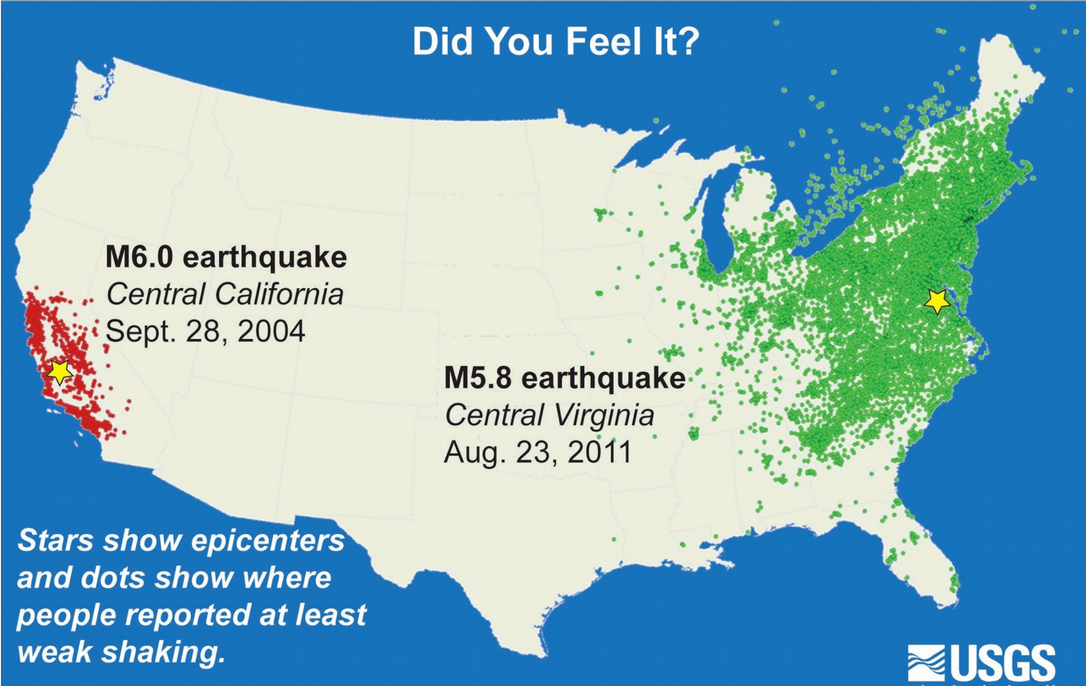


Kenner and Segall, 2000, Science

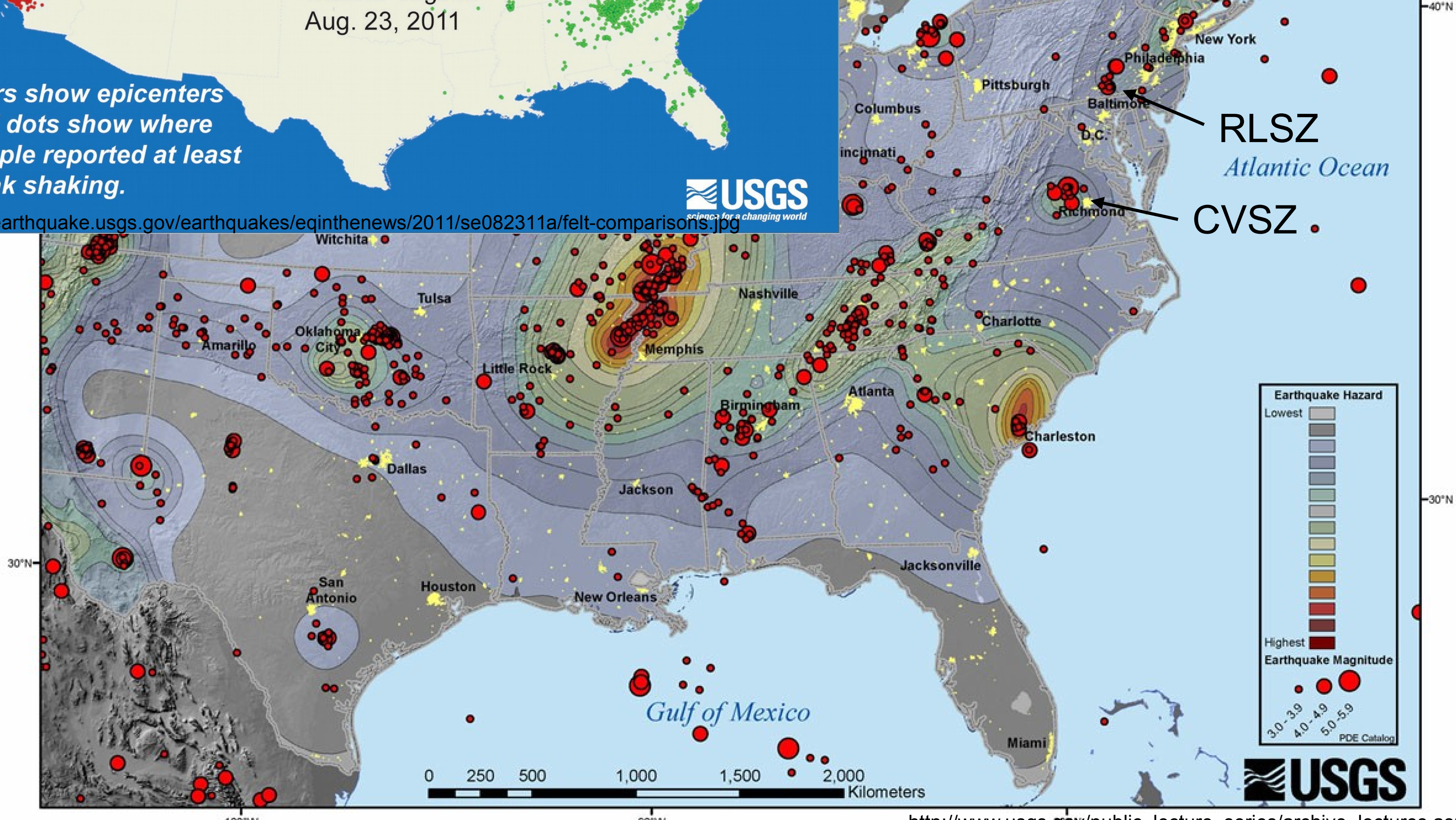
Systems-level model for CEUS intraplate earthquakes



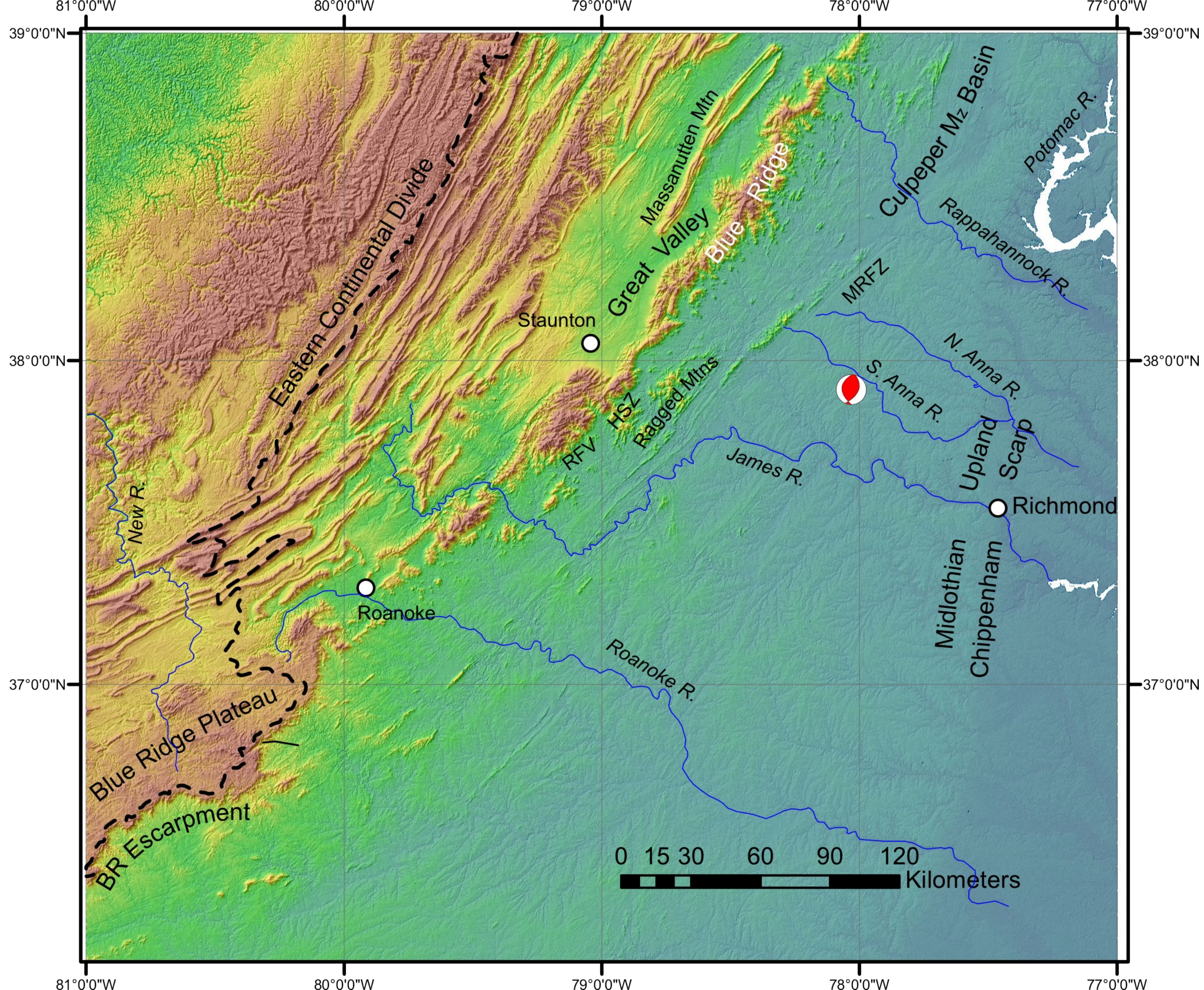
Crustal strains by Bill Holt, unpublished data

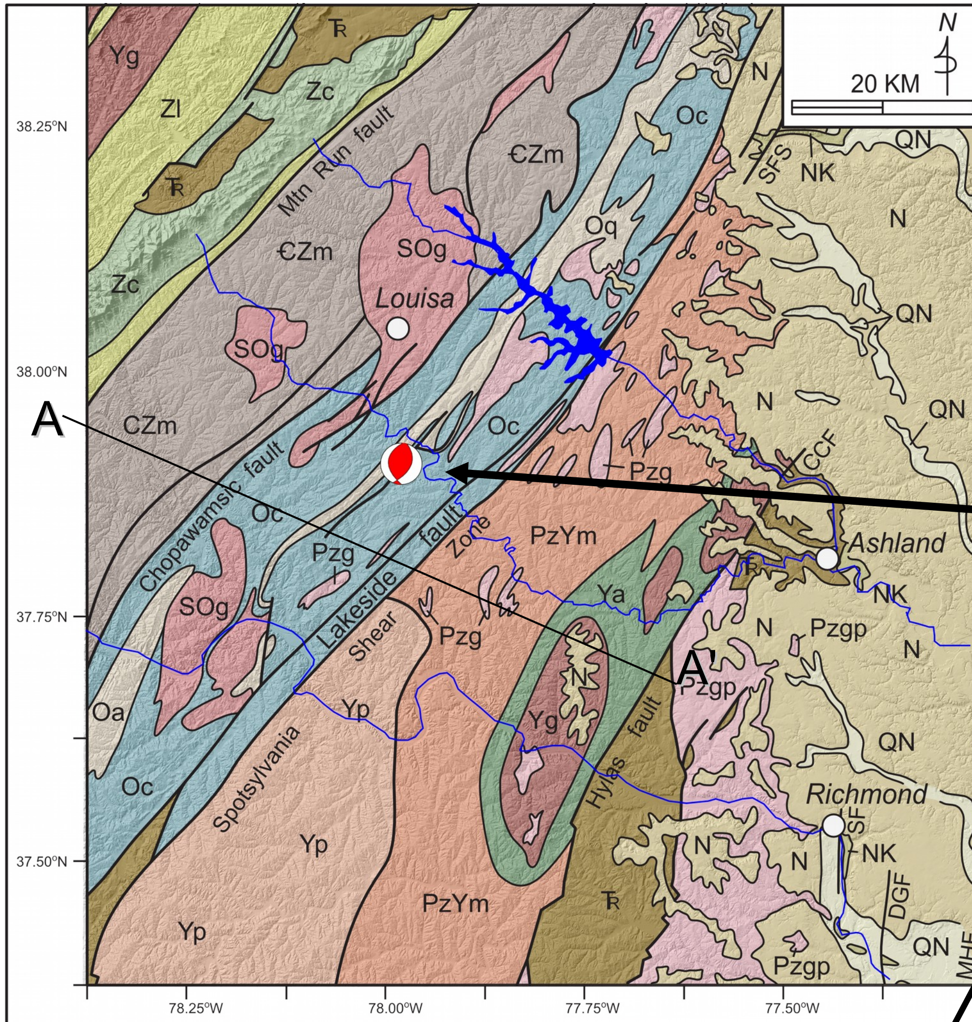


http://earthquake.usgs.gov/earthquakes/eqinthenews/2011/se082311a/felt-comparisons.jpg



http://www.usgs.gov/public_lecture_series/archive_lectures.asp.


81°0'0"W
80°0'0"W
79°0'0"W
78°0'0"W
77°0'0"W
39°0'0"N
38°0'0"N
37°0'0"N
Eastern Continental Divide
Massanutten Mtn
Great Valley
Blue Ridge
Culpeper Mz Basin
Potomac R.
Rappahannock R.
MRFZ
Staunton
N. Anna R.
S. Anna R.
Ragged Mtns
HSZ
RFV
James R.
Upland Scarp
Richmond
New R.
Roanoke
Midlothian
Chippenham
Roanoke R.
Blue Ridge Plateau
BR Escarpment
0 15 30 60 90 120
Kilometers

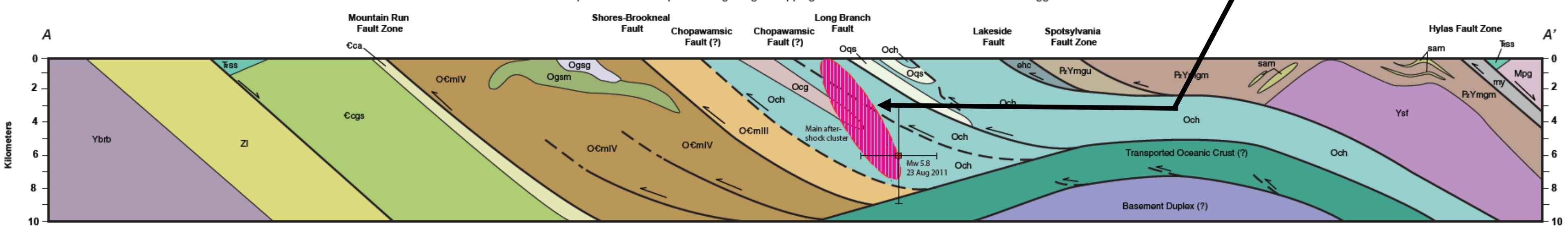


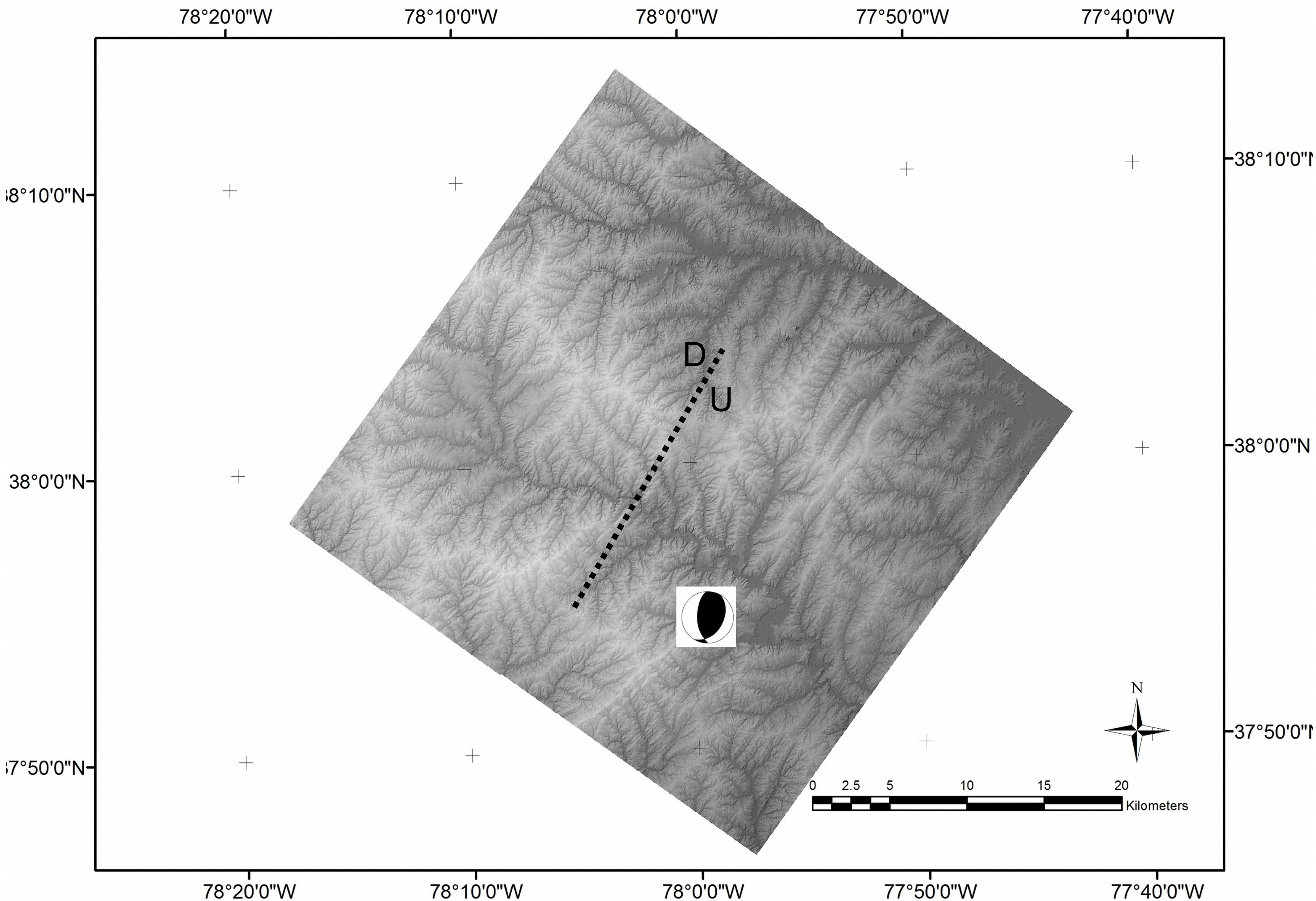
Mineral earthquake Fault

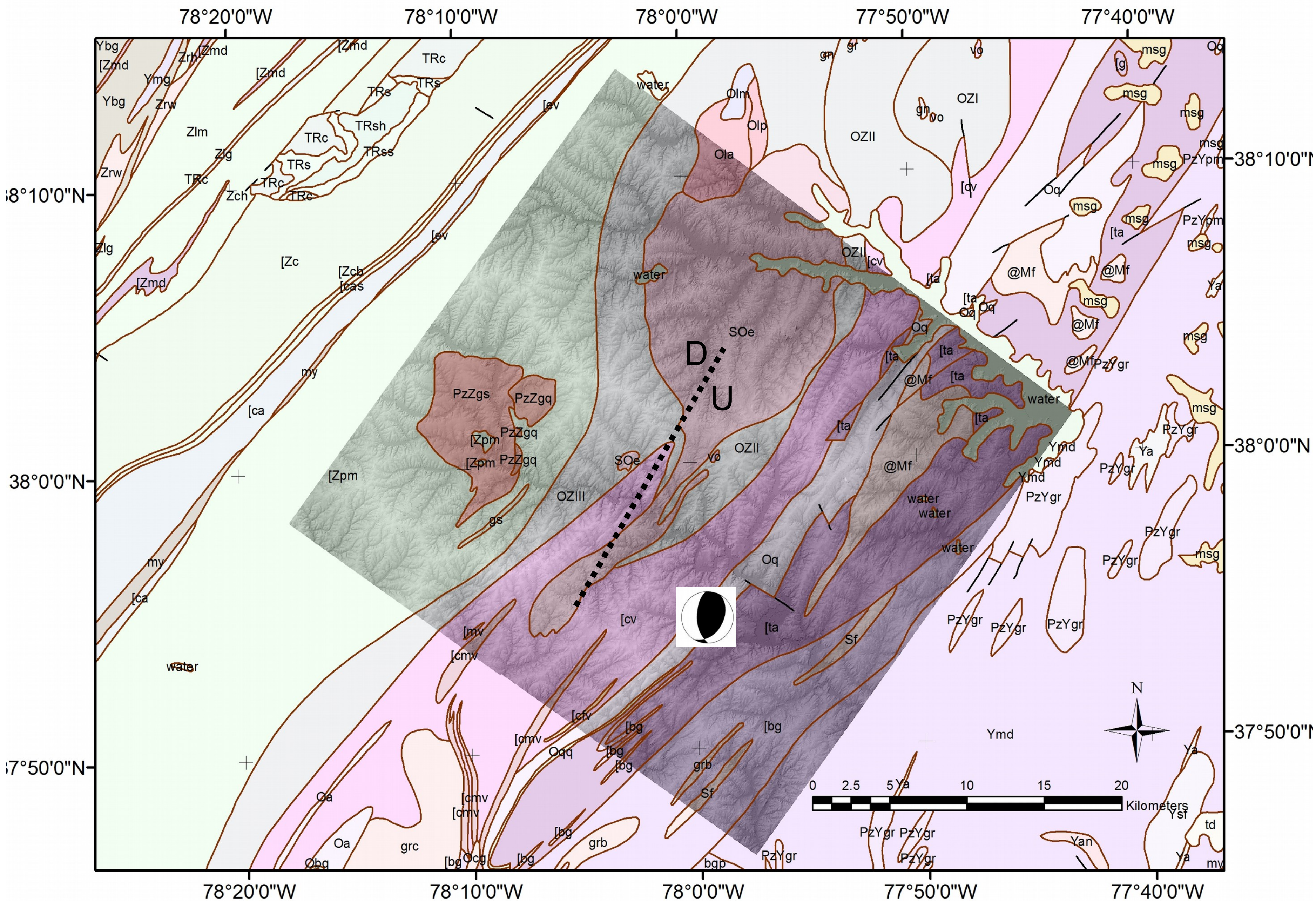
Cross-section courtesy of David Spears and Amy Gilmer
Division of Geology and Mineral Resources
Virginia Department of Mines, Minerals, and Energy

Interpretive Geologic Cross-section from the Eastern Blue Ridge to the Eastern Piedmont, Virginia
Including the 23 August 2011 Mw 5.8 Louisa County Earthquake

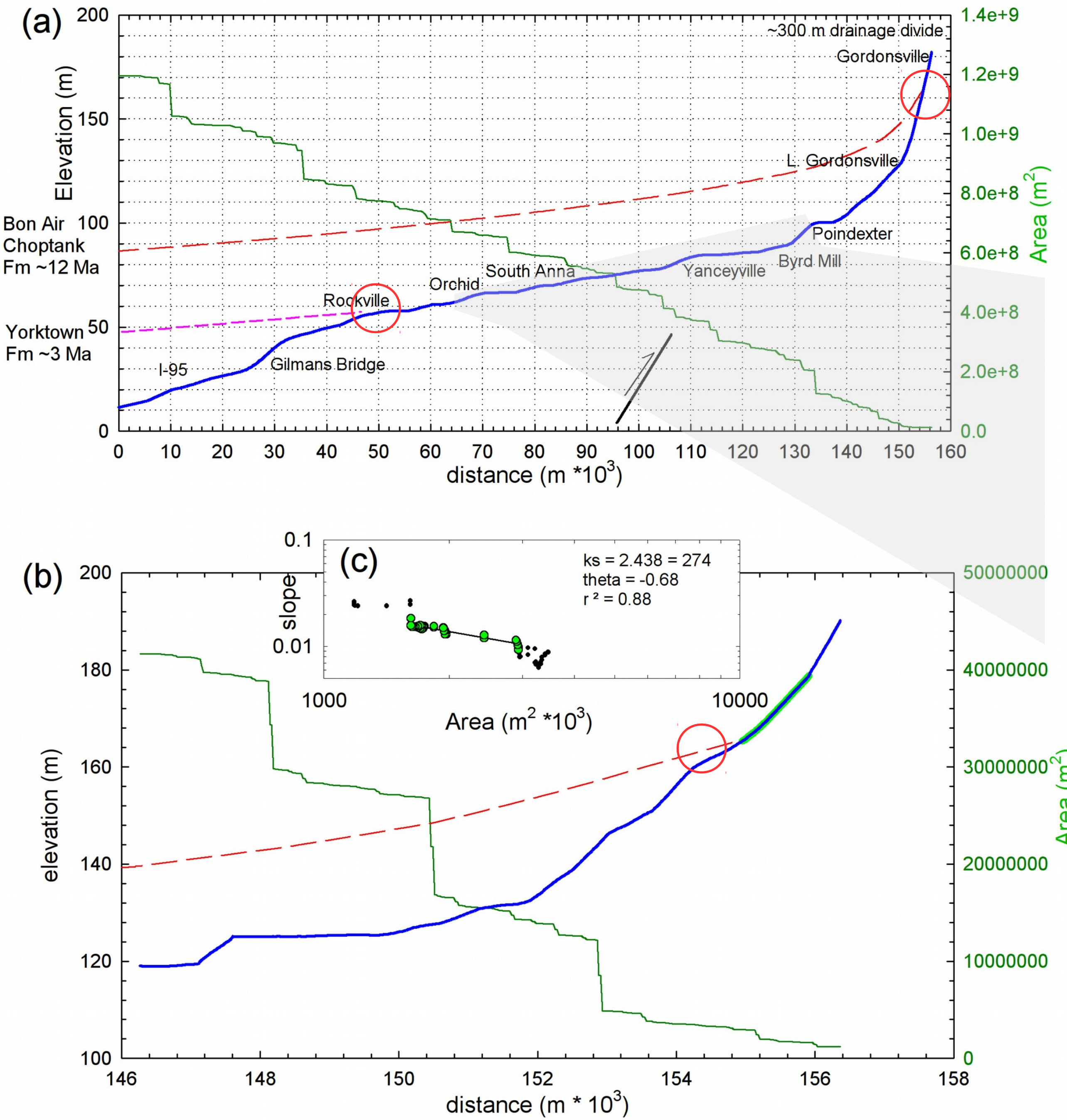
Cross-section based on published and unpublished geologic mapping and the I-64 seismic line. No vertical exaggeration.




78°20'0"W
78°10'0"W
78°0'0"W
77°50'0"W
77°40'0"W
38°10'0"N
38°0'0"N
37°50'0"N
D
U
N
0
2.5
5
10
15
20
Kilometers

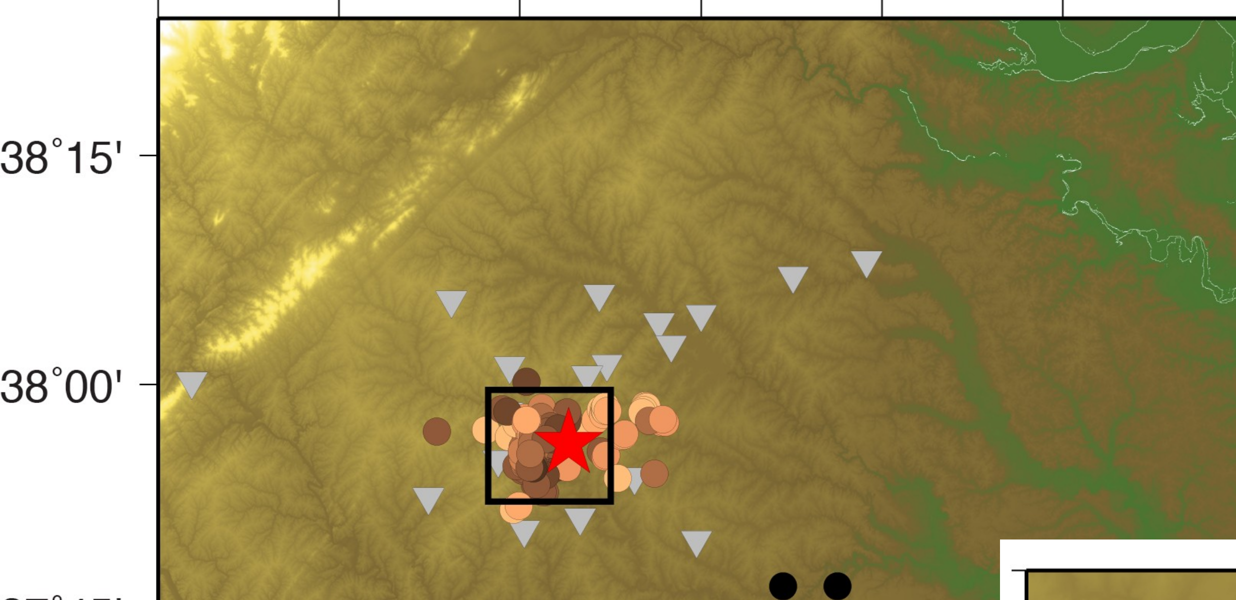

78°20'0"W
78°10'0"W
78°0'0"W
77°50'0"W
77°40'0"W
38°10'0"N
38°0'0"N
37°50'0"N
D
U
0
2.5
5
10
15
20
Kilometers
N
Ybg
[Zmd
Zrh
Ymg
Zrw
Zlm
Zlg
Zch
TRc
TRs
TRsh
TRss
[ev
[Zc
[Zcb
[cas
my
[ca
water
Olm
Olp
Ola
OZII
OZIII
SOe
Oq
[cv
[ta
@Mf
msg
PzYpm
PzYgr
Ya
Ymd
Ysf
td
Yan
PzZgs
PzZgq
[Zpm
gs
vo
[mv
[cmv
[bg
Oqq
grb
Sf
Oa
grc
Obq
Ocg
bgp

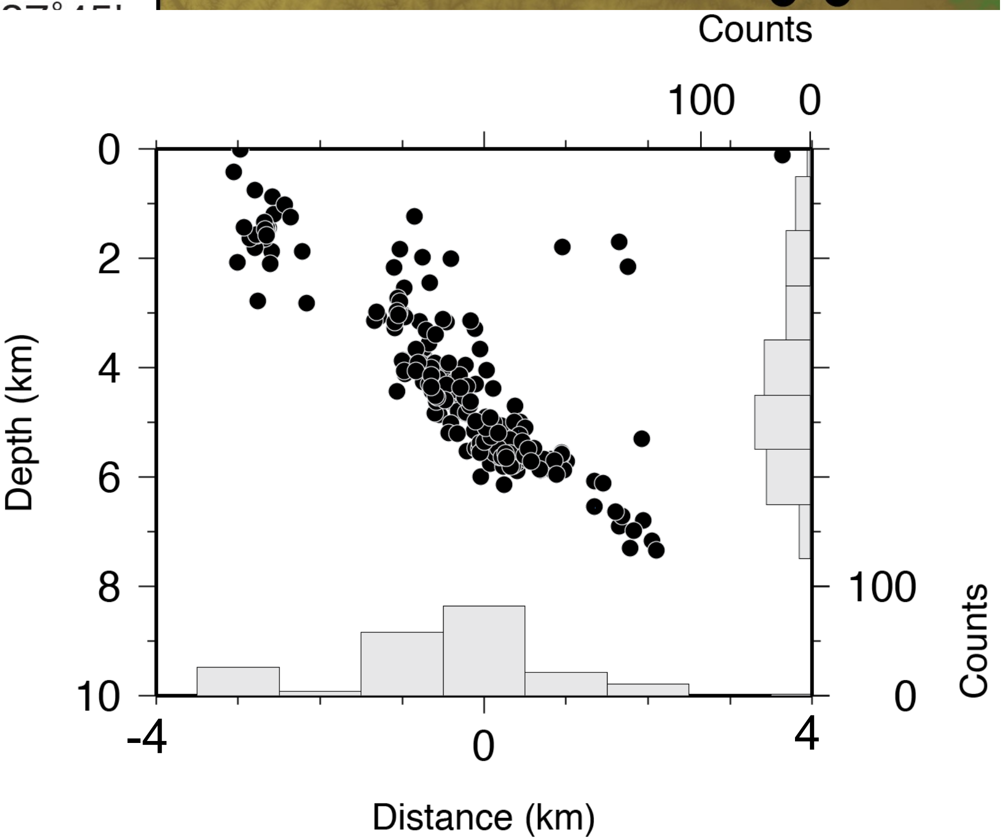
Two large knickpoints related to base level fall at the Fall Zone

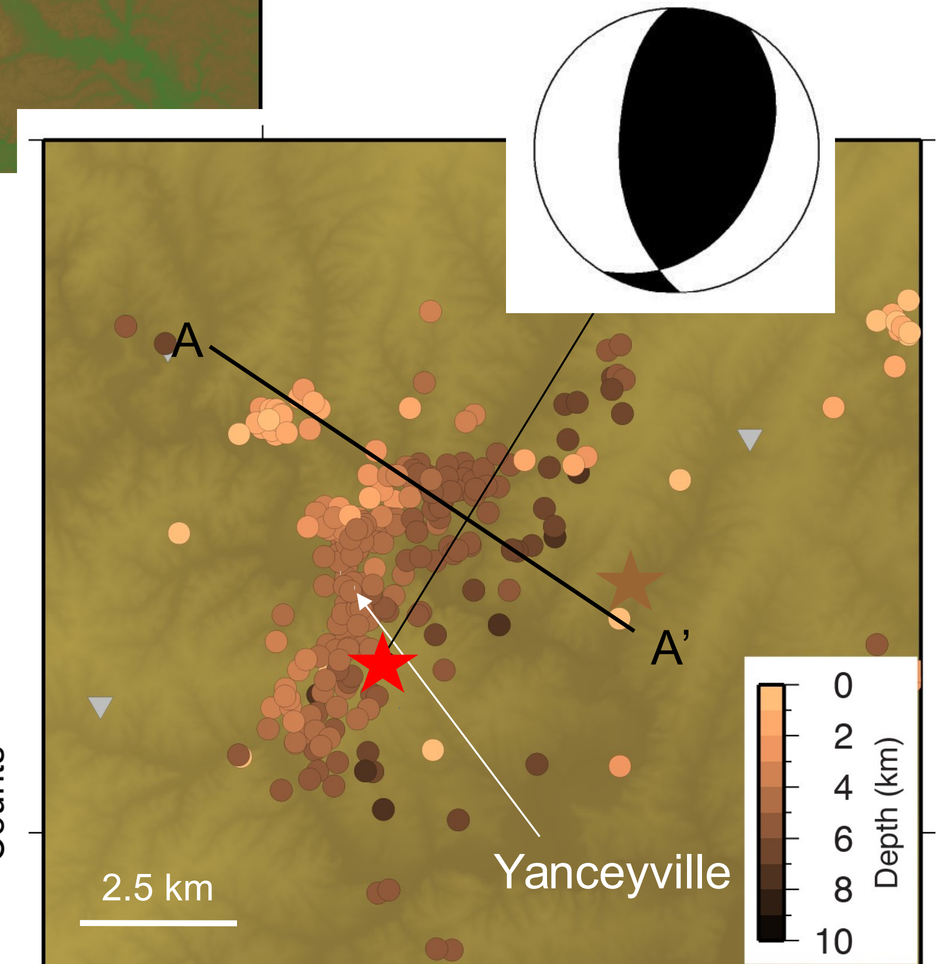


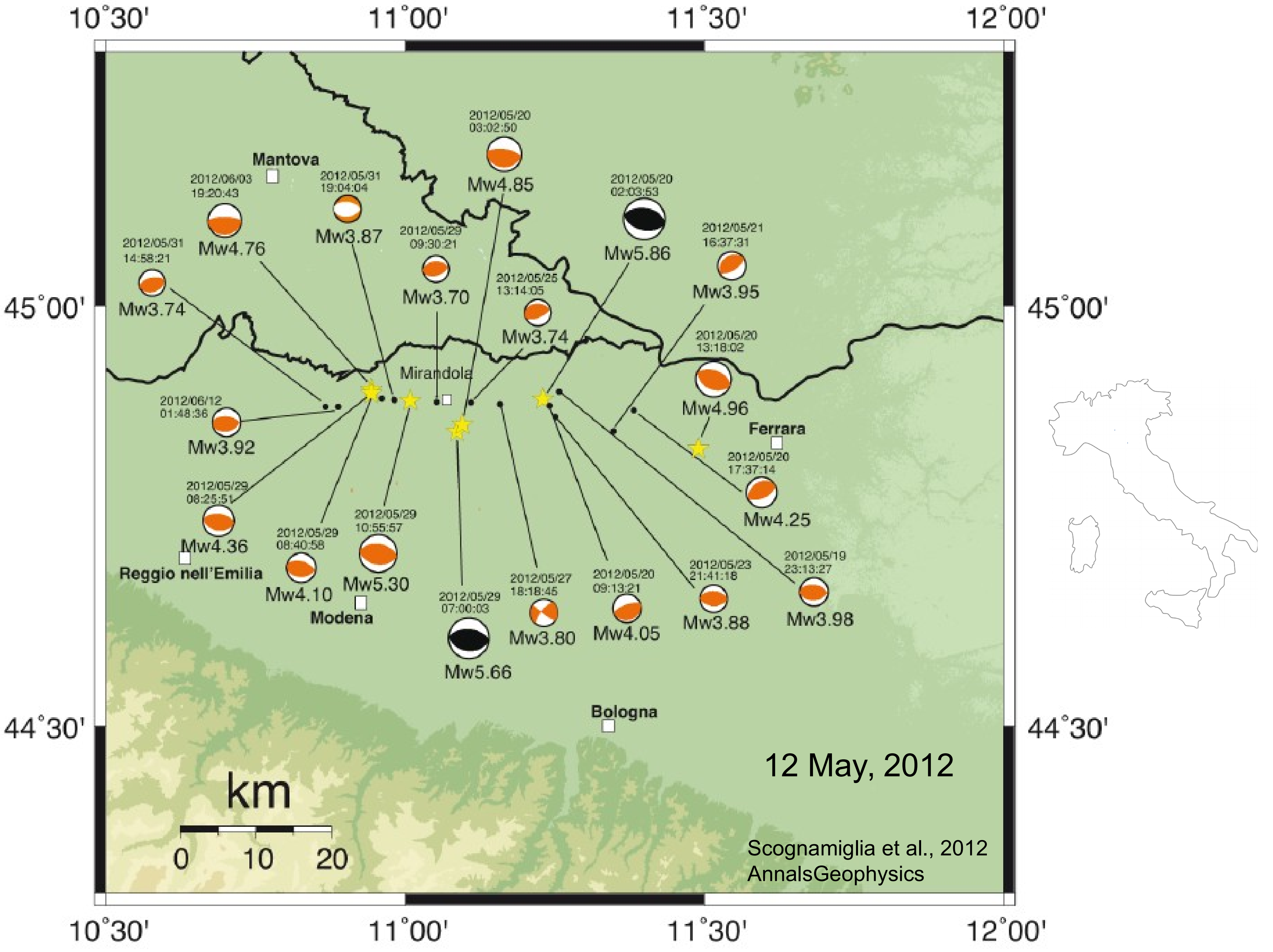
Many smaller knickpoints that “decorate” the middle reaches of the stream, perhaps related to rock-type or intraplate seismicity

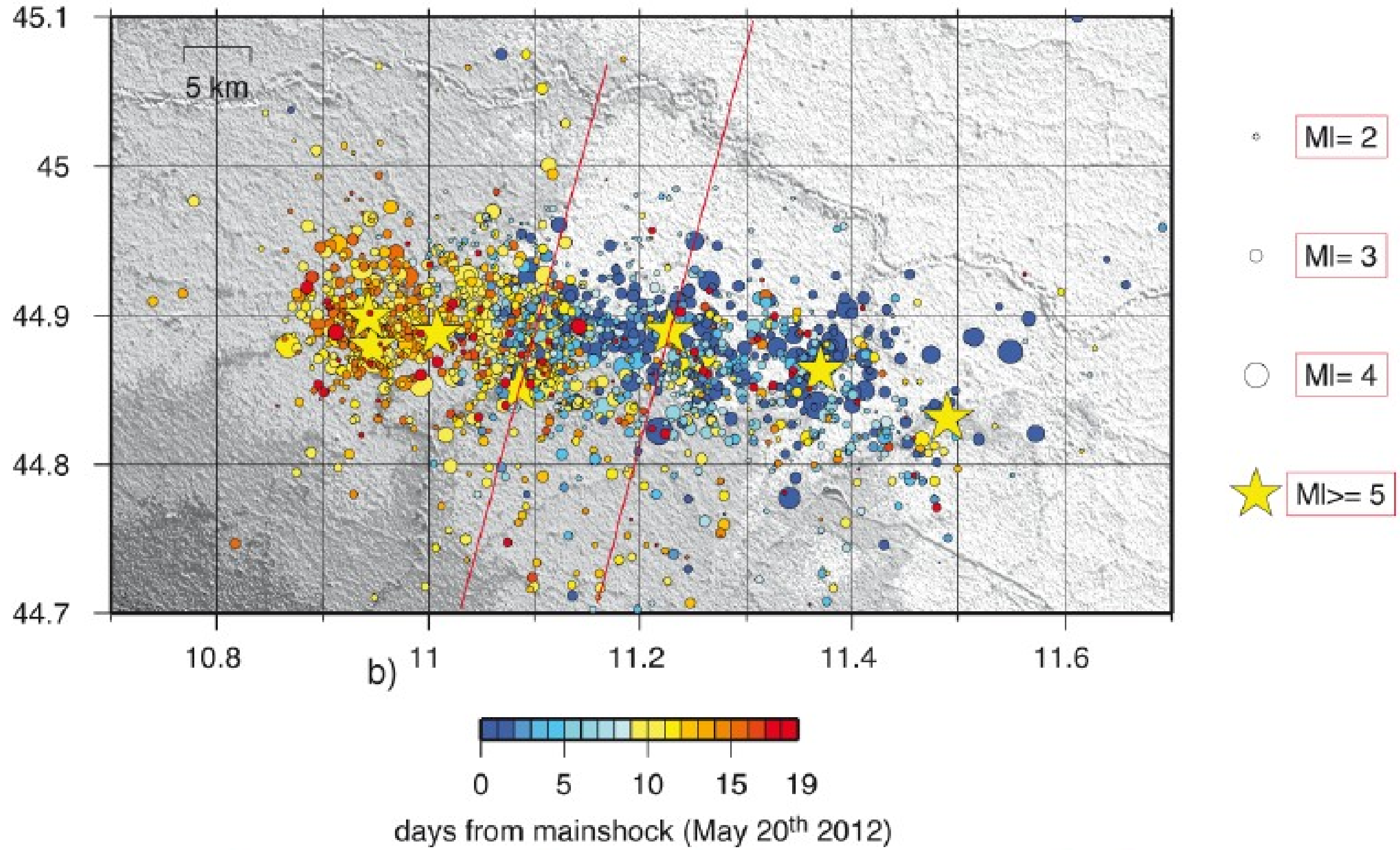
Mineral Fault / Earthquake
Depth ~6 km
Dip ~50°
Strike length ~ 10 km
M 5.8
throw ~0.1 m
(Wells and Coppersmith, 1984)



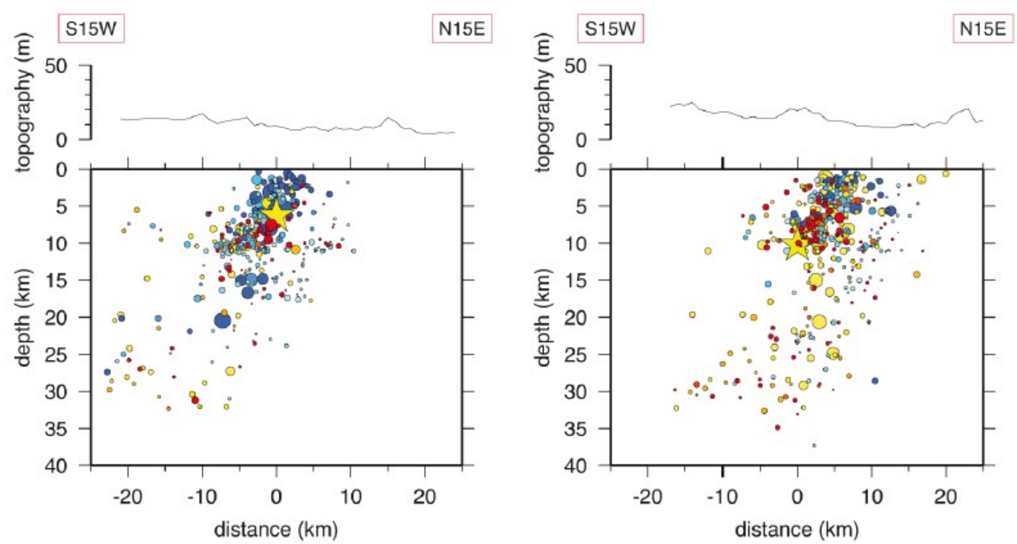




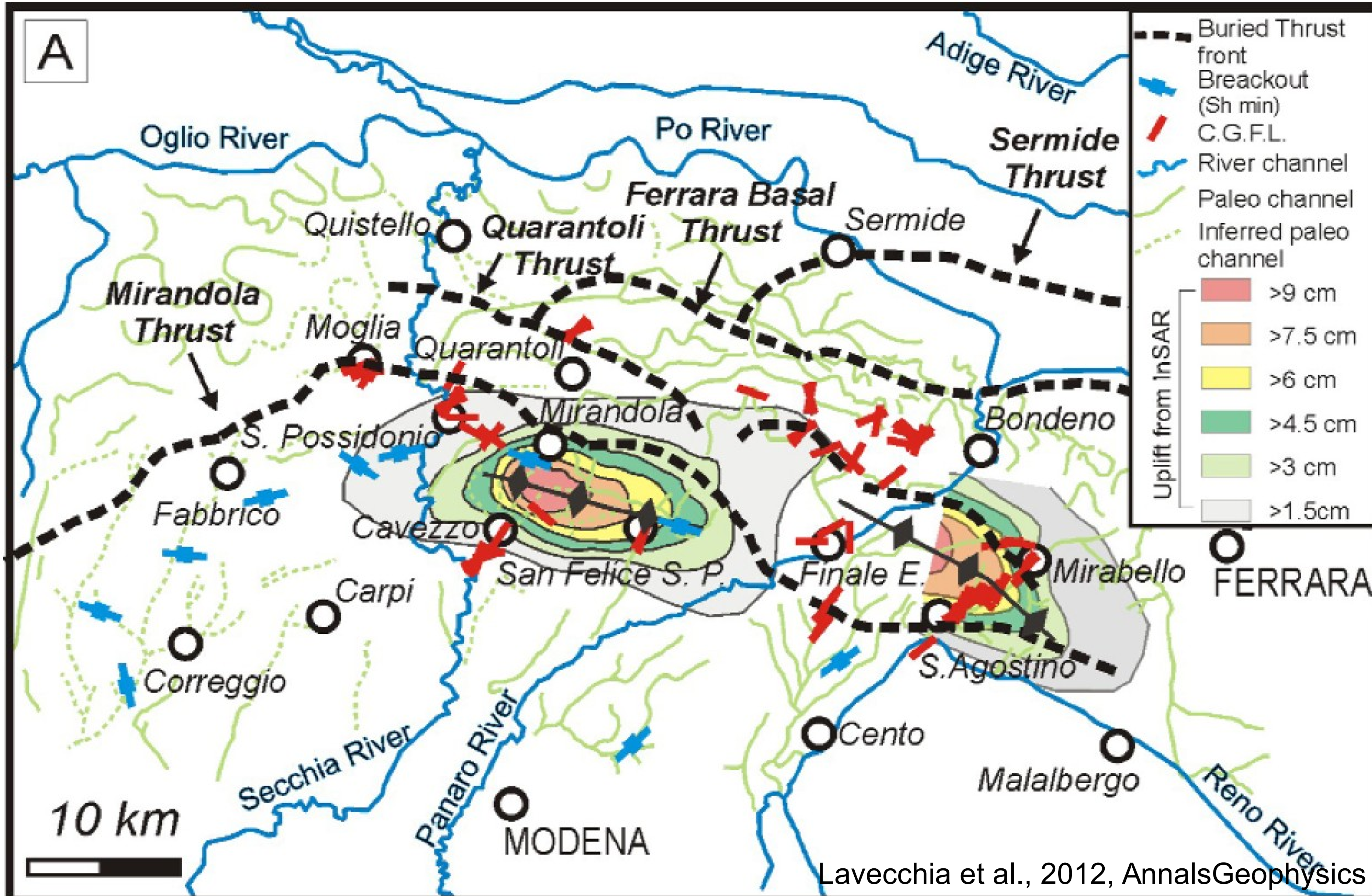

10°30'
11°00'
11°30'
12°00'
45°00'
44°30'
Mantova
Mirandola
Ferrara
Reggio nell'Emilia
Modena
Bologna
2012/05/20
03:02:50
Mw4.85
2012/06/03
19:20:43
Mw4.76
2012/05/31
19:04:04
Mw3.87
2012/05/20
02:03:53
Mw5.86
2012/05/29
09:30:21
Mw3.70
2012/05/21
16:37:31
Mw3.95
2012/05/31
14:58:21
Mw3.74
2012/05/25
13:14:05
Mw3.74
2012/05/20
13:18:02
Mw4.96
2012/06/12
01:48:36
Mw3.92
2012/05/20
17:37:14
Mw4.25
2012/05/29
08:25:51
Mw4.36
2012/05/29
10:55:57
Mw5.30
2012/05/29
08:40:58
Mw4.10
2012/05/19
23:13:27
Mw3.98
2012/05/23
21:41:18
Mw3.88
2012/05/20
09:13:21
Mw4.05
2012/05/27
18:18:45
Mw3.80
2012/05/29
07:00:03
Mw5.66
12 May, 2012
km
0
10
20
Scognamiglia et al., 2012
AnnalsGeophysics



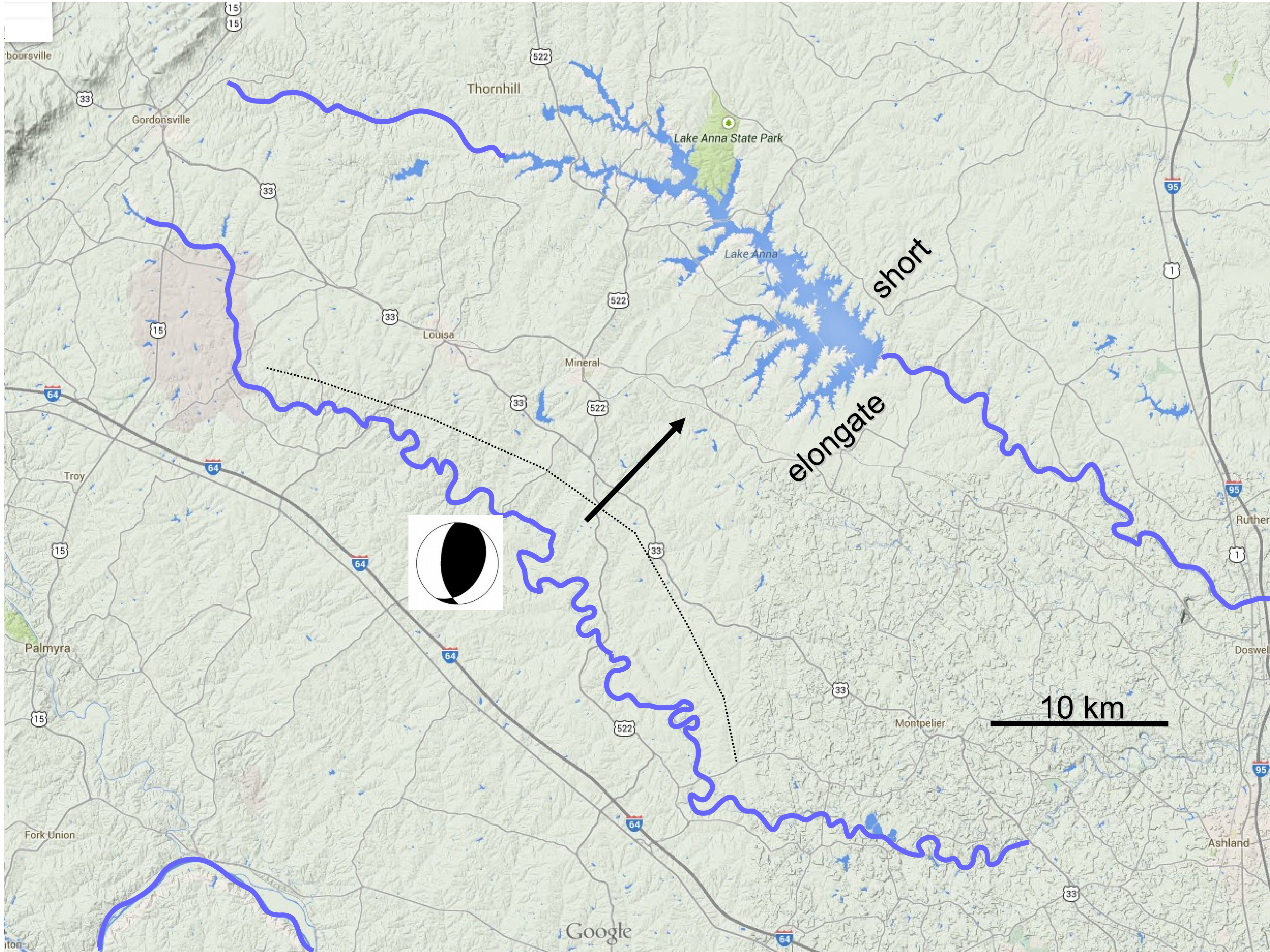
Depth ~ 6 km
Dip ~ 50°
M =5.8



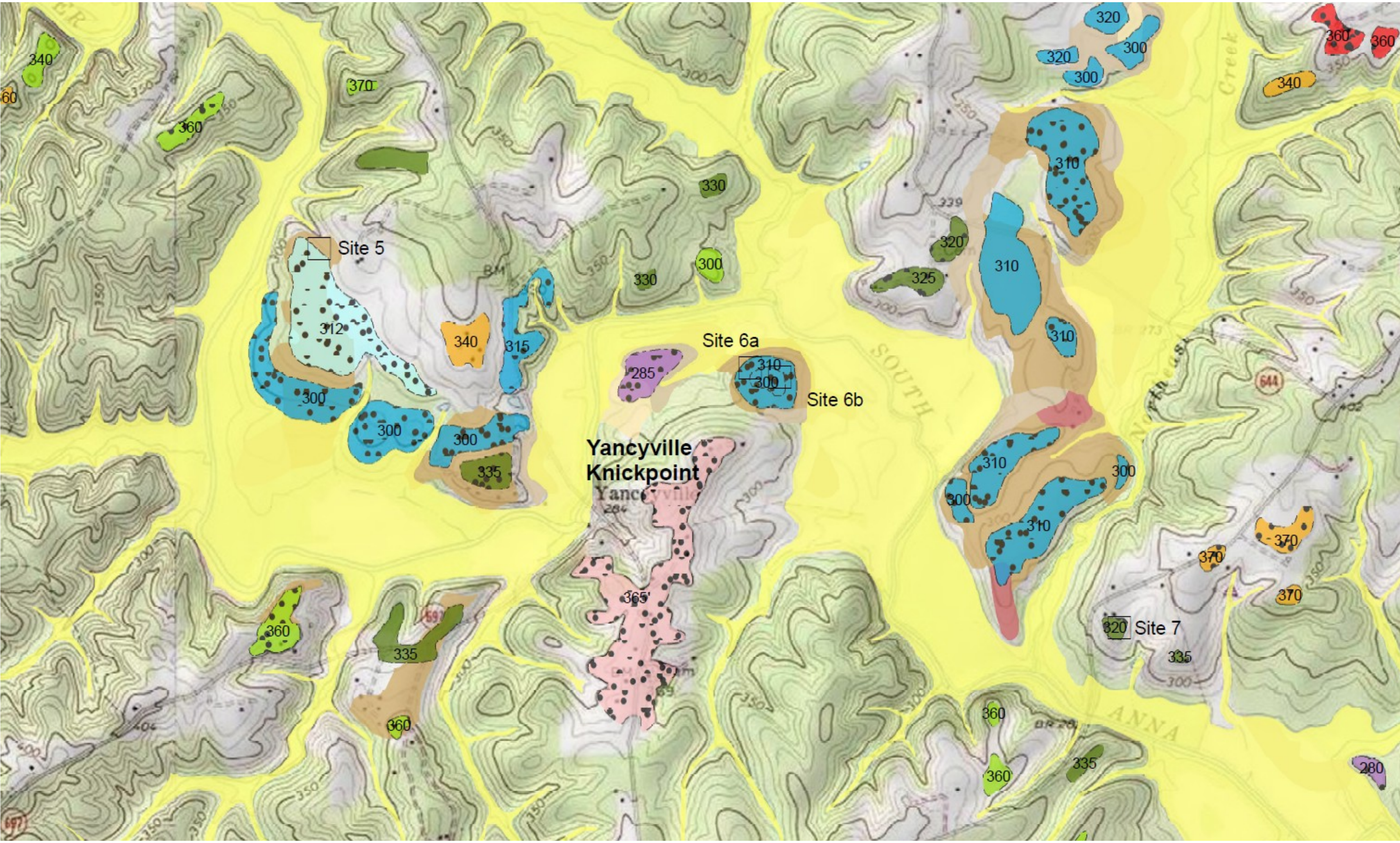
Scognamiglia et al., 2012
AnnalsGeophysics



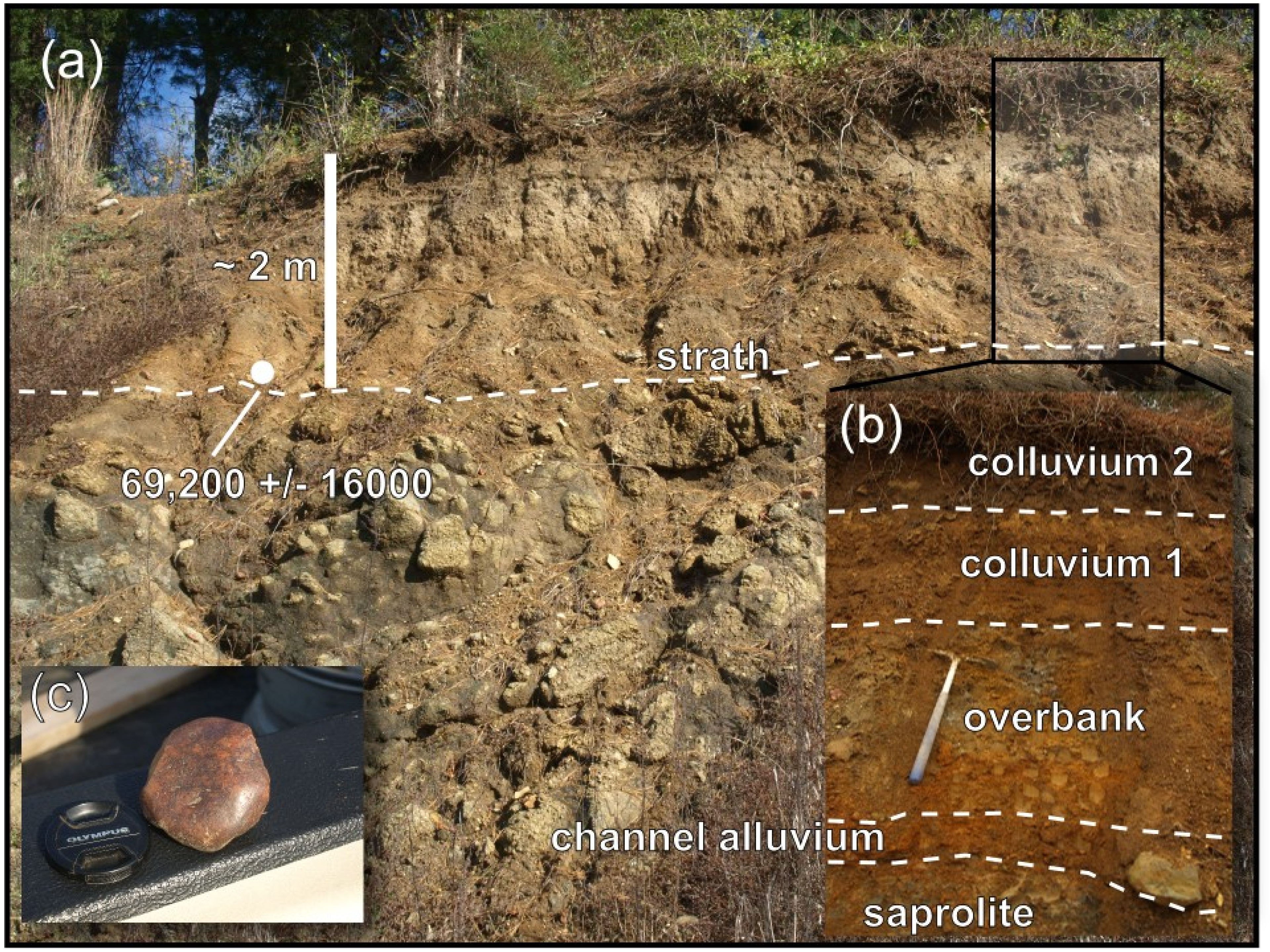
Lavecchia et al., 2012, AnnalsGeophysics



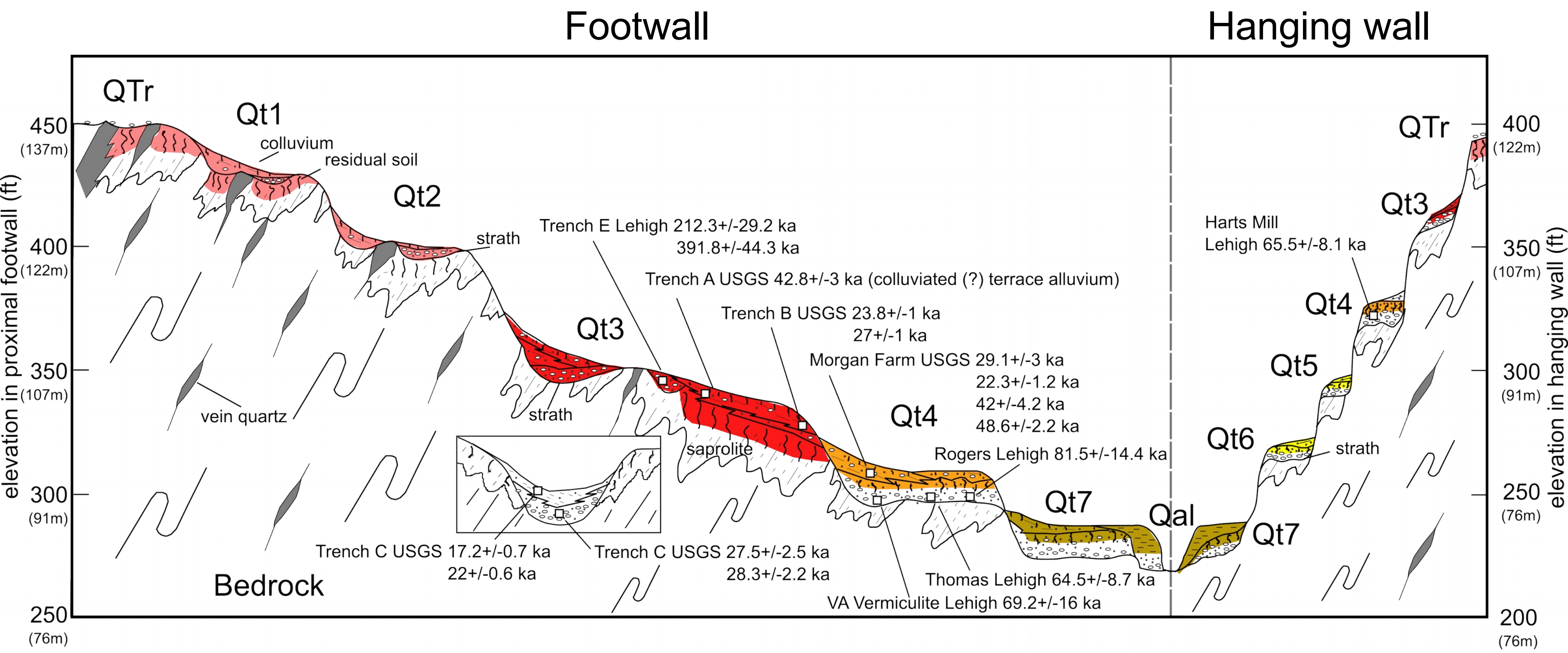
short
elongate
10 km
Thornhill
Lake Anna State Park
Lake Anna
Gordonsville
Louisa
Mineral
Troy
Palmyra
Fork Union
Montpelier
Ashland
Doswel
Ruther
rboursville
Google



Helen Malenda, EDMAP, G13AC00115

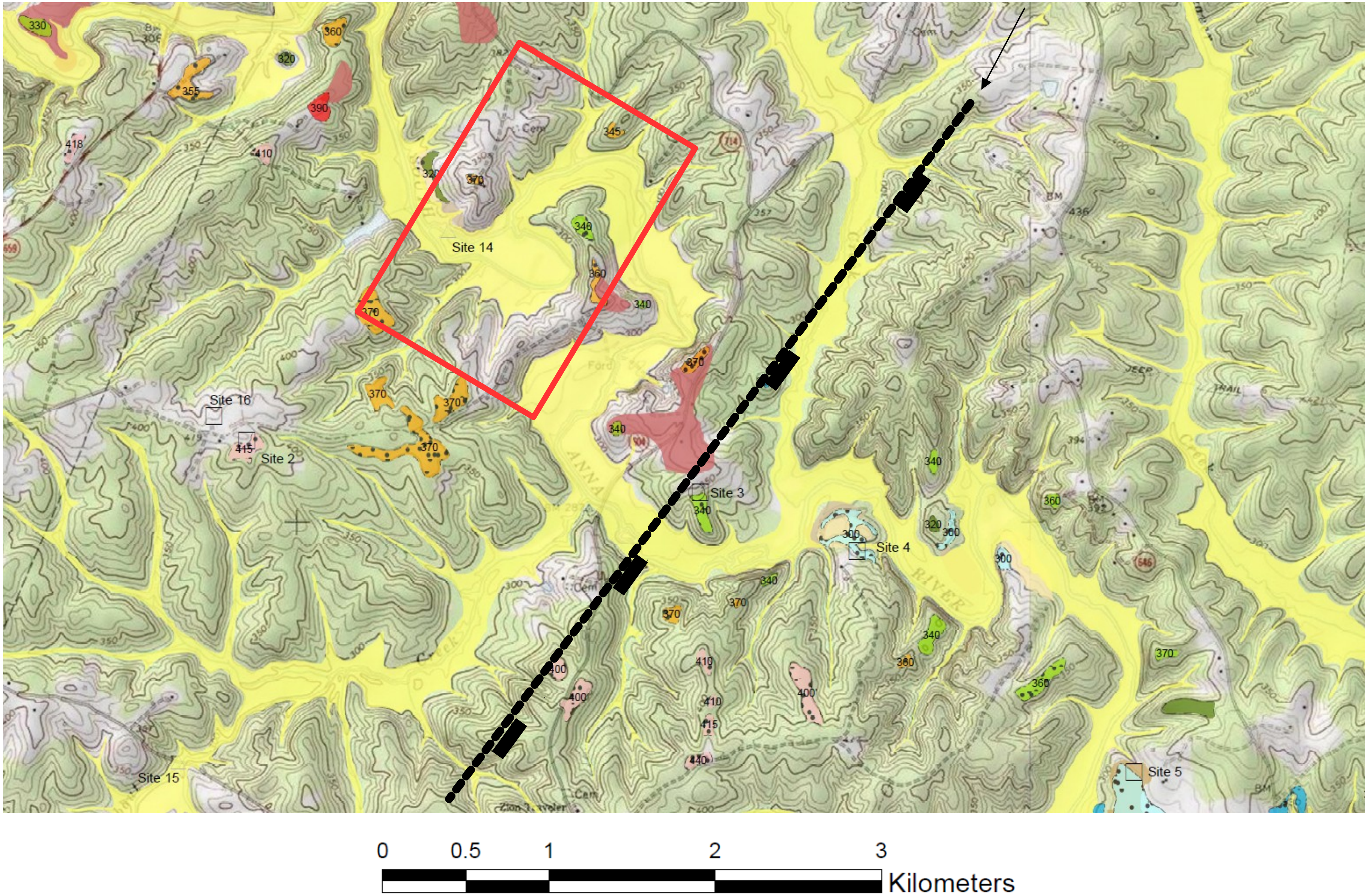


(a)
~ 2 m
strath
69,200 +/- 16000
(b)
colluvium 2
colluvium 1
overbank
channel alluvium
saprolite
(c)
OLYMPUS

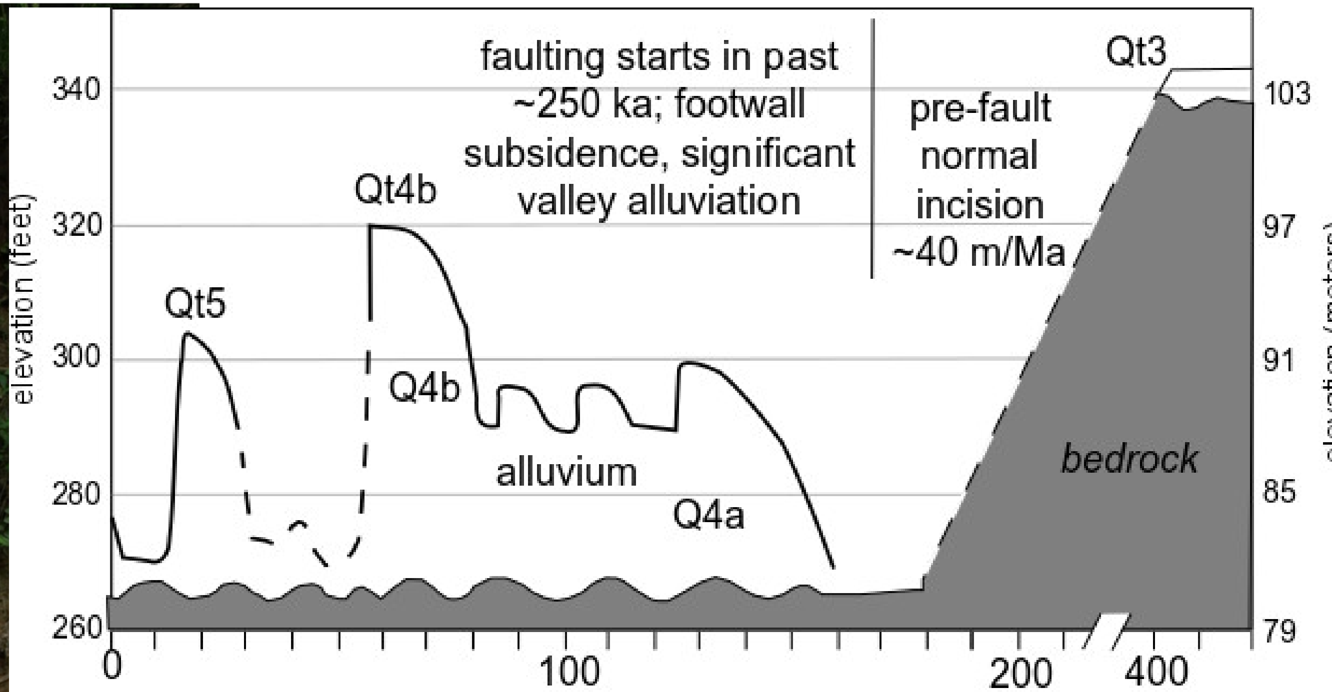

Footwall
Hanging wall
elevation in proximal footwall (ft)
elevation in hanging wall (ft)
450
(137m)
400
(122m)
350
(107m)
300
(91m)
250
(76m)
400
(122m)
350
(107m)
300
(91m)
250
(76m)
200
(76m)
QTr
Qt1
colluvium
residual soil
Qt2
strath
Trench E Lehigh 212.3+/-29.2 ka
391.8+/-44.3 ka
Trench A USGS 42.8+/-3 ka (colluviated (?) terrace alluvium)
Trench B USGS 23.8+/-1 ka
27+/-1 ka
Morgan Farm USGS 29.1+/-3 ka
22.3+/-1.2 ka
42+/-4.2 ka
48.6+/-2.2 ka
Qt3
Qt4
strath
vein quartz
saprolite
Rogers Lehigh 81.5+/-14.4 ka
Qt7
Qal
Trench C USGS 17.2+/-0.7 ka
22+/-0.6 ka
Trench C USGS 27.5+/-2.5 ka
28.3+/-2.2 ka
Thomas Lehigh 64.5+/-8.7 ka
VA Vermiculite Lehigh 69.2+/-16 ka
Bedrock
QTr
Qt3
Harts Mill
Lehigh 65.5+/-8.1 ka
Qt4
Qt5
Qt6
strath
Qt7

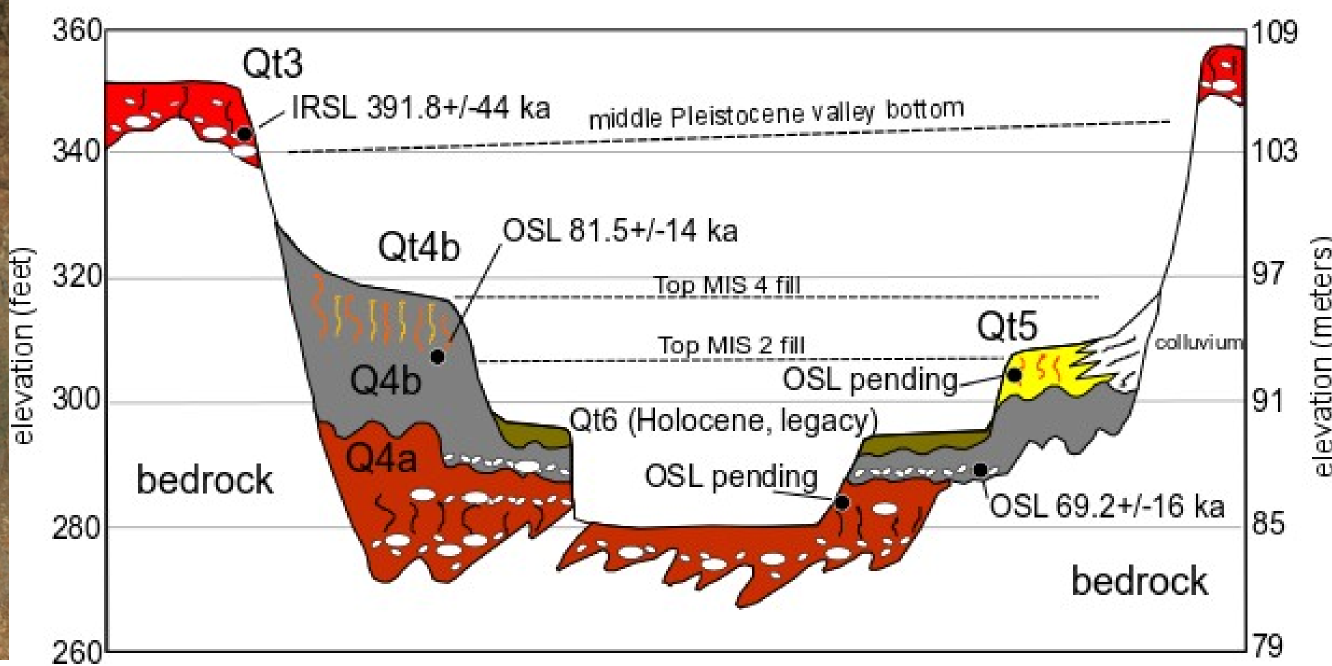
Horseshoe Farm

Approximate surface projection of fault that ruptured in 2011




Horseshoe Farm


faulting starts in past
~250 ka; footwall
subsidence, significant
valley alluviation
pre-fault
normal
incision
~40 m/Ma
Qt3
Qt4b
Qt5
Q4b
alluvium
Q4a
bedrock
elevation (feet)
340
320
300
280
260
103
97
91
85
79
0
100
200
400


Qt3
IRSL 391.8+/-44 ka
middle Pleistocene valley bottom
Qt4b
OSL 81.5+/-14 ka
Top MIS 4 fill
Top MIS 2 fill
Qt5
colluvium
OSL pending
Q4b
Qt6 (Holocene, legacy)
Q4a
bedrock
OSL pending
OSL 69.2+/-16 ka
bedrock
elevation (feet)
elevation (meters)
360
340
320
300
280
260
109
103
97
91
85
79

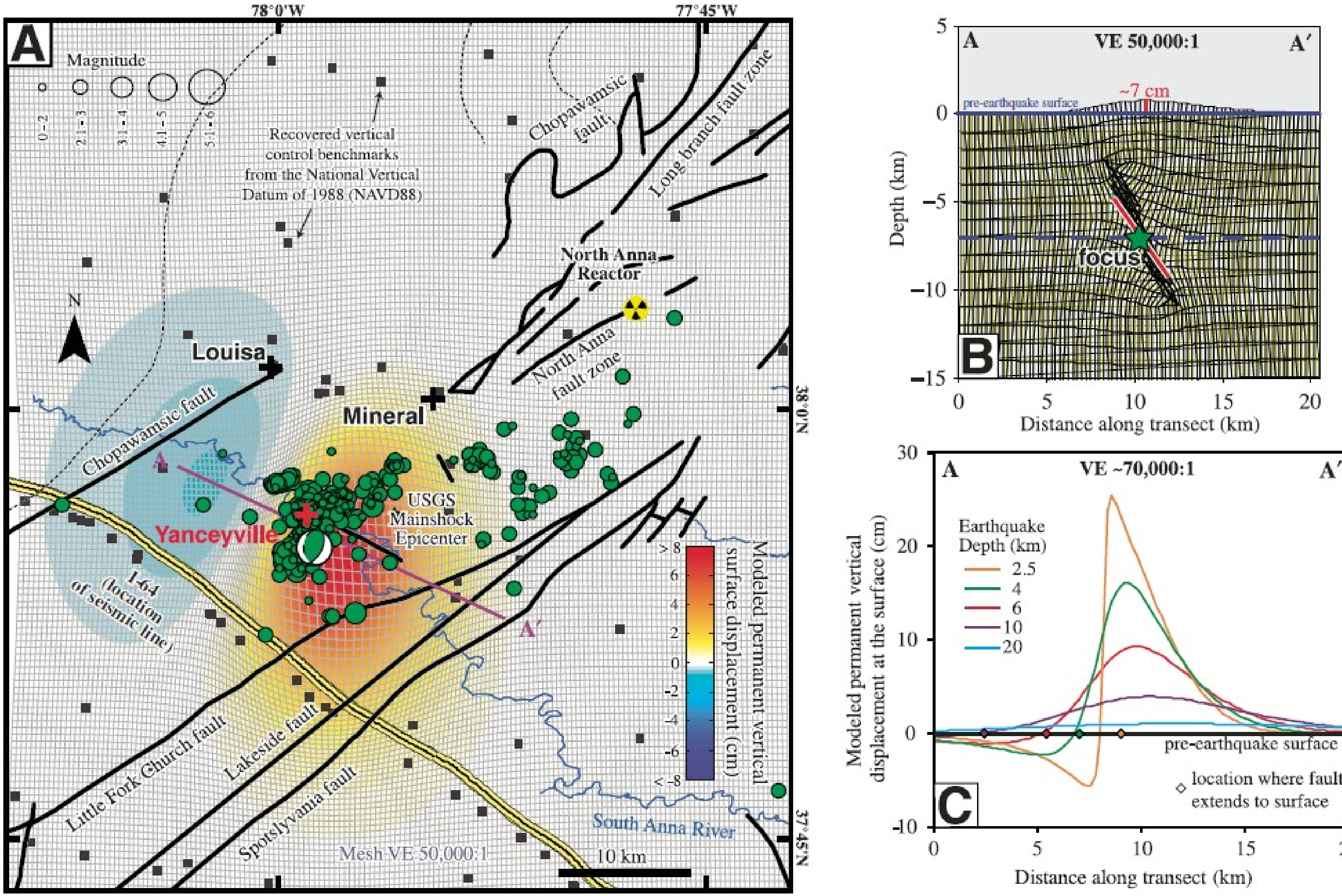
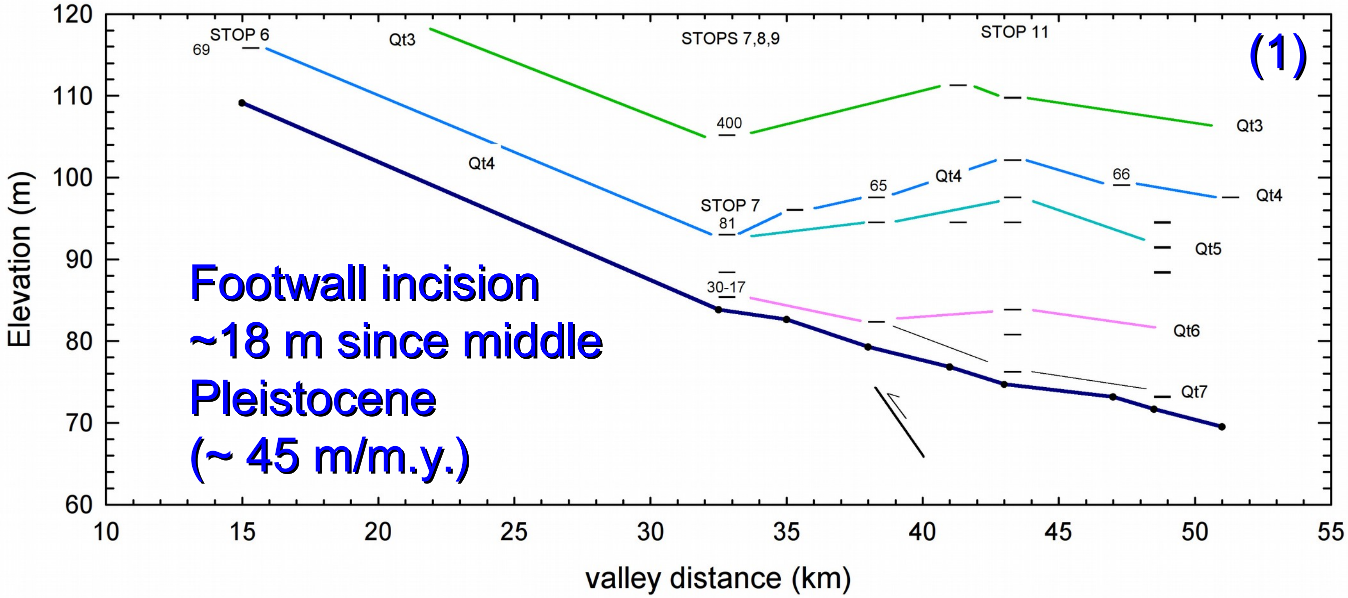


Figure 11. (A) Map of permanent vertical displacement expected at Earth's surface from the Mineral earthquake for a focus depth of 7 km at the center of the rupture. Calculation is based on empirical relations for same slip and dimensions (Wells and Coppersmith, 1994) and a Coulomb elastic dislocation model. Benchmark locations are from the National Geodetic Survey. Geographic Coordinate System: World Geodetic System (WGS 1984). Projection: Datum WGS 1984. VE—vertical exaggeration; USGS—U.S. Geological Survey. (B) Rupture plane and corresponding displacement model for slip generated by an M_w 5.8 earthquake with a depth of 7 km (preferred depth). Maximum upward displacement at the surface along transect A-A′ crossing the rupture is ~7 cm. Maximum downward displacement is ~1 cm. (C) Profile of vertical displacement at the surface for a range of depths.

Walsh et al., 2015, GSA SP 509.

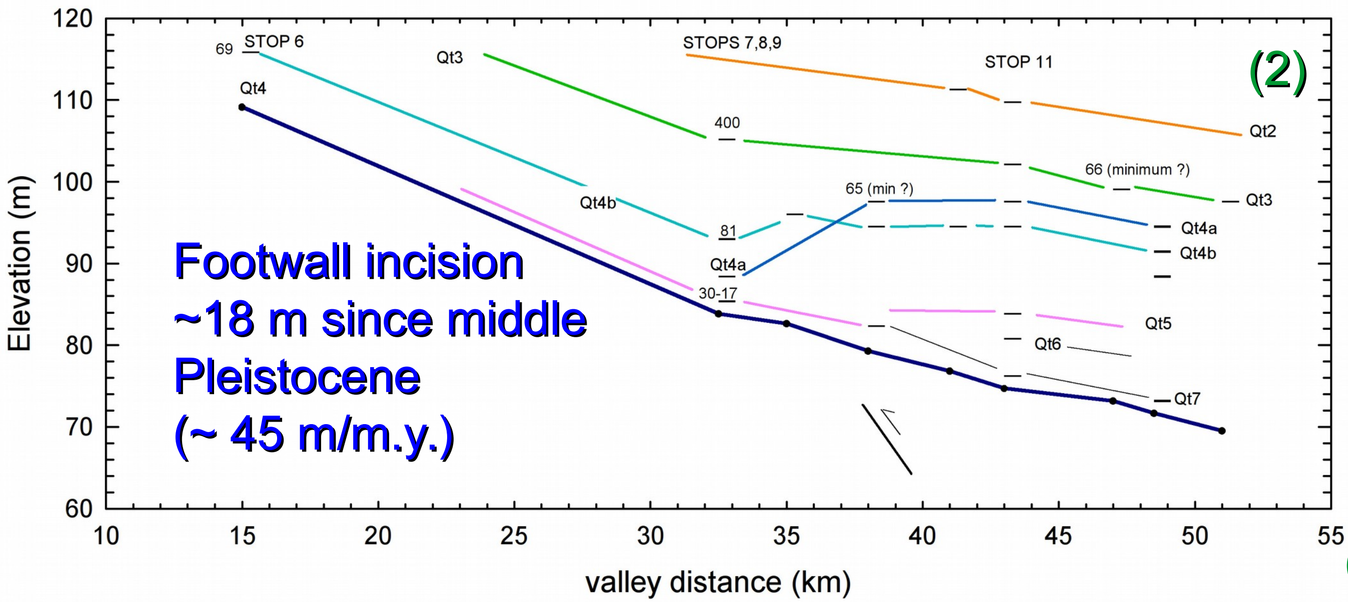


(1) Hanging wall incision
~34 m since mid Pleist.
(~115 m/m.y.)

assuming that fault slip is driving ~8-16 m of rock uplift in ~400 ka,

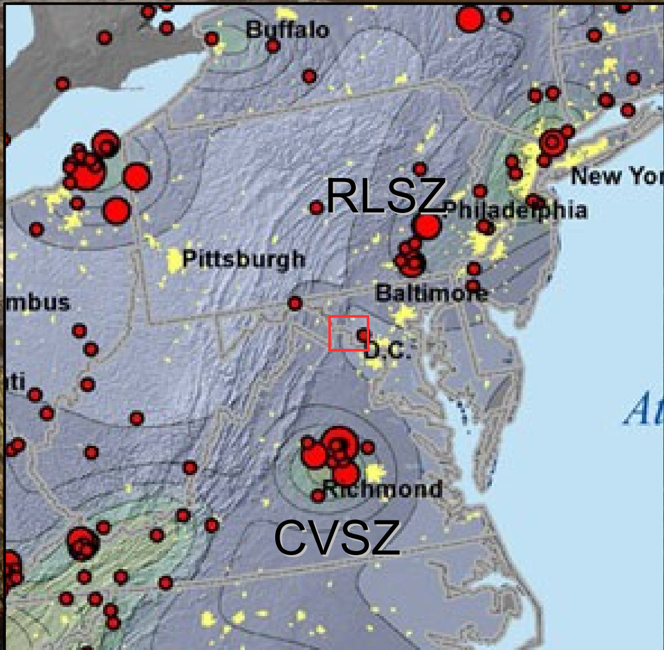
and Mineral earthquake -scale events generate ~7 cm of co-seismic fold growth (Walsh et al, 2015),

That is ~114-228 earthquakes with a R.I. of ~3,500 - 1750 yrs. since the middle Pleist.



(2) Hanging wall incision
~26 m since mid Pleist.
(~65 m/m.y)

Great Falls of the Potomac....large base level fall and river incision in the VA-MD Piedmont that is currently located between recognized (dense) clusters of seismicity in CVSZ and RLSZ.....

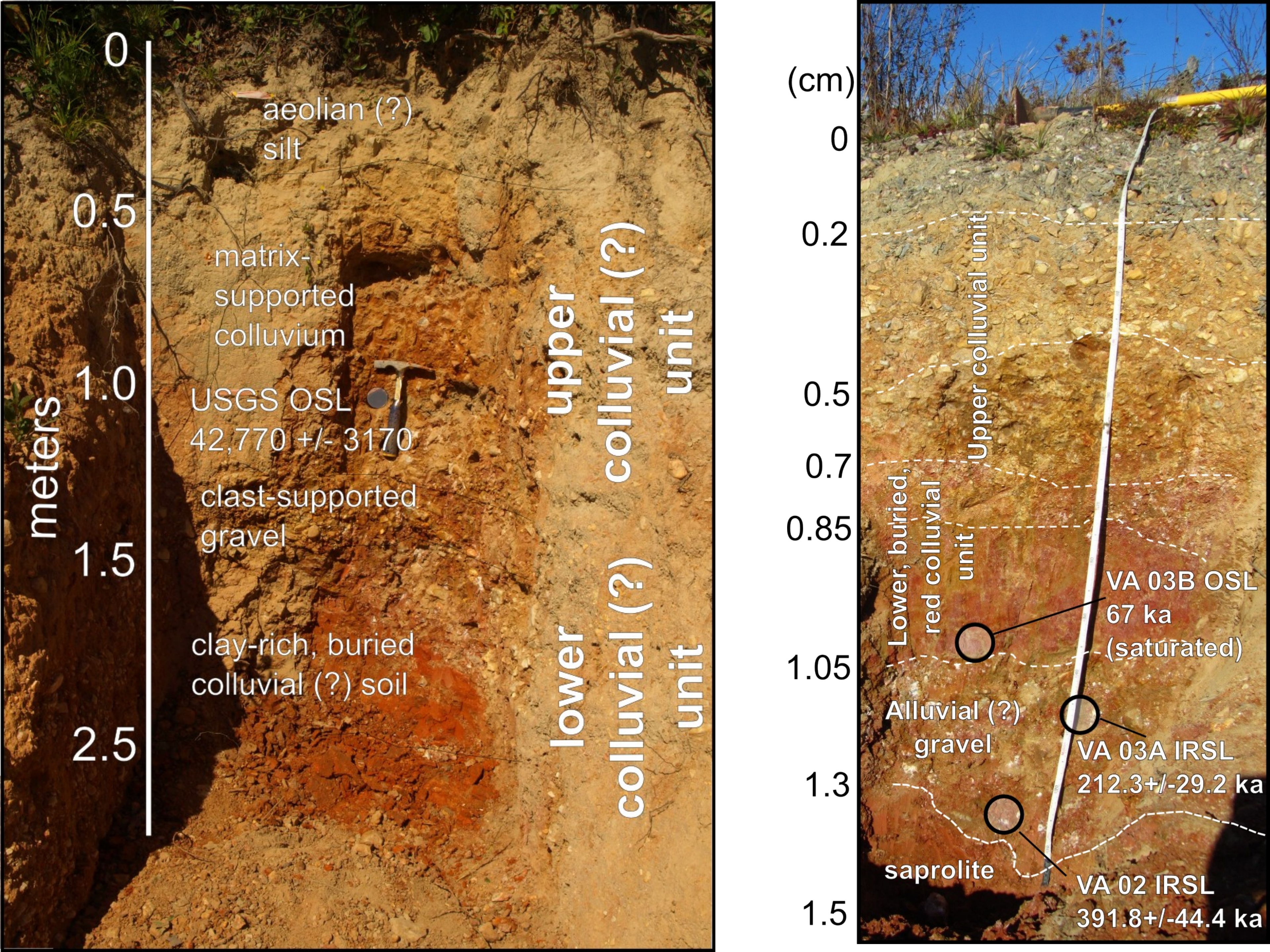


Conclusions

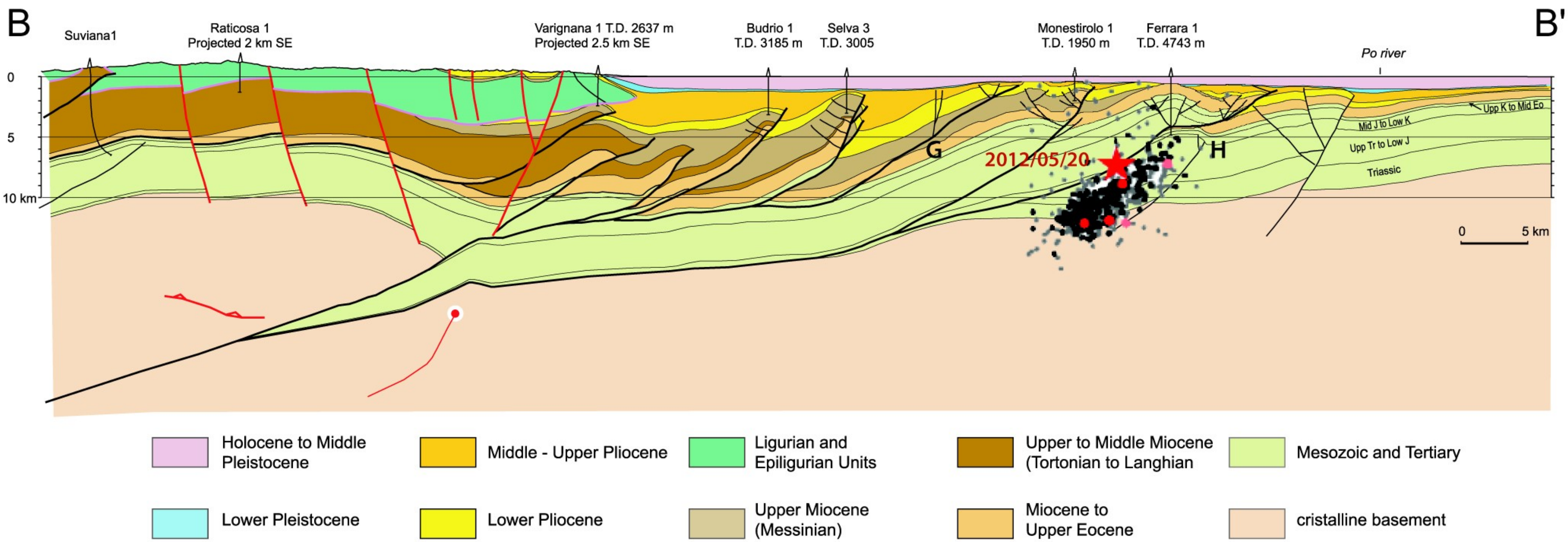
Direct evidence for local crustal deformation of the Appalachian landscape is evident in the warped terraces of the South Anna River that flows above the epicenter of the 23 August, 2011 Mineral earthquake.

GPS geodesy may struggle to measure crustal strains in the seismic zones, but maybe this is the wrong place to capture the elastic phase of the visco-elastic oscillator. Geomorphic geodesy can measure the accumulated strain of permanent co-seismic deformation, from many earthquakes.

What we do not know, can hurt us. Nearly all intraplate earthquake investigations have been focused in seismic zones; we should also be looking in the aseismic gaps for evidence of crustal strains in CEUS; geomorphic paleogeodesy is one tool that can help identify crustal strains in places that are currently “aseismic”.



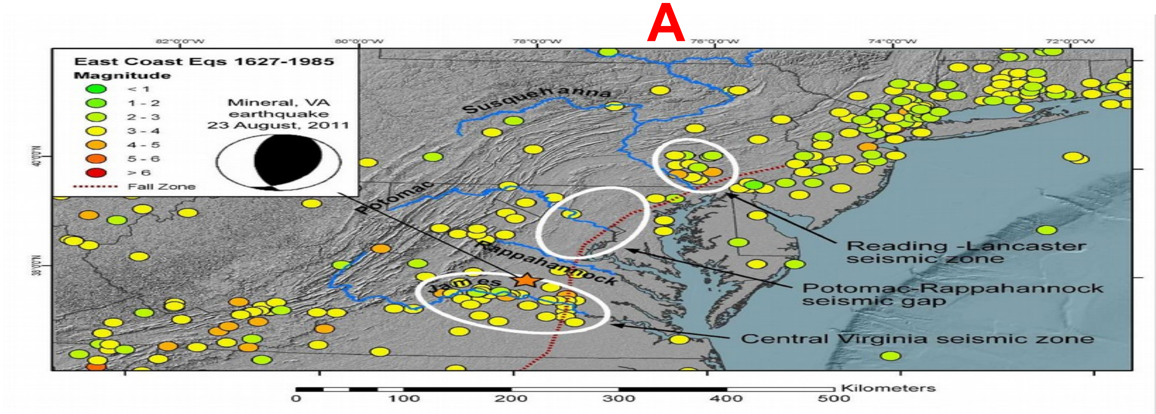
0
0.5
1.0
1.5
2.5
meters
aeolian (?)
silt
matrix-
supported
colluvium
USGS OSL
42,770 +/- 3170
clast-supported
gravel
clay-rich, buried
colluvial (?) soil
upper
colluvial (?)
unit
lower
colluvial (?)
unit
(cm)
0
0.2
0.5
0.7
0.85
1.05
1.3
1.5
Upper colluvial unit
Lower, buried,
red colluvial
unit
VA 03B OSL
67 ka
(saturated)
Alluvial (?)
gravel
VA 03A IRSL
212.3+/-29.2 ka
saprolite
VA 02 IRSL
391.8+/-44.4 ka



Picotti and Pazzaglia, 2006; Picotti, 2012

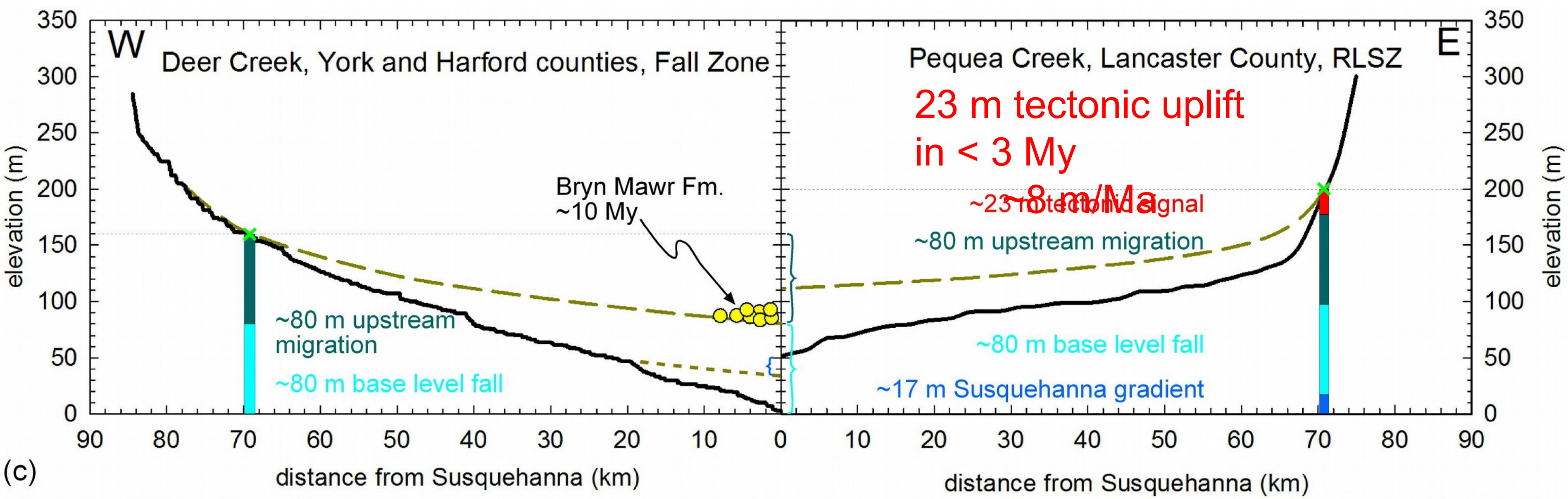
B

A

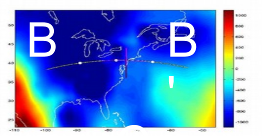

East Coast Eqs 1627-1985
Magnitude
< 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 6
> 6
Fall Zone
Mineral, VA
earthquake
23 August, 2011
Susquehanna
Potomac
Rappahannock
James
Reading -Lancaster
seismic zone
Potomac-Rappahannock
seismic gap
Central Virginia seismic zone
0 100 200 300 400 500 Kilometers

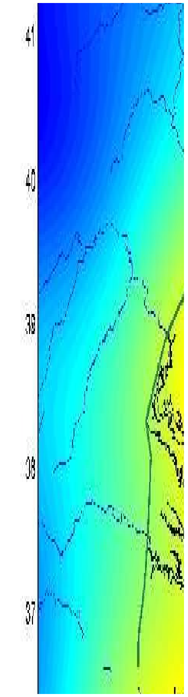
A

B


W
Deer Creek, York and Harford counties, Fall Zone
E
Pequea Creek, Lancaster County, RLSZ
23 m tectonic uplift
in < 3 My
~8 m/Ma
~23 m tectonic signal
~80 m upstream migration
~80 m base level fall
~17 m Susquehanna gradient
Bryn Mawr Fm.
~10 My
~80 m upstream
migration
~80 m base level fall
elevation (m)
distance from Susquehanna (km)
(c)

Eastern U.S. Dynamic topography (Moucha et al., 2008, EPSL)

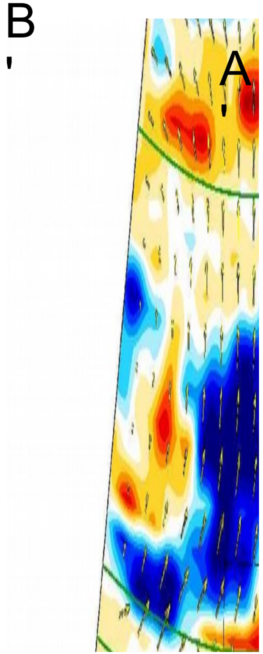




A

B

B
'

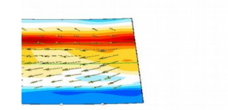


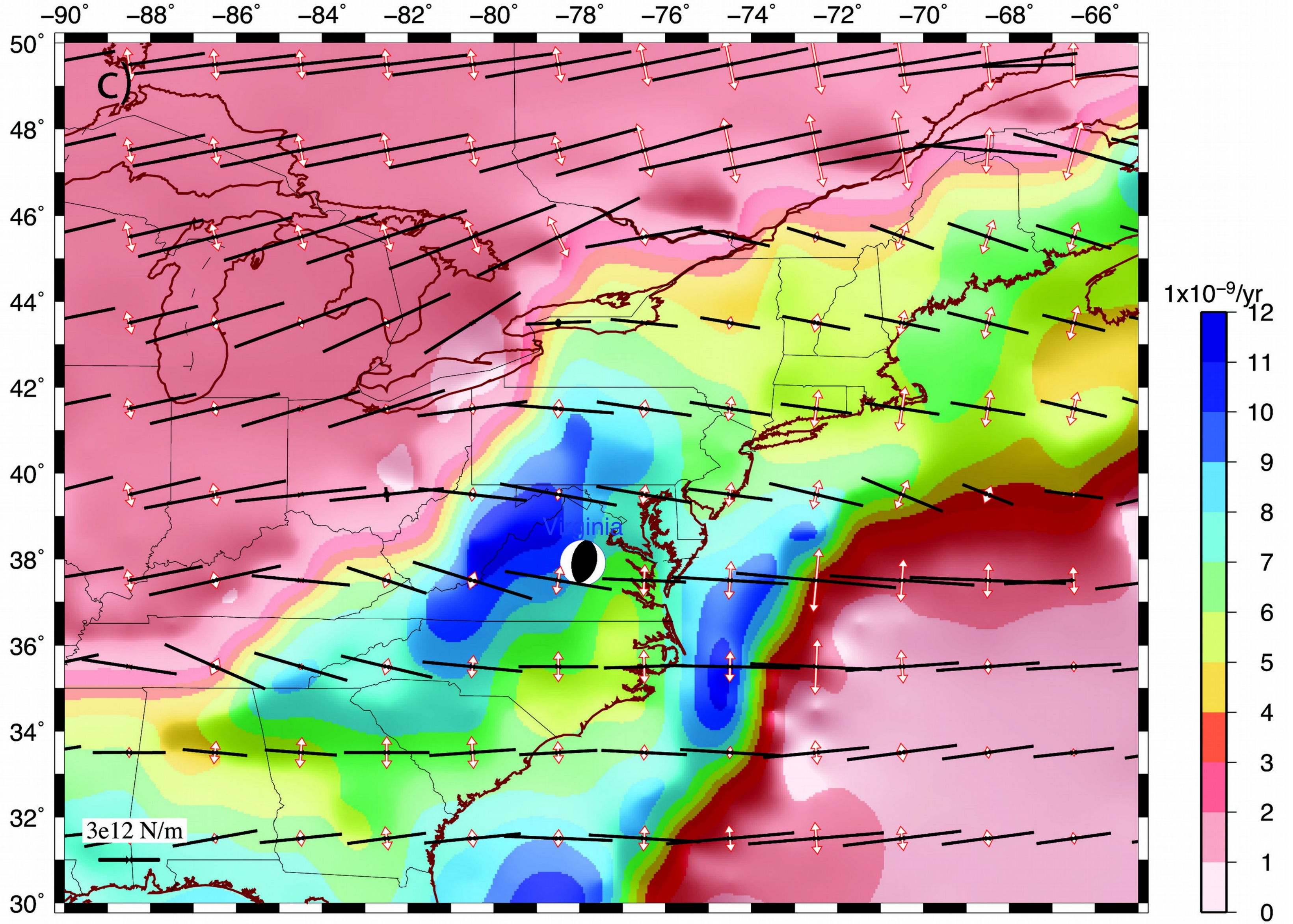
B

B
'

C

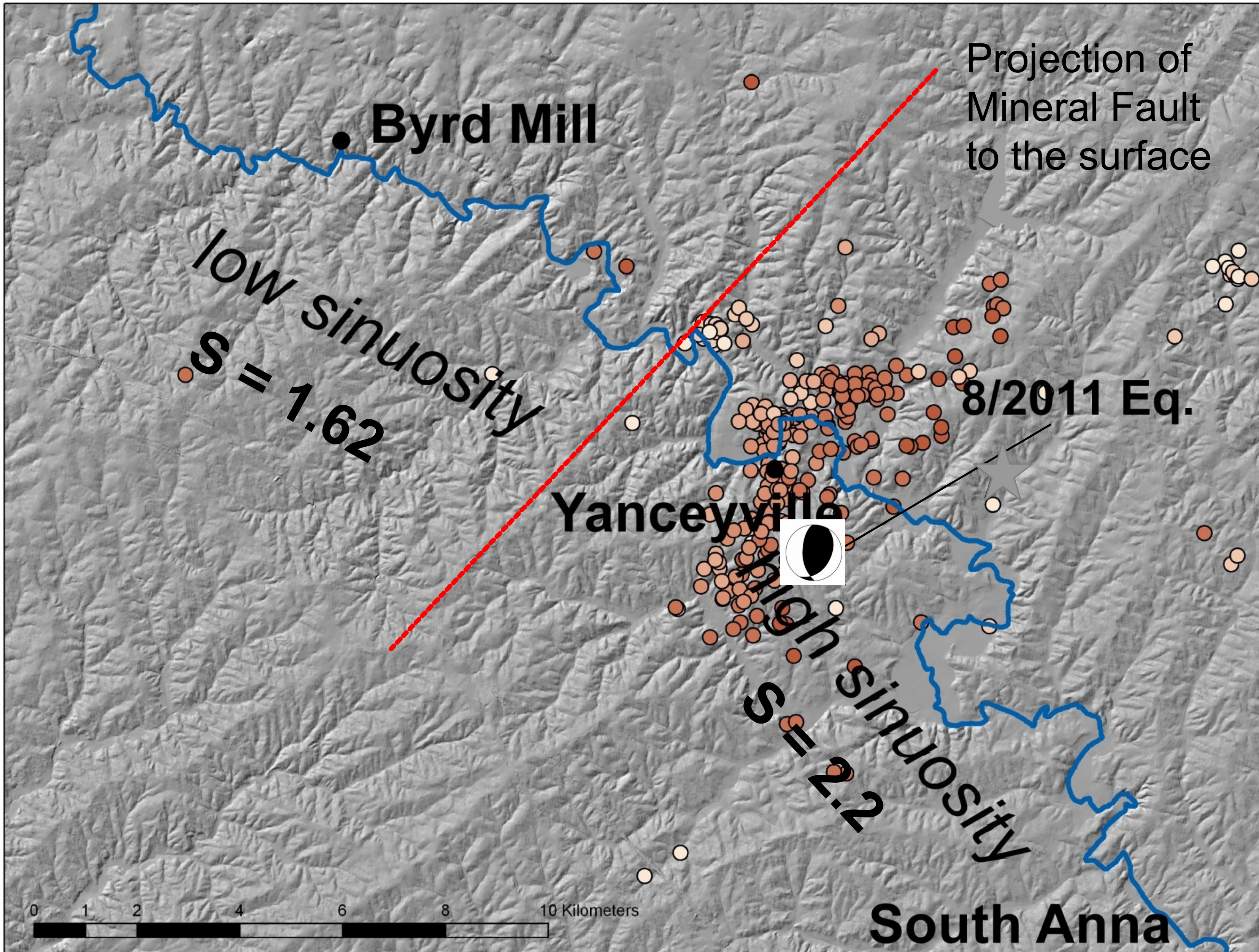
C
'





Contoured second invariant of strain rate for the lithosphere in parts of ENAM, together with depth-integrated deviatoric stresses, obtained from a global model and using a craton viscosity and old ocean (Müller et al., 2008, 1997) lithosphere viscosity of $1x10^{24}$ Pa-s. Bold vectors are principal axes of compression and open vectors are principal axes of tension. The craton distribution was obtained from the tomography model in Simmons et al. (2006).

Holt, unpublished data


Projection of
Mineral Fault
to the surface
Byrd Mill
low sinuosity
S = 1.62
8/2011 Eq.
Yanceyville
high sinuosity
S = 2.2
0 1 2 4 6 8 10 Kilometers
South Anna