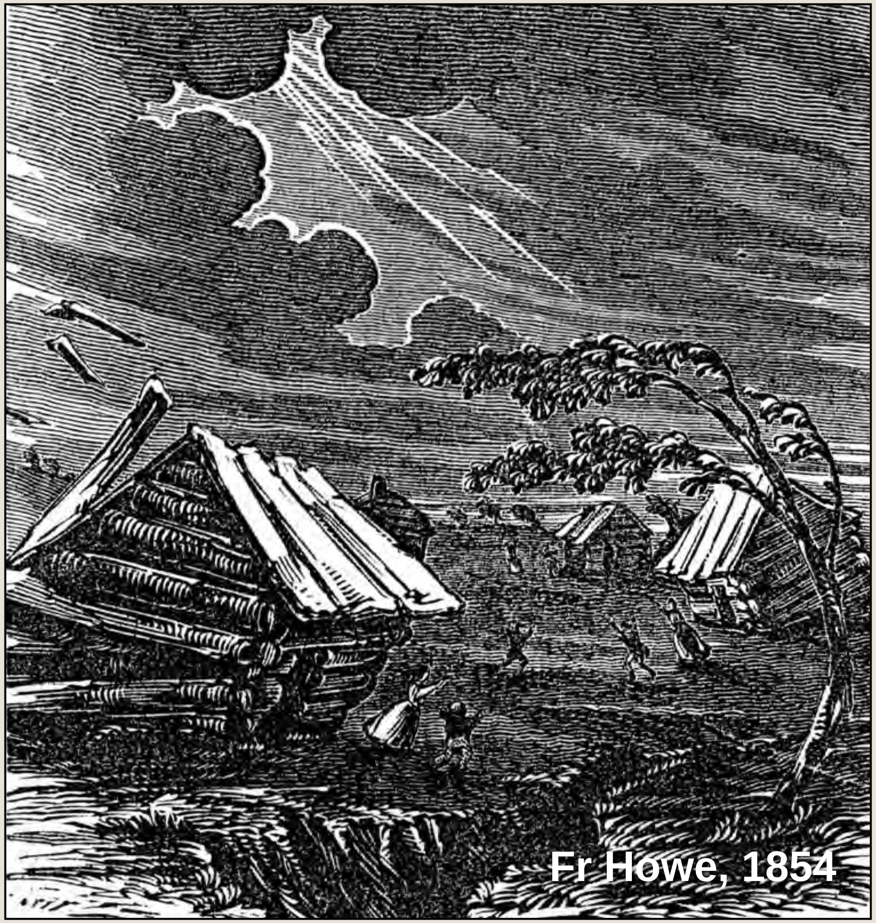
NRC Paleoliquefaction Training Workshop in the New Madrid Seismic Zone



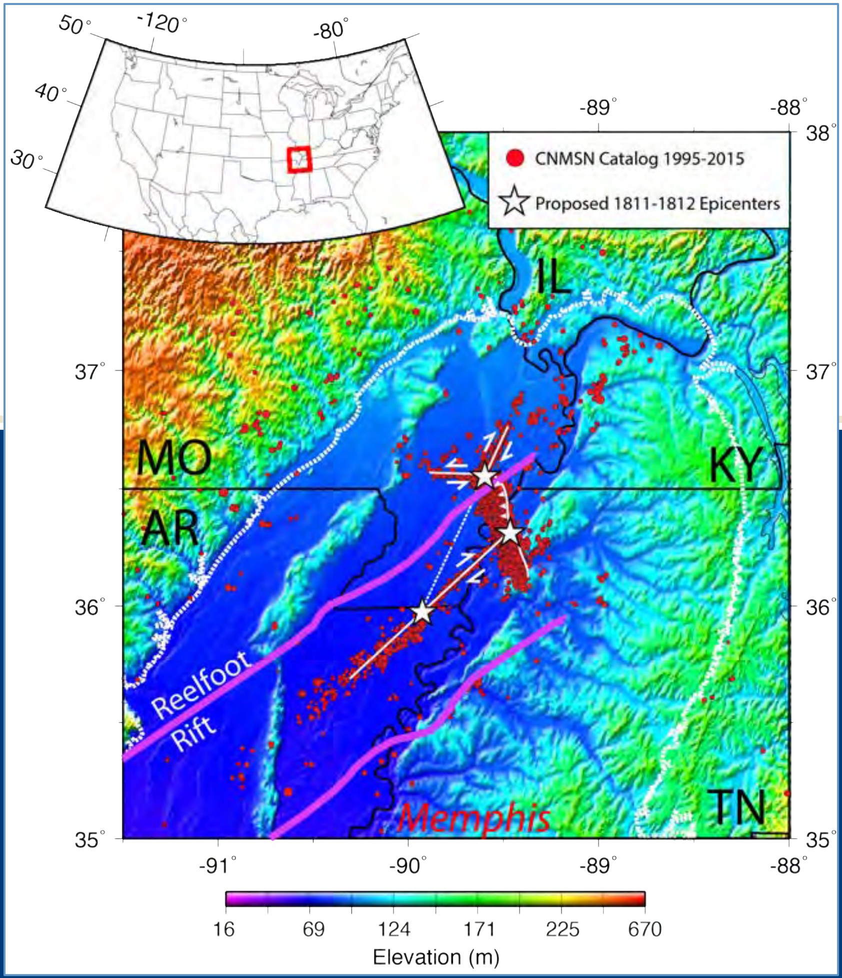
Organized by M. Tuttle & Associates
Blytheville, Arkansas
November 10-13th, 2015

Presentations

1. “Complex faulting, seismicity, and swarm activity within the New Madrid Seismic Zone,” by Heather R. DeShon
2. “Paleoliquefaction studies: Learning from historical and modern cases of liquefaction & dating paleoliquefaction features,” by Martitia Tuttle
3. “Geophysical imaging techniques at paleoliquefaction sites,” by Lorraine Wolf
4. “Paleoseismology of Marianna, Arkansas, area: Application of ground-penetrating radar,” by Haydar Al-Shukri, Hanan Mahdi, and Martitia Tuttle
5. “NHPA, NEPA, and ESA: Federal regulations affecting paleoseismology studies,” by Thomas Weaver
6. “Seismic geotechnics,” by Paul W. Mayne
7. “New in-situ test developments 2014,” by Paul W. Mayne
8. “Evaluation of scenario earthquakes,” by Kathleen Dyer-Williams

Presentations Cont’d

9. “Radiocarbon dating and its use in paleoliquefaction studies,” by Darden Hood
10. “Optically stimulated luminescence dating for paleoseismology,” by Steven L. Forman, Liliana C. Marin, Xiaohua Gua, Ashley Ramsey, Chris Dickey, Connor Mayhut
11. “Archaeology and its uses in earthquake studies,” by Mary Evelyn Starr (not included due to lack of citations and references)
12. “2010-2011 Canterbury earthquake sequence: hidden faults, liquefaction, rock fall, economic impact, government response,” by Pilar Villamor
13. “Recent advances in paleoliquefaction back-calculation procedures,” by Russell A. Green and Brett Maurer
14. “The USGS seismic hazard maps,” by Chuck Mueller and members of the USGS NSHM Project
15. “NRC Training Workshop Wrapup: Discussion and recommendations,” facilitated by Lorraine Wolf and Martitia Tuttle



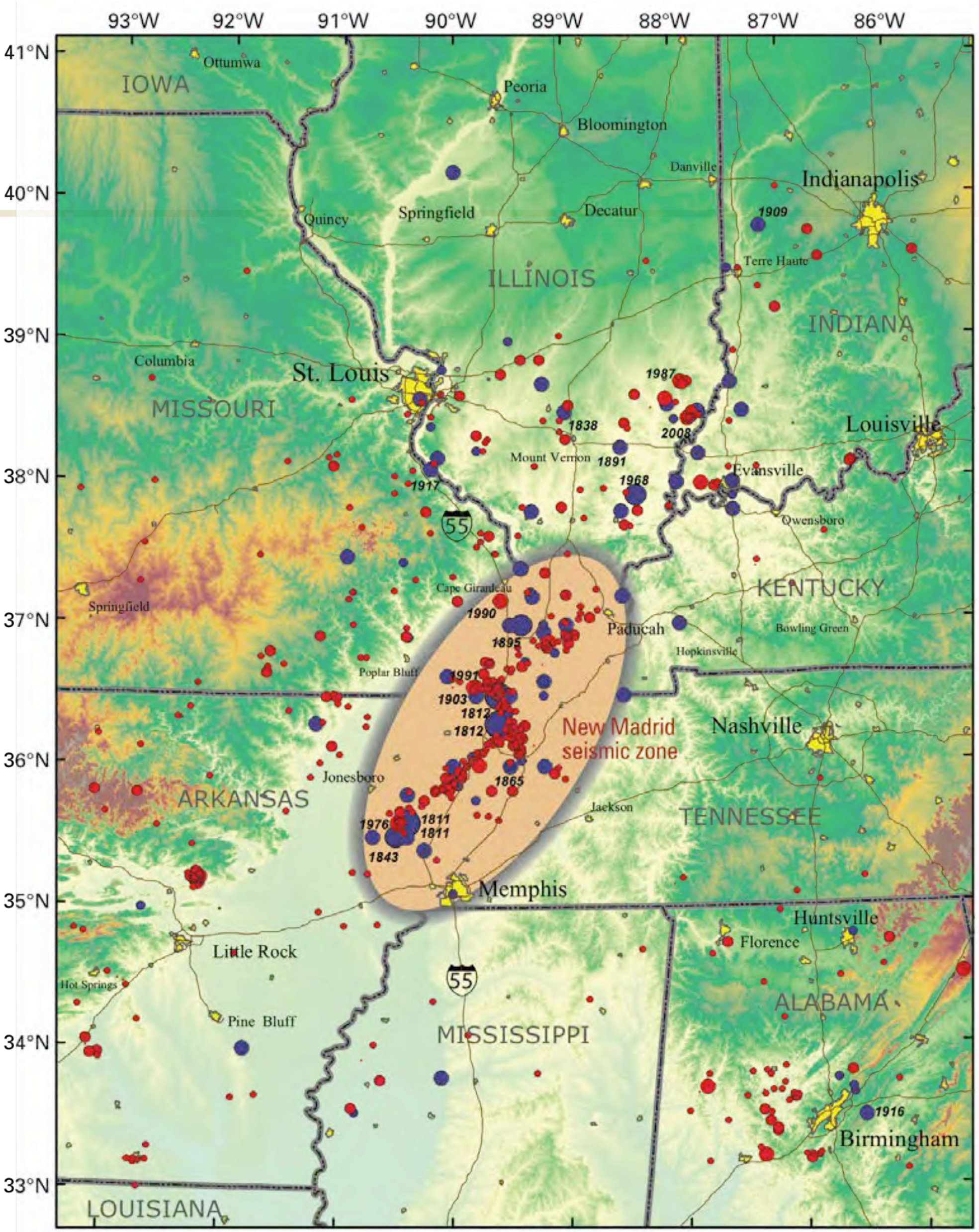
Complex faulting, seismicity, and swarm activity within the New Madrid Seismic Zone

Heather R. DeShon

NRC Paleoliquefaction Training
Blytheville, AR
11/10/2015

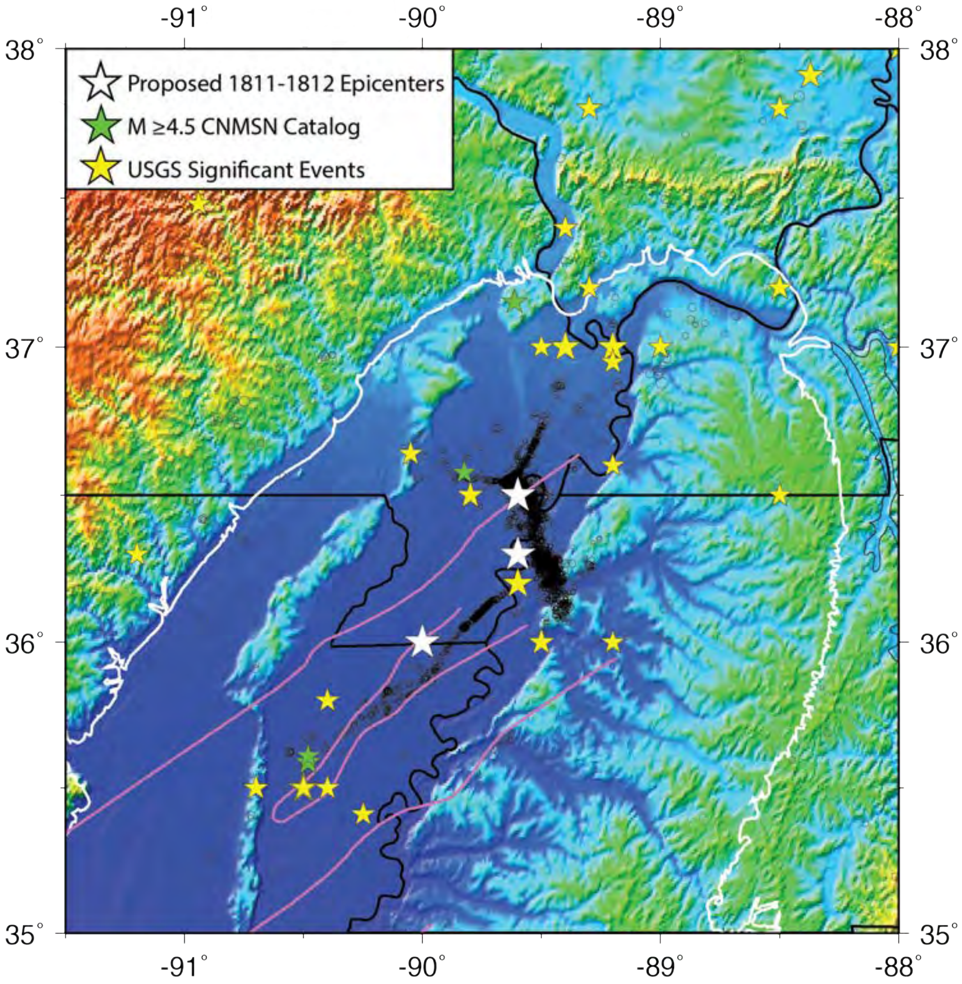
Outline

- Historic Seismicity
- History of Catalogs & Station Coverage
- High-Resolution Earthquake Location
- Seismicity Patterns
- Conclusions

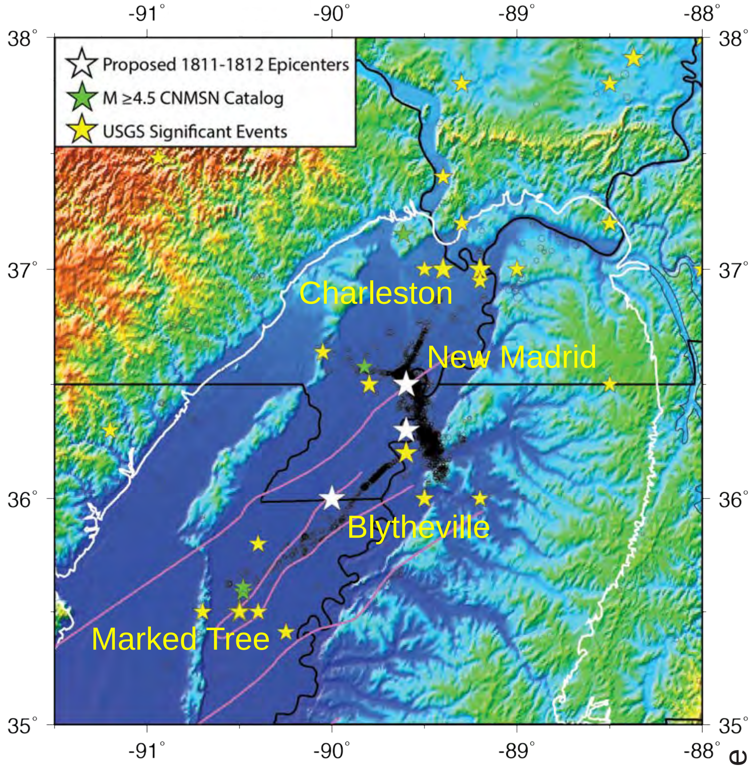


New Madrid Seismic Zone

- Sits within the Mississippi embayment
- Possibly reactivation of faults associated with Cambrian age rifting
- ~200 earthquakes/year



Historic Seismicity

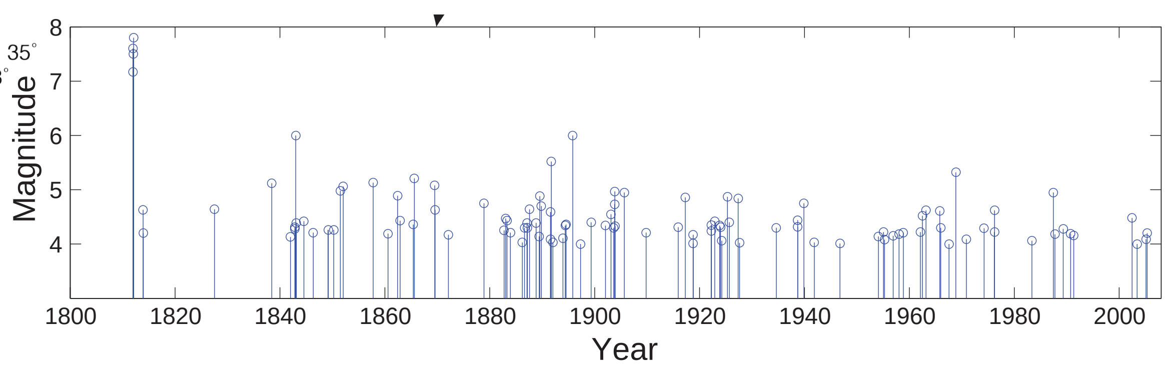


1811-1812 New Madrid events (M7-8)

- Dec. 1811 M7.1-7.5 (Axial/CWG)
- Dec. 1811 M7 (*Dawn Aftershock*)
- Jan. 1812 M7.0-7.3 (North Limb or IL)
- Feb. 1812 M7.4-7.5 (Reelfoot)

1843 Marked Tree, AR (M5.4-6.3)

1895 Charleston, MO (M6.6)



Paleoseismic History

Figure removed due to copyright issues.

Please see publications by Martitia Tuttle regarding the paleoseismic history of the New Madrid seismic zone.

Aftershocks? Not Likely

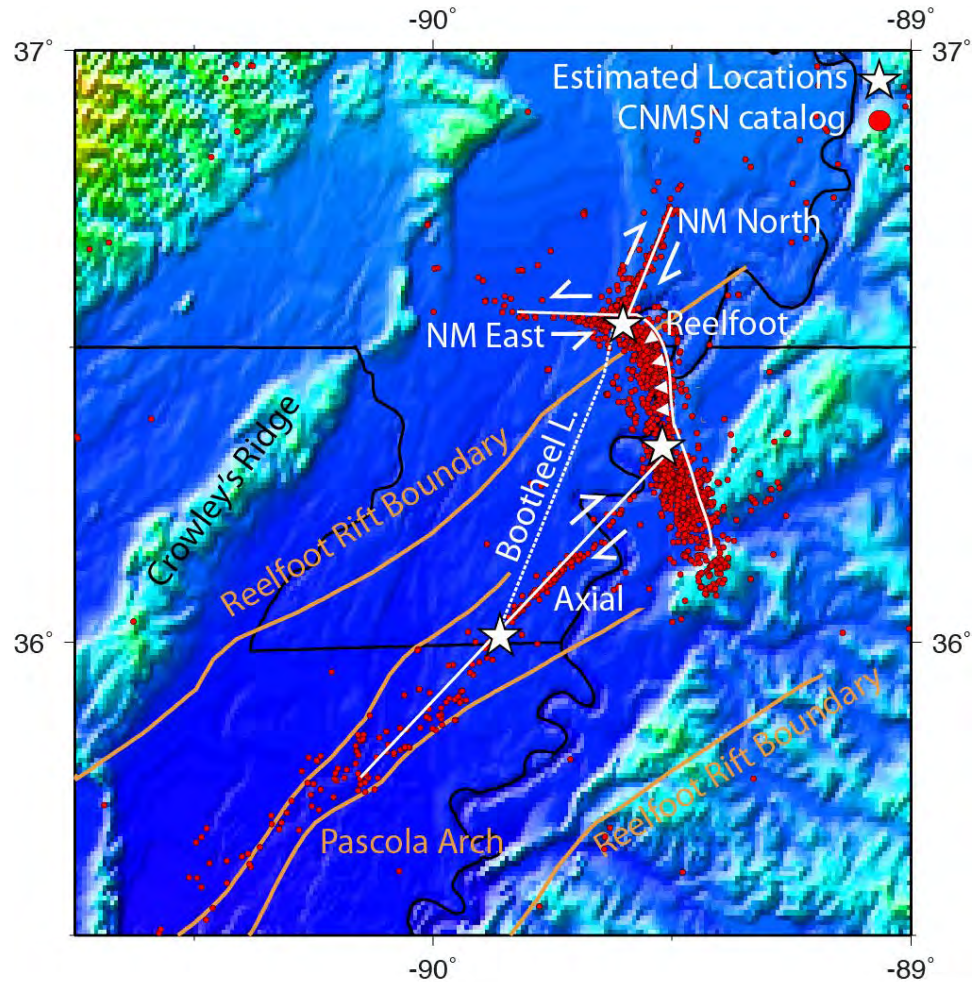
<5% probability that the 1811-1812 sequence has so few M6 earthquakes

Suggests current strain accumulation

Figures removed due to copyright issues. Please see Figures 1 and 2 in Page and Hough, 2014

The Fault System

- Microseismicity occurs primarily along 4 arms
  - Axial strike-slip fault
    aka Cottonwood Grove
  - Reelfoot thrust fault
  - New Madrid north ss
  - New Madrid west ss

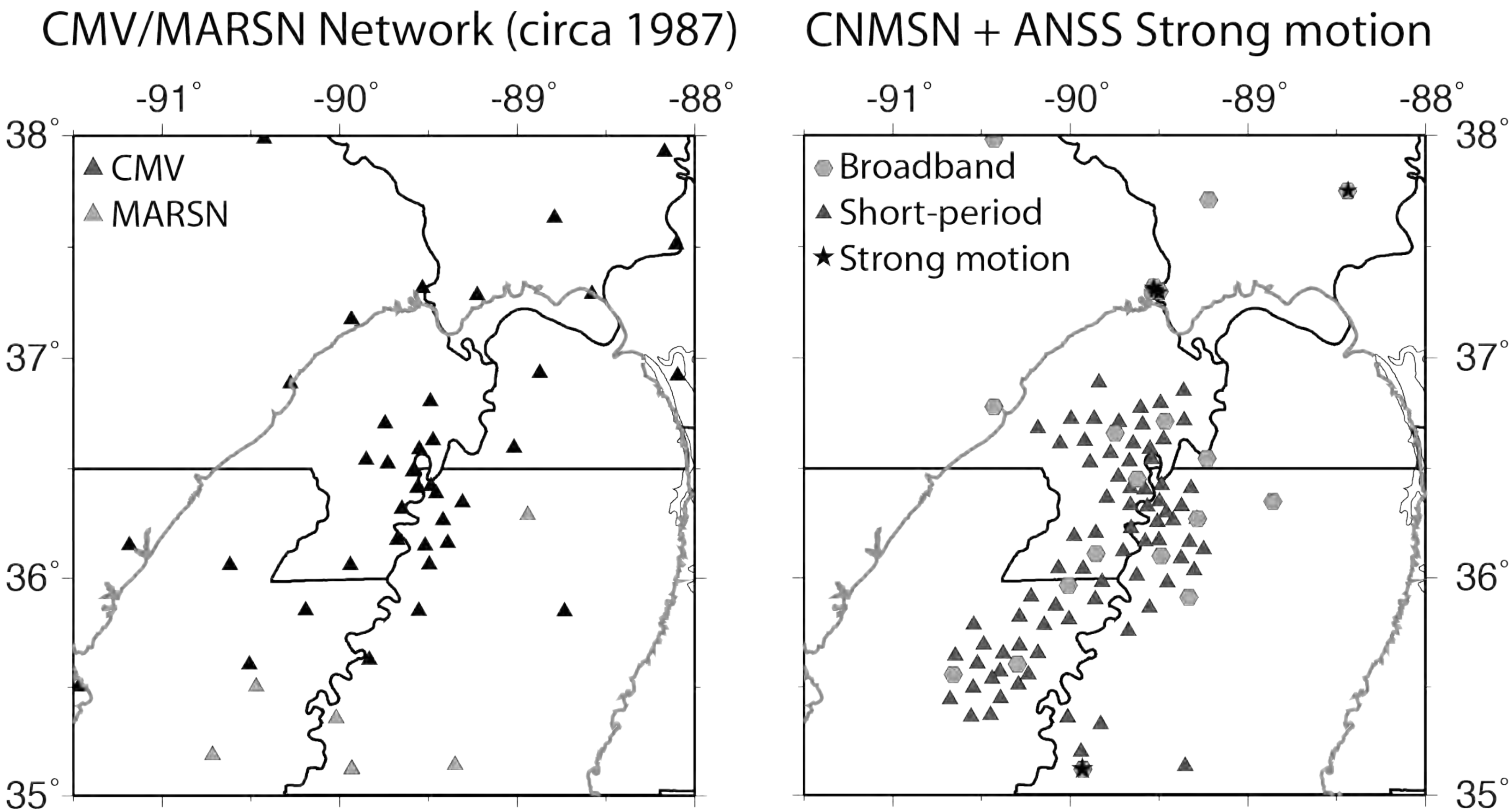


Point of slide: Fault names change over time and by author.

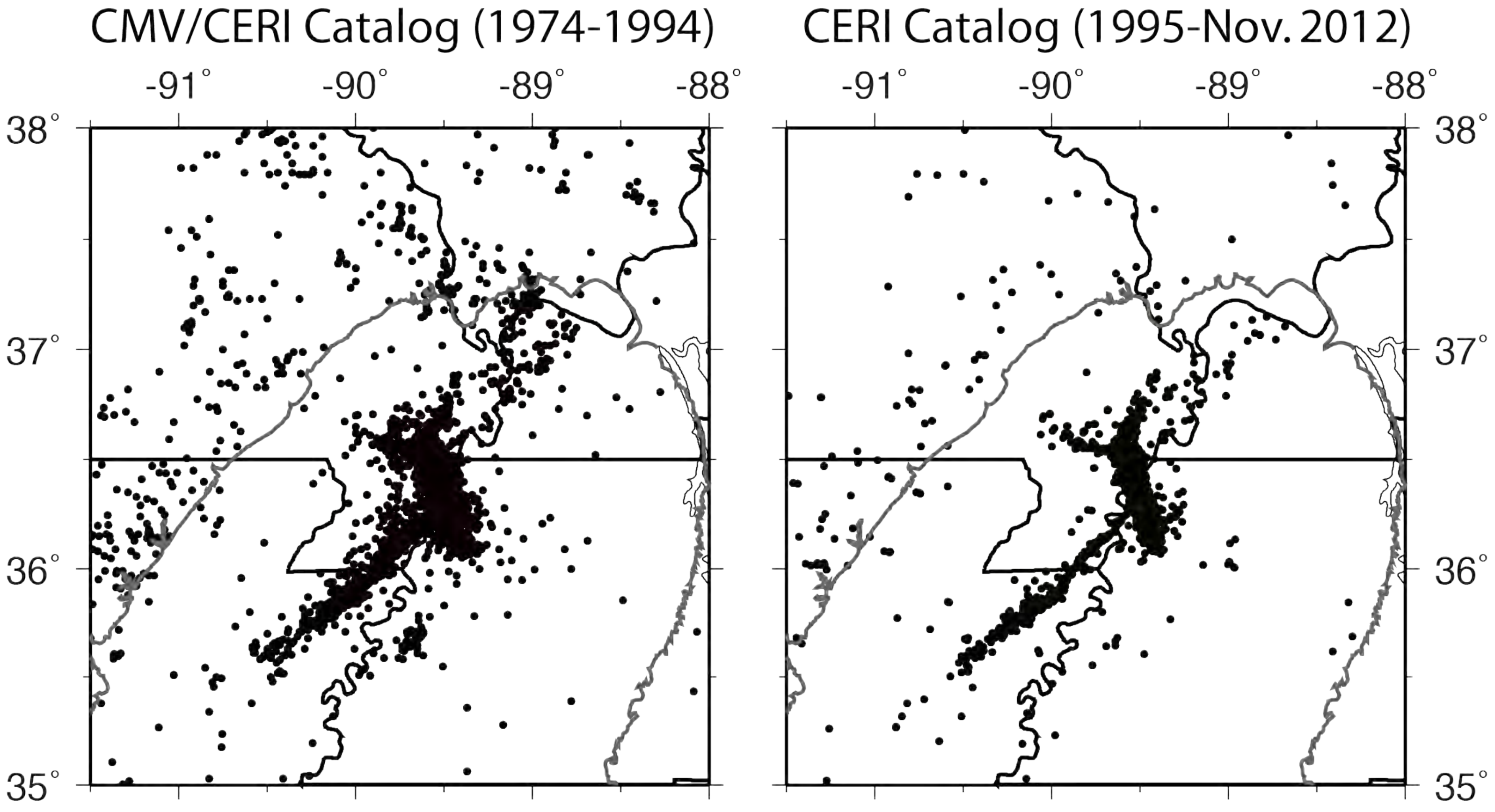
Figures removed due to copyright issues.

Please see in Pratt, 2012 and Guo et al., 2014

Network History



Catalog History



USArray Transportable Array – Nov. 2012

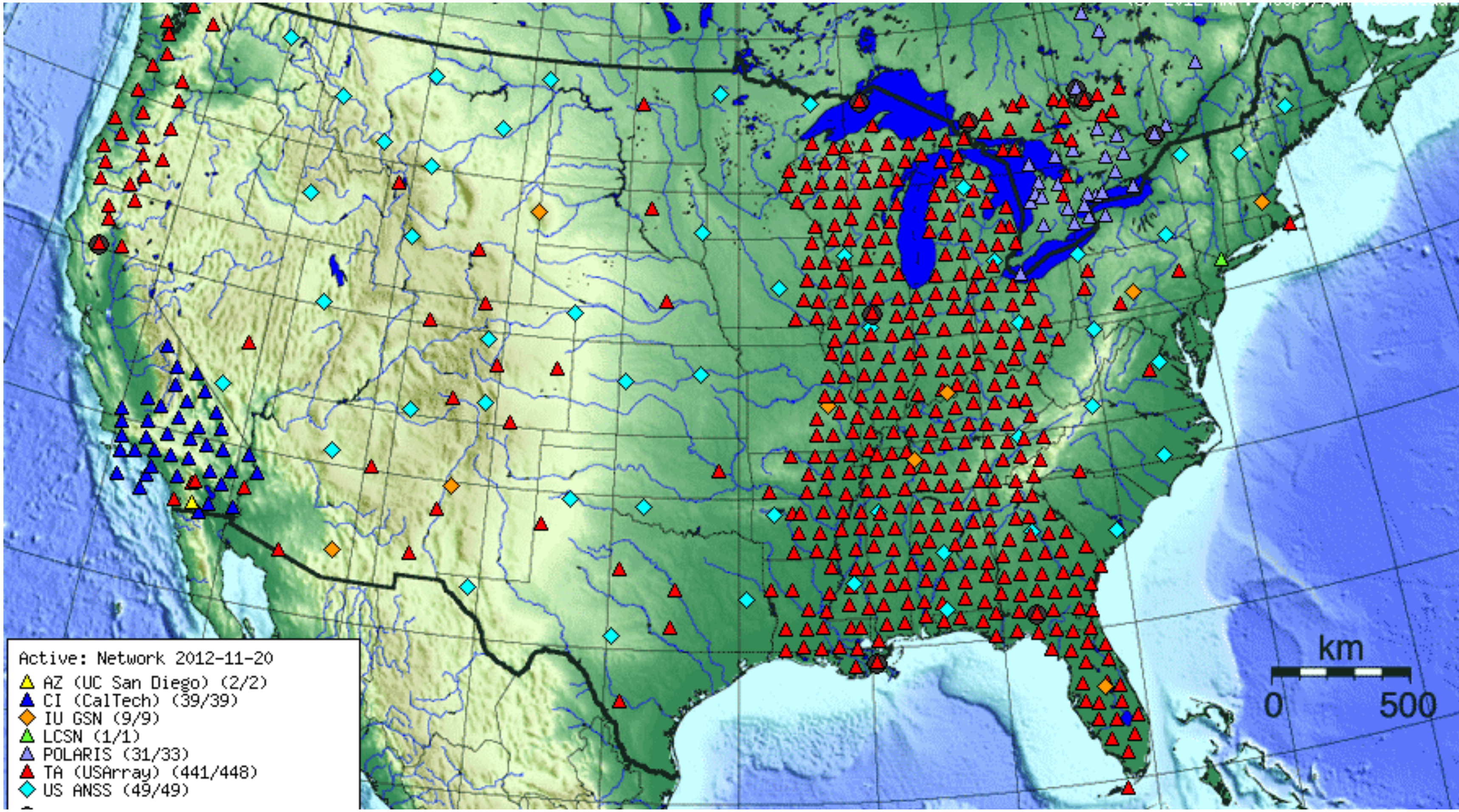
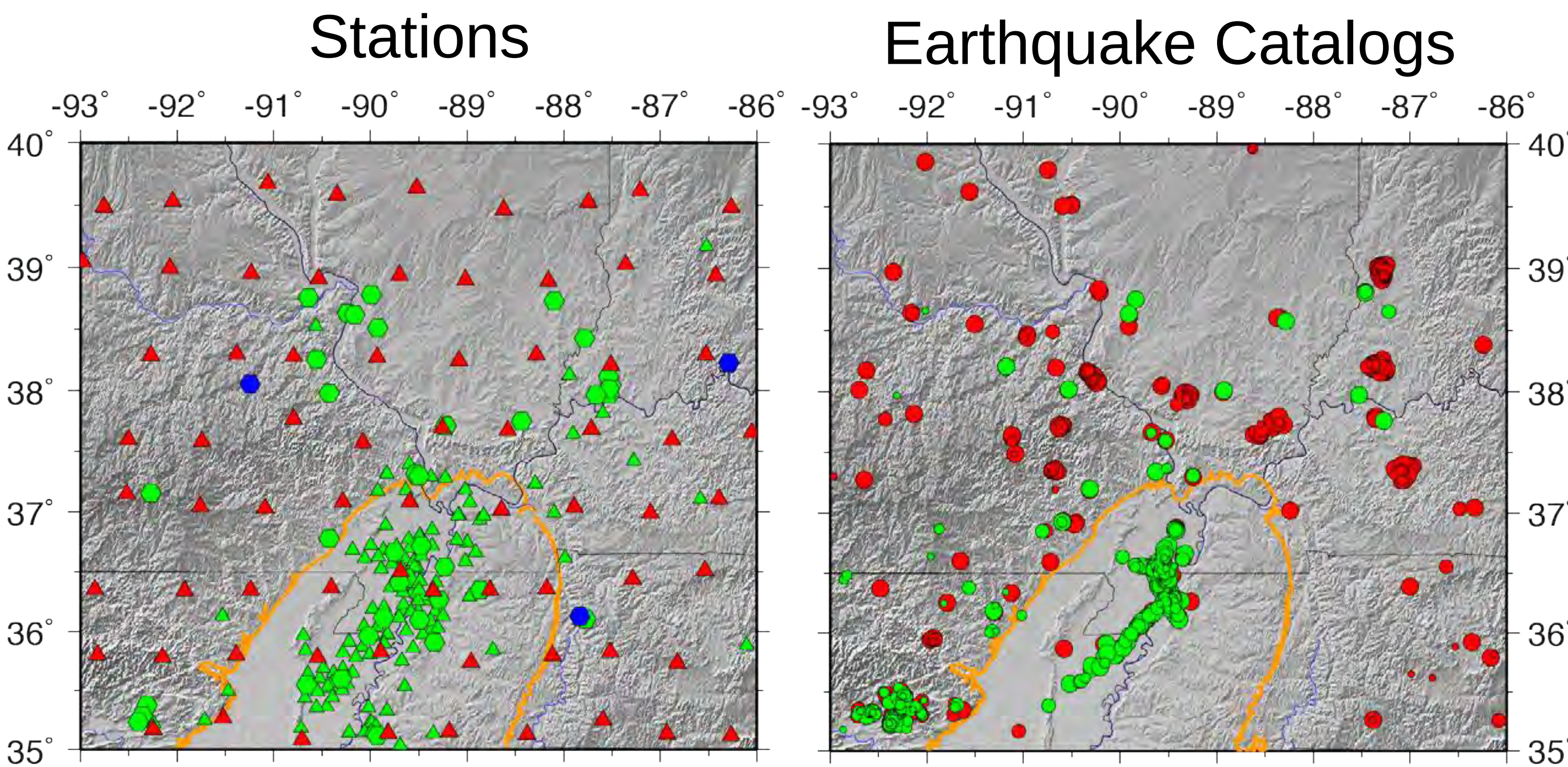


Figure taken from the NSF Earthscope website circa 2012

Combined Data – 7/1/2011 to 10/31/2012



Transportable Array & Array National Facility Catalog

CNMSN Stations & Catalog

IU Network

Work in progress: NELE & OIINK

OIINK

NELE

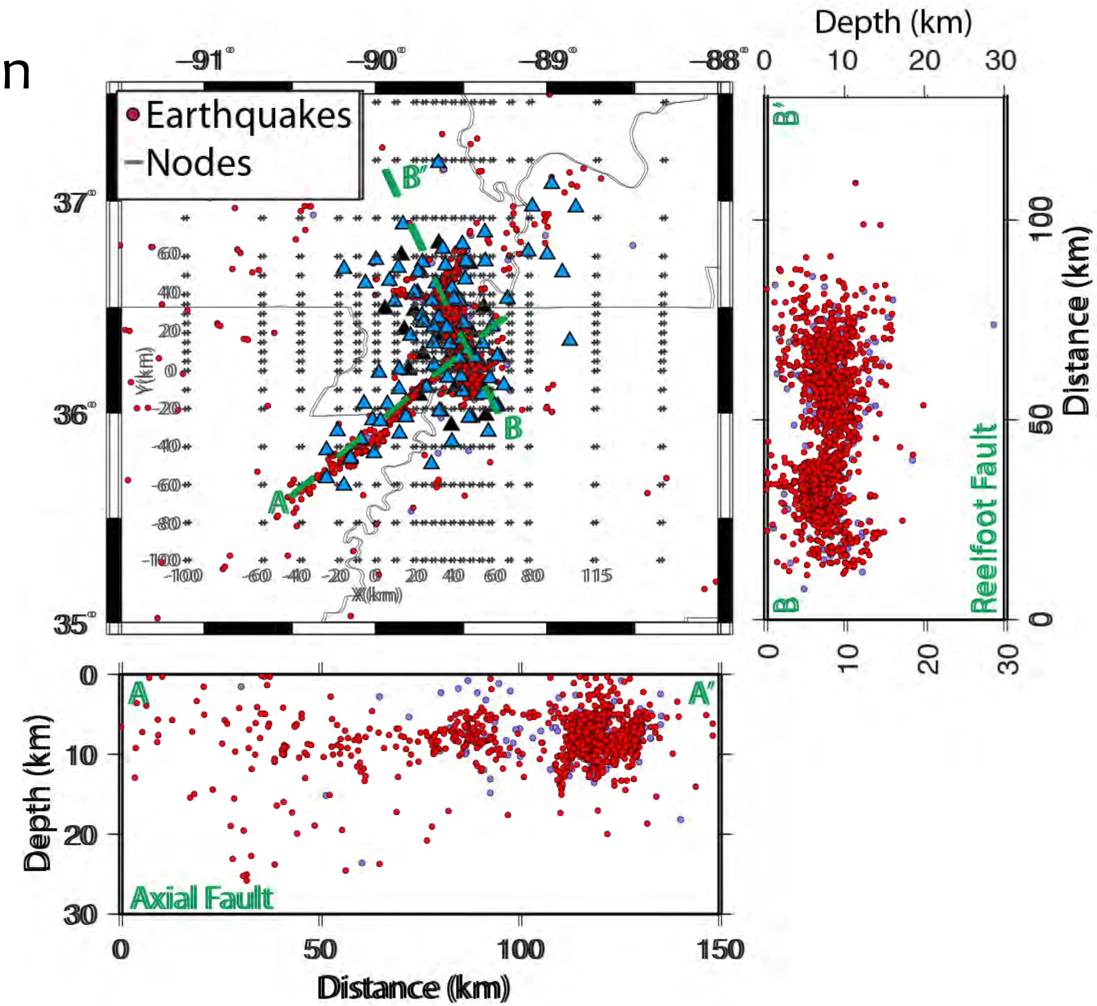
Figure modified from the NSF Earthscope website circa 2015

High-resolution Earthquake Location

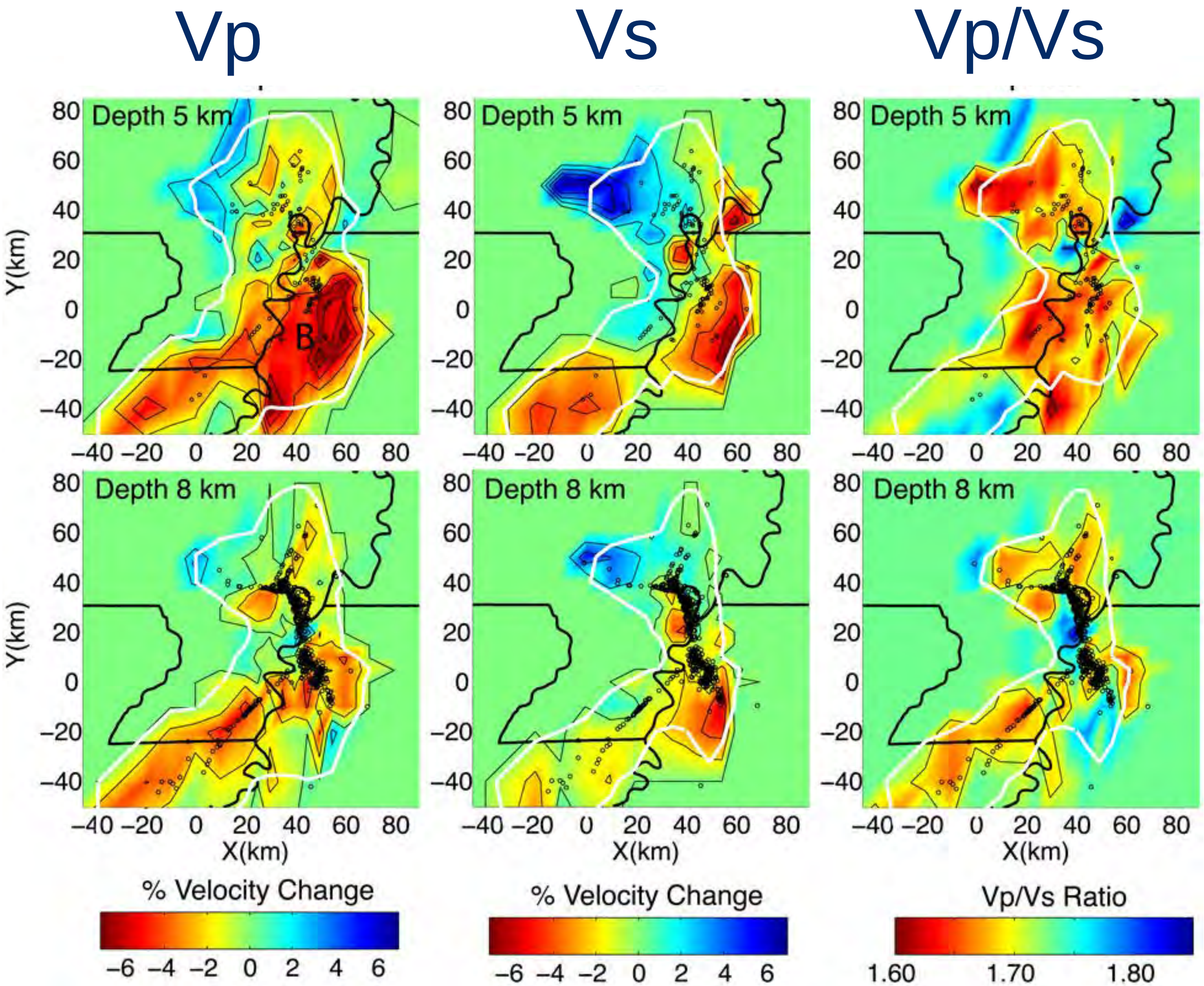
- Double-difference Location
  - accurate to 200-300 m epicentrally and 400-500 m in depth;
  - absolute errors ~2x larger

• PANDA data (1989-1992)

• CNMSN (1995-2011)

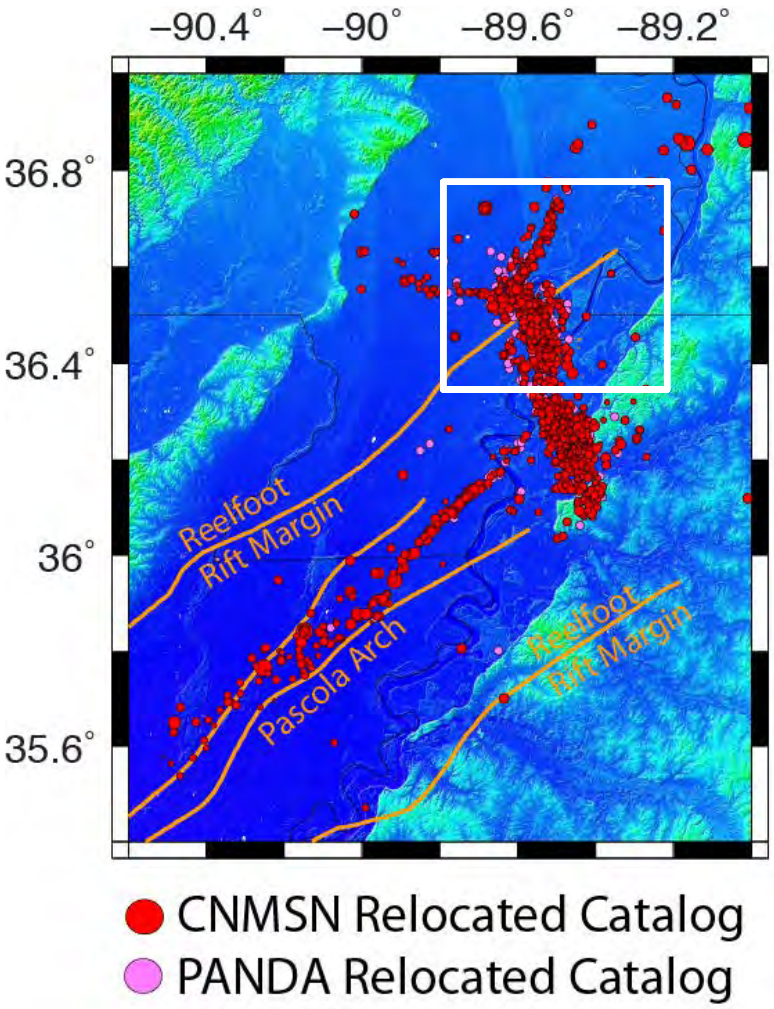


3D Velocity Model – Vp, Vs, Vp/Vs



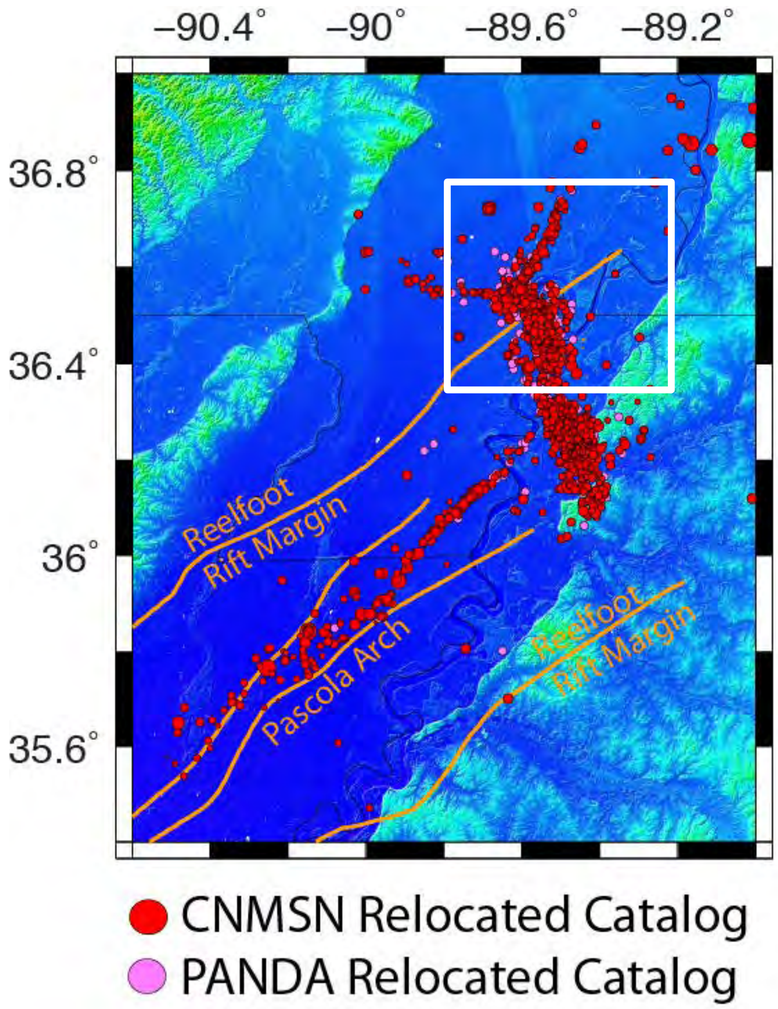
Dunn *et al.* (2013)

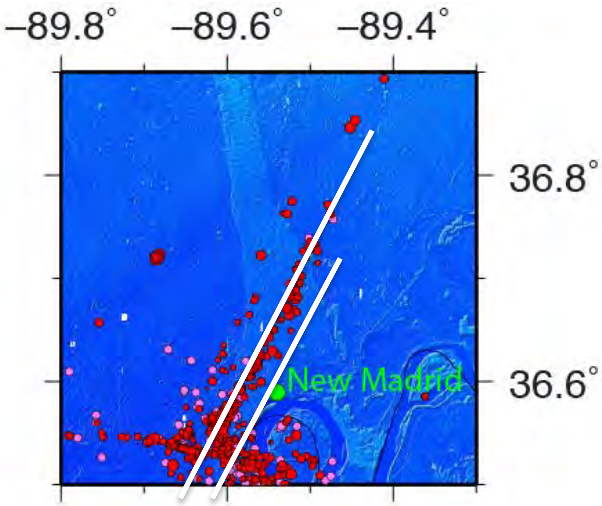
Relocation Results



1) Axial fault seismicity south of 36º remains diffuse
2) A few earthquakes remain near the liquefaction defined Bootheel lineament
3) There are some events along the eastern margin and/or Meeman-Shelby fault

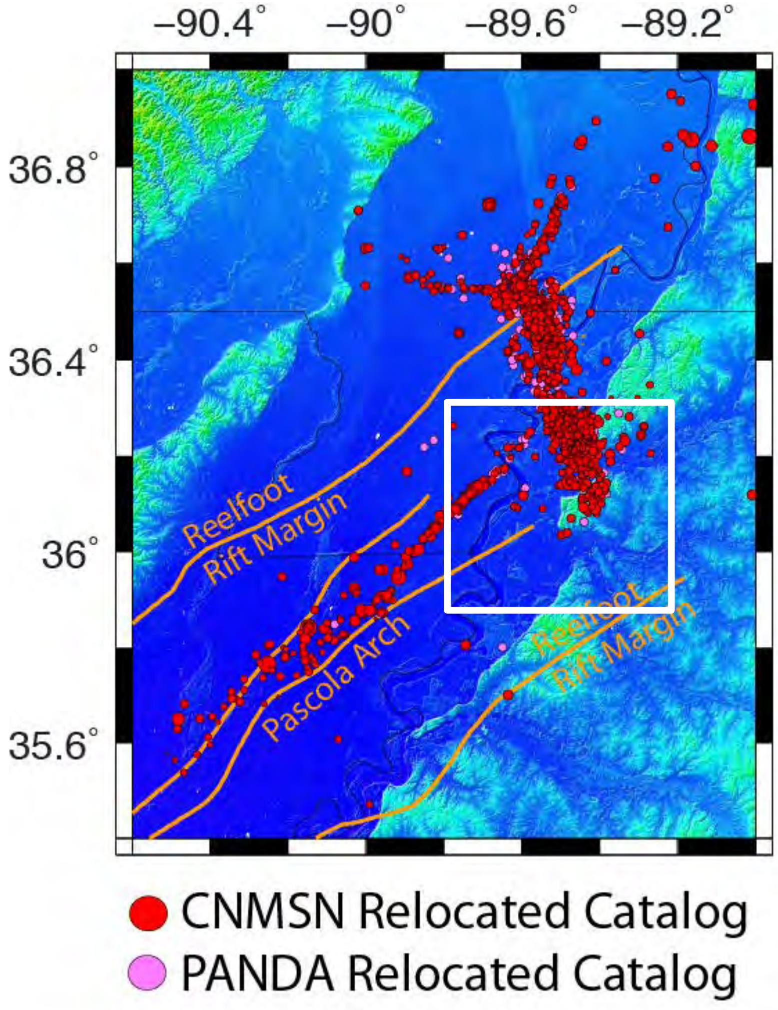
New Madrid North





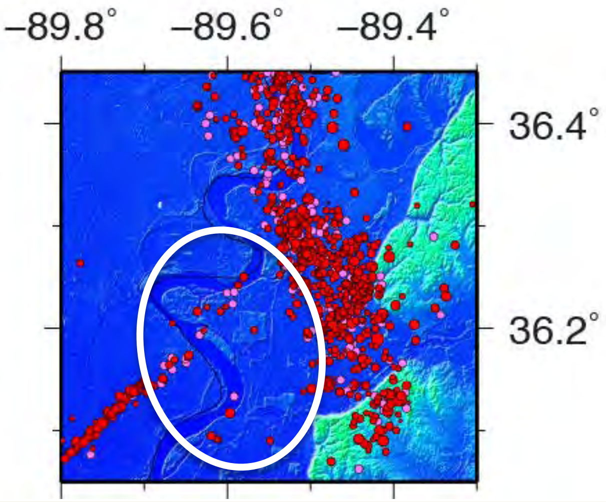
4) New Madrid North is two sub-parallel stands of seismicity

Axial Fault



5) Event density decreases as the Axial fault intersects the Reelfoot South fault

6) Events to the SE along off



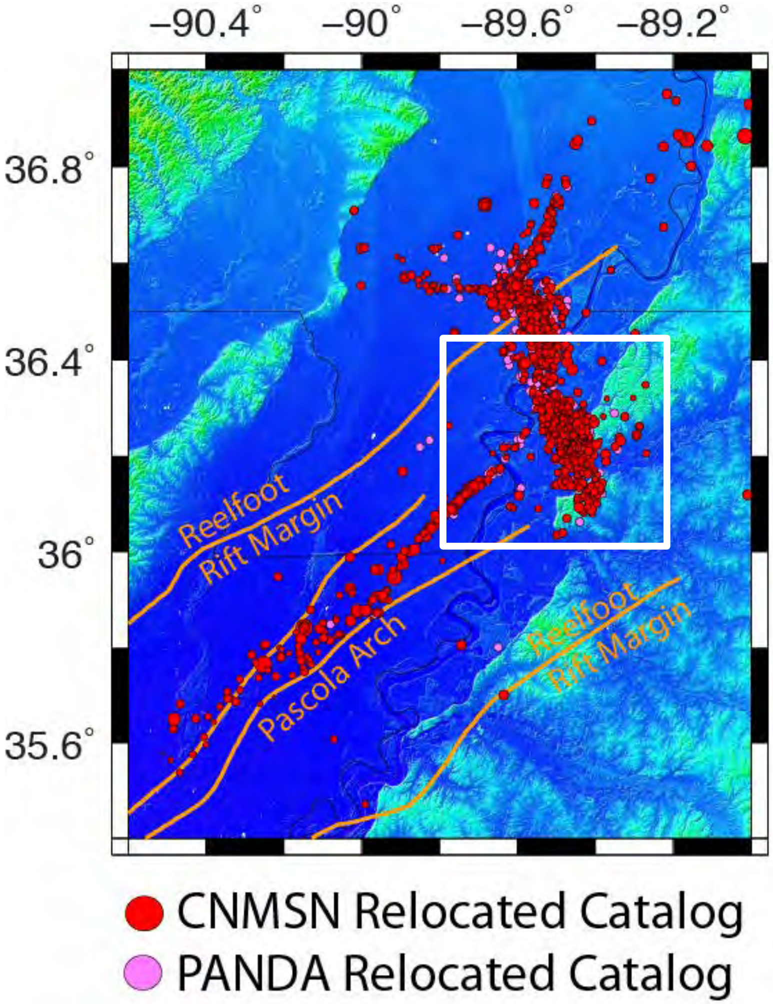
Comparison to Reflection Survey

Figure removed due to copyright issues.

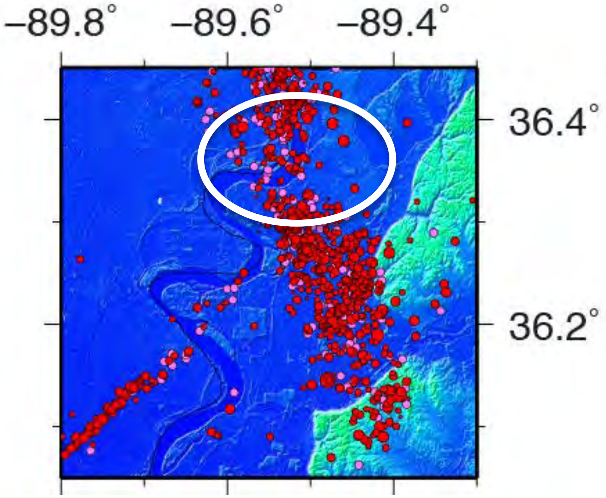
Please see figure showing Mississippi River active source data collected across the Axial and Cottonword Grove faults, New Madrid seismic zone, in Guo et al. 2014

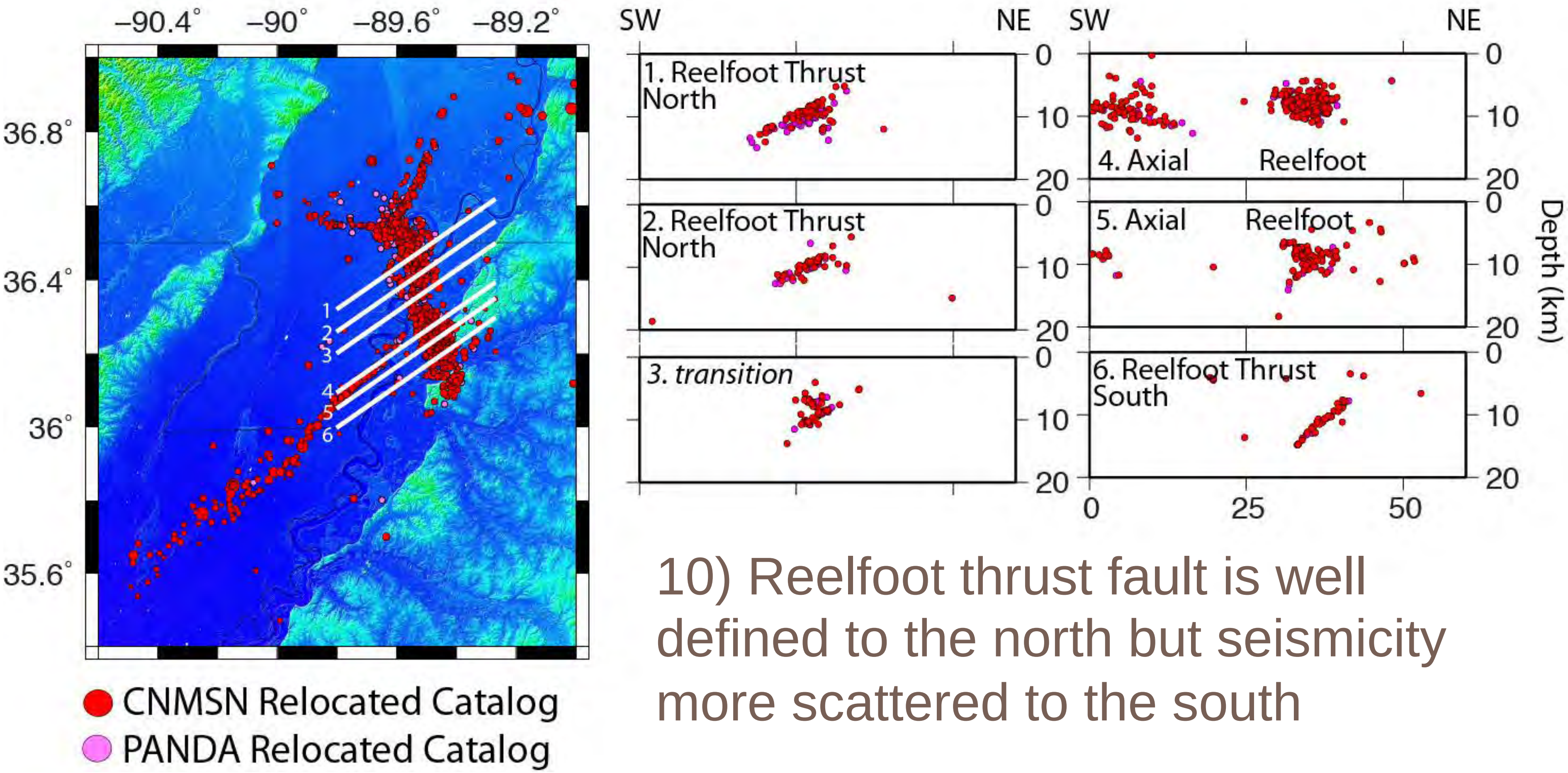
8) Near surface faulting is more complex than faulting within the basement granites

Reelfoot Fault



9) Event density low along Reelfoot transition; associated with high Vp/Vs ratio





10) Reelfoot thrust fault is well defined to the north but seismicity more scattered to the south

Comparison to Reflection Survey

Figure removed due to copyright issues.

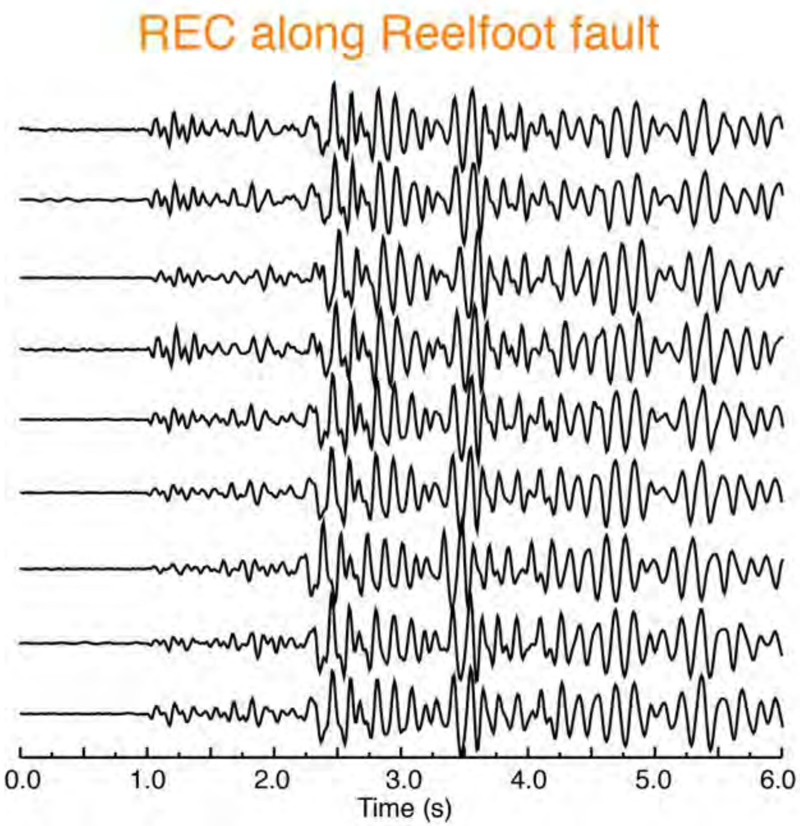
Please see figure showing Mississippi River active source data collected across the Reelfoot fault, New Madrid seismic zone, in Guo et al. 2014

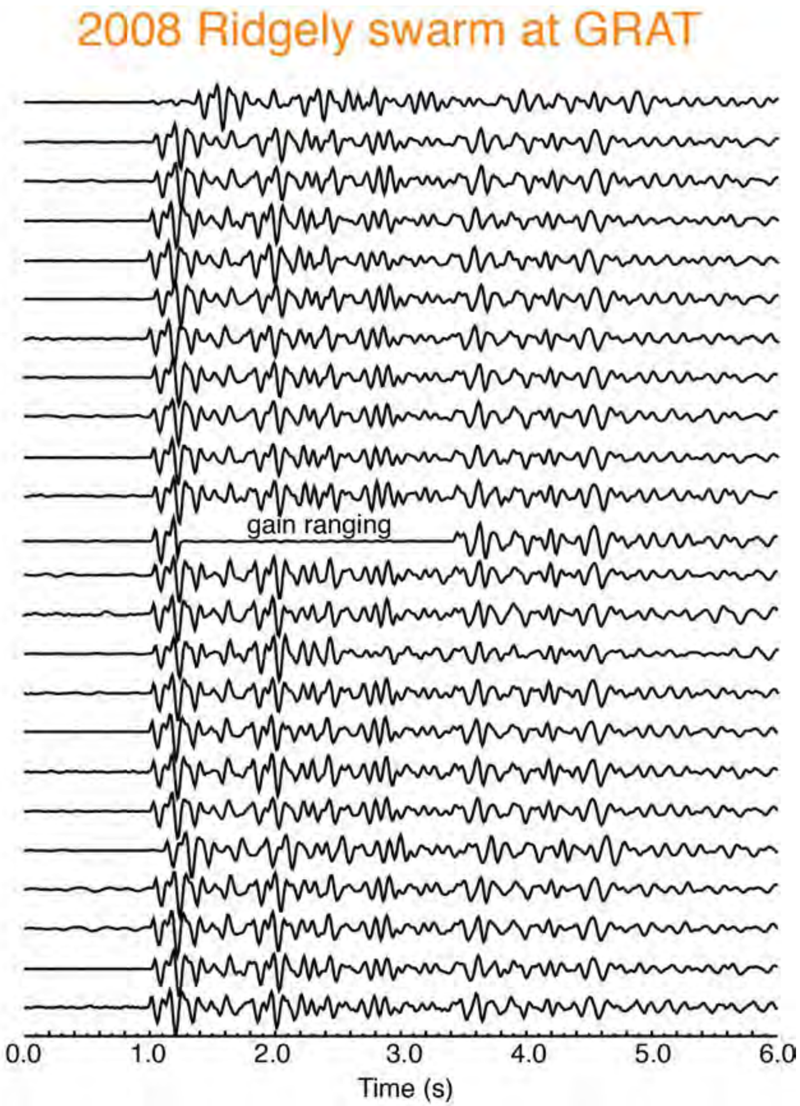
11) Reelfoot North and New Markham thrusts at the surface become single thrust fault at depth

Guo et al. 2014

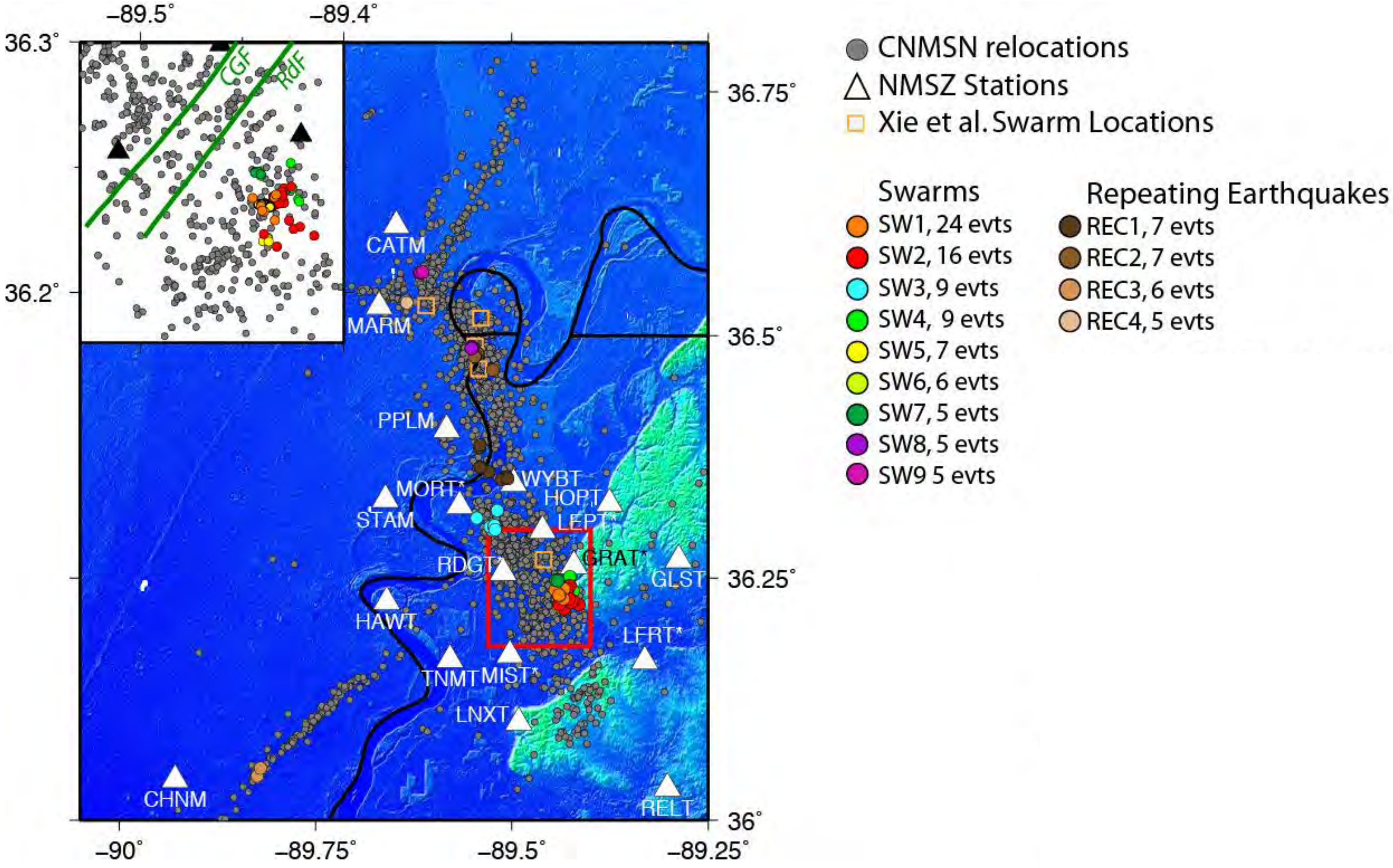
Swarms & Repeating Earthquakes

- Swarms – highly similar waveforms recurring over a short (<1 day) time span
- Repeating earthquakes – nearly identical waveforms separated in time





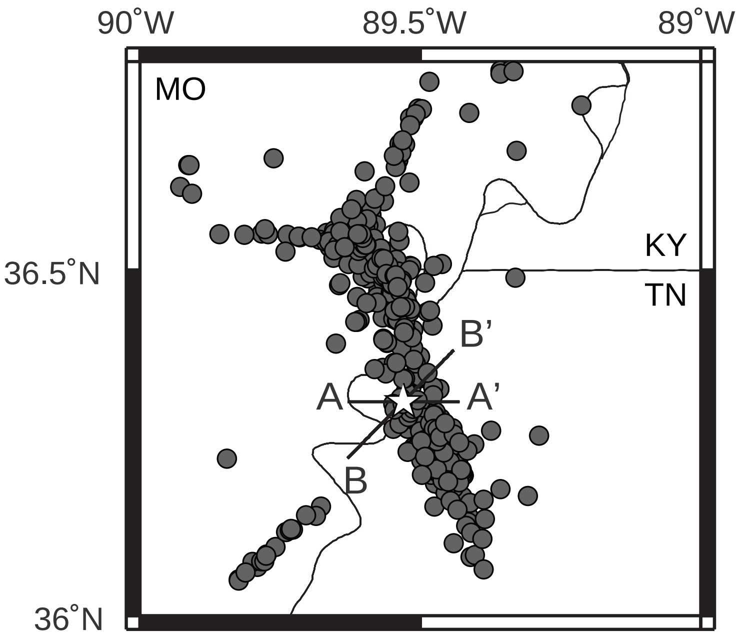
Swarms & Repeating Earthquakes

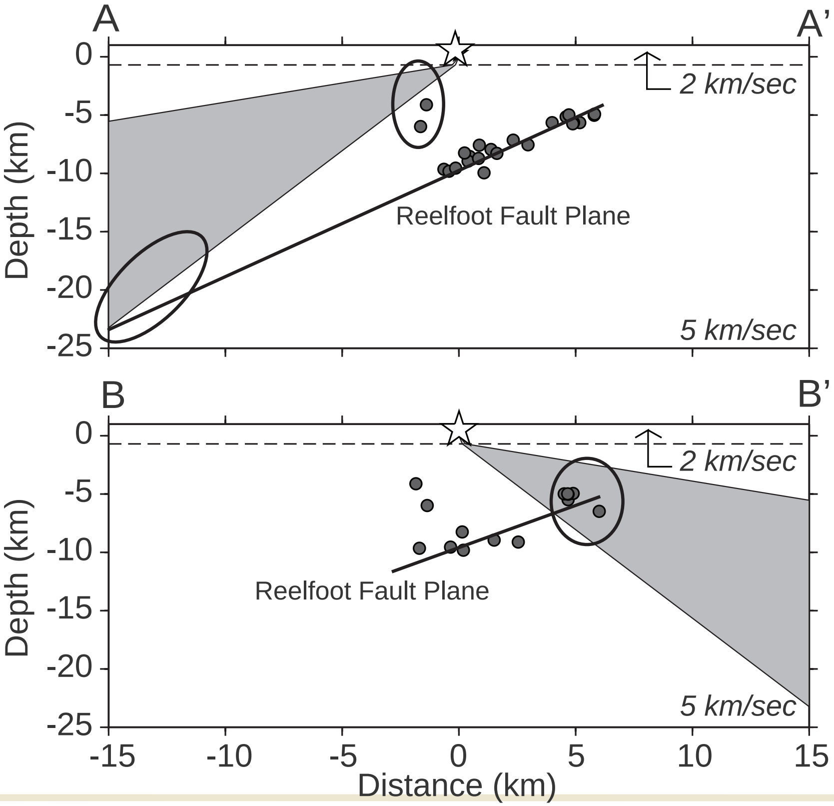


Bisrat *et al.* (2014)

Microearthquakes (M~ -1)

- A reflection/refraction experiment, recorded a sequence of high frequency signals that moved across a linear array at 3-25 km/s (Langston et al., 2010).
- Similar signal noted on a 19-station array





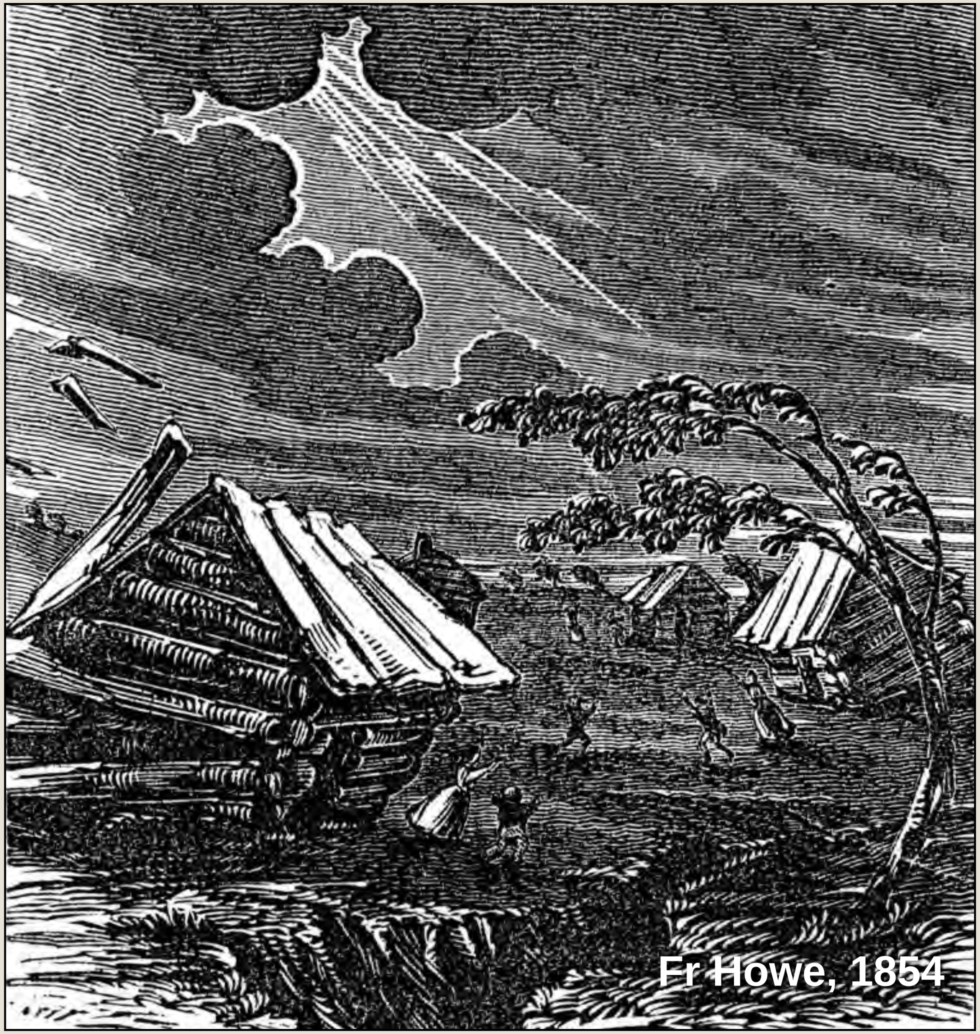
Summary

- New Madrid Seismic Zone can produce large (M>7) earthquakes and has over multiple seismic cycles
- Current seismicity is likely not aftershocks of 1811-1812 and strain is being accumulated within the seismic zone
- Surface deformation is complex and denser areas of microseismicity may not reflect all potentially active faults
- Earthquake catalogs and station distributions have changed over time and all dots are not created equal
- NMSZ faults have a wide range of event behavior – just like other actively loaded faults

Acknowledgements

- Co-authors on original study: M. Beatrice Magnani, Christine Powell and Shishay Bisrat
- Special thanks to Mitch Withers, Steve Horton, Jer-ming Chiu, Meredith Dunn, Lei Guo, the PANDA crew & the Mississippi Moonwalk crews for collecting and initial analysis of these data
- Funded in part by the USGS NEHRP program and CERI, U. of Memphis

Paleoliquefaction Studies



Martitia Tuttle
M. Tuttle & Associates

Outline

✧ Historical and modern cases of eq-induced liquefaction

- opportunities to learn how to recognize liquefaction features
- analogues for interpretation paleoliquefaction events
- targets for paleoliquefaction studies

✧ Dating of liquefaction features

- critical to constrain ages of features as best as possible
- well-constrained ages of features help to correlate features across region & to estimate timing, source areas, magnitudes, and recurrence times of paleoearthquakes
- poorly constrained ages can lead large uncertainties of paleoearthquake characteristics

1811-1812 M~7-8 New Madrid Earthquakes

From Fuller, 1912, "The New Madrid earthquakes," *U.S. Geol. Surv. Bull. 494*

"sand sloughs…cracks as large as any of those of the last great disturbance…*with trees fully 200 years old grown on their bottoms"…pointing "to a considerably earlier origin."*

Sand Blows, Sand Sloughs, & Sand Dikes

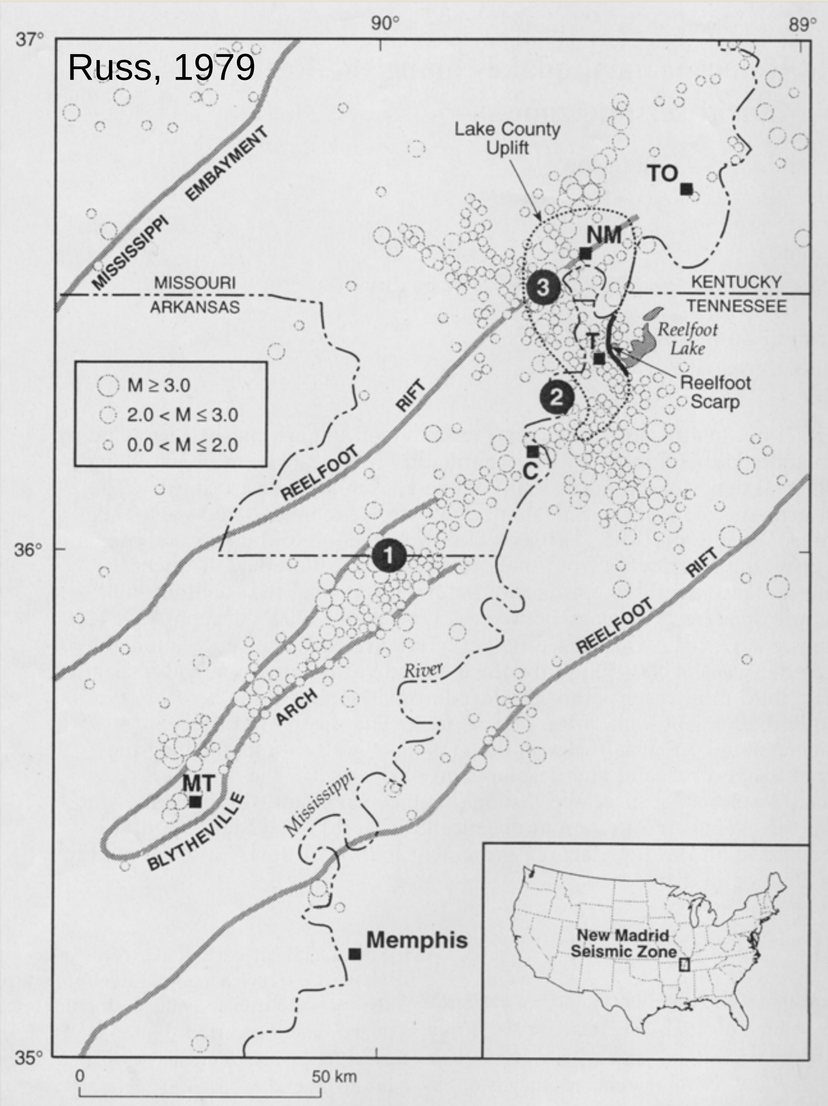
Fuller, 1912

Sand Sloughs Predating 1811-1812

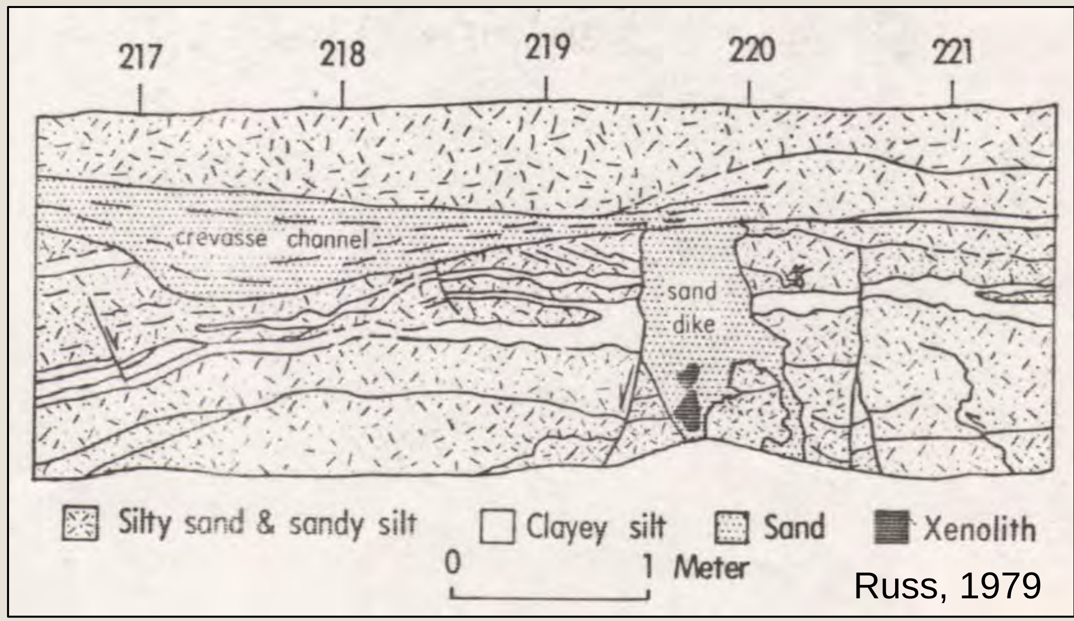
Fuller, 1912

Signature of 1811-1812 & Prior New Madrid Eqs

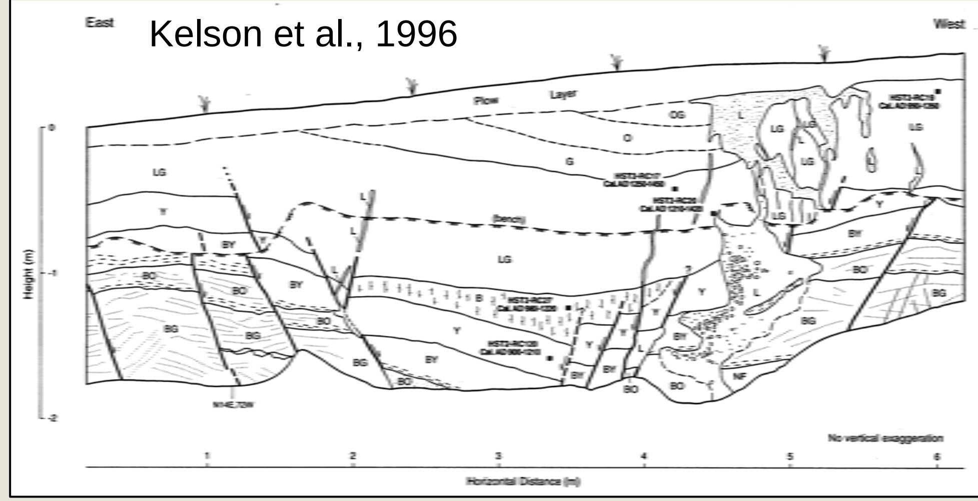
- During past 40-50 years, investigators have built on Fuller's careful documentation of liquefaction-related effects of 1811-1812 and prior eqs



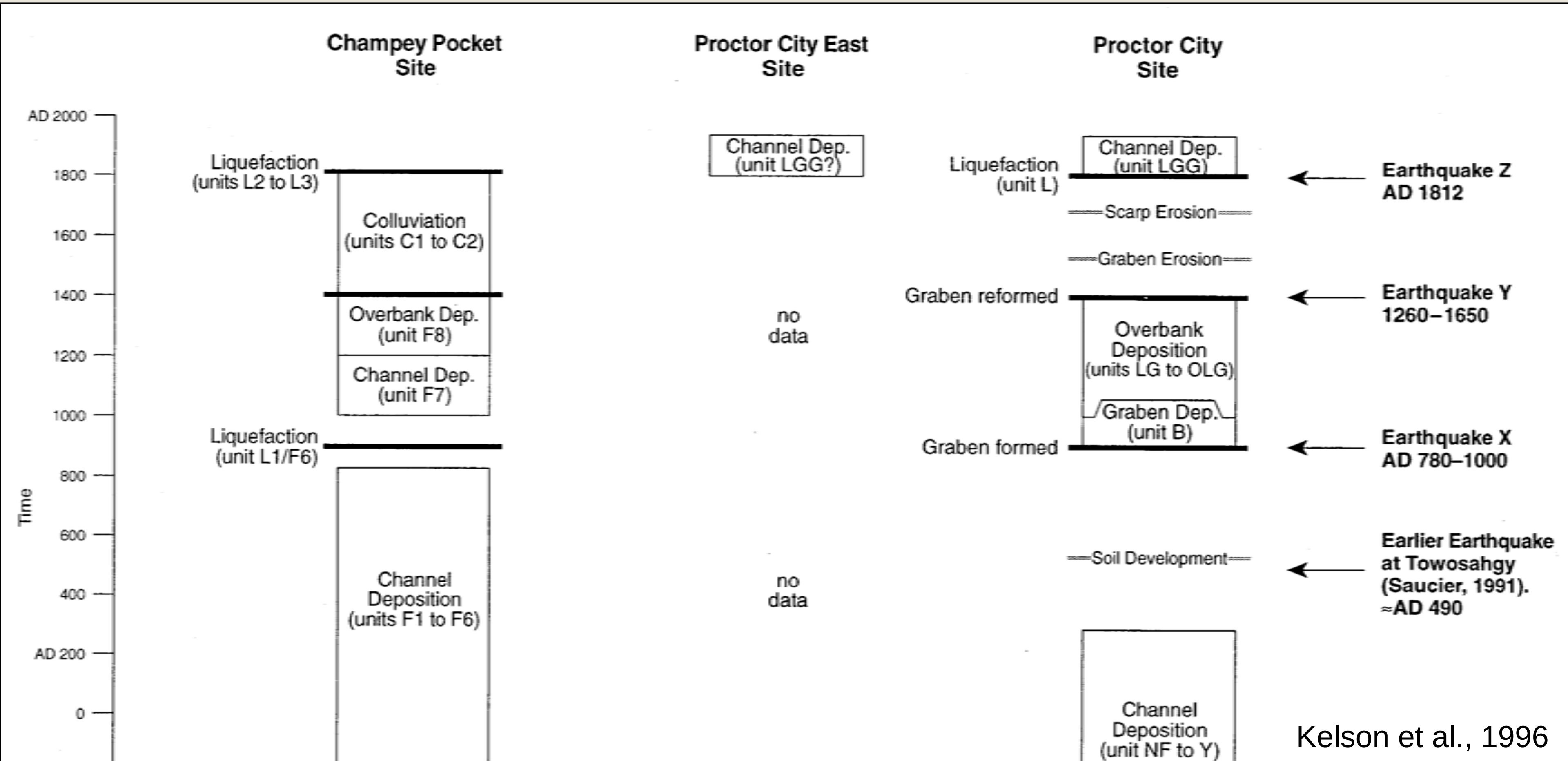
- Russ (1979) identified pre-1811 liquefaction features, as well as deformation related to faulting, in trenches of Reelfoot fault scarp



- Later, also in trenches of Reelfoot scarp, Kelson et al. (1996) identified 2 generations of liquefaction features related to 1811-1812 earthquakes and to an event between A.D. 780-1000

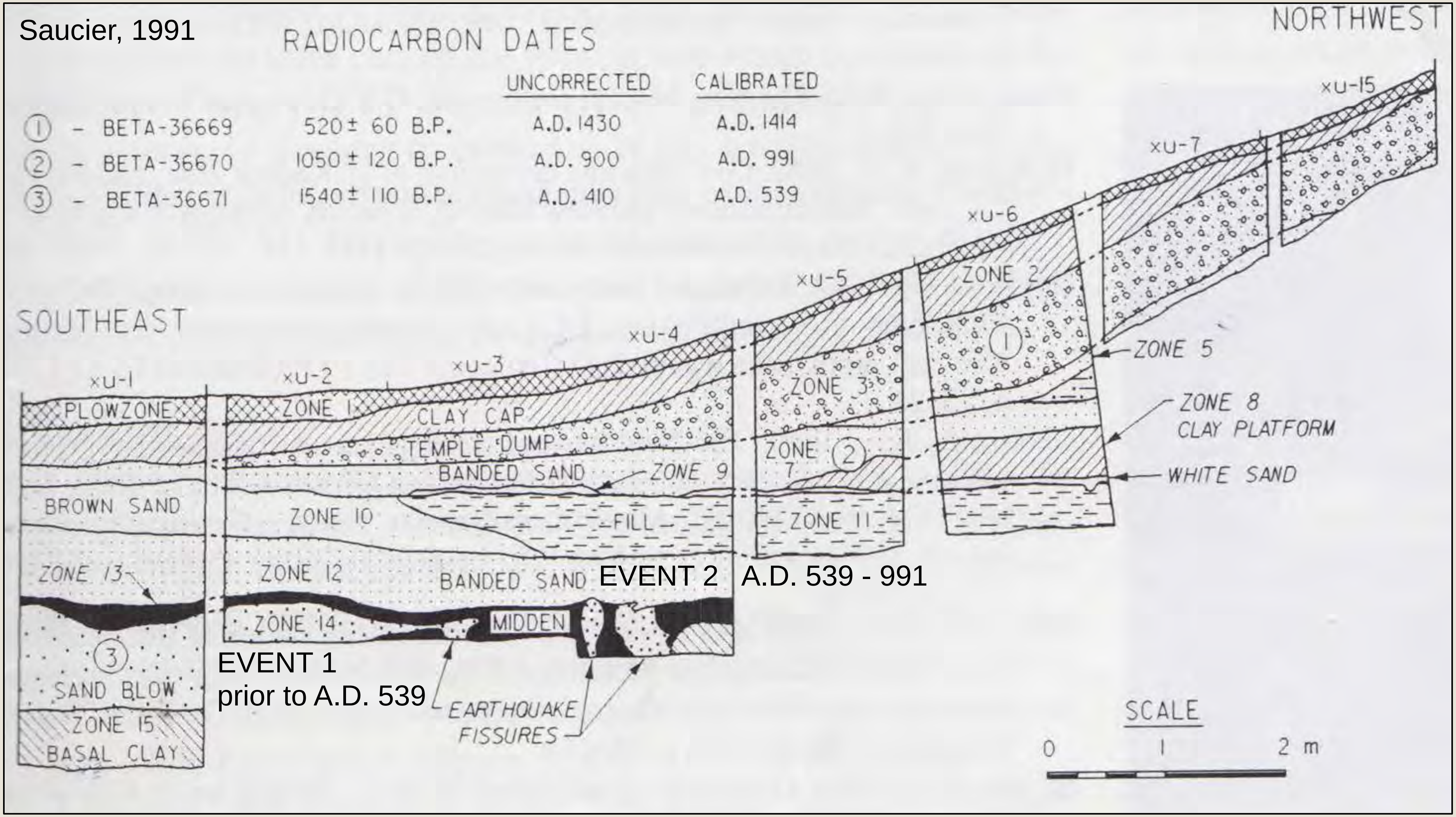


Kelson et al., 1996

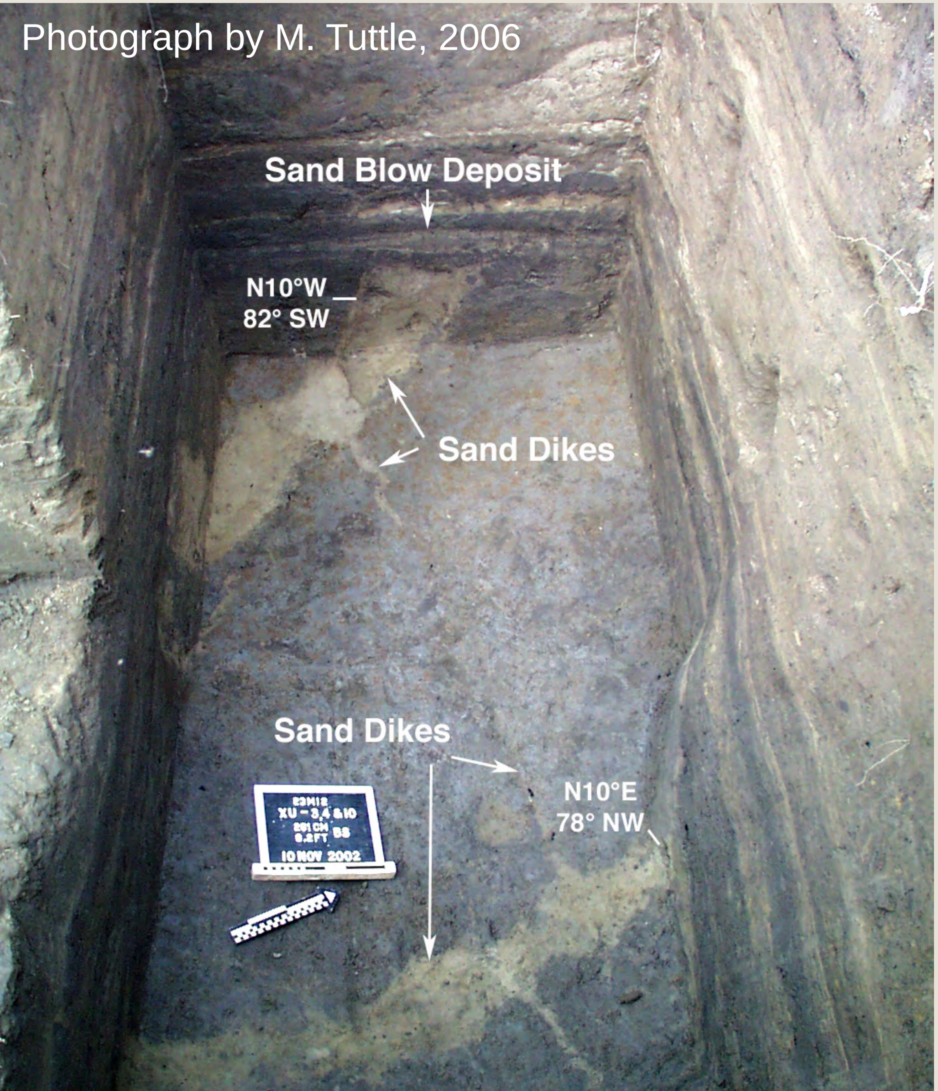


Kelson et al., 1996

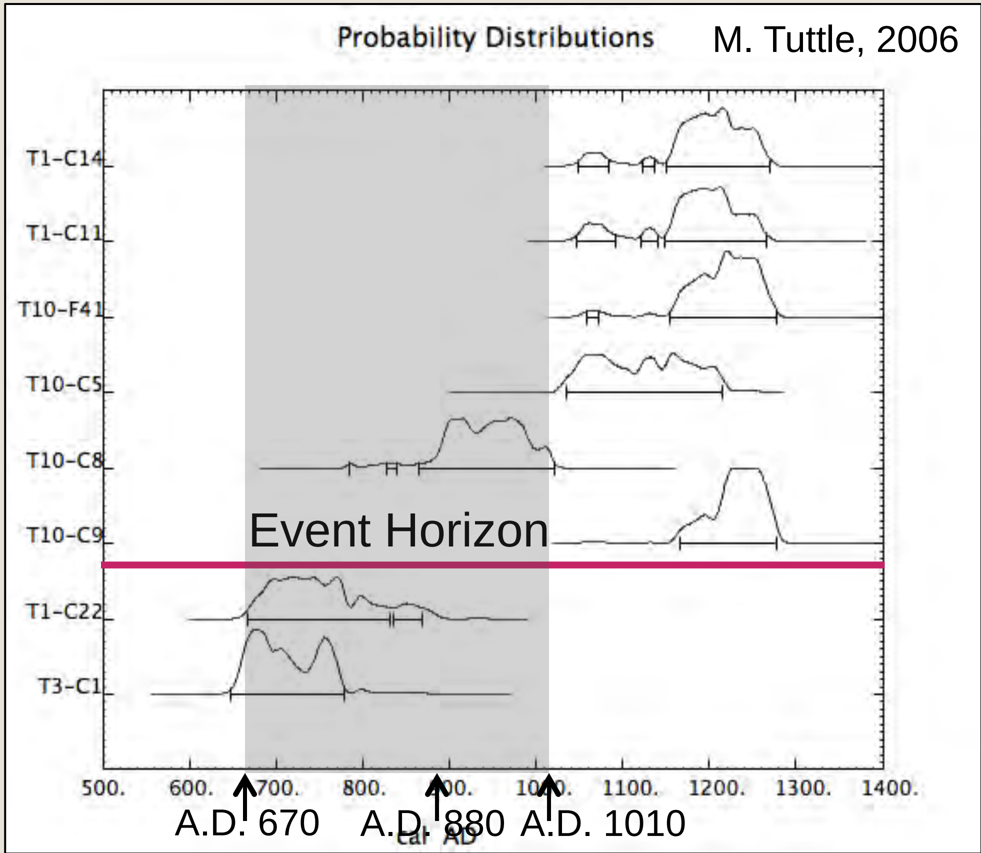
- Saucier (1991) & Price also identified 2 generations of pre-1811 liquefaction features in past 2 kyr at Towosahgy mound in SE MO



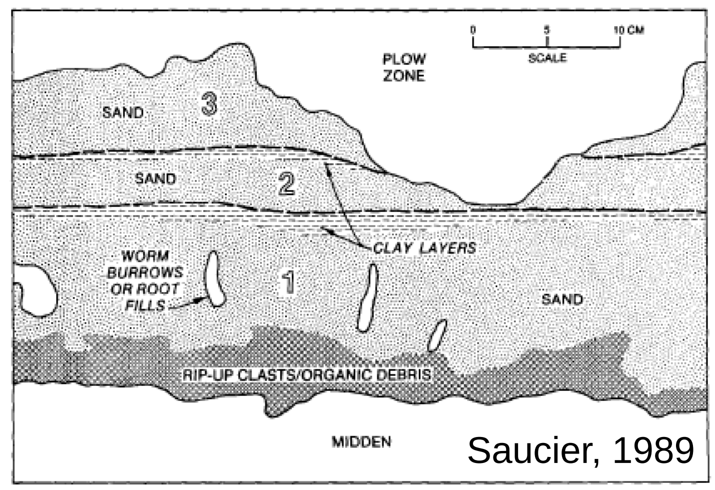
- ✧ Tuttle et al. (2006) reopened Towosahgy test units and found 2 generations of liquefaction features
- ✧ Artifact assemblage above and below sand blow suggests it formed during L. Wood.- E. Miss. Period (A.D. 800-1000)



- ✧ Dating indicates sand blow formed between A.D. 670-1010; younger sand dikes formed since A.D. 1010

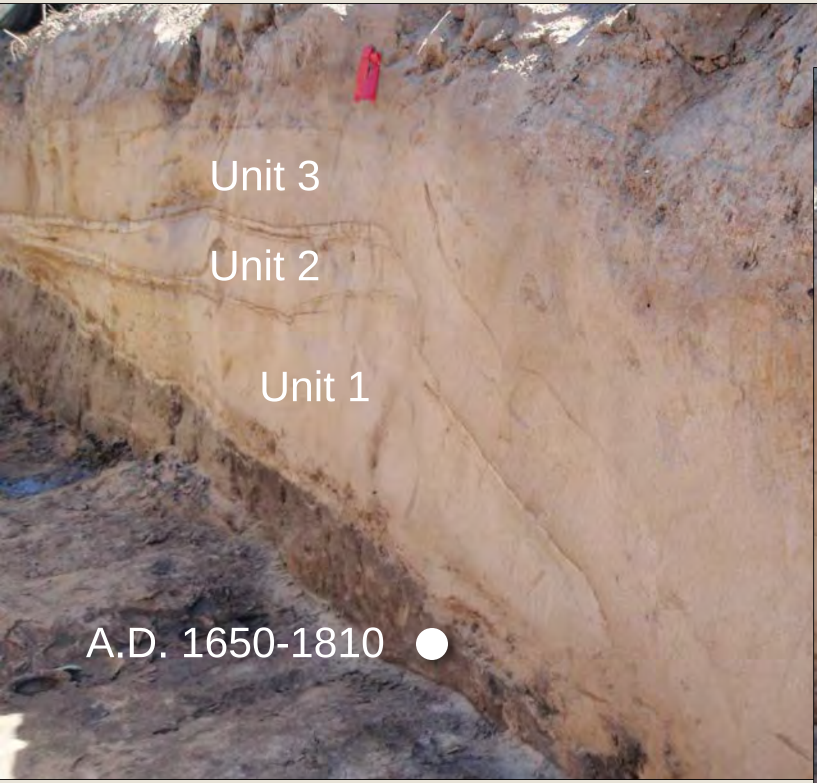


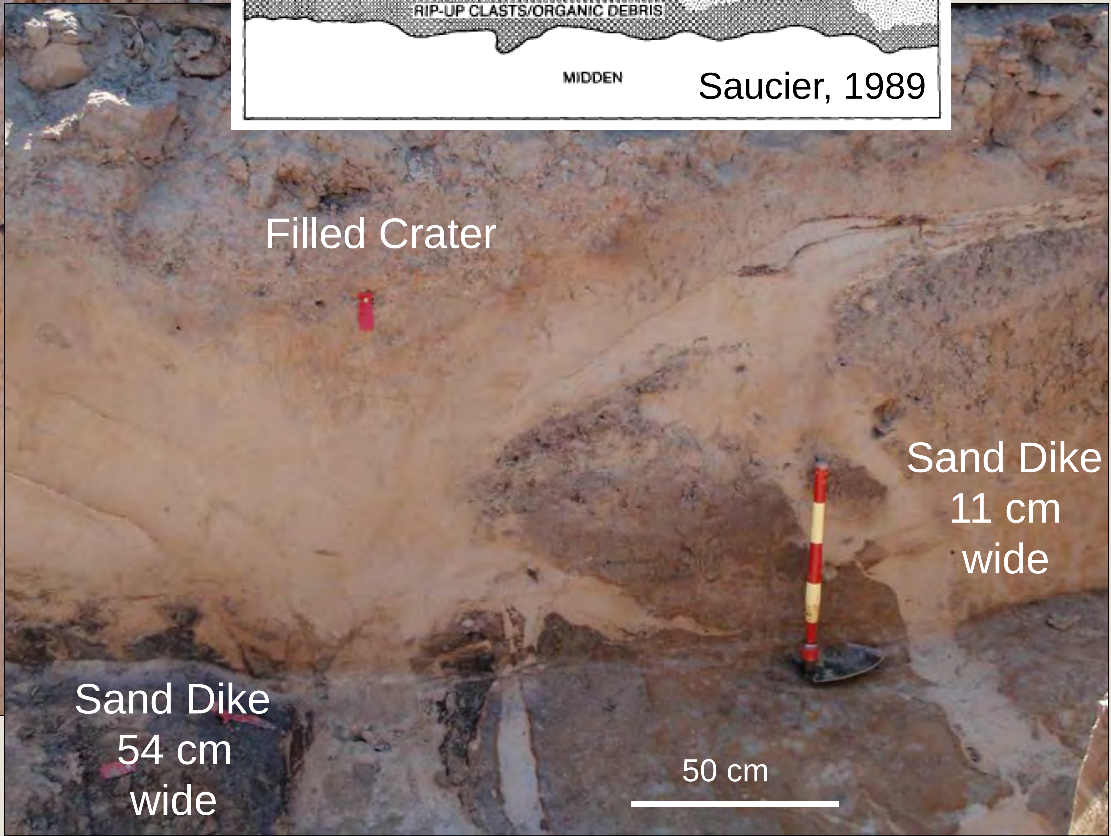
- ✧ Saucier (1989) realized that historical sand blows are compound structures made up of depositional layers related to liquefaction during multiple eqs in 1811-1812 sequence



Saucier, 1989

1811 &1812 Compound Sand Blow & Feeder Dikes



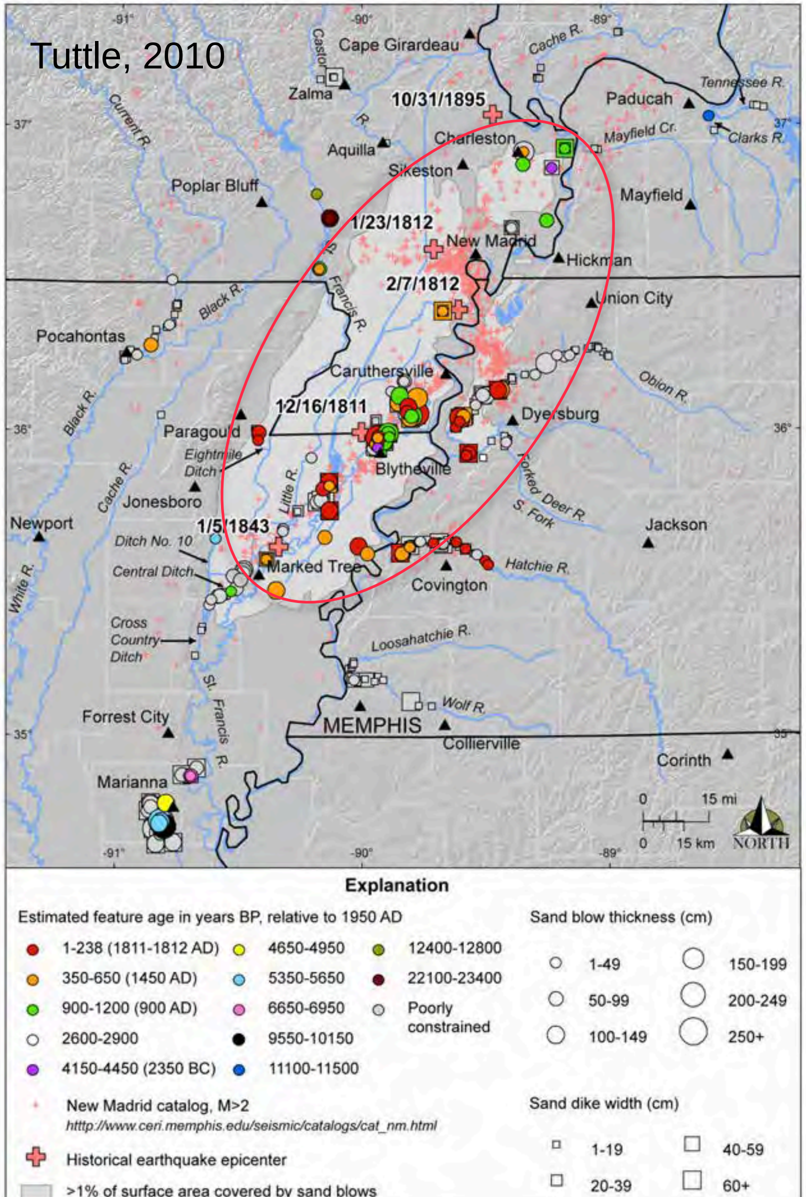


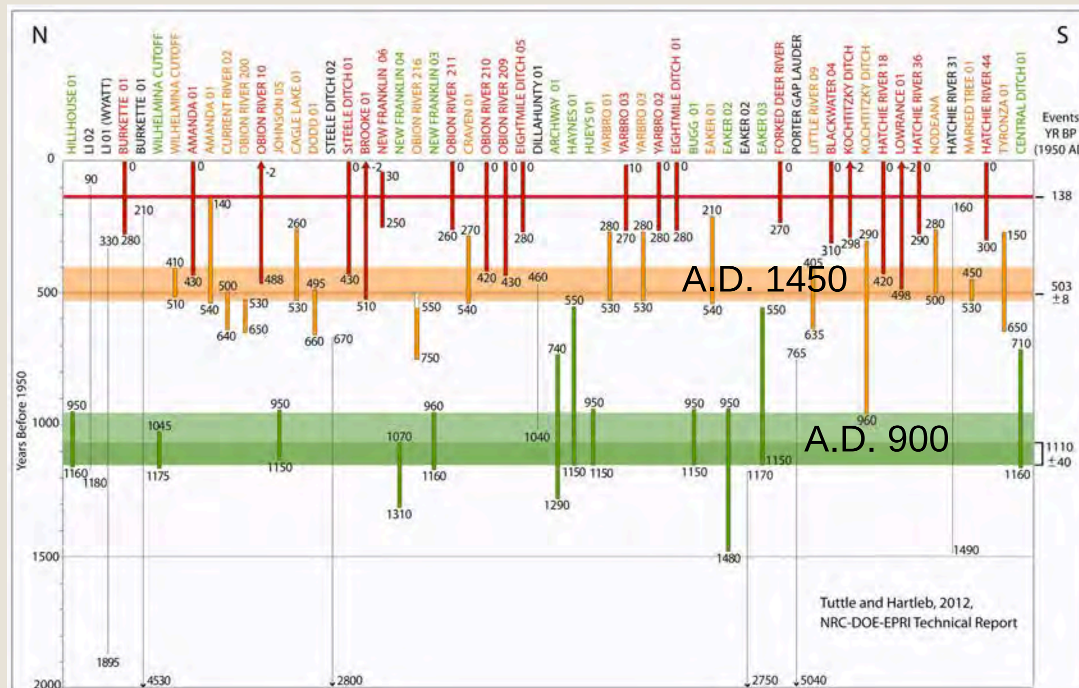
Photographs by M. Tuttle, 2010

- Tuttle et al. (2002) realized that some pre-1811 sand blows also are compound structures related to multiple eqs in a sequence

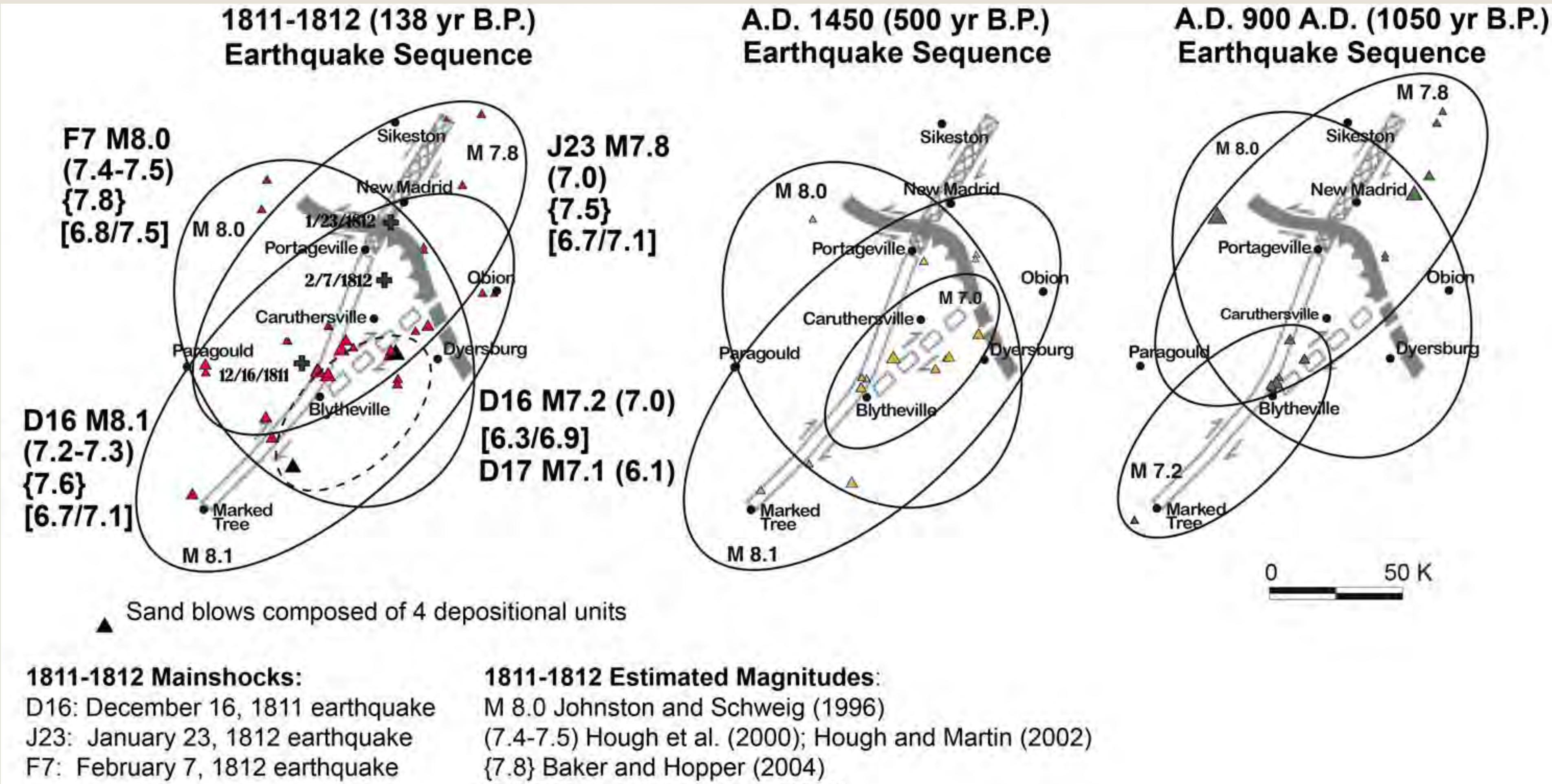
Compound Sand Blow & Feeder Dikes - A.D. 900 Earthquakes

✧ During past 20 years, we found, measured, dated 100s paleoliquefaction features in fields and along rivers & compared them with historic features





- For paleoevents, areal distribution and size of paleoliquefaction features are similar to those that formed in 1811-1812; interpreted paleoevents to be centered in the NMSZ and to have similar magnitudes



Modified from Tuttle et al., 2002

1886 M~7 Charleston, SC Earthquake

From Dutton, 1889, “The Charleston earthquake,” *U.S. Geological Survey 9th Annual Report*

“Wherever [quicksand] occurs near the surface the craterlets are abundant….”

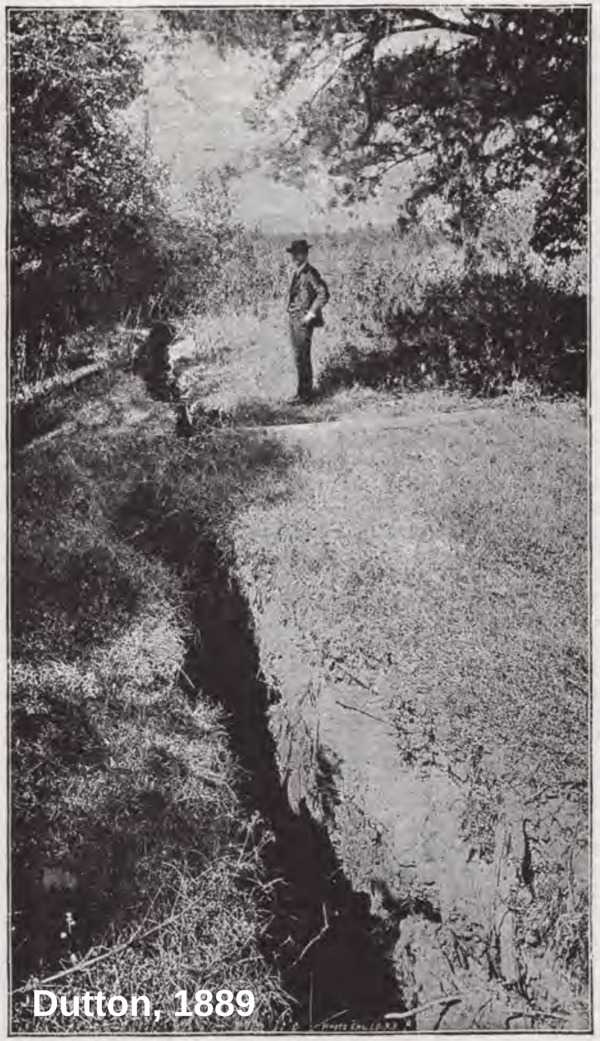
1886 Sand-Blow Crater

U. S. GEOLOGICAL SURVEY NINTH ANNUAL REPORT PL. XX

A LARGE CRATERLET.

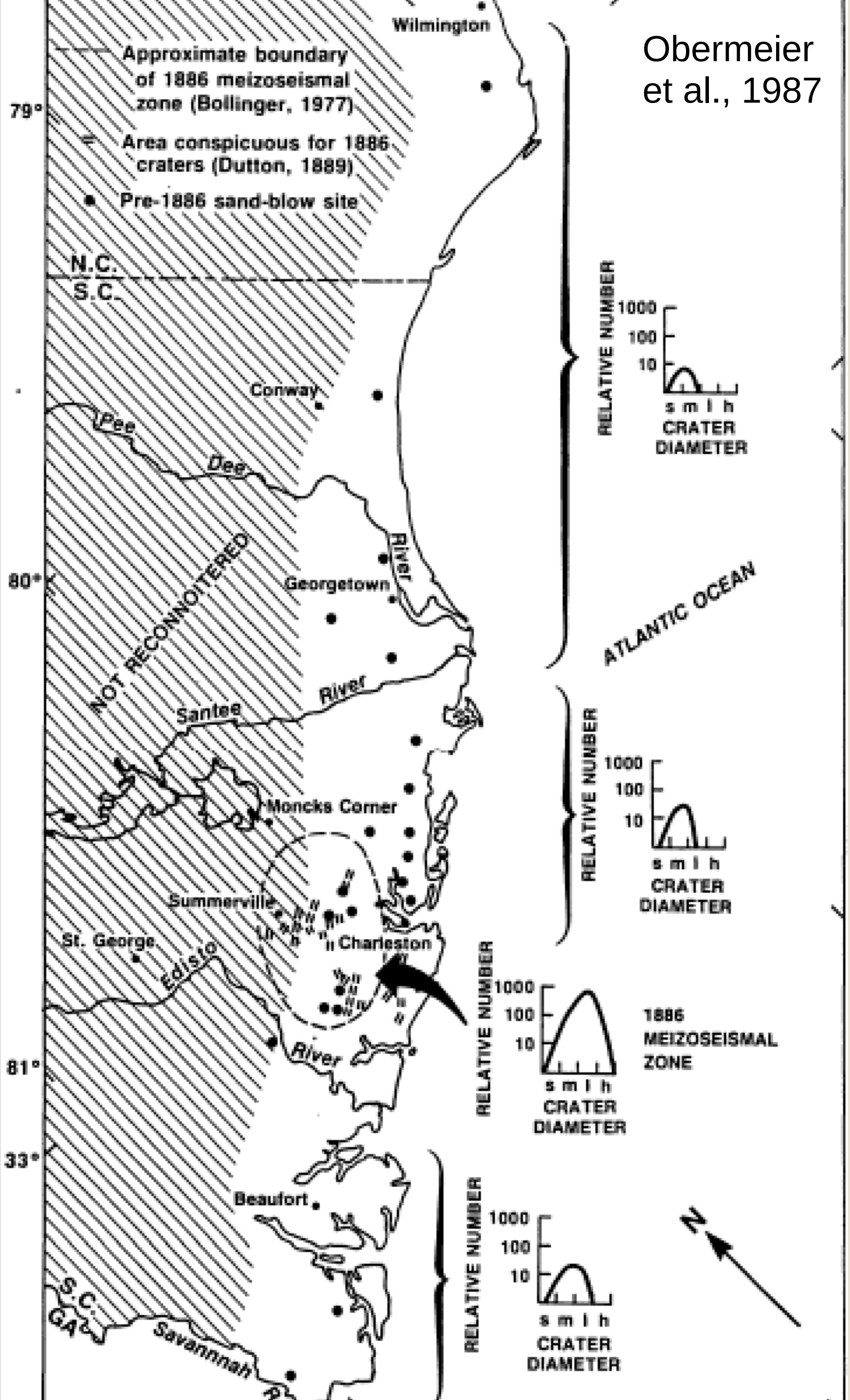
1886 Ground Fissure

U. S. GEOLOGICAL SURVEY NINTH ANNUAL REPORT PL. XXIII



FISSURE ON THE BANK OF THE ASHLEY RIVER.

- ✧ In 1980s & 1990s, Talwani & Cox (1985), Weems et al. (1986), Obermeier et al. (1987), Amick (1990), Schaeffer (1996) worked at liquefaction sites, many described by Dutton (e.g., Ten Mile Hill)
  - *Spatial concentration* of 1886 and paleoliquefaction features decreases away from Charleston
  - *Size* of 1886 and paleolique-faction features decreases away from Charleston

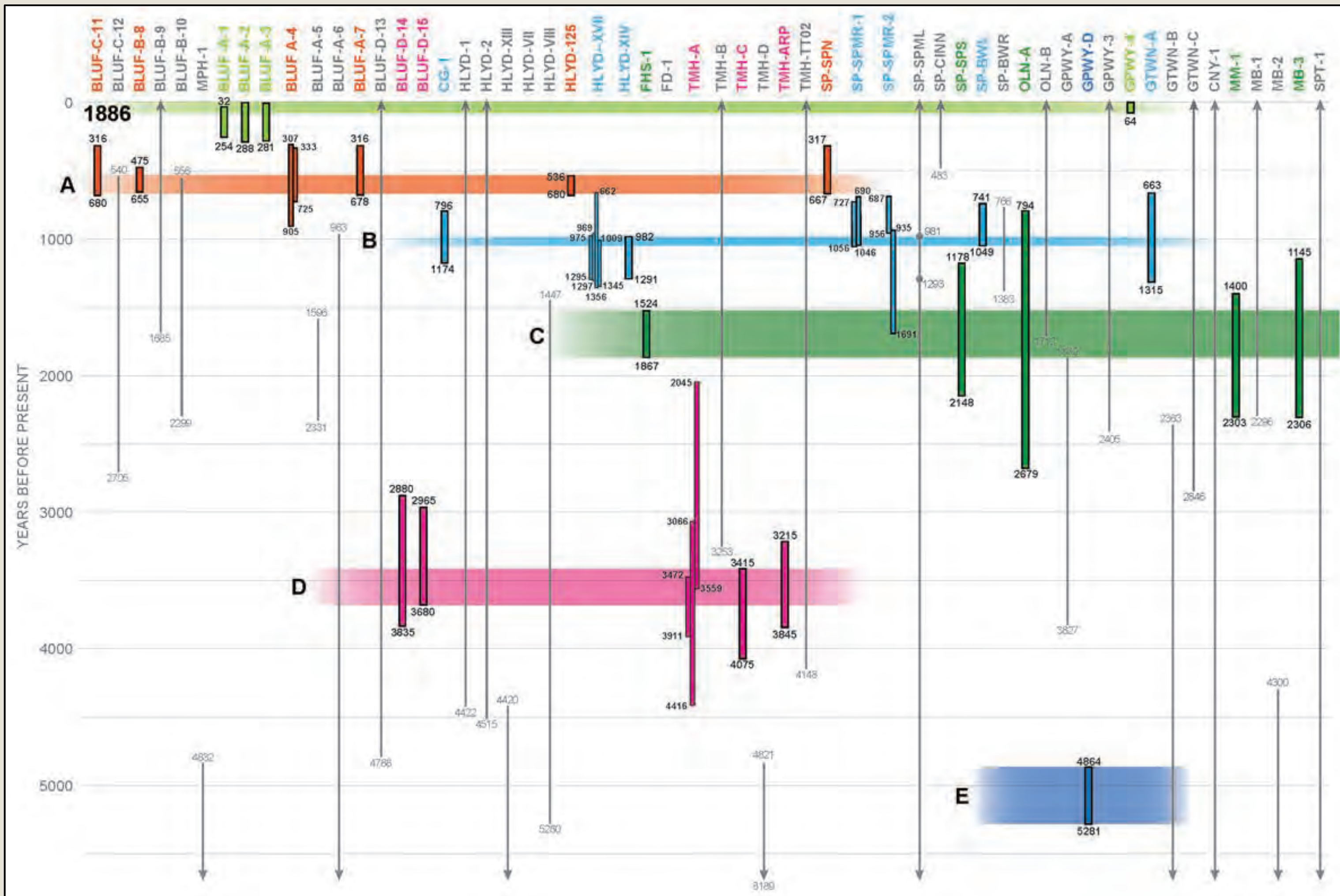


Obermeier et al., 1987

✧ Talwani and Schaeffer (2001) compiled radiocarbon dates, interpreted timing of paleoearthquake, and estimated recurrence time of ~600 yr; later EPRI-DOE-NRC (2012) recalibrated and reinterpreted dates

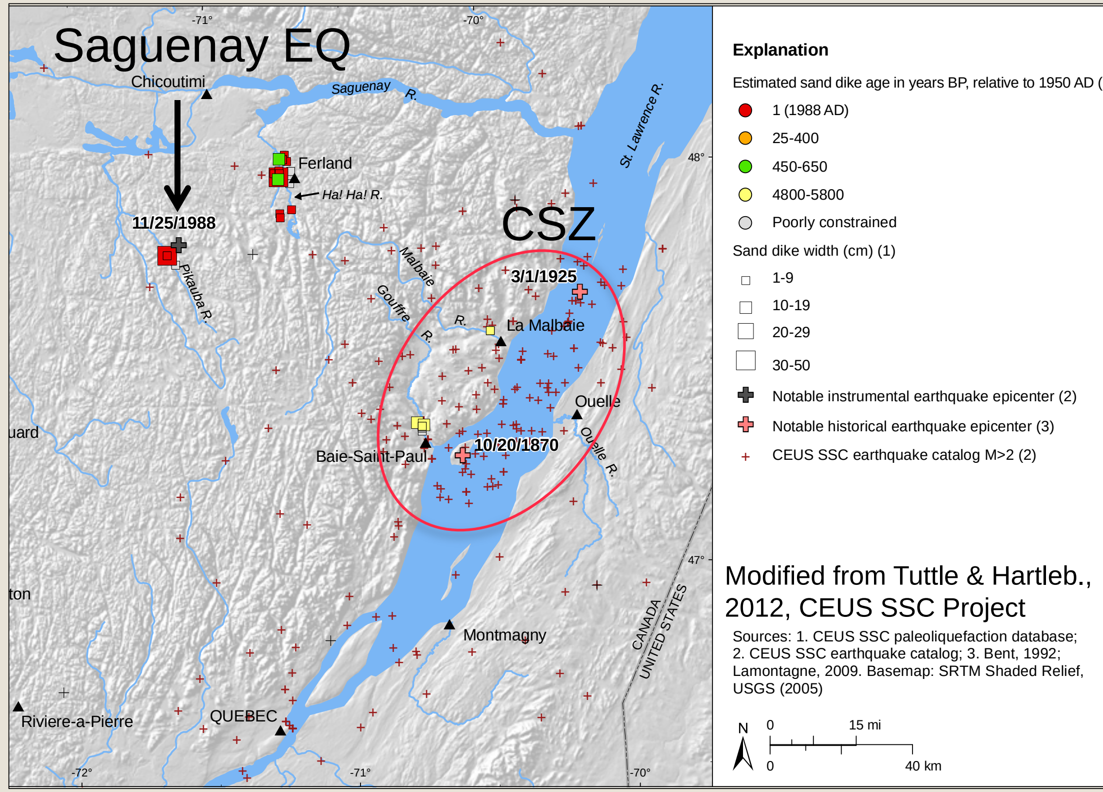
Contemporary Ages Only To Constrain Timing

EPRI et al., 2012



1988 M 5.9 Saguenay, Quebec Earthquake

Liquefaction up to 30 km from epicenter



- Saguenay earthquake centered in an historically aseismic area ~80 km NW of CSZ
- No surface rupture associated with ~28 km deep earthquake
- Surface geologic signature – liquefaction features, not faulting

Tuttle et al., 1990 & 1992

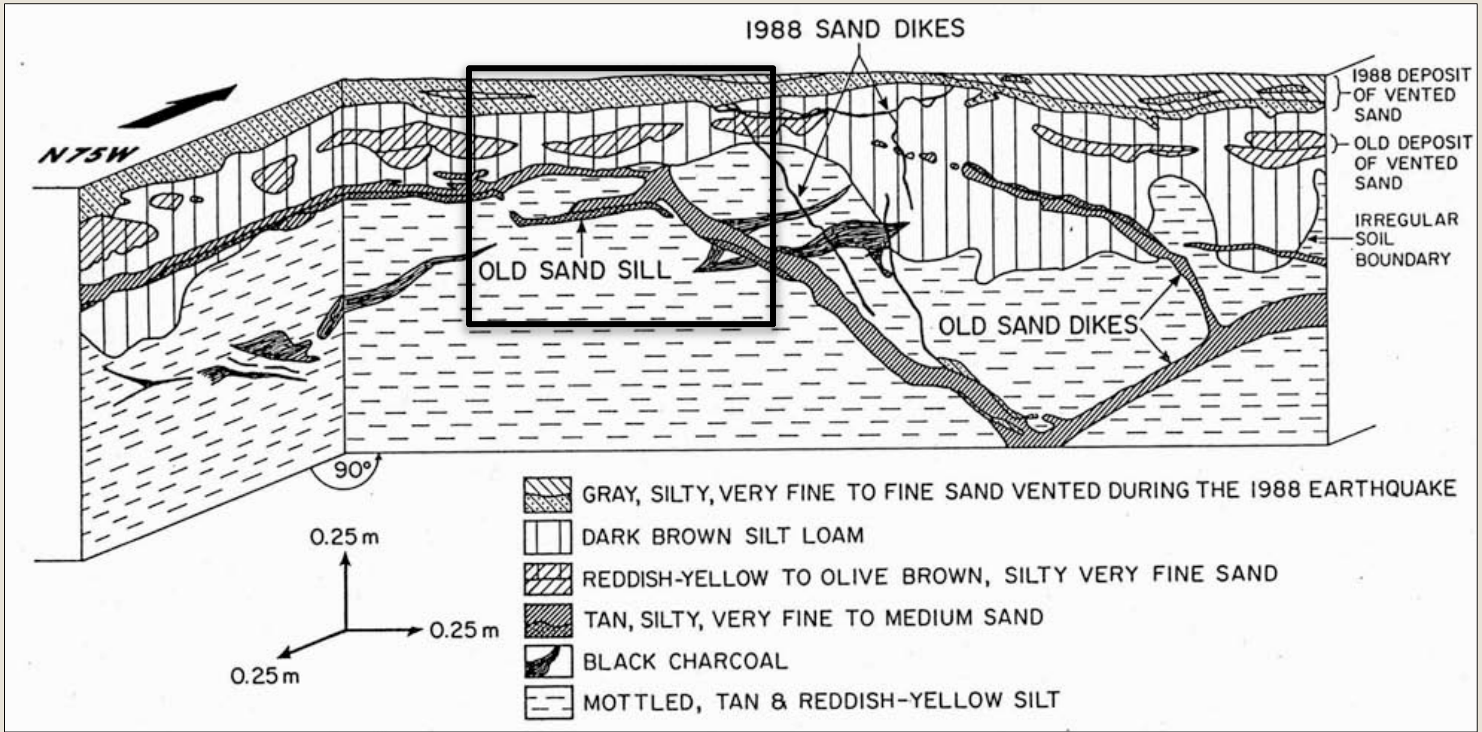
1988 M 5.9 Saguenay, Quebec Earthquake

Modern and Paleoliquefaction Liquefaction Features

} 1988 Sand Blow

} A.D. 1420 +/- 200 yr Sand Blow

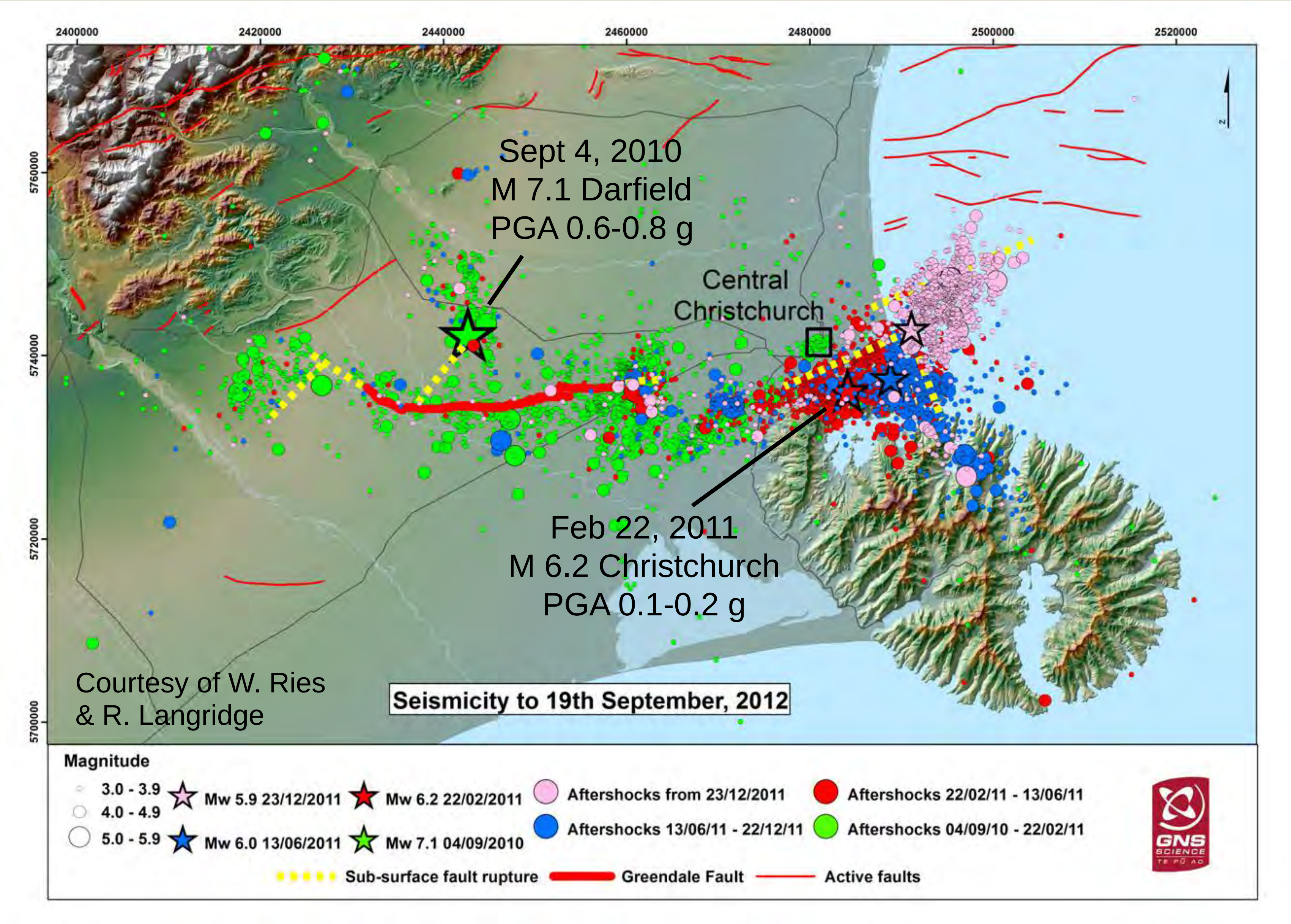
} 1988 Sand Dikes Inject Along Margins of Older Dikes



Tuttle et al., 1990 & 1992

2010-2011 Canterbury New Zealand Sequence

Liquefaction Induced by Multiple Earthquakes



✧ Hardwick site - repeated liquefaction produced compound sand blows

Compound Sand Blow
Sept 2010 & Feb 2011 Eqs

Photographs by C. Hardwick, 2011

Compound Sand Blow
Sept 2010, Feb & June 2011 Eqs

Compound Sand Blow

NZ Liquefaction Events

Unit 4. Feb 22, 2011 - M 5.6 →

Unit 3. Feb 22, 2011 - M 5.5 →

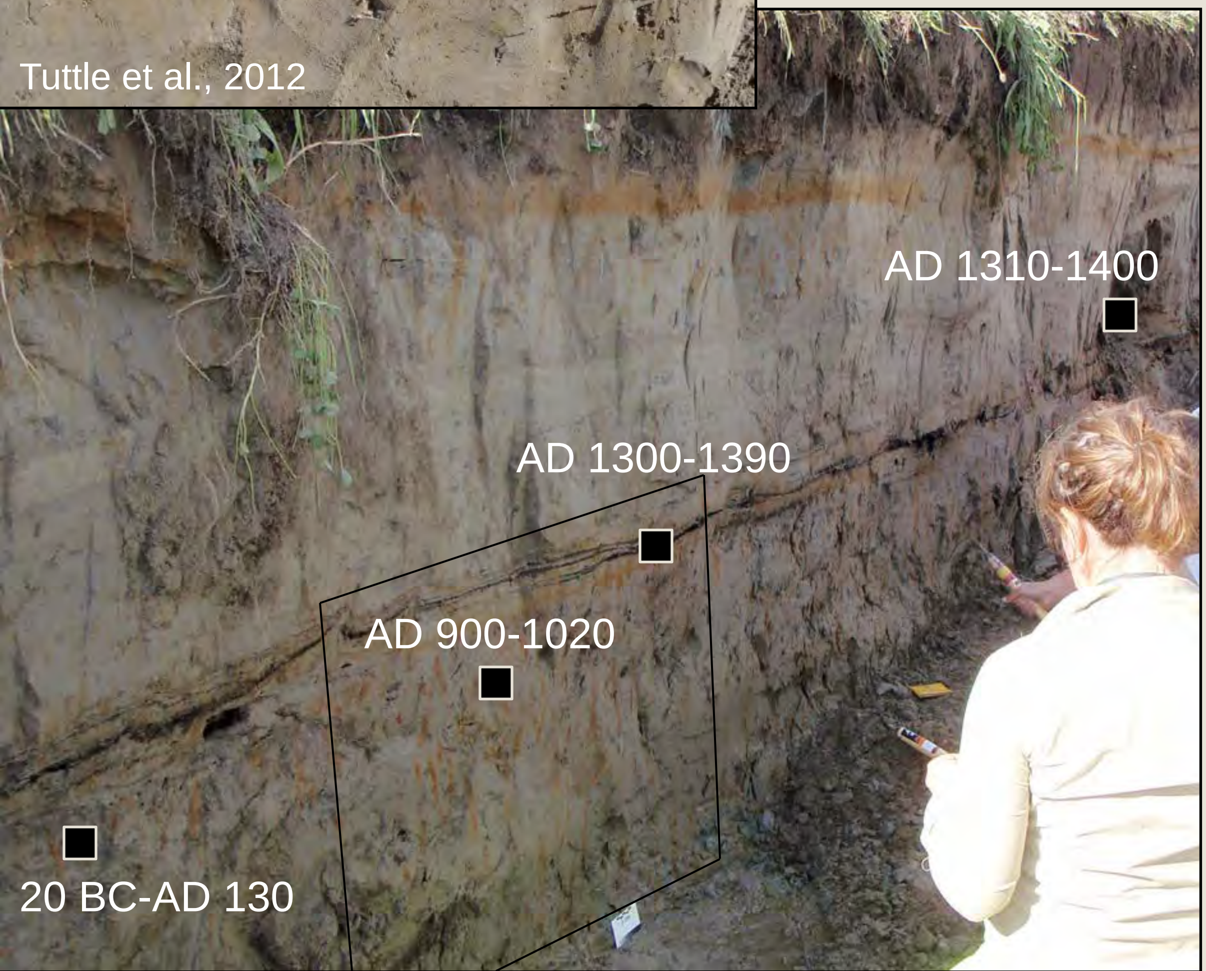
Unit 2. Feb 22, 2011 - M 6.2 →

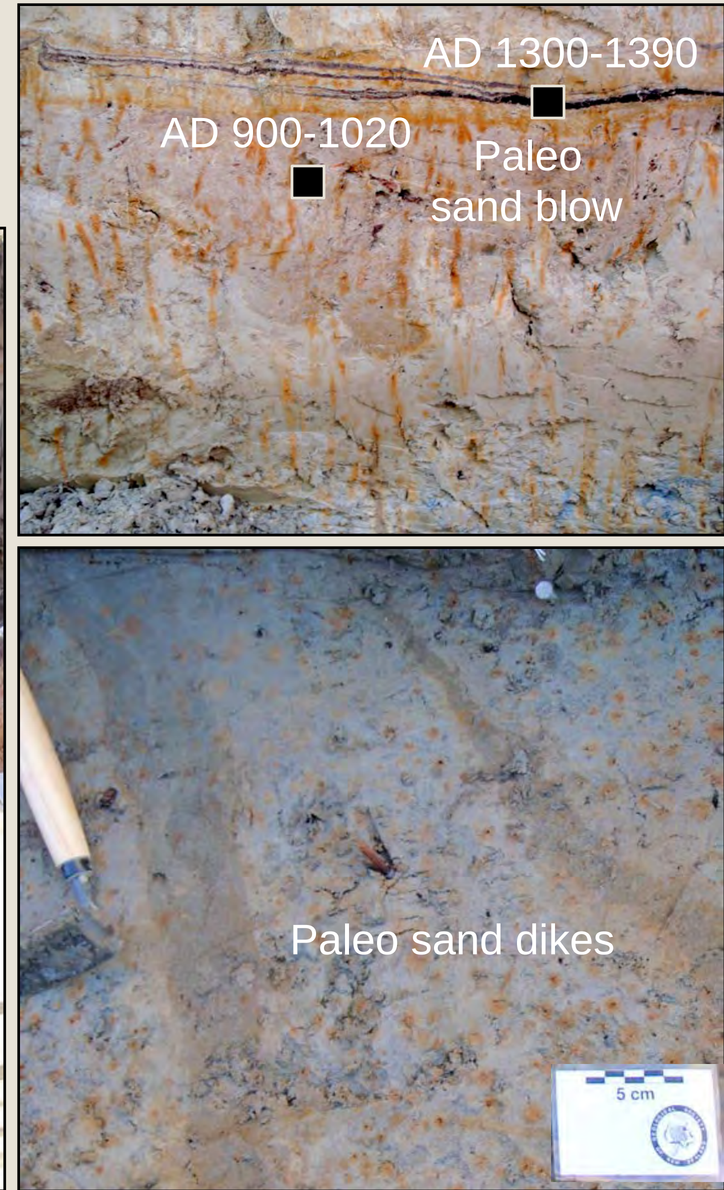
Unit 1. Sept 4, 2010 - M 7.1 →

Note: many soil clasts in basal unit; very thin silty layers capping units

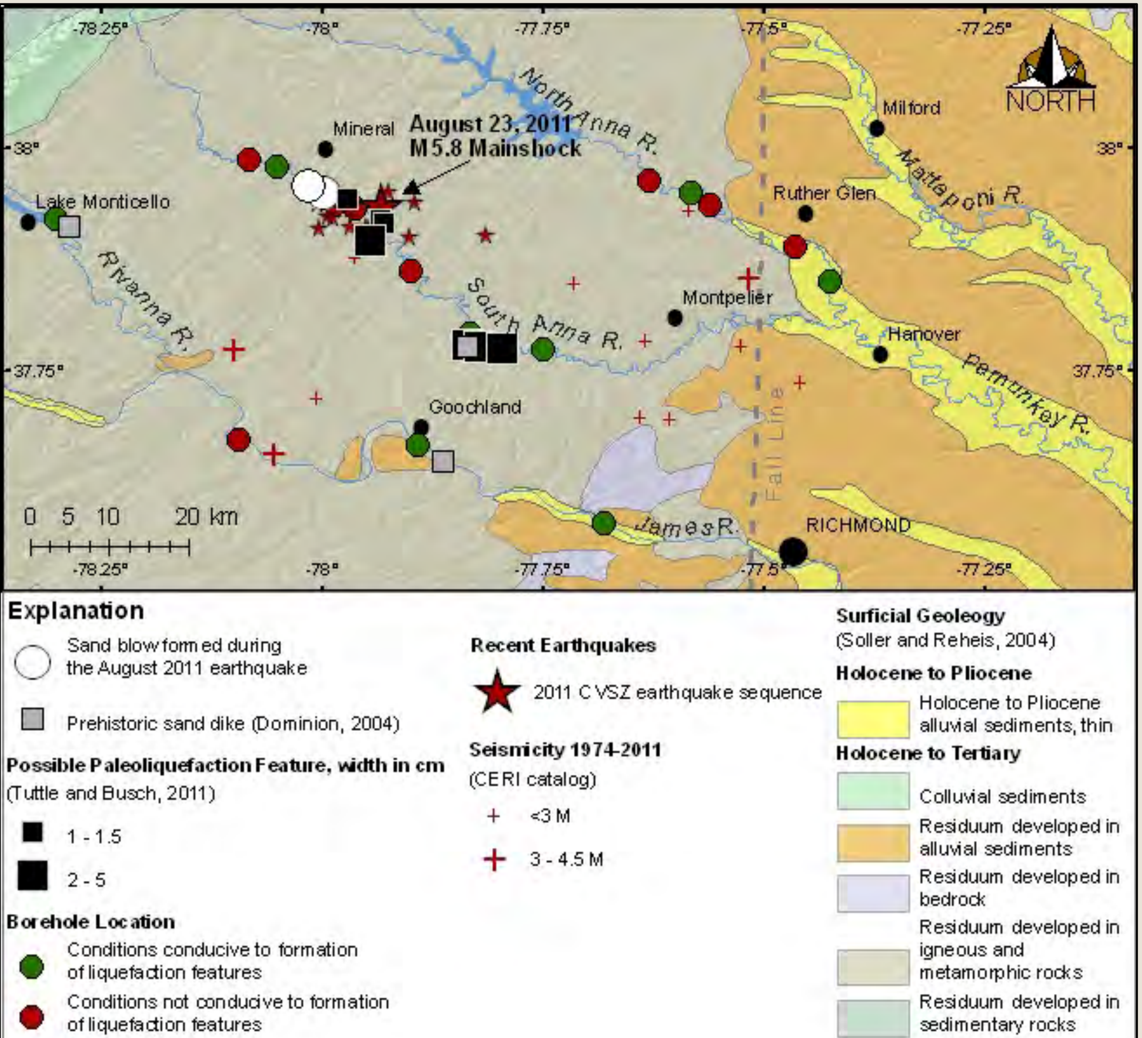
Tuttle et al., 2012

- ✧ Paleoliquefaction found at modern liq. sites
- ✧ Crevasse splay buried and preserved





2011 M 5.7 Mineral, VA Earthquake
Liquefaction features in epicentral area

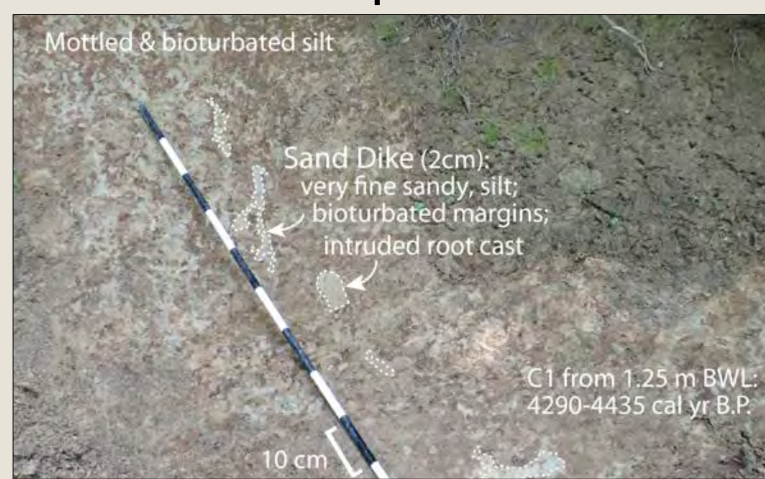


Tuttle et al., 2015

2011 Sand Blows in River Bed

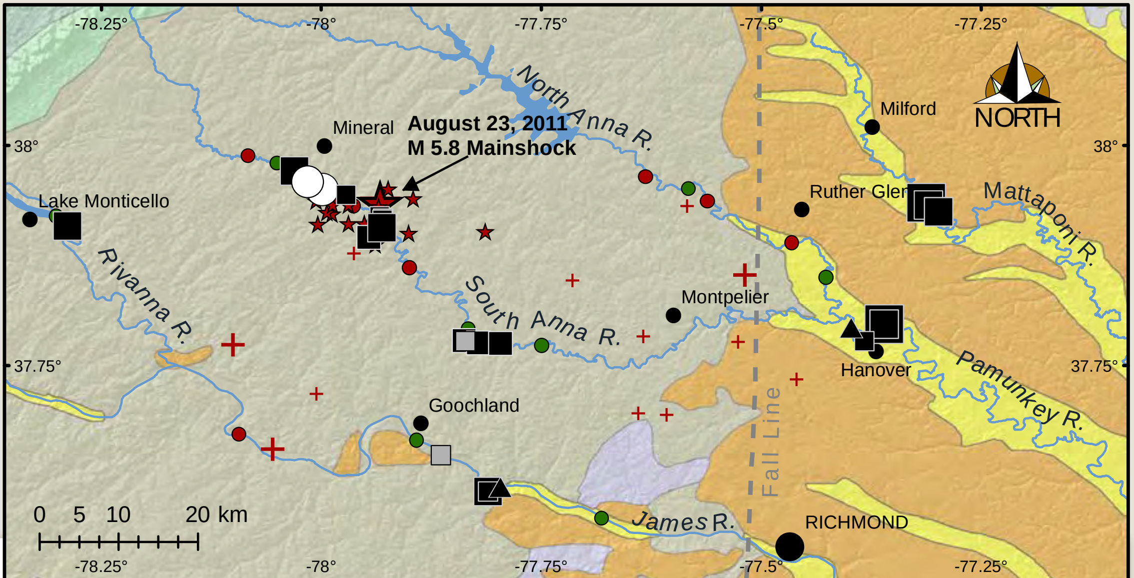
2011 Sand Vented Thru Crayfish Burrow

Possible Paleoliquefaction Feature



Paleoliquefaction Features in CVSZ

- ✧ Ages poorly constrained; C14 & OSL dating of sediment - past 4.5 kyr
- ✧ Info needed to interpret timing, location, & magnitude



Explanation

- Sand blow formed during the August 2011 earthquake
- Prehistoric sand dike (Dominion, 2004)
- SSD

Paleoliquefaction Feature, width in cm
(Tuttle and Busch, 2011;Tuttle, Carter, Dunahue, 2015)

- 1 - 1.5 cm
- 2 - 5 cm
- 6 - 9 cm

Borehole Location

- Conditions conducive to formation of liquefaction features
- Conditions not conducive to formation of liquefaction features

Recent Earthquakes

- 2011 CVSZ earthquake sequence

Seismicity 1974-2011
(CERI catalog)

- <3 M
- 3 - 4.5 M

Surficial Geoleogy
(Soller and Reheis, 2004)

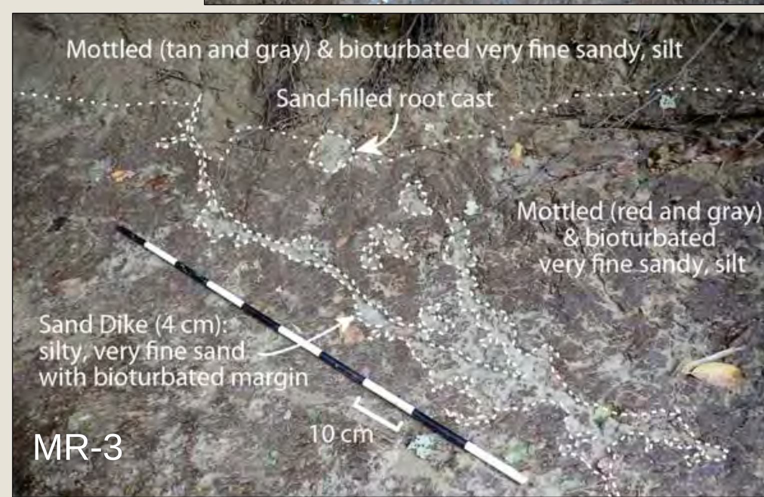
Holocene to Pliocene

- Holocene to Pliocene alluvial sediments, thin

Holocene to Tertiary

- Colluvial sediments
- Residuum developed in alluvial sediments
- Residuum developed in bedrock
- Residuum developed in igneous and metamorphic rocks
- Residuum developed in sedimentary rocks

Tuttle et al., 2015



2011 M 5.7 Mineral, VA Earthquake

Main Points

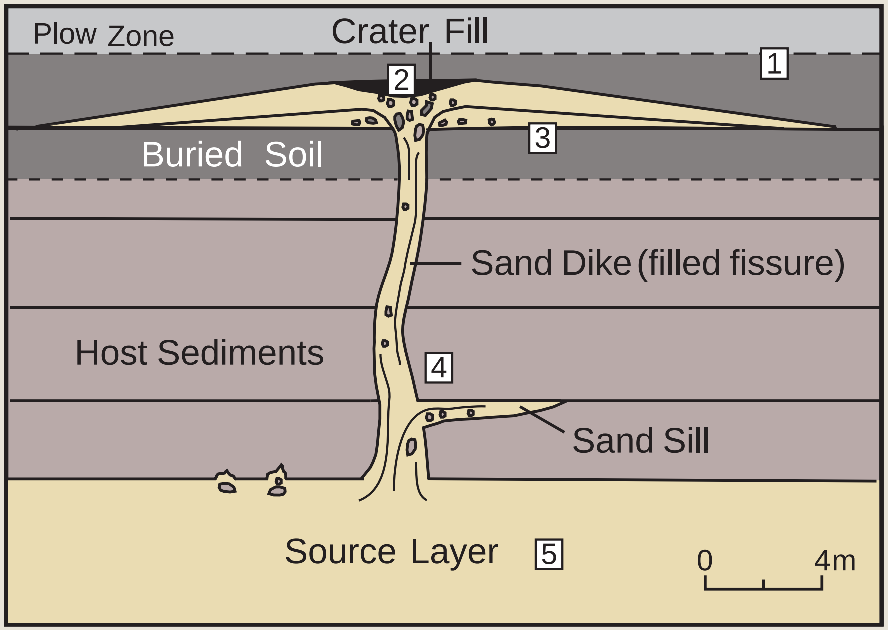
Fr Carter, 2011

- ✧ Liquefaction induced by paleoearthquakes may have resulted in slurry of water and sand venting through animal burrows and root casts
- ✧ Small paleoliquefaction features were bioturbated in the weathering zone making them difficult to identify
- ✧ Important to search for features when the river levels are very low to examine features deeper in the section

Dating of Liquefaction Features

- ✧ Critical to obtain well-constrained ages of features to correlate across region
- ✧ More likely to do this with sand blows than sand dikes and sills

Vertical Profile Through Sand Blow



Modified from Tuttle & Hartleb, 2012

Sample	Description	Age Yr BP	Constraint
1	Charcoal within soil above sand blow	650 - 740	Minimum
2	Leaves accumulated in crater	950 - 1050	Close minimum
3	Twigs in buried soil immediately below sand blow	1050 - 1150	Close maximum
4	Charcoal within host sediments	2750 - 2680	Maximum
5	Tree trunk bedded within sand layer	4530 - 4720	Maximum; source layer age

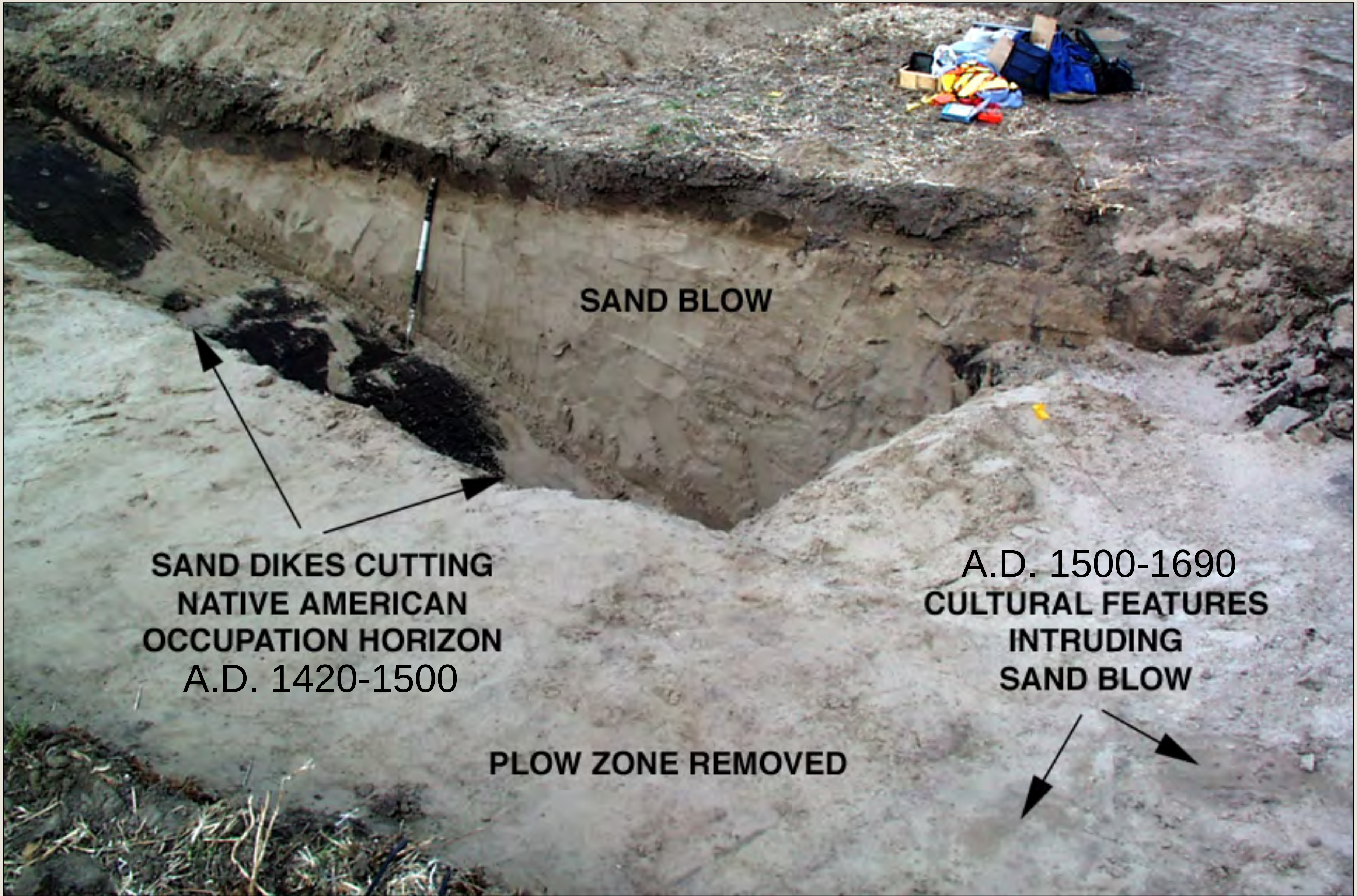
Age Estimate of Sand Blow = **Average of Minimum Minimum and Maximum Maximum Constraining Ages** ± **Uncertainty**

Example:

Age Estimate of Sand Blow = $\frac{950 + 1150}{2}$ = **1050 Yr BP** ± **100 yr (800 to 1000 C.E.)**

Age Estimate of Sand Blow

Dating post molds above and occupation horizon below: A.D. 1420-1690

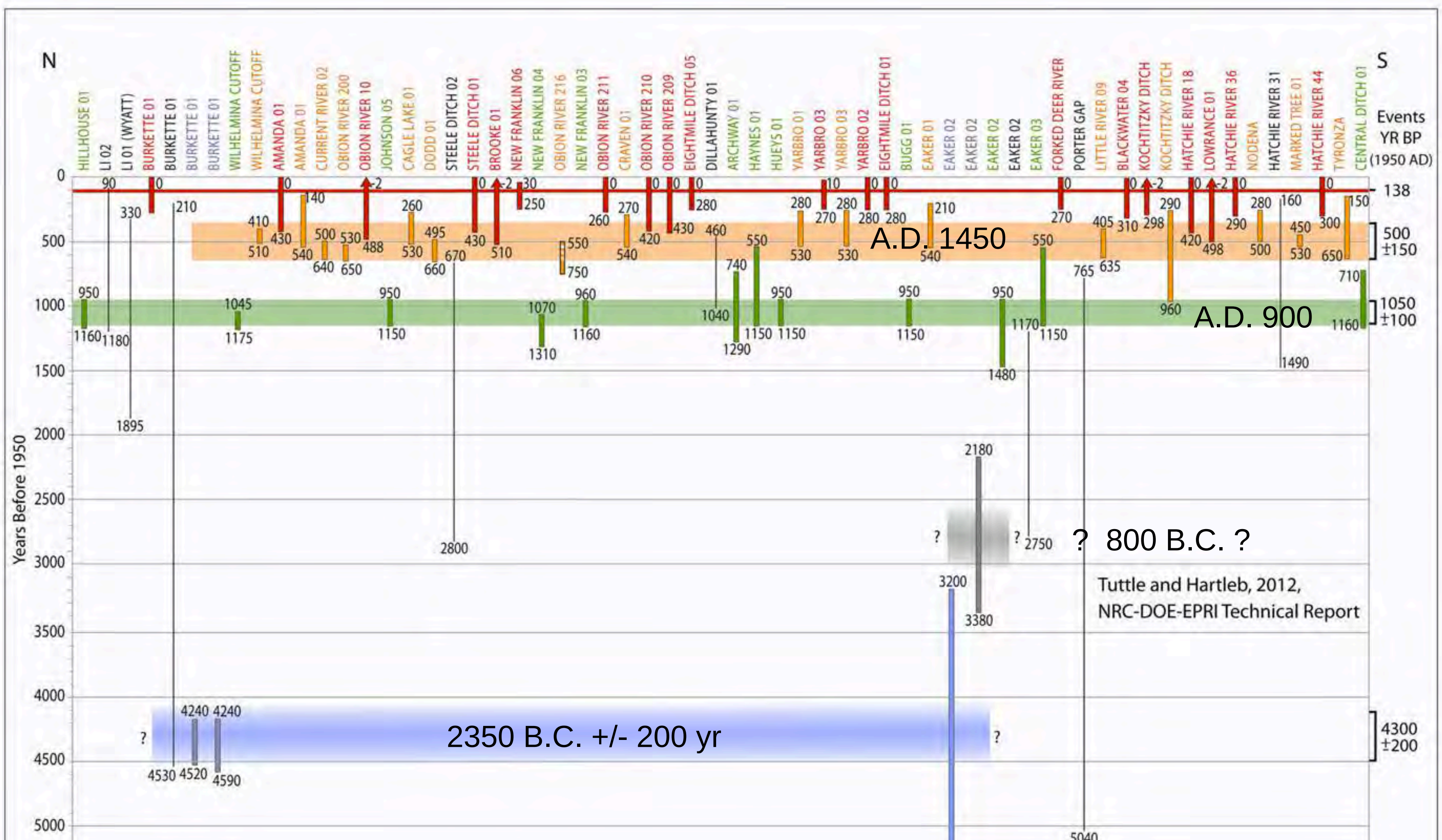


Age Estimate of Sand Dikes

Dating sediment crosscut by sand dikes: < 5 kyr B.P.;
only rarely possible to establish minimum age constraint

Estimation of Paleoearthquake Timing

- Narrowly bracket ages of numerous sand blows across region
- Estimate timing of event and chronologically correlate features
- Estimate source area, magnitude, and recurrence time
- Little data or poor age constraint - likely to have large uncertainties



Conclusions

✧ Historical & modern cases of eq-induced liquefaction

- provide opportunities to understand characteristics of liquefaction features (e.g., compound sand blows result from eq clustering) and geologic factors influencing liquefaction and related ground failures
- provide opportunities to identify setting where paleoliquefaction features may have formed and be preserved as well as to develop investigative techniques
- provide targets for paleoliquefaction studies
- serve as modern analogues for interpreting paleoliquefaction events

✧ Dating of paleoliquefaction features

- critical to constrain ages of features as best as possible
- sand blows more likely than dikes and sills to provide well-constrained ages
- search for samples that will provide close maximum, minimum, and contemporary ages
- surficial geology can limit age and completeness of paleoeq record

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Enjoy The Delta

Geophysical Imaging Techniques at Paleoliquefaction Sites

NRC Workshop 11/2015

Lorraine Wolf

AUBURN UNIVERSITY

Several geophysical methods are useful for paleoliquefaction studies

- Electrical Resistivity
- Magnetics/Gradiometry
- Ground Penetrating Radar
- Electromagnetics
- Seismics

- Each method has advantages and disadvantages
- Multiple methods will minimize inherent ambiguities

Electrical Resistivity

- Easy to use
- Reasonable acquisition time with automated switching system and multiple electrodes
- Excellent resolution providing that there is sufficient contrast between host sediments and liquefaction features
- Subject to anthropogenic noise

Magnetics/Gradiometry

- Magnetic surveys are useful at archeological sites
- They are sensitive to cultural features such as baked clay/pottery/ artifacts that possess a remanent magnetism from minerals that are heated then cooled
- They are not very useful for finding the liquefaction features, which consist of sediments (minerals) that vary in magnetic susceptibility; however values can reflect disturbed ground
- Magnetometers measure the total magnetic field; since we look for small variations, gradiometry is better

Magnetic Methods

For shallow high-resolution imaging, gradiometers produce more useful results than magnetic maps of total field anomaly

Magnetic gradiometer map of cemetery (Jones, 2006).

Gradiometer survey

- Employs 2 sensors separated by ~1 meter
- Both measure total field and a difference is taken
- Can be vertical or horizontal gradient

(www.gemsys.ca/site-characterization-for-using-overhauser-magnetometer/)

(http://sustainablearchaeology.org/facility-equipment.html)

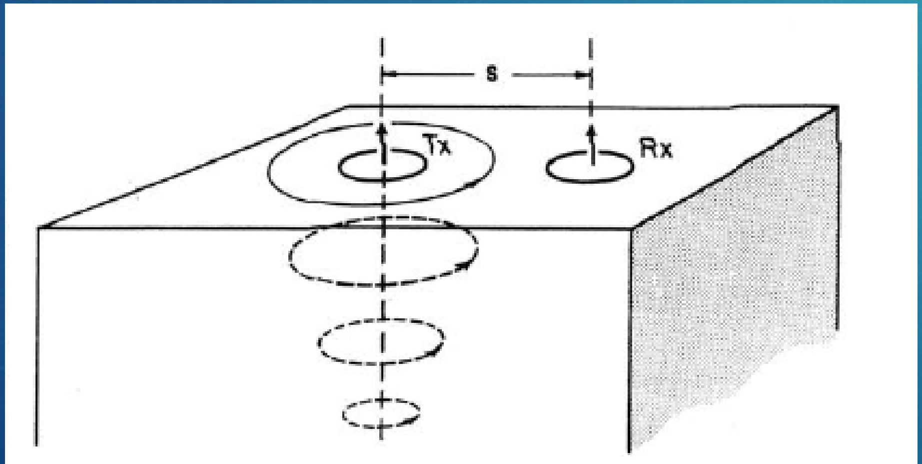
Ground Penetrating Radar

(Haydar will discuss)

(http://www.leakmasters.net/ground-penetrating-radar/)

Electromagnetics

- Good reconnaissance tool
- Fixed antennae penetrates at an ~ constant depth
- Variable frequency instrument can image at multiple depths (skin depth is a function of frequency)

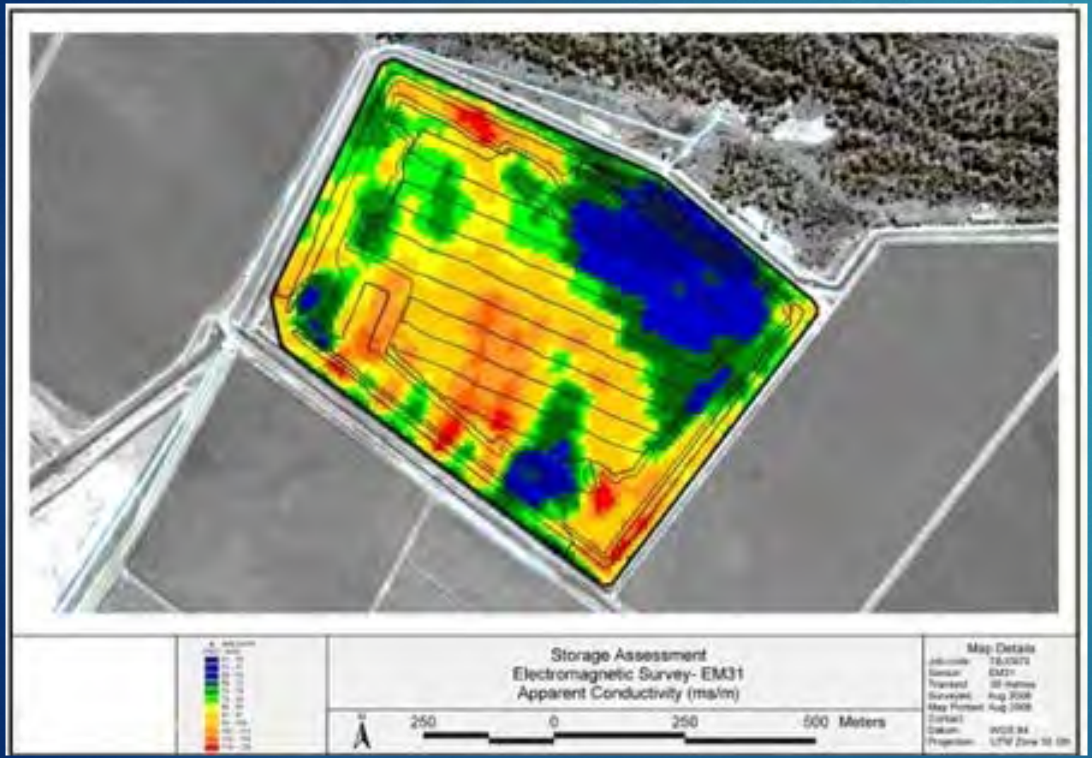


(From McNeill, 1980)

http://www.geophysical.biz/webfoto30.jpg

Electromagnetics

- Fast but heavy instrumentation can be tiresome



http://static.fairfaxrural.com.au/multimedia/images/crop/450x0/621563.jpg

http://www.ldeo.columbia.edu/~aziz/myweb3/photogallery

Seismic Methods

Reflection

- Hard to image depths < 2 m
- Imaging tends to be too deep
- Trench excavation ~ < 2 m
- Refraction

Refraction

- Not good for imaging lateral changes
- May be somewhat useful for source layer

MASW

- Useful but may lack resolution


(www.uky.edu/KGS/emsweb/trenton/shearsource.jpg)

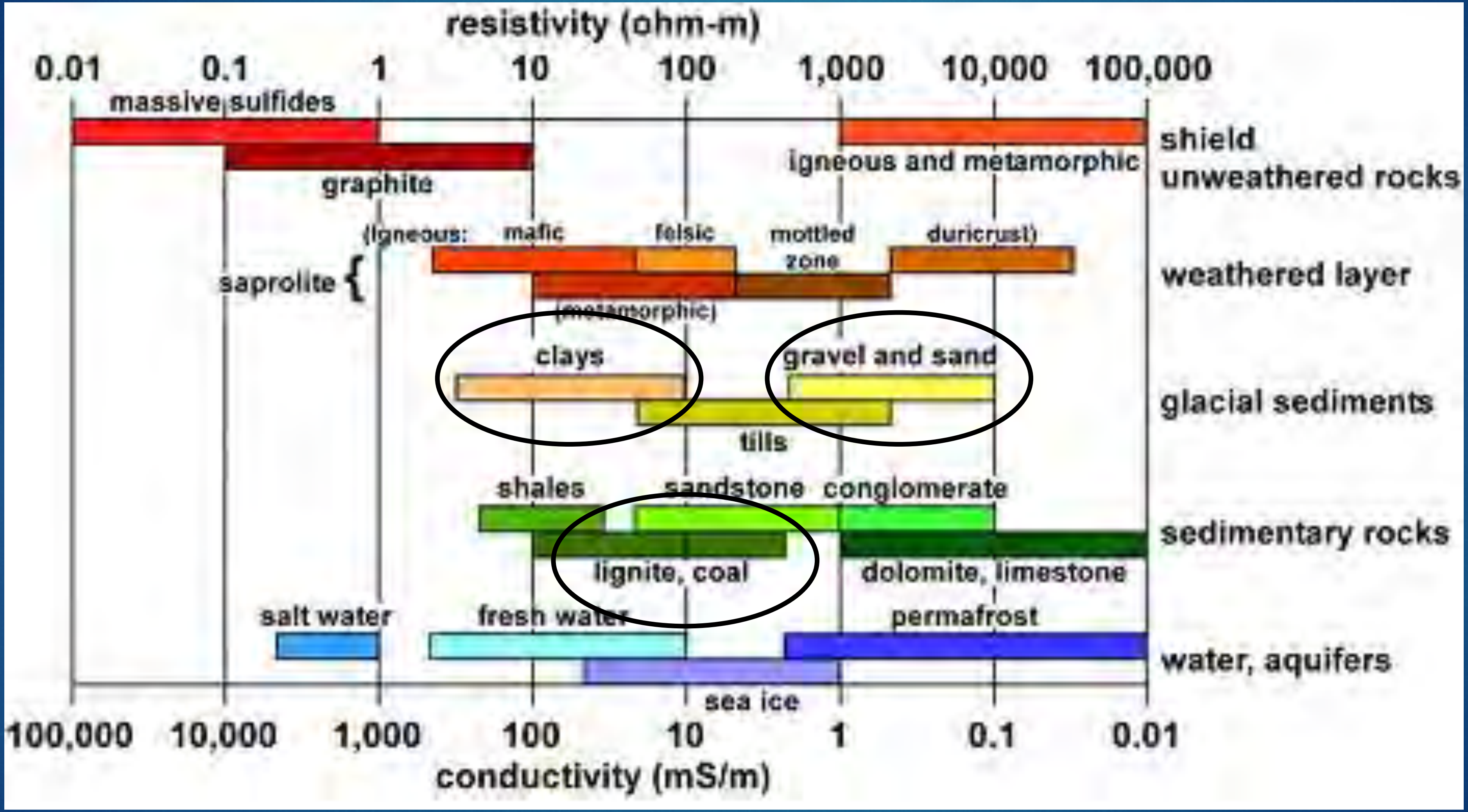
(from www.geofact.de)

Electrical Resistivity

Resistivity of soil and rock is affected by

- Moisture content (dominant)
- Dissolved pore fluids (electrolytes)
- Porosity
- Temperature (decrease with increasing T)
- Resistivity of solid material (minerals)

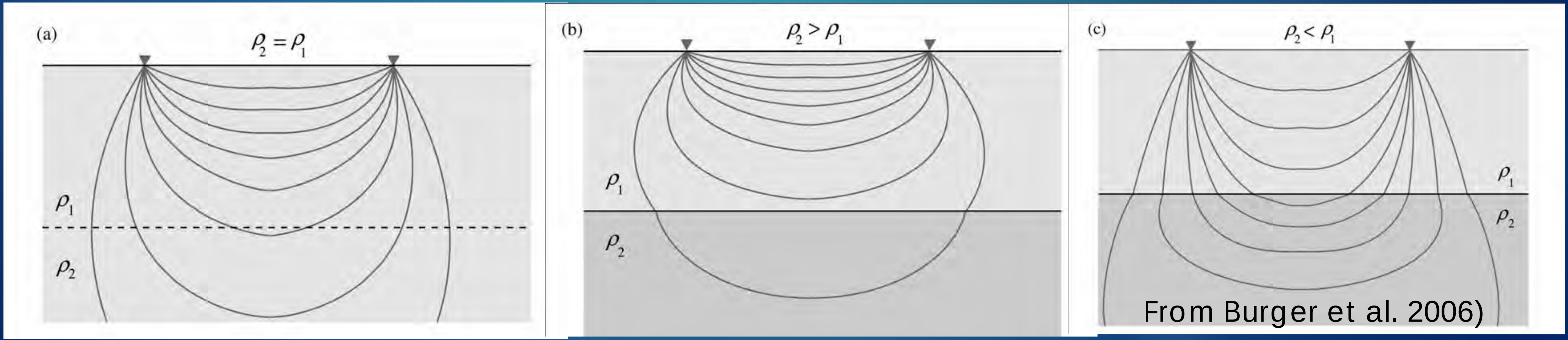
Resistivity of some common materials



Modified from Palacky, 1988)

2D assumptions

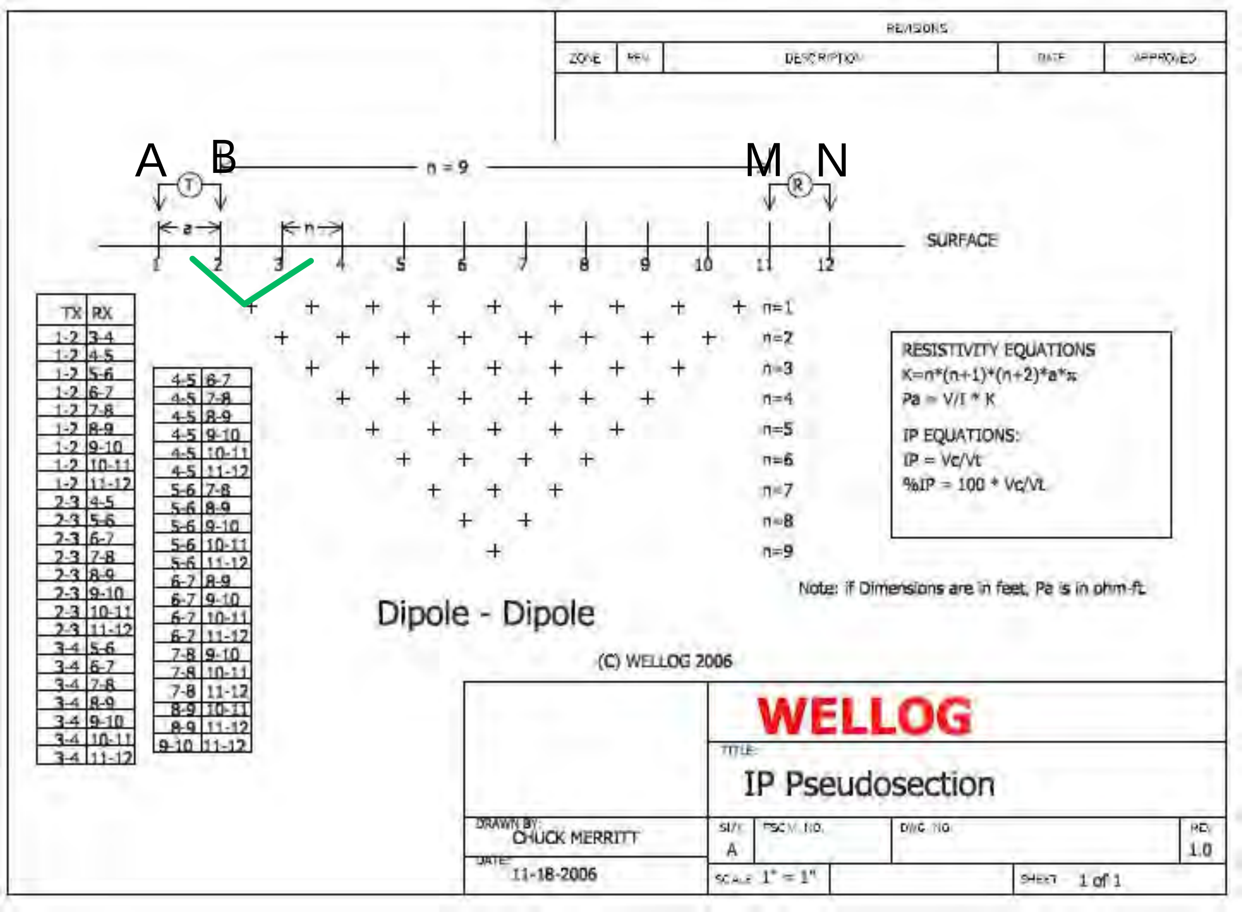
- Resistivity is a function of ρ (x,z) in a 3D reality
- If earth is homogeneous, apparent ρ = true ρ
- Apparent ρ is a weighted sum of resistivity distribution in the entire earth
- Although it is plotted at a point, it is not a direct measurement of that location



From Burger et al. 2006)

Dipole – Dipole Array

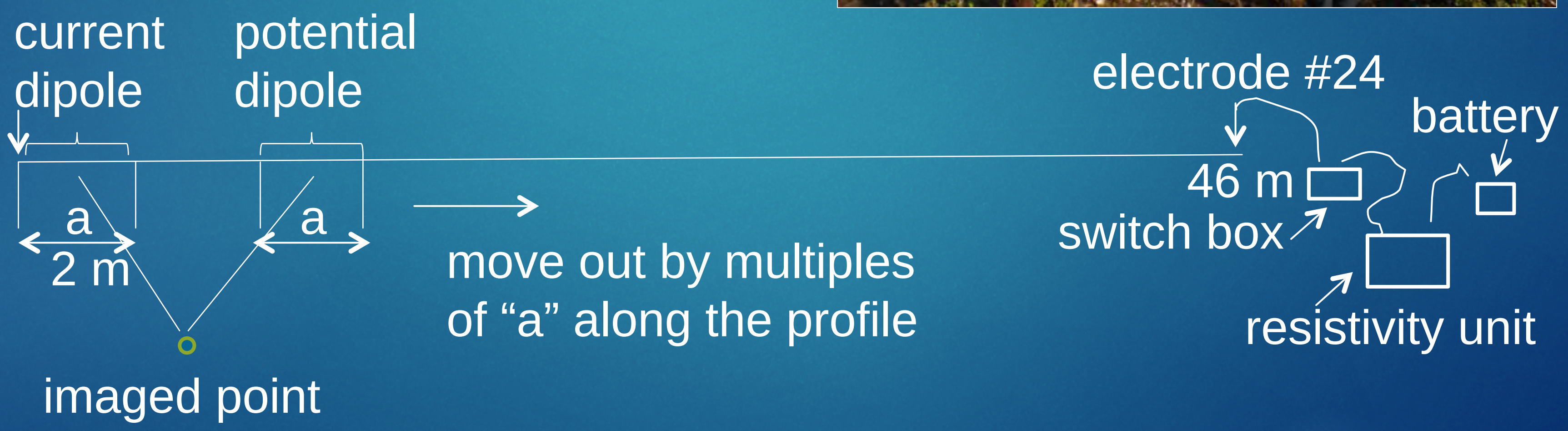
- DC current injected through electrodes A and B
- Potential is measured between M and N
- Apparent resistivity is derived from current (I), measured voltage (V), and geometric factor (K)
- $\rho = K \, \Delta V / I$
- $K = \pi n(n+1)(n+2) a \frac{\Delta V}{I}$



(Modified from www.wellog.com/ip_pseudosection/ip_pseudosection.jpg)

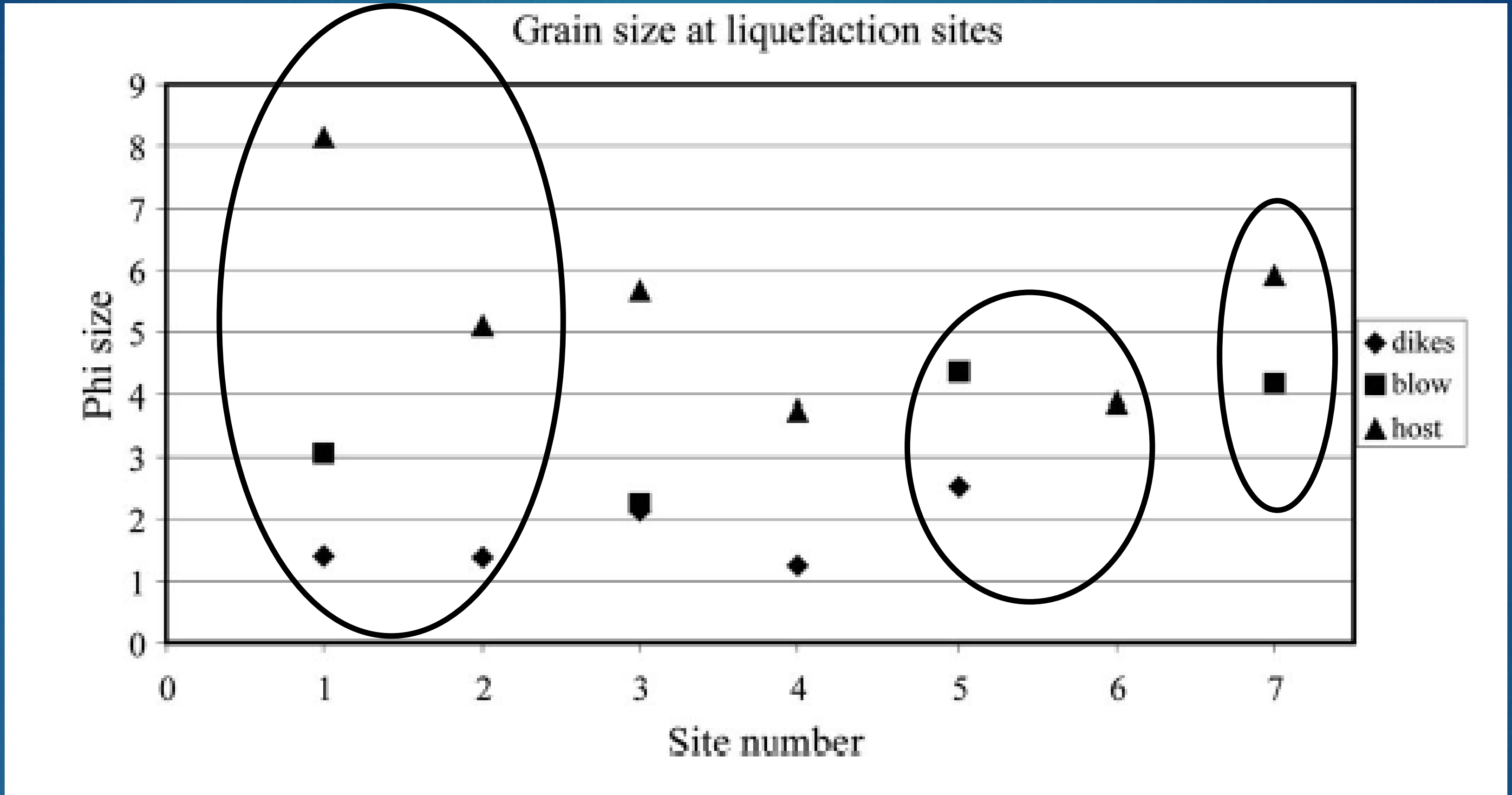
Geophysical Survey set up

AGI SuperSting Resistivity System with automatic switching: 24-48 electrodes, a spacing= 2 m, profile length= 46 - 94 m



(Wolf, 2015)

Effect of Relative Grain Size



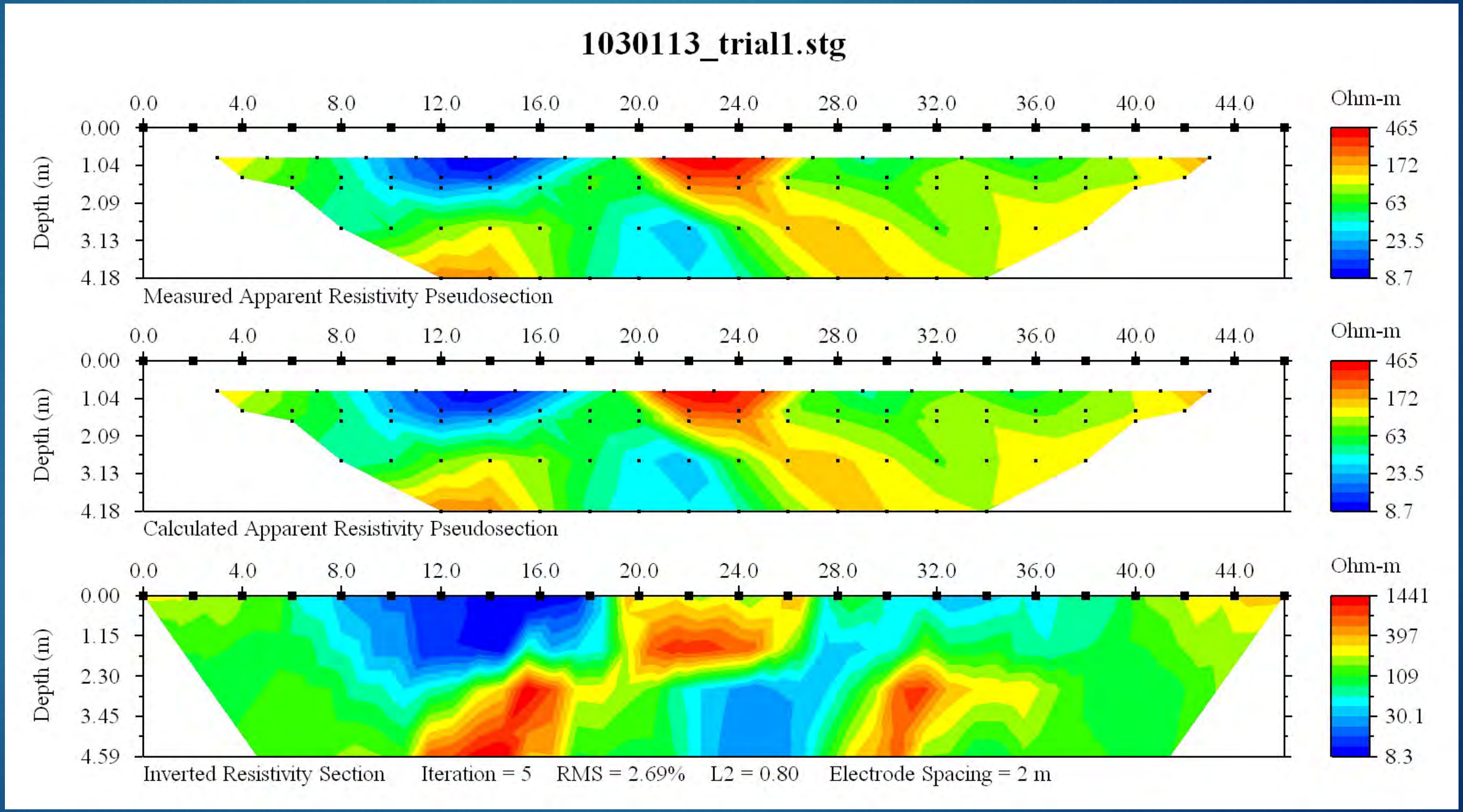
Host sediment (triangles) corresponds to sediment sizes of silts and clays
Sand blows correspond to fine to very fine sand; sand dikes correspond to mostly medium sand.
Where contrast is greater (e.g., sites 1 and 2), resolution is good. Site numbers 5 and 6 represent two trenches at the same site (modified from Hardesty et al., 2010).

Apparent resistivity ⟶ True resistivity

Pseudosection with apparent resisitvity

Synthetic created from true resistivty section

Inverted for true resistivity



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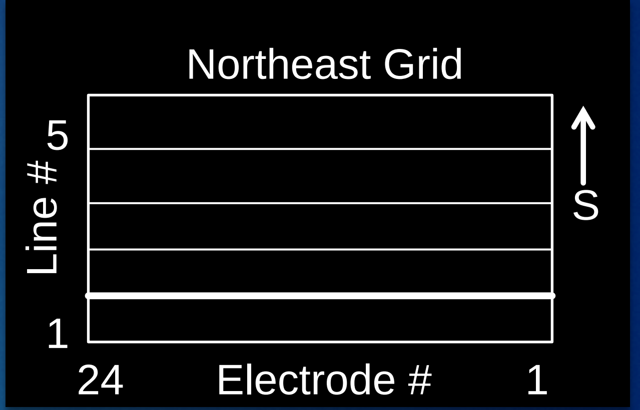
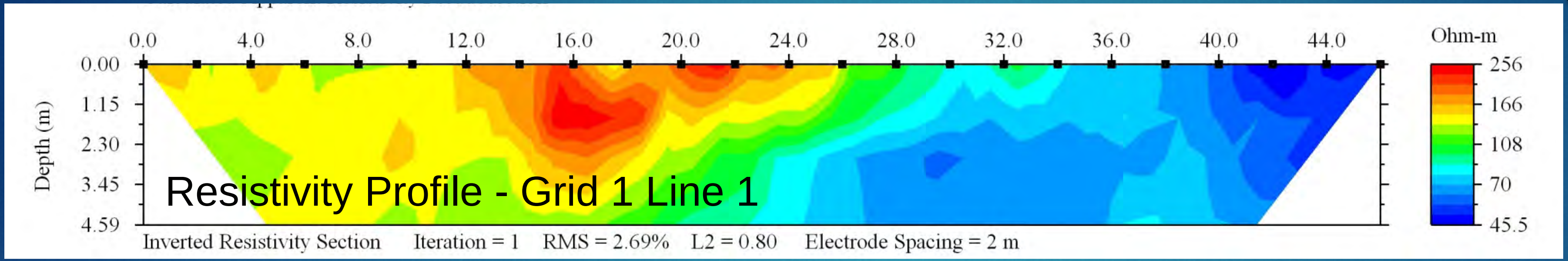
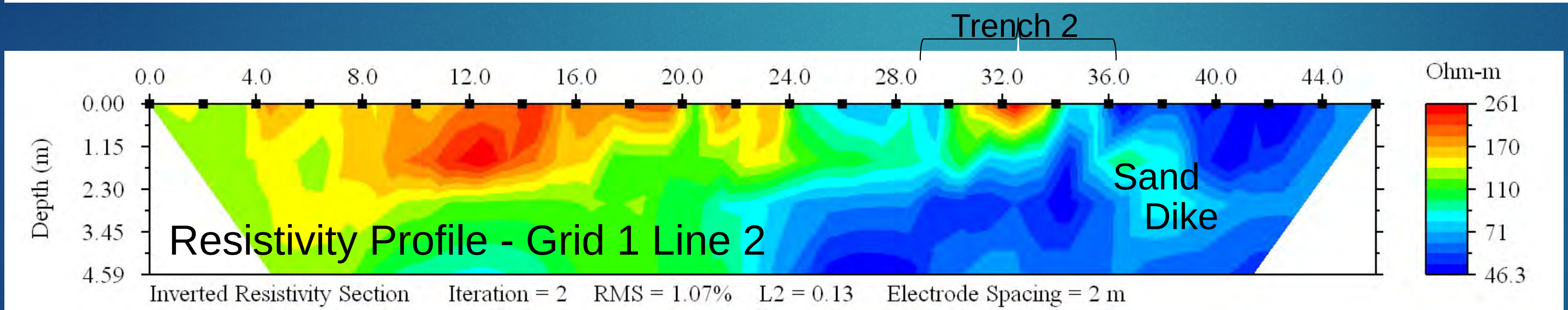
(Wolf, 2015)

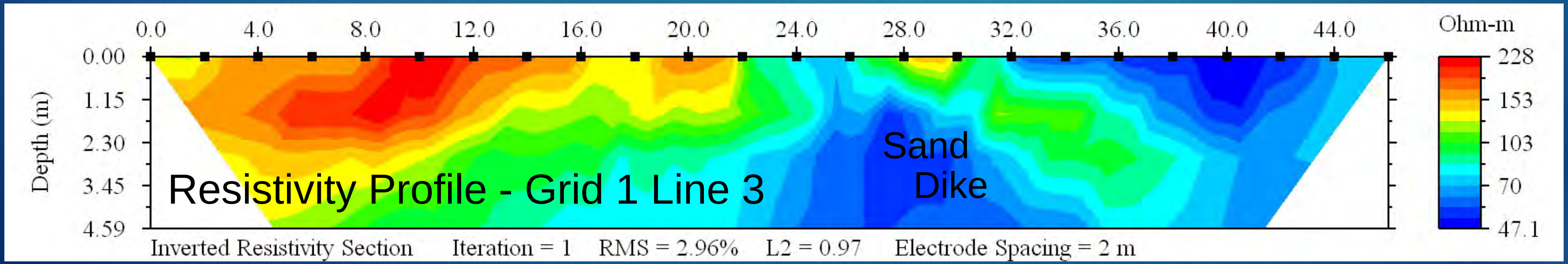
Geophysical Surveys

- Thin zones of higher resistivity interpreted as sand dikes
- Area of lower resistivity is finer & wetter channel fill deposits



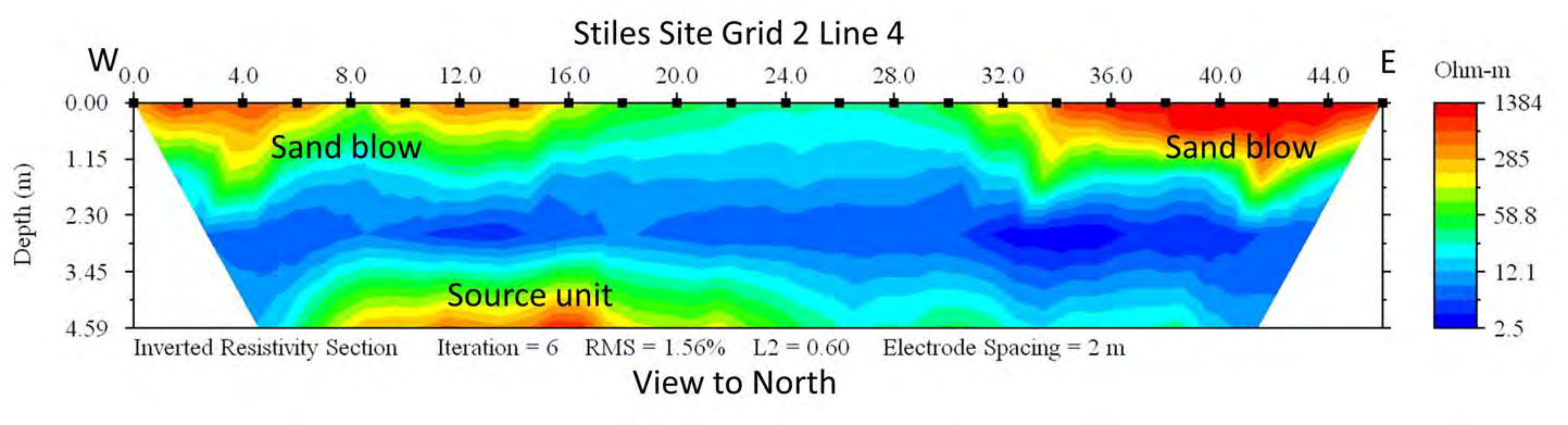


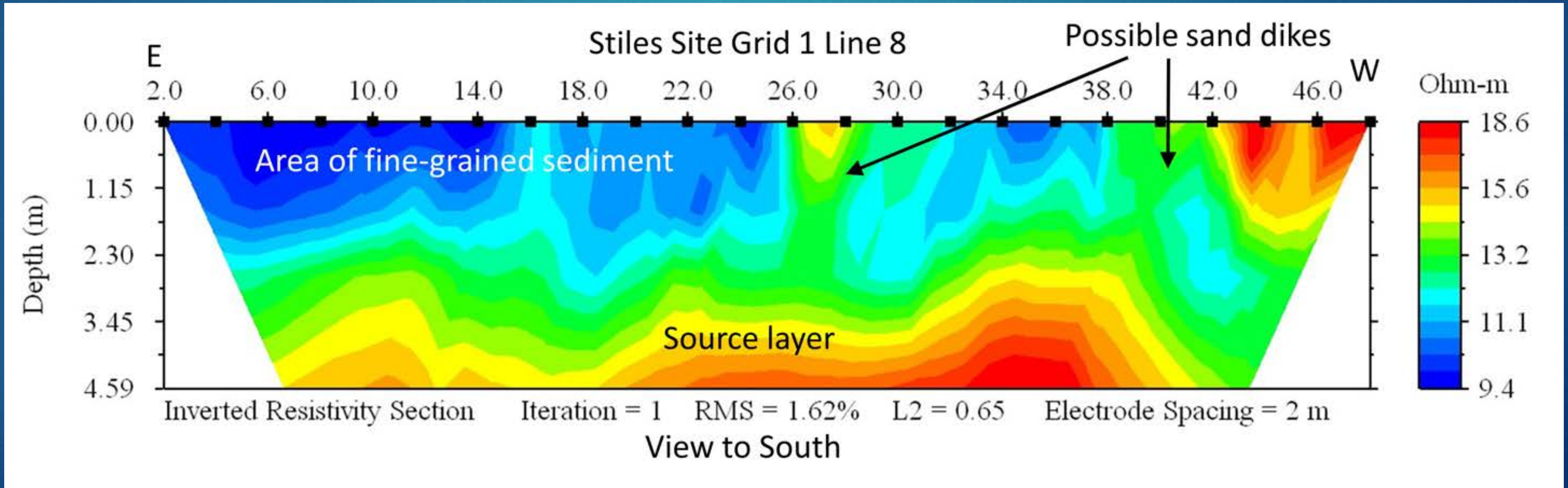




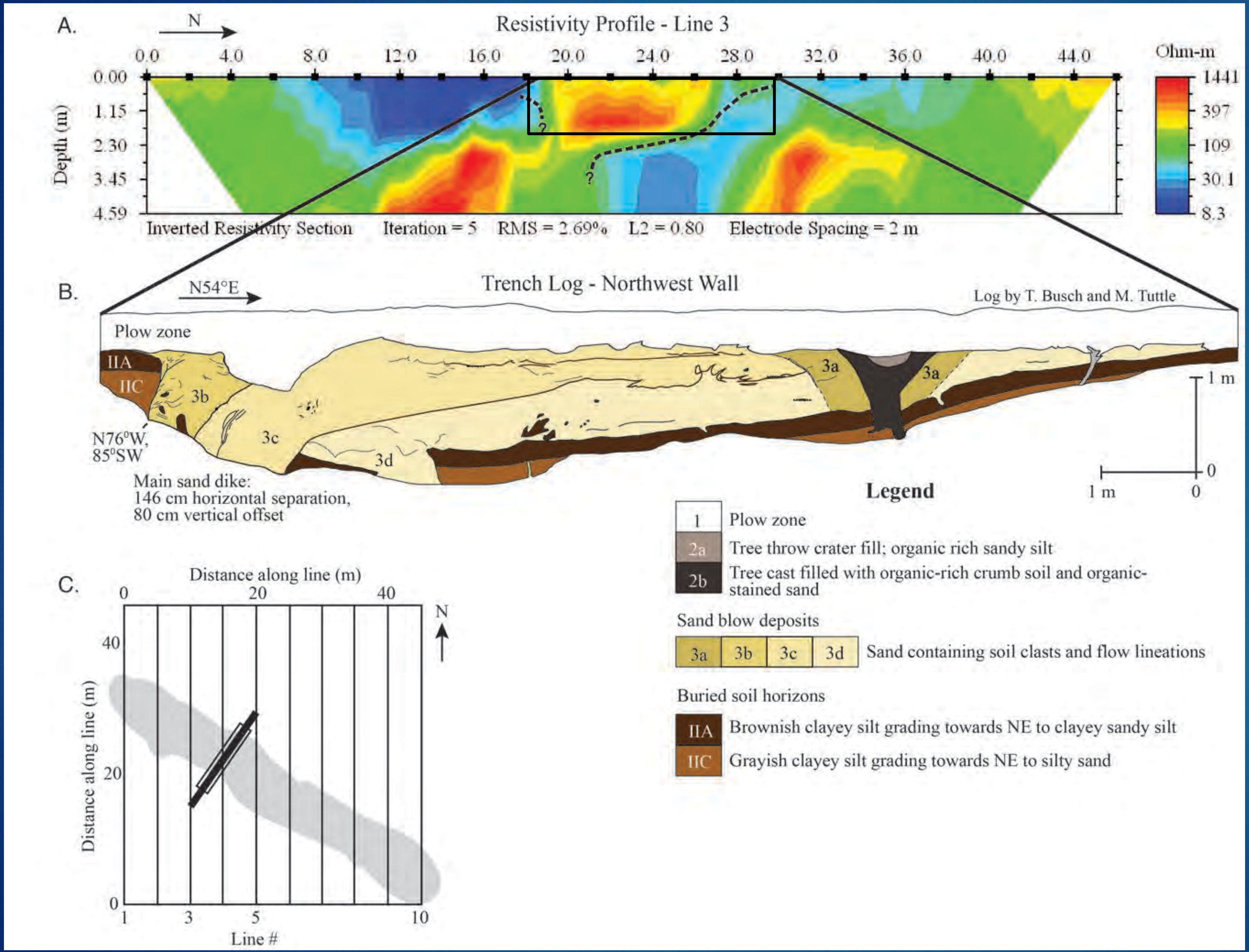
(Wolf, 2015)

2 profiles from Stiles site





(Wolf, 2015)



Positive Identification of Liquefaction Features by Locating Feeder Dikes

(Wolf and Tuttle, 2015)

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