Paleoseismology of Marianna, AR, area; Application of Ground Penetrating Radar

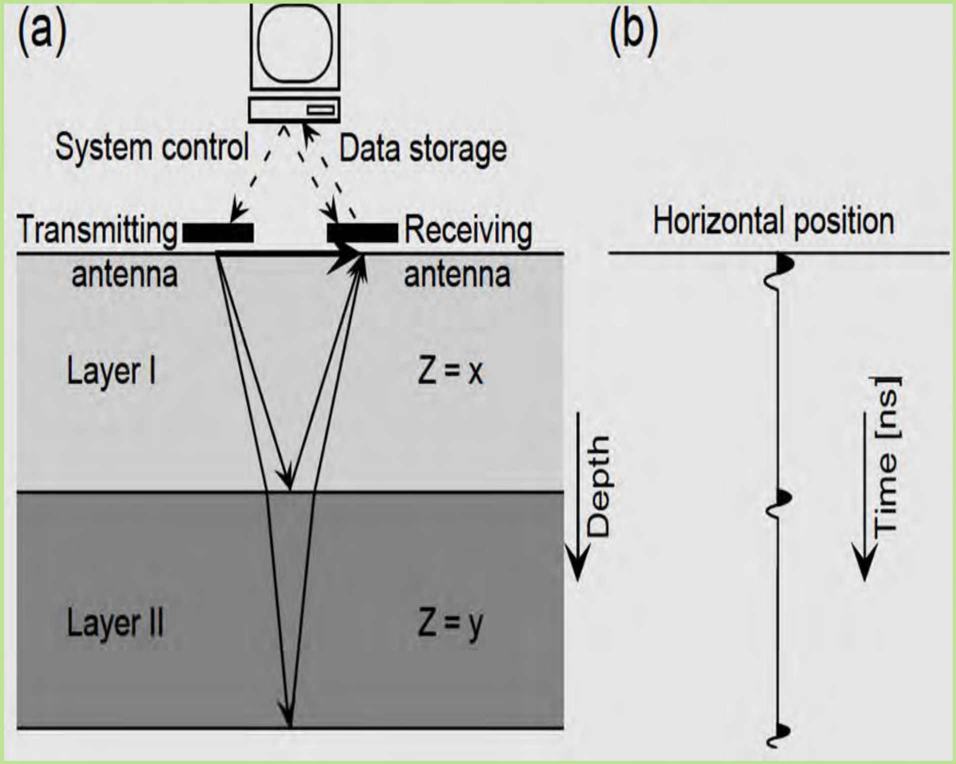
Haydar Al-Shukri, Hanan Mahdi, and Martitia Tuttle

NRC Paleoliquefaction Training Workshop

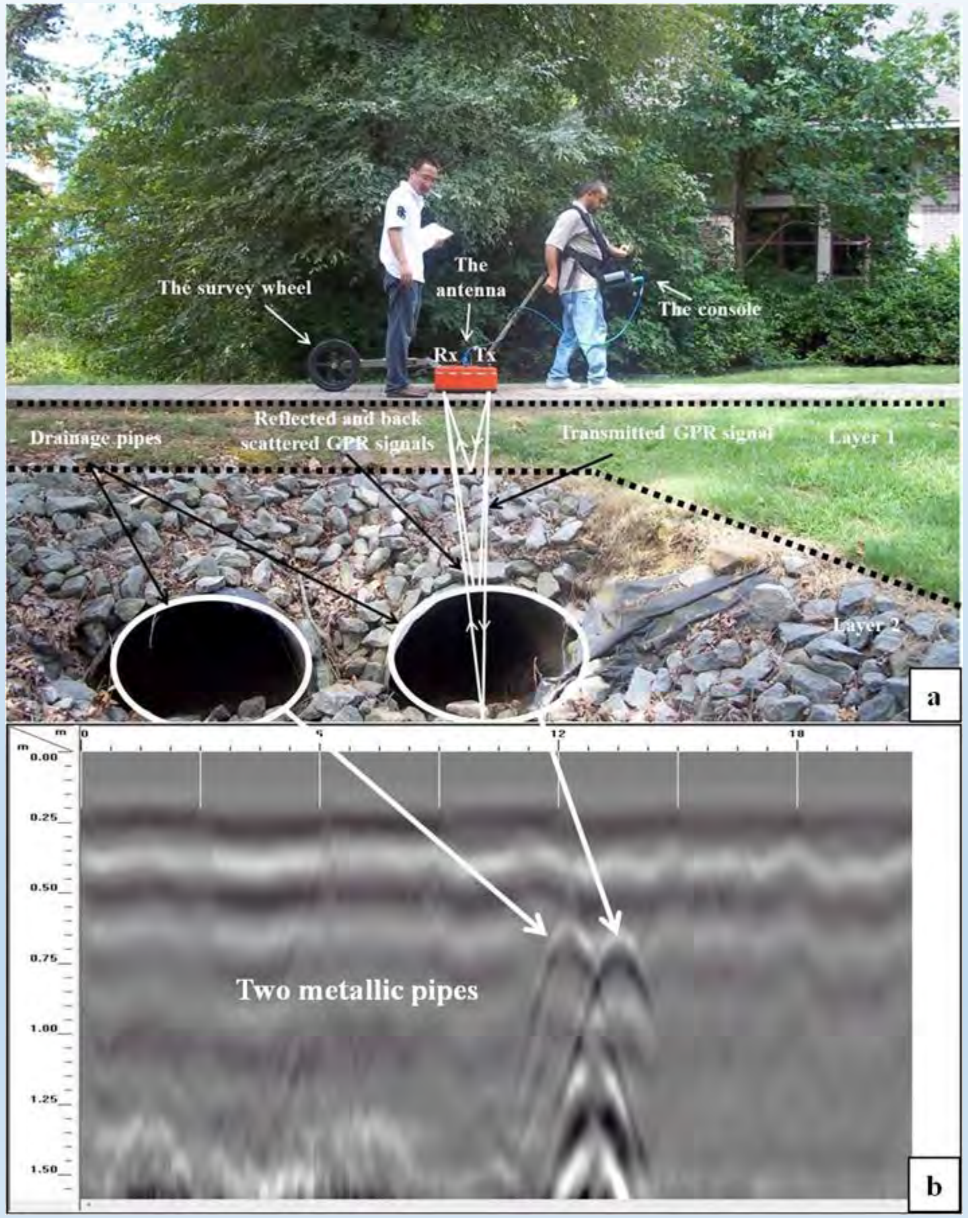
Blytheville, AR

November 10-13th, 2015

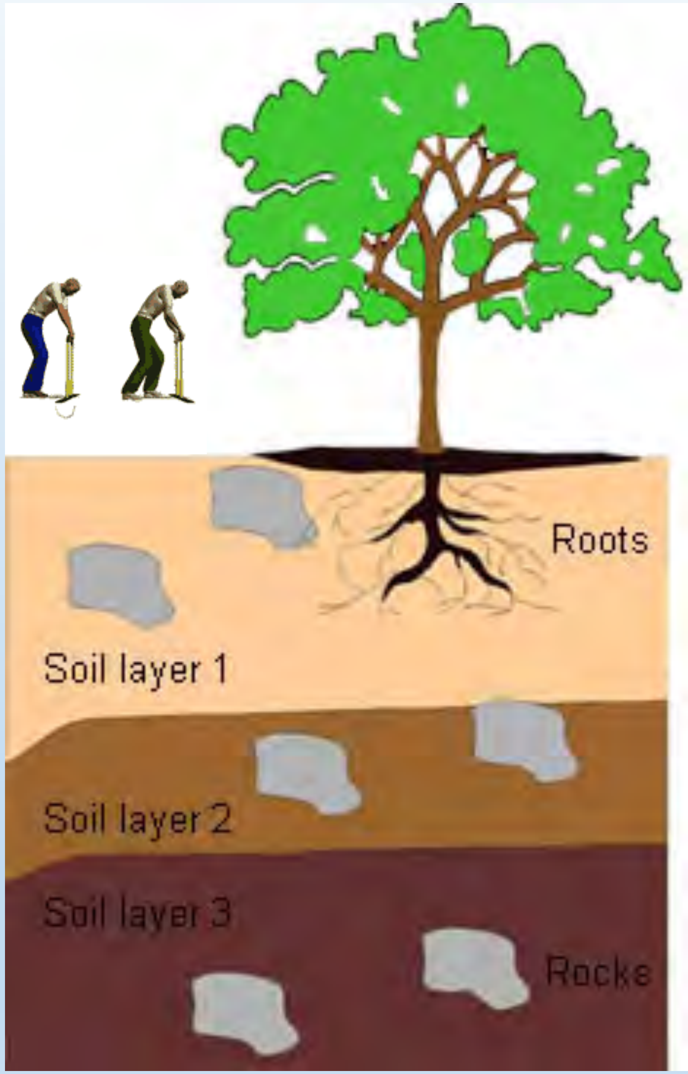
GROUND PENETRATING RADAR "GPR"



Van Dam and Schlager, 2000



PARAMETERS EFFECTING PENETRATION DEPTH OF GPR SIGNAL



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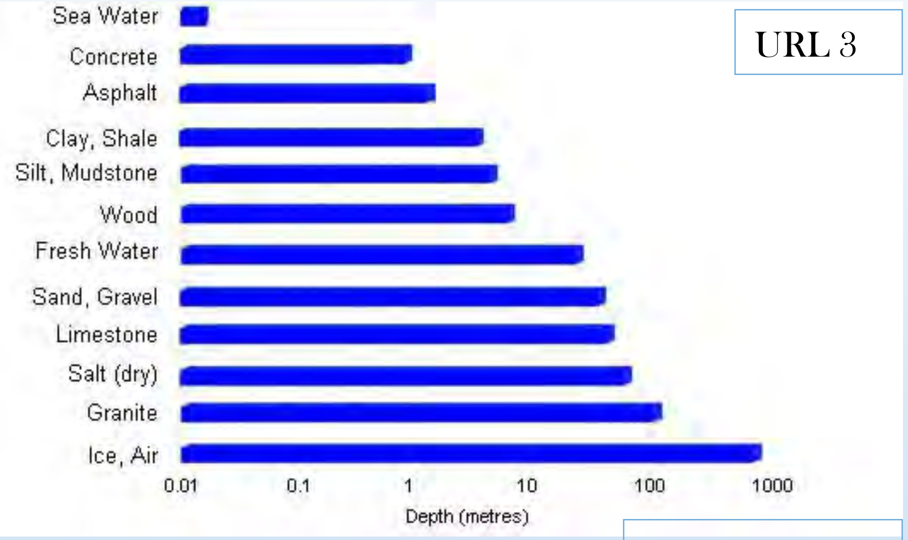


URL 3

Wilchek, 2000

Antenna Frequency (MHz)	Vertical Resolution (m)	Depth of Penetration (m)
25	≥1.0	5-30
50	≥0.5	5-20
100	0.1-1.0	2-15
200	0.05-0.5	1-10
400	>0.05	1-5
1000	cm	0.05-2

Ground Penetrating Radar

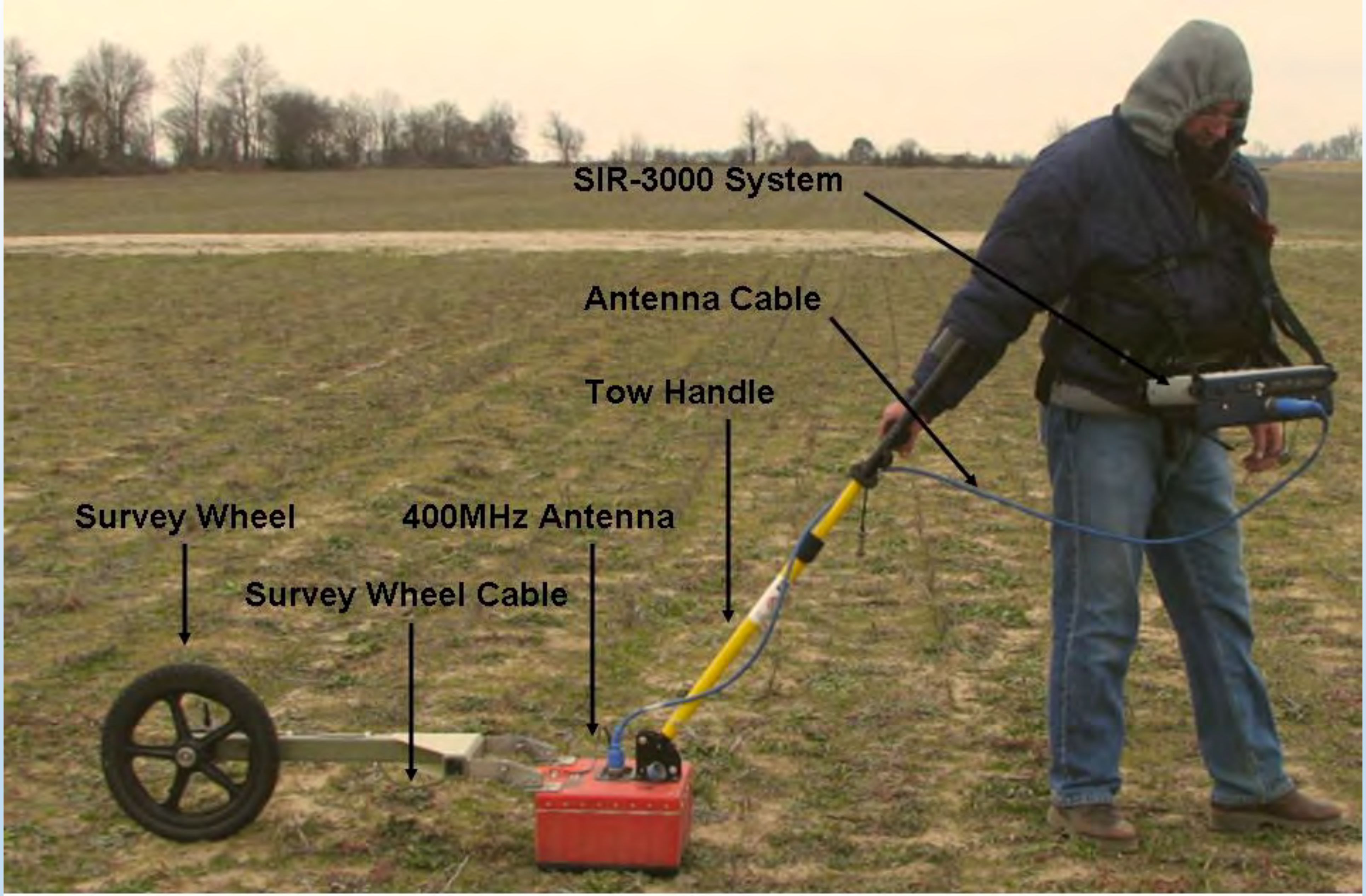
GPR Advantages:

1. It is a non-invasive method.
2. Vehicle operated system that can be run at a normal traffic speeds.
3. Continuous profile measurements are efficient for larg surveys
4. Provides 2-D and 3-D high-resolution images.
5. Provides real-time analysis.
6. Powerful in detecting small changes in physical and electric properties of the material
7. Very sensitive to changes in the hydrological conditions of soil.

Ground Penetrating Radar

- Ground Penetrating Radar (GPR) is a geophysical tool used to investigate the subsurface through 2-D and 3-D high-resolution images

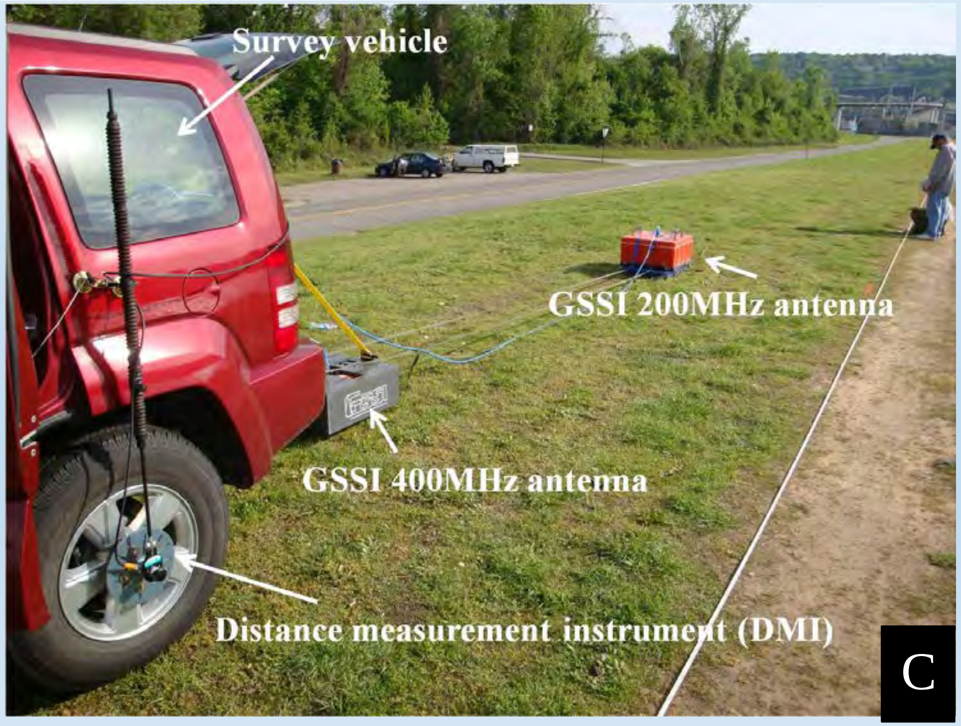
- Applications of GPR:
  - Hydrology
  - Archaeological applications
  - Highways and road investigations
  - Geological applications
  - Environmental applications
  - Engineering and geotechnical applications


SIR-3000 System
Antenna Cable
Tow Handle
Survey Wheel
400MHz Antenna
Survey Wheel Cable

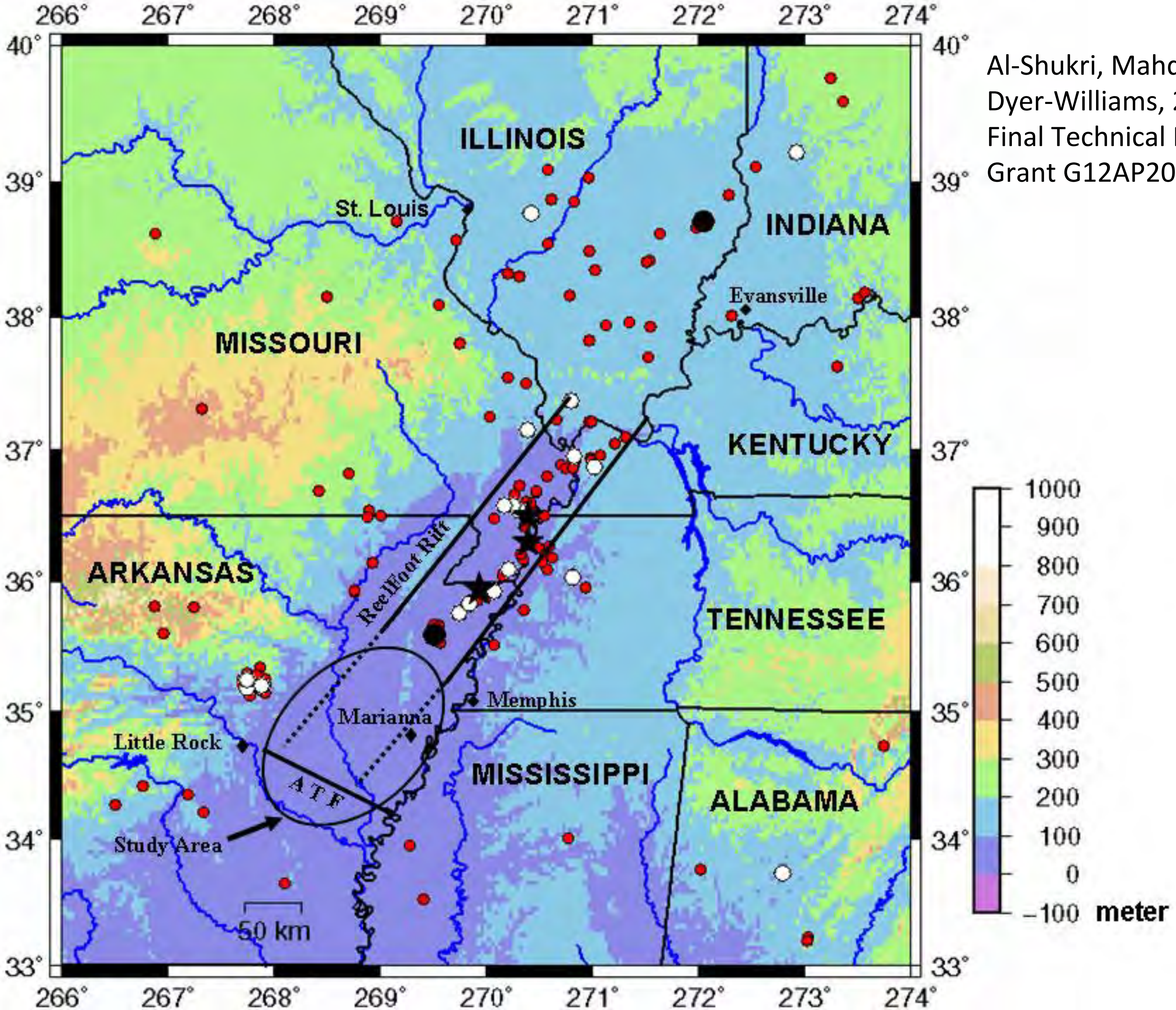
Ground Penetrating Radar System

GSSI SIR-3000 System

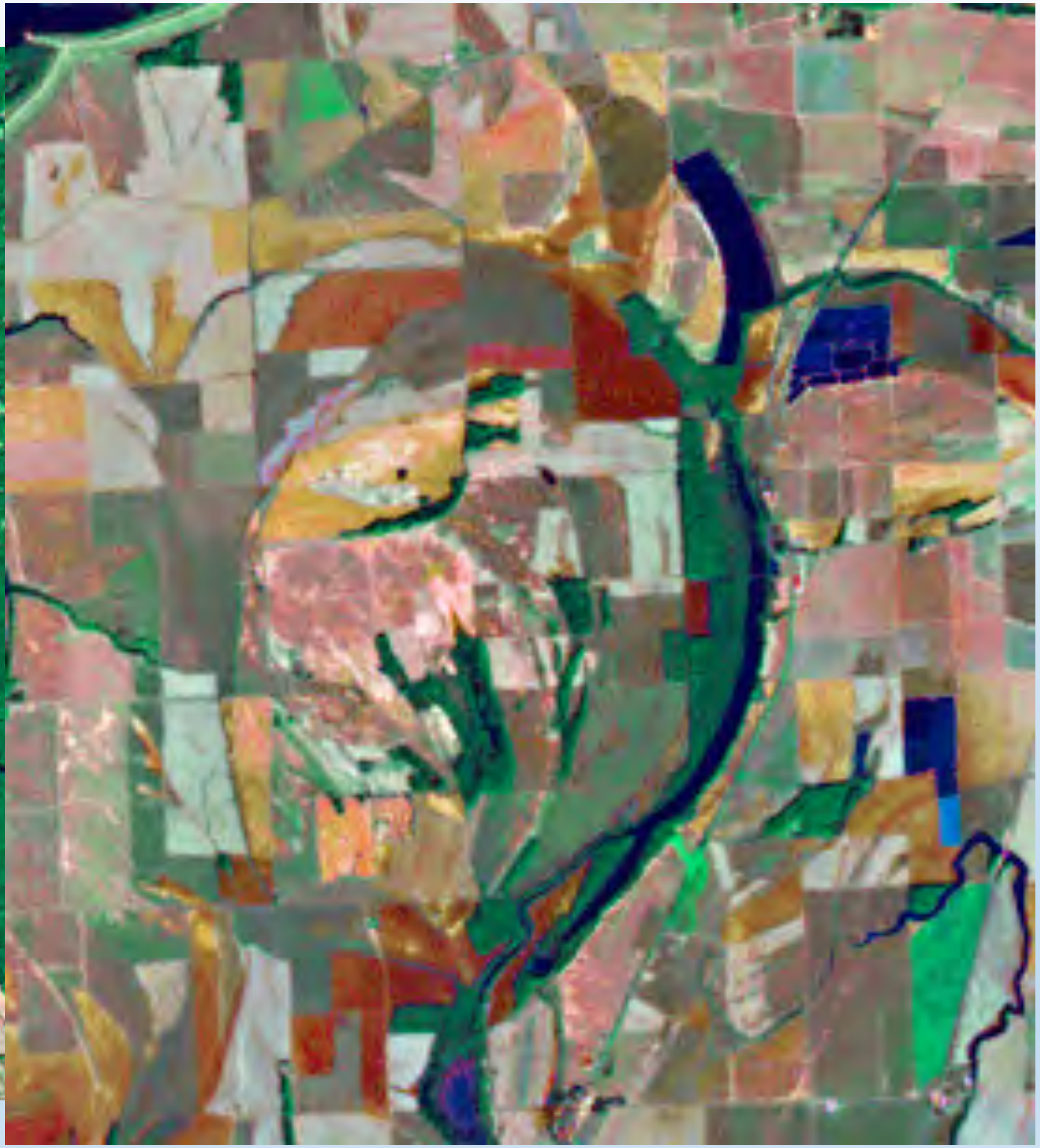
GSSI SIR-30 System



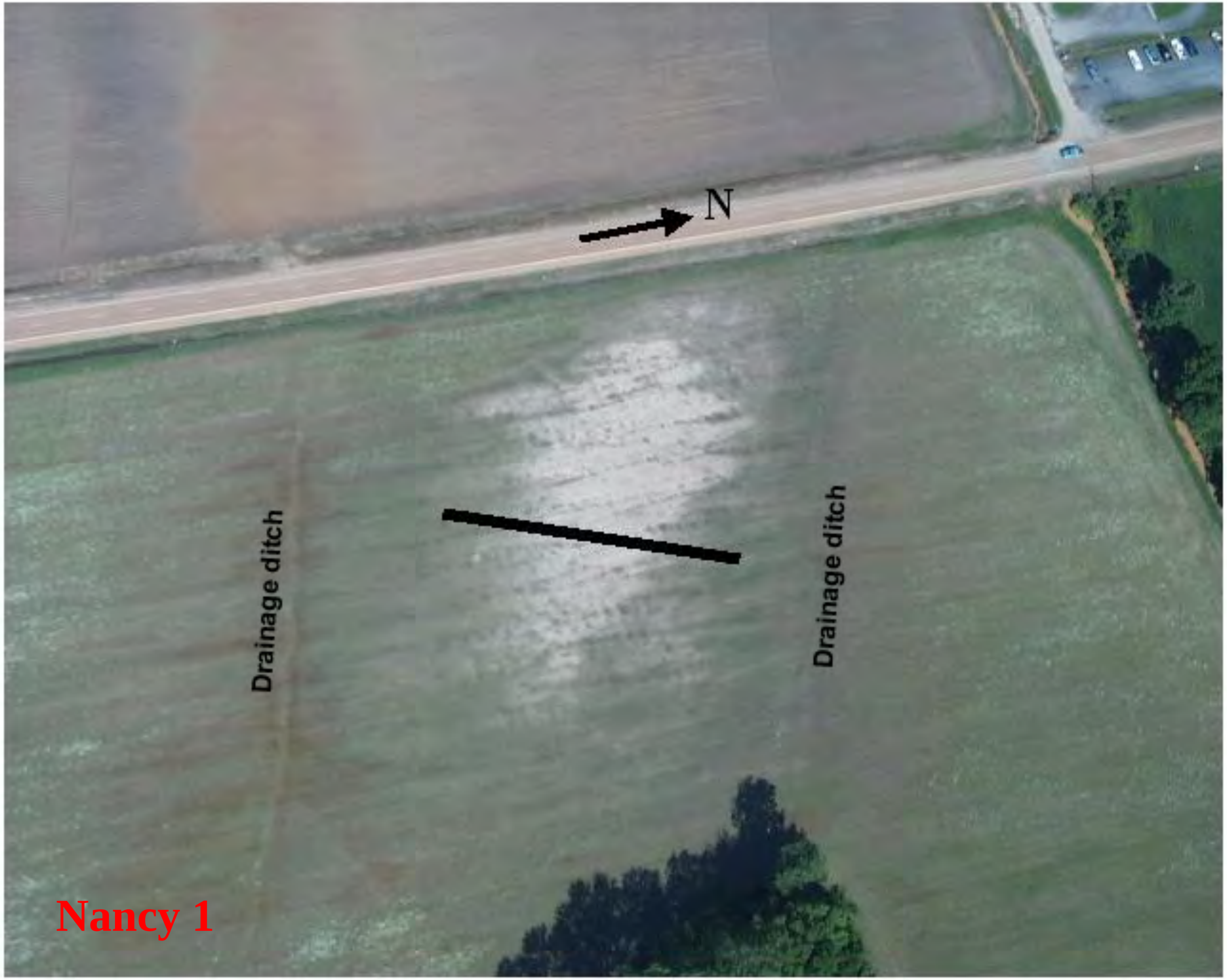
Paleoseismology of Marianna



Al-Shukri, Mahdi, Tuttle, Dyer-Williams, 2015, Final Technical Report, USGS Grant G12AP20093, 31 p.

N98502
8-36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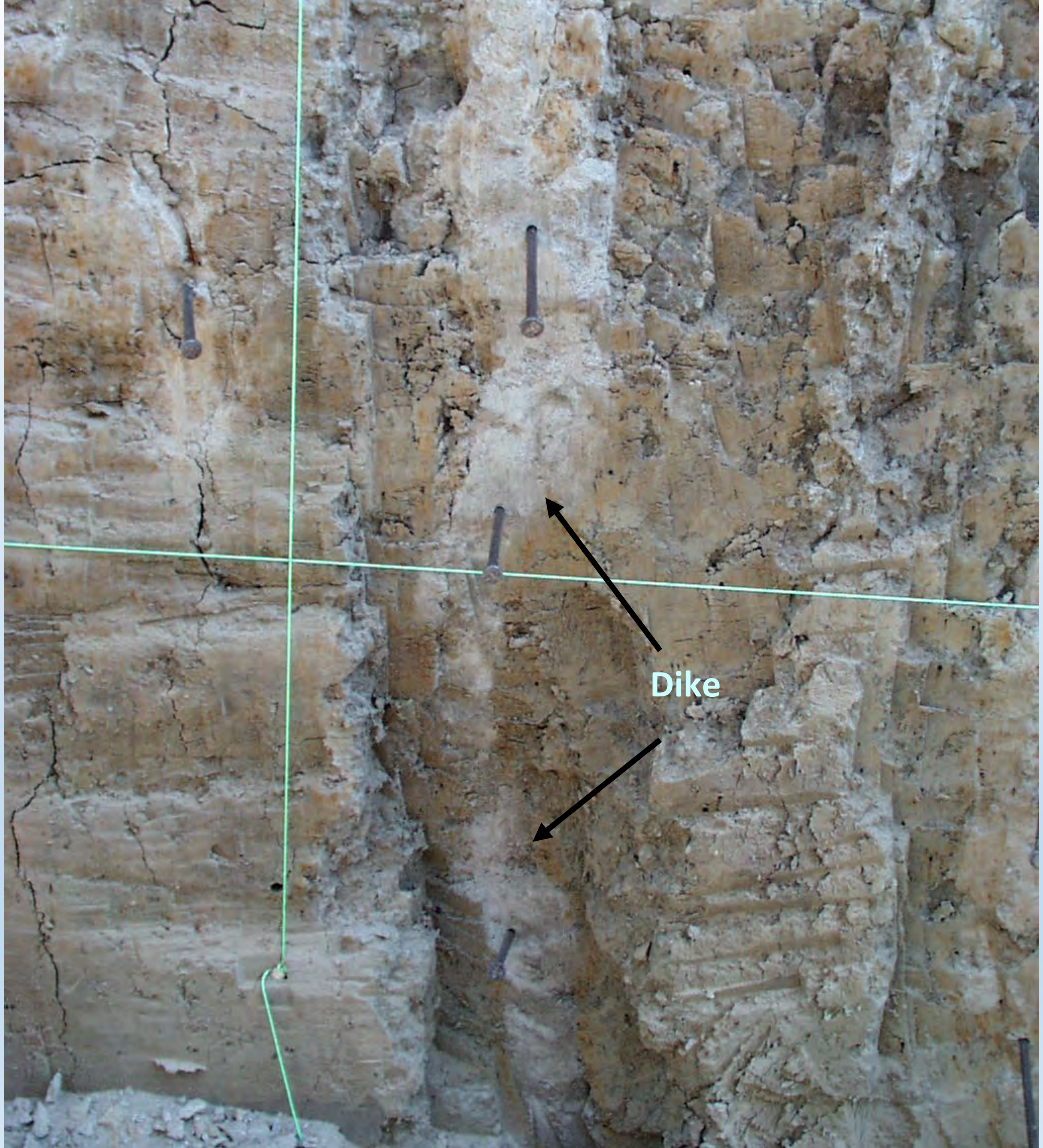
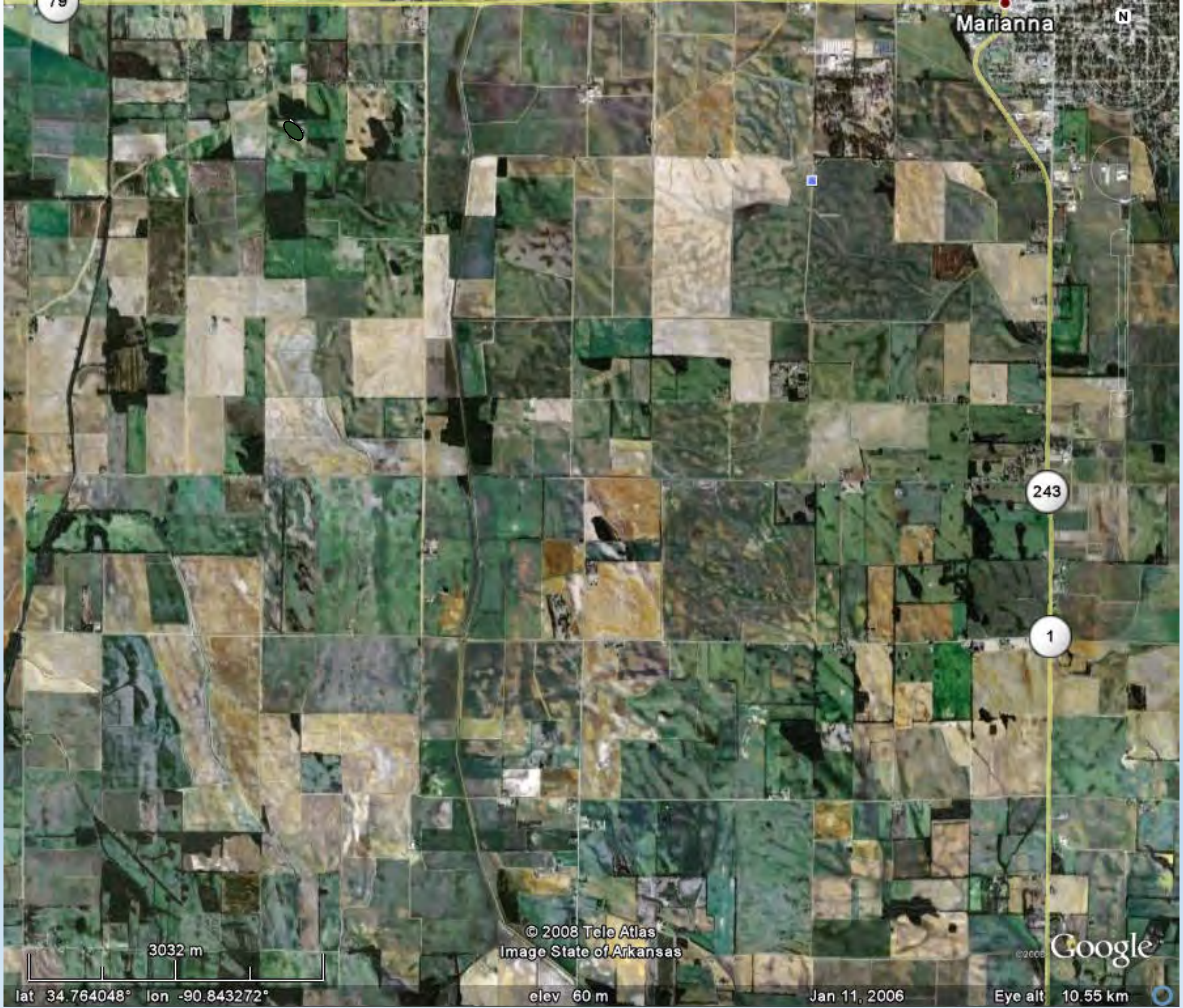
Drainage ditch
Drainage ditch
Nancy 1

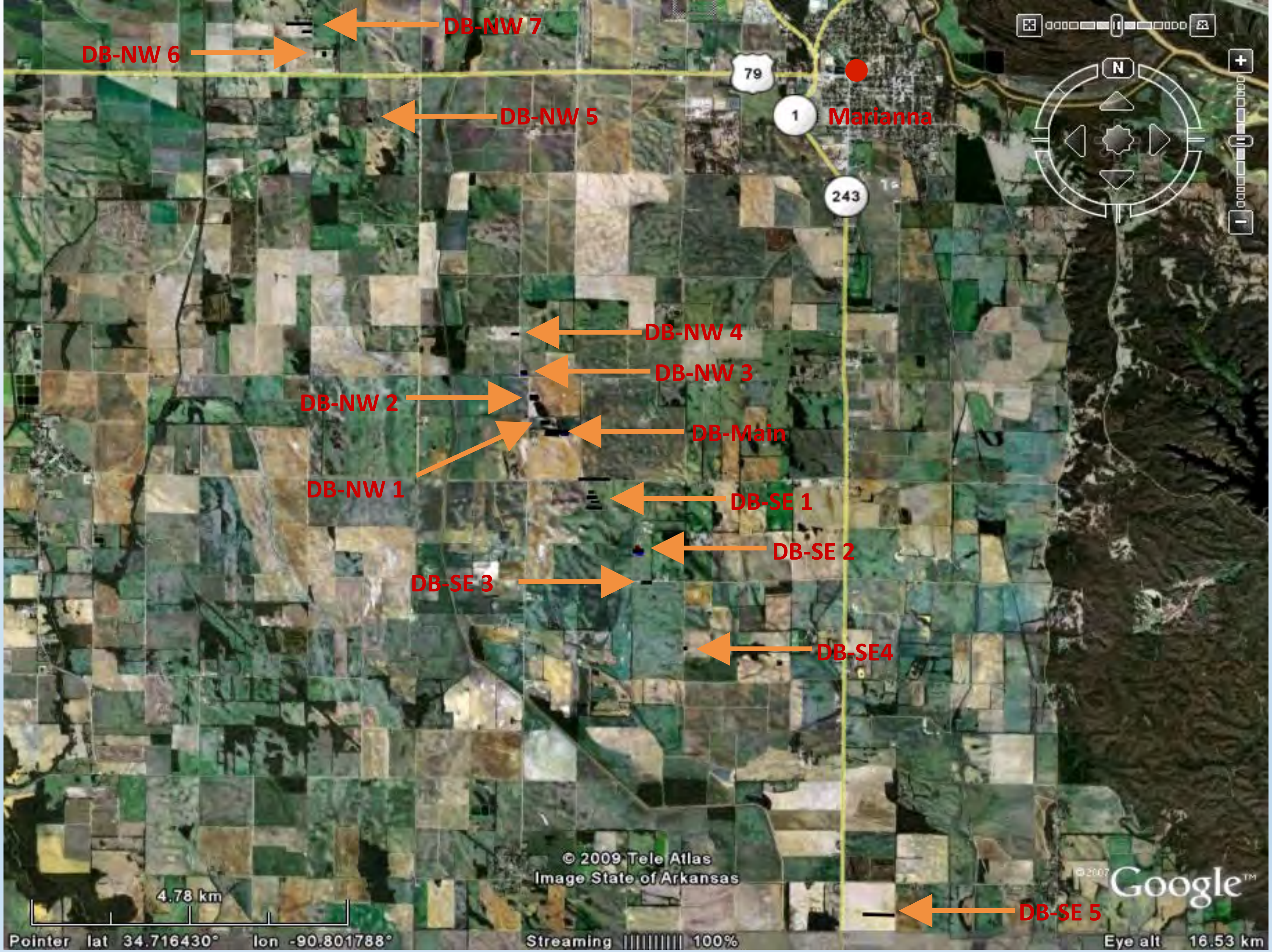

Dike


Sand
Clay
Sand
Clay

Al-Shukri, Mahdi, Al Kadi, and Tuttle, 2010, Final Technical Report, USGS Grant 07HQGR0069, 24 p.



Marianna
N
243
1
© 2008 Tele Atlas
Image State of Arkansas
3032 m
Google
lat 34.764048° lon -90.843272°
elev 60 m
Jan 11, 2006
Eye alt 10.55 km



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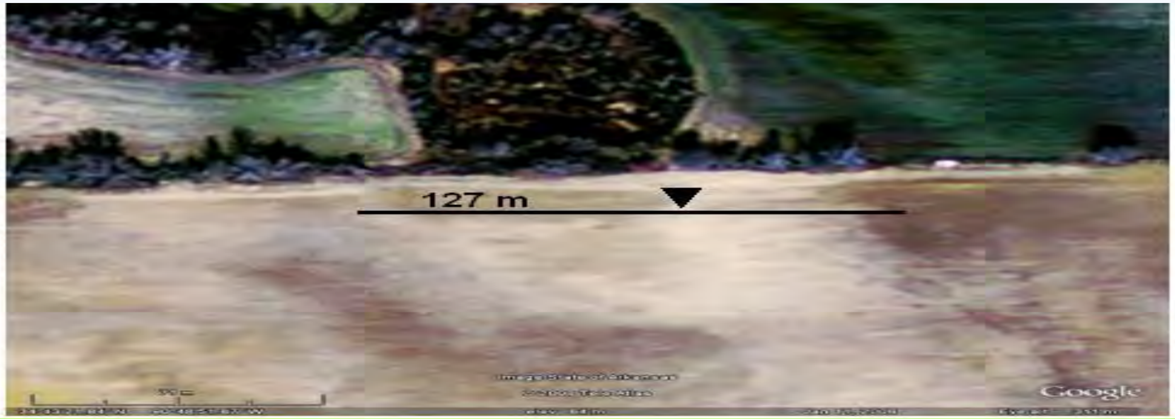
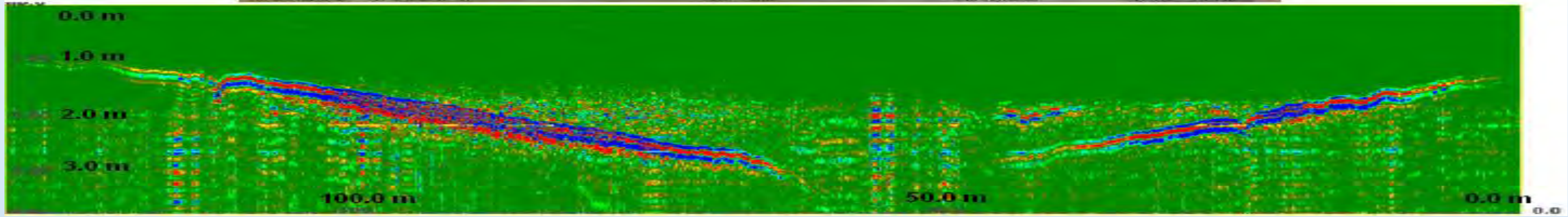




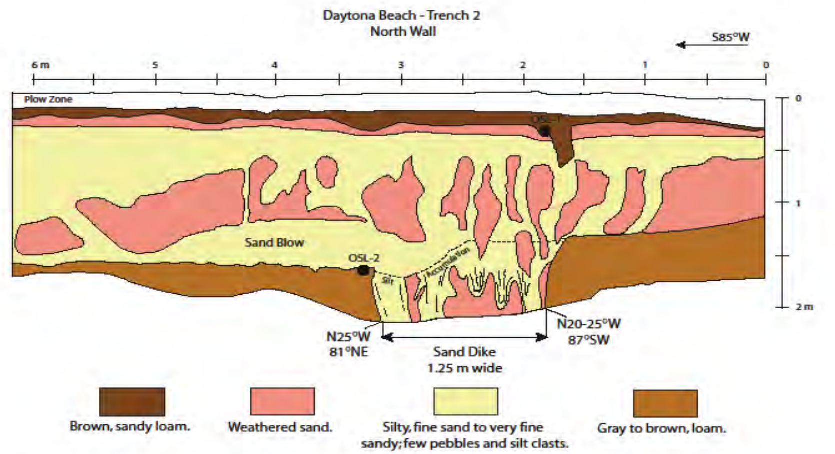
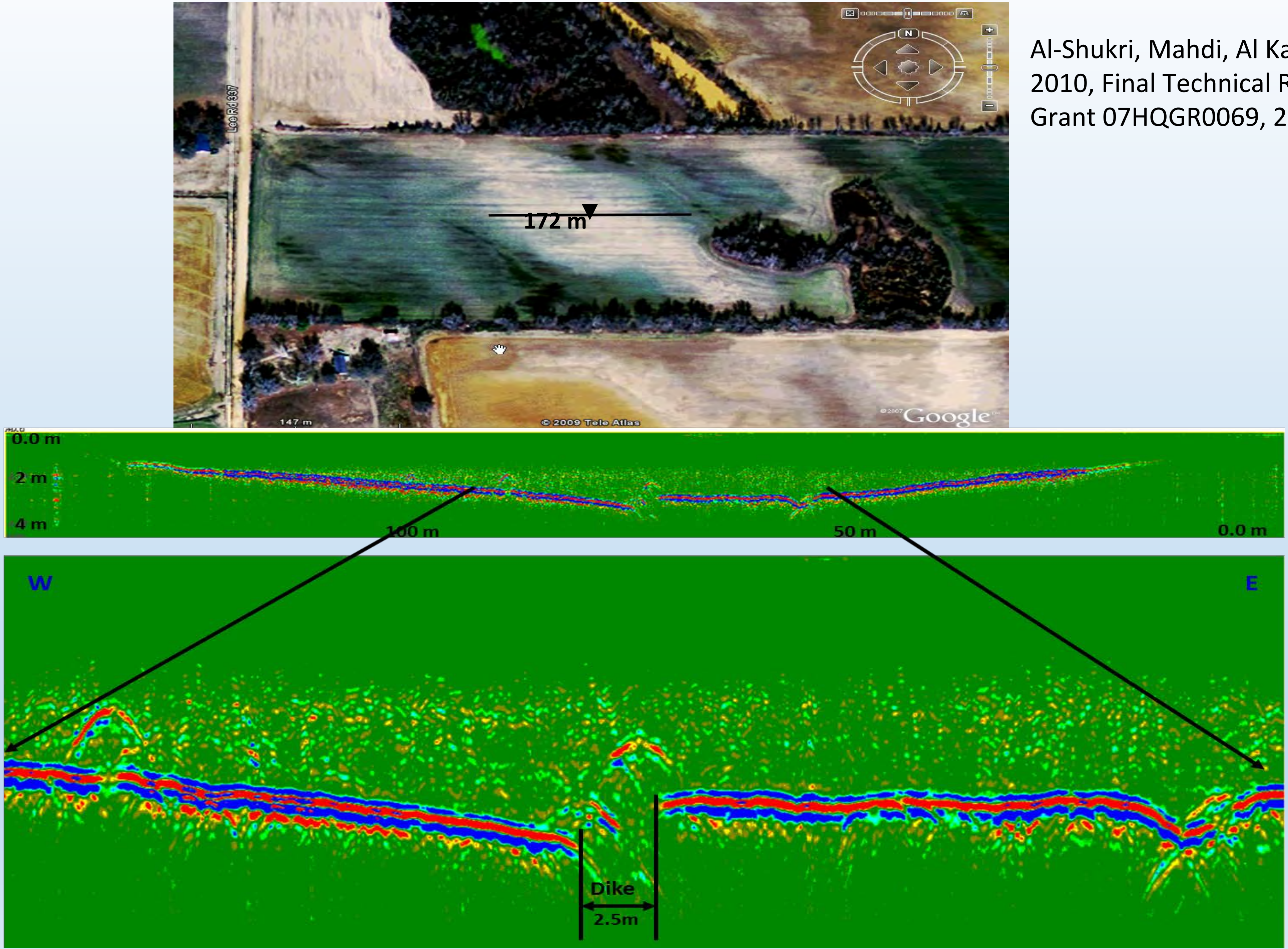


Figure Z. Log of trench 2 wall at Daytona Beach site near Marianna, Arkansas. Liquefaction-related ground failure includes formation of 1.25-m-wide sand dike and 1.45-m-thick sand blow as well as 30 cm of vertical displacement of surface soil across sand dike. Note weathering and silt accumulation in sand blow and dike. Log by M. Tuttle and H. Al-Shukri.

Tuttle, Al-Shukri, Mahdi, 2006, Seismological Research Letters



Al-Shukri, Mahdi, Al Kadi, and Tuttle, 2010, Final Technical Report, USGS Grant 07HQGR0069, 24 p.

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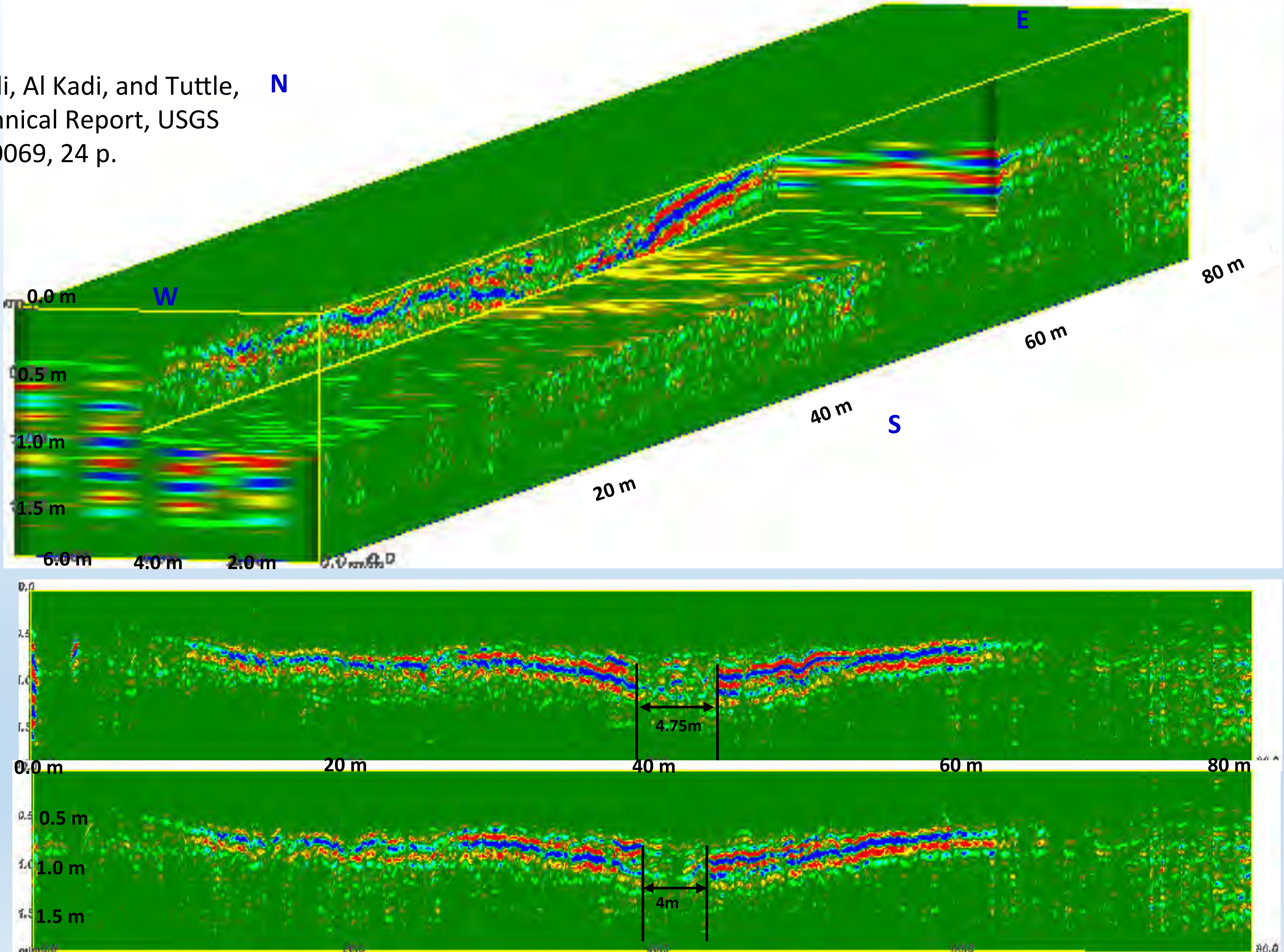
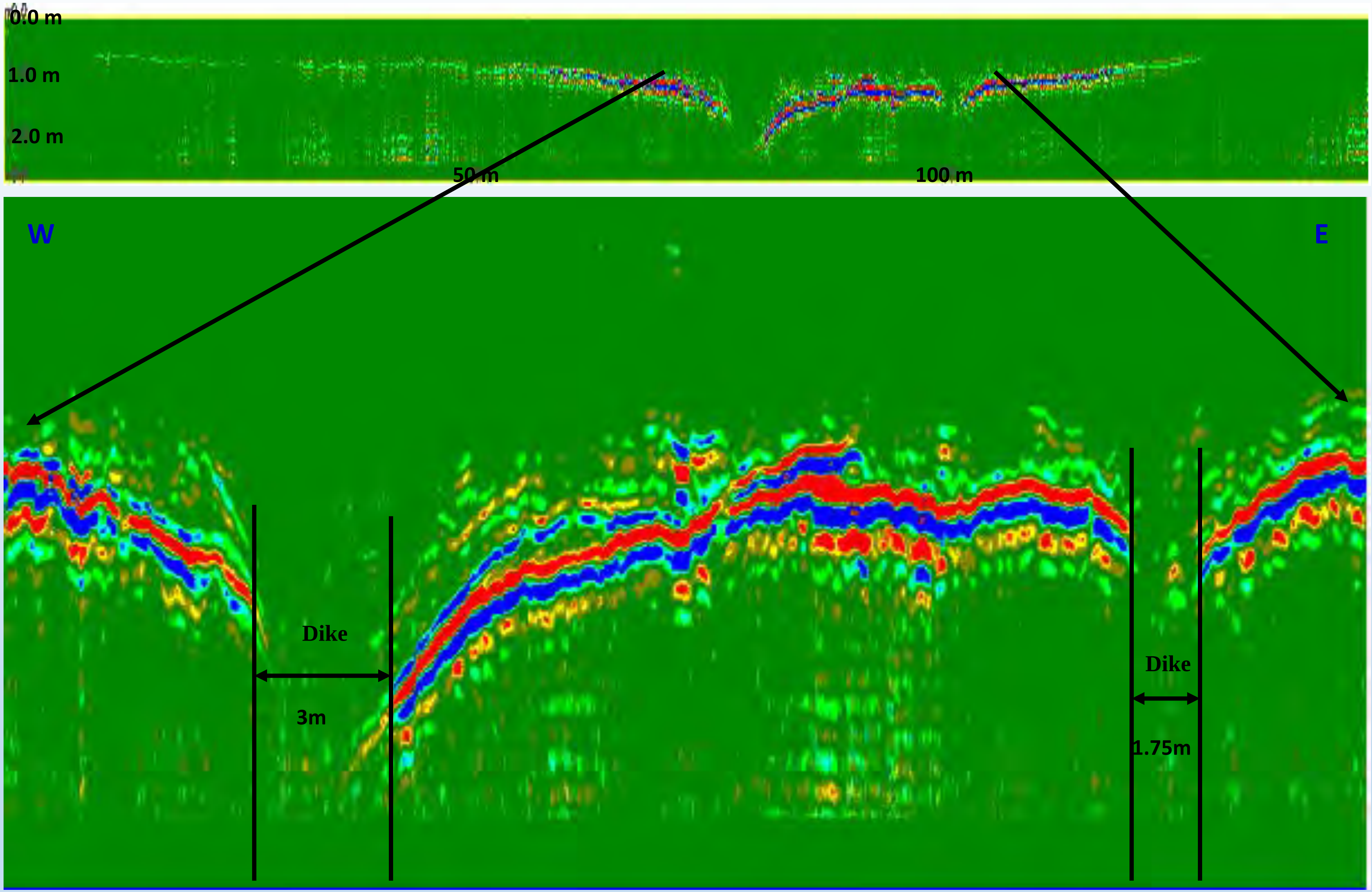



479 m
243
Key Corner Rd
N
Al-Shukri, Mahdi, Al Kadi, and Tuttle, 2010, Final Technical Report, USGS Grant 07HQGR0069, 24 p.
75 m
159 m
148m
100 m
5 m
237 m
© 2009 Tele Atlas
Image State of Arkansas
©2007 Google™
187 m
Pointer lat 34.713269° lon -90.808386°
Streaming |||||||||| 100%
Eye alt



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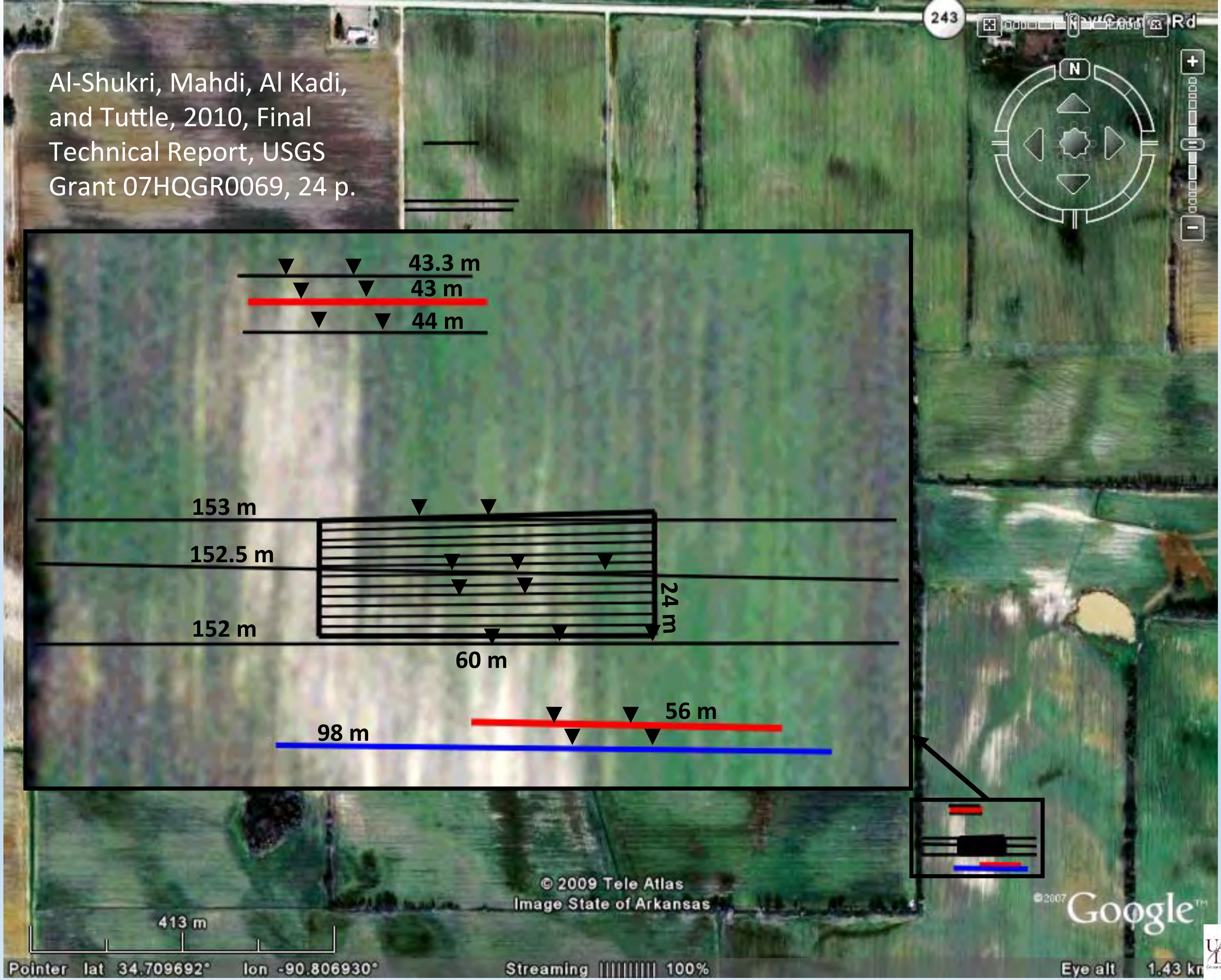
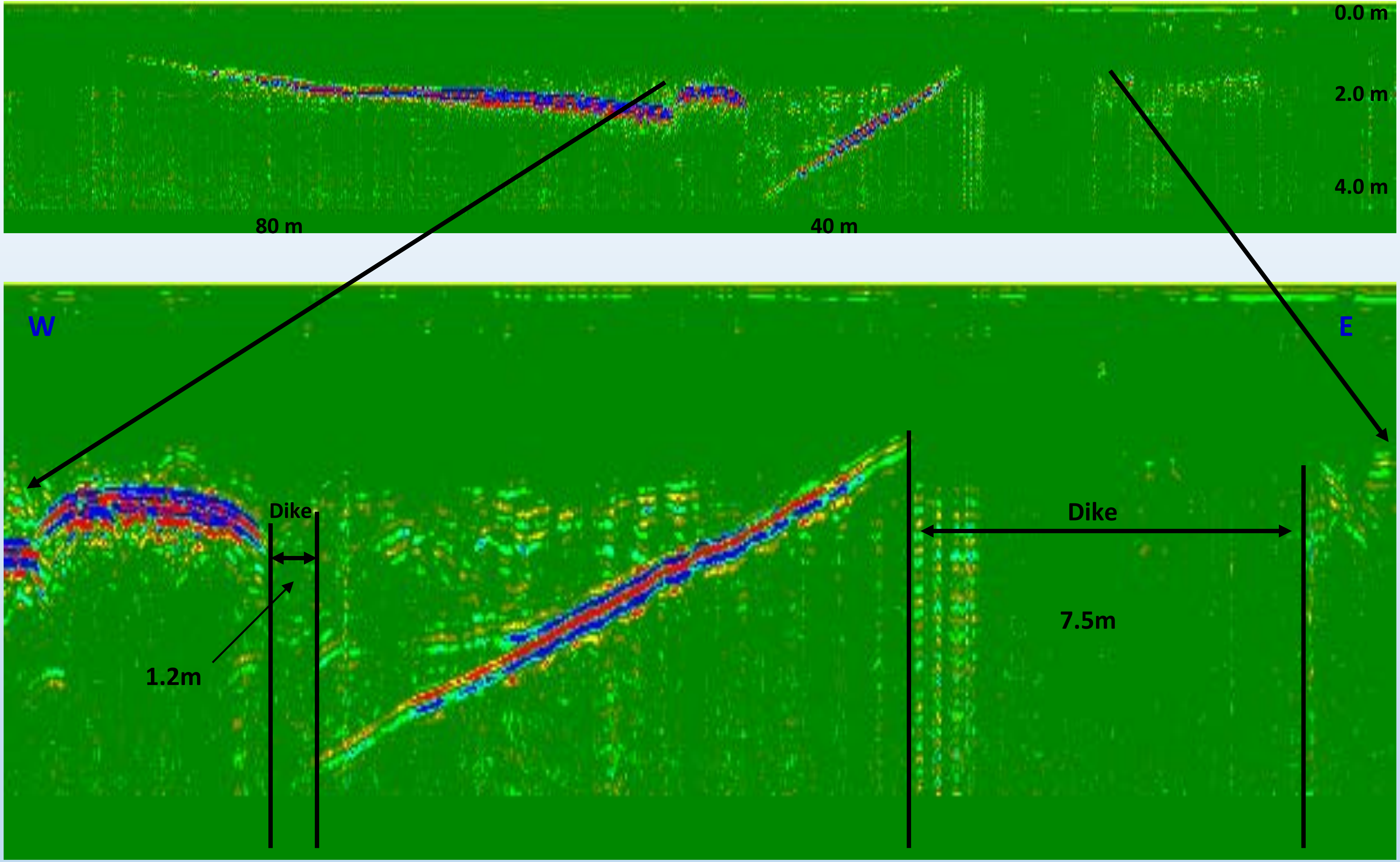


Al-Shukri, Mahdi, Al Kadi, and Tuttle, 2010, Final Technical Report, USGS Grant 07HQGR0069, 24 p.
243
N
43.3 m
43 m
44 m
153 m
152.5 m
152 m
24 m
60 m
56 m
98 m
© 2009 Tele Atlas
Image State of Arkansas
©2007 Google
413 m
Pointer lat 34.709692° lon -90.806930°
Streaming 100%
Eye alt



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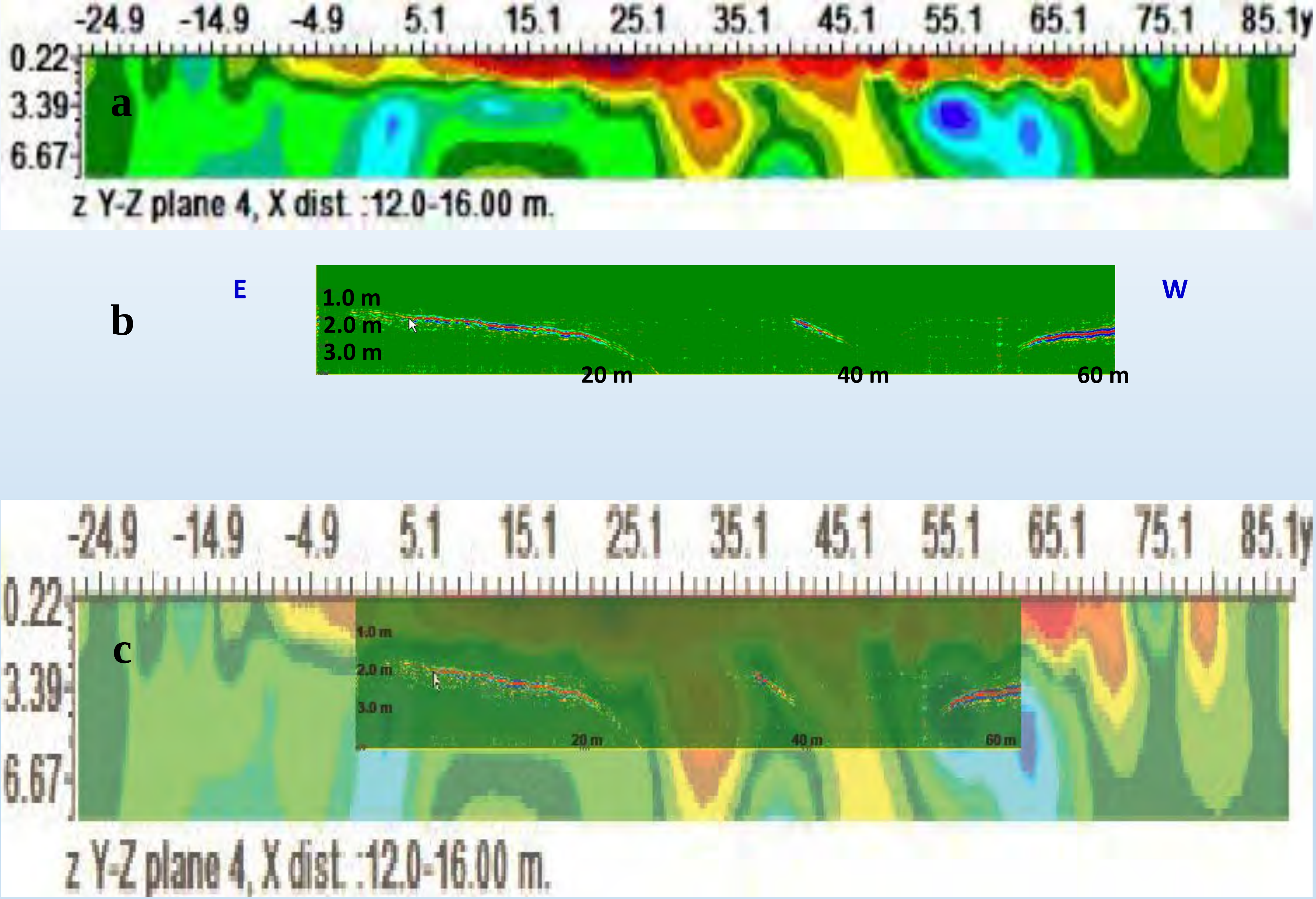

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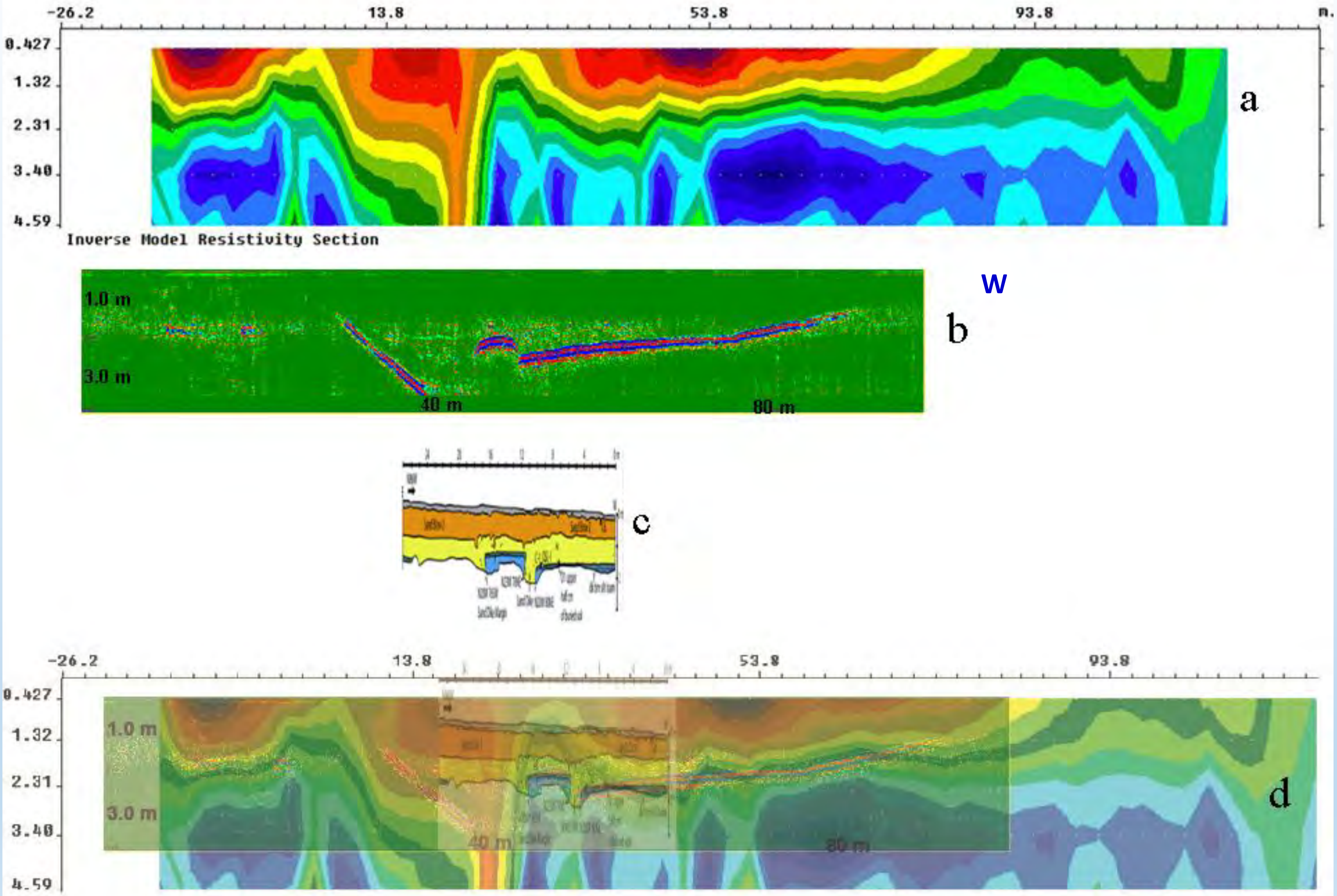

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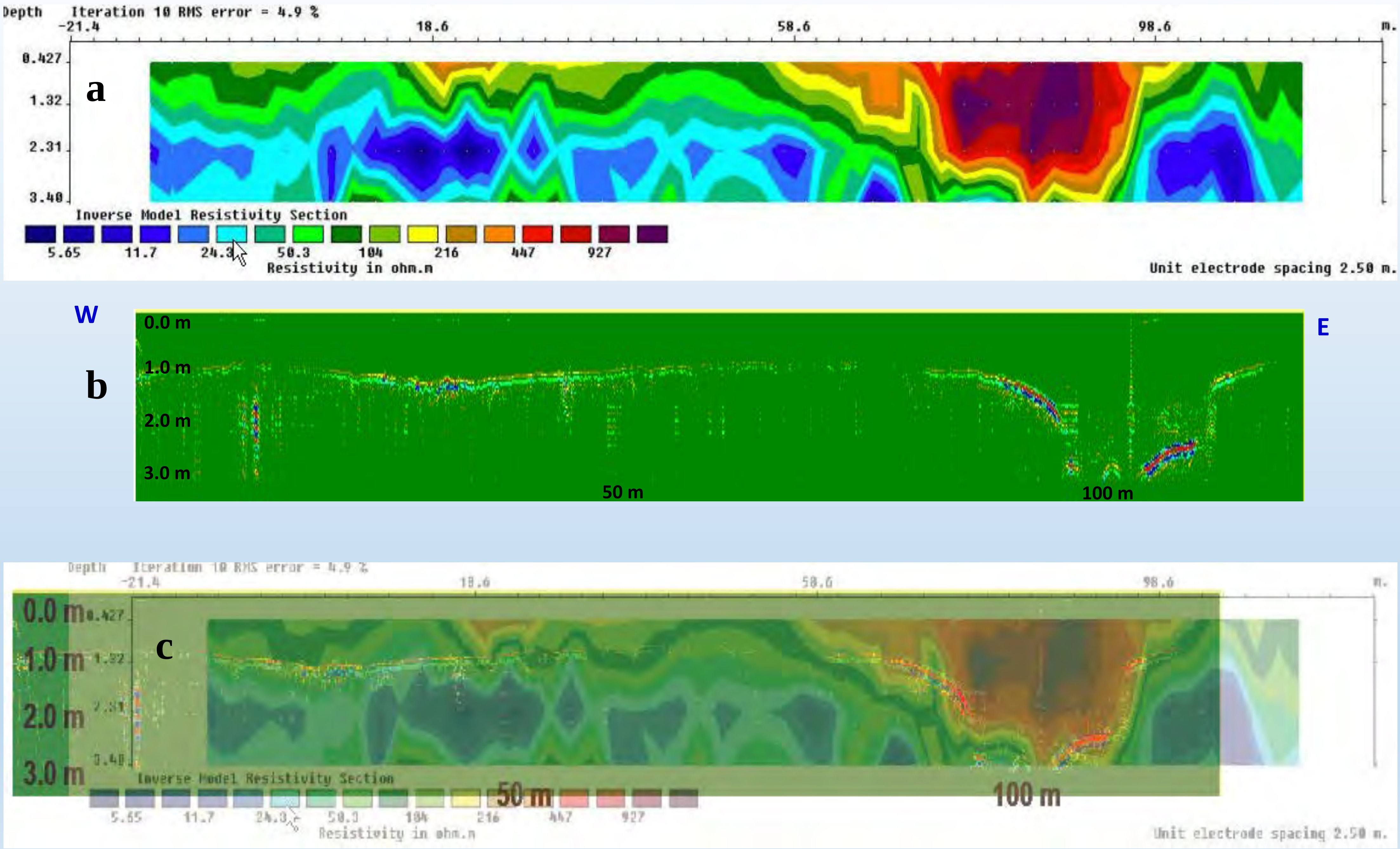

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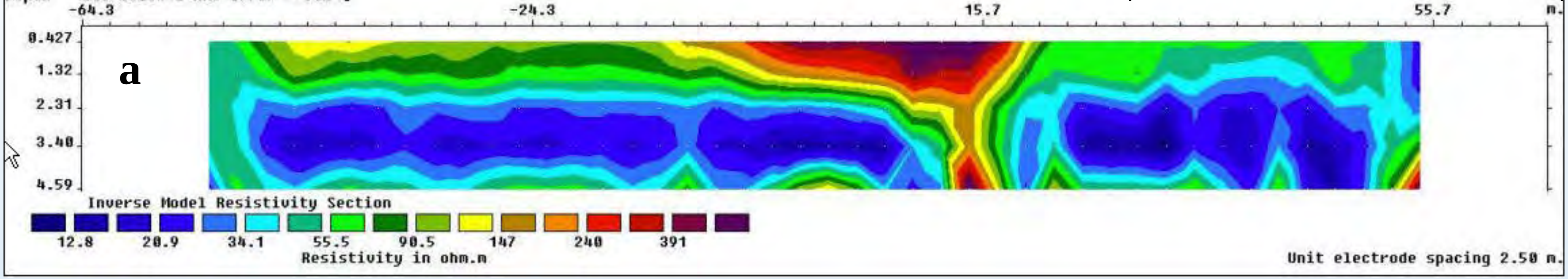

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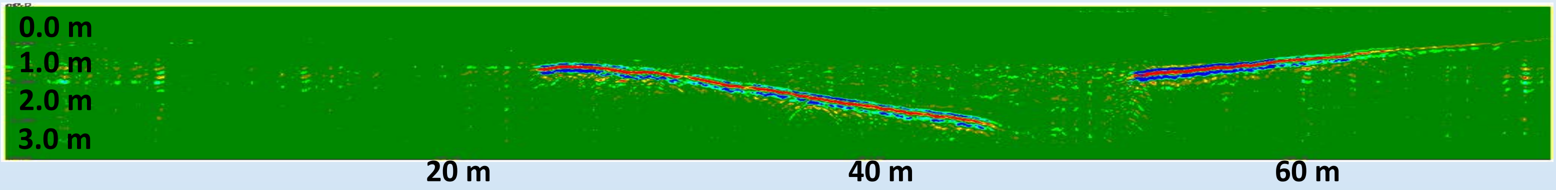

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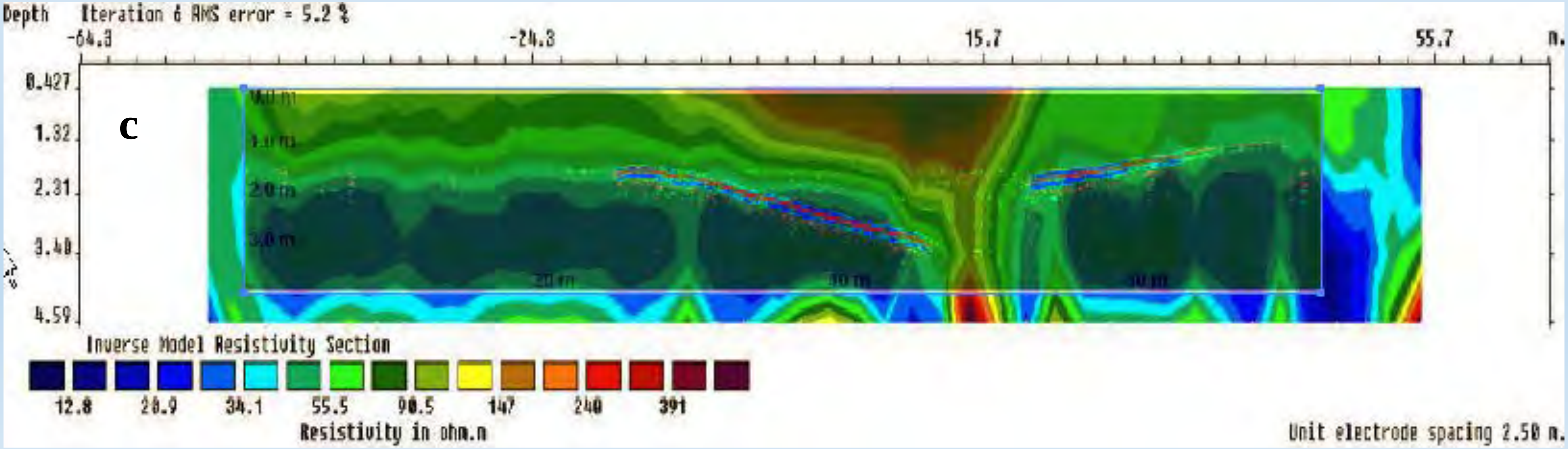

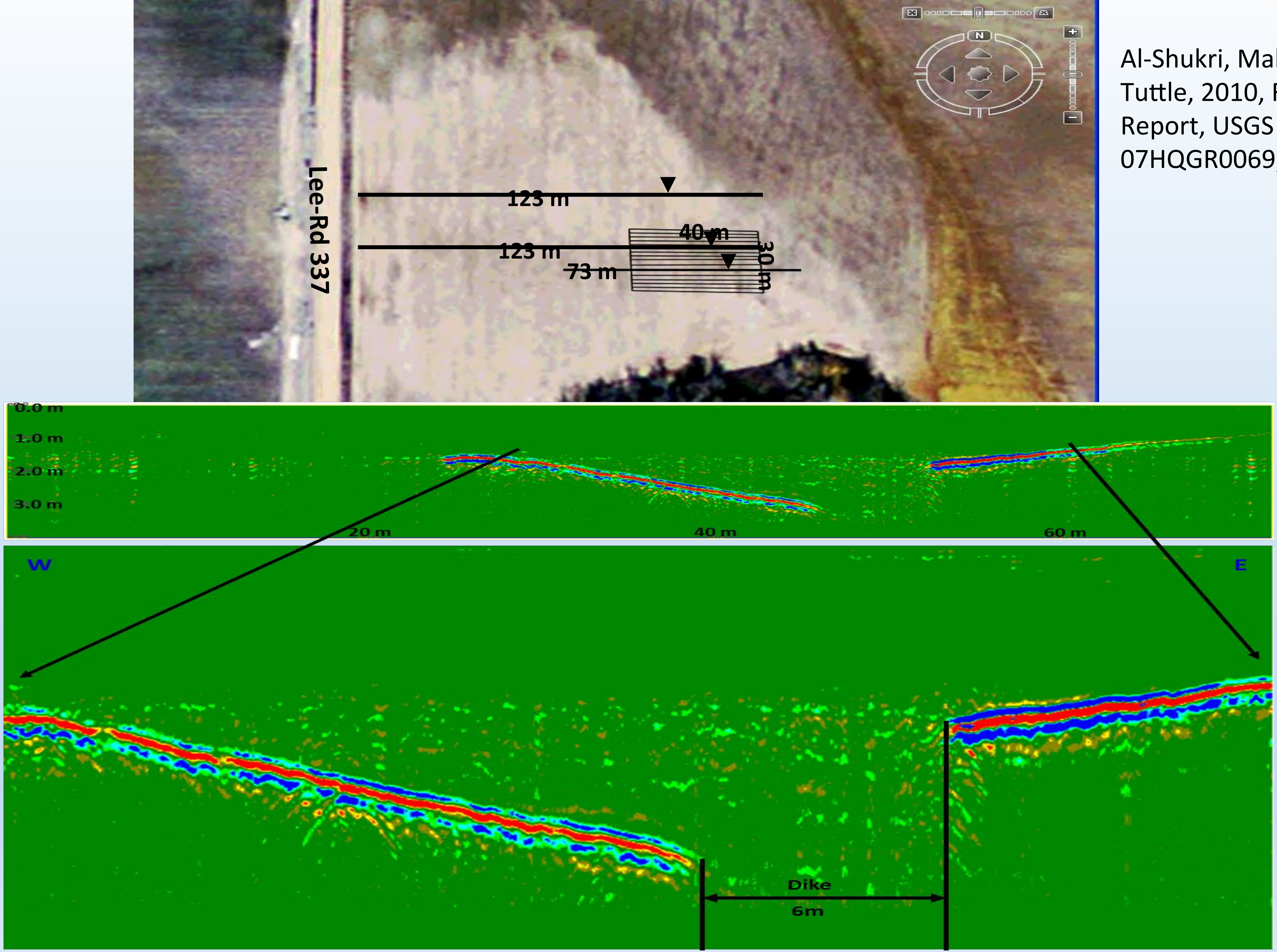

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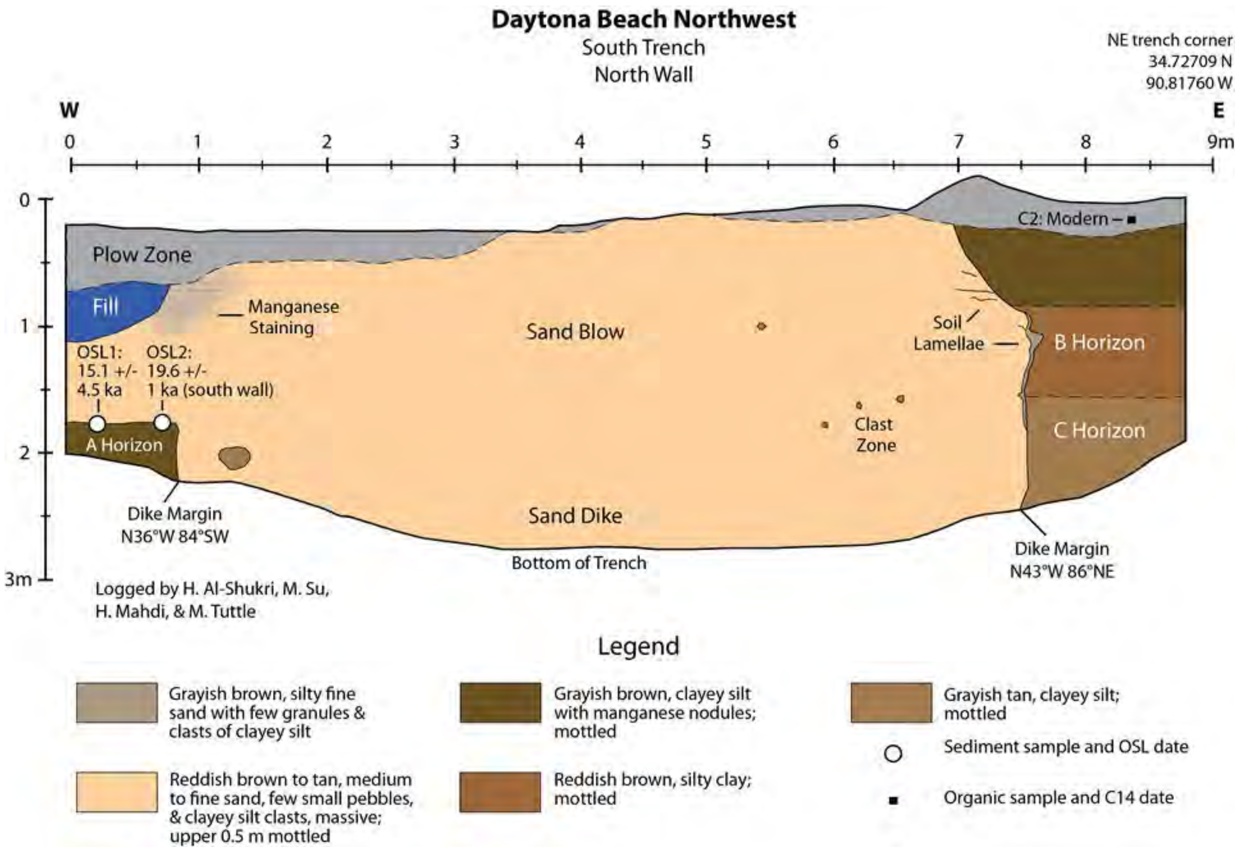

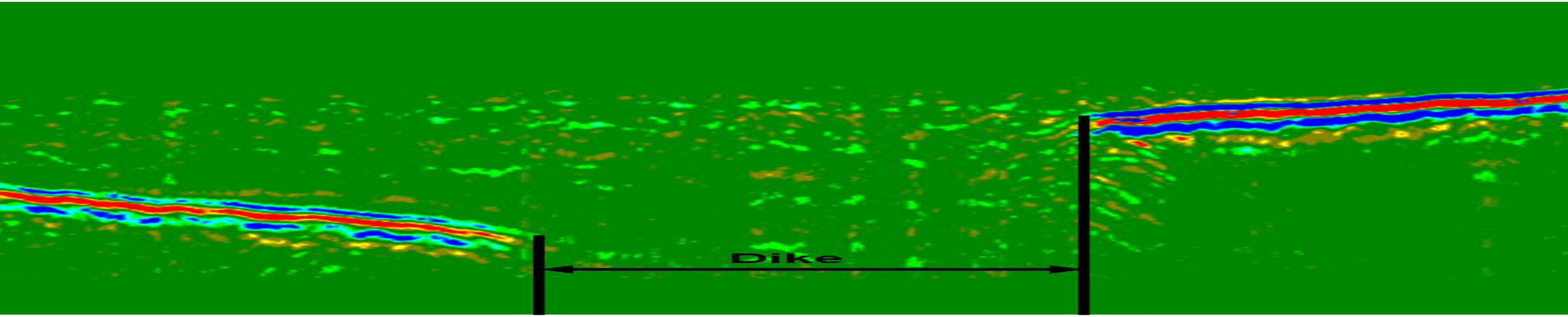

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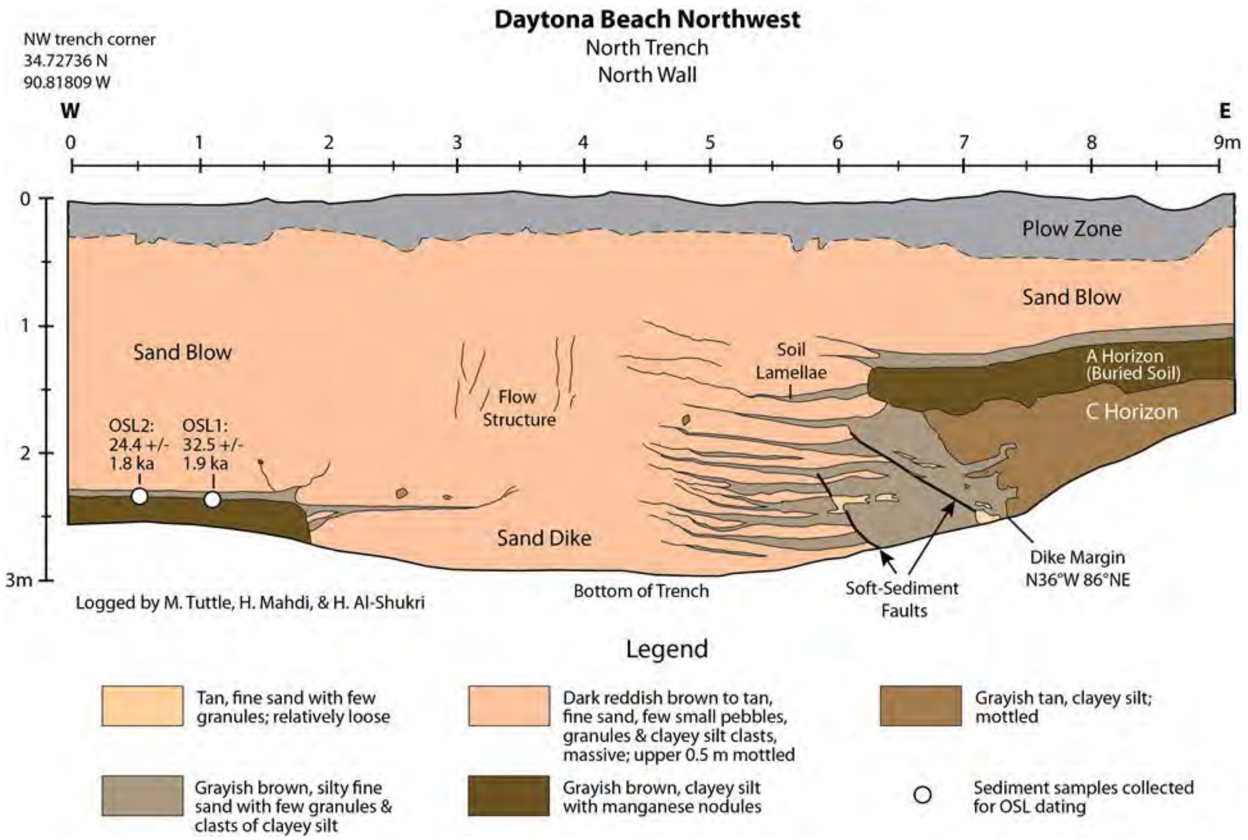

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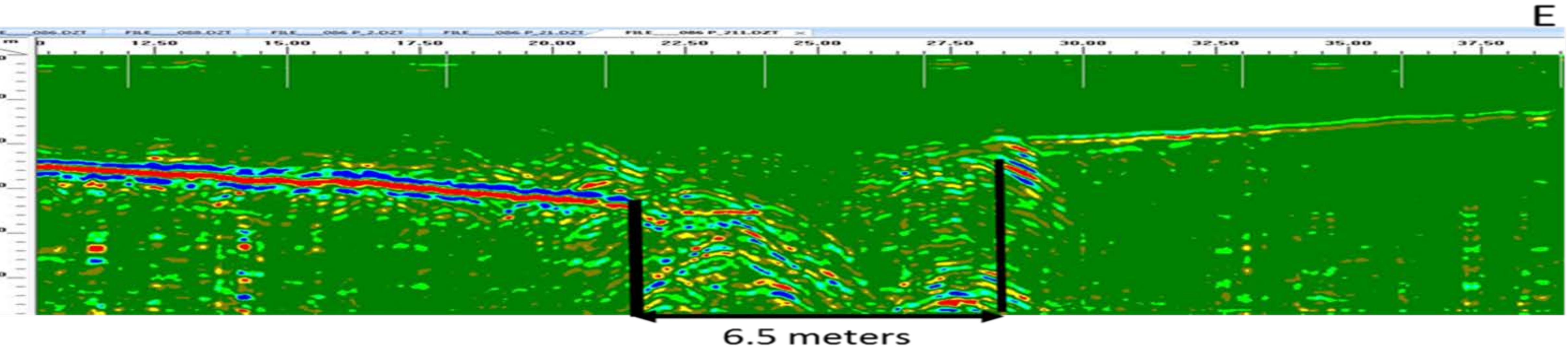

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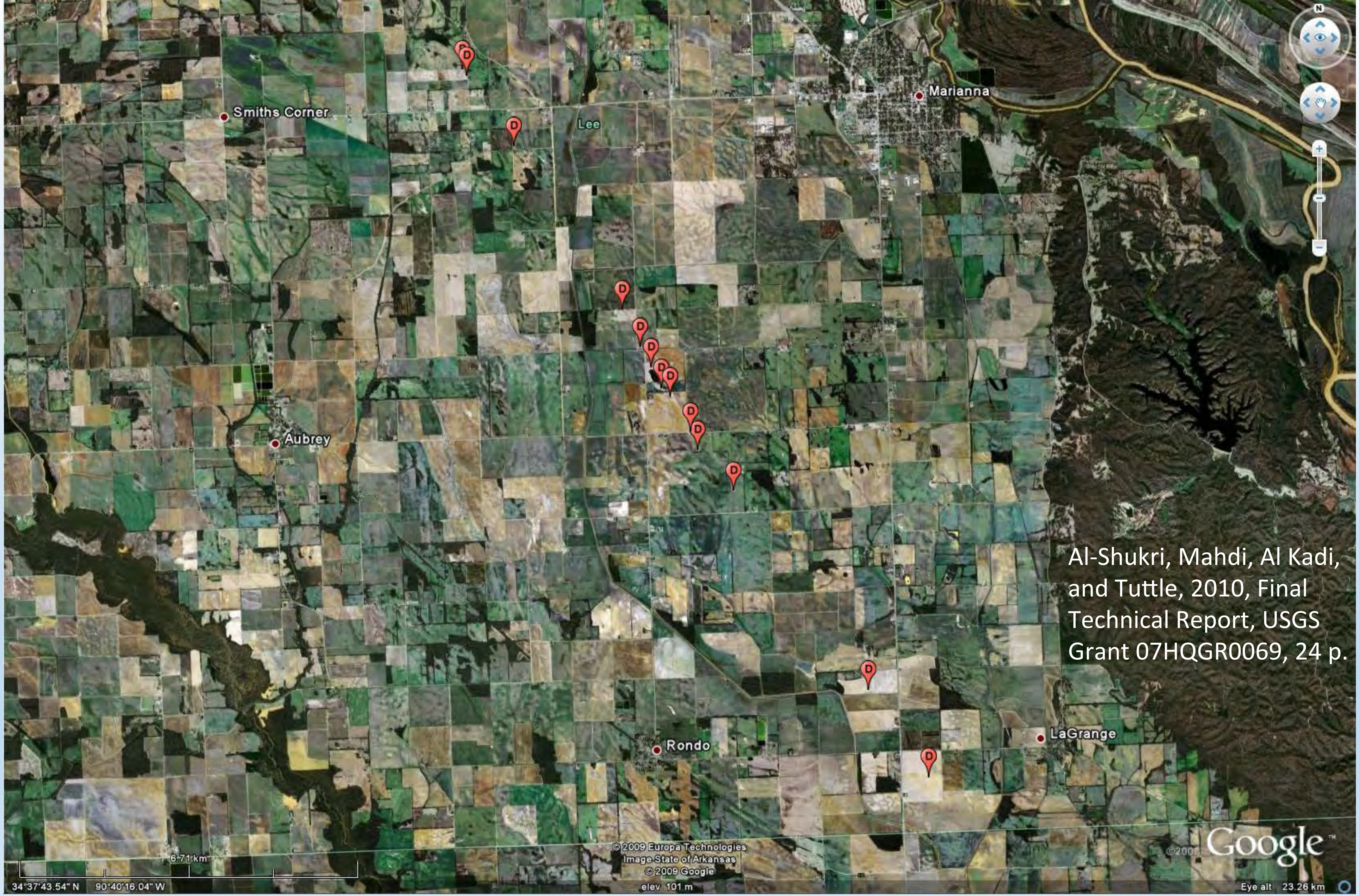

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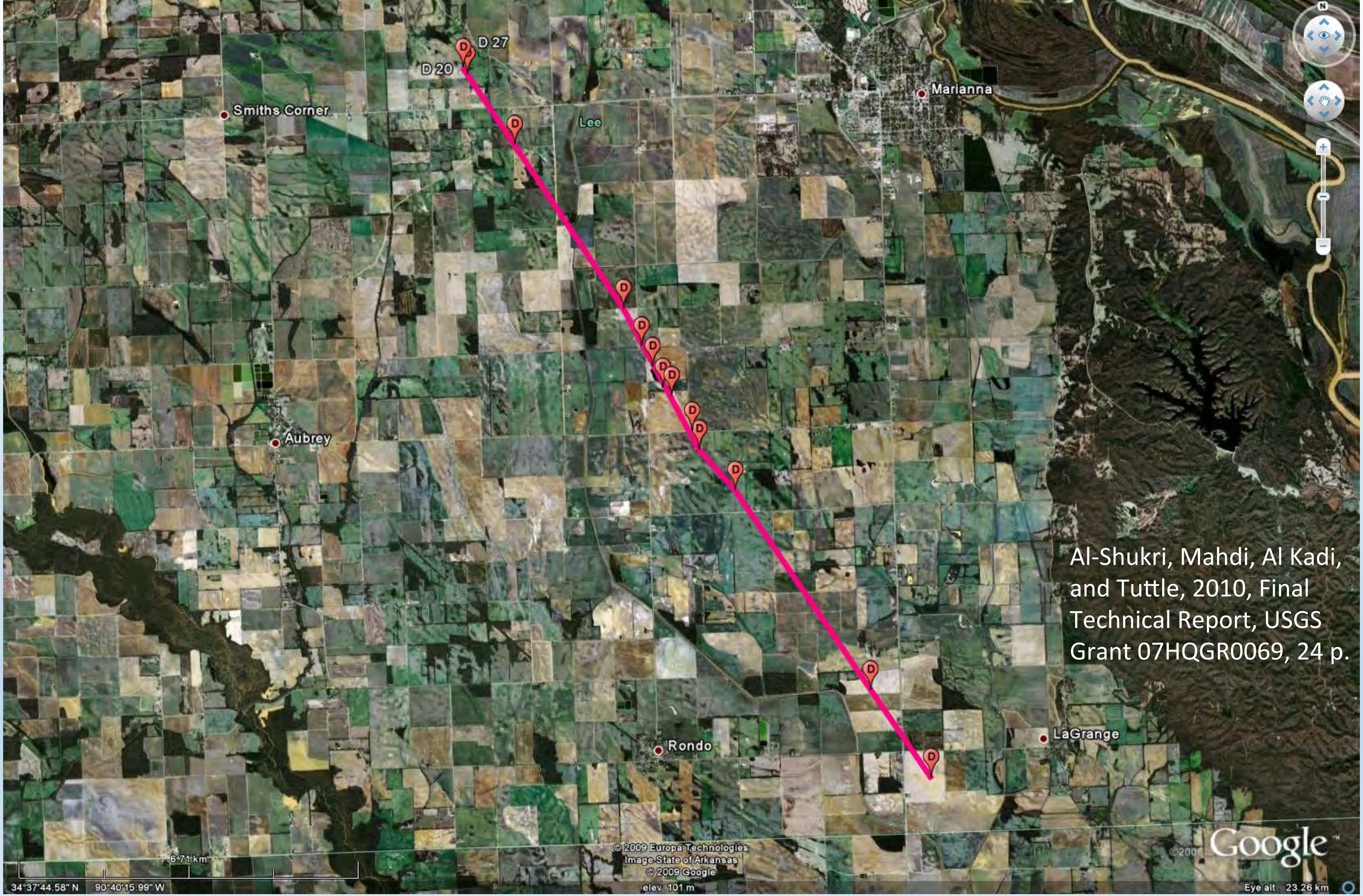

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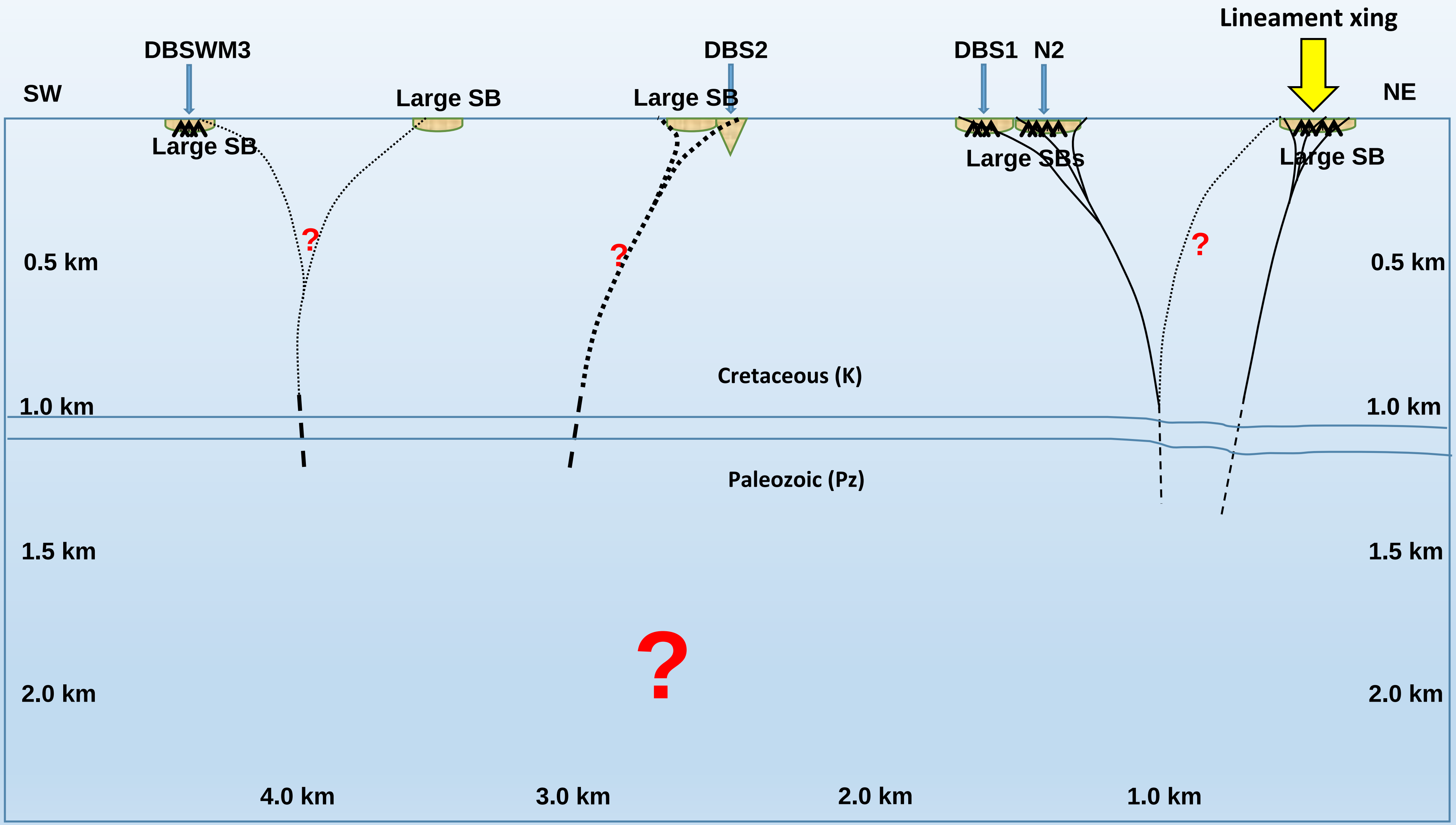

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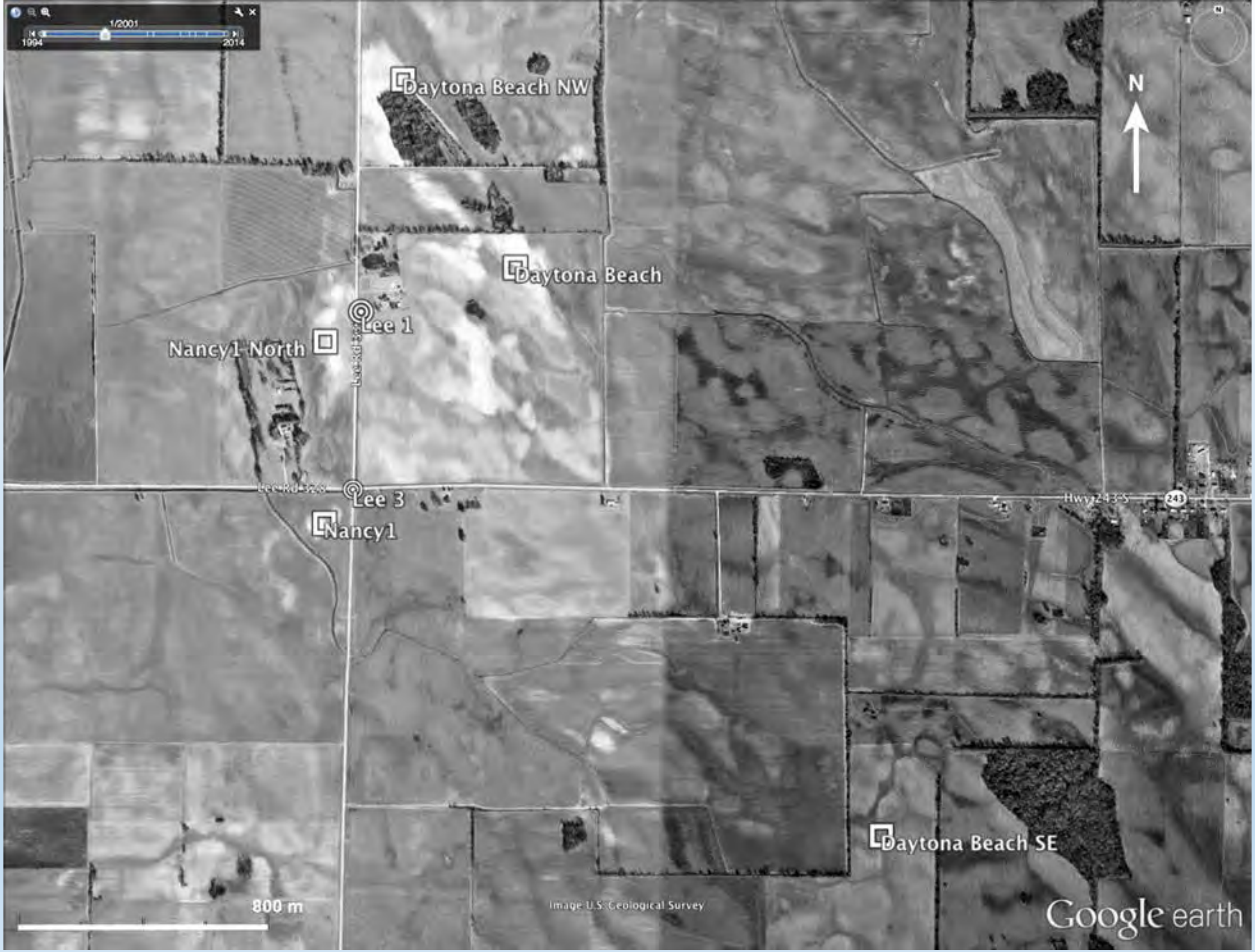


Al-Shukri, Mahdi, Tuttle, Dyer-Williams, 2015, Final Technical Report, USGS Grant G12AP20093, 31 p.

Results

- The sand blows concentrated near Marianna area
- The intensity (number and size) of sand blows reduced n all directions
- A new source zone
- Independent of the New Madrid SZ
- Has been extensively active in the past 5K years
- Our geotechnical analysis suggests that earthquakes in the M 6-6.5 range could induce liquefaction and therefore be responsible for the formation of the large sand blows.
- Several large earthquakes took place in the area
- The risk has not been evaluated yet
- The return period has not been determined and more research is need

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

NHPA, NEPA & ESA: Federal Regulations Affecting Paleoseismology Studies

Thomas Weaver, Ph.D., P.E.
US NRC

Background

- May 2011: Paleoliquefaction Project Starts
- September 2011: M. Tuttle sends letter to Arkansas SHPO, Quapaw THPO and Osage THPO regarding future trench excavations
- October 2011: Letter sent to NRC by Arkansas SHPO
- Compliance with NHPA, NEPA & ESA begins

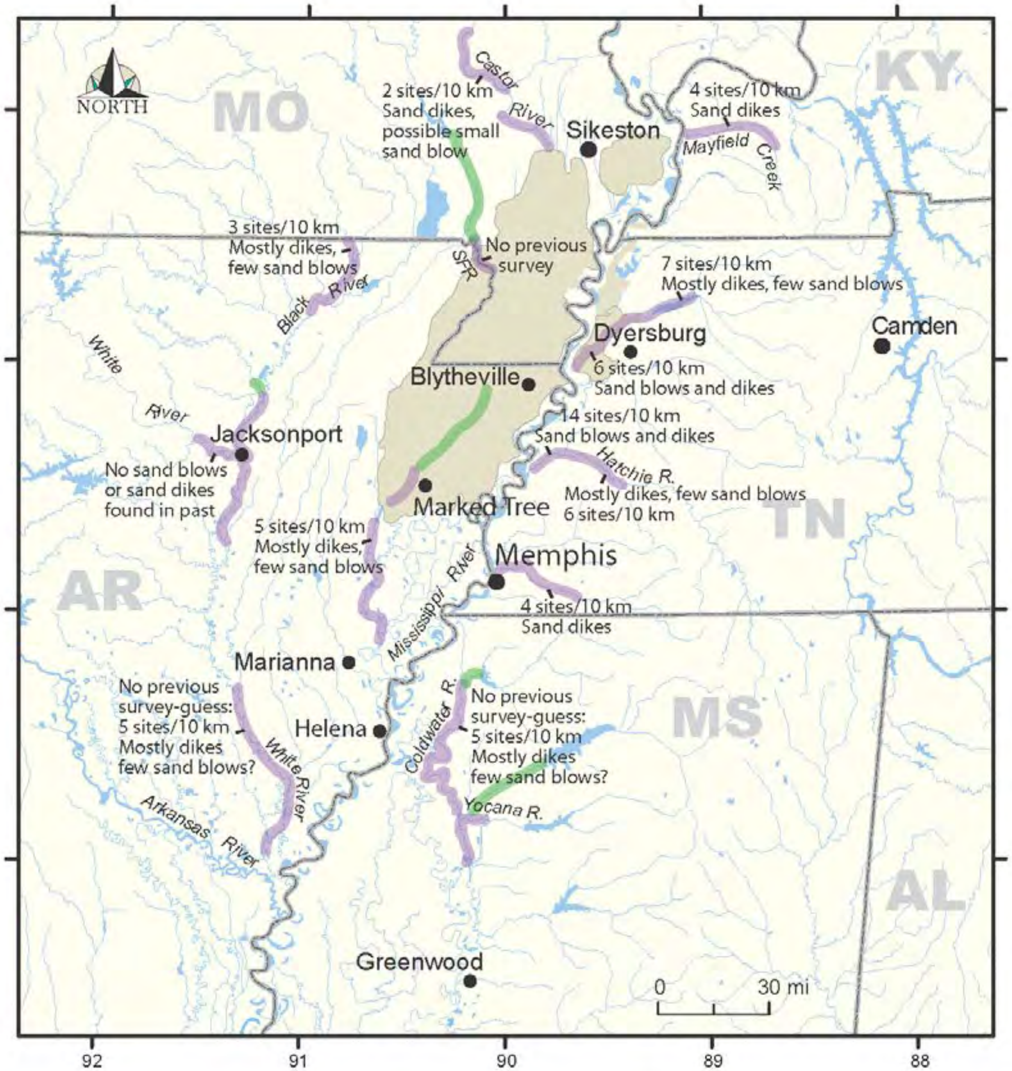
National Historic Preservation Act

- NHPA became law in 1966
  - Section 106 (54 U.S.C. 306108)
- Regulation: 36 CFR Part 800
- Applicable when:
  - Federal agency undertaking, and
  - Potential for undertaking to affect properties in or eligible for listing in the National Register for Historic Places

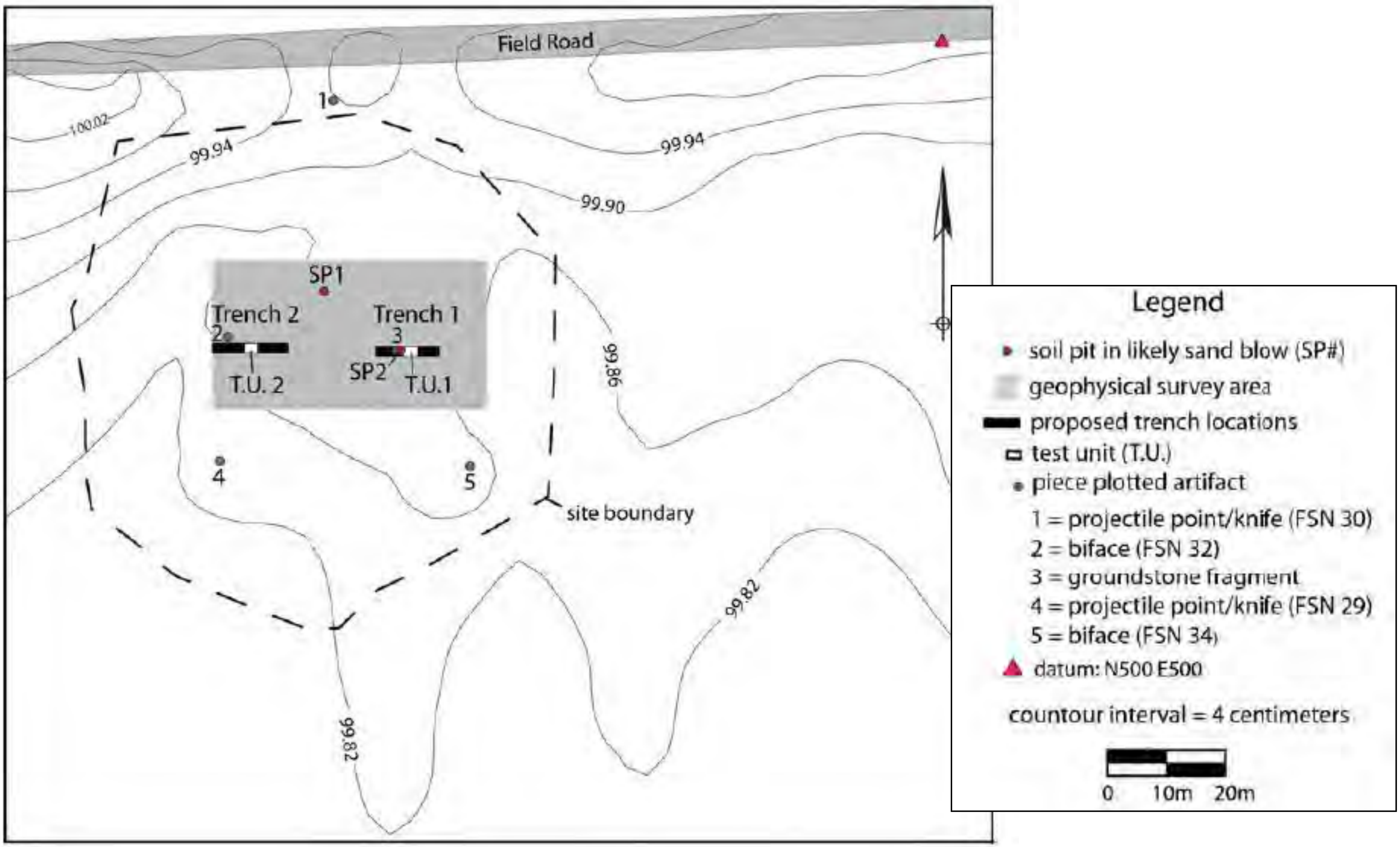
Experience with Section 106 Process

- Define scope of work and identify area of potential effects
- Informal consultation with SHPOs
- Complete evaluation of potential for activity to cause adverse effects to historic property
- Official correspondence with SHPOs and THPOs
  - SHPOs and THPOs have 30 days to respond
- Memorandum of Agreement for sites with historic property

APE for River Reconnaissance



Site Evaluation for Trenches



Experience with Section 106 Process

- River reconnaissance
  - Will not cause adverse effect on historic property
  - Communicate with SHPO and THPOs, allowing state and tribes to comment
- Trenches
  - Perform detailed site evaluation
  - Provide SHPOs and THPOs with letter including NRC's National Register Evaluation Recommendation and Finding of Effect

National Environmental Policy Act

- NEPA became law in 1970
  - 42 U.S.C. Chapter 55 Sections 4321 – 4370
  - Section 102: requires federal agencies to incorporate environmental considerations
- Regulation
  - 40 CFR Part 1500 – 1508
  - 10 CFR Part 51
    - 10 CFR 51.22: Categorical Exclusion
    - 10 CFR 51.30: Environmental Assessment
    - 10 CFR 51.33: Finding of No Significant Impact

NEPA Experience/Process

- Evaluate environmental impacts
- Prepare Environmental Assessment
  - Document impacts to historical and cultural resources (106 process)
  - Document compliance with ESA
  - Consider alternatives (e.g. “No-Action”)
  - Finding of no significant impact
- OGC Concurrence Required
- Federal Register Notice

Endangered Species Act

- ESA became law in 1972
  - 16 U.S.C. 1531 - 1544
  - Section 7 (16 U.S.C. 1535), Requires Federal agencies to consult with U.S. Fish and Wildlife Services and National Marine Fisheries Service
- Consultation with USFWS
  - Phone call followed up by email correspondence
  - U.S. Fish and Wildlife Service's Information for Planning and Conservation (IPaC) tool (https://ecos.fws.gov/ipac)
  - Note to file on our endangered species review (make publicly available in ADAMS)

Notes to Remember

- Federal agency, NRC, is responsible for complying with NHPA, NEPA, and ESA
- Contractor needs to be aware of process and requirements to provide information to NRC
- Keep a record of NHPA, NEPA, and ESA related calls
- Archeologists and environmental scientists needed to evaluate data and conclude “no adverse effects” or “no significant impact”. NRC staff or contractors (e.g. PNNL).

Notes to Remember

- Plan for at least 3 minimum from time 106 letters sent to SHPOs and THPOs until EA notice published in Federal Register
- Place documents in Public ADAMS
  - Letters to and from SHPOs and THPOs
  - Correspondence with USFWS and other federal agencies (e.g. email correspondence)
  - Keep a record of all accession numbers for future reference in EA
- Redaction process

Path Forward

- Continue with current process
  - Section 106 Process
  - Consultation with USFWS
  - Develop EA
- Categorical Exclusion
  - Requires rulemaking

Resources

- NRC
  - OGC
    - Joan Olmstead: NHPA and Section 106 expertise
    - Andy Pessin: NEPA expertise
  - NMSS, Federal State and Tribal Liaison Branch
    - Stuart Easson
  - NRO
    - Jennifer Davis, Archeologist
  - RES
    - Thomas Weaver and Sarah Tabatabai
- Contractors
  - Pacific Northwest National Laboratory, Tara O'Neil

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

M. TUTTLE & ASSOCIATES
Specializing in Paleoseismology and Seismic Hazard Assessment

Georgia Institute of Technology

Seismic Geotechnics

NRC Paleoliquefaction Training Workshop

Paul W. Mayne, PhD, P.E.

Blytheville, AR - 11 Nov 2015

Seismic Geotechnics - Overview

- Seismic Ground Hazards
- Soil Behavior and Laboratory Studies
- Site Response and Ground Motions
- Soil Liquefaction Evaluation of Sands (Simplified Cyclic Stress-Based Approach)
- In-Situ Tests: SPT, CPT, DMT, V_s
- Competing Methods: NCEER vs. UCD vs. UCB vs. J&B
- Seismic Piezocone Tests (SCPTu) at Paleoliquefaction Sites in *New Madrid Seismic Zone*

High Levels of Ground Shaking

Mexico City Earthquake, 1985

Excessive Levels of Ground Shaking

2011 Earthquake M = 5.8 - Mineral, Virginia

scitechdaily.com

Haiti Earthquake - 12 Jan 2010

Christchurch, New Zealand - Sept 2010

Chile - 27 Feb 2010

Nakaminato, Japan - 11 March 2011

Seismic Ground Hazards

- Loss of Life & Injury
- Heavy ground shaking
- Bearing Capacity Failure
- Settlement & Subsidence
- Flow Failures (Dams, Reservoirs, Embankments; Flooding)
- Lateral Spreading (Slopes, Docks, Walls)
- Sand boils, dikes, sills, fissures, and vents.

Copper River
Alaska
Nov 2002

Ahmedabad
India
Jan 2001

Shrinkansen
HS rail
Japan
Oct 2004

Seismic Ground Hazards

Haiti 2010 (courtesy Univ. Idaho)

Bearing Capacity and Foundation Failures

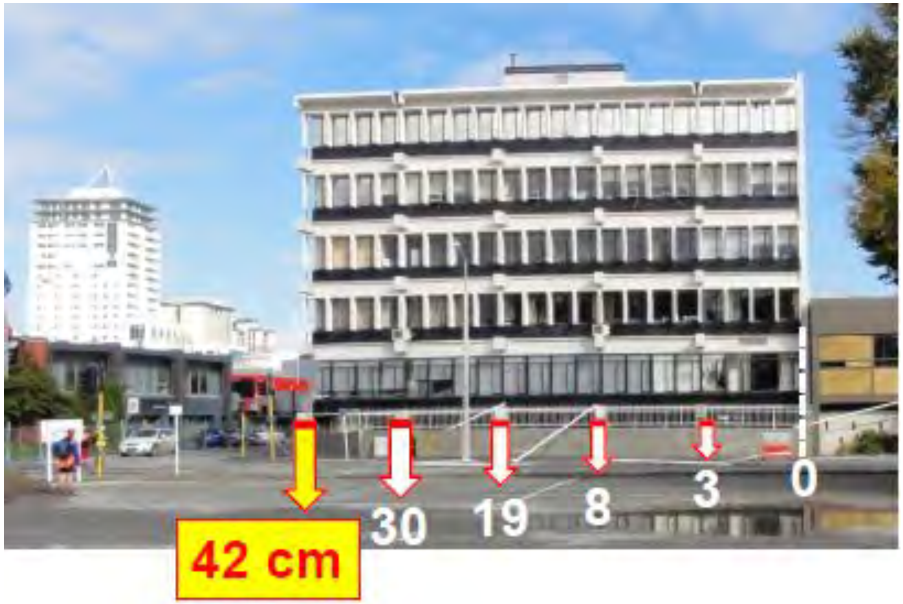
Chi-Chi, Taiwan 1999

Ismit, Turkey 1999

Seismic Ground Hazards

Subsidence and Settlement

Christchurch 2011 (Green, et al 2013)



Tohoku Japan 2011

1-m settlement - Wanigawa Water Plant Japan 2011

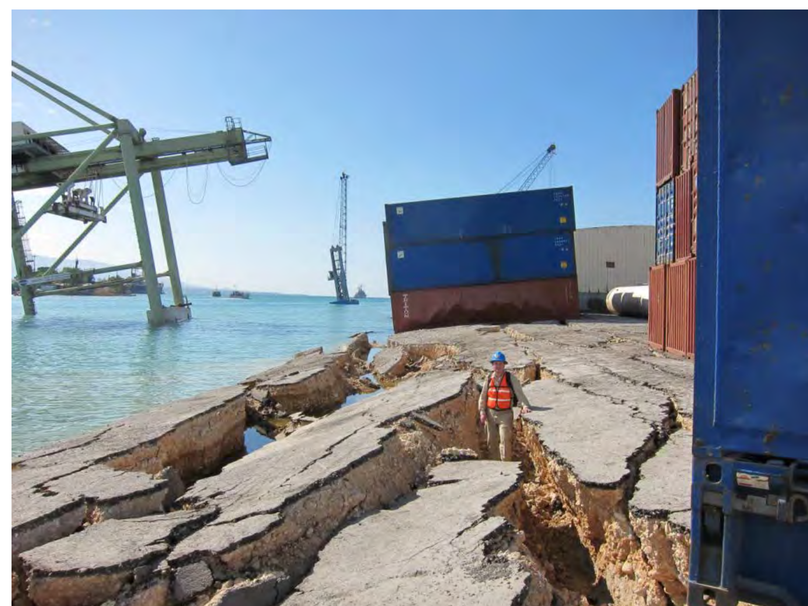
Seismic Ground Hazards

Christchurch NZ (Russell Green 2011)

Lateral Spreading

Chile 2010 (courtesy J. Bray & J.D. Frost)

Haiti 2010 (courtesy Glenn J. Rix)

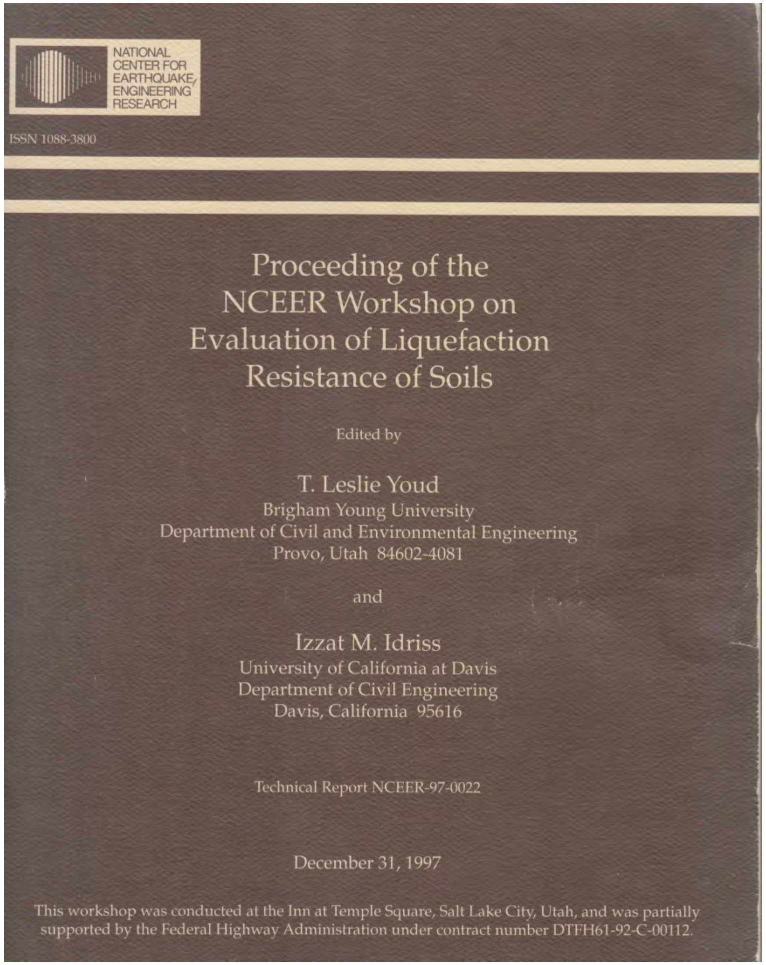


Soil Liquefaction

NCEER Workshop on Evaluation of Liquefaction Resistance of Soils

National Center for Earthquake Engineering Research (NCEER)

Consensus Report Paper published by Youd et al. (ASCE J. Geotech & Geoenv. Engrg: Oct. 2001; closure: March 2003)



Edited by T.L. Youd and I.M. Idriss (1997), 276 pages

Liquefaction

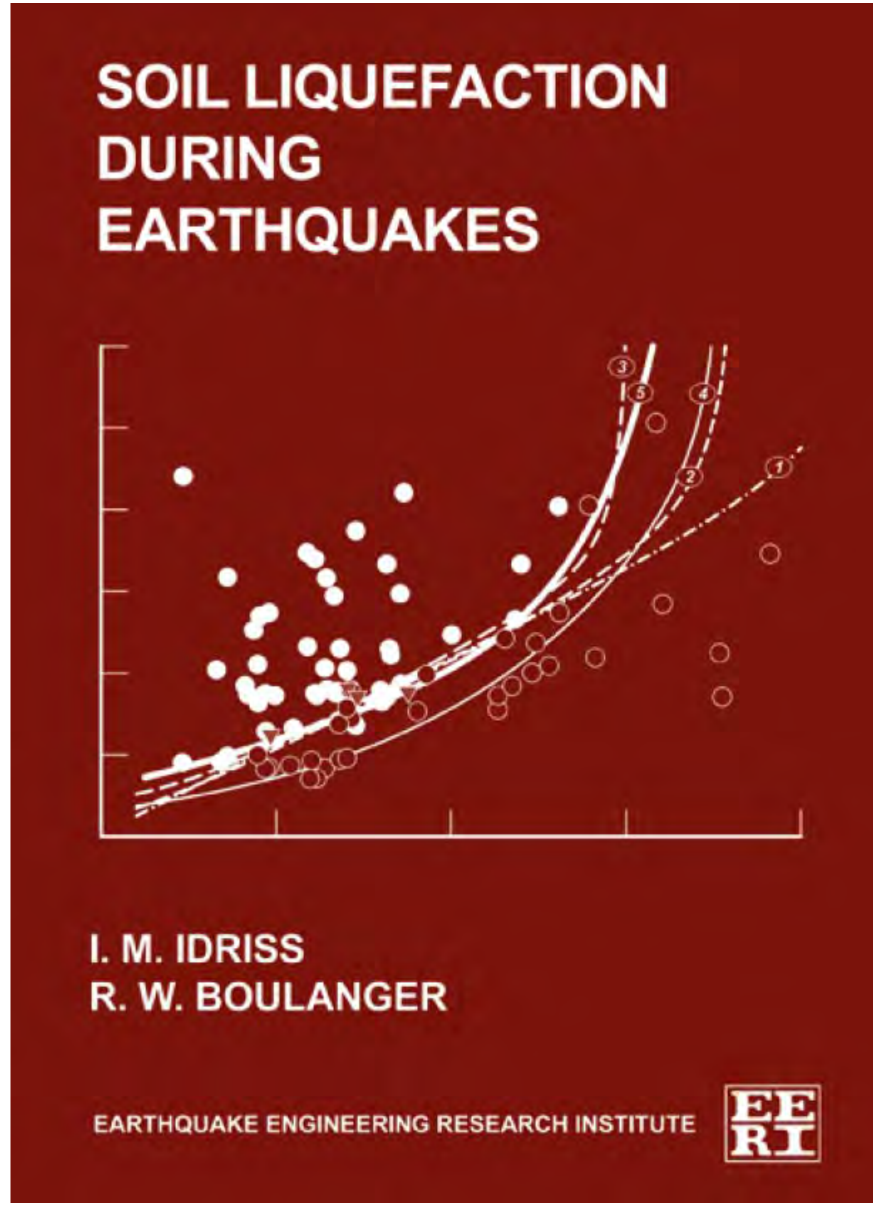
- **Principle of effective stress:** $\sigma_{vo}' = \sigma_{vo} - u$
- **When porewater pressure (u) equals total overburden stress (σ_{v0}), effective stress is zero, thus causing liquefaction (Seed & Lee, 1966)**
- **"Quick Sand":** $\sigma_{vo} = u_o$
- **Cyclic stresses cause accumulation of positive excess porewater pressures** ($u = \Delta u + u_0$) **in saturated granular soils:** $\sigma_{vo}' = \sigma_{vo} - (u_o + \Delta u)$

Soil Liquefaction During Earthquakes

Earthquake Engineering
Research Institute (EERI)
www.eeri.org

Idriss and Boulanger:
Monograph No. MNO-12
(2008)

UCD = University of California
at Davis



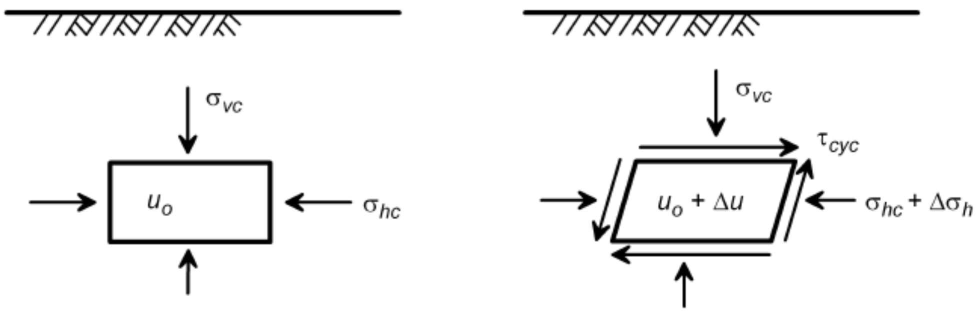
Liquefaction Defined

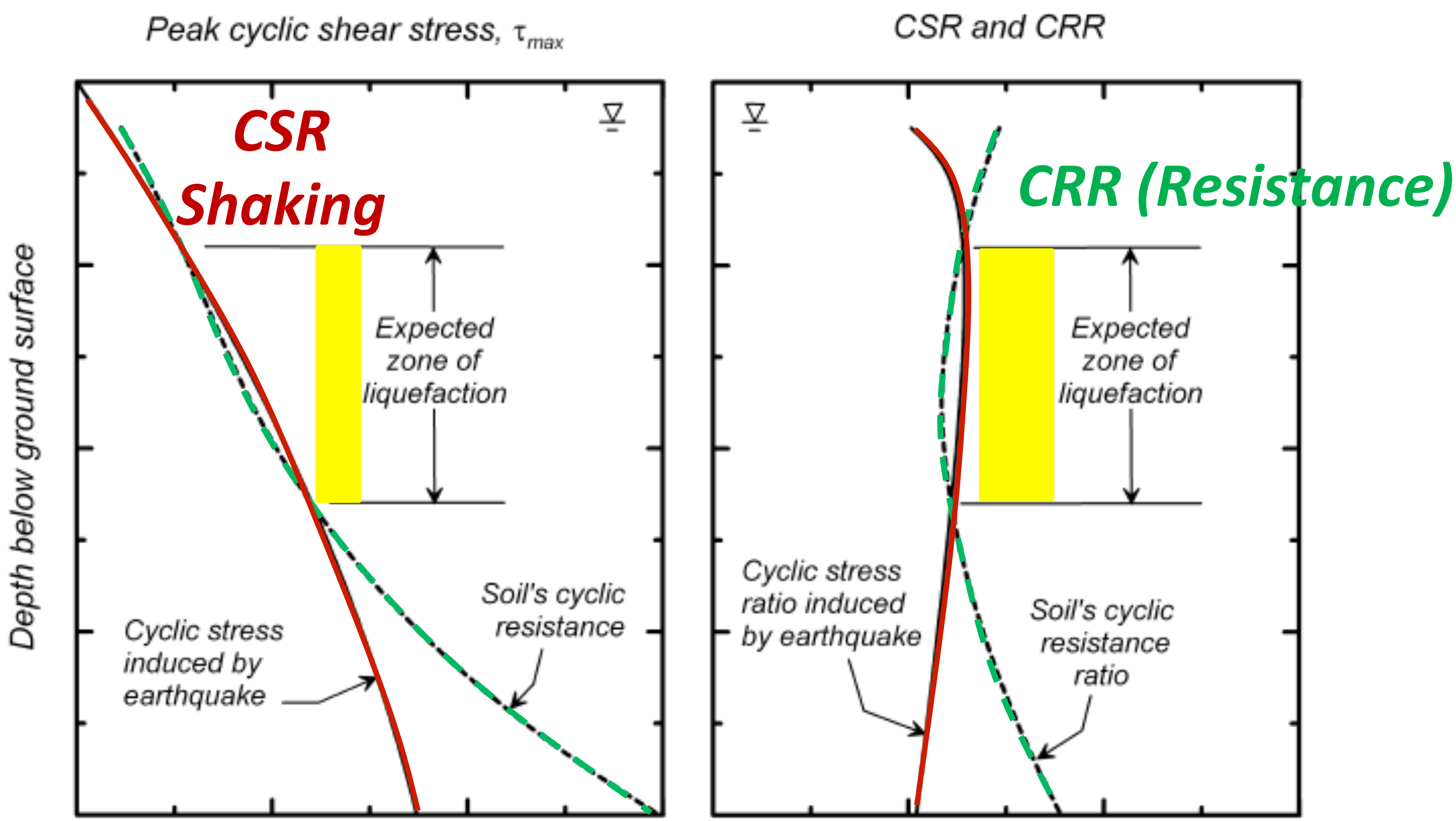
- **Flow Liquefaction:** First-time loading; Applies to strain-softening soils; Large deformations may occur even after triggering load ceases.
- **Cyclic Liquefaction:** Contractive soils (loose sands) subjected to cyclic stress reversals. Applies to most EQ-related response. Most Common.
- **Cyclic Mobility:** One-way cyclic loading with softening. Deformations cease when load terminated.
- **Cyclic Softening:** Reduced strength and stiffness applied to clays and silts.

Soil Liquefaction Behavior (I&B 2008)

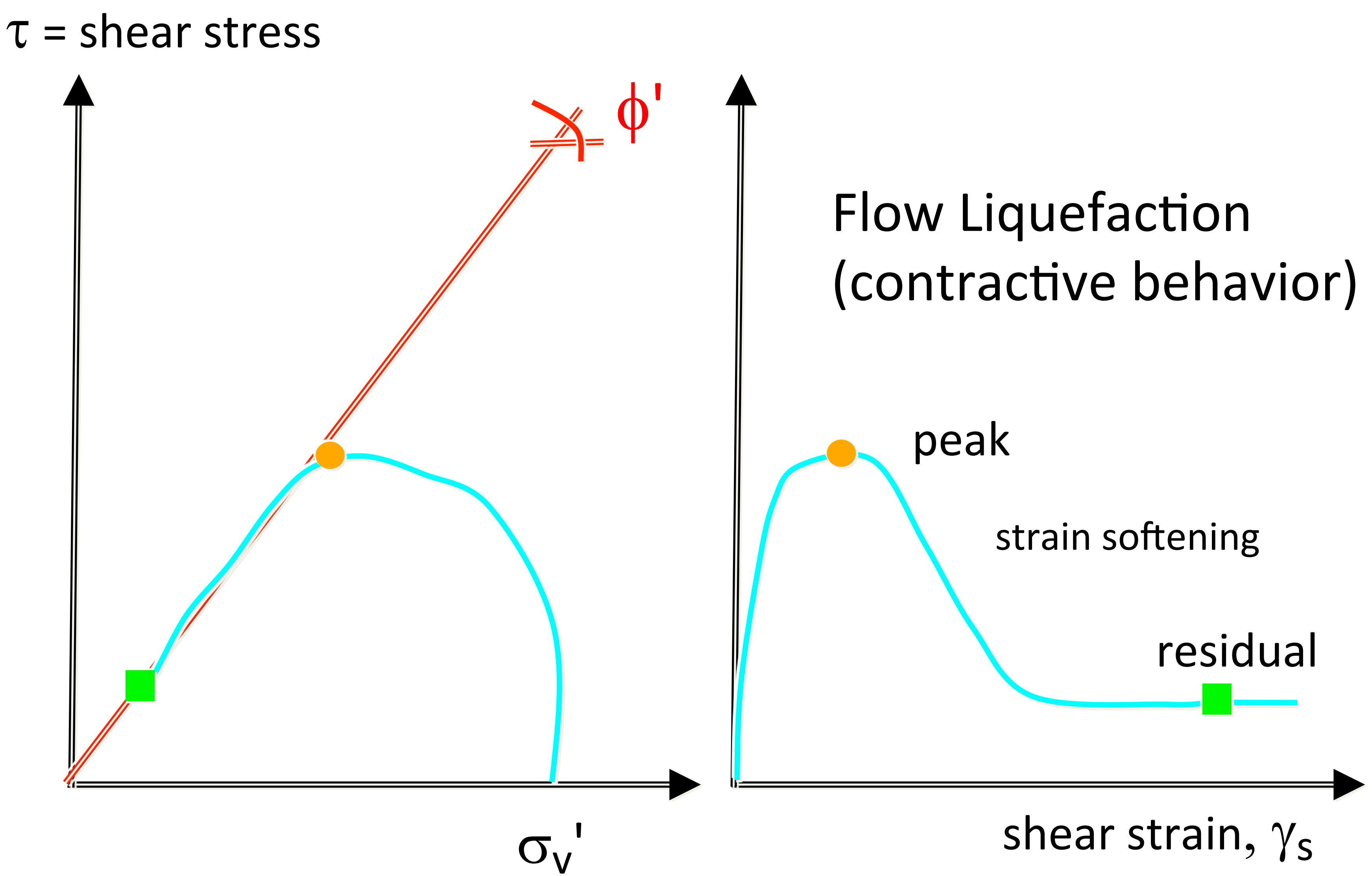
Initial K_0 State

Simple Shear Mode

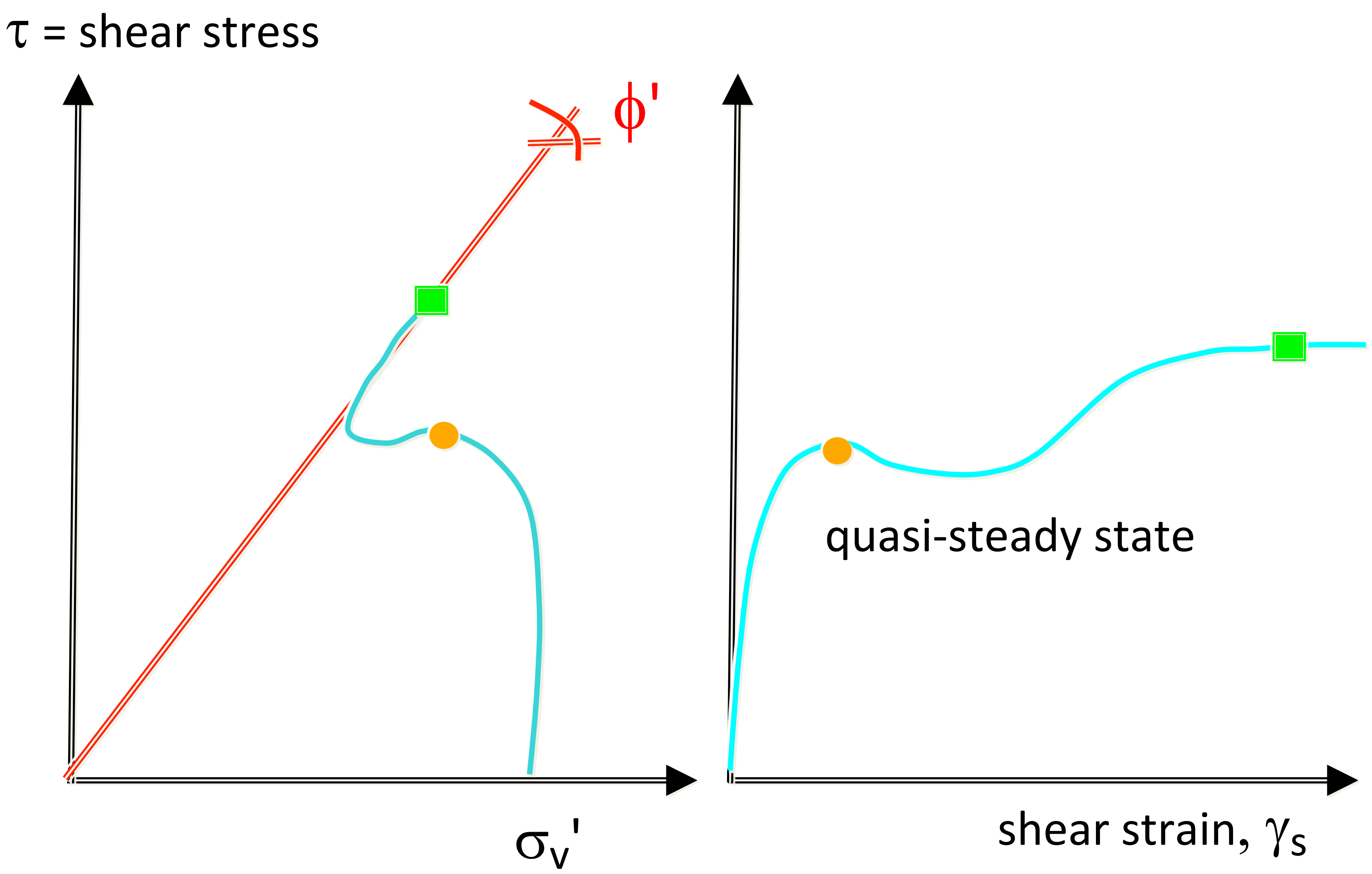




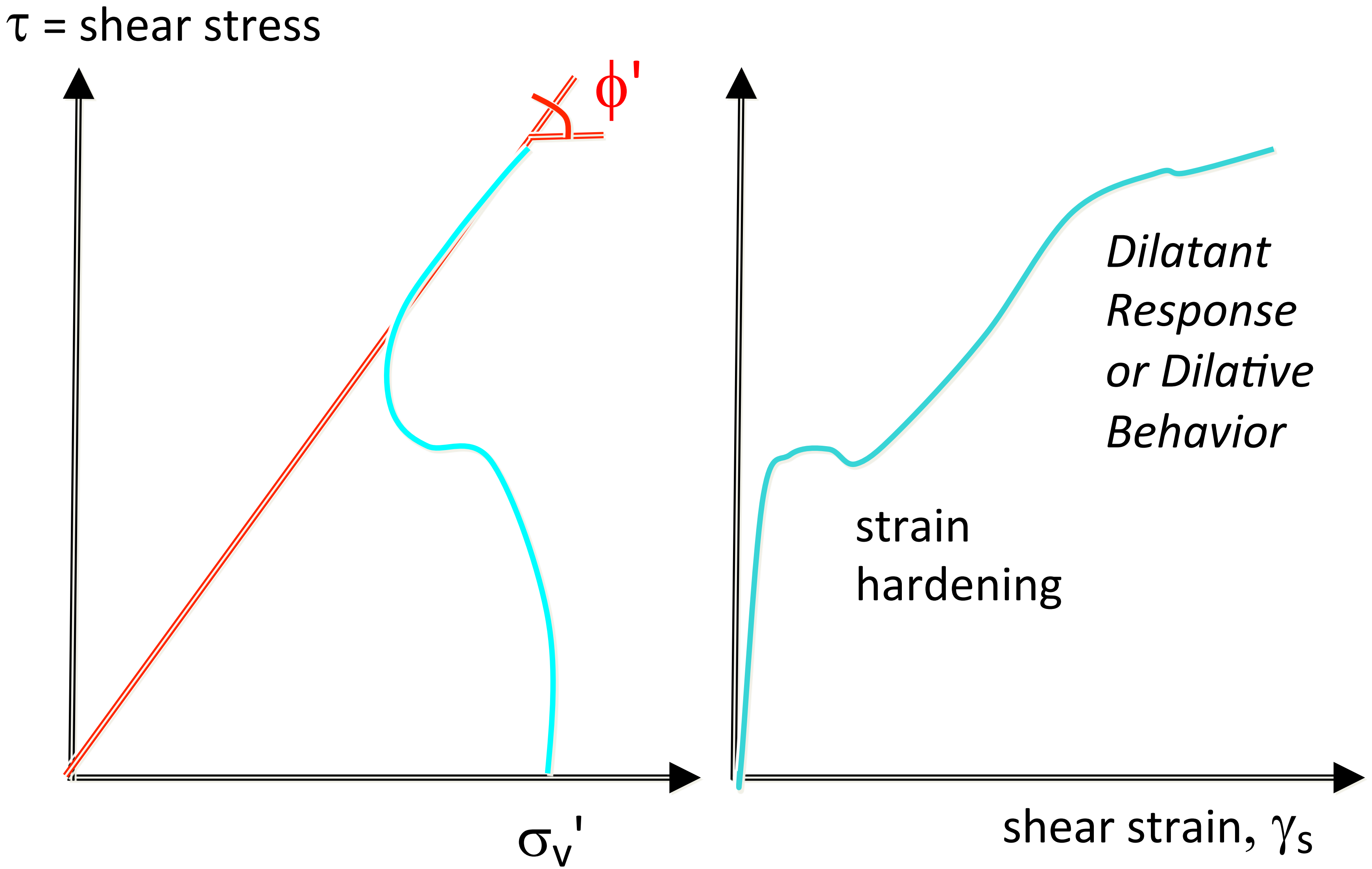
Stress Paths during Liquefaction



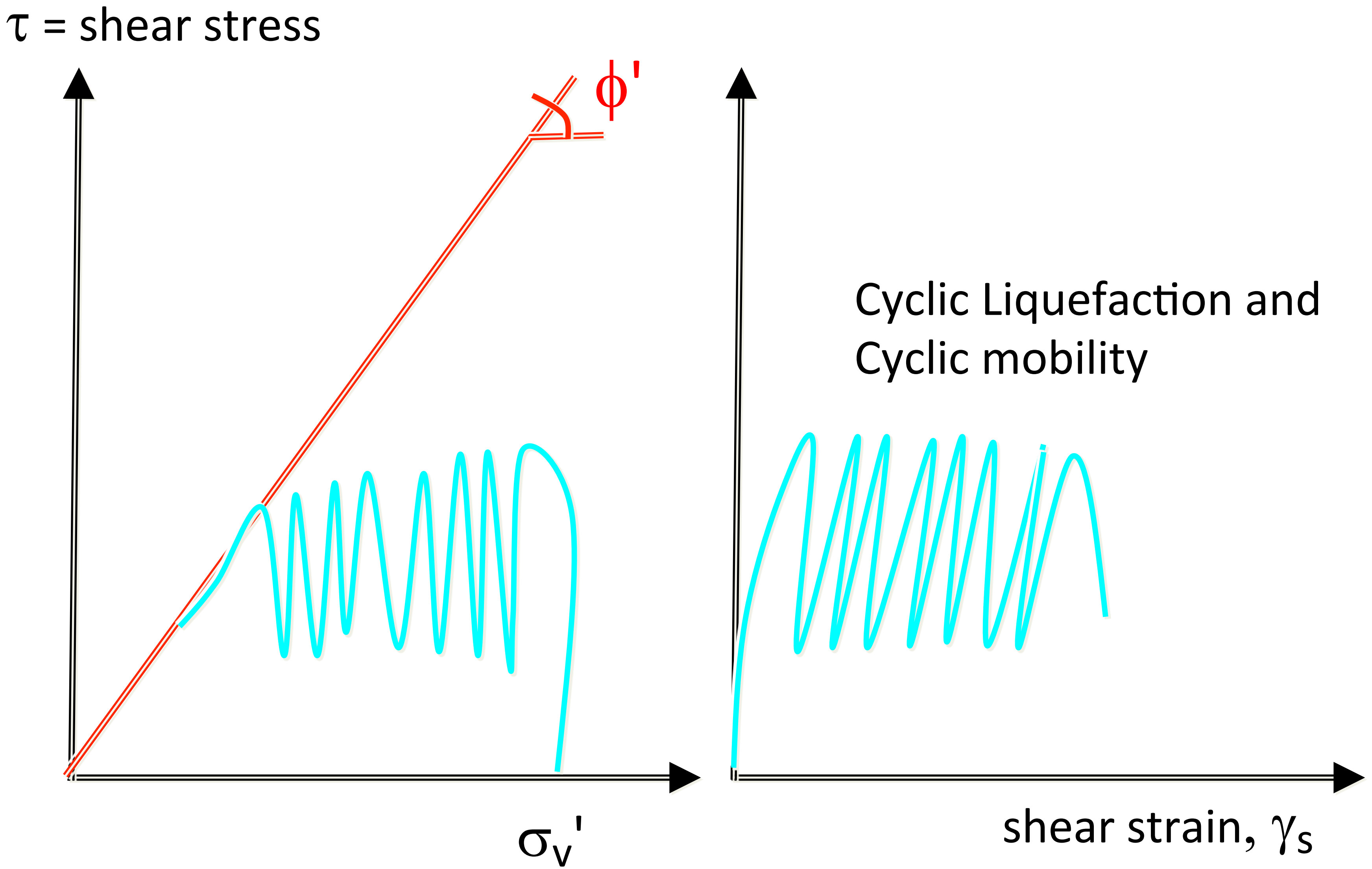
Stress Paths for Sand Response



Stress Paths for Sand Response



Stress Paths During Liquefaction



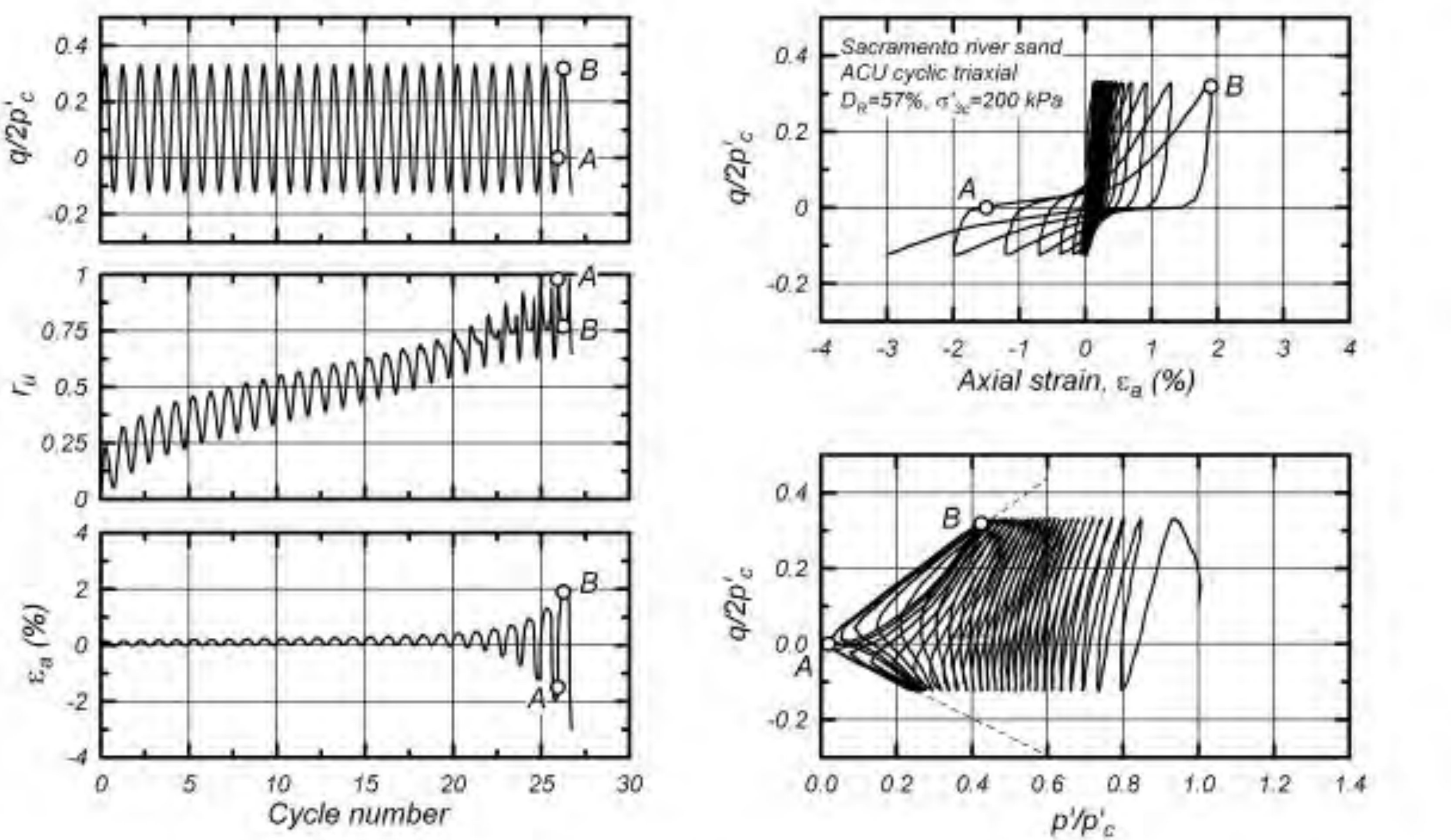
Soil Liquefaction - Lab Tests on Sacramento Sand

Undrained Cyclic Triaxial Tests by Boulanger & Truman (1996)

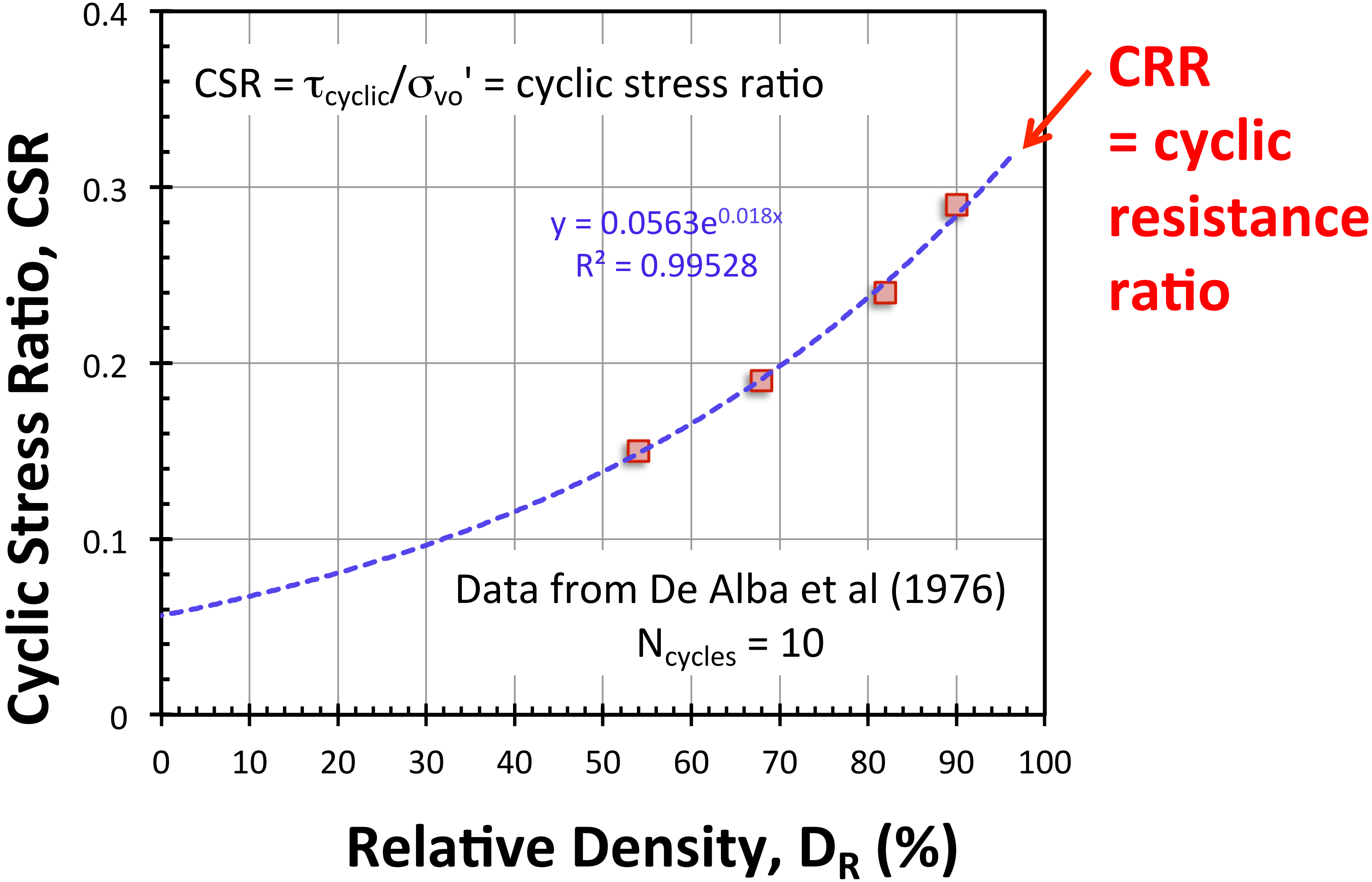
For Triaxial Shear: $r_u = \Delta u/\sigma_3'$

For Simple Shear: $r_u = \Delta u/\sigma_v'$

"Initial Liquefaction" when $r_u = 1$



Soil Liquefaction - Laboratory Tests



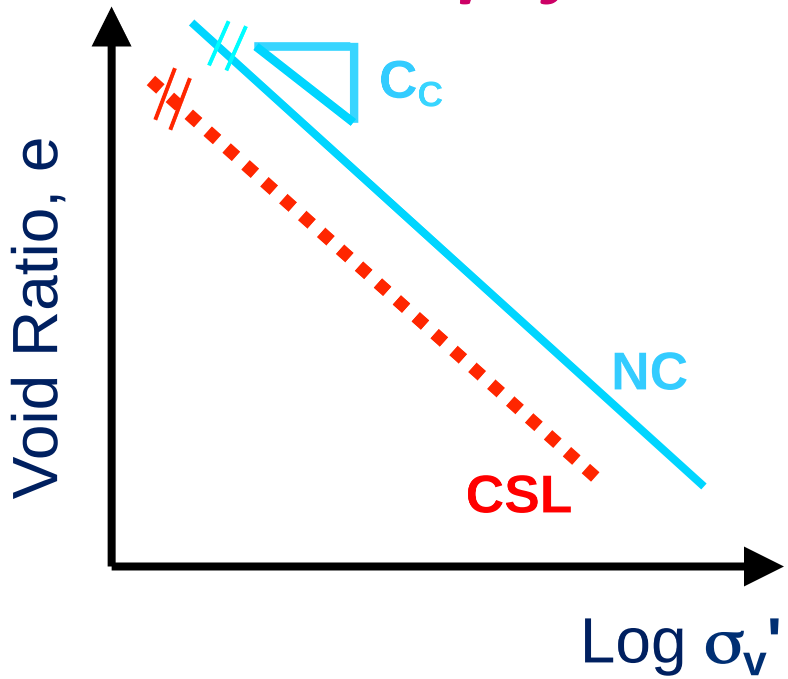
PPT Presentation

Critical-State Soil Mechanics For Dummies

http://geosystems.ce.gatech.edu/Faculty/Mayne/papers/index.html

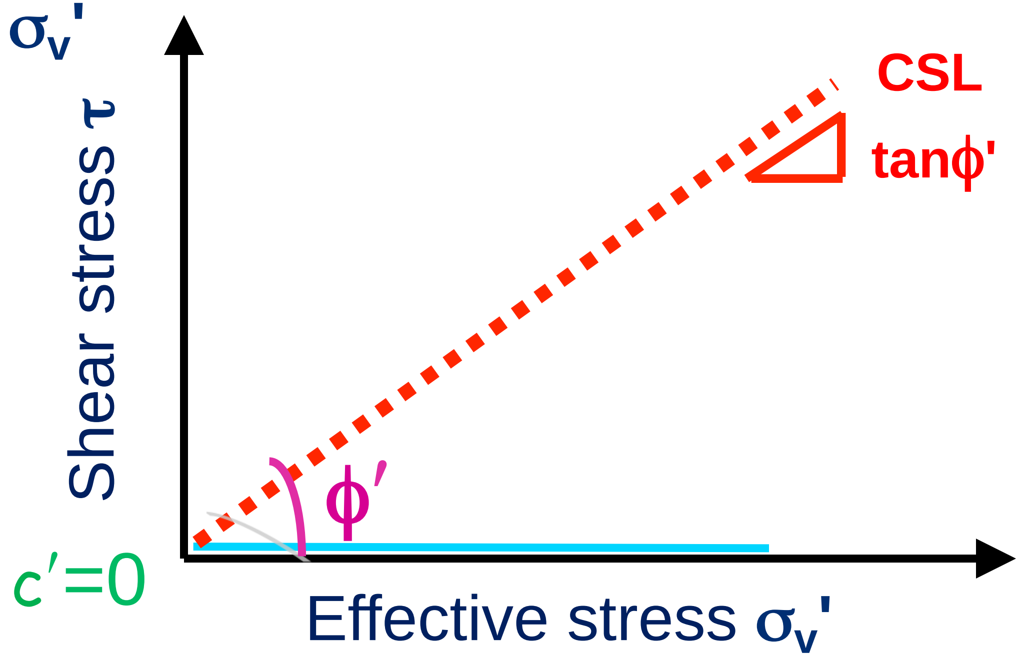
Mayne, P.W., Coop, M.R., Springman, S., Huang, A-B., and Zornberg, J. (2009). State-of-the-Art Paper (SOA-1): Geomaterial Behavior and Testing. *Proc. 17th Intl. Conf. Soil Mechanics & Geotechnical Engineering*, Vol. 4 (ICSMGE, Alexandria, Egypt), Millpress/IOS Press Rotterdam: 2777-2872.

Simplified Critical State Soil Mechanics



CSSM = Link between initial stress state, consolidation, shearing, strength, porewater pressure response, contractive vs. dilative behavior, and static vs. cyclic soil response

CSSM Premise:
"Regardless of initial stress state, all shearing follows stress paths that fail on the critical state line (CSL)"



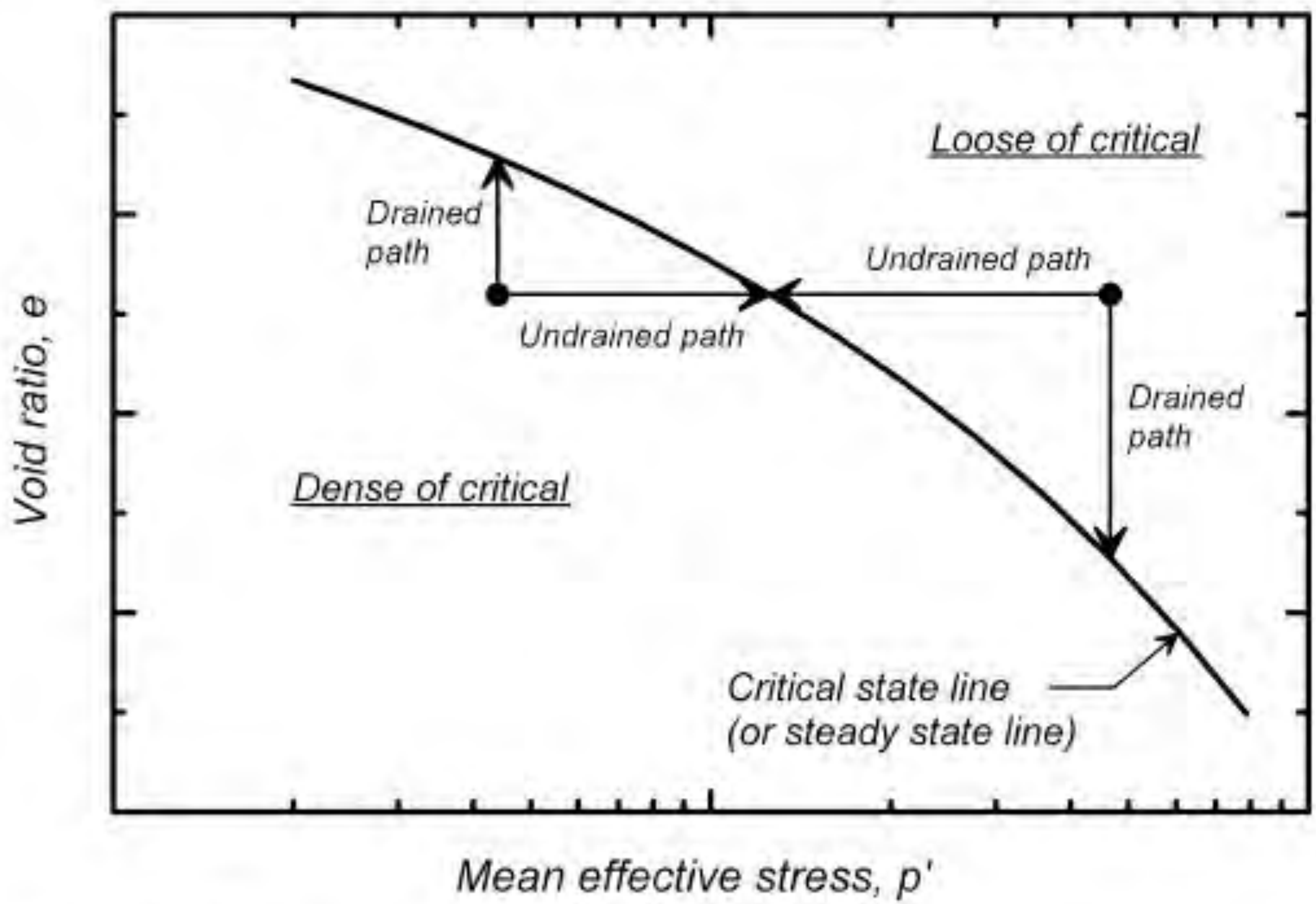
Critical State Soil Mechanics (CSSM)

- **Constitutive Soil Models based on CSSM**
  - Original Cam-Clay (1968)
  - Modified Cam Clay (1969)
  - NorSand (Jefferies 1993)
  - Bounding Surface (Dafalias)
  - MIT-E3 (Whittle, 1993)
  - MIT-S1 (Pestana, 2001)
  - Cap Model (Baladi 1985)
  - "Ber-Klay" (UCB 2000)
  - PM4SAND (UCD 2012)
  - others (Adachi, Oka, Ohta, Dafalias, Nova, Wood, Huerkel)

- **FEM Packages**
  - FLAC
  - PLAXIS
  - ABAQUS
  - CRISP
  - TNO-DIANA
  - SIGMA-W
  - SOIL VISION 3D
  - OASYS
  - ADINA
  - OPENSEES
  - QUAKE/W
  - RS2

Soil Liquefaction - EERI MNO-12 (2008)

Monotonic Drained and Undrained Loading of Sands (Contractive vs. Dilative)



Basic Premises for Liquefaction

- Loose saturated Holocene sands and granular soils (age < 10,000 years)
- contractive sands below groundwater table
- Design EQ with moment magnitude M = 7.5
- Duration = 15 cycles
- Approx. frequency f = 1 cycle/sec
- Also, reference level for effective overburden stress = 1 atm ≈ 100 kPa

Liquefaction Evaluation by CPT

NCEER/NSF Consensus Report (Youd, et al. 2001)

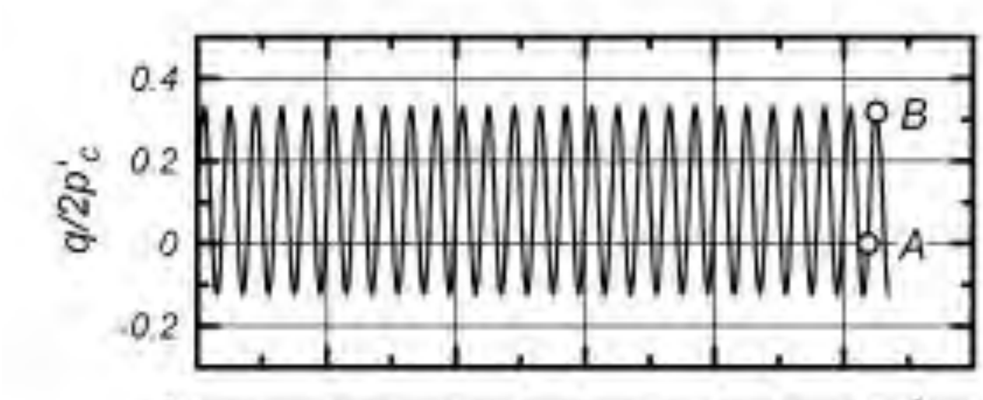
- Simplified Approach uses *Cyclic Stress Ratio* (CSR):

$$CSR = \frac{\tau_{ave}}{\sigma'_{vo}} = 0.65 \cdot \left(\frac{a_{\max}}{g} \right) \cdot \left(\frac{\sigma_{vo}}{\sigma'_{vo}} \right) \cdot r_d$$

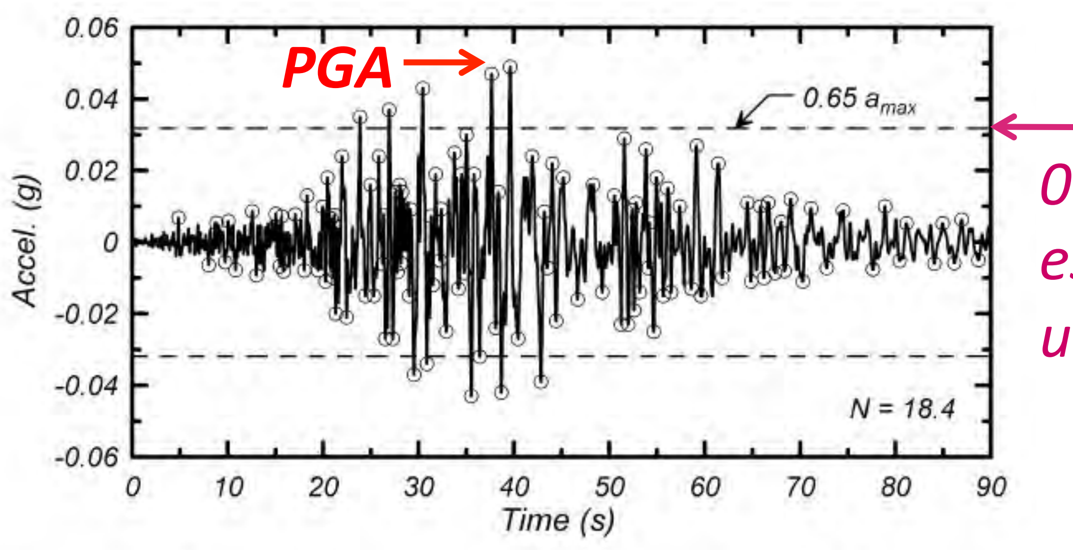
- τ = average cyclic shear stresses
- a_{max}/g = PGA = peak (horiz.) ground acceleration
- σ_{vo} = total vertical (overburden) stress
- σ_{vo}' = effective vertical stress
- r_d = stress reduction coefficient

Soil Liquefaction - UCD Method

Lab Testing for based on uniform cycles of CSR = τ_{cyclic}/σ_v'



Field Measurements Use Peak Value



0.65 PGA = estimate of uniform CSR

Liquefaction Evaluation by CPT

NCEER/NSF Consensus Report (Youd, et al. 2001)

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$$CSR = \frac{\tau_{ave}}{\sigma_{vo}'} = 0.65 \cdot \left(\frac{a_{max}}{g}\right) \cdot \left(\frac{\sigma_{vo}}{\sigma_{vo}'}\right) \cdot r_d$$

- τ = average cyclic shear stresses
- a_{max}/g = PGA = peak (horiz.) ground acceleration
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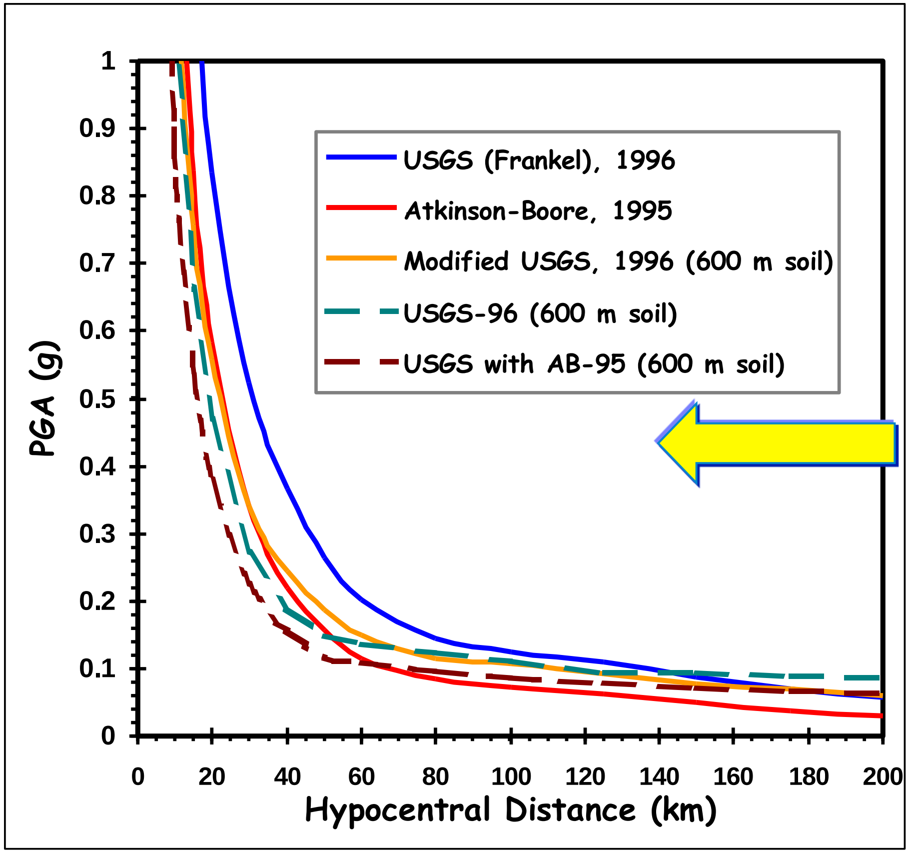
- σ_{vo}' = effective vertical stress
- r_d = stress reduction coefficient

Ground Motion Attenuation

INPUT: Moment Magnitude (M_w) + Hypocentral Distance (d)

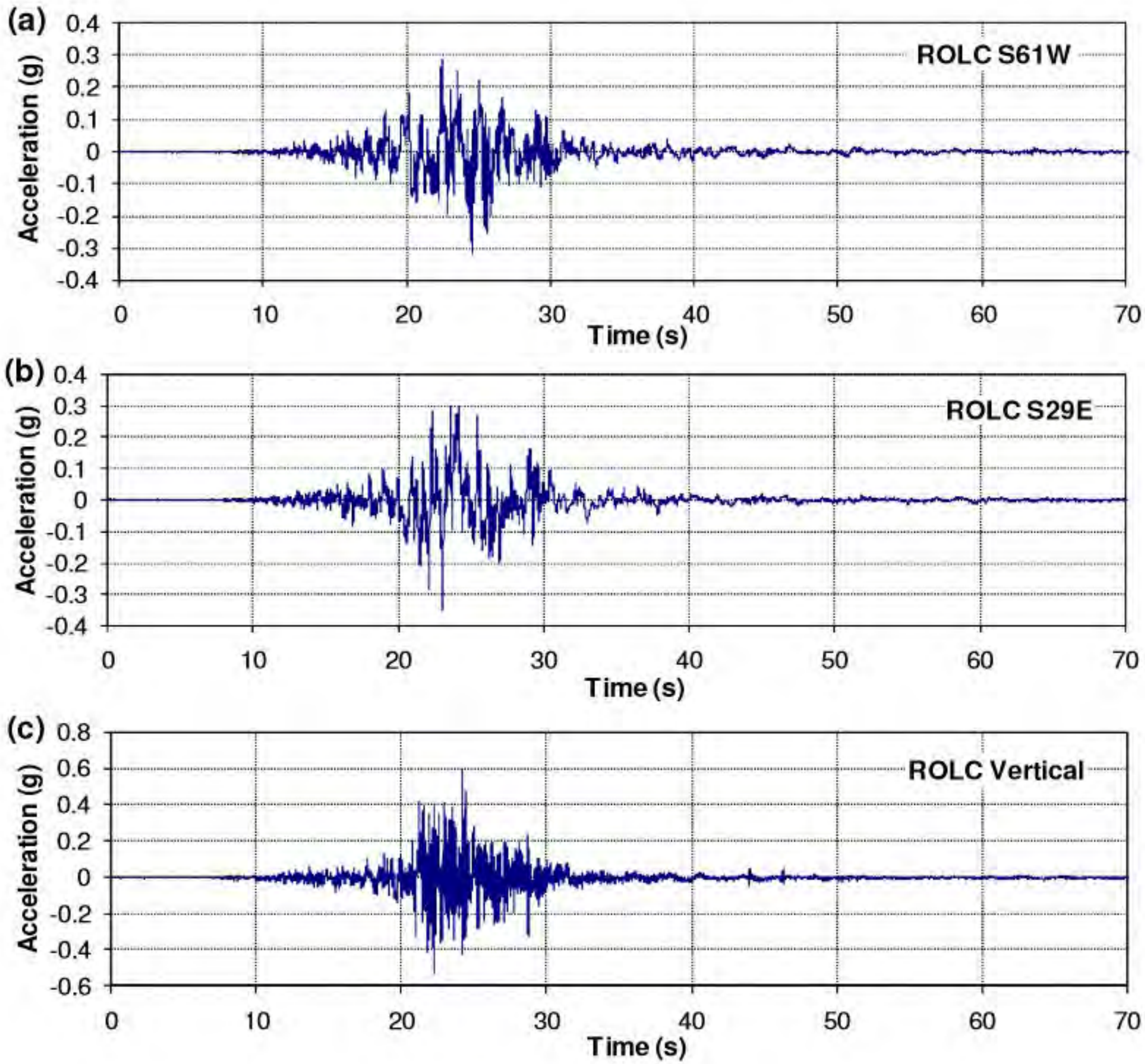
Attenuation Relationships



- Herrmann & Akinci (1999)
- Wen & Wu (1999)
- NEHRP (1997)
- Boore & Joyner (1991)
- SMSIM (Boore, 2002):
  www.daveboore.com

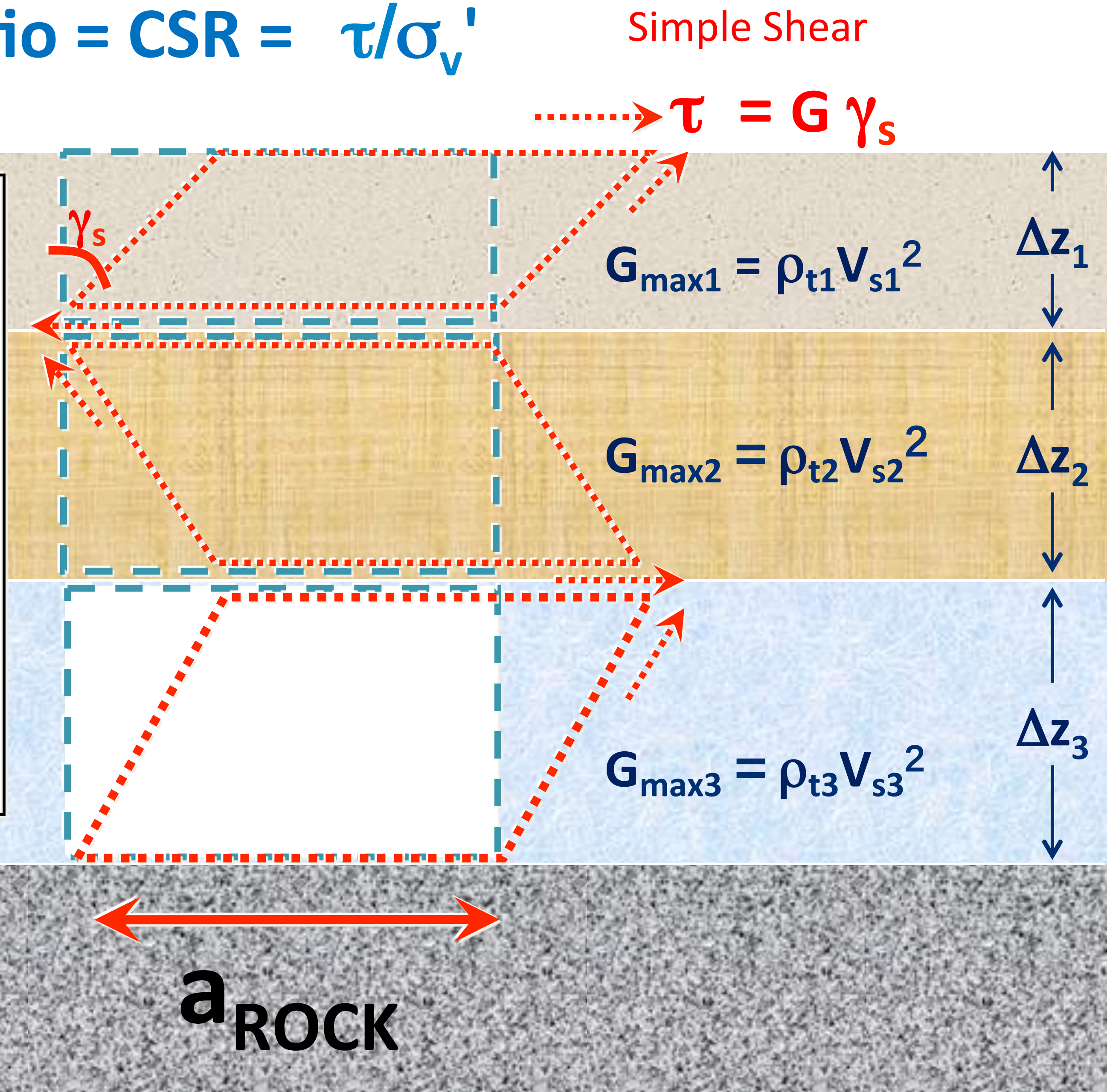
Peak Ground Acceleration (PGA or a_{max})

Acceleration-Time Record



Site-Specific Ground Shaking Analysis

Cyclic Stress Ratio = CSR = τ/σ_v'



PARAMETERS

- τ = shear stress
- G = shear modulus
- γ_s = shear strain
- σ_v' = effective stress
- Δz = layer thickness
- G_{max} = initial small-strain shear modulus
- ρ_t = total mass density
- V_s = shear wave velocity

Ground Motions: Site-Specific Analyses

Equivalent Linear Elastic Methods → **CSR**

- SHAKE (Schnabel, et al. 1972)
- EduShake: www.proshake.com
- ProShake: www.proshake.com
- SHAKE2000: www.shake2000.com
- RASCALS (Silva, 1992)
- DeepSoil V6.0 (Park & Hashash 2004): http://deepsoil.cee.illinois.edu/

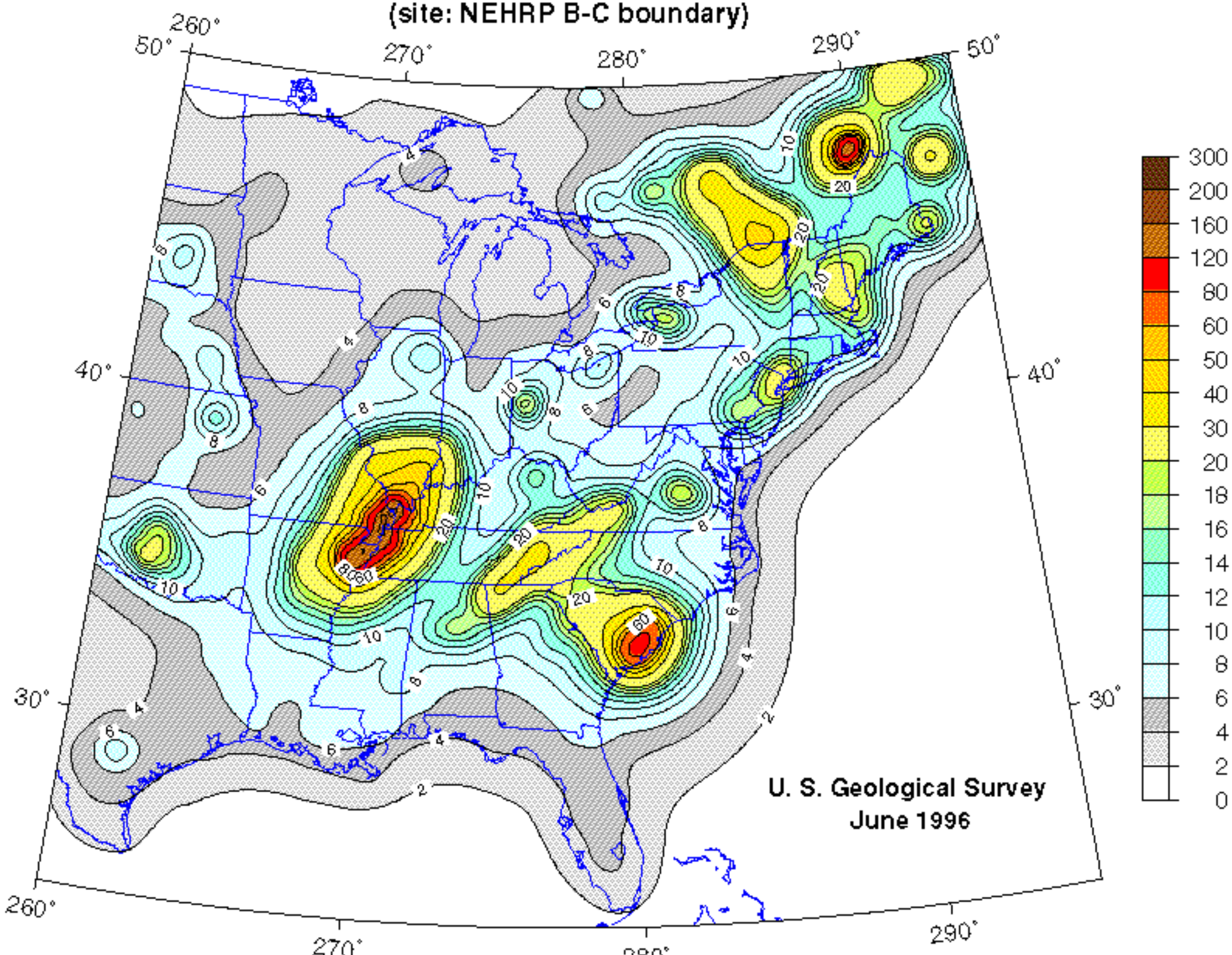
*Also see Geotechnical & Geoenv. Service Directory: www.ggsd.com with 1761 geotech software programs

Ground Motions: Site-Specific Analyses

Nonlinear Ground Response Methods → **CSR**

- CHARSOIL (Streeter, et al. 1973)
- MASH (Martin & Seed, 1978)
- DESRA (Lee & Finn, 1978)
- TESS (Pyke 1985)
- DYNA1d (Prevost, 1989)
- SUMDES (Li, et al. 1992)
- D-MOD (Matasovic, 1993)
- DESRAMOD2 (Vucetic, 1998)
- DESRMUSC (Qiu, 1998)
- D-MOD2000: www.geomotions.com
- DeepSoil (Park & Hashash 2003)
- DEEPSOIL V6.0 (Hashash, 2015): http://deepsoil.cee.illinois.edu/

Peak Acceleration (%g) with 2% Probability of Exceedance in 50 Years
(site: NEHRP B-C boundary)




DANGER
QUICKSAND
Waitakere City Council
Te Taiao o Waitakere
Waitakere City Parks
For
quiries Phone 839 0400

Liquefaction Evaluation by CPT

NCEER/NSF Consensus Report (Youd, et al. 2001)

- Simplified Approach uses *Cyclic Stress Ratio* (CSR):

$$CSR = \frac{\tau_{ave}}{\sigma_{vo}^{'}} = 0.65 \cdot \left(\frac{a_{\max}}{g}\right) \cdot \left(\frac{\sigma_{vo}}{\sigma_{vo}^{'}}\right) \cdot r_d$$

- τ = average cyclic shear stresses
- a_{max}/g = PGA = peak (horiz.) ground acceleration
- σ_{vo} = total vertical (overburden) stress
- σ_{vo}' = effective vertical stress
- r_d = stress reduction coefficient

Overburden Stresses

- Need unit weight (γ_t)
- Groundwater table depth, z_w
- Total vertical (overburden) stress: σ_{vo}
- $\sigma_{vo} = \int \gamma_t \, dz \approx \sum (\gamma_{ti} \cdot \Delta z_i)$
- Hydrostatic porewater pressure: u_0
  - $u_0 = (z - z_w) \cdot \gamma_w$ (*sat*) or $u_0 = 0$ (*dry*)
  - consider capillarity above groundwater table
- Effective vertical (overburden) stress = σ_{vo}'
- $\sigma_{vo}' = \sigma_{vo} - u_0$ ***(principle of effective stress)***

Liquefaction Evaluation by CPT

NCEER/NSF Consensus Report (Youd, et al. 2001)

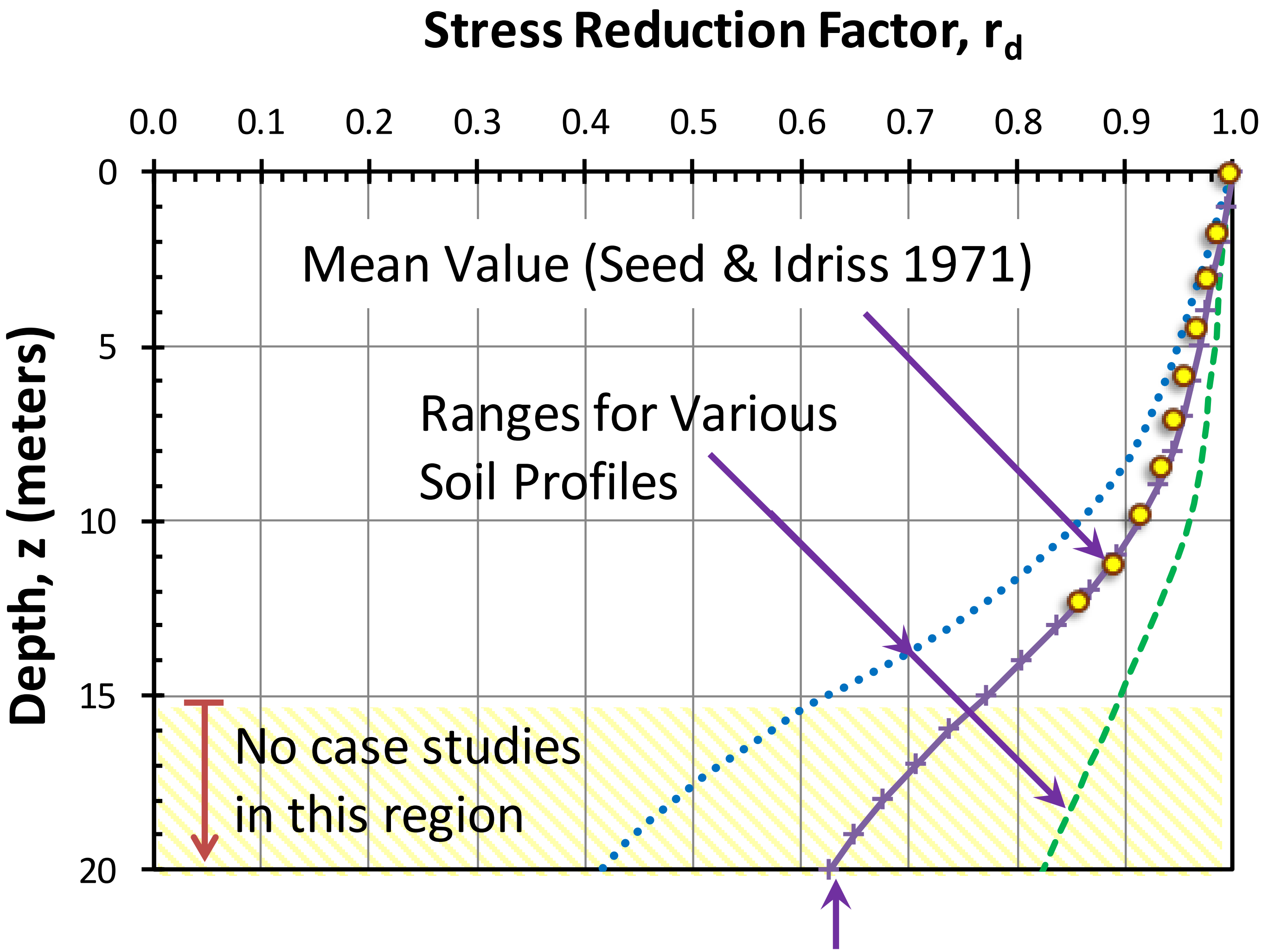
- Simplified Approach uses *Cyclic Stress Ratio* (CSR):

$$CSR = \frac{\tau_{ave}}{\sigma'_{vo}} = 0.65 \cdot \left(\frac{a_{\max}}{g} \right) \cdot \left(\frac{\sigma_{vo}}{\sigma'_{vo}} \right) \cdot r_d$$

- τ = average cyclic shear stresses
- a_{max}/g = PGA = peak (horiz.) ground acceleration
- σ_{vo} = total vertical (overburden) stress
- σ_{vo}' = effective vertical stress
- r_d = stress reduction coefficient

NOTE: Referenced to EQ magnitude M_w = 7.5

Stress Reduction Factor, r_d



$$r_d = \frac{1 - 0.411 z^{0.5} + 0.0405 z + 0.00175 z^{1.5}}{1 - 0.418 z^{0.5} + 0.0573 z - 0.00621 z^{1.5} + 0.00121 z^2}$$

"Say, ... there is something wrong here....
We may have to move shortly"

The Far Side

by Gary Larson
(April 13, 2003)

Soil Liquefaction - Simplified CSR Approach

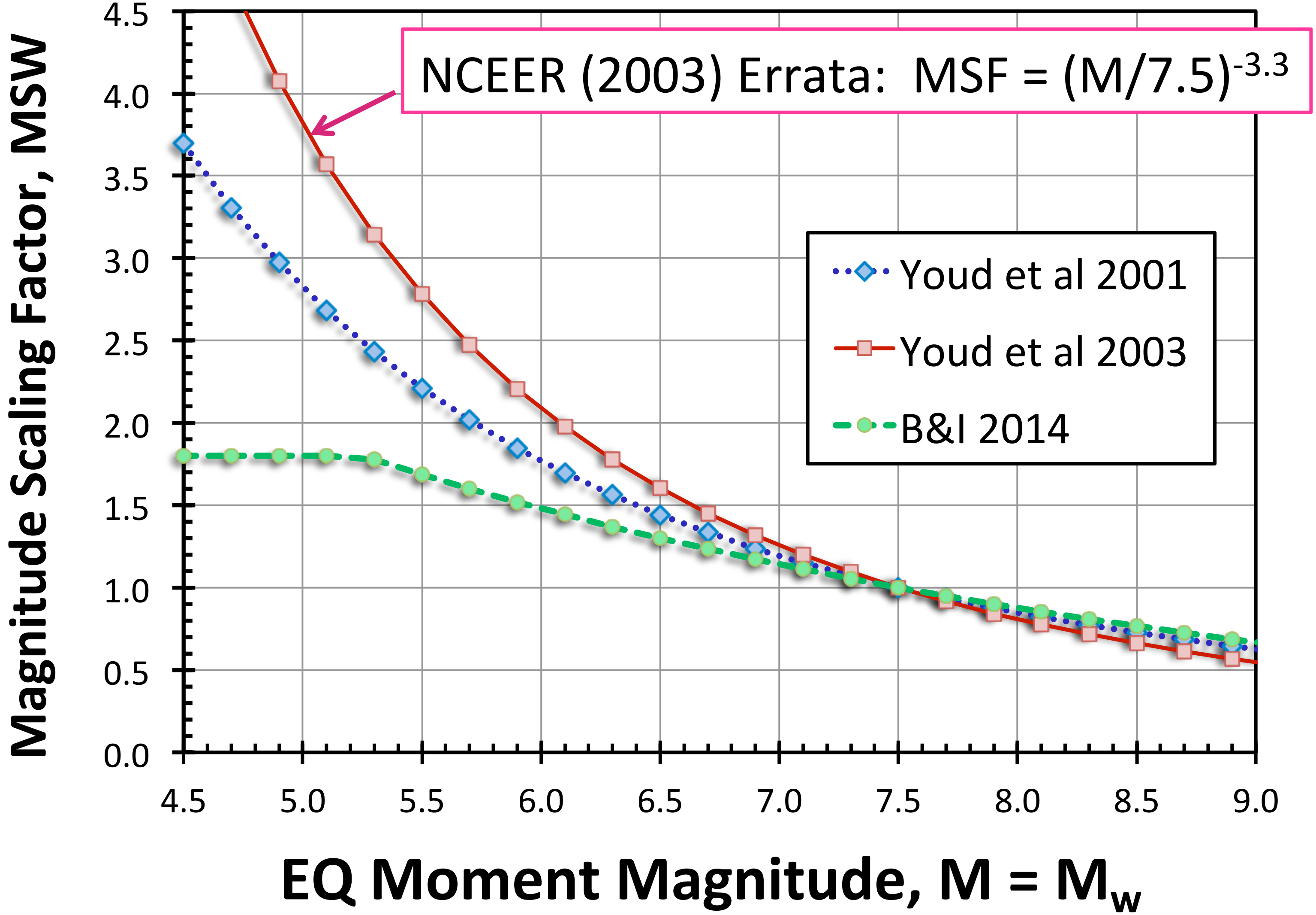
- Basic simplified expression for cyclic stress ratio (CSR)

$$CSR = \frac{\tau_{ave}}{\sigma'_{vo}} = 0.65 \cdot \left(\frac{a_{\max}}{g} \right) \cdot \left(\frac{\sigma_{vo}}{\sigma'_{vo}} \right) \cdot r_d$$

- Needs adjustment factor for different magnitude earthquakes (or duration)
- Define factor MSF = magnitude scaling factor
- Adjust CSR to value for equivalent magnitude M = 7.5:

$$CSR_{7.5} = \frac{\tau_{ave}}{\sigma'_{vo}} = 0.65 \cdot \left(\frac{a_{\max}}{g} \right) \cdot \left(\frac{\sigma_{vo}}{\sigma'_{vo}} \right) \cdot \frac{r_d}{MSF}$$

Magnitude Scaling Factor, MSF

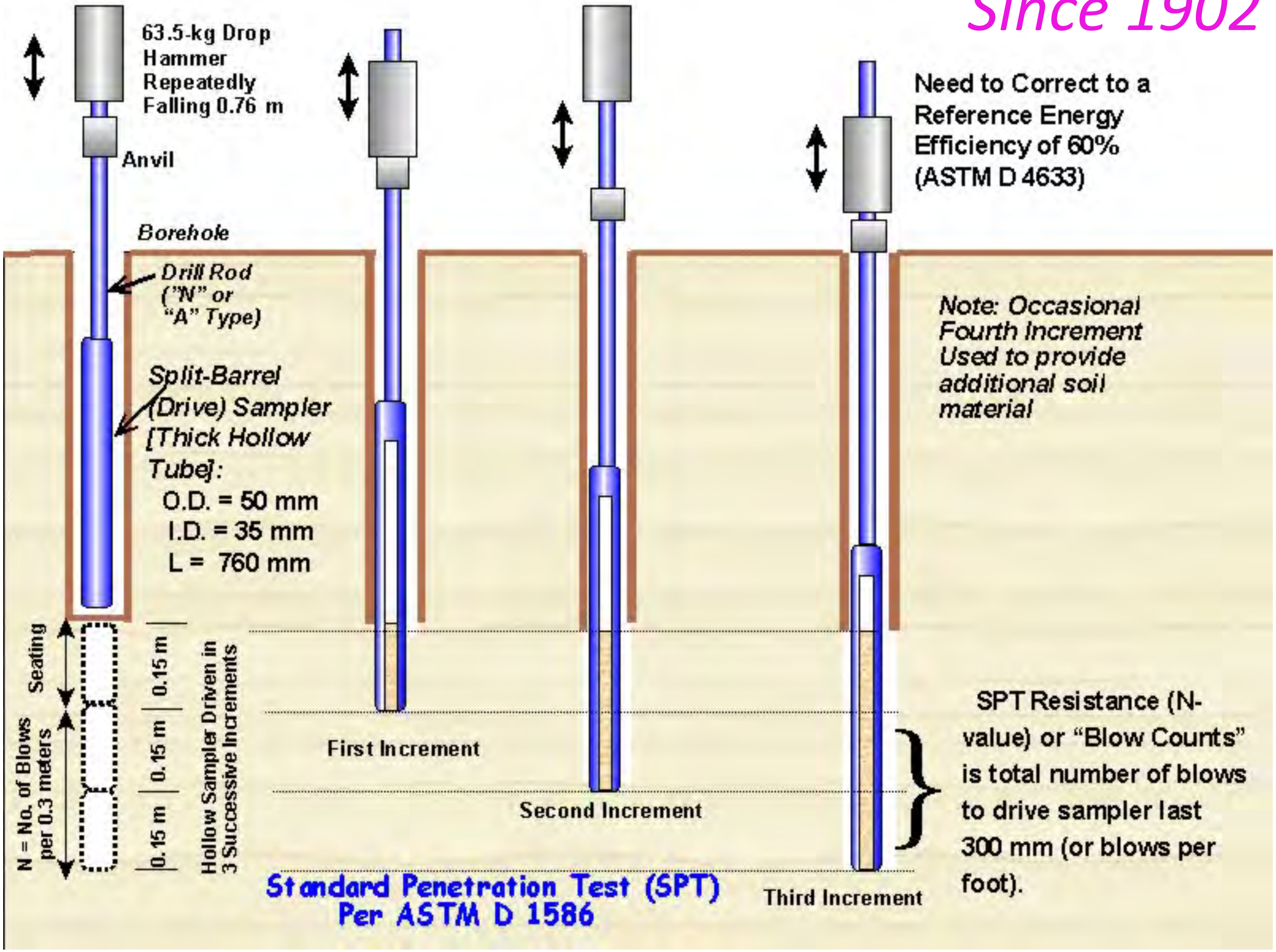


Overview
In-Situ Tests for Seismic Geotechnics

- Geophysics: Electromagnetics; Mechanical Waves
  - Shear Wave Velocity (V_s) Measurements
  - Crosshole (CHT), Downhole (DHT), Rayleigh Wave Methods (SASW, MASW, ReMi)
- Standard Penetration Test (SPT)
- Cone Penetration Tests (CPT)
- Flat Plate Dilatometer Test (DMT)
- Hybrid geotechnical-geophysics tests
  - Seismic Piezocone (SCPTu)
  - Seismic Dilatometer (SDMT)

Standard Penetration Test (SPT)

Since 1902



SPT Hammers

PINWEIGHT

SAFETY

DONUT

AUTO

Calibration of SPT Hammer & System

Modified after Kulhawy and Mayne (1990)

Hammer Type	Operation Method	Typical Range of Energy Ratios
Pinweight	Manual	30 - 40
Donut	Manual	40 - 55
Safety	Manual	55 - 75
Automatic	Auto	45 - 95

Corrections to SPT N-value

- $N_{measured}$ = raw SPT Resistance reported in blows per foot (bpf) per ASTM D 1586. Note: in SI units, N is in units of blows/0.3 m

- $N_{60} = (ER/60)\, N_{measured} = C_E \cdot N_{meas}$ = Energy-Corrected N Value where ER = energy ratio or rated efficiency (ASTM D 4633). Note: 30% < ER < 100% with average ER = 60% in the U.S. circa 1985

- $N_{60} \approx C_E \cdot C_B \cdot C_S \cdot C_R \cdot N_{meas}$ = Fully corrected N value

  - C_R: Rod length correction
  - C_S: Split spoon liner correction
  - C_B: Borehole diameter correction
  - C_E: Energy correction

Corrections to SPT N-value

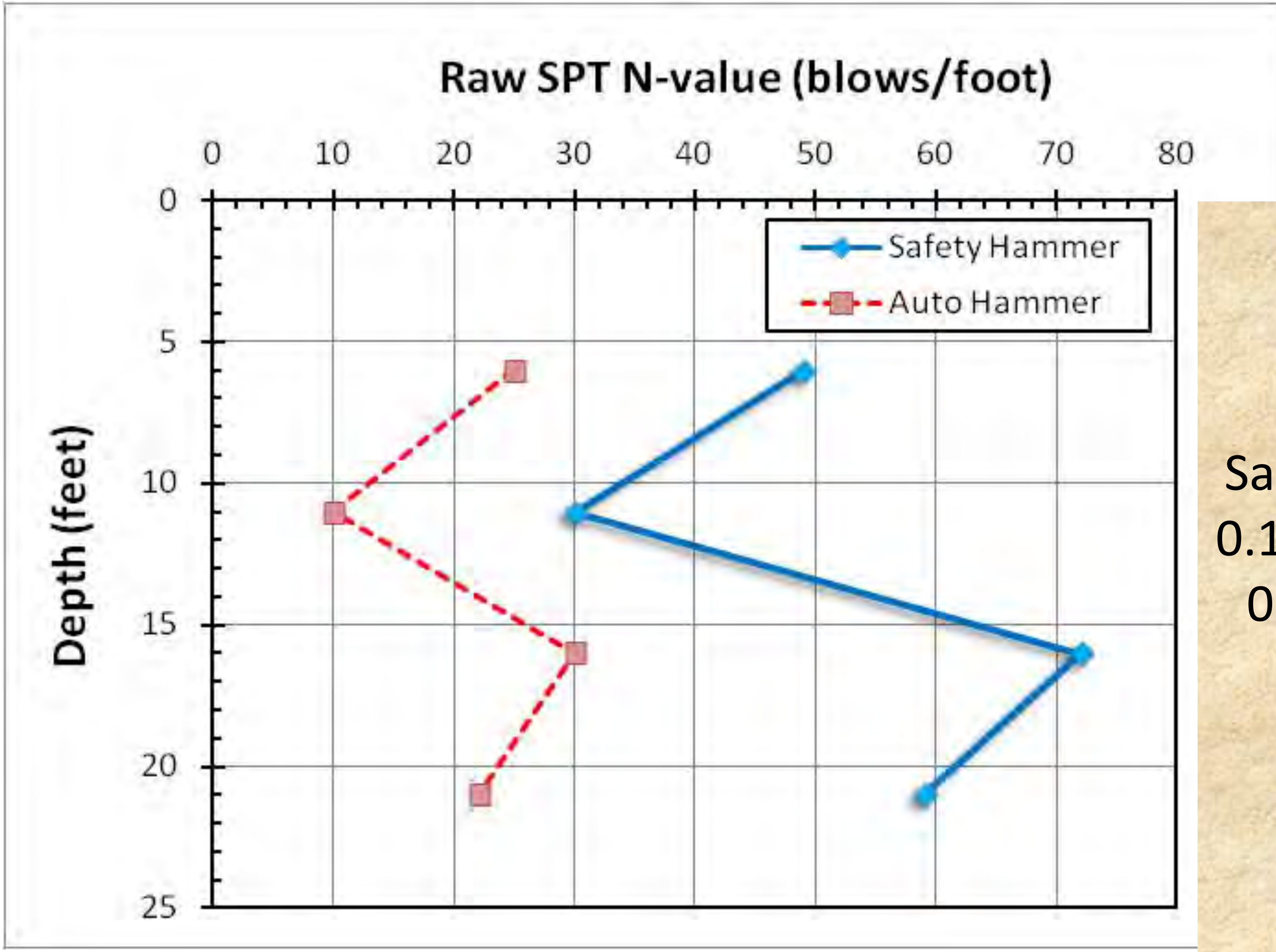
- For Clean Sands: Stress-normalization of SPT-N value: $(N_1)_{60} = C_N N_{60}$ = Energy-corrected N-value normalized to an effective overburden stress of one atmosphere. Note: this is often called an "overburden correction".

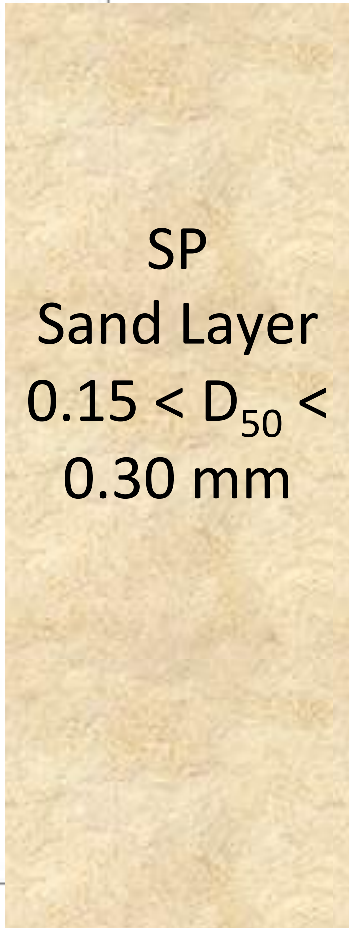
- Classically: $(N_1)_{60} = (N_{60})/(\sigma_{vo}')^{0.5}$ with stress given in atmospheres. Alternatively: $C_N = (\sigma_{atm}/\sigma_{vo}')^{0.5}$ where σ_{atm} = 1 atm ≈ 1 bar = 100 kPa ≈ 1 tsf).

- Recent approach by Boulanger & Idriss (2003, 2008, 2014), the exponent m = 0.5 is a variable that is dependent on relative density of the sand.

Northwestern University

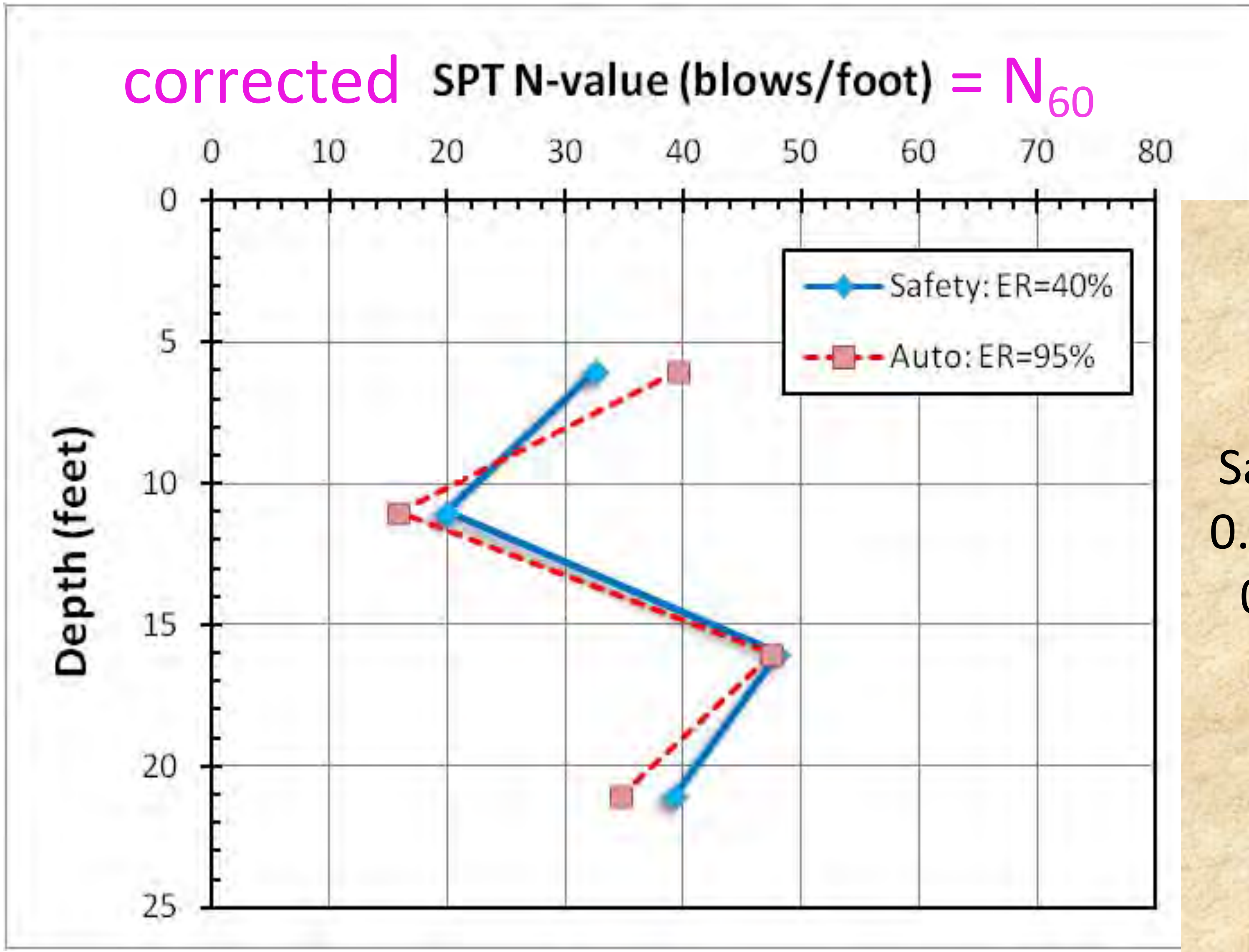
National Geotechnical Experimentation Site (Finno 2000)





Northwestern University

National Geotechnical Experimentation Site (Finno 2000)



SP

Sand Layer

$0.15 < D_{50} < 0.30$ mm

Calibration of SPT Hammer & System

ASTM D 4633 - Energy Measurements
SPT Analyzer by Pile Dynamics Inc.

Calibration of Auto Hammer Energy Ratios

Manufacturer Type	ID No.	Mean Energy Ratio (%)	Reference
Diedrich D-120	ID 26	46	UDOT
Diedrich D-50	321870551	56	GRL
CME 850	ID 21	62.7	UDOT
BK-81 w/ AW-J rods	B2	68.6	ASCE
Mobile B-80	ID 18	70.4	UDOT
SK w/ CME hammer	B6	72.9	ASCE
Diedrich D50	UF5	76	UF
CME 55	UF2	78.4	FDOT
CME 850	296002	79	GRL
CME 45	UF1	80.7	UF
CME 85	UF4	81.2	UF
CME 75 w/ AW-J rods	A3	81.4	ASCE
CME 75	UF3	83.1	UF
CME 750	ID 4	86.6	UDOT
Mobile B-57	DR-35	93	GRL
CME 75 rig	ID 10	94.6	UDOT

Factor of 2.1

Disadvantage of SPT (I&B 2008)

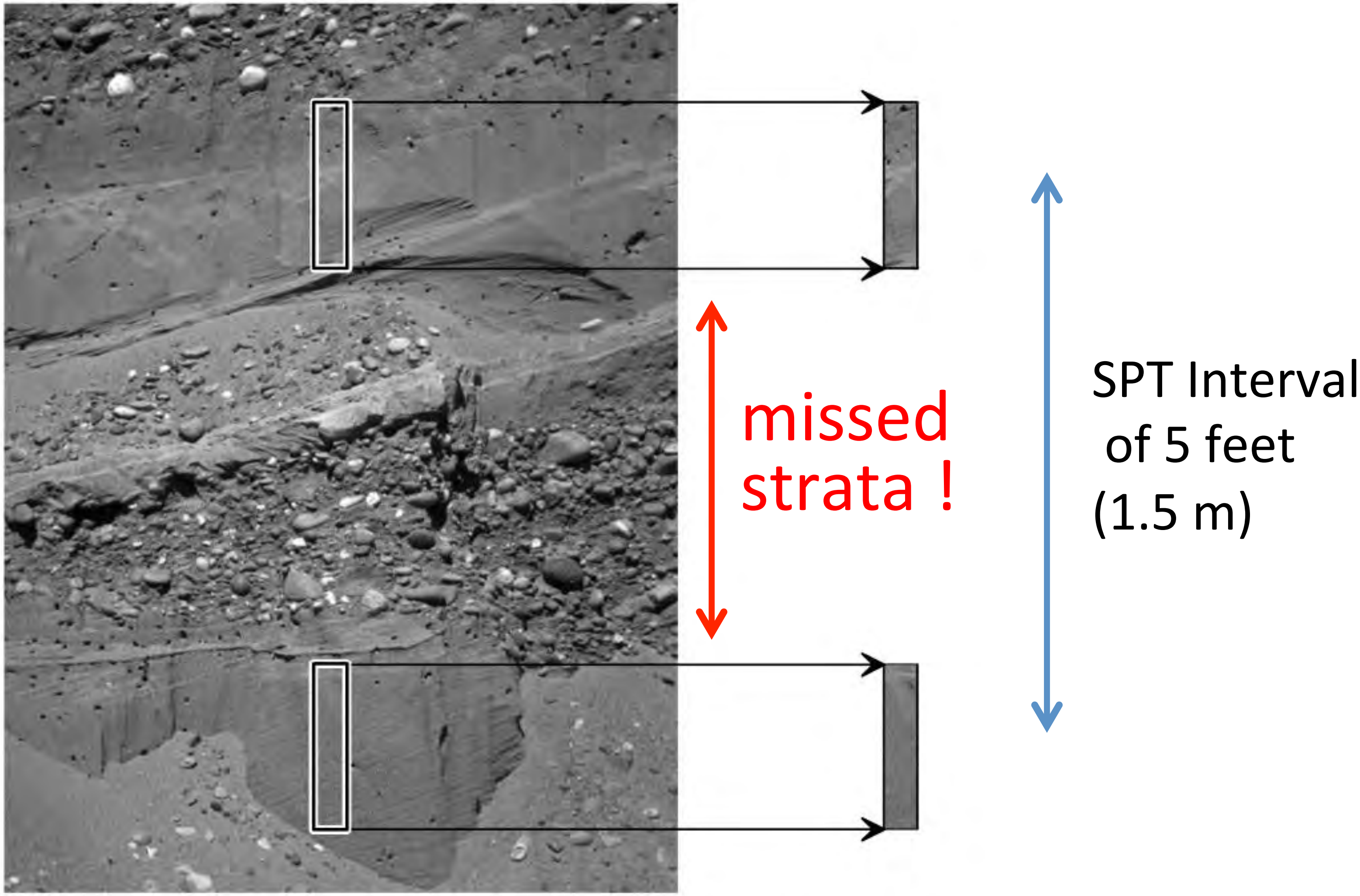
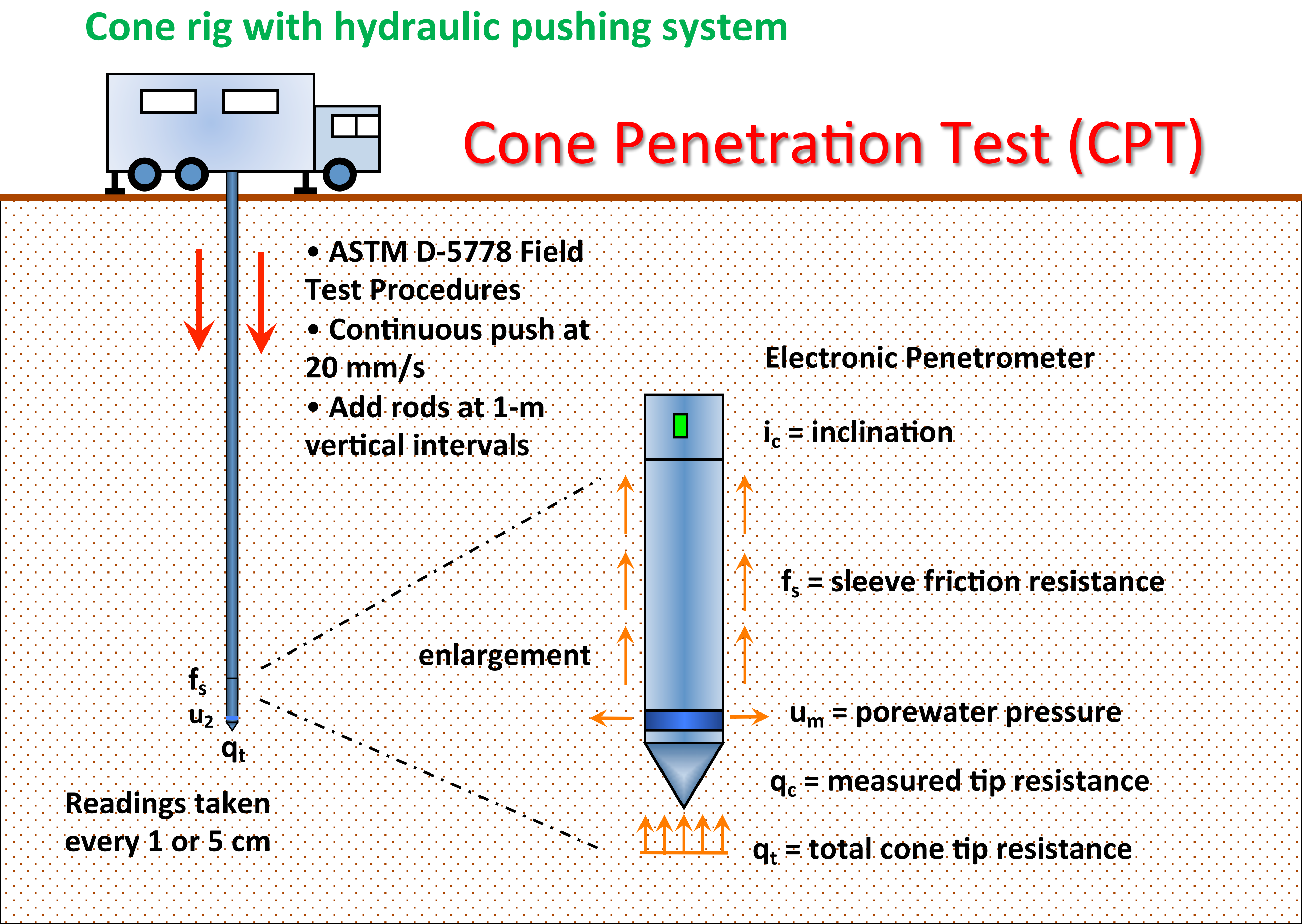


Figure 57. An excavation face showing the interlayering of sand, gravelly sand, and sandy gravel in an alluvial deposit and the portion of the deposit that would be observed via SPT samples at 1.5-m intervals.

Cone Penetration Test (CPT)

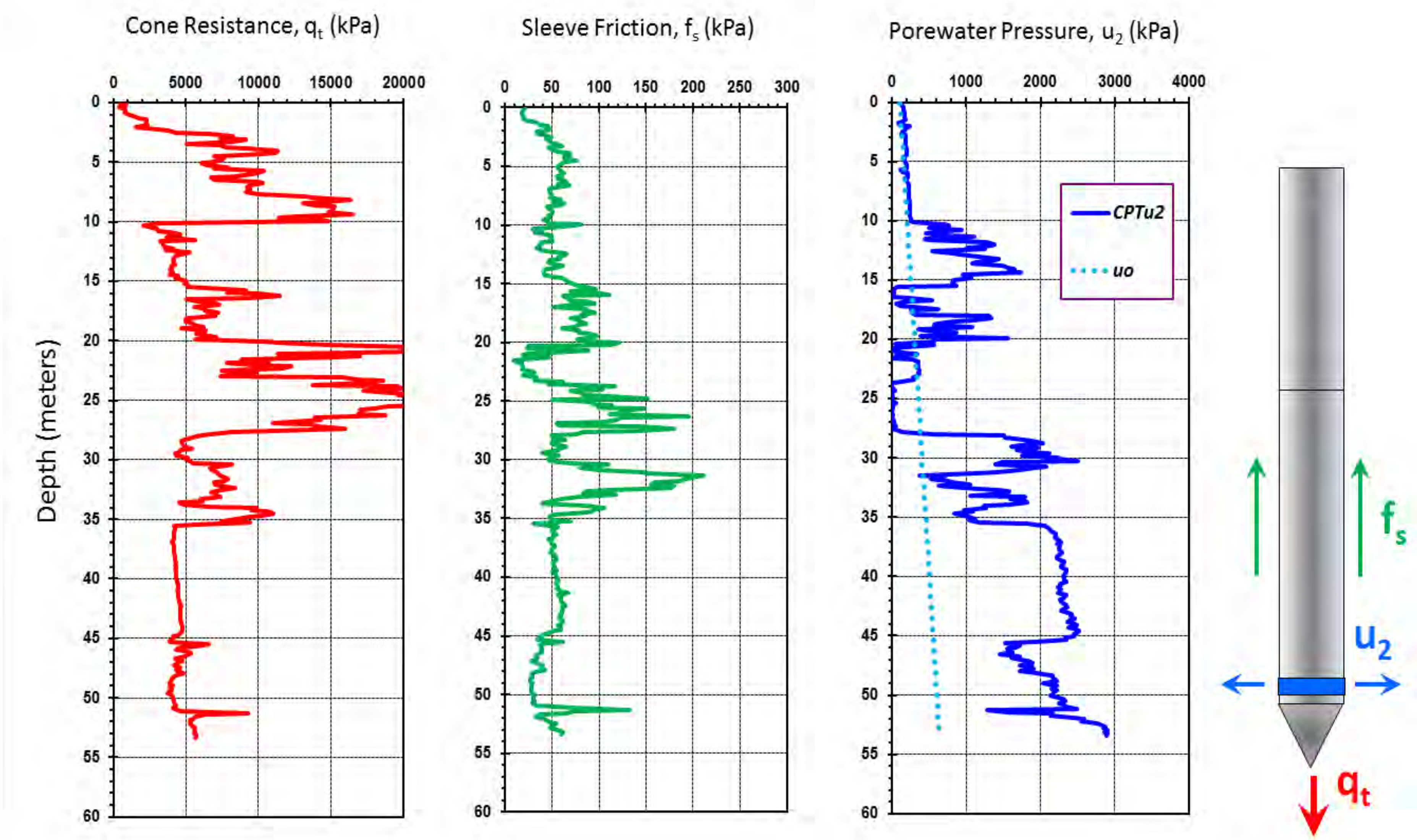


Cone Penetrometer Testing

- Electronic Steel Probes with 60° Apex Tip
- ASTM D 5778 Procedures
- Hydraulic Push at 20 mm/s
- No Boring, No Samples, No Cuttings, No Spoil
- Continuous readings of stress, friction, pressure

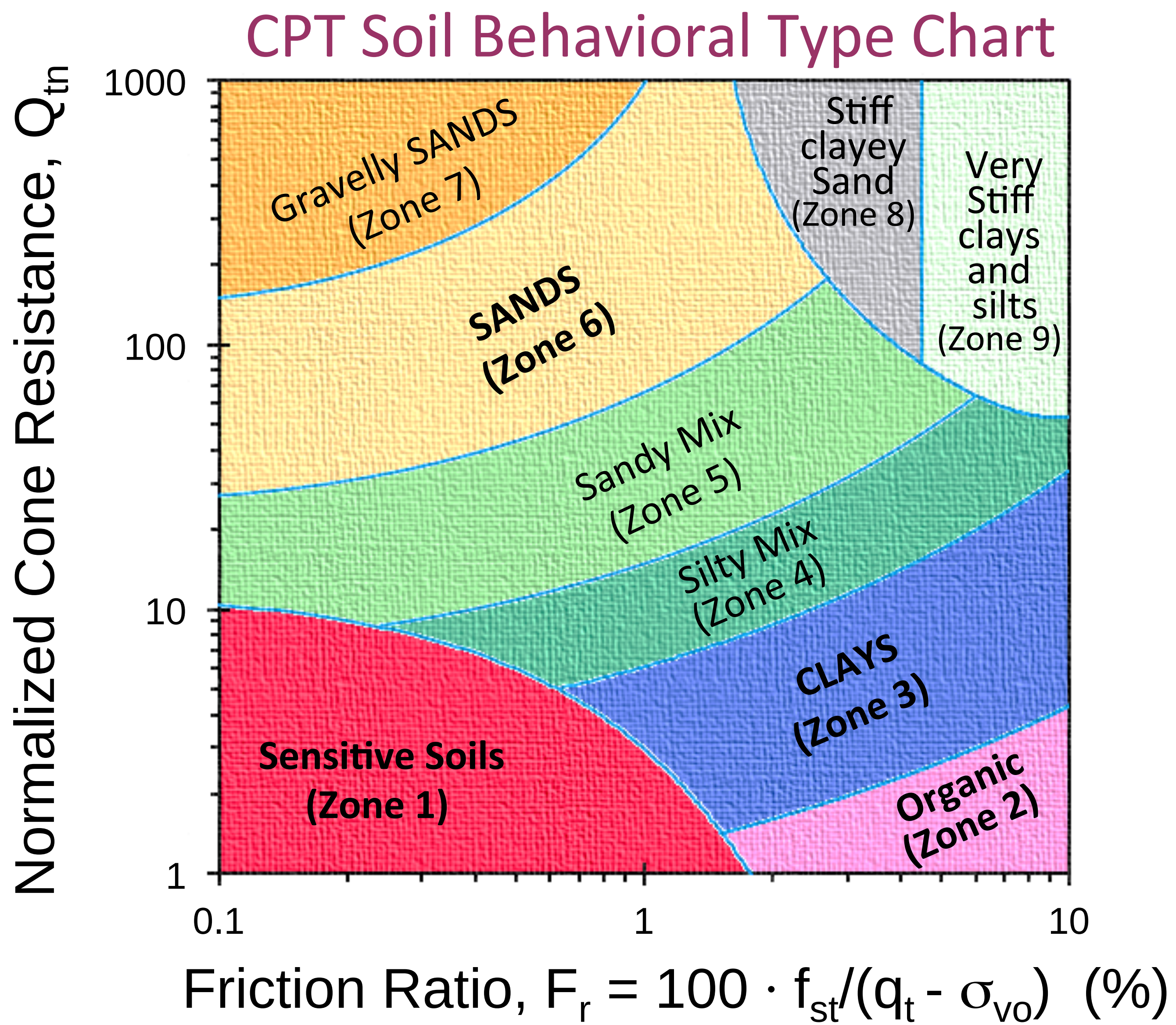
Cone Penetration Vehicles

Geostratigraphy by CPTu in Portsmouth, Virginia



Advantages of Cone Penetrometer Testing

- Continuous profiling of soil layers with depth
- Multiple readings: q_t, f_s, u_2 with depth
- Digital electronic recordings logged directly to computer
- Fast, accurate, and repeatable with immediate results
- Theoretical, analytical, and empirical methods for geotechnical interpretation



CPT Soil Behavioral Type Chart
Normalized Cone Resistance, Qtn
1000
100
10
1
0.1
1
10
Friction Ratio, Fr = 100 · fst/(qt - σvo) (%)
Gravelly SANDS (Zone 7)
SANDS (Zone 6)
Stiff clayey Sand (Zone 8)
Very Stiff clays and silts (Zone 9)
Sandy Mix (Zone 5)
Silty Mix (Zone 4)
CLAYS (Zone 3)
Sensitive Soils (Zone 1)
Organic (Zone 2)

Soil Behavioral Type (SBTn) Chart for normalized CPT

(after Robertson 2009)

9 - ZONE SBT

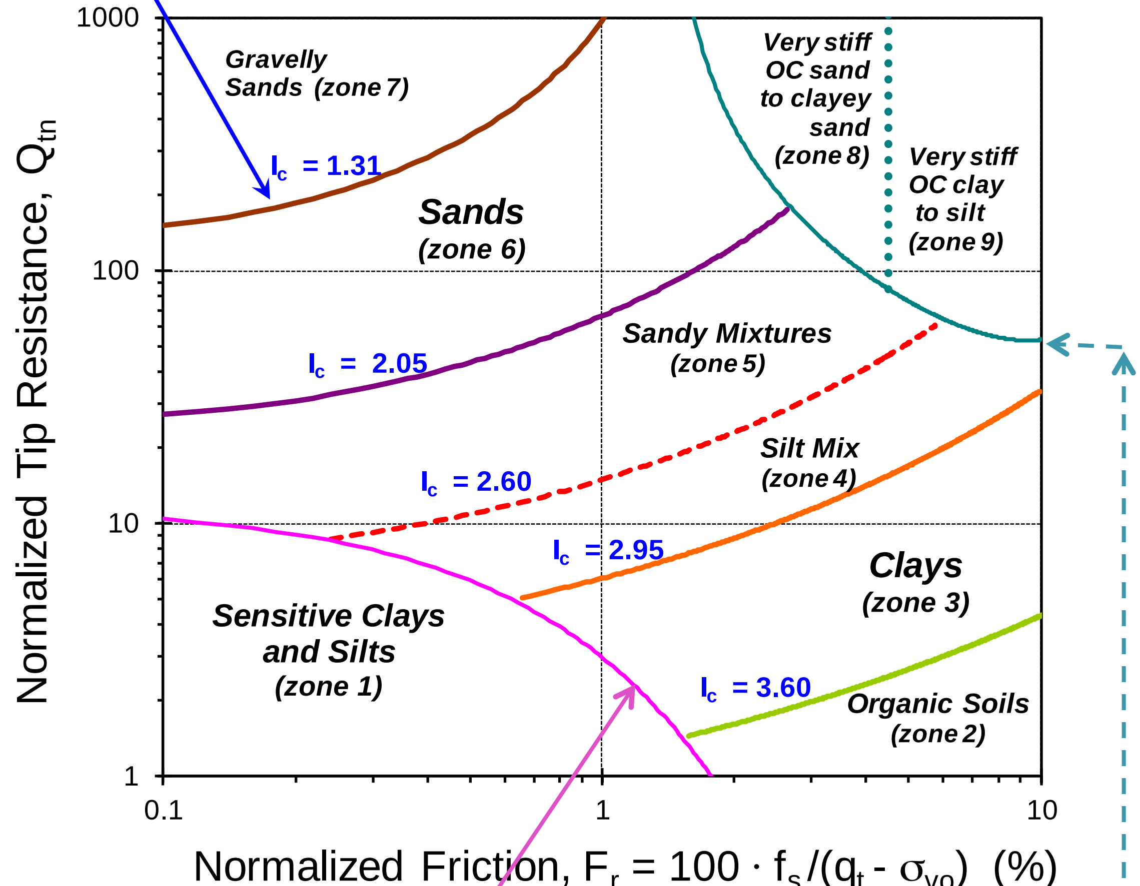
Notes:

$$Q_{tn} = \frac{(q_t - \sigma_{vo}) / \sigma_{atm}}{(\sigma_{vo}' / \sigma_{atm})^n}$$

Exponent: $n = 0.381 \cdot I_c + 0.05 \cdot (\sigma_{vo}' / \sigma_{atm}) - 0.15$

Focal Point

I_c = Radius: $I_c = \sqrt{(3.47 - \log Q_{tn})^2 + (1.22 + \log F_r)^2}$



$I_c < 2.6$: Drained
$I_c > 2.6$: Undrained

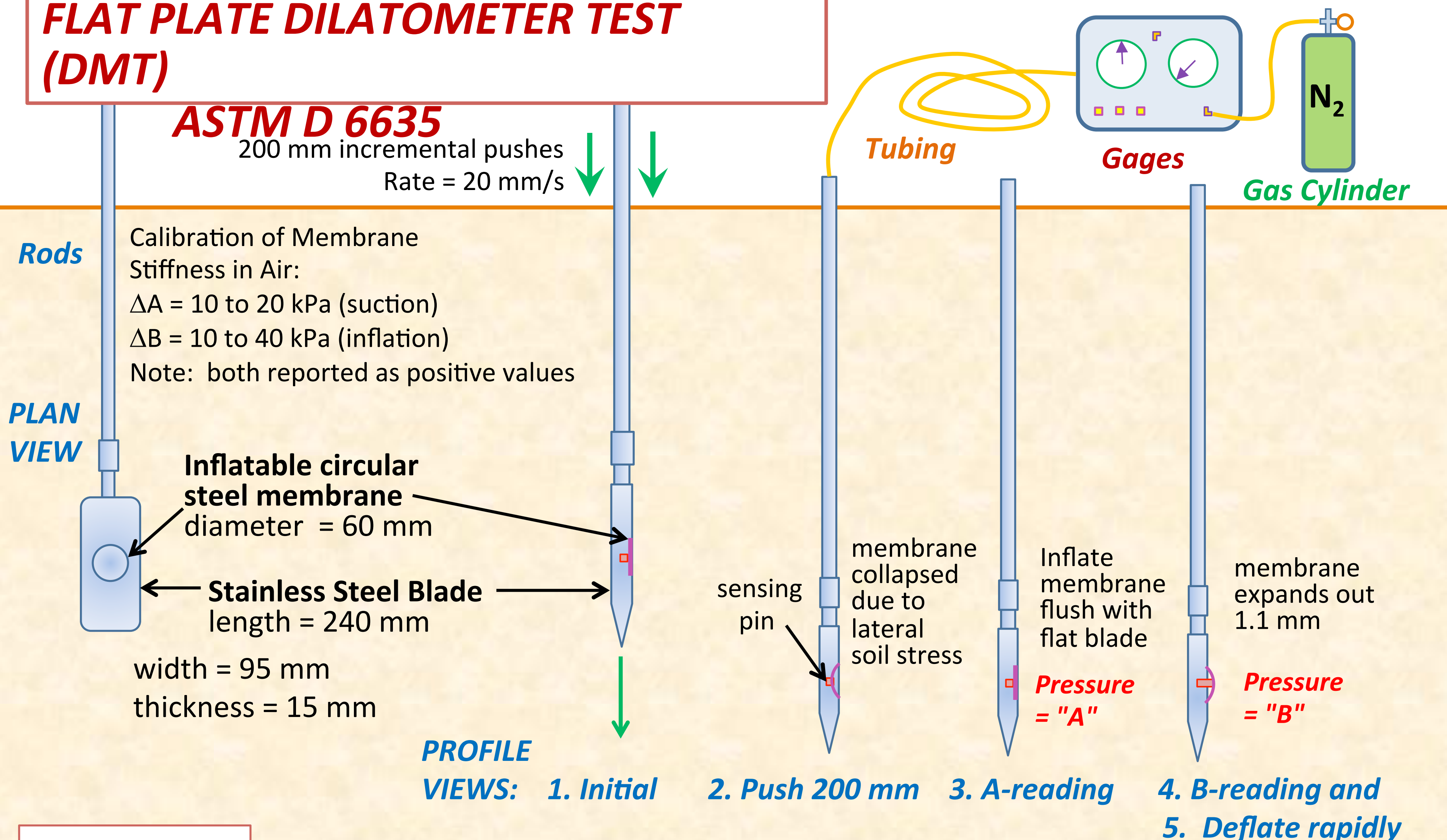
Approximate Algorithm Steps:

a. Find sensitive soils of zone 1 identified when: $Q_{tn} < 12 \exp(-1.4 F_r)$

b. Identify: Zone 8 ($1.5 < F_r < 4.5\%$) and Zone 9 ($F_r > 4.5\%$): $Q_{tn} \geq \dfrac{1}{+0.006(F_r - 0.9) - 0.0004(F_r - 0.9)^2 - 0.002}$

c. Use CPT index I_c for Zones 2 through 7

FLAT PLATE DILATOMETER TEST (DMT)



DMT INDICES

$I_D = (p_1 - p_0)/(p_0 - u_0)$ = material index

$E_D = 34.7\,(p_1 - p_0)$ = dilatometer modulus

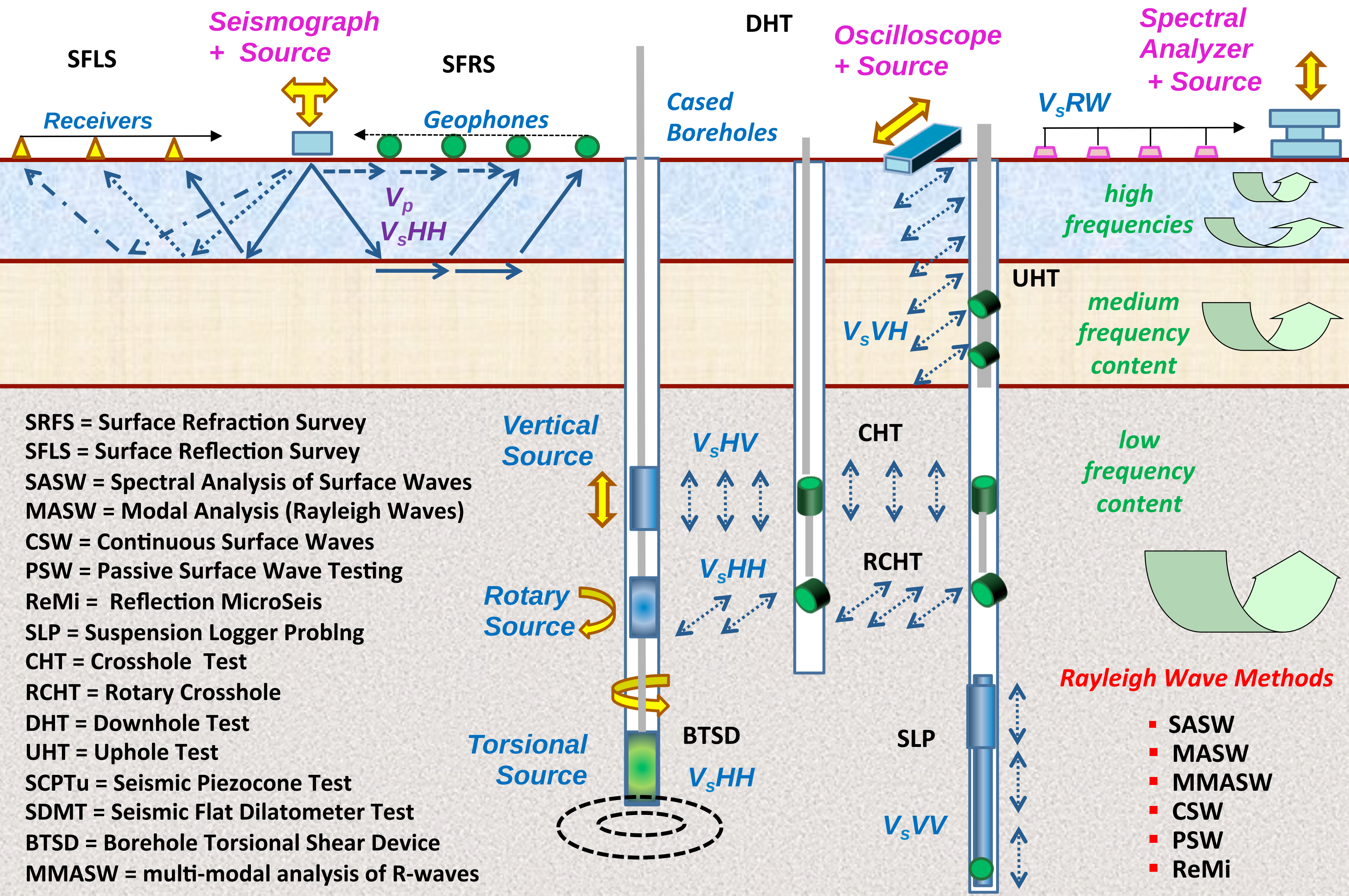
$K_D = (p_0 - u_0)/\sigma_{vo}'$ = horizontal stress index

Corrected DMT Readings:

$p_0 = 1.05(A+\Delta A) - 0.05\,(B-\Delta B)$ = contact pressure

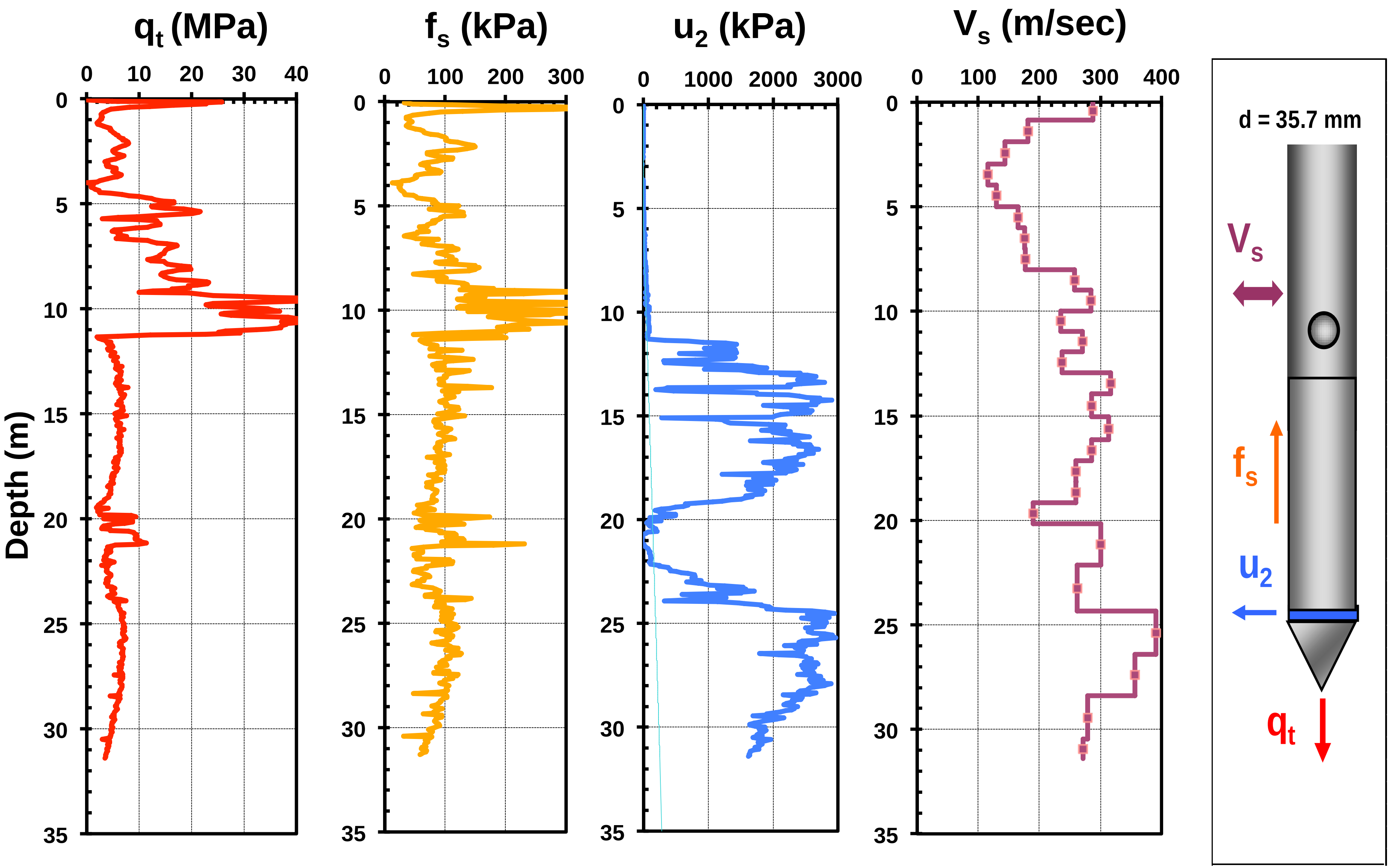
$p_1 = B - \Delta B$ = expansion pressure

Field Geophysics - Mechanical Wave Methods



SRFS = Surface Refraction Survey
SFLS = Surface Reflection Survey
SASW = Spectral Analysis of Surface Waves
MASW = Modal Analysis (Rayleigh Waves)
CSW = Continuous Surface Waves
PSW = Passive Surface Wave Testing
ReMi = Reflection MicroSeis
SLP = Suspension Logger Problng
CHT = Crosshole Test
RCHT = Rotary Crosshole
DHT = Downhole Test
UHT = Uphole Test
SCPTu = Seismic Piezocone Test
SDMT = Seismic Flat Dilatometer Test
BTSD = Borehole Torsional Shear Device
MMASW = multi-modal analysis of R-waves

SCPTu Sounding – Memphis, TN



Cost Comparison to profile V_s to 30 m

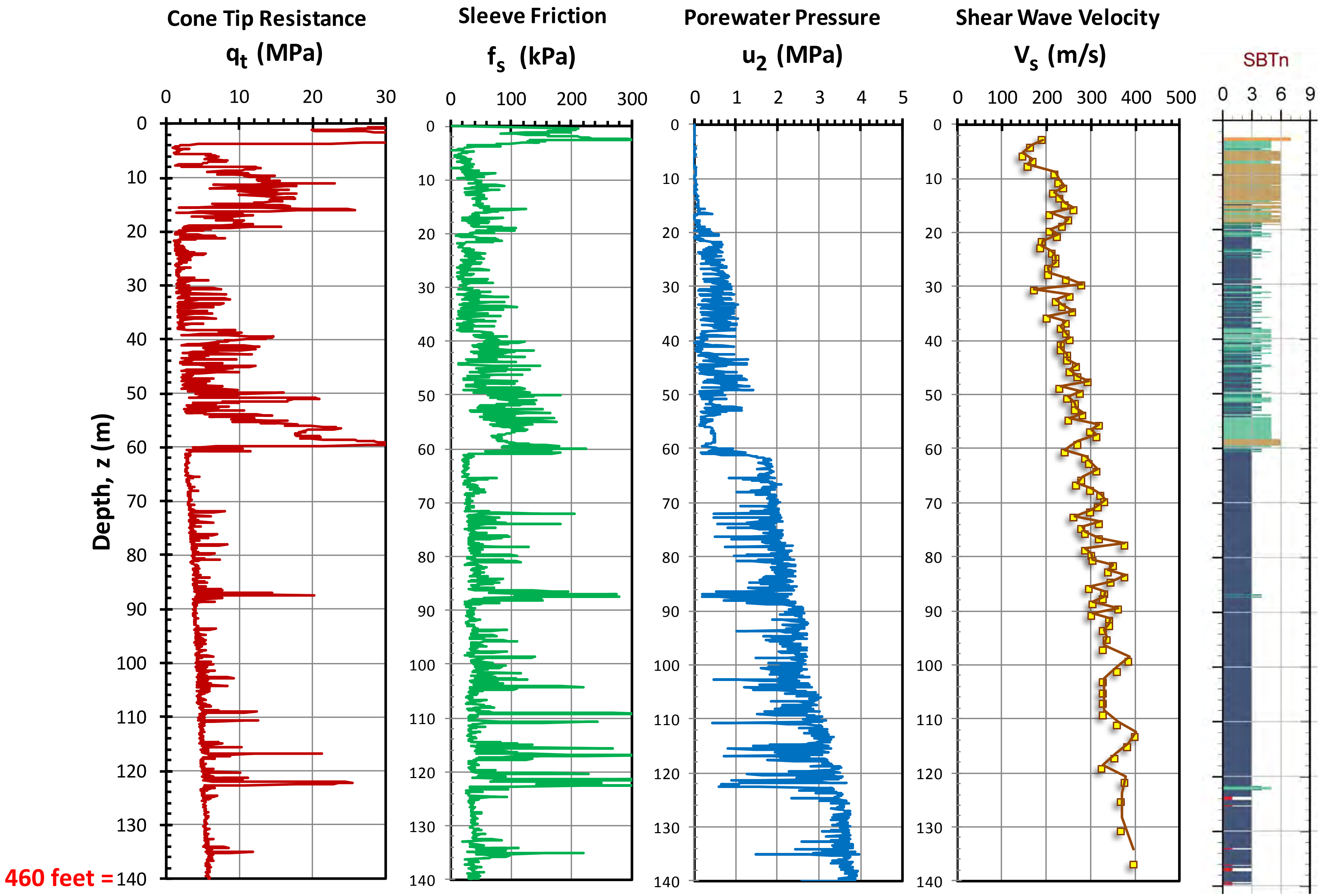
METHOD	TYPICAL COST
Suspension Logging (PSSL)	$ 35,000#
Crosshole Testing (CHT)	$ 20,000
Downhole Testing (DHT)	$ 9,000
Surface Waves (SASW, MASW)	$ 4,500
ReMi Passive Surface Waves	$ 2,500
Seismic Piezocone*	$ 2,000

NOTE:

Typically only economical for profiling z > 60 m

* Includes 4 separate readings with depth: q_t, f_s, u_2, and V_s

Deep SCPTu - British Columbia

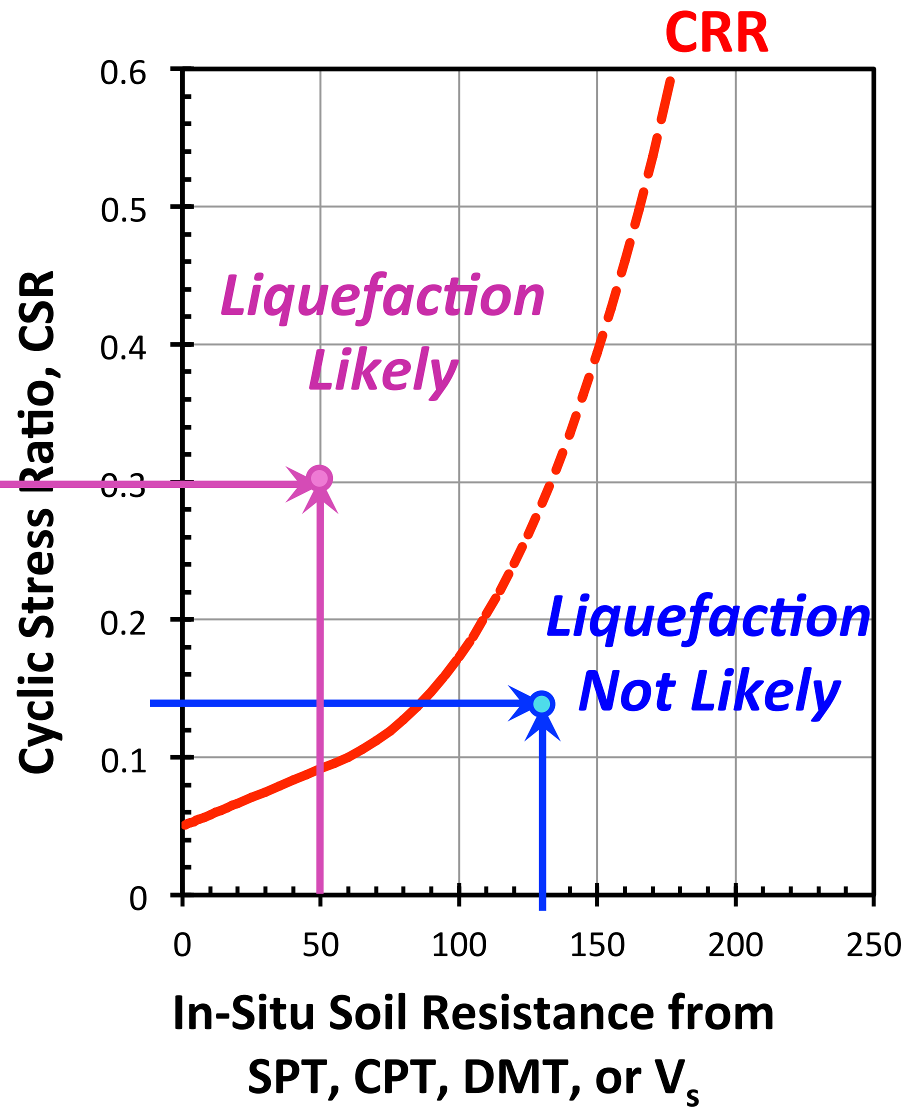


Simplified Cyclic Stress-Based Procedures

- Level of Ground Shaking:

$$CSR_{7.5} = \frac{\tau_{ave}}{\sigma'_{vo}} = 0.65 \cdot \left(\frac{a_{max}}{g}\right) \cdot \left(\frac{\sigma_{vo}}{\sigma'_{vo}}\right) \cdot \frac{r_d}{MSF}$$

- Soil resistance based on in-situ field tests:
  - **SPT = standard penetration**
  - **CPT = cone penetration**
  - **V_s = shear wave velocity**
  - **DMT = flat dilatometer**
- Compare CSR with *Cyclic Resistance Ratio (CRR)* for likelihood for liquefaction.



Evidence of Liquefaction

Christchurch NZ 2011

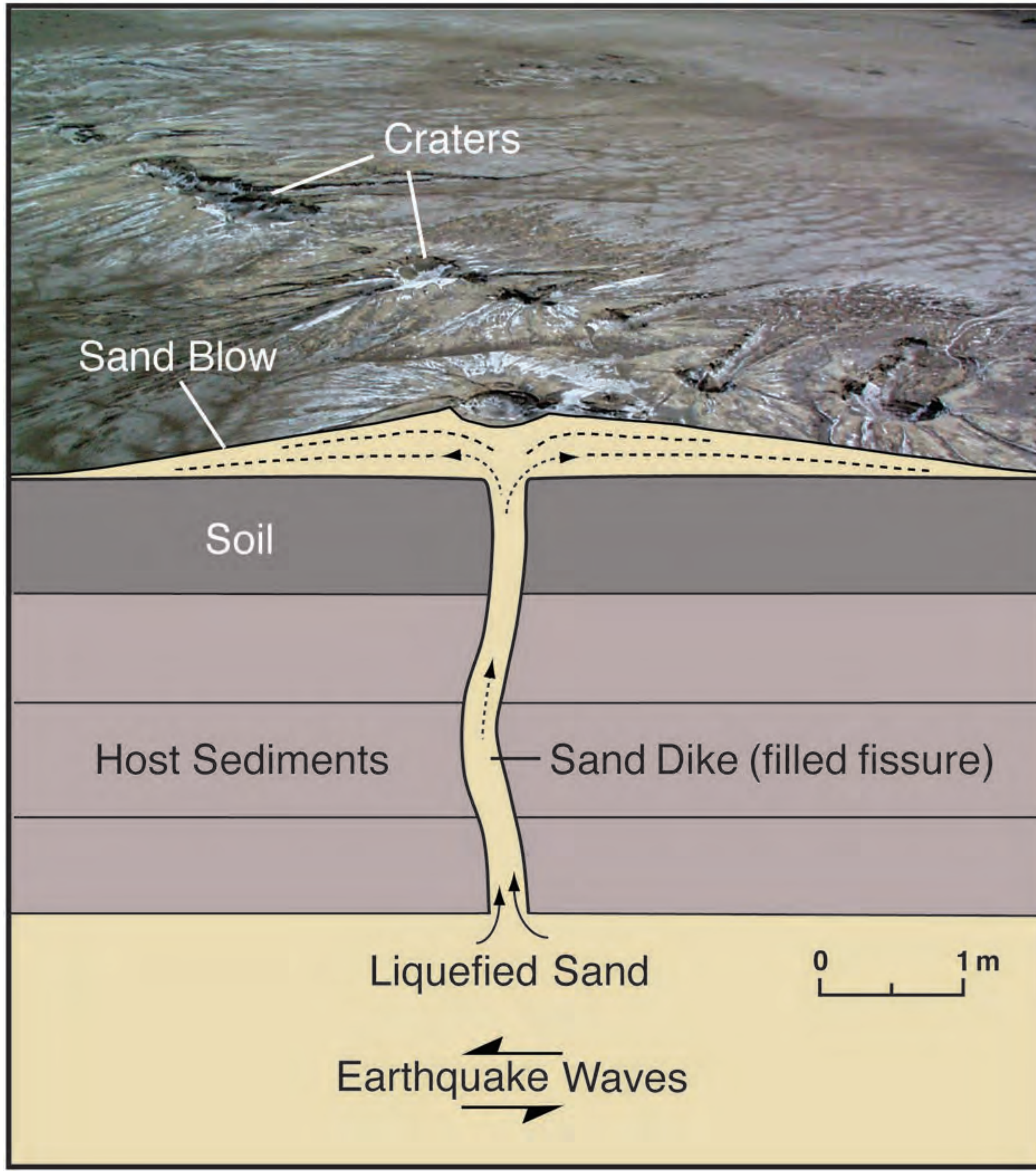
Christchurch NZ 2011

Sand Boils
(Bhuj 2001)

Sand Boils
(Chile 2010)

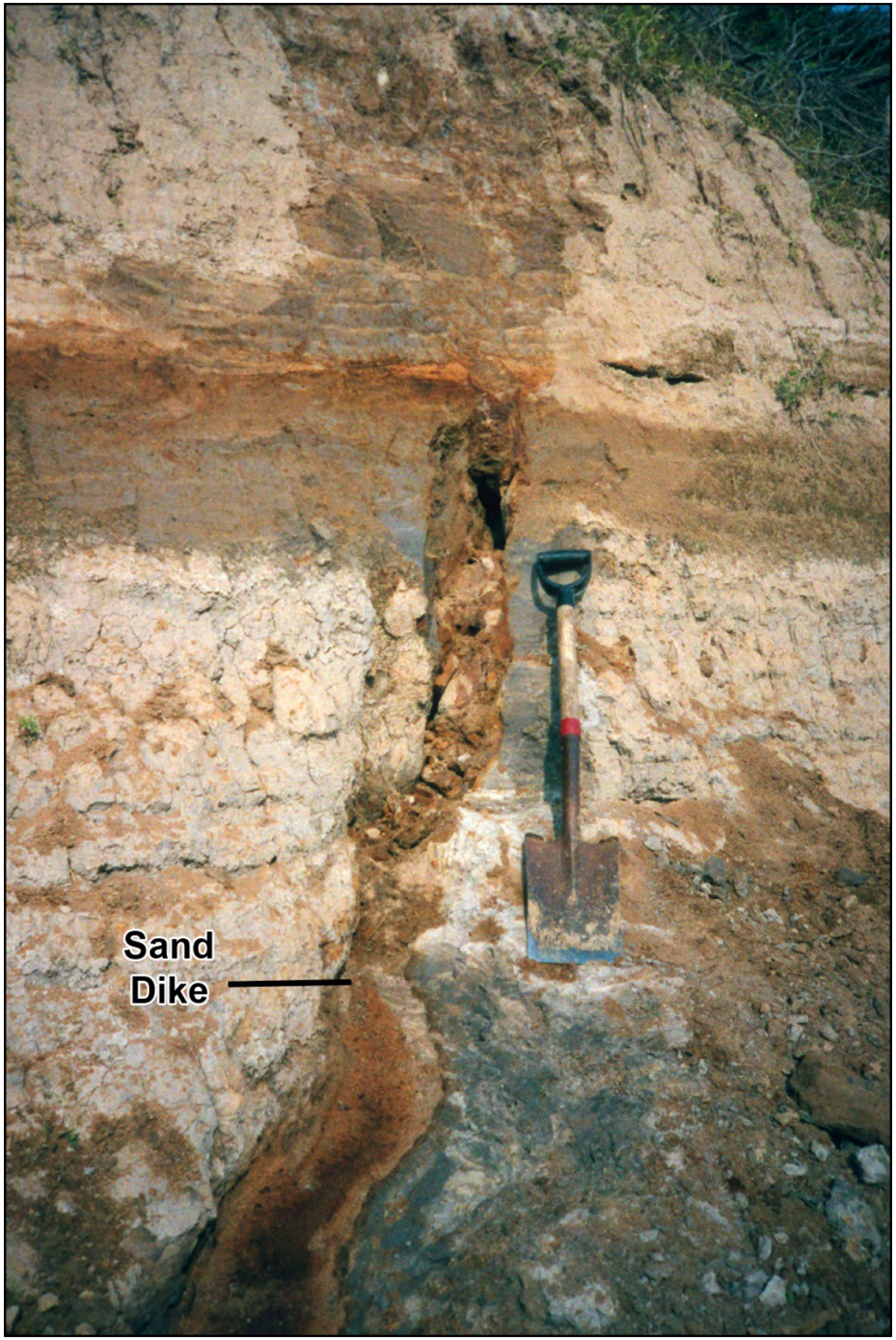
Evidence of Soil Liquefaction

Paleoliquefaction Studies (Sims and Garvin 1995)



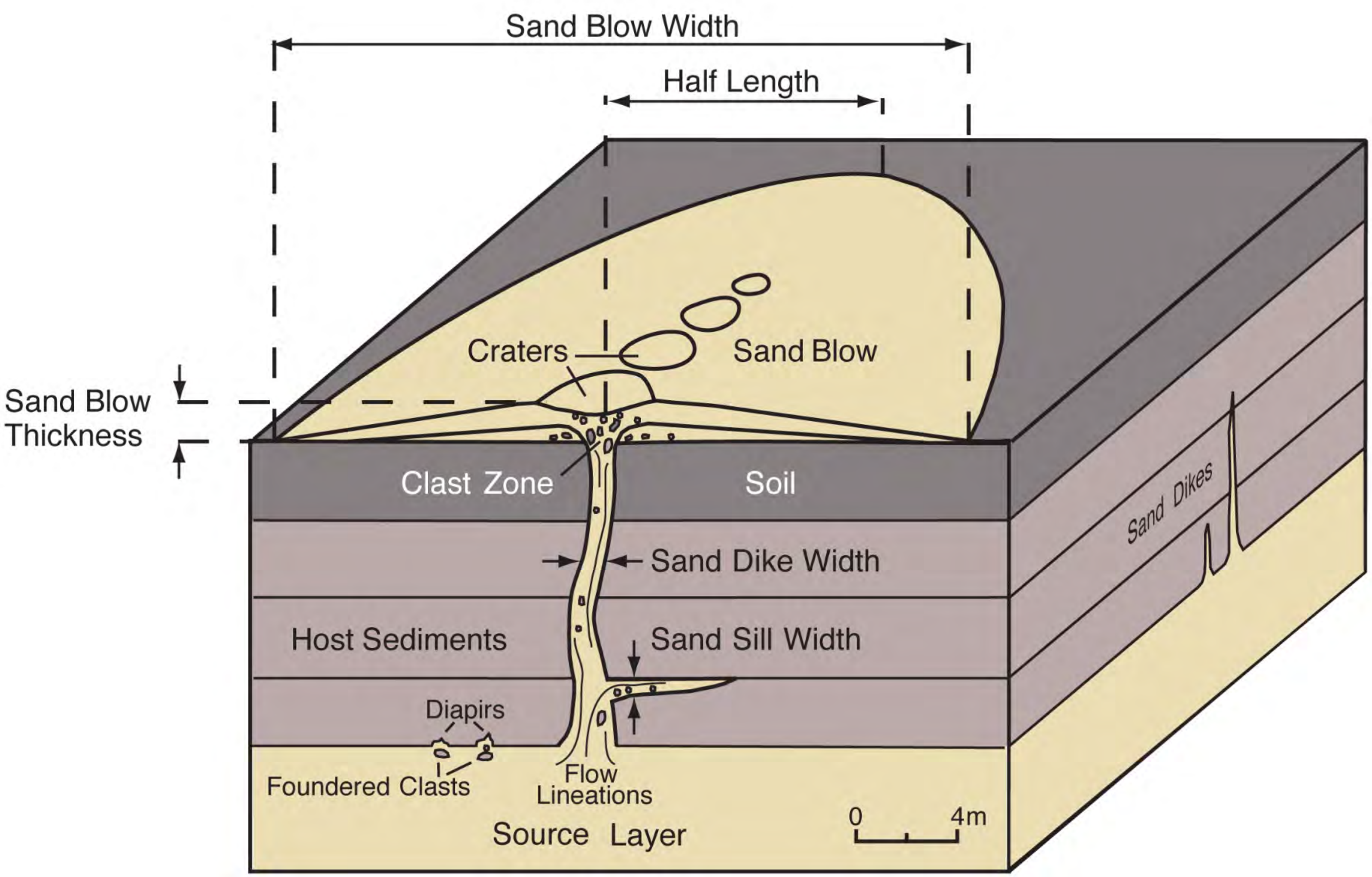
Evidence of Soil Liquefaction

Paleoliquefaction Studies (Tuttle 2015)

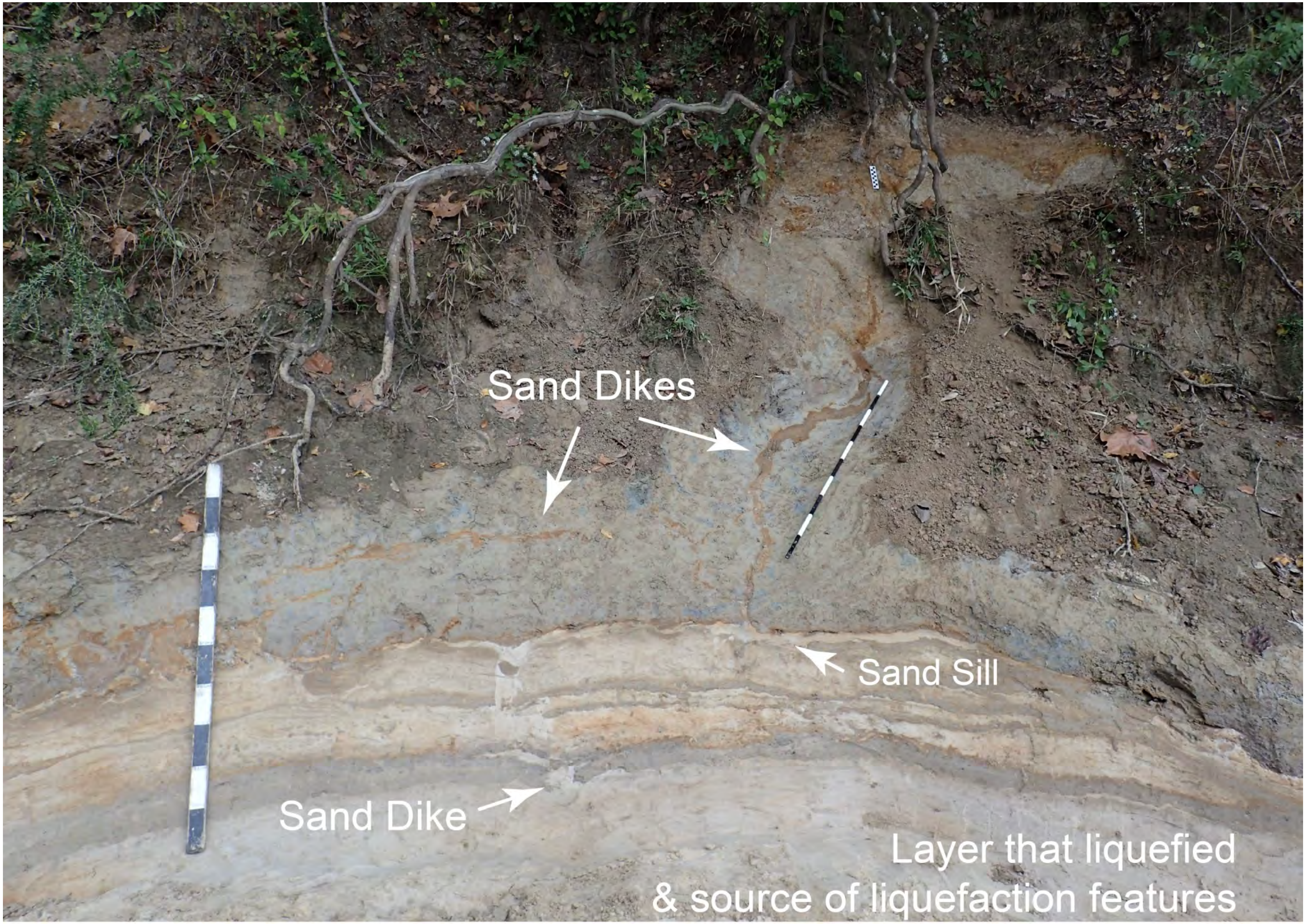


Evidence of Soil Liquefaction

Paleoliquefaction Studies (Tuttle 2015)

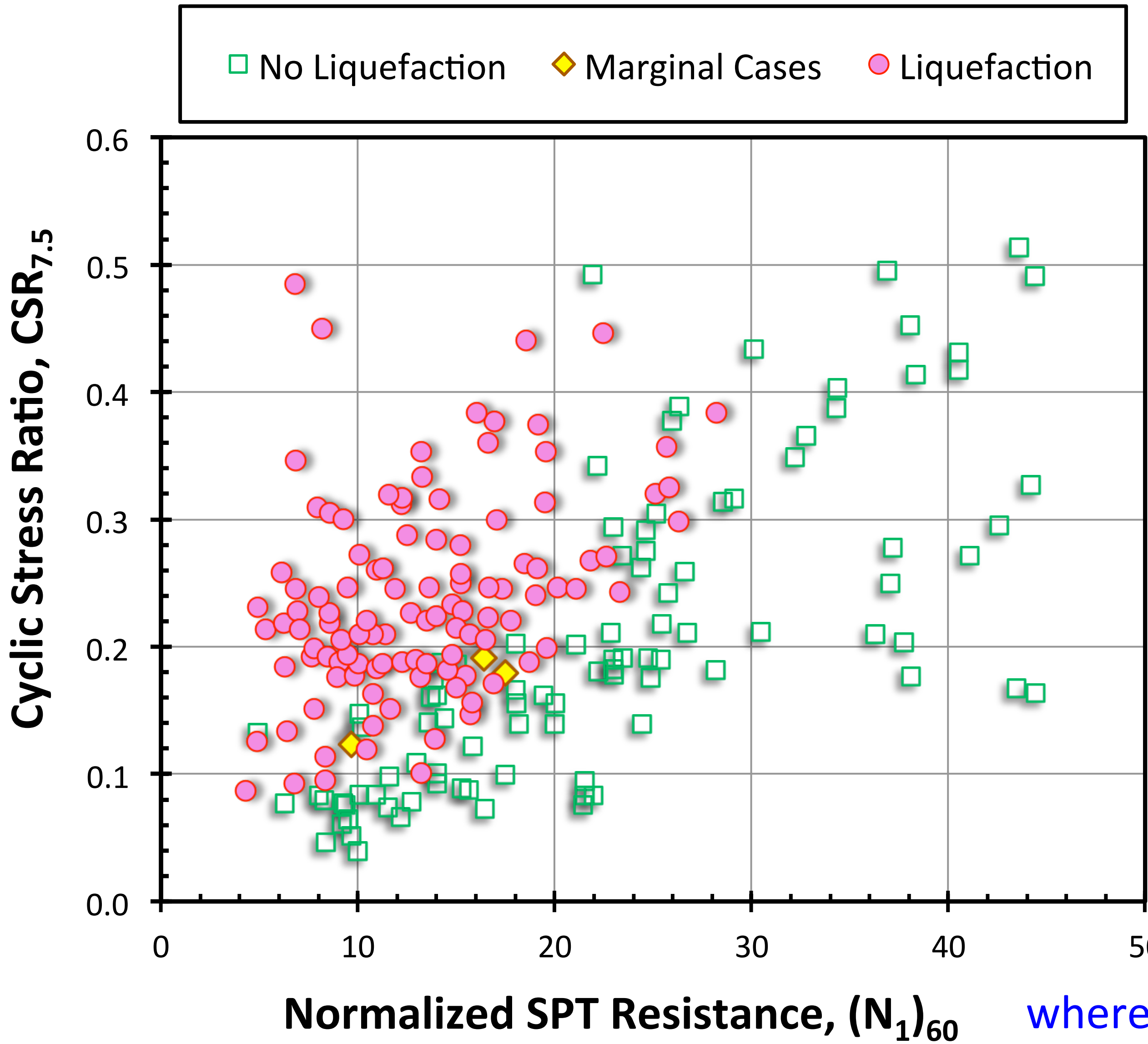


Paleoliquefaction Studies (Tuttle 2015)



Evaluate Soil Resistance to Liquefaction

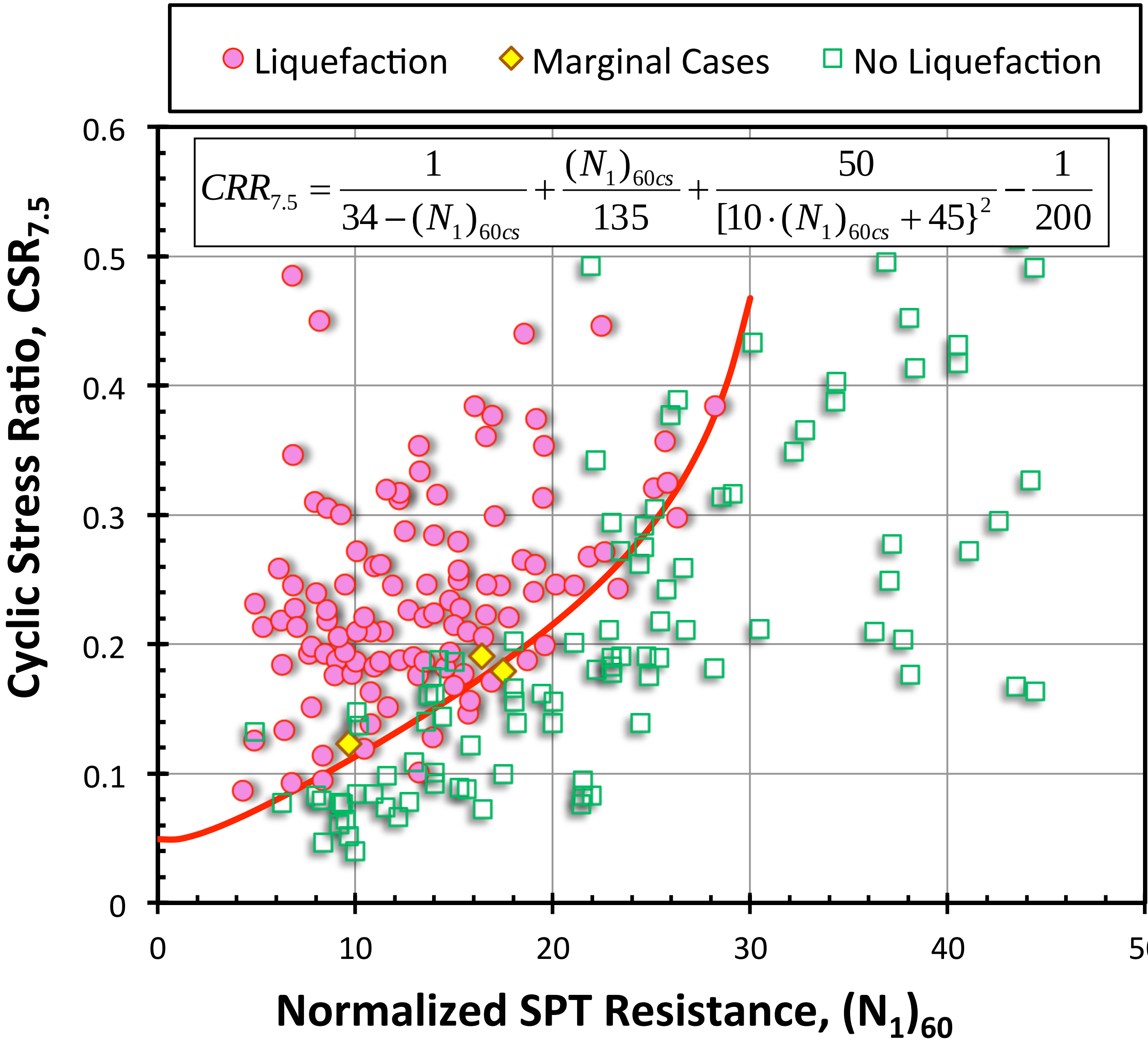
Case History Sites Having Experienced an Earthquake



where $(N_1)_{60}$
$= N_{60}/(\sigma_{vo}'/\sigma_{atm})^{0.5}$

Evaluate Soil Resistance to Liquefaction

Case History Sites Having Experienced an Earthquake

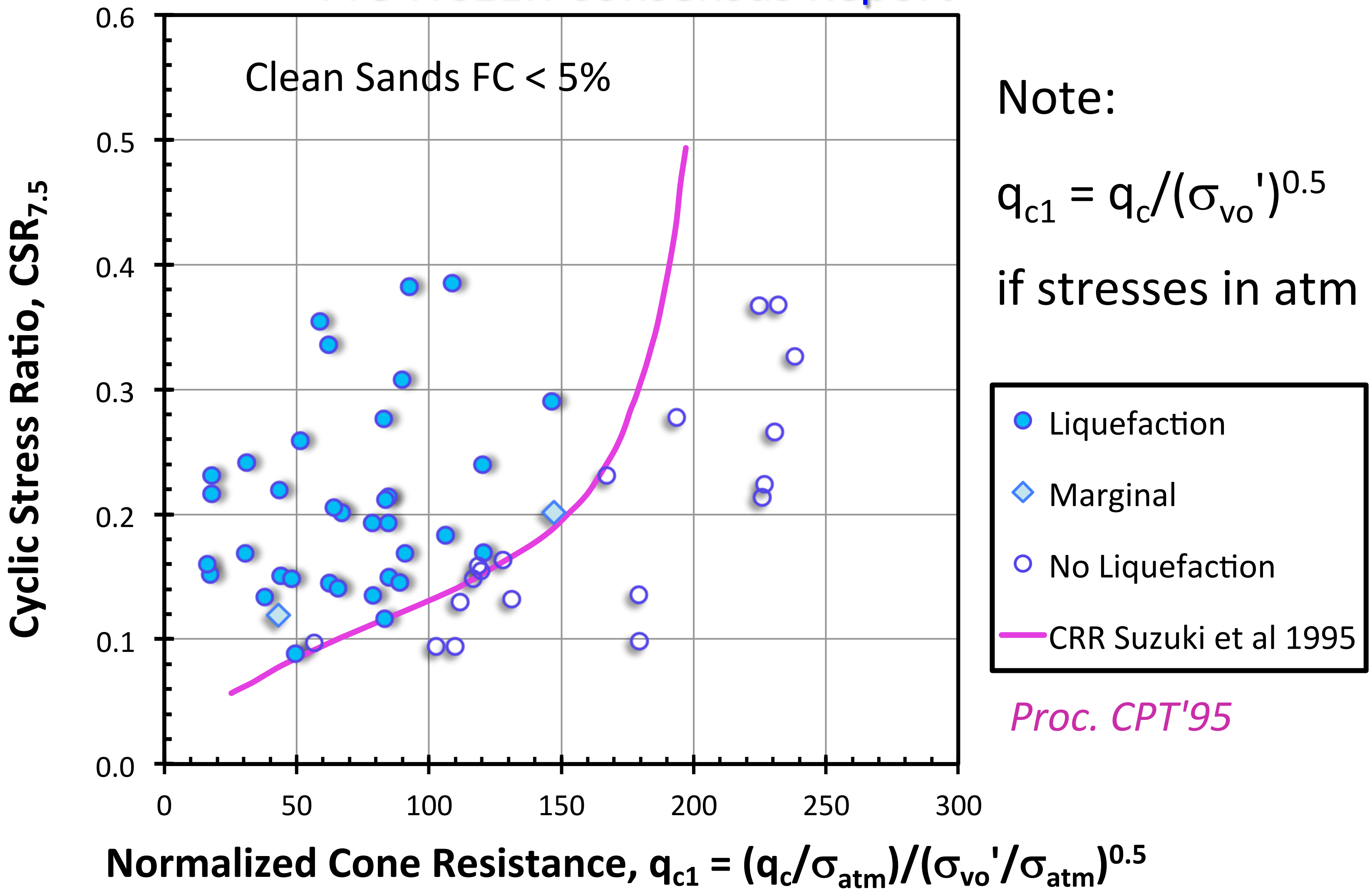


NCEER (2001)

Only valid for $(N_1)_{60} < 30$

Evaluate Soil Resistance to Liquefaction from CPT

Pre-NCEER Consensus Report



Note:

$q_{c1} = q_c/(\sigma_{vo}')^{0.5}$

if stresses in atm

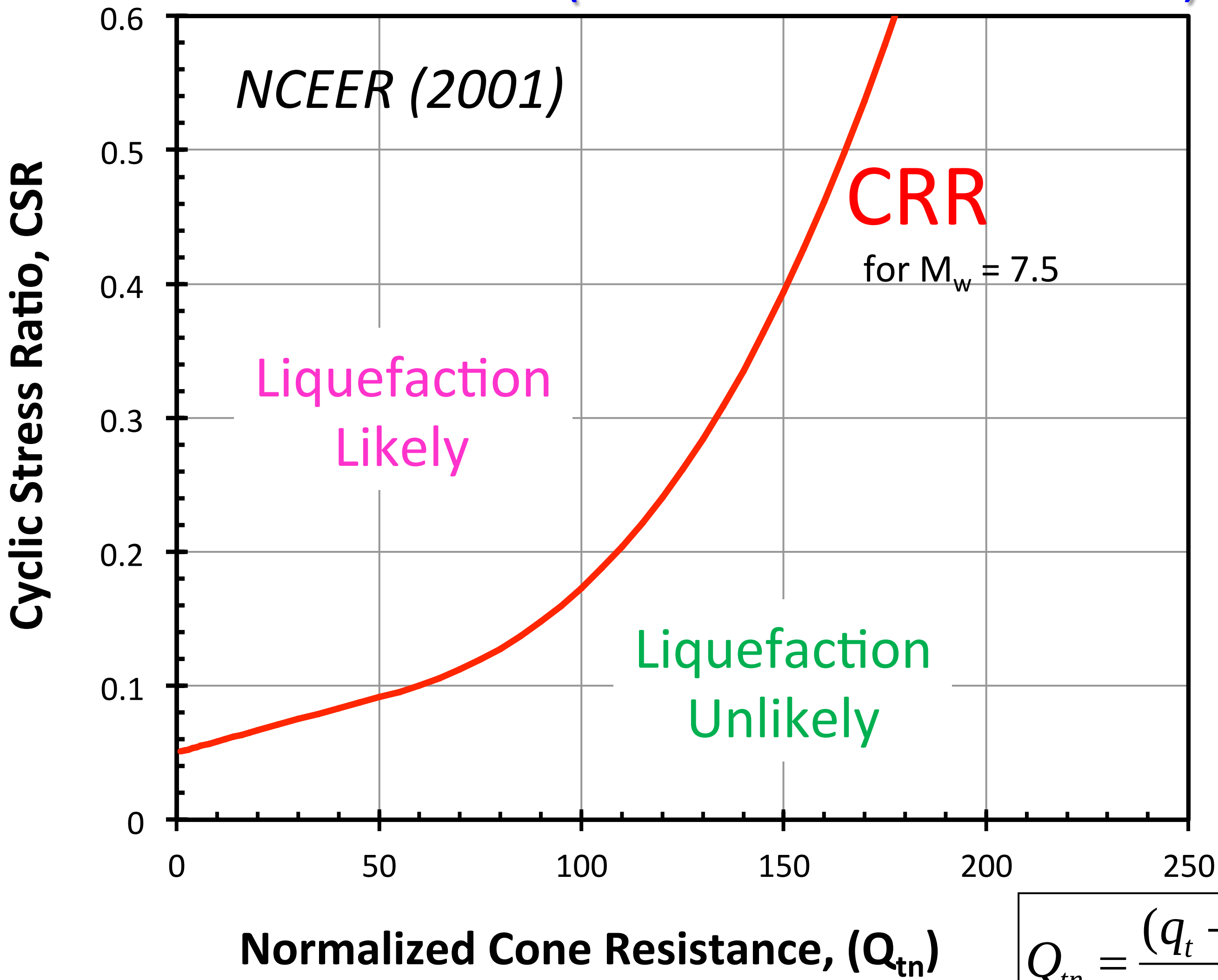
Proc. CPT'95

Competing CPT Liquefaction Evaluation

- Pre-NCEER
  - De Alba et al. (1986)
  - Shibata & Teparaksa (1988)
  - Suzuki et al. (1995)
  - Stark & Olson (1995)
- Competing CPT Liquefaction Methods:
  - NCEER/NSF (2001); Robertson & Wride 1998)
  - U-CA-Berkeley (Cetin 2004; Moss et al. 2006)
  - U-CA-Davis (Idriss & Boulanger 2004; 2006)
  - State Parameter (Jefferies & Been 2006)

Evaluate Soil Liquefaction by CPT

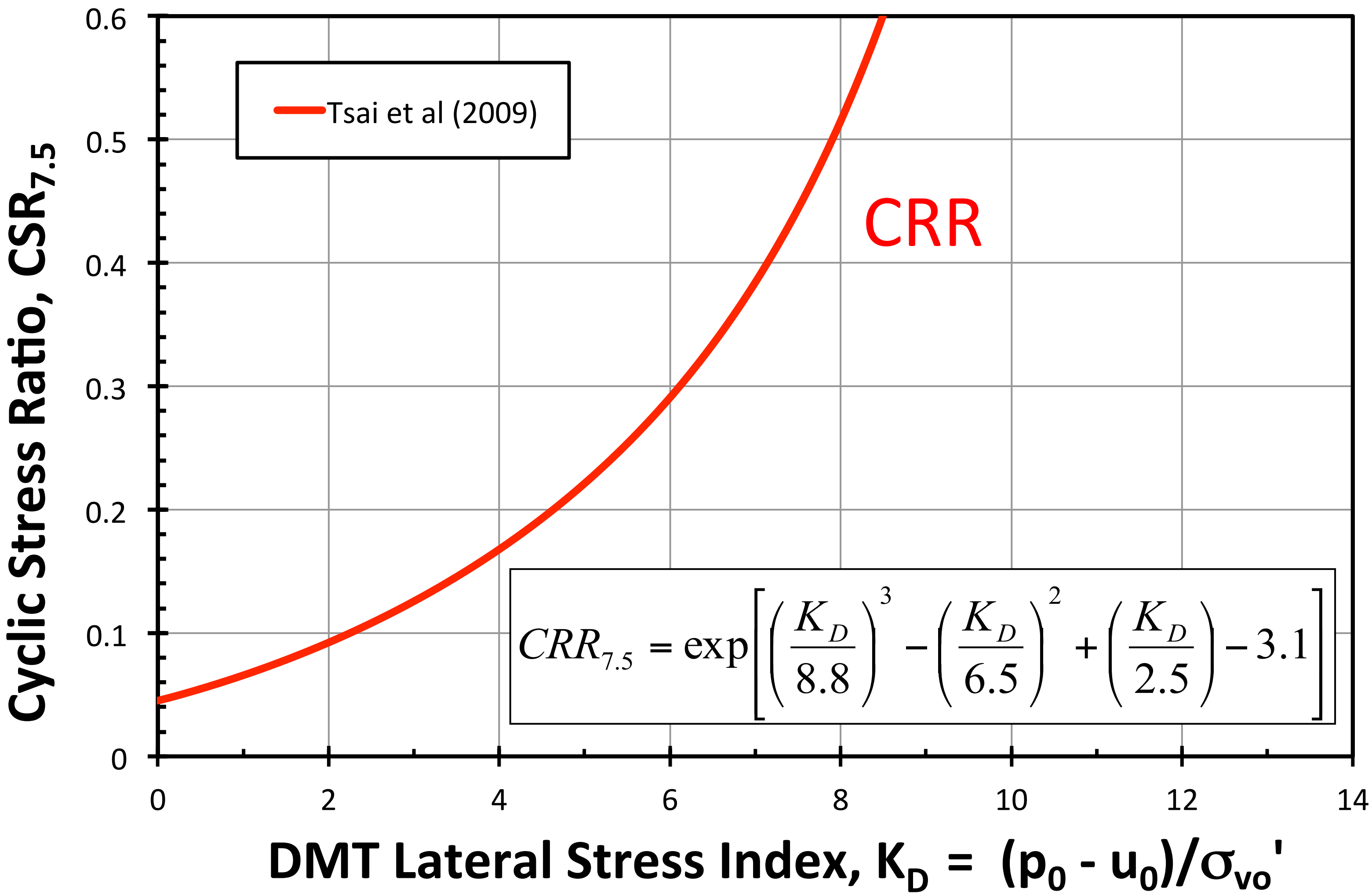
for clean sands (Robertson & Wride 1998)



$$Q_{tn} = \frac{(q_t - \sigma_{vo}) / \sigma_{atm}}{(\sigma_{vo}' / \sigma_{atm})^n}$$

Evaluate Soil Resistance to Liquefaction from DMT

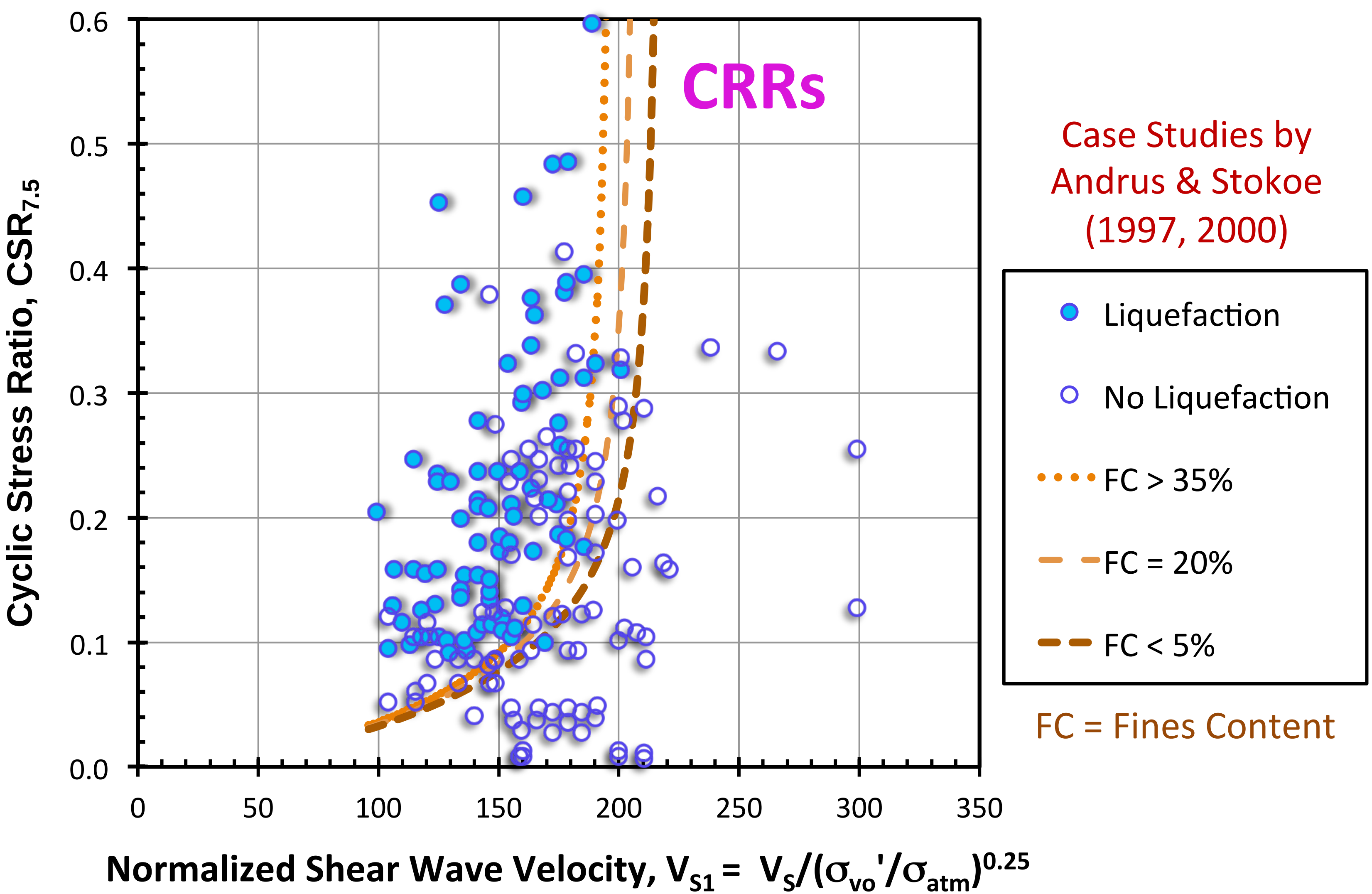
Tsai, P-H., Lee, D-H., Kung, G.T-C., and Juang, C.H. (2009). "Simplified DMT-based methods for evaluating liquefaction resistance of Soils." *Engineering Geology,* Vol. 103: 13-22



$$CRR_{7.5} = \exp\left[\left(\frac{K_D}{8.8}\right)^3 - \left(\frac{K_D}{6.5}\right)^2 + \left(\frac{K_D}{2.5}\right) - 3.1\right]$$

Liquefaction evaluation by shear wave velocity

NCEER Consensus Report (2001)



Calculated Factor of Safety for Triggering of Soil Liquefaction

FS_{Liq} = Factor of Safety:

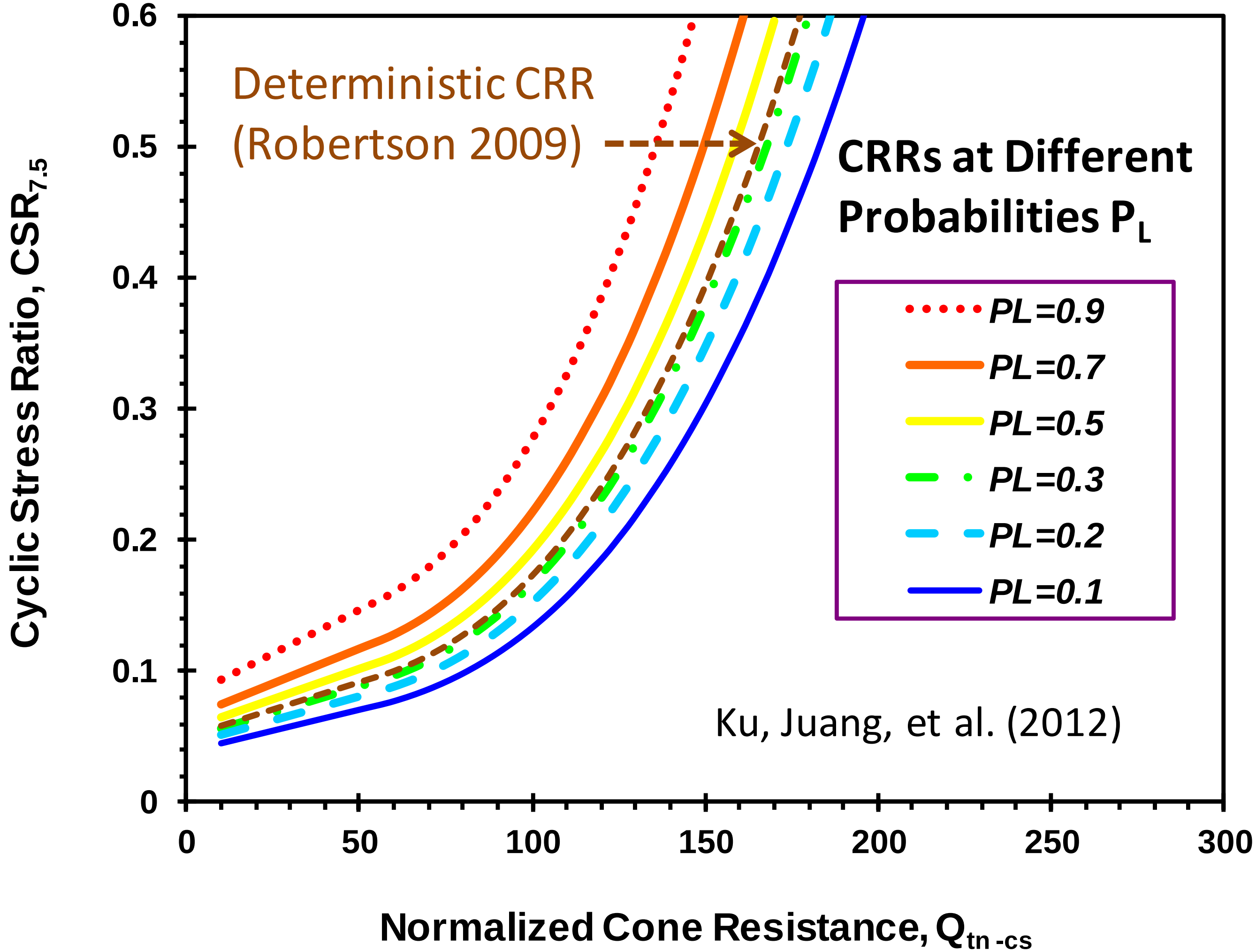
$$FS_{Liq} = \frac{CRR_{7.5}}{CSR_{7.5}}$$

where CRR and CSR are at comparable earthquake magnitudes, i.e. M = 7.5

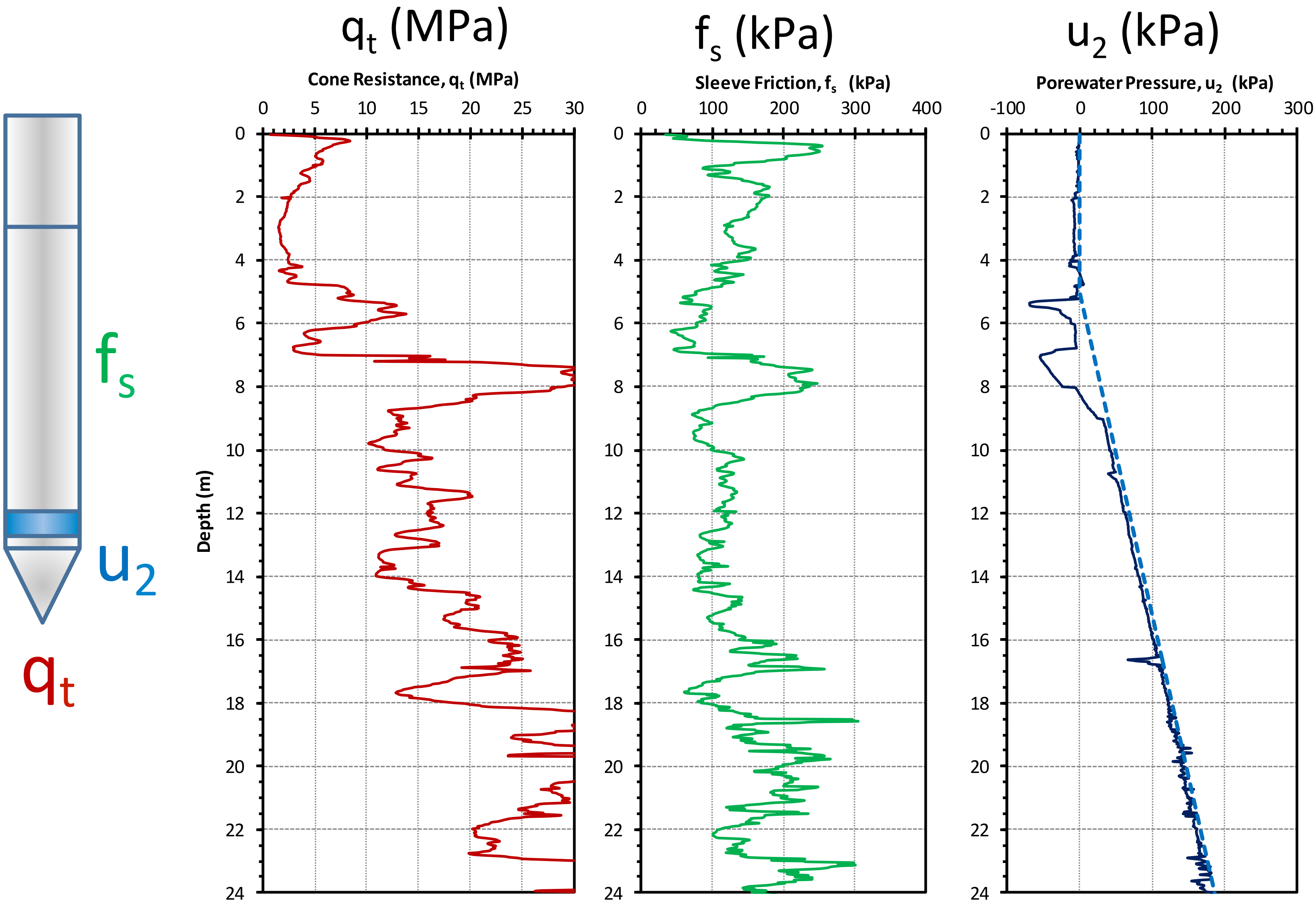
Updated Probabilistic CRRs for CPT

Ku and Juang et al.
Canadian Geot J. (2012):

$$P_L \approx \frac{1}{1+(FS/0.9)^6}$$



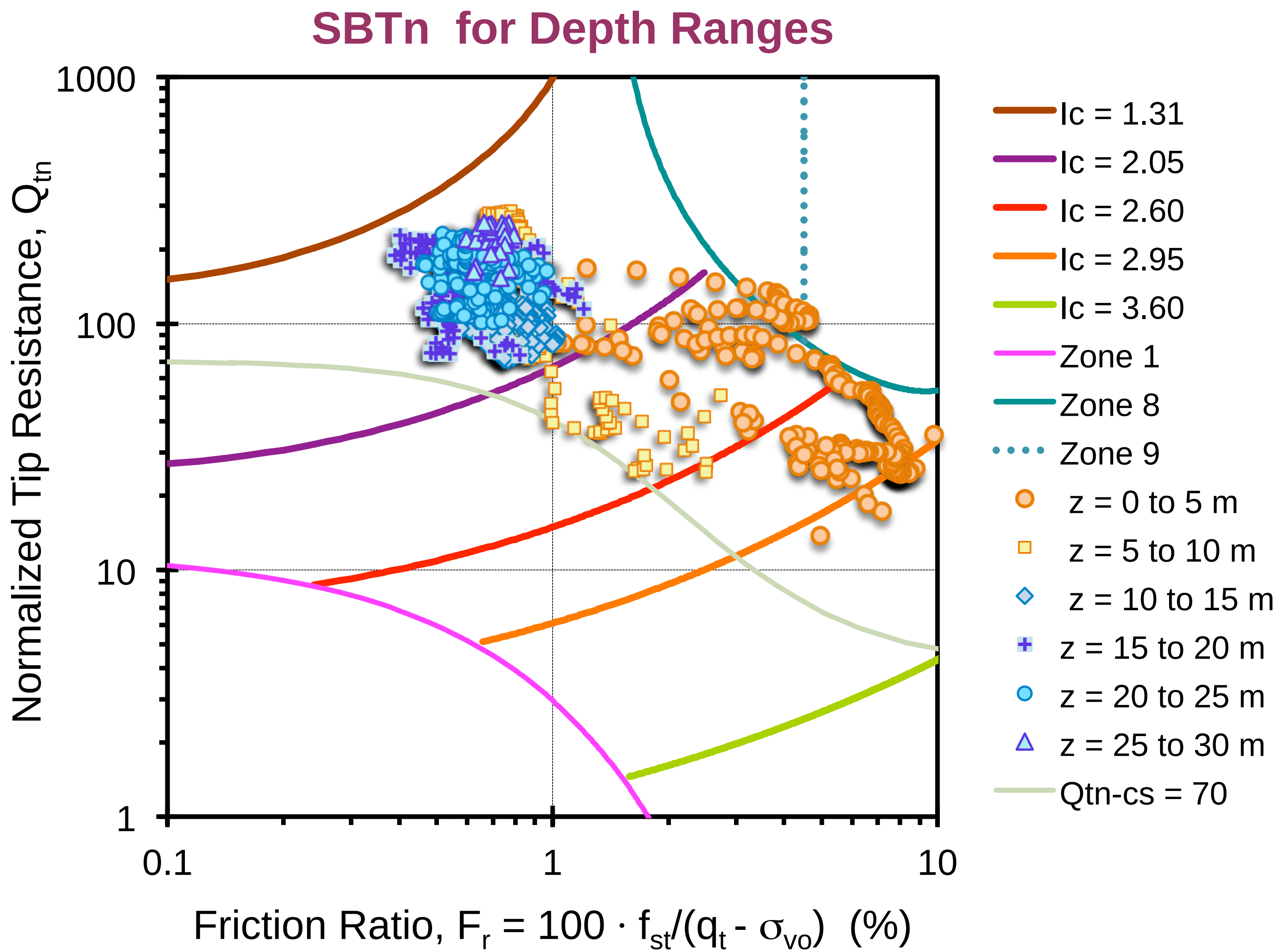
Liquefaction Analysis
CPTu-12 at Marked Tree, AR



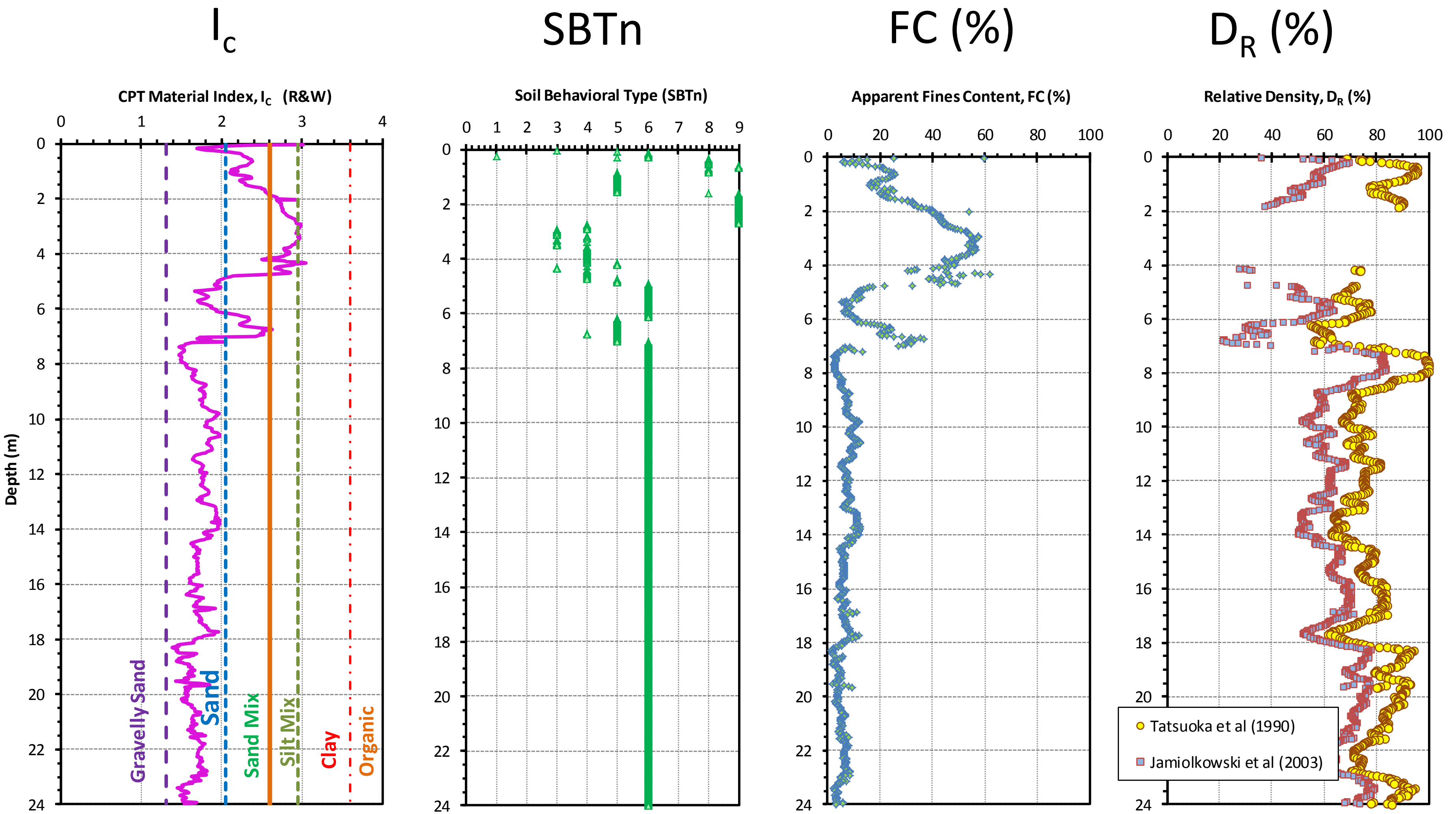
Marked Tree, Arkansas

FILE INFORMATION		INPUT DATA:				
Project Name and Location =		NMSZ Paleoliquefaction			Magnitude Scaling Factor	
CPT File to Read for Data =		Marked Tree CPTu-12			Calculated	
Max. ground acceleration =		0.19	= PGA (units of g's)		MSF =	0.96
Moment Magnitude, M_w =		7.6		Limiting Liq Depth =		30
Groundwater, z_w (meters) =		5	Choice	Condition	Input Parameters	
Max. depth of interest (m) =		99.00	1	Level Ground	None	
Start depth of interest (m) =		0.01	2	Gentle Slope	Give S (%)=	1
SBT Limit for Sand	Cutoff Ic=	2.6	3	Level w/ Free Face	L (m) =	60
Level or Slope or Freeface Case =		1	4	Slope w/ Free Face	H (m) =	5

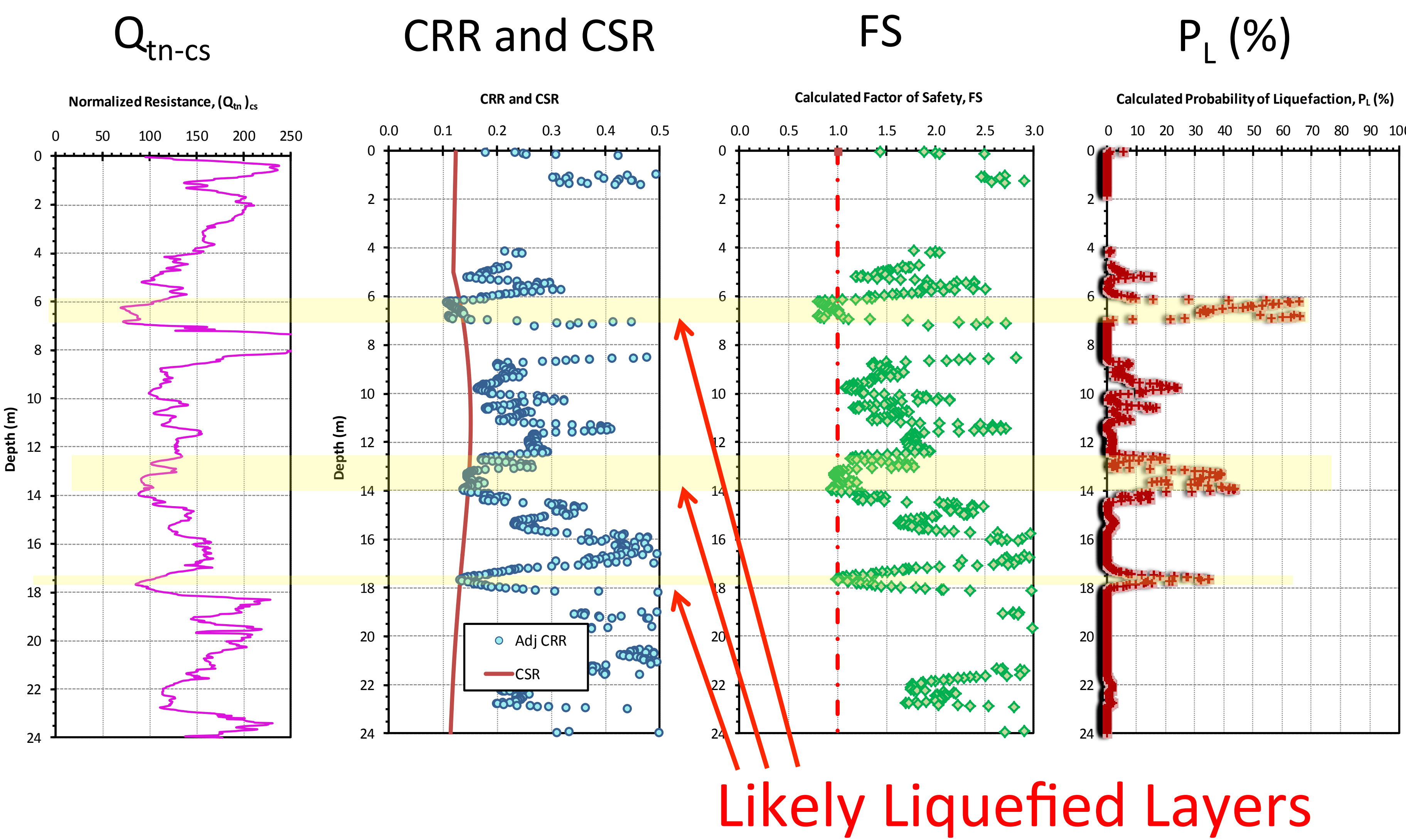
Liquefaction Analysis
CPTu-12 at Marked Tree, AR



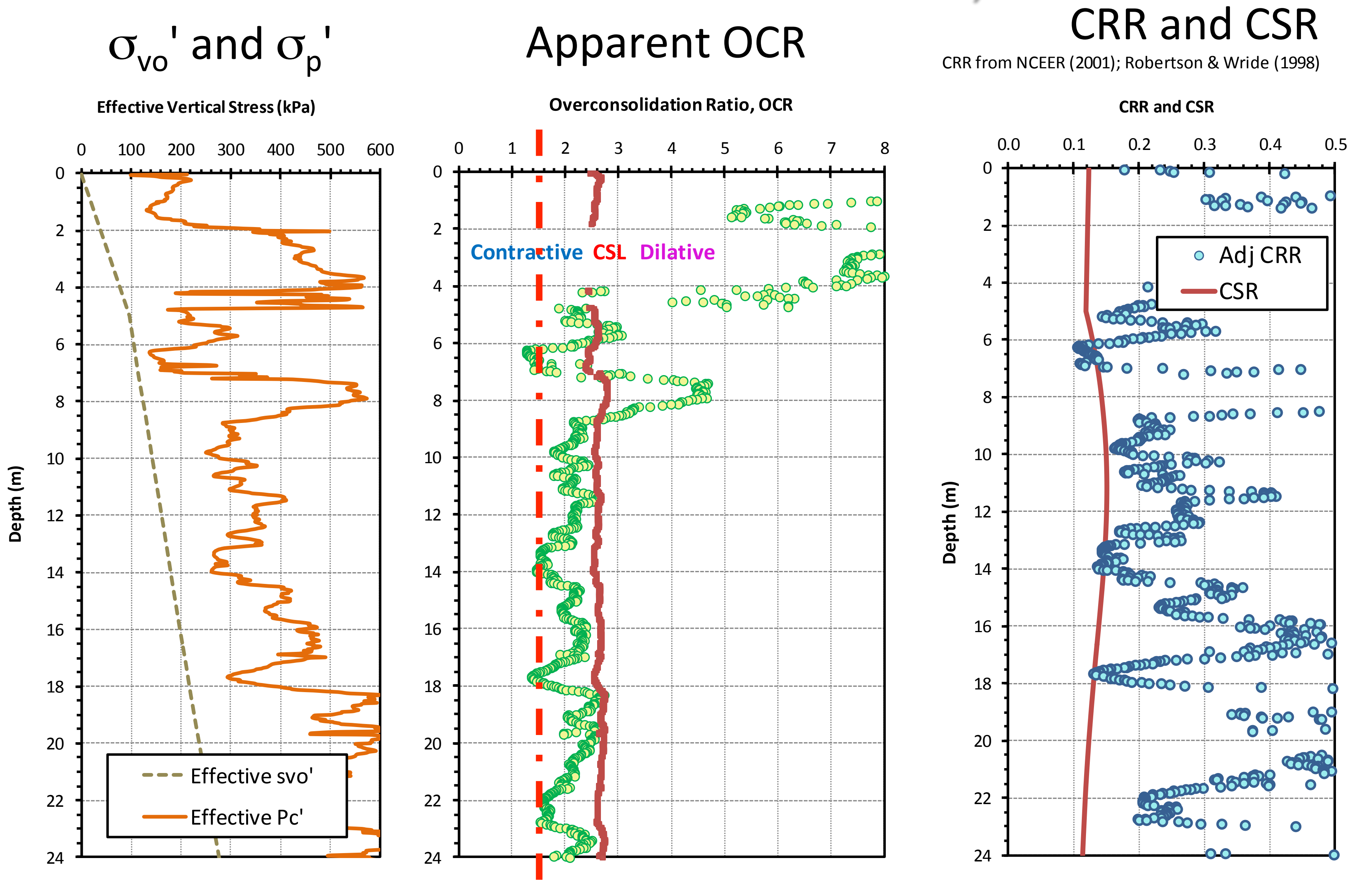
Liquefaction Analysis
CPTu-12 at Marked Tree, AR



Liquefaction Analysis
CPTu-12 at Marked Tree, AR



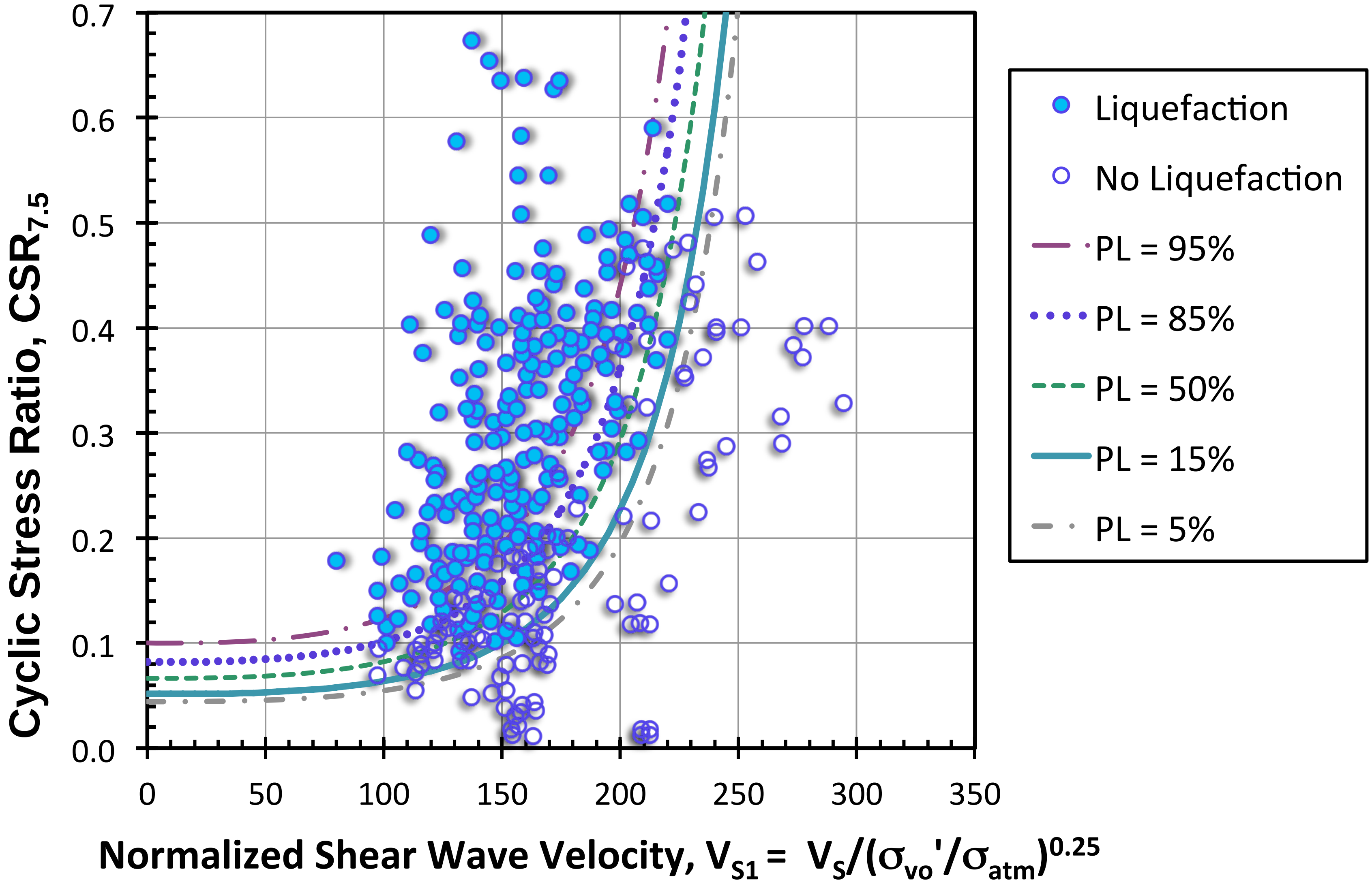
Liquefaction Analysis
CPTu-12 at Marked Tree, AR



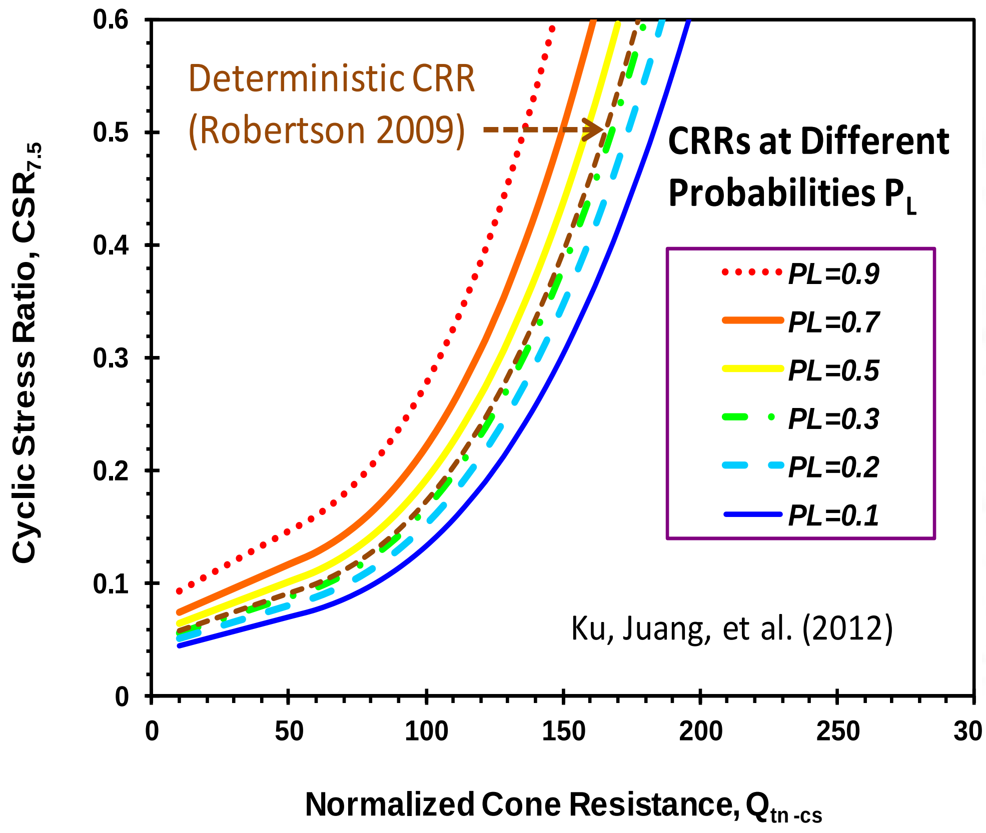
Liquefaction evaluation by shear wave velocity

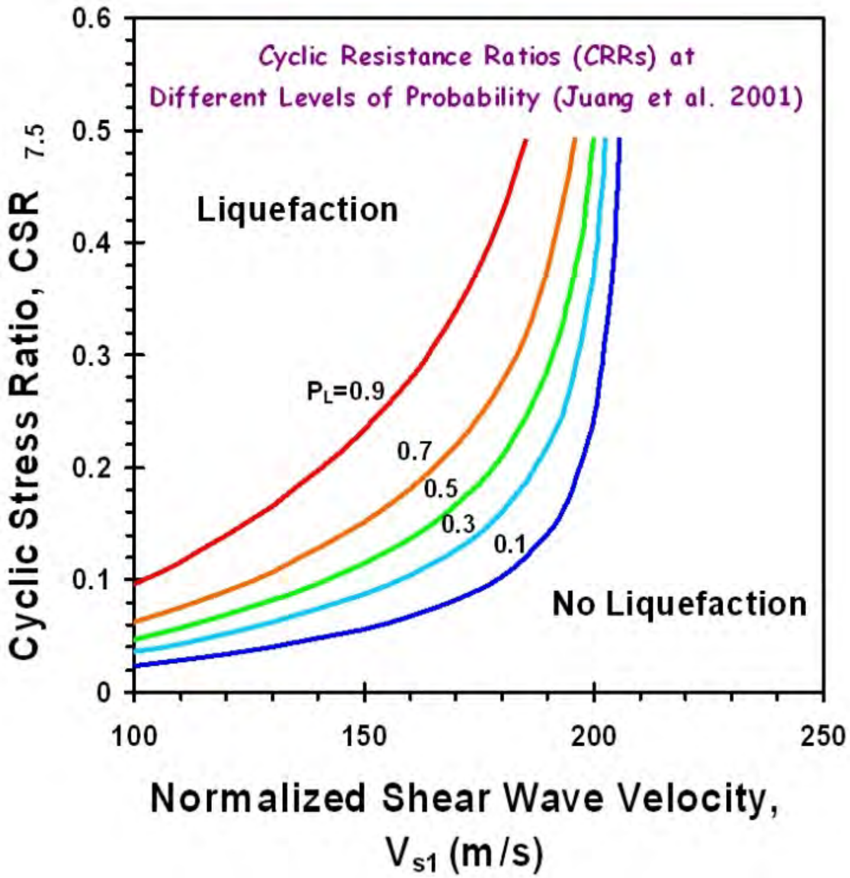
301 New Case Studies over 11 years

Kayen et al. (ASCE JGGE 2013)

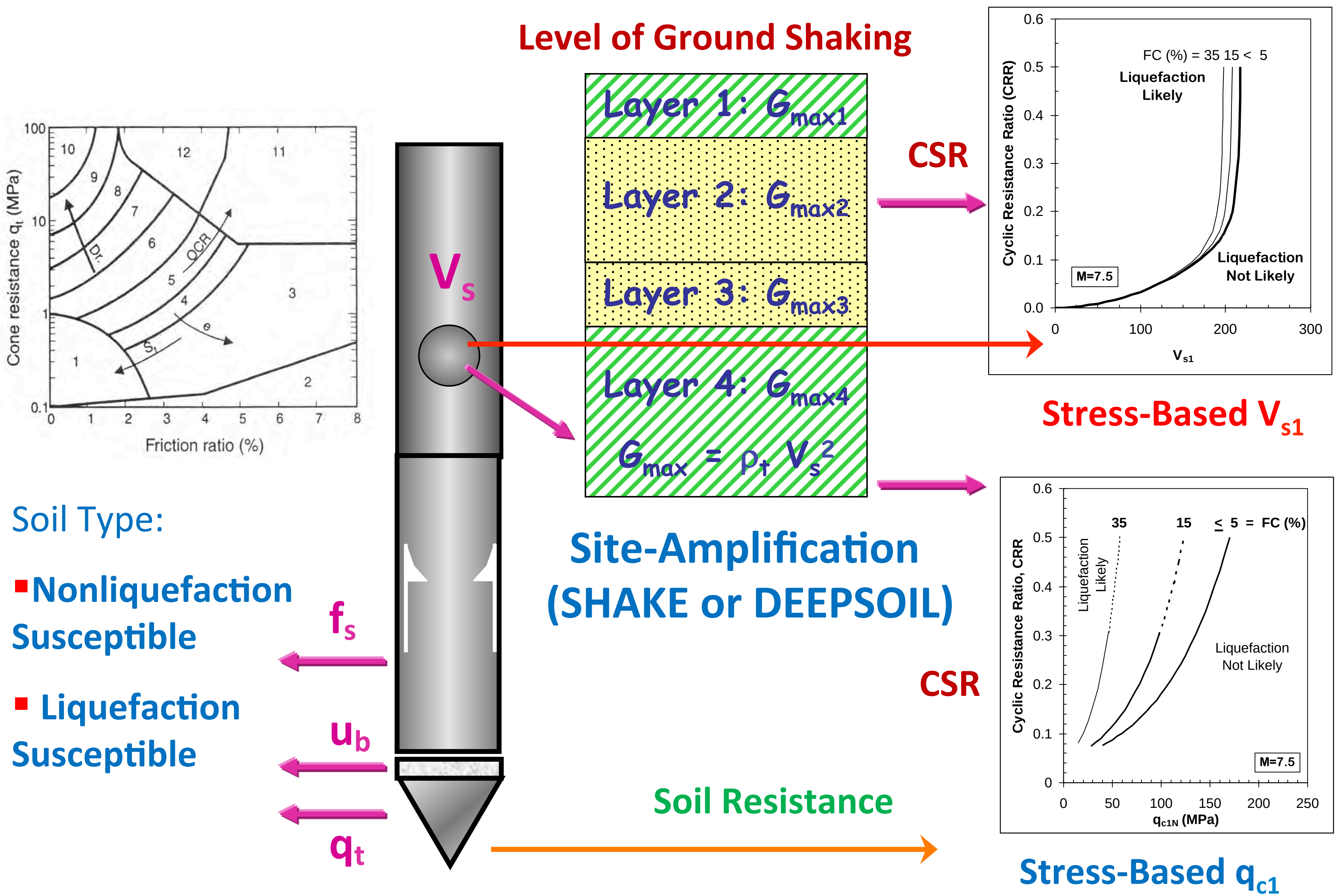


Dual Assessments of Soil Liquefaction Potential offered by SCPTu





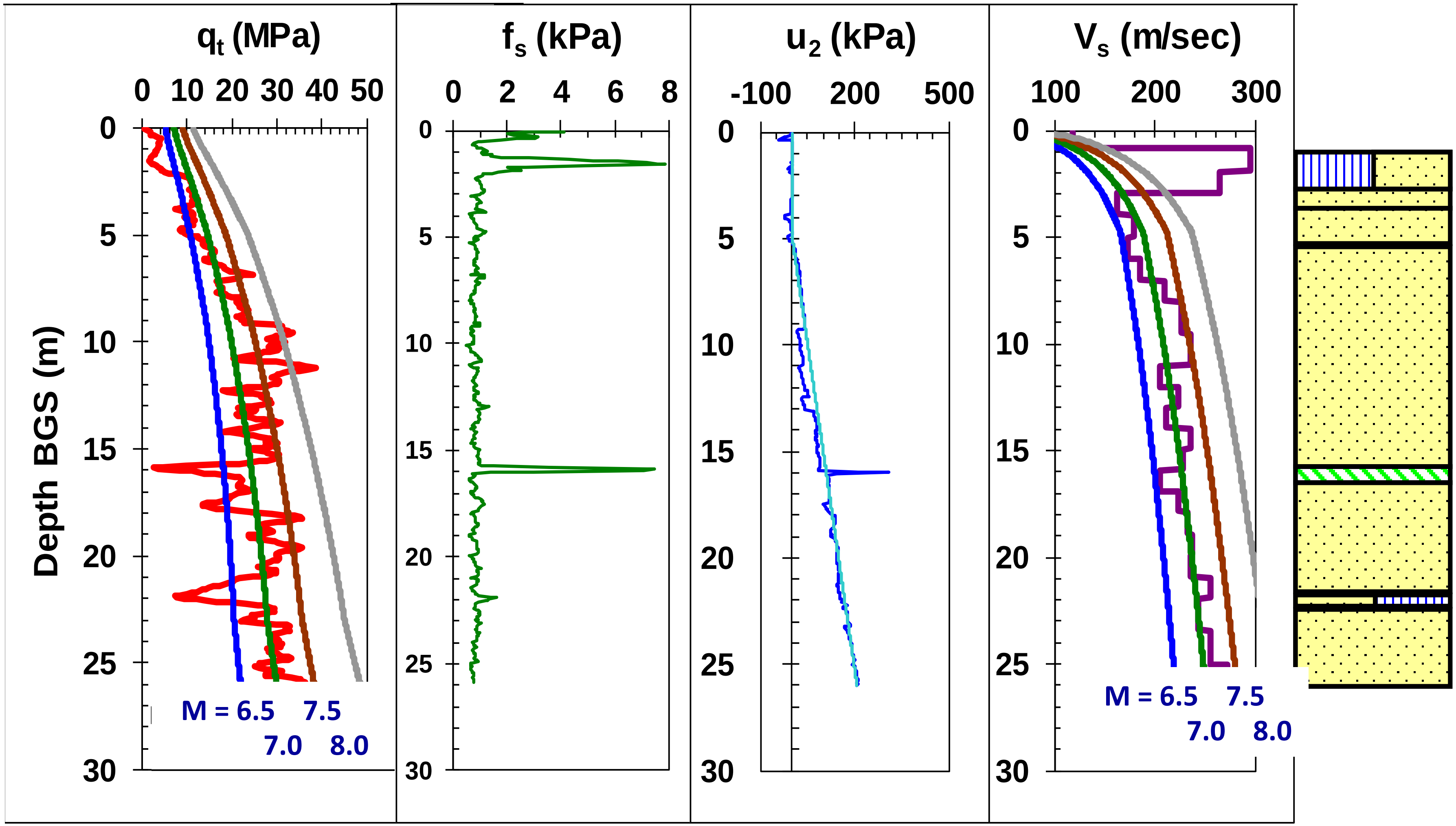
Seismic Cone Tests to Evaluate Seismic Ground Hazards



SCPTu Offers Redundancy in Seismic Evaluations

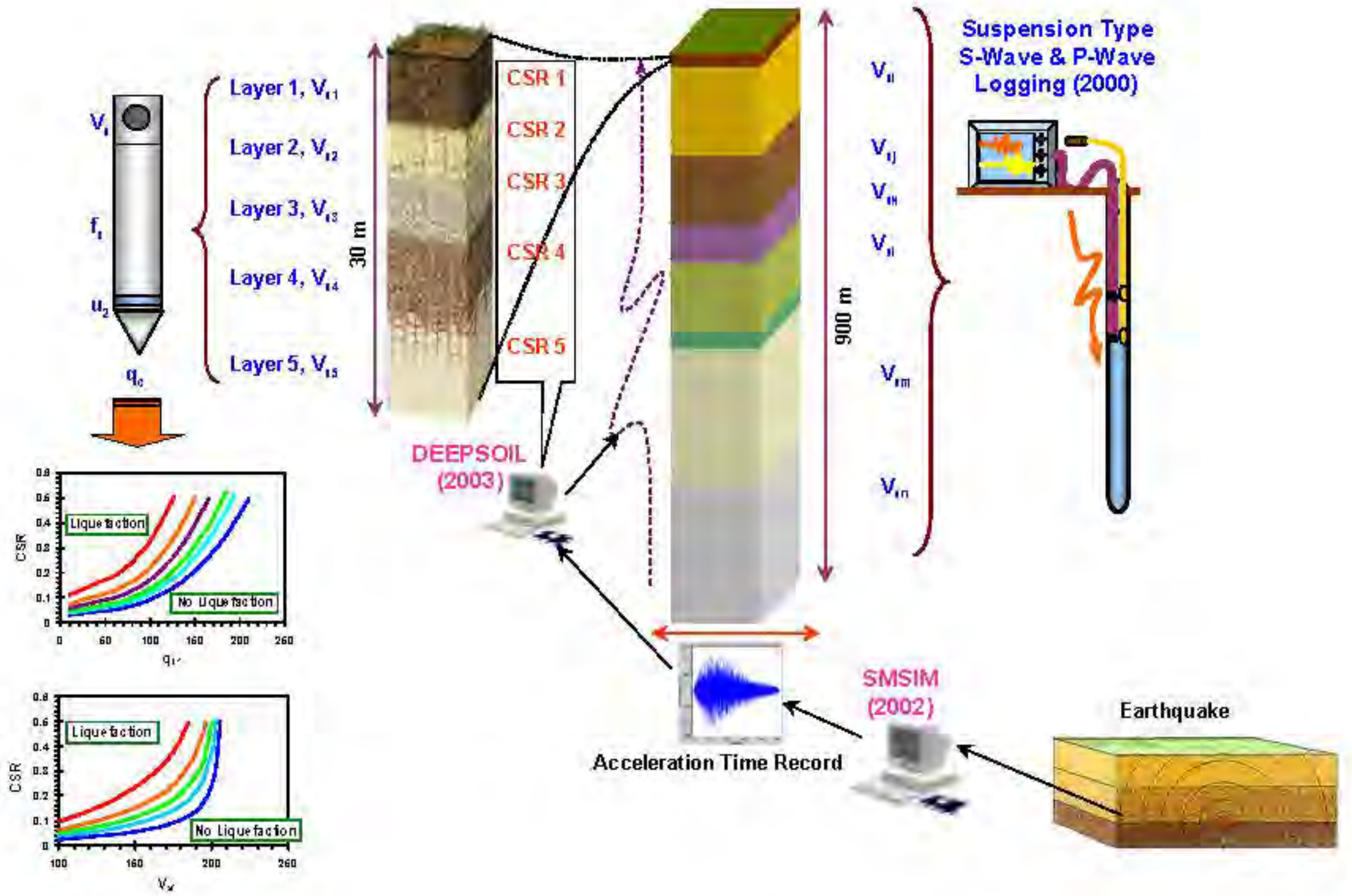
Example from Paleoliquefaction Site, Blytheville, AR

New Madrid Seismic Zone



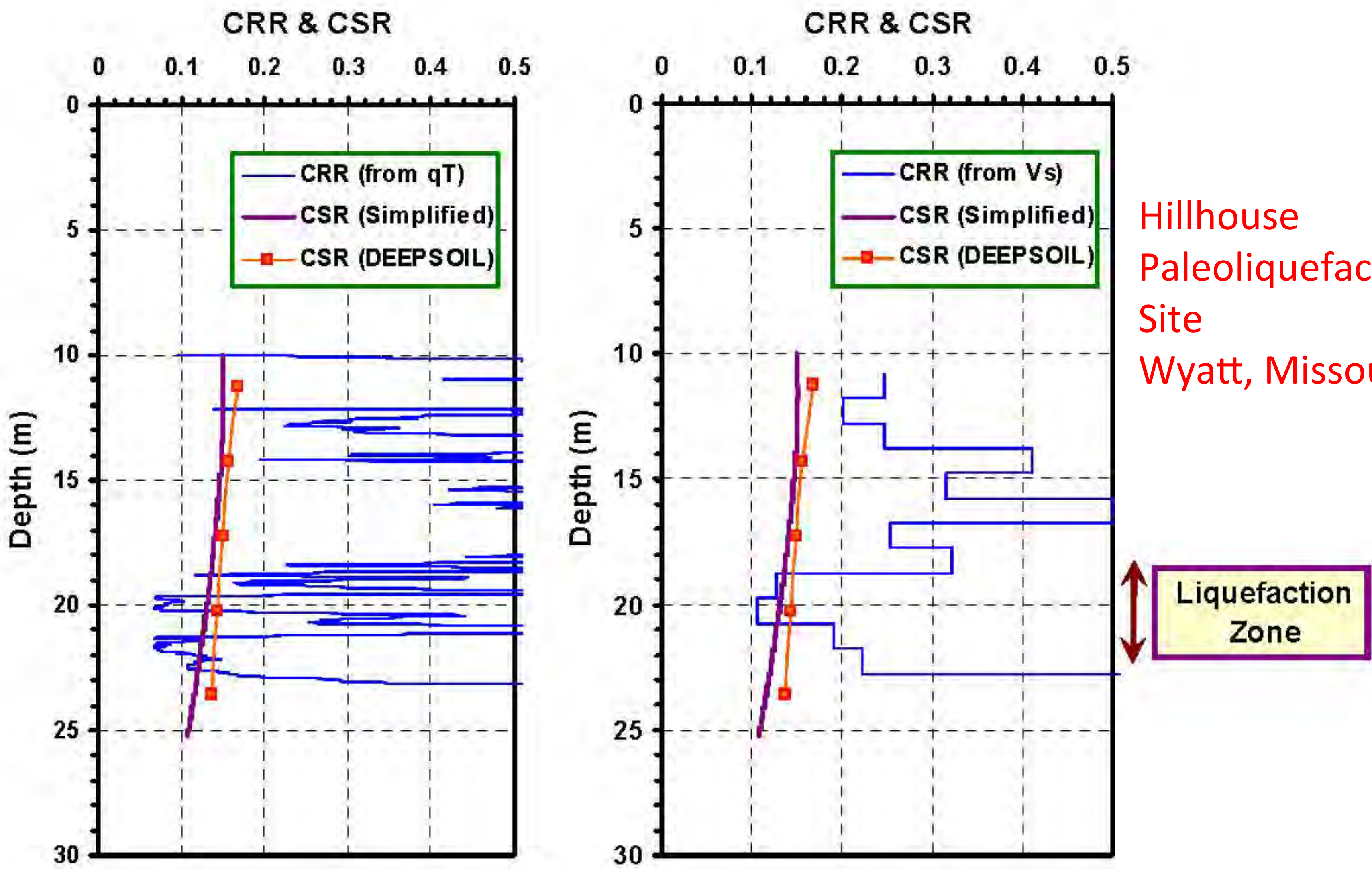
Soil Liquefaction Evaluated by SCPTu

Methodology for New Madrid Seismic Zone (Liao 2005)



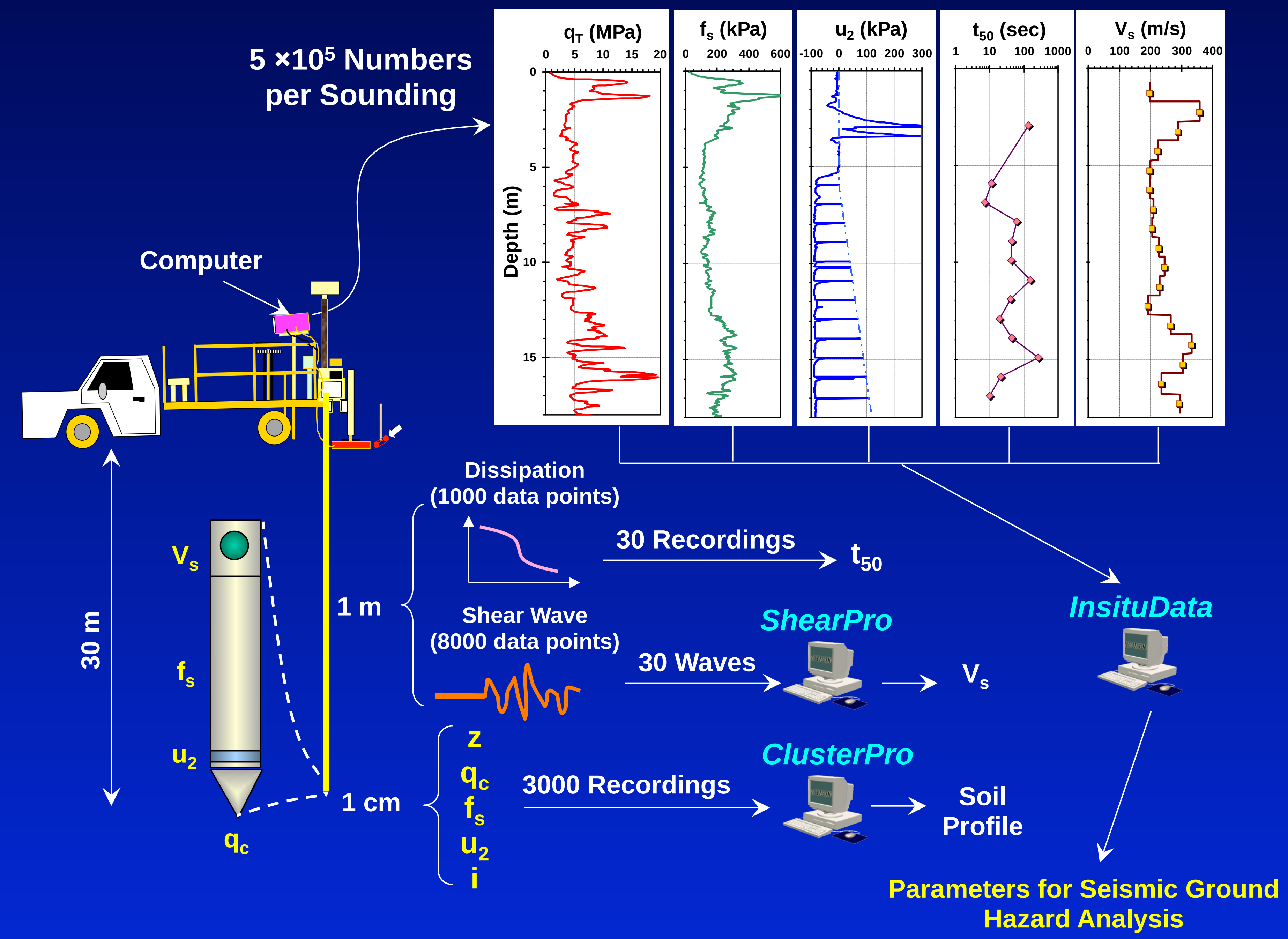
Soil Liquefaction Evaluated by SCPTu

Methodology for New Madrid Seismic Zone (Liao 2005)



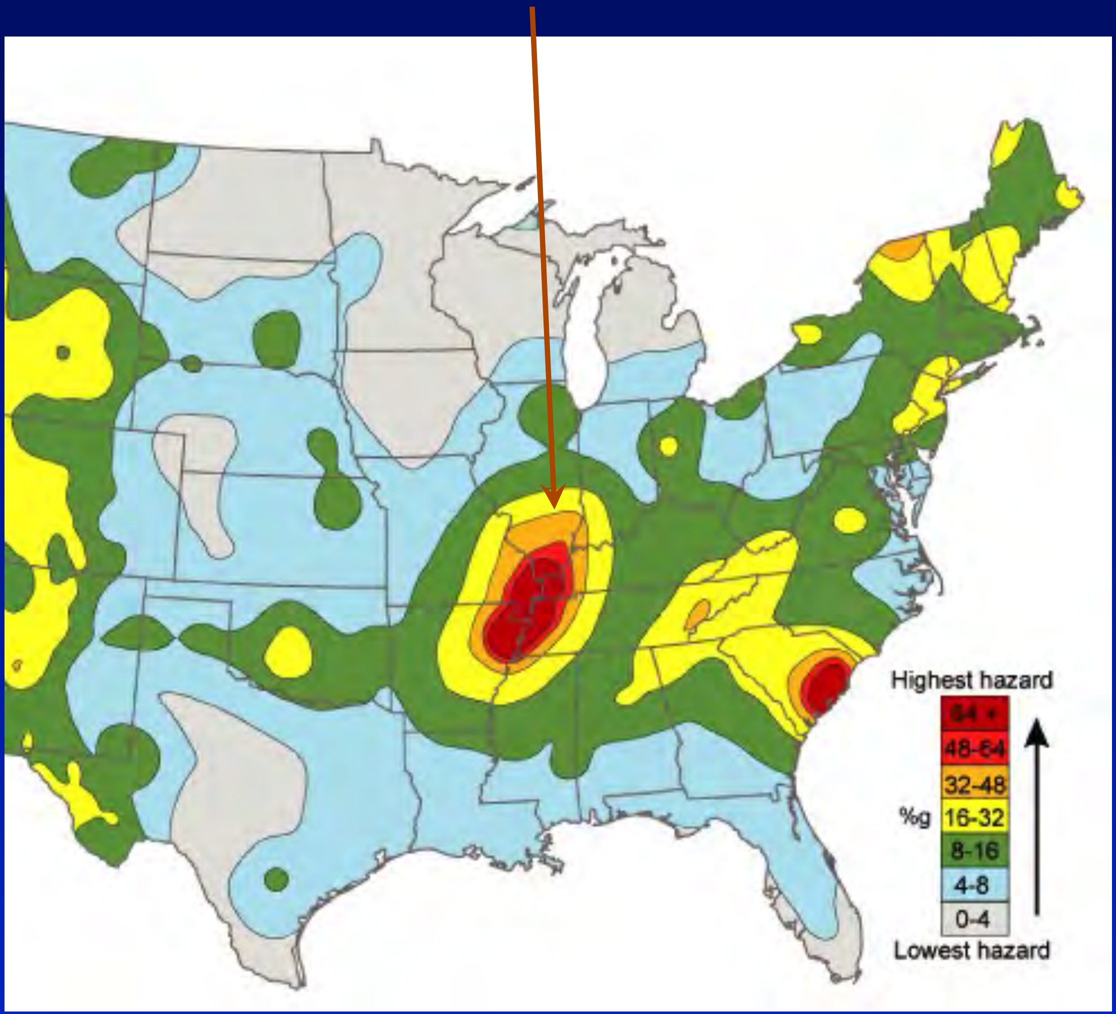
Hillhouse Paleoliquefaction Site

Wyatt, Missouri



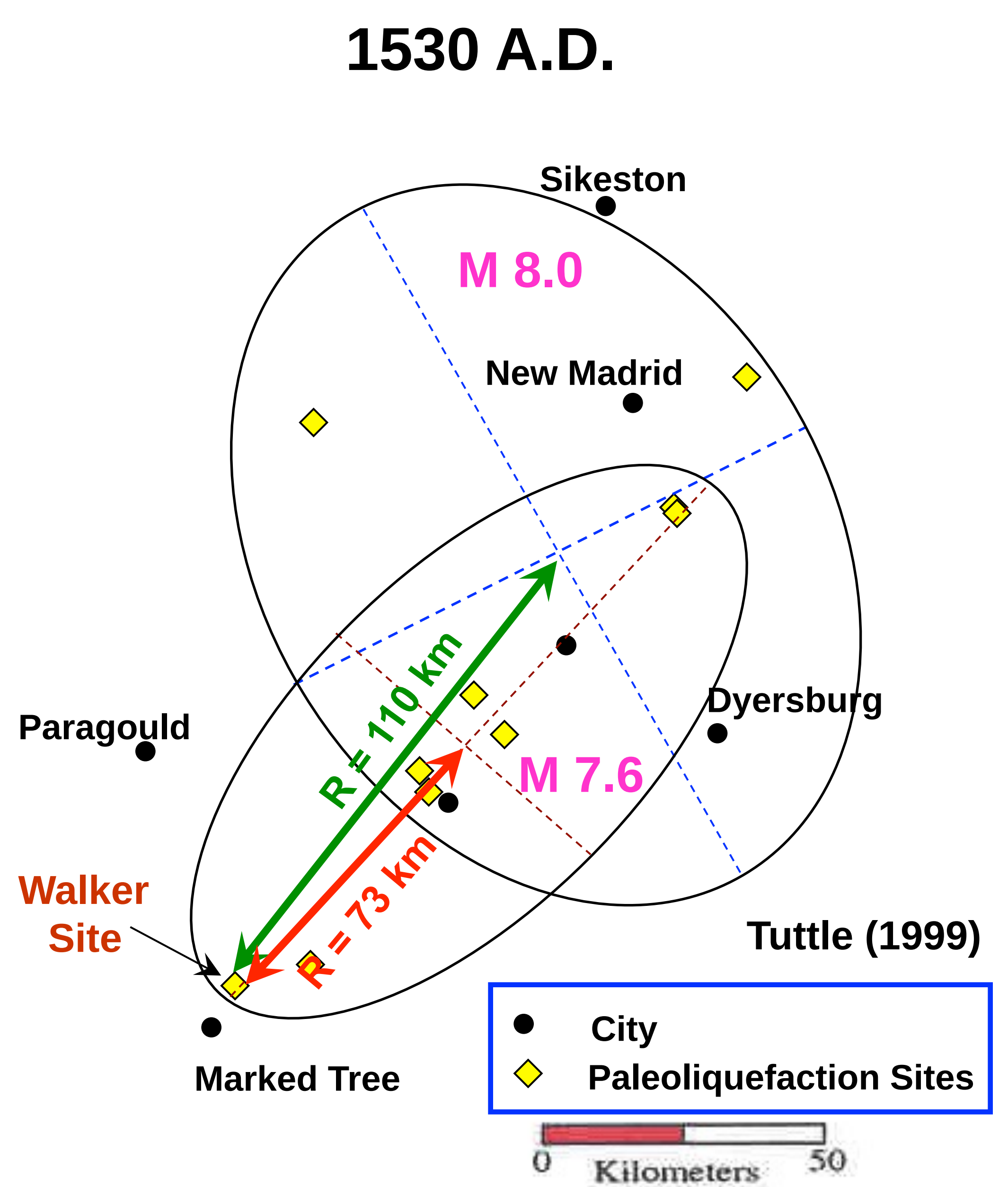
5 ×10⁵ Numbers per Sounding
Computer
qT (MPa)
fs (kPa)
u2 (kPa)
t50 (sec)
Vs (m/s)
Depth (m)
30 m
Vs
fs
u2
qc
1 m
1 cm
Dissipation (1000 data points)
Shear Wave (8000 data points)
30 Recordings
t50
ShearPro
30 Waves
Vs
z
qc
fs
u2
i
ClusterPro
3000 Recordings
Soil Profile
InsituData
Parameters for Seismic Ground Hazard Analysis

New Madrid Seismic Zone

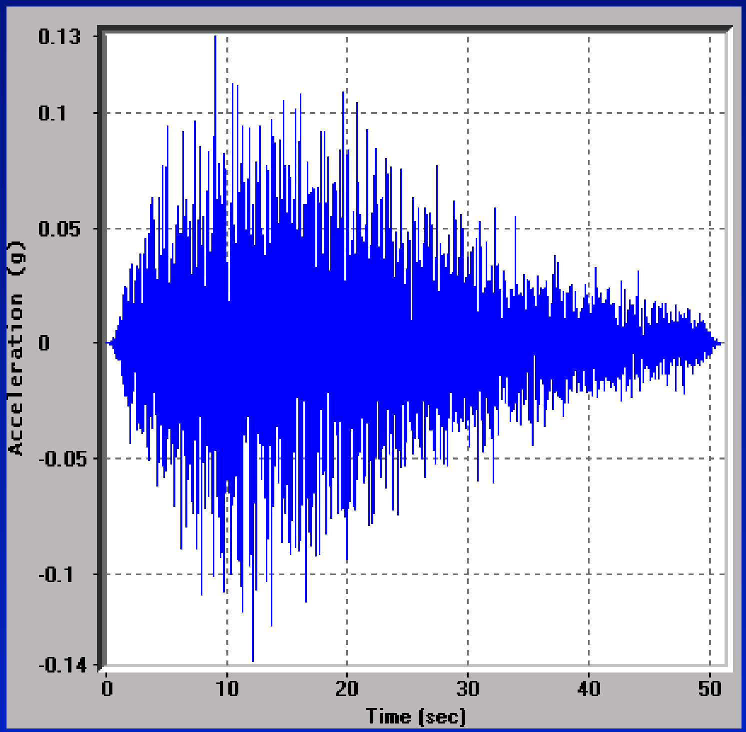


U. S. Geological Survey earthquake hazard map showing peak ground acceleration (PGA) having a 2% probability of being exceeded in the next 50 years for a firm rock site condition

Walker Paleoliquefaction Site, Marked Tree, AR



- Bedrock motion generated using SMSIM (Boore, 2002)



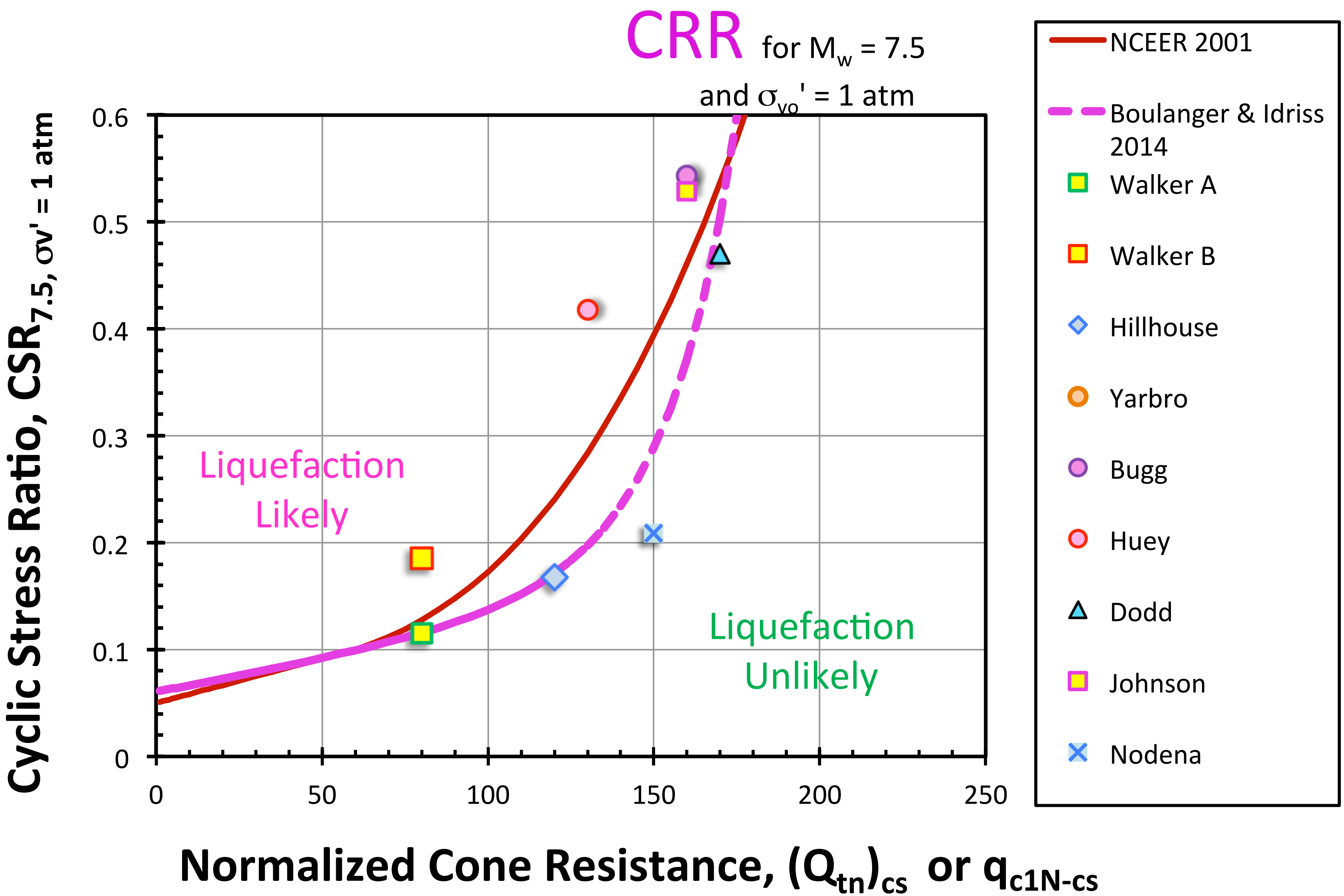
R = 73 km

NMSZ Paleoliquefaction Sites

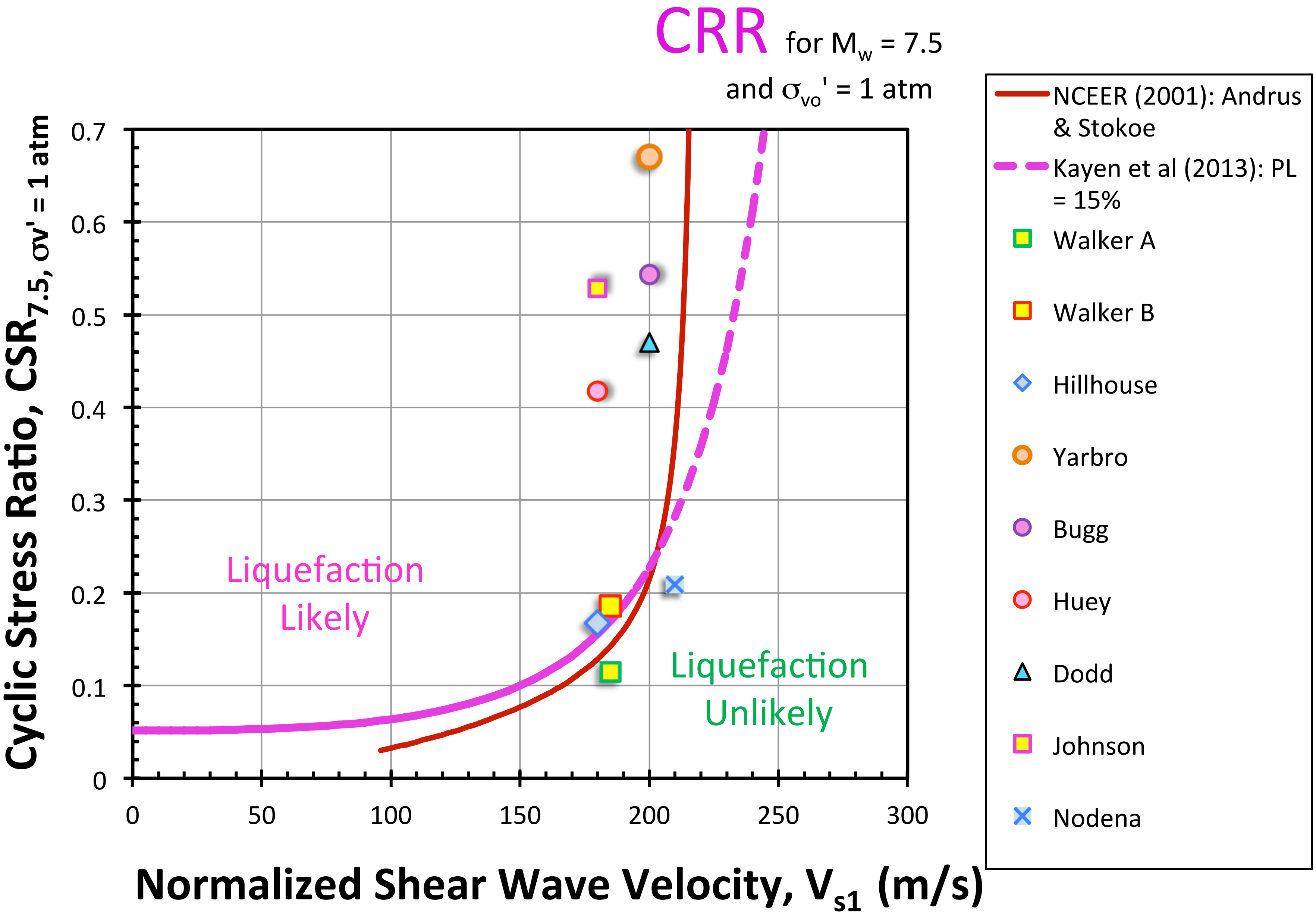
Modified after Liao (2004)

Site	R (km)	M_w	MSF	CSR	CSR7.5	q_{t1}	q_{t1-cs}	V_{s1} (m/s)
Walker A	73	7.6	0.96	0.11	0.11	80	80	185
Walker B	110	8	0.81	0.15	0.19	80	80	185
Hillhouse	65	8.1	0.78	0.13	0.17	120	120	180
Yarbro	5	8.1	0.78	0.52	0.67	80	80	200
Bugg	25	7.6	0.96	0.52	0.54	160	160	200
Hueys	25	7.6	0.96	0.40	0.42	130	130	180
Dodd	8	7.6	0.96	0.45	0.47	150	170	200
Johnson	28	8.1	0.78	0.41	0.53	160	160	180
Nodena	48	7.6	0.96	0.20	0.21	150	150	210

NMSZ Paleoliquefaction Sites



NMSZ Paleoliquefaction Sites

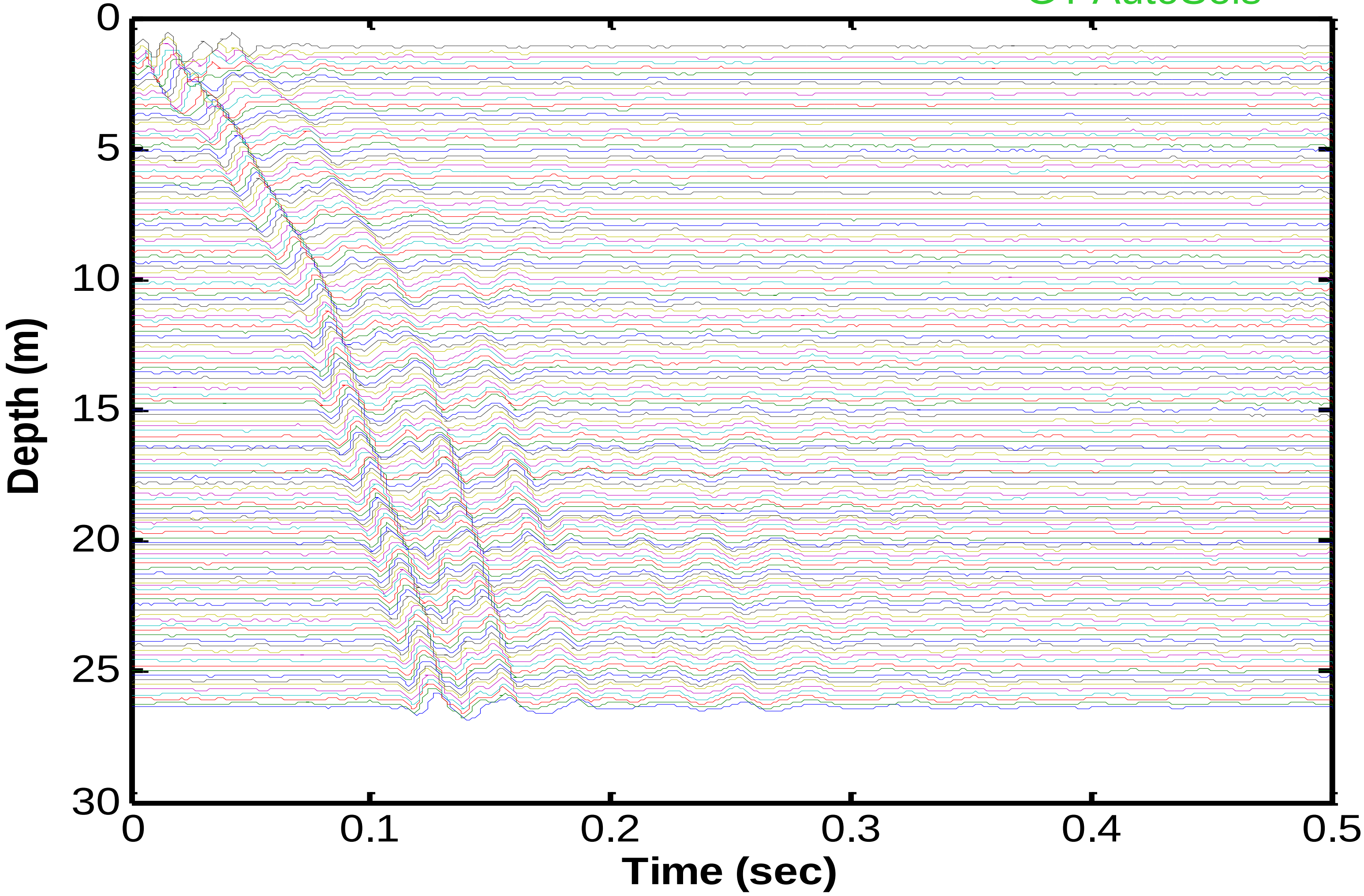


New In-Situ Test Developments 2014

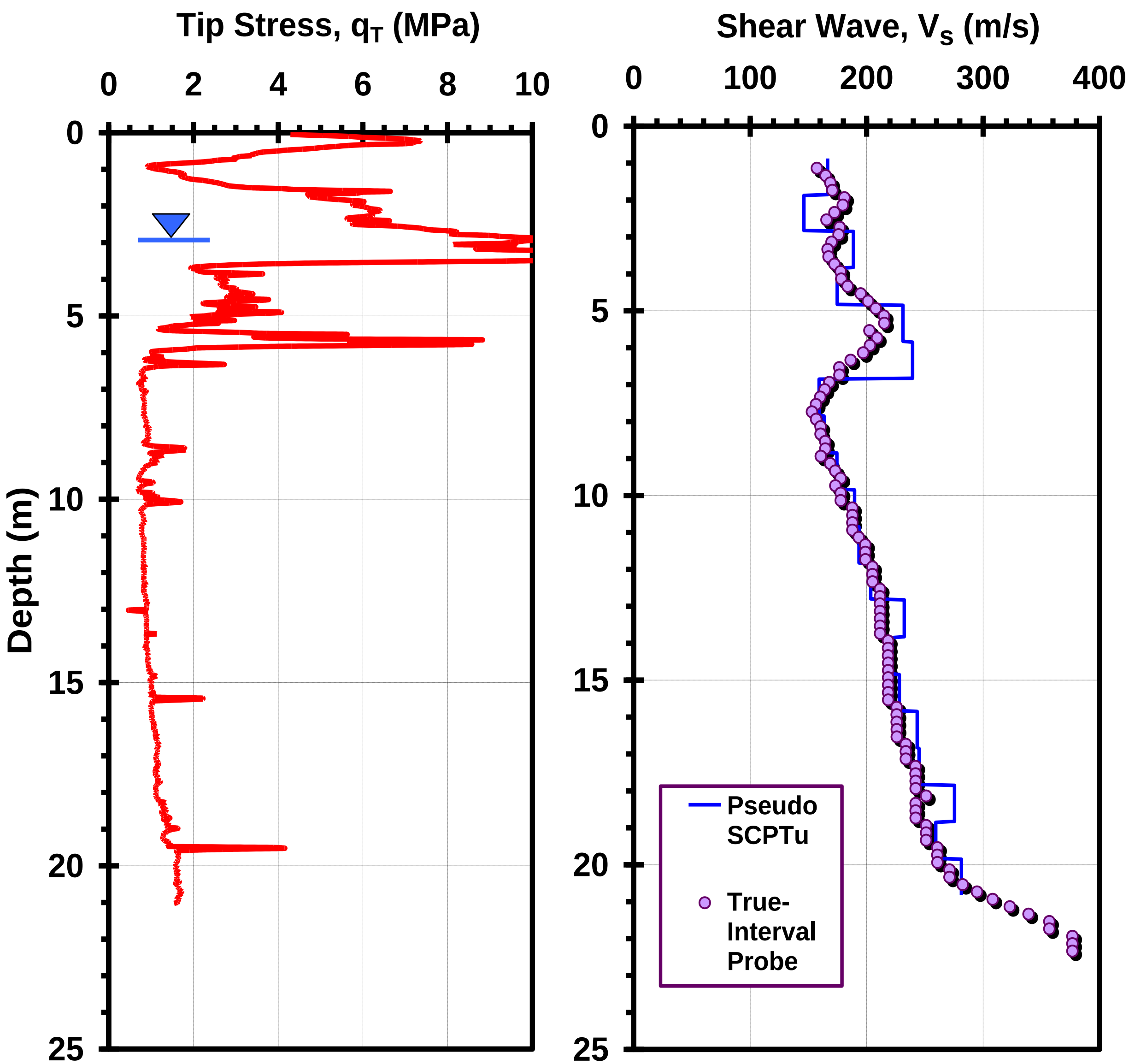
Paul W. Mayne, PhD, P.E.
paul.mayne@ce.gatech.edu

Frequent-interval and Continuous V_s profiling

GT AutoSeis



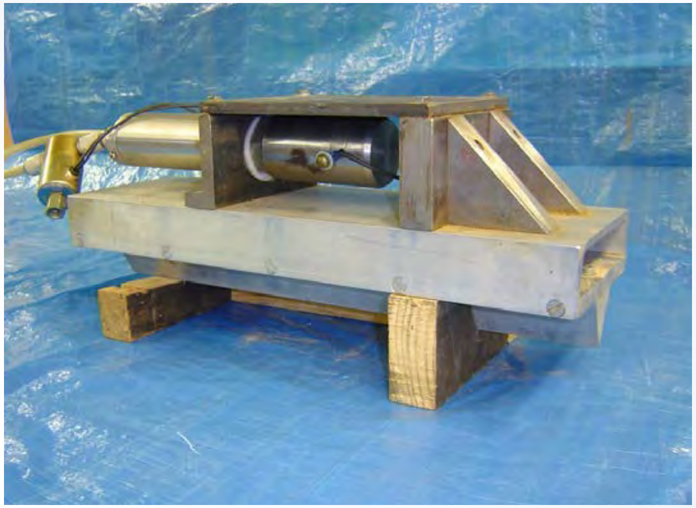
FREQUENT INTERVAL V_s METHOD

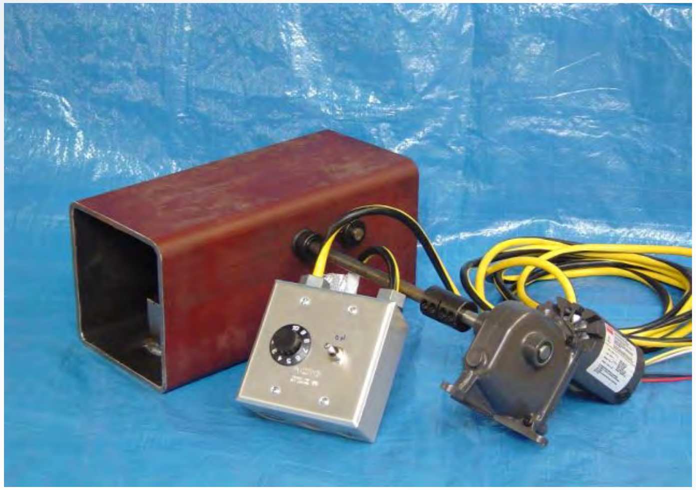


Lake Michigan

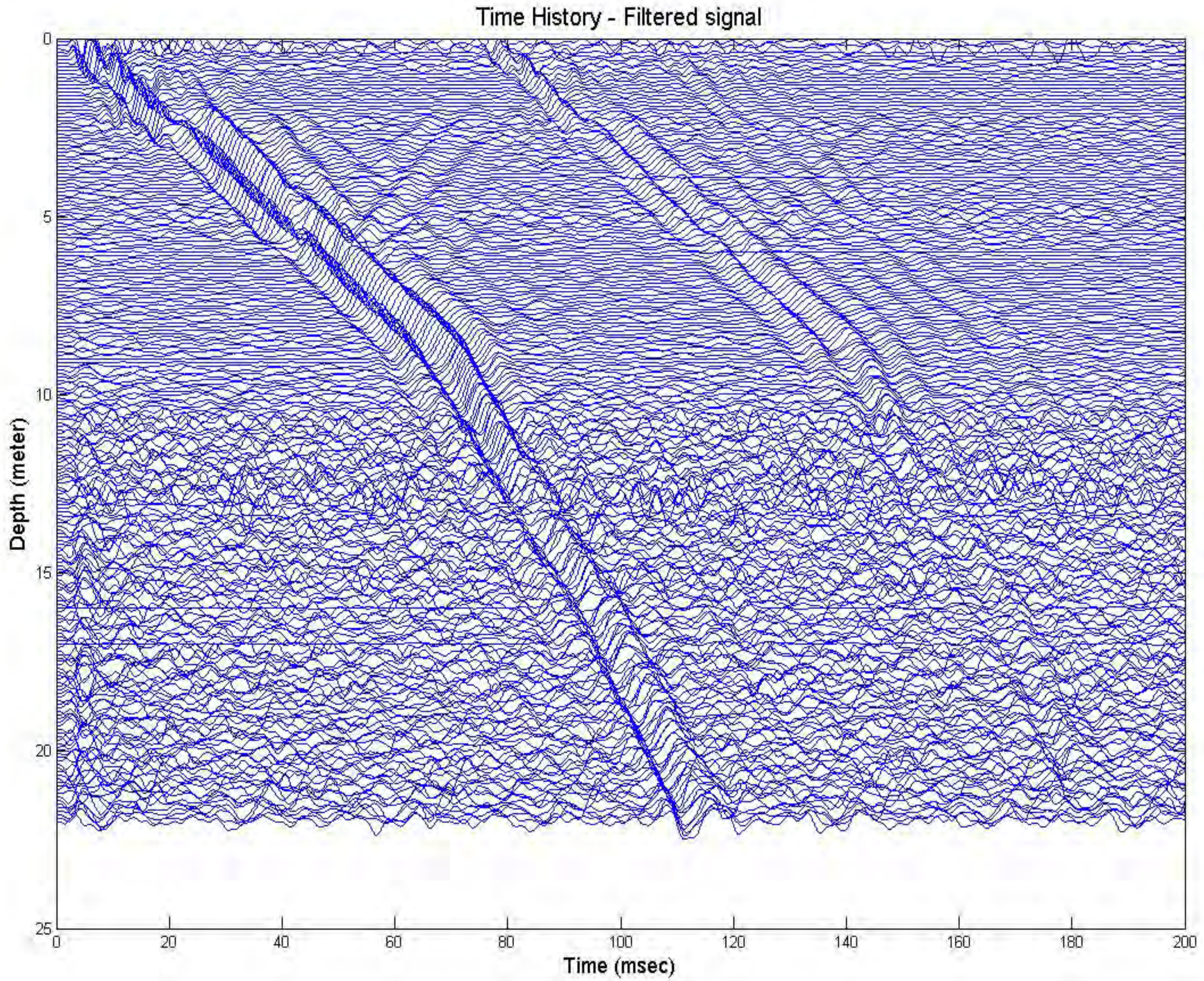
Soft Chicago clays at Northwestern University

Automated Seismic Sources



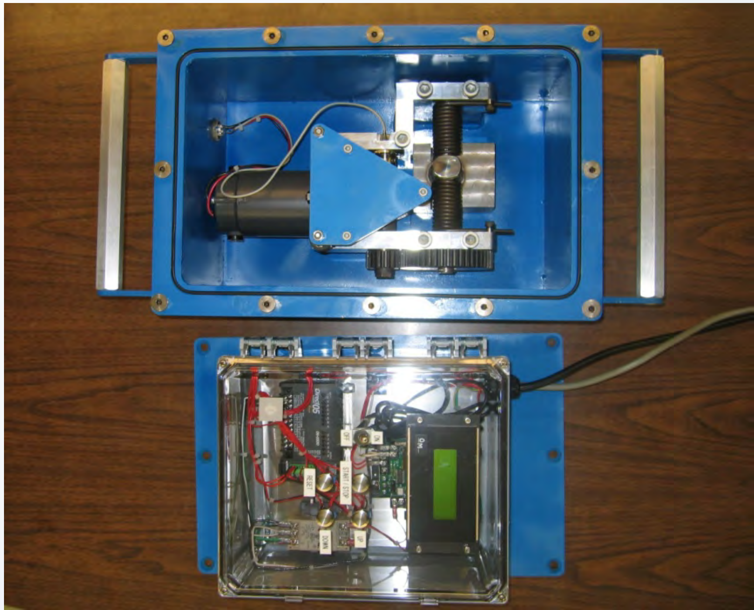


Wavelet signals from continuous V_s at Norfolk

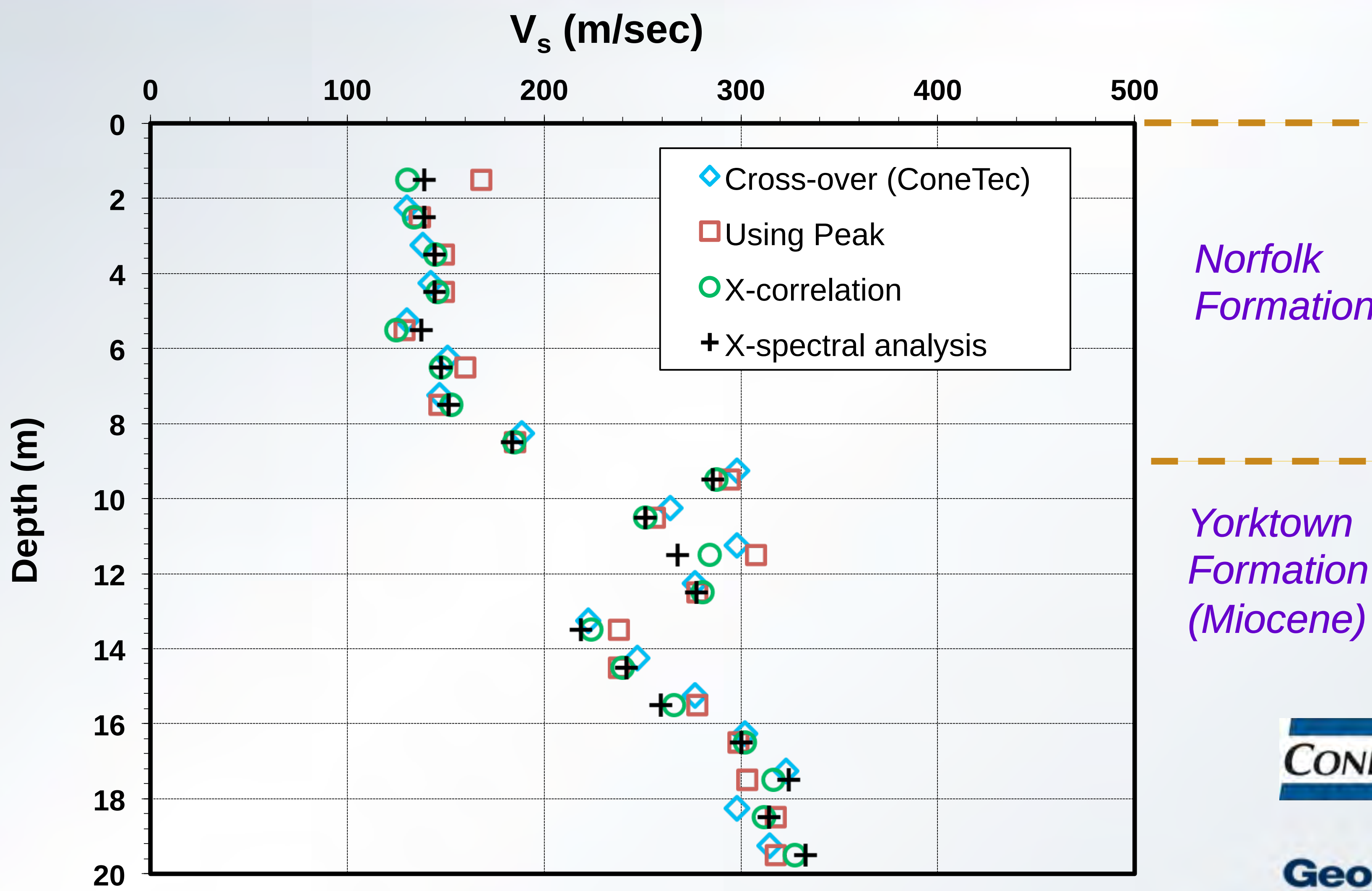


GT Roto AutoSeis

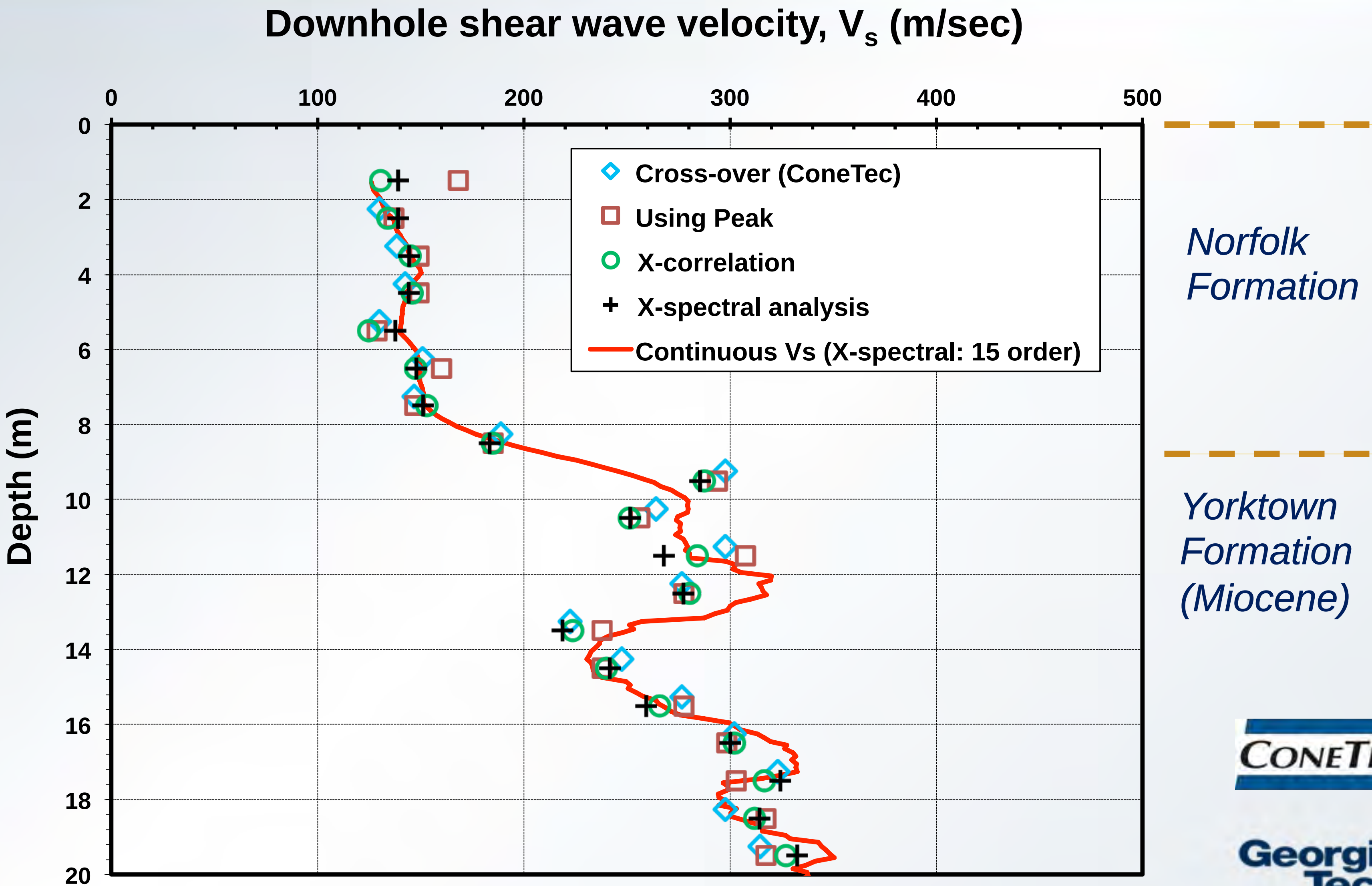
- Electro-Mechanical off 12-volt
- AC or DC power; variable speed
- Repeatable, Portable, reach 30-m depths
- Can generate shear wavelets every 1 second
- Patent received in February 2010



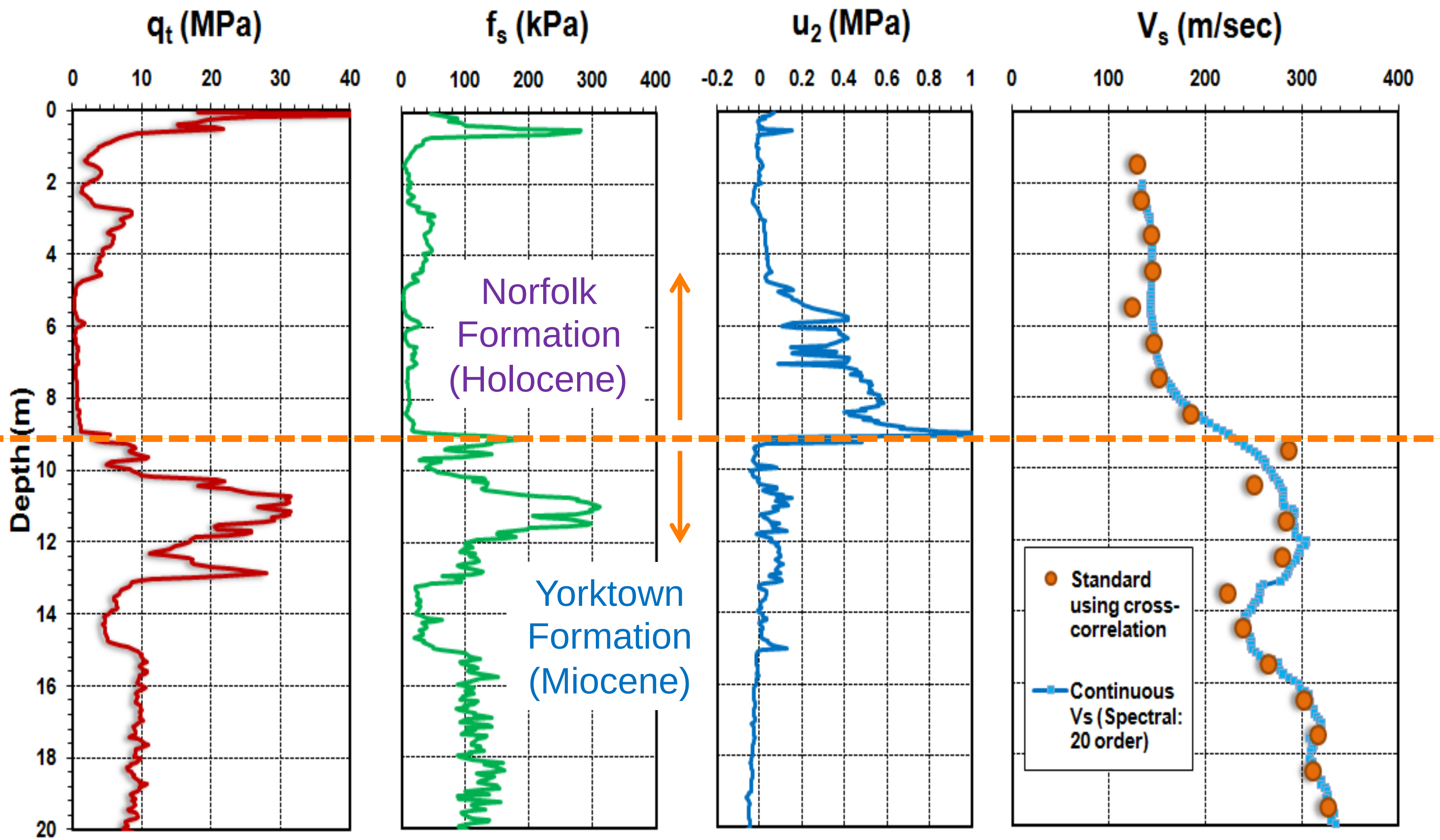
Conventional Downhole Test at Norfolk
V_s comparison of interpreted V_s data



V_s comparison of all methods - Norfolk

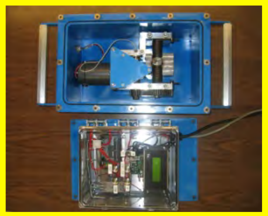


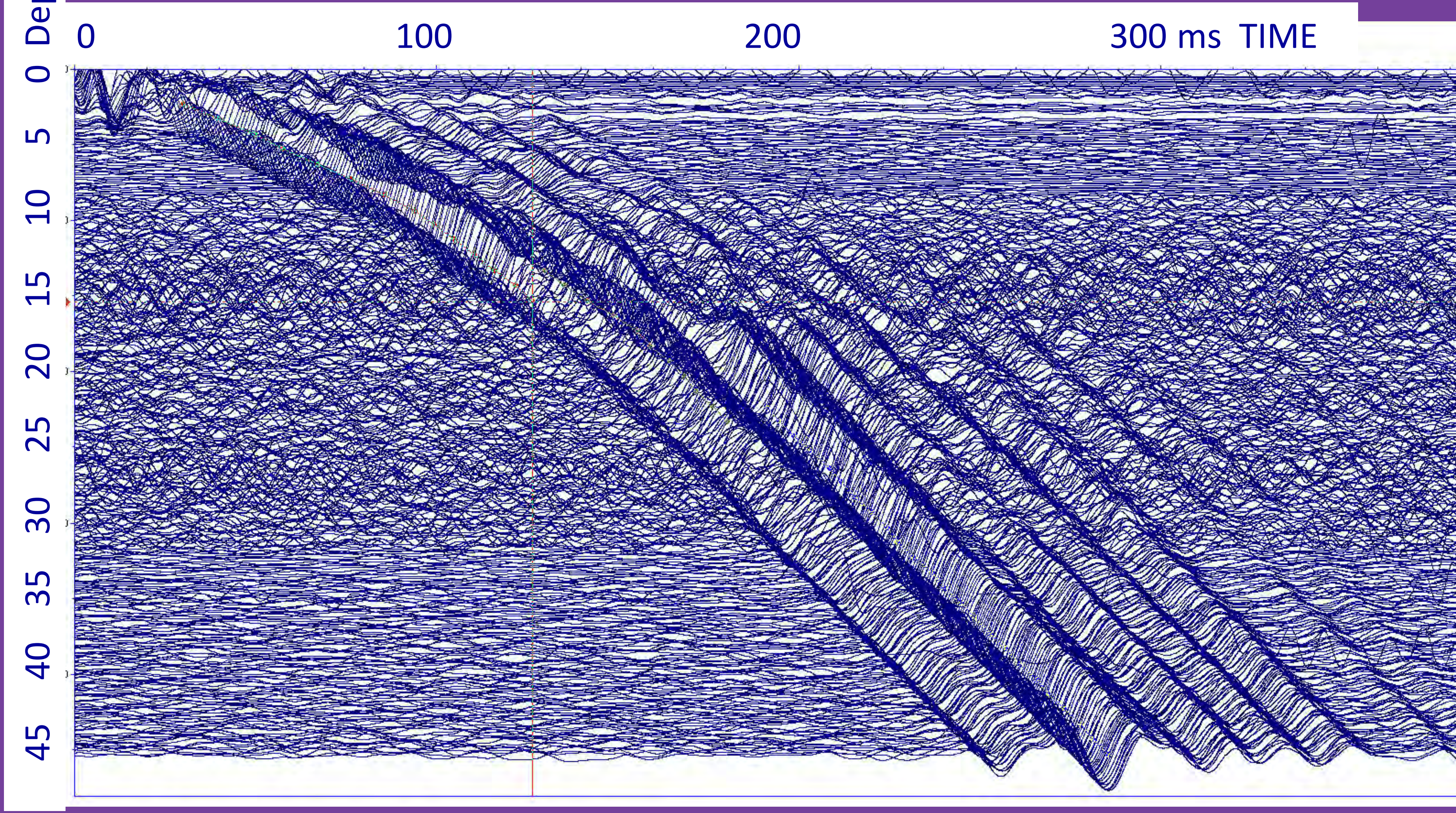
Continuous-interval SCPTu at Norfolk, VA



Continuous V_s profiling to 45 meters

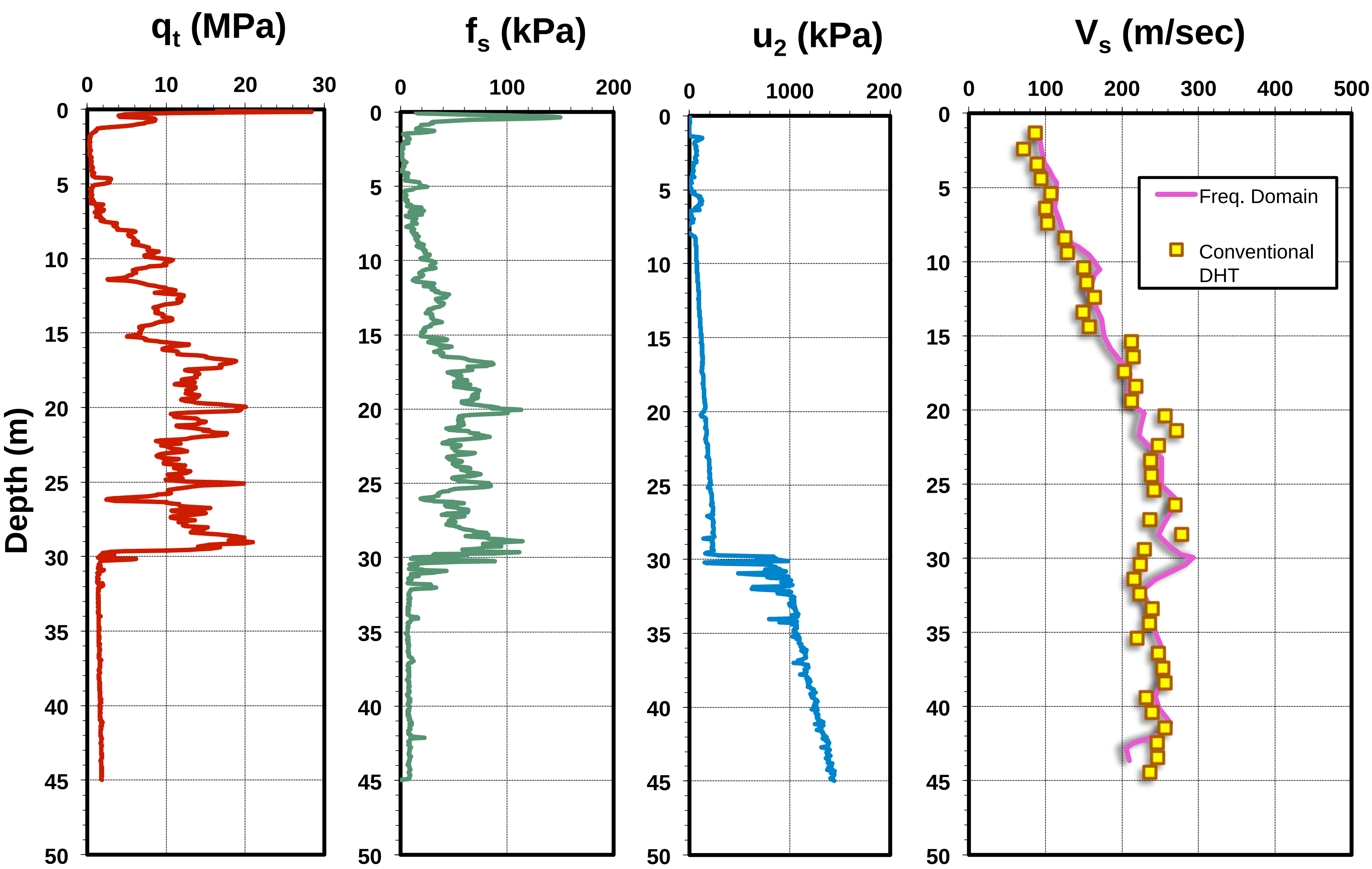
GT AutoSeis





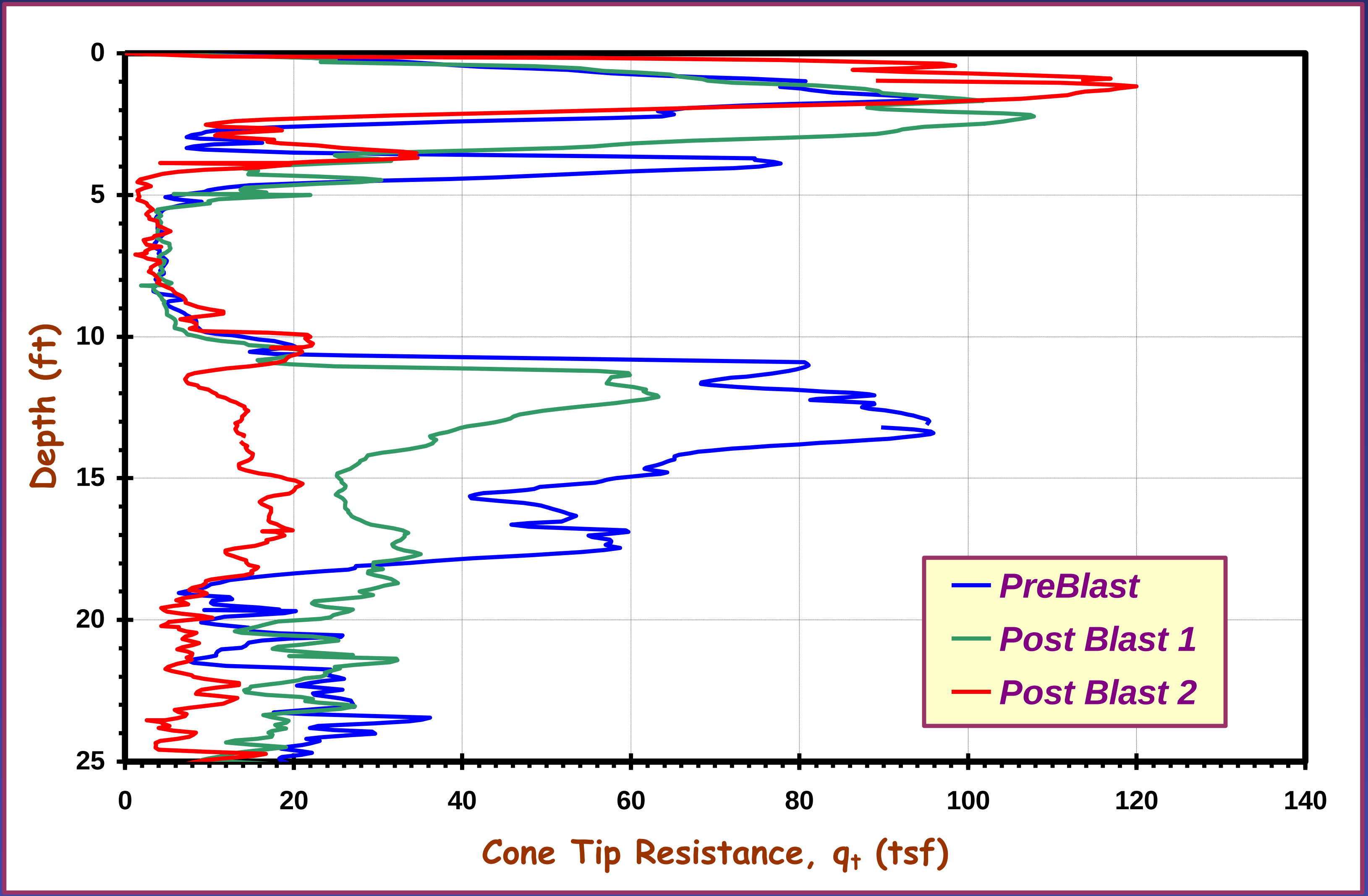
courtesy Dave Woeller - ConeTec

Continuous-Interval Seismic Piezocone, BC

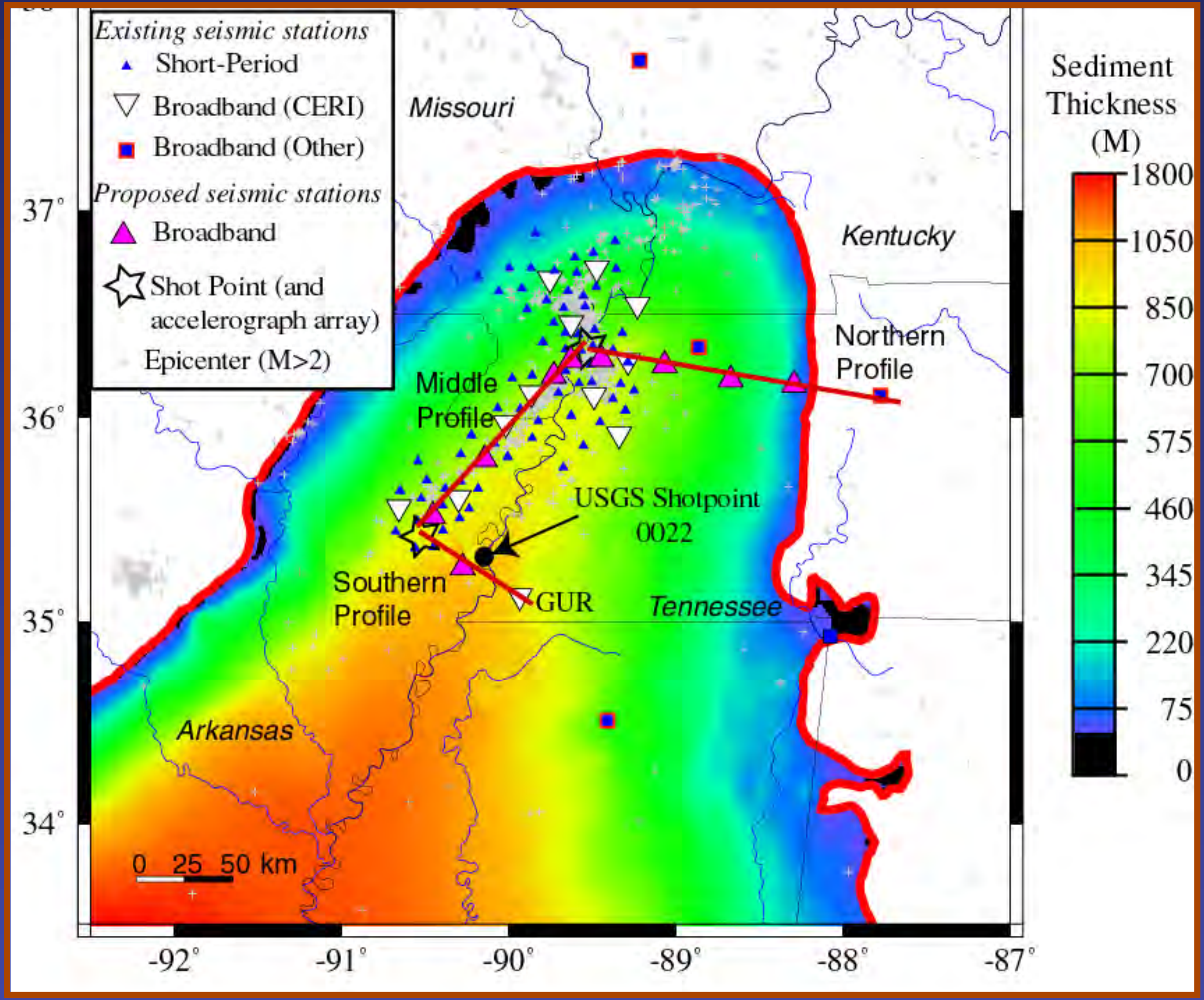


Blast-Induced Liquefaction

Cooper River Bridge, Charleston SC



Embayment Seismic Excitation Experiment (ESEE)



Embayment Seismic Excitation Experiment (ESEE)

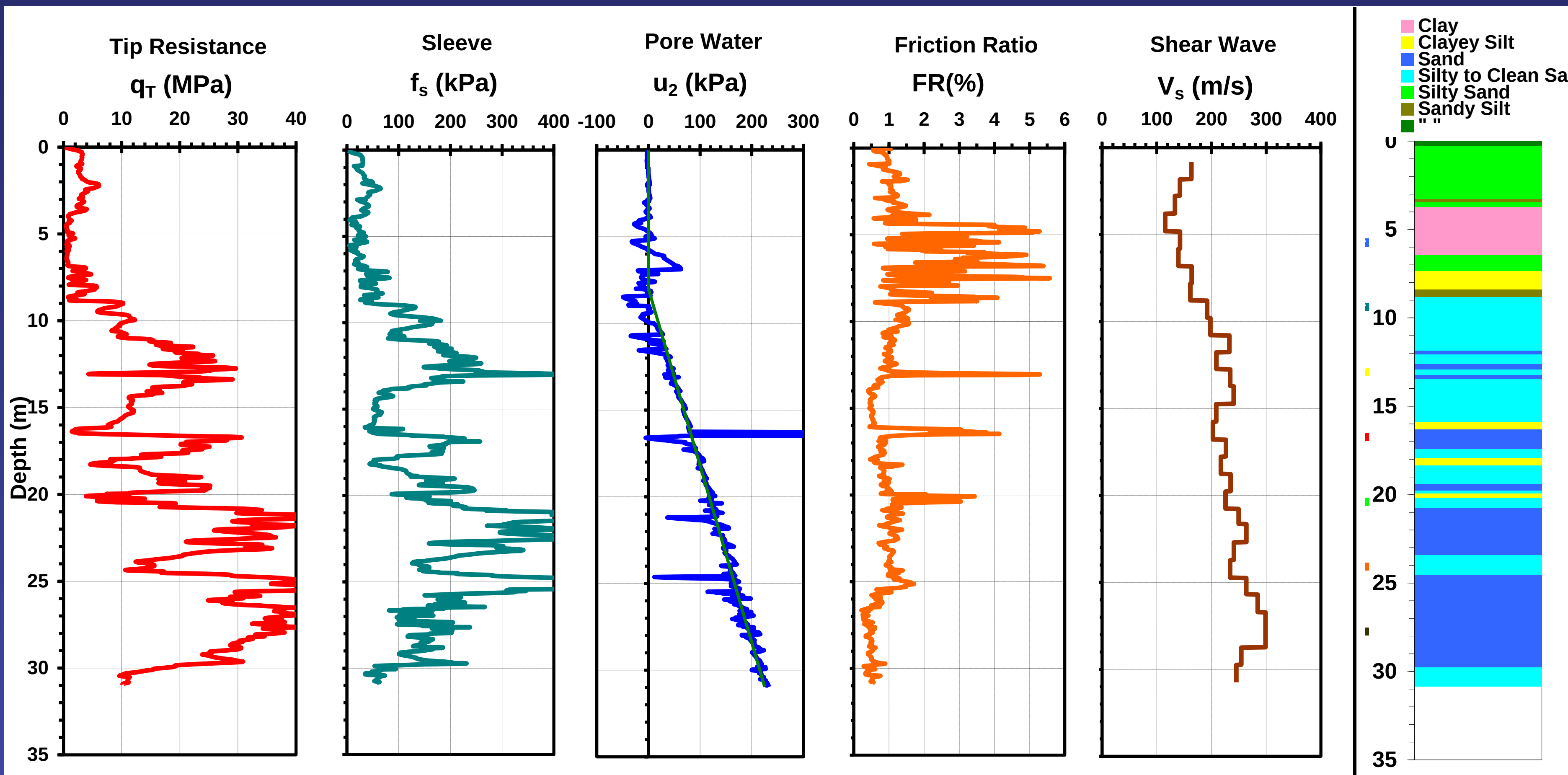
- Initial Baseline data collection before the HD-5 events
- Explosives-induced liquefaction at depths 80 to 160 feet
- 2500 lbs charge at Marked Tree site, Arkansas.
- 5000 lbs at Mooring, Tennessee.

Embayment Seismic Excitation Experiments (ESEE)

AR: One borehole with 1180 kg of explosives;

TN: Two boreholes with total 2268 kg of explosives.

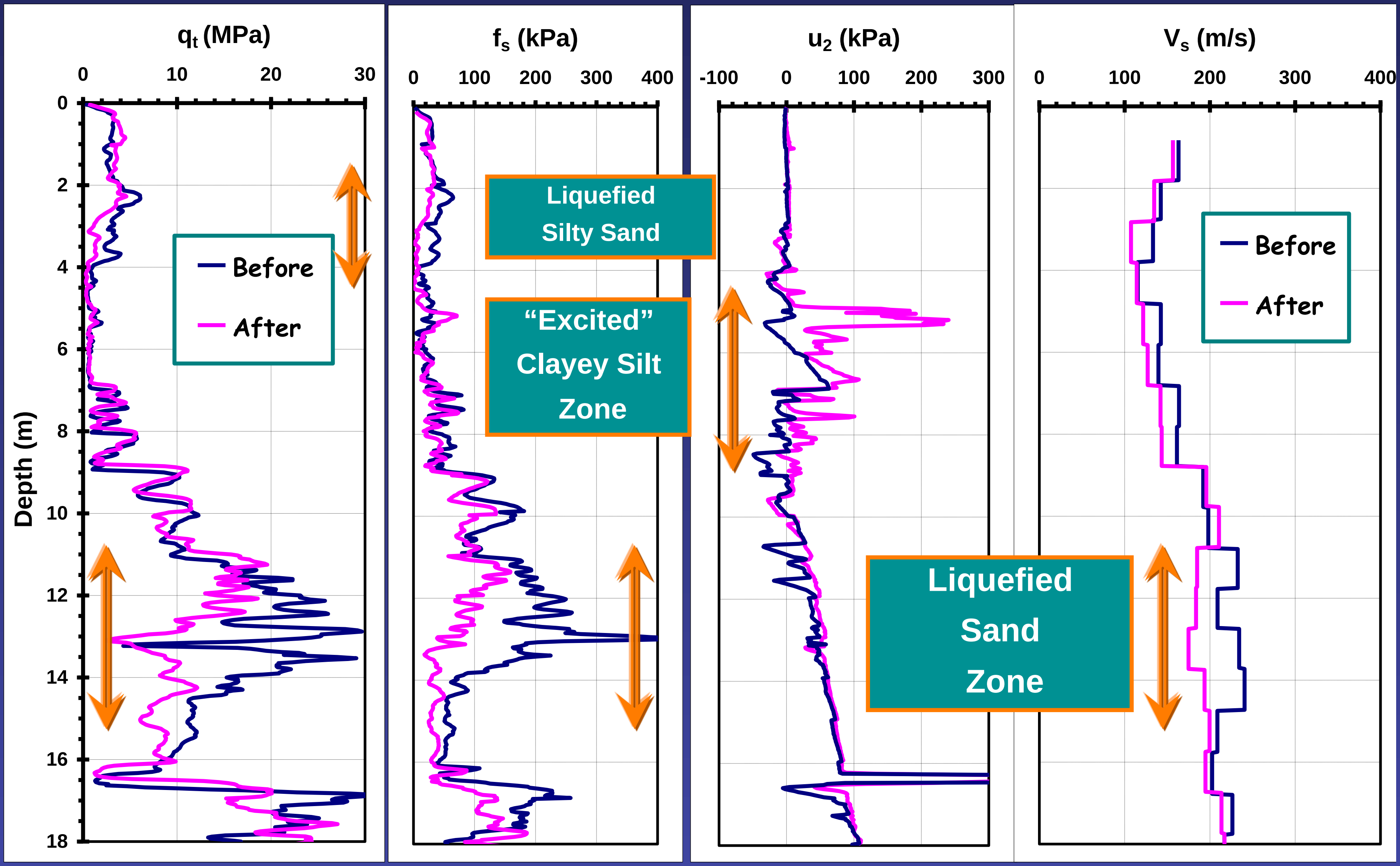
Pre-Blast ESEE Event, Mooring/TN



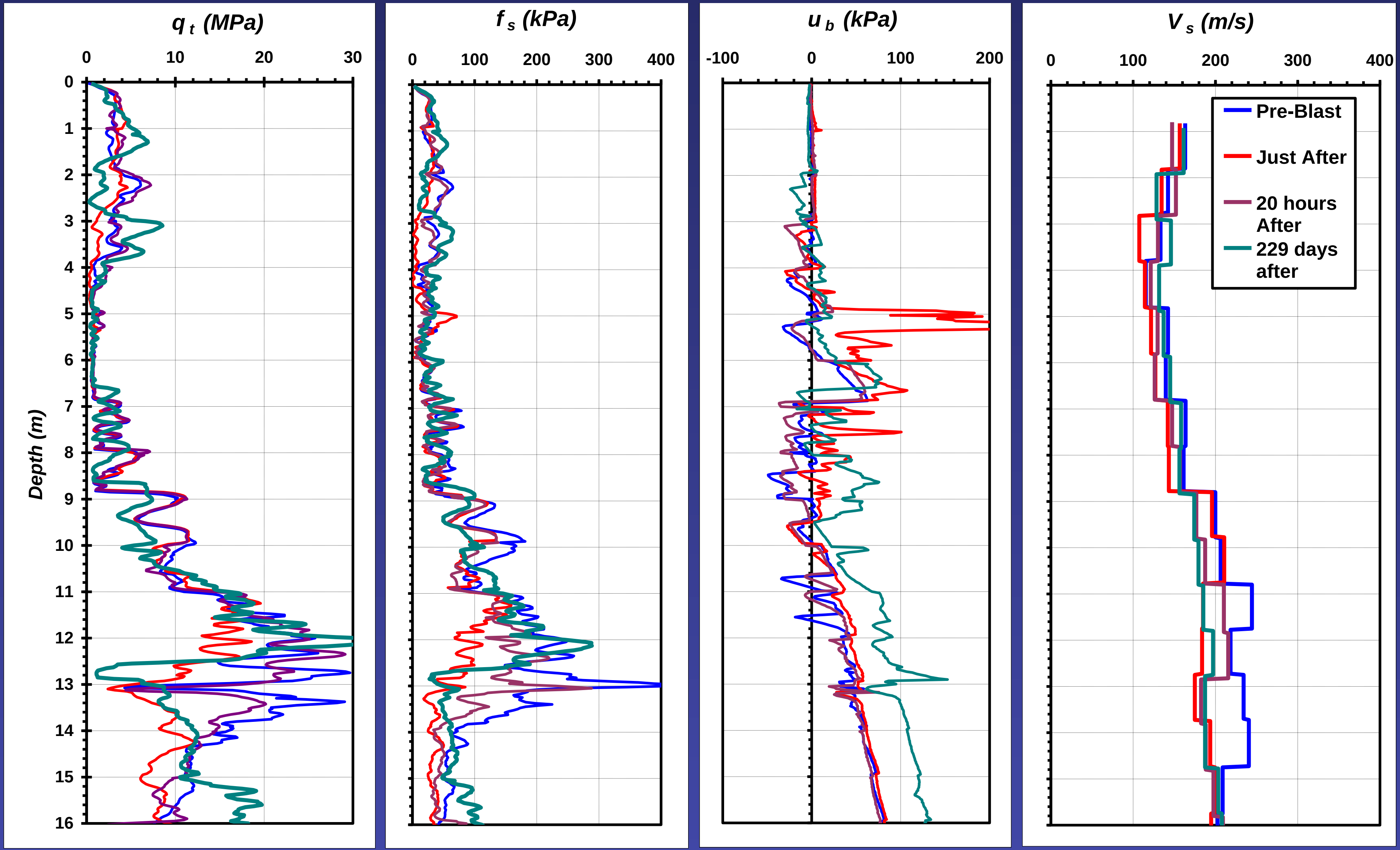
CPTs After ESEE Charge

- Field data collection after HD-5 events continued well into the midnight hours.
- Rig shown here at Mooring test site around 12 midnight with lighting as charges were denoted late night.

Compare SCPTu Before & After ESEE Event

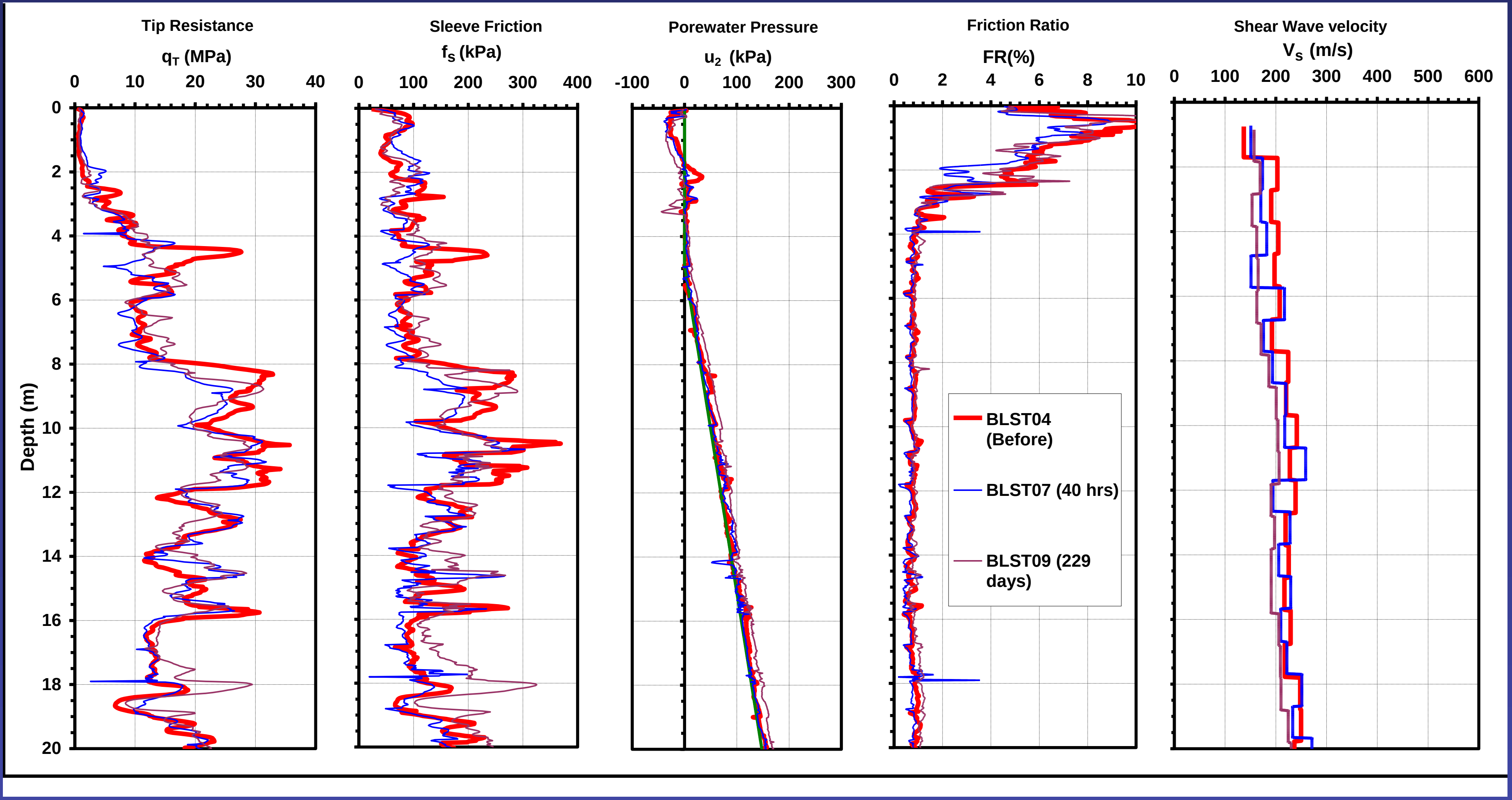


ESEE Results at Mooring, Tennessee Test Site
Before, After, and Aged SCPTu Soundings



ESEE Results at Marked Tree, Arkansas Site

Before, After, and Aged SCPTu Soundings



Evaluation of Scenario Earthquakes

K. Dyer-Williams

M. TUTTLE & ASSOCIATES
Specializing in Paleoseismology and Seismic Hazard Assessment

The Steps

1. Acquire (generate, request) and tabulate pre-existing borehole data for area of survey
2. Select methodology to be used (e.g., simplified or cyclic stress, energy)
3. Select regionally appropriate ground motion prediction equation
4. Measure (determine, estimate) distance to earthquake source. e.g., inferred epicenter(s) hypothetical source, fault, fault zone, historical event, etc.

The Steps Cont'd

5. Perform liquefaction potential analysis
6. Identify magnitude (M) and distance combination(s) that best matches observed distribution of liquefaction features
7. Integrate results into regional setting
8. Interpret magnitude and source area of paleoevent that caused the observed liquefaction features

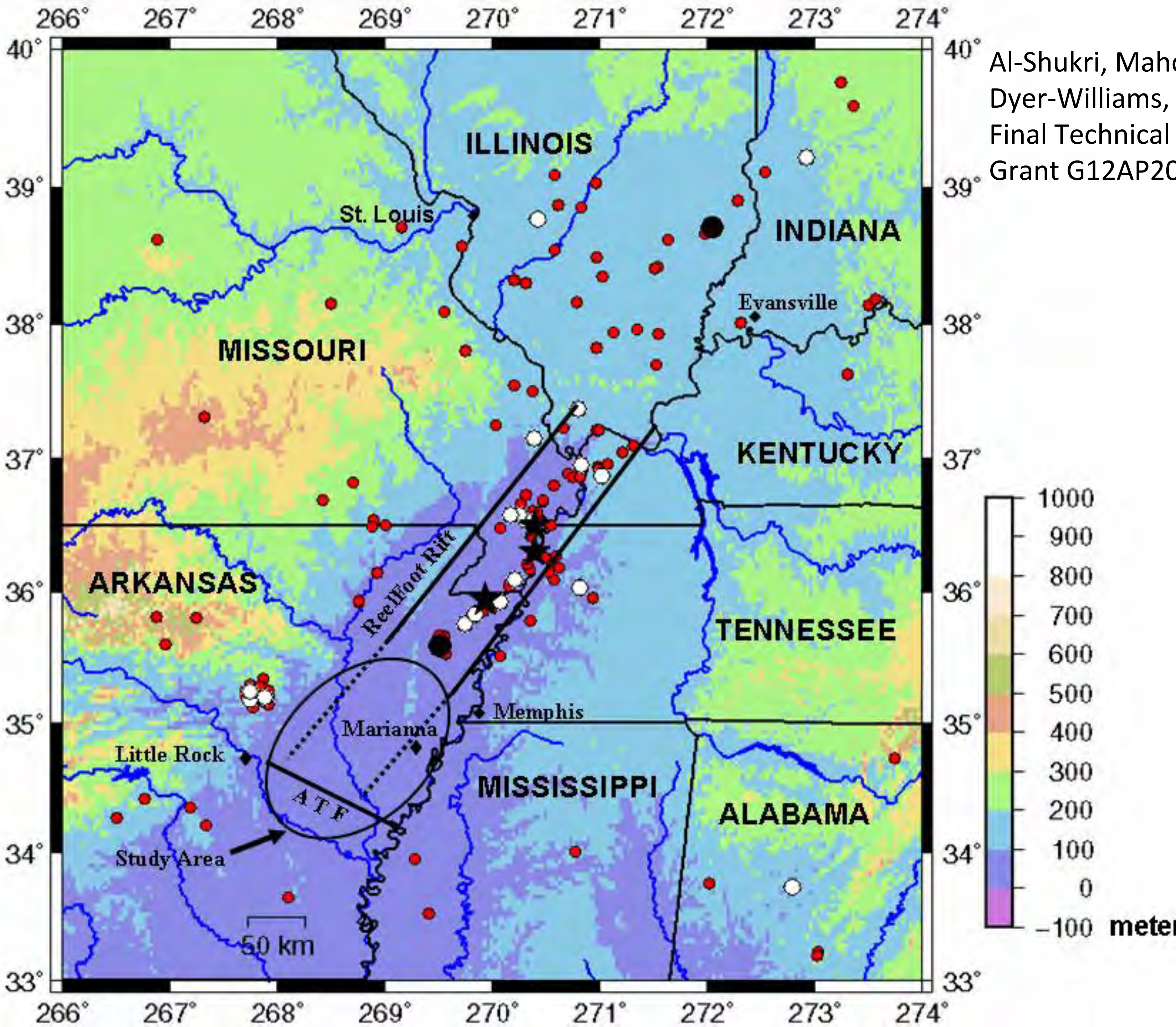
Sources of Uncertainty

- Seismic parameters (e.g., amplitude, duration, frequency, and directivity), regional ground motion attenuation, and local site effects
- Limitations of the data set (e.g., limited availability of data from some soundings, variability in the quality of the available data)
- Identification of the layer that liquefied
- Changes in geotechnical properties of the layer due to liquefaction and to post-liquefaction effects related to aging and groundwater fluctuation
- Quality of the field assessment
- Testing devices and techniques

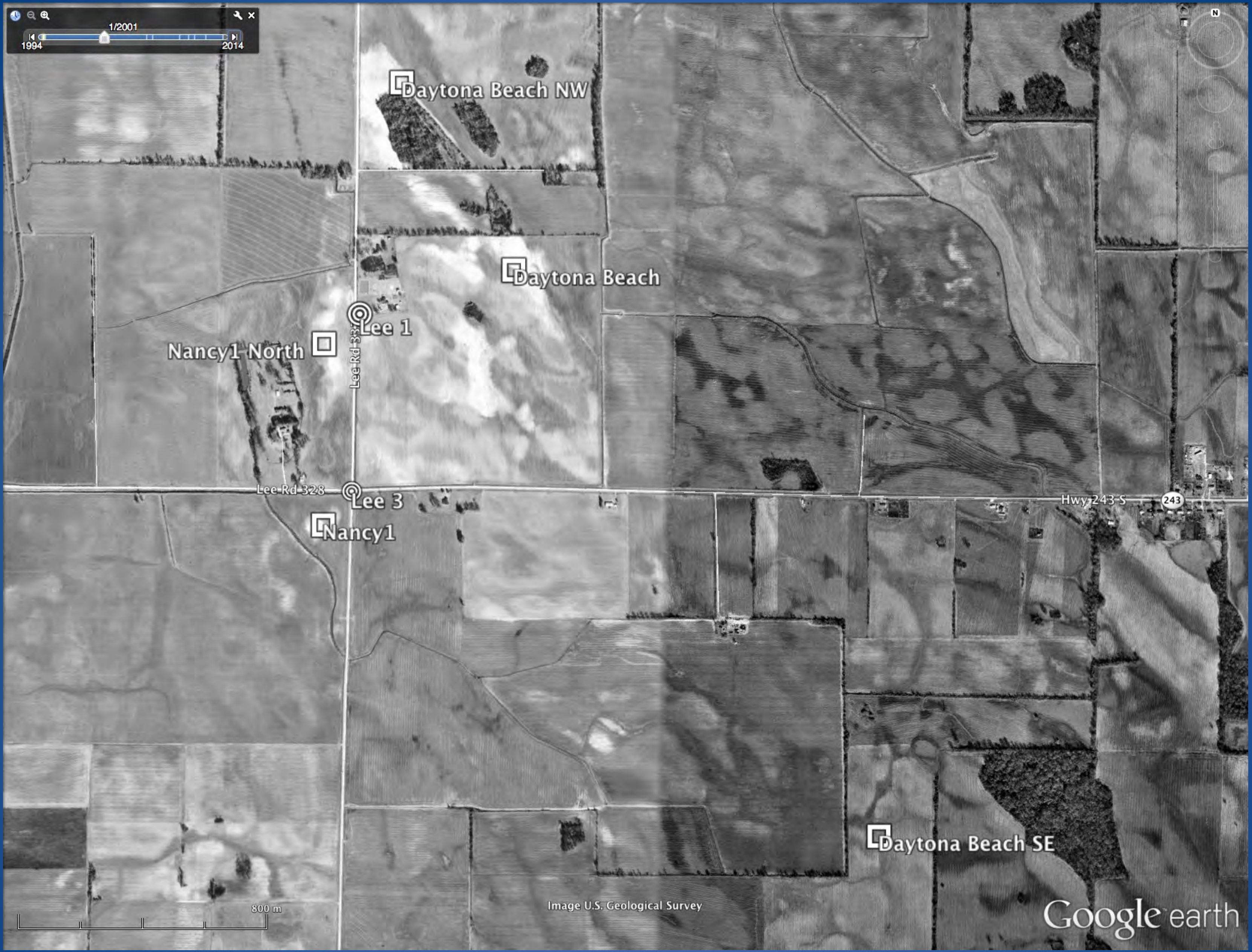
The Daytona Beach Example
(Dyer-Williams, Tuttle, Al-Shukri, and Mahdi, 2015)

Though Marianna is southwest of the NMSZ, it may be relevant to the long-term behavior of the Reelfoot fault system.

- We evaluated scenario earthquakes at distances of 5 km and 10 km because
  (1) Daytona Beach and Nancy1 sand blows are thought to occur immediately above the active faults that produced paleoearthquakes in the area
  (2) seismicity in the Mississippi Embayment typically occurs between 5-10 km depth.



Al-Shukri, Mahdi, Tuttle, Dyer-Williams, 2015, Final Technical Report, USG Grant G12AP20093, 31 p.

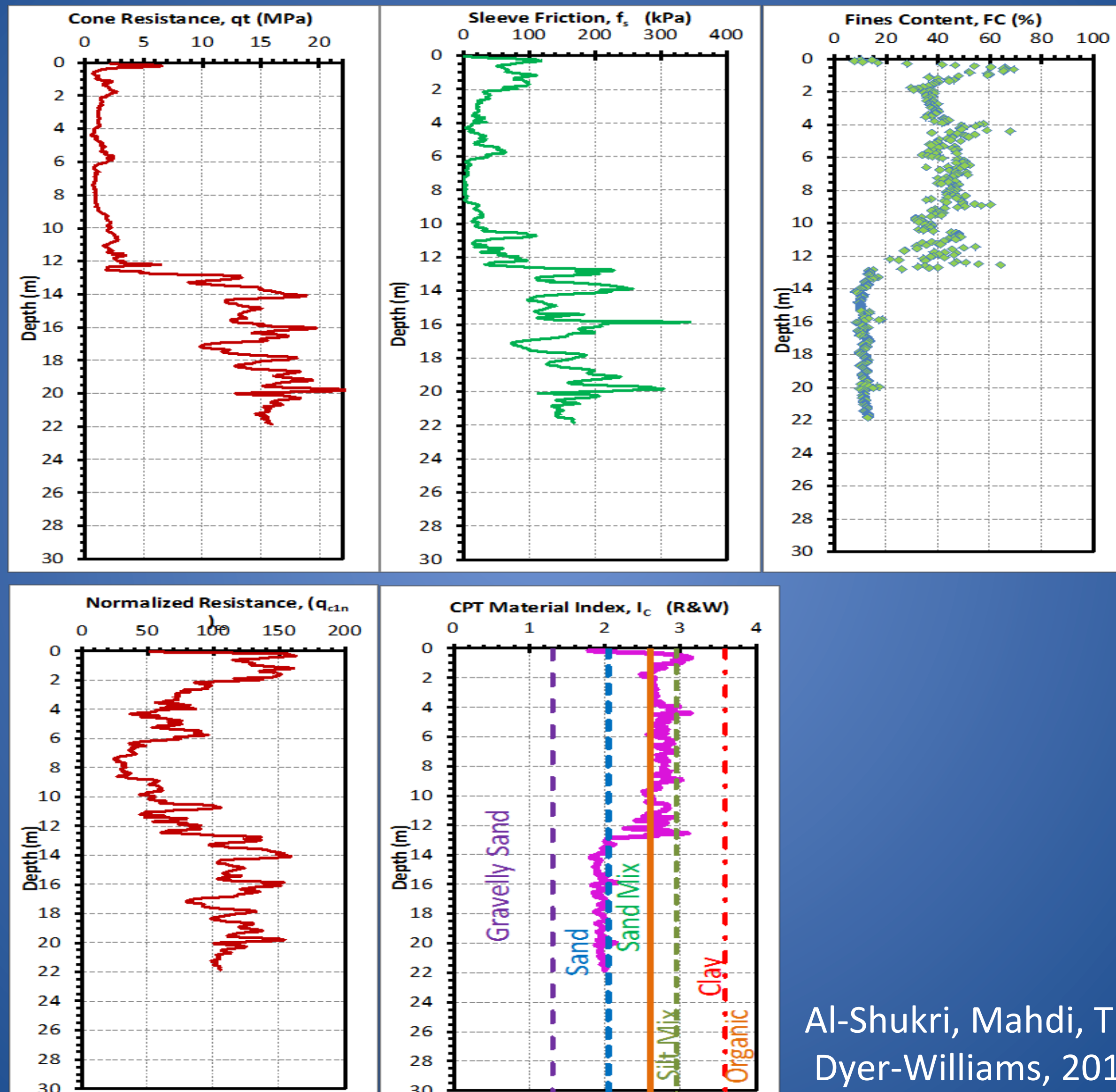


Paleoseismic study sites are indicated by white squares and CPT sites are indicated by white concentric circles; figure from Al-Shukri et al., 2015.

The Daytona Beach Example Cont'd

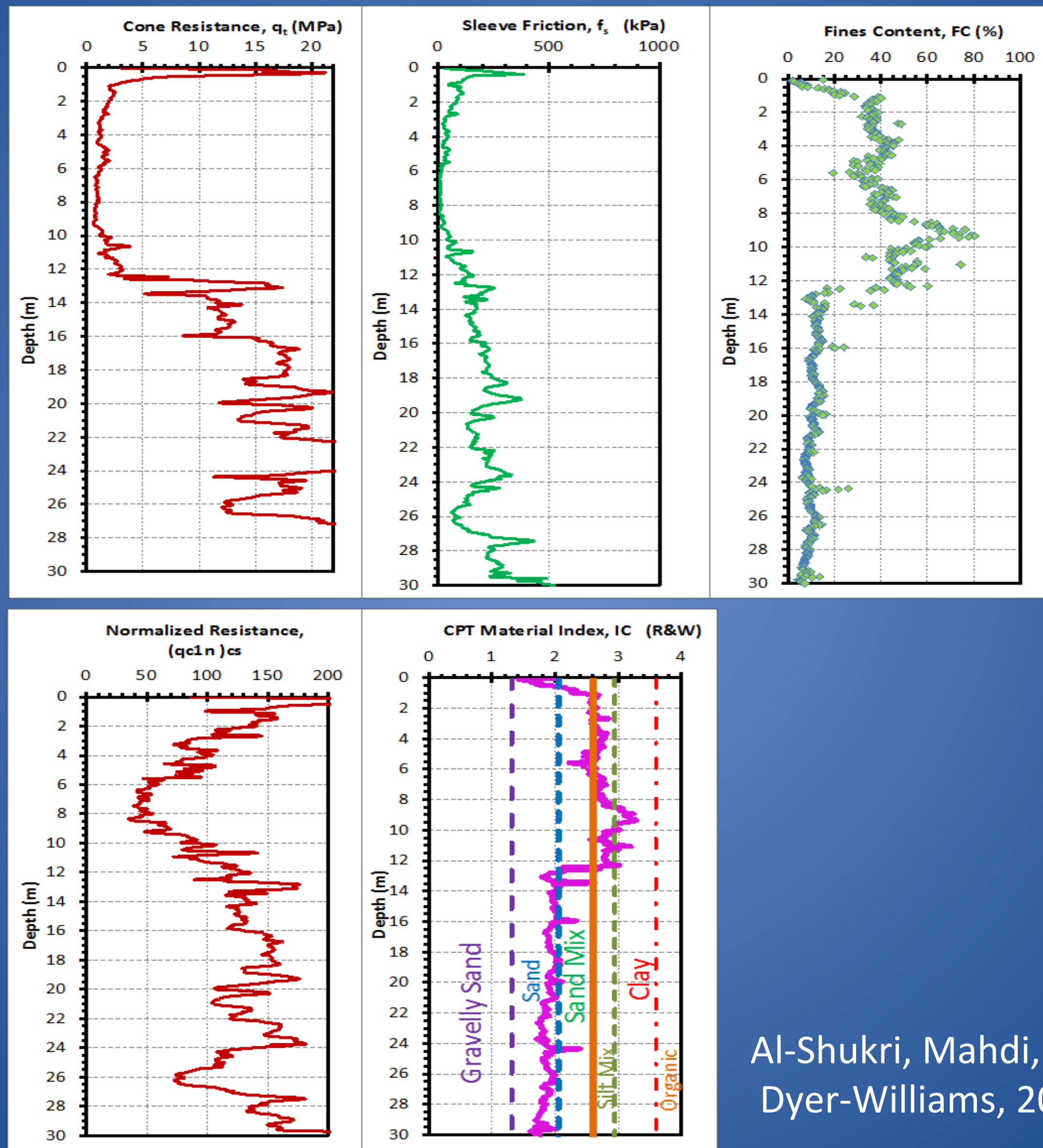
- The geotechnical information was obtained from *in situ* testing performed by the U.S. Geological Survey (Holzer and Noce) in 2004. We used the CPT data collected at sites Lee 1 and 3 and the ground motion prediction equations (GMPEs) of Atkinson (2010) in the analysis
- Two water table depths (1.5 m and 5 m) were considered in the analysis since the water table may have been deeper at the time of the paleo-earthquakes (Early-Mid Holocene).
- The results of the analysis are presented in Tables 1a and 1b and summarized below.

CPT data at site Lee 1 southwest of Marianna, Arkansas (from USGS - Holzer and Noce)



Al-Shukri, Mahdi, Tuttle, Dyer-Williams, 2015

CPT data at site Lee 3 southwest of Marianna, Arkansas (from USGS - Holzer and Noce)



Al-Shukri, Mahdi, Tuttle, Dyer-Williams, 2015

Table 1a. Summary Results of Analysis for Daytona Beach Northwest - Lee 1

(Al-Shukri, Mahdi, Tuttle, Dyer-Williams, 2015)

Moment Magnitude	Distance (km)	Liquefaction[1] Water Table 1.5 m	Liquefaction[1] Water Table 5 m
5.5	5	N	N
5.5	10	N	N
6	5	L	L
6	10	N	N
6.5	5	L	L
6.5	10	L	L

Footnote: 1. L = liquefaction likely; N = liquefaction not likely

Table 1b. Summary Results of Analysis for Daytona Beach Northwest- Lee 3

(Al-Shukri, Mahdi, Tuttle, Dyer-Williams, 2015)

Moment Magnitude	Distance (km)	Liquefaction[1] Water Table 1.5 m	Liquefaction[1] Water Table 5 m
5.5	5	N	N
5.5	10	N	N
6	5	L	L
6	10	N	N
6.5	5	L	L
6.5	10	L	L

Footnote: 1. L = liquefaction likely; N = liquefaction not likely

Daytona Beach Results

- An earthquake of **M** 5.5 would produce little if any liquefaction at either of the CPT sites (Lee1 and Lee3) whether the water table was at 1.5 m or 5 m depth; whereas, an earthquake of **M** 6 at a distance of 5 km or a **M** 6.5 at 10 km is likely to induce liquefaction in much of the sandy sediment below 12.5-13 m regardless of the water-table depth
- Earthquakes in the **M** 6-6.5 range could induce liquefaction in a thick section of sandy sediment below 12.5-13 m and therefore be responsible for the formation of the large sand blows

Summing Up

- Using liquefaction potential analysis, scenario earthquakes (various magnitude and distance combinations) are evaluated that would or would not explain observed areal and size distribution of liquefaction features
- Factors contributing to uncertainties include quality of geotechnical data used in analysis, confidence in the layer that liquefied and conditions at the time of the earthquake, and knowledge of seismic parameters – the event itself, regional attenuation of ground motion, and site effects

NRC Paleoliquefaction Training Workshop
November 10-13th, 2015
Blytheville, Arkansas

Radiocarbon dating and its use in paleoliquefaction studies

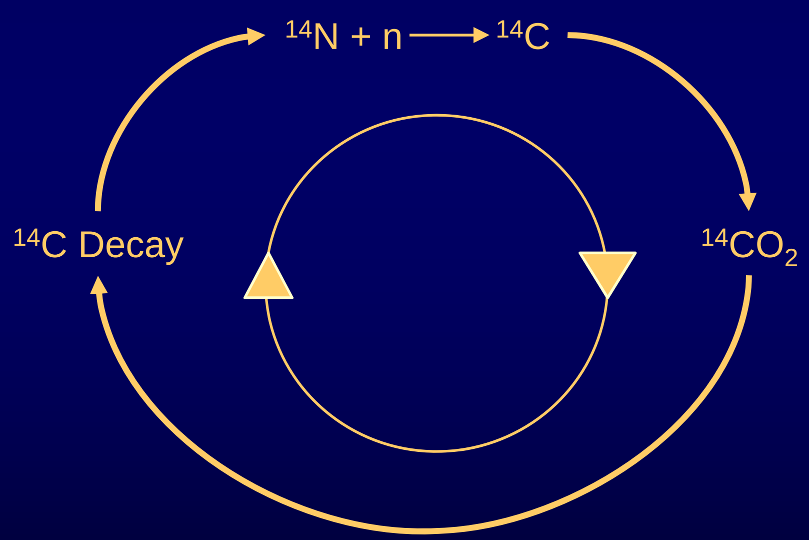
Darden Hood, President
Beta Analytic Inc.
www.radiocarbon.com

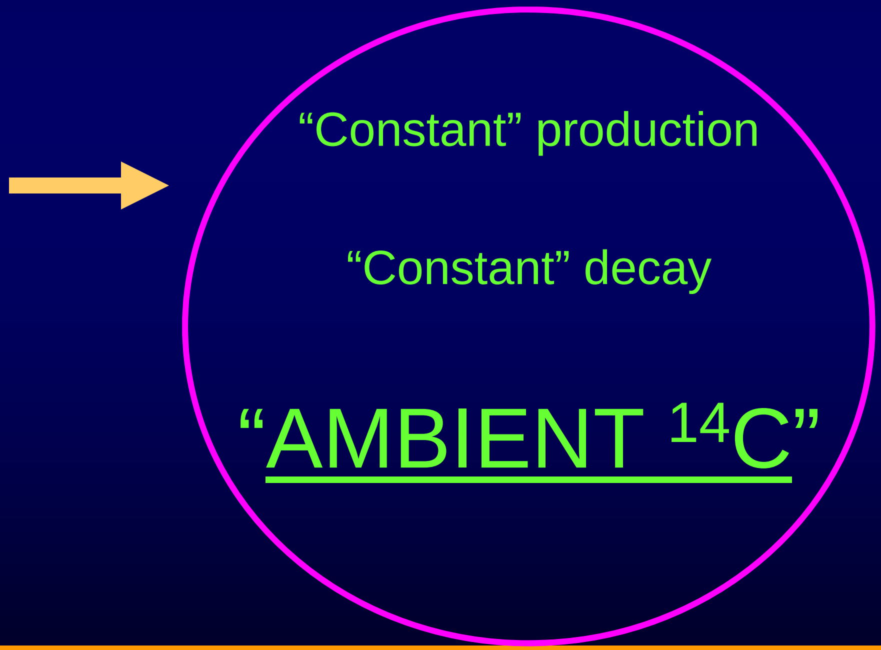
On-going formation and decay of radiocarbon within the atmosphere

Nitrogen (^{14}N) + cosmic neutrons → Radiocarbon (^{14}C)

Radiocarbon immediately oxidizes → Carbon Dioxide ($^{14}CO_2$)

The radiocarbon immediately starts to decay ($T^{1/2}$ = 5730 years)

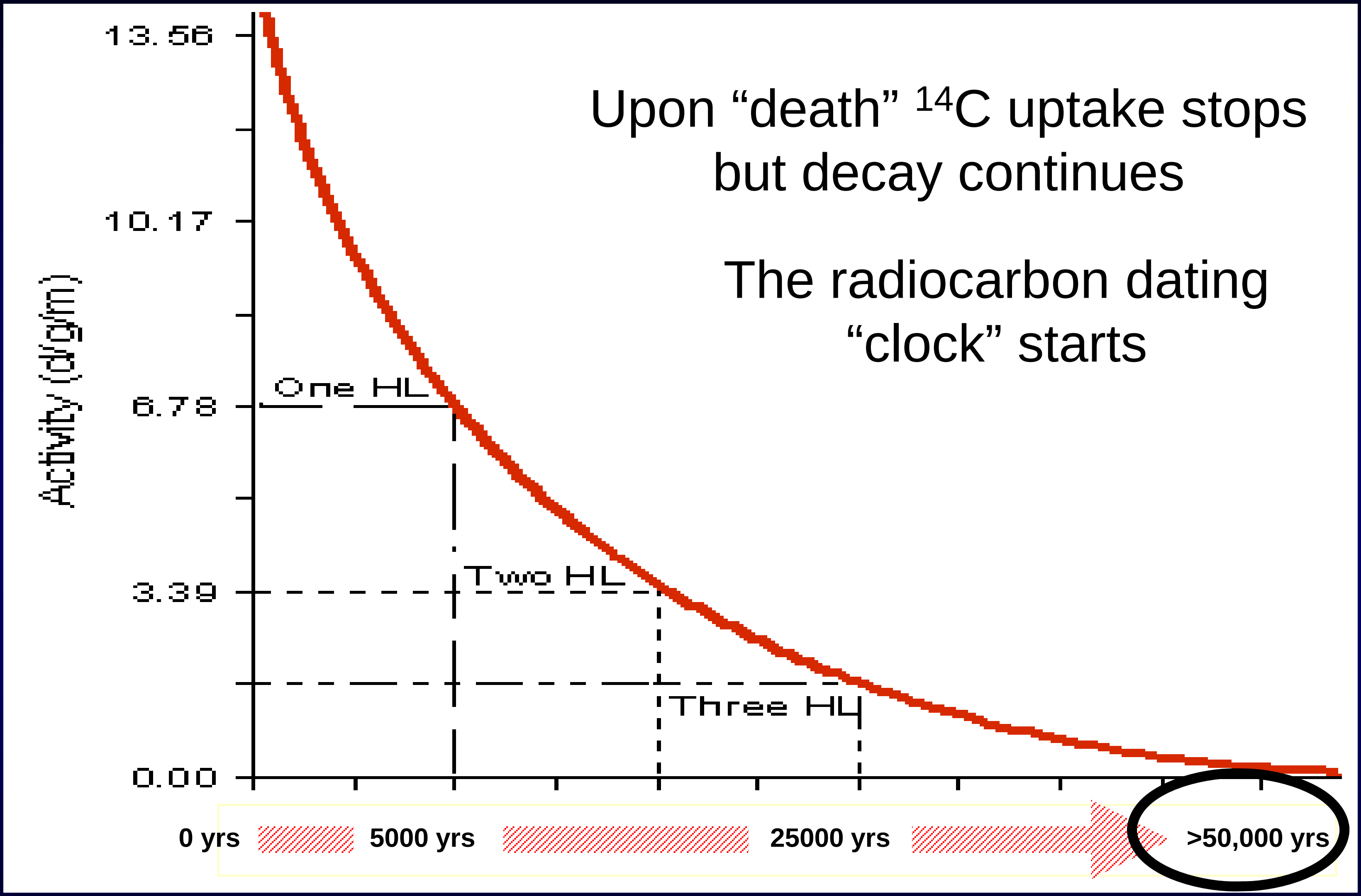




Radiocarbon is removed from the atmosphere by plants.

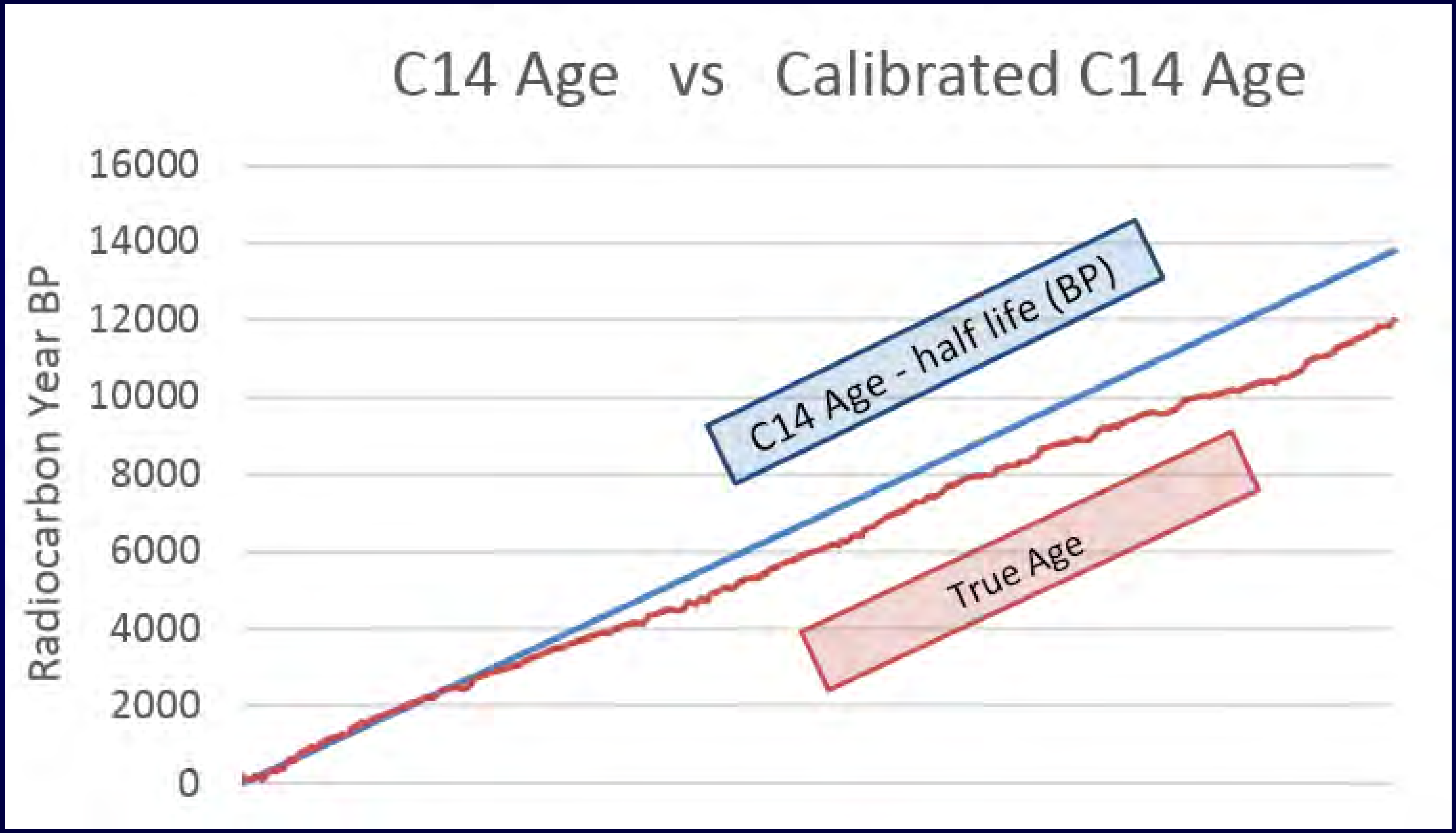
Plants take in the $^{14}CO_2$ during photosynthesis – thus including ^{14}C into the food chain → Living organisms are in ^{14}C equilibrium with atmosphere

$$^{14}CO_2 \text{ uptake} \rightleftharpoons {}^{14}C \text{ Decay}$$



13.56
10.17
6.78
3.39
0.00
Activity (d/g/m)
One HL
Two HL
Three HL
Upon "death" ^{14}C uptake stops but decay continues
The radiocarbon dating "clock" starts
0 yrs
5000 yrs
25000 yrs
>50,000 yrs

Fluctuation in atmospheric C14 content through time has to be accounted for



Radiocarbon dating results

Fraction Modern (fM) : E.G. 0.5000 +/- 0.0020

The sample 14C/12C relative to the 14C/12C ratio of NIST-4990C expressed as a fraction

Percent Modern Carbon (pMC) : E.G. 50.00 +/- 0.20 pMC

Fraction modern expressed in percent.

Radiocarbon Age (BP) : E.G. 5568 +/- 24 BP

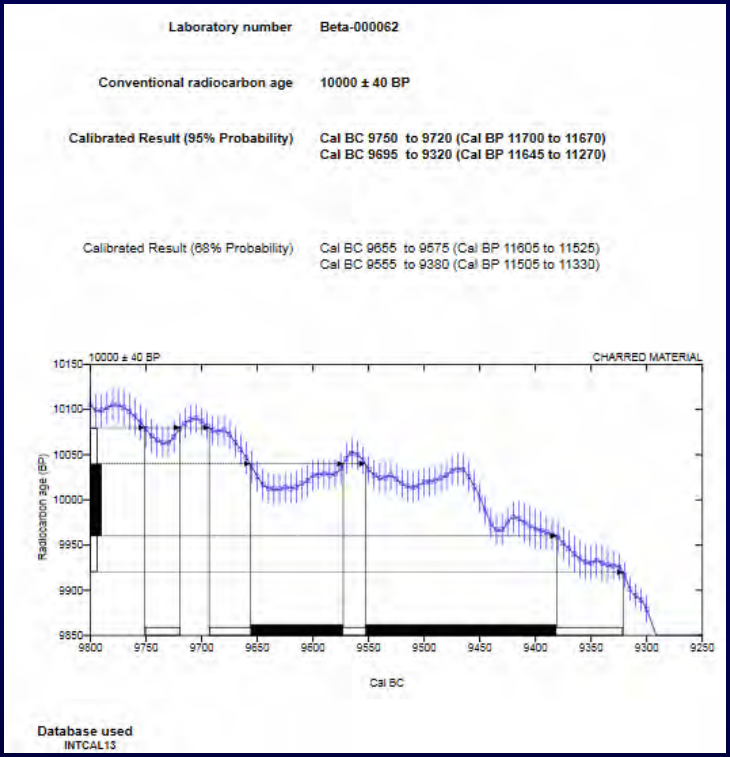
- 8033 x ln (fM). The activity of NIST-4990C is taken as AD 1950, also termed 0 BP (before present). The radiocarbon age is the calculated age in years before AD 1950 and cited as a mean +/- 1 relative standard deviation (1 sigma). Counting error only!

Delta 14C – relative C14 content to NIST-4900C expressed in per mil (o/oo)

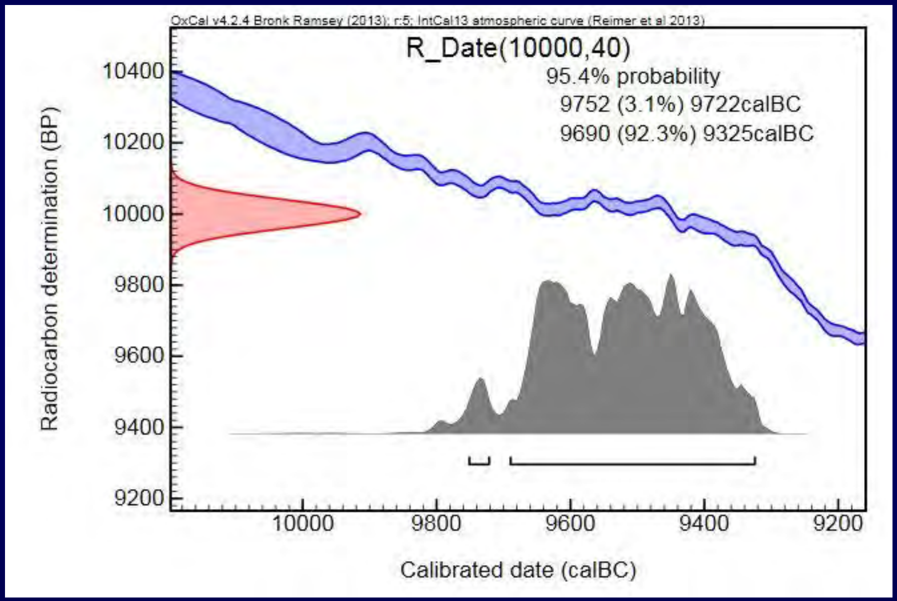
Δ14C, absolute pMC – Delta 14C and pMC adjusted for the decay of NIST-1990C between 1950 and the measurement date of the sample.

Calendar calibrated radiocarbon dating results

Calendar Calibrated Age Range (cal BP or cal AD/BC): The calendar time scale equivalent to the radiocarbon age. Determined by comparison with internationally accepted databases (INTCAL13). Reported as a range or ranges.

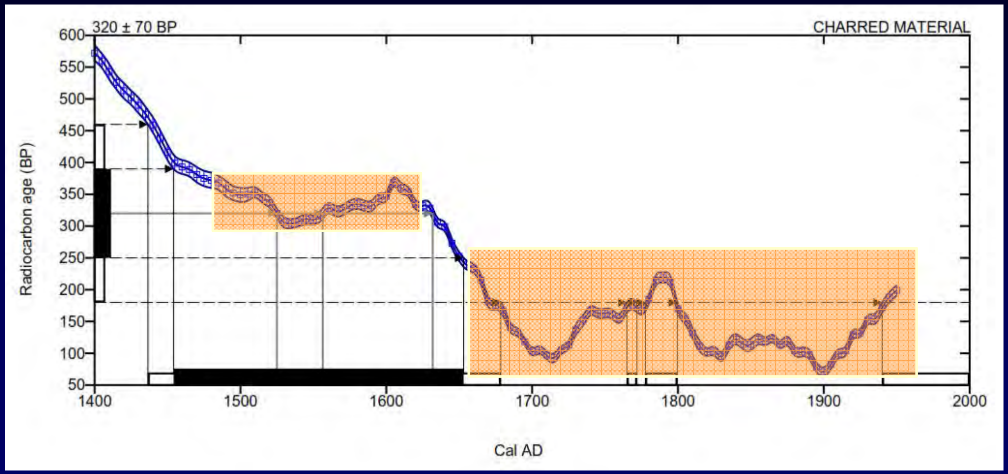


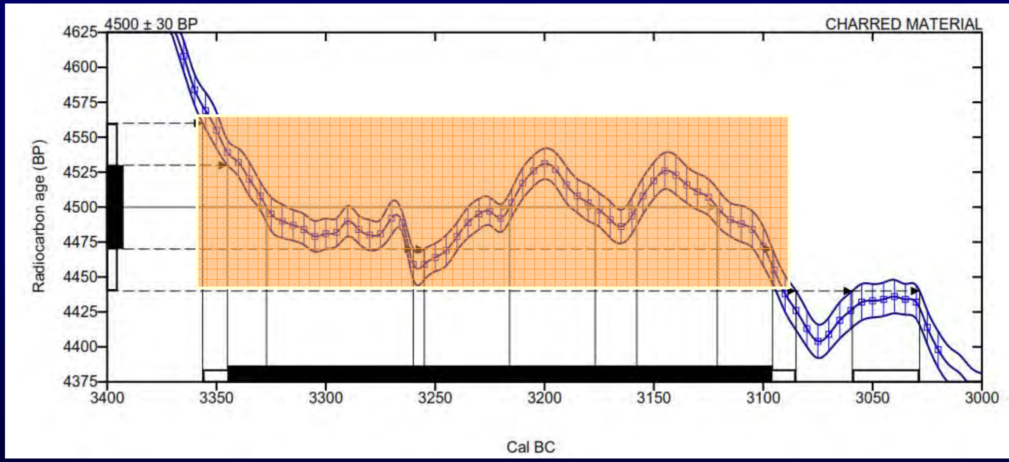
Intercept method



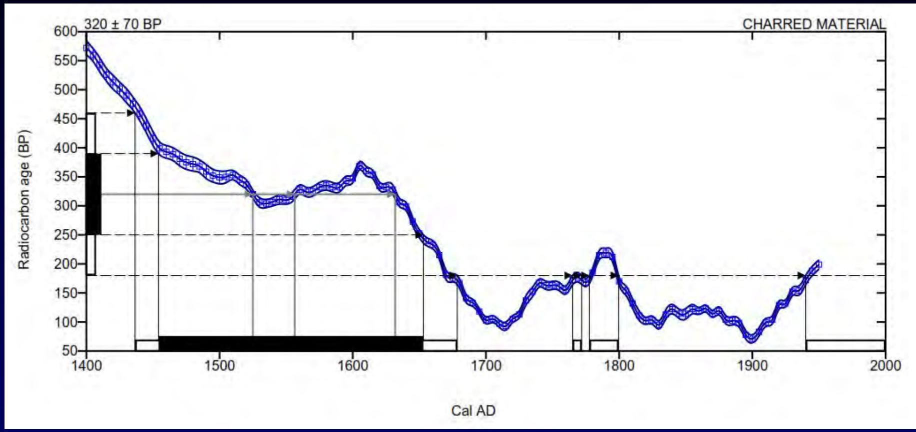
High probability density method

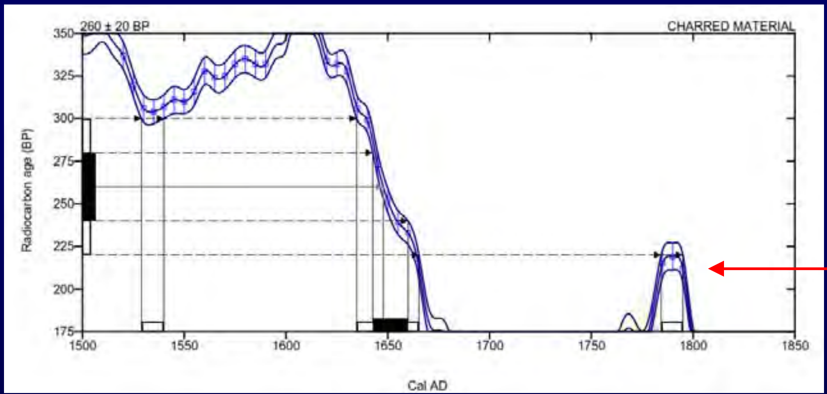
Calibration Plateaus

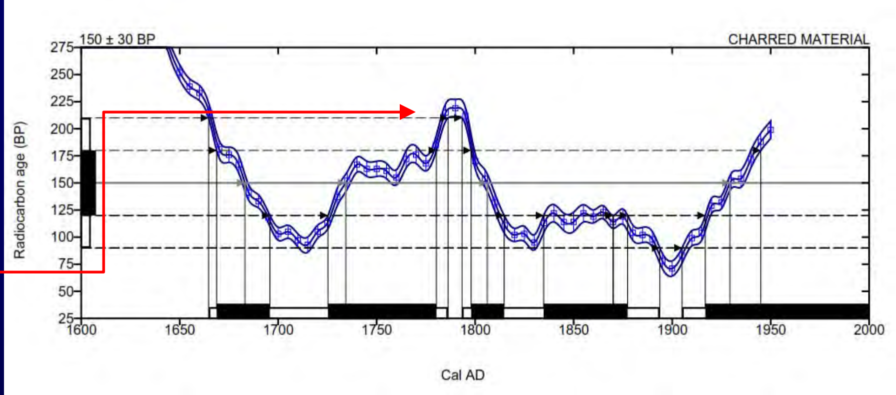




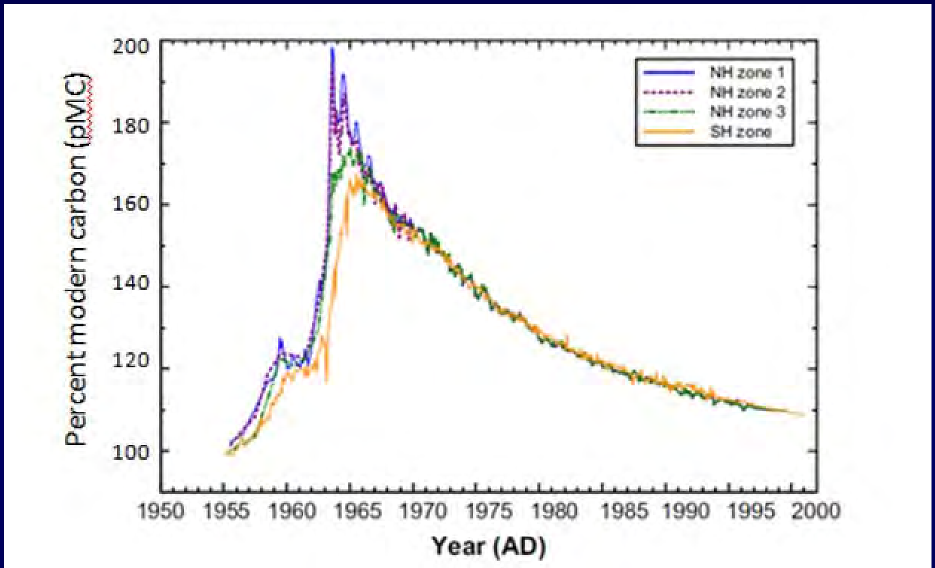
Calibration Wiggles



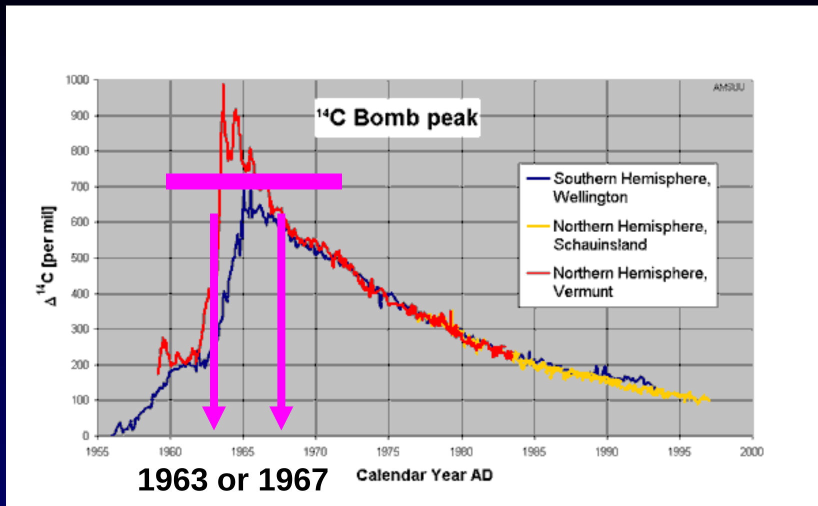




Bomb Carbon → Percent Modern Carbon (pMC) > 100%

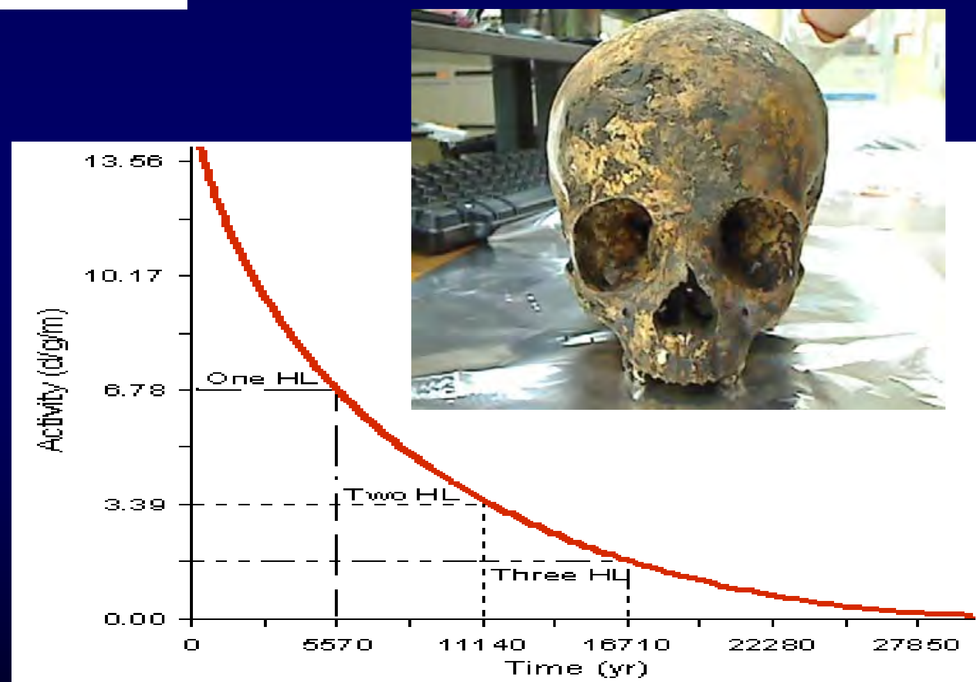


Hua, Q., Barbetti, M., 2004, Review of Tropospheric Bomb 14C Data for Carbon Cycle Modeling and Age Calibration Purposes, Radiocarbon 46, p 1273–1298.



Forensic Tool

Which is it; archaeological or recent?

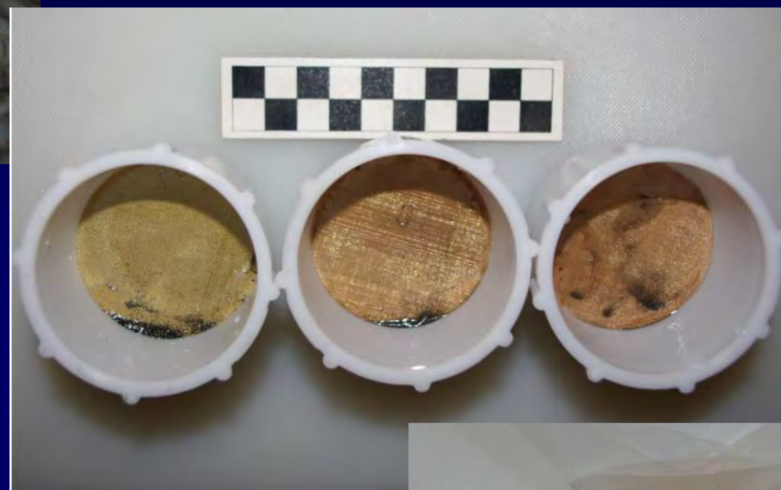


Old wood effect – each ring is one year older

Log cores well !

Only tiny samples are needed


CM




CM

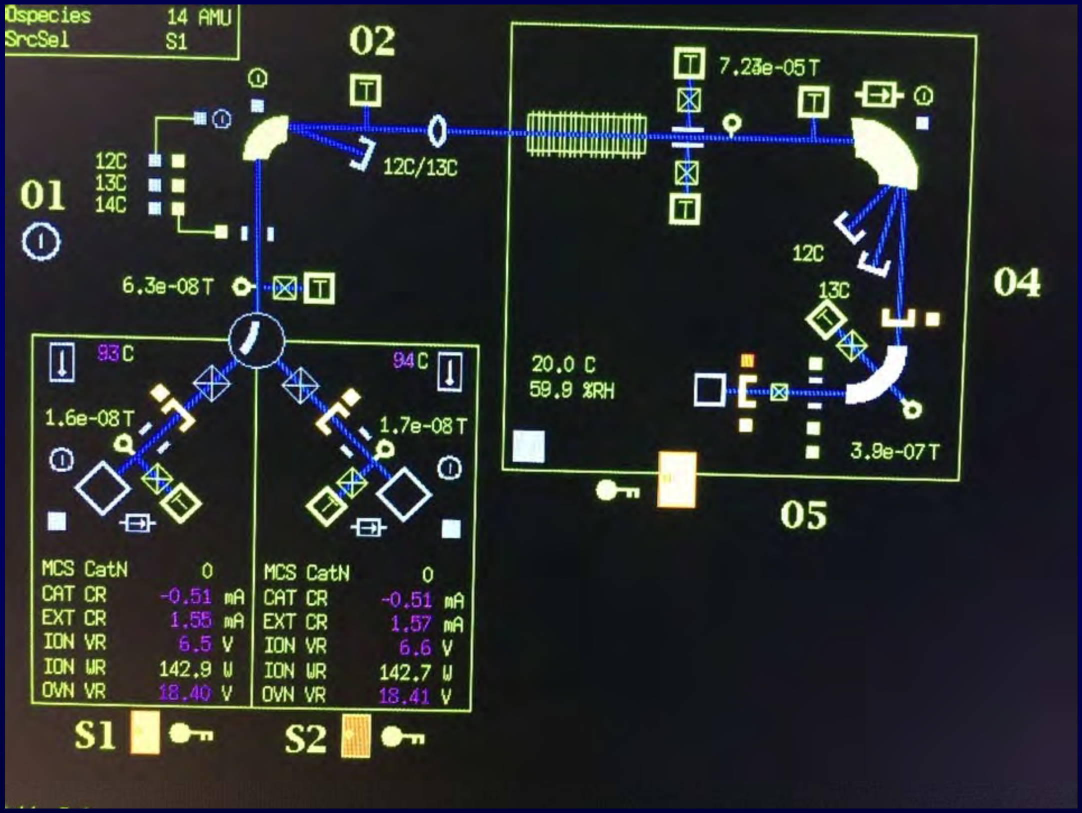
Tiny samples are suitable

(1mm x 1mm background)

Carbon is extracted as graphite and measured by AMS

AMS - Accelerator Mass Spectrometry

Steering atoms through a particle accelerator to compare the 14C/12C ratio of the sample to the 14C/12C ratio of the modern reference – separates atoms which are only 1 neutron different in weight!



Optically Stimulated Luminescence Dating for Paleoseismology

(with a focus on paleoliquifaction features)

Steven L. Forman
Liliana C. Marin
Xiaohua Gua
Ashley Ramsey
Chris Dickey
Connor Mayhut

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Department of Geology
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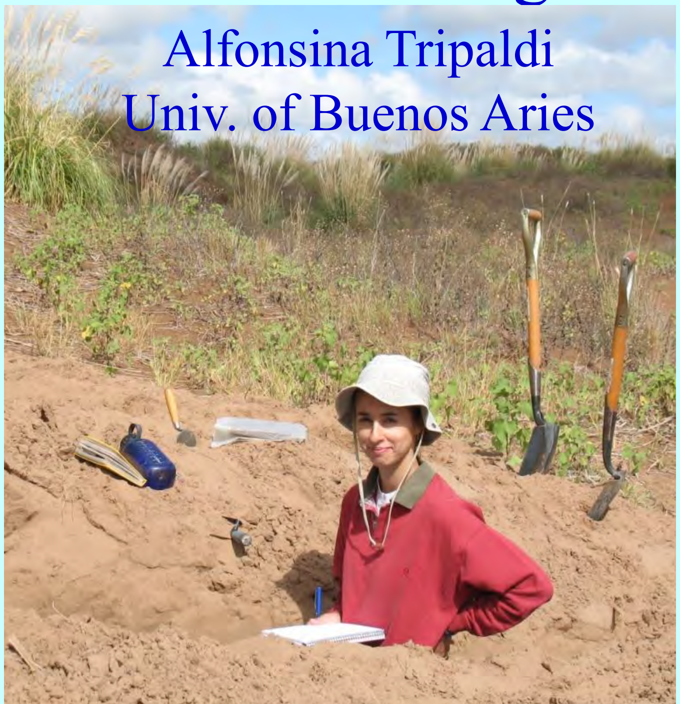
Web site: http://www.baylor.edu/geology

Sponsored research through the National Science Foundation, U.S. Geological Survey, NASA, National Park System.

Colleagues and (past) Students

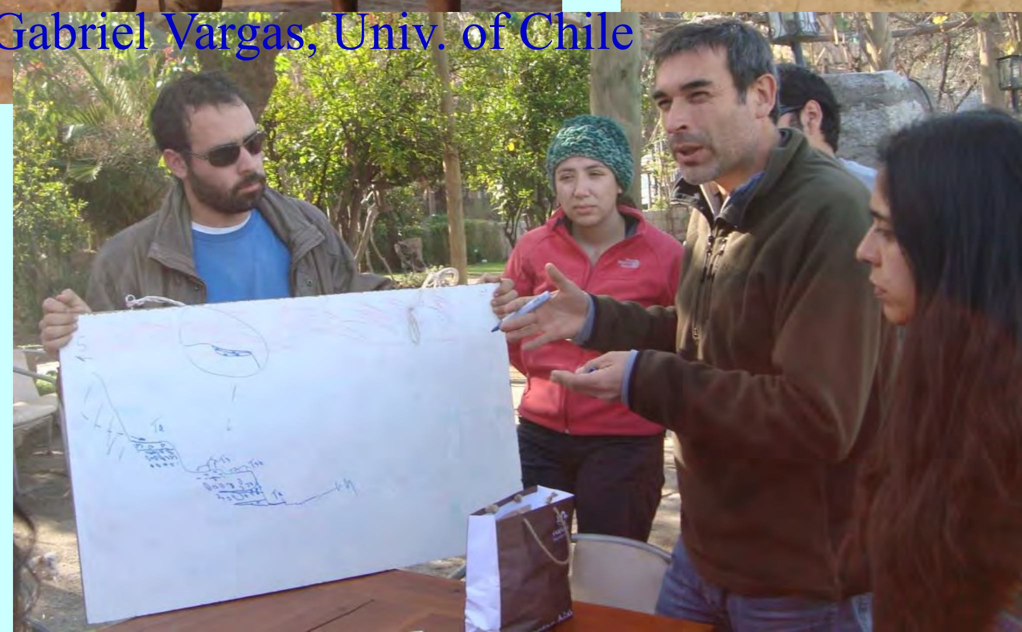


Alfonsina Tripaldi
Univ. of Buenos Aries

Chris Bloszies

David Wright, SNU

Cristina Londono
St. Louis Univ.

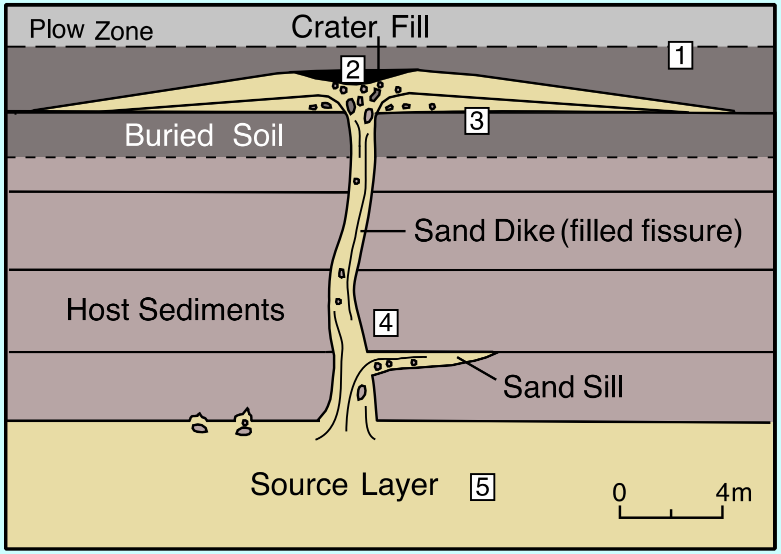


Gabriel Vargas, Univ. of Chile

What will be presented?

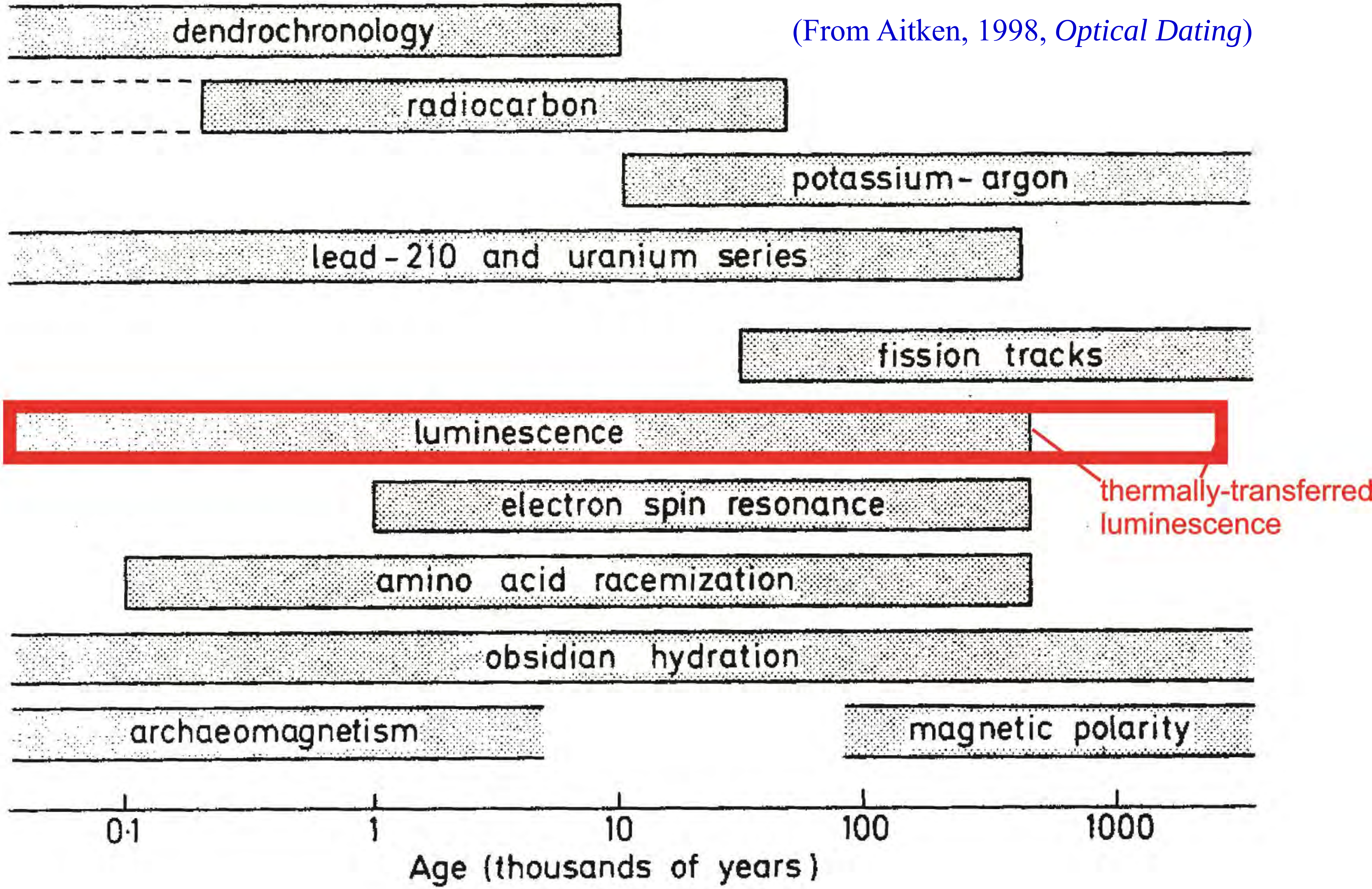
- Basics of optical stimulated luminescence (OSL) dating
- Relation of OSL dating to sedimentary processes
- Single aliquot regeneration dating
- Single grain regeneration dating
- Accuracy of OSL dating past 1000 years
- Two case studies: (1) The eolian revolution!
  (2) San Ramon Fault, Chile
- Perspectives on OSL dating sand blows

Please ask questions, interrupt and challenge me!

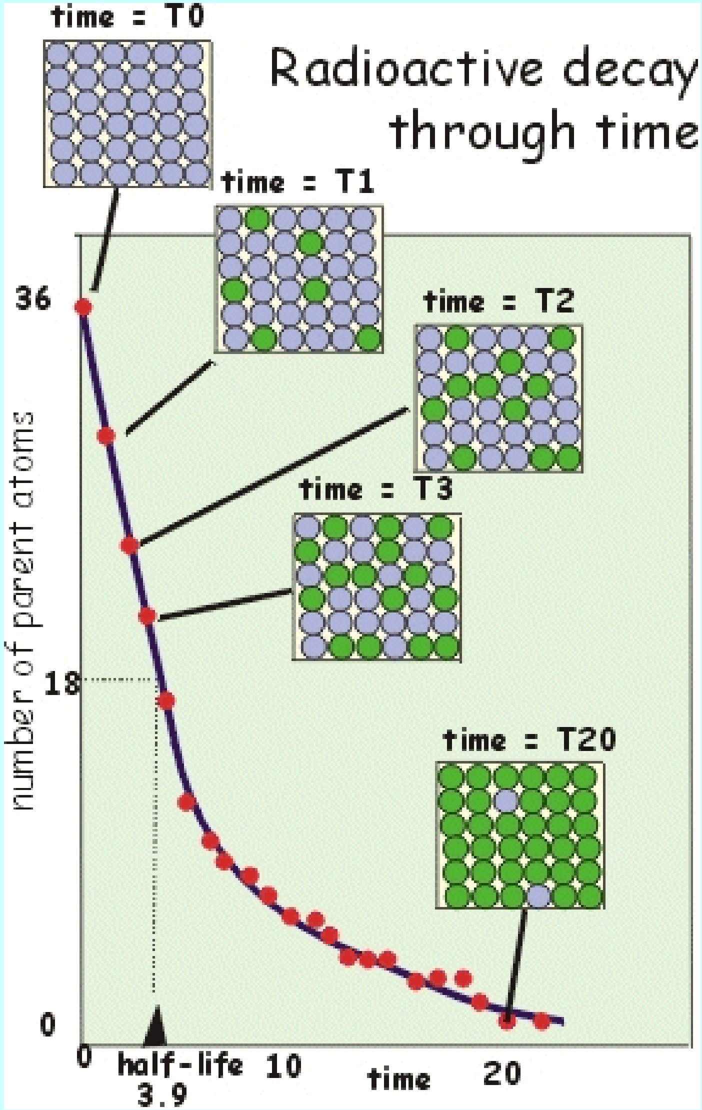


Quaternary geochronology: Luminescence dating applicable for sediments spanning the past ca. 2.6 million years

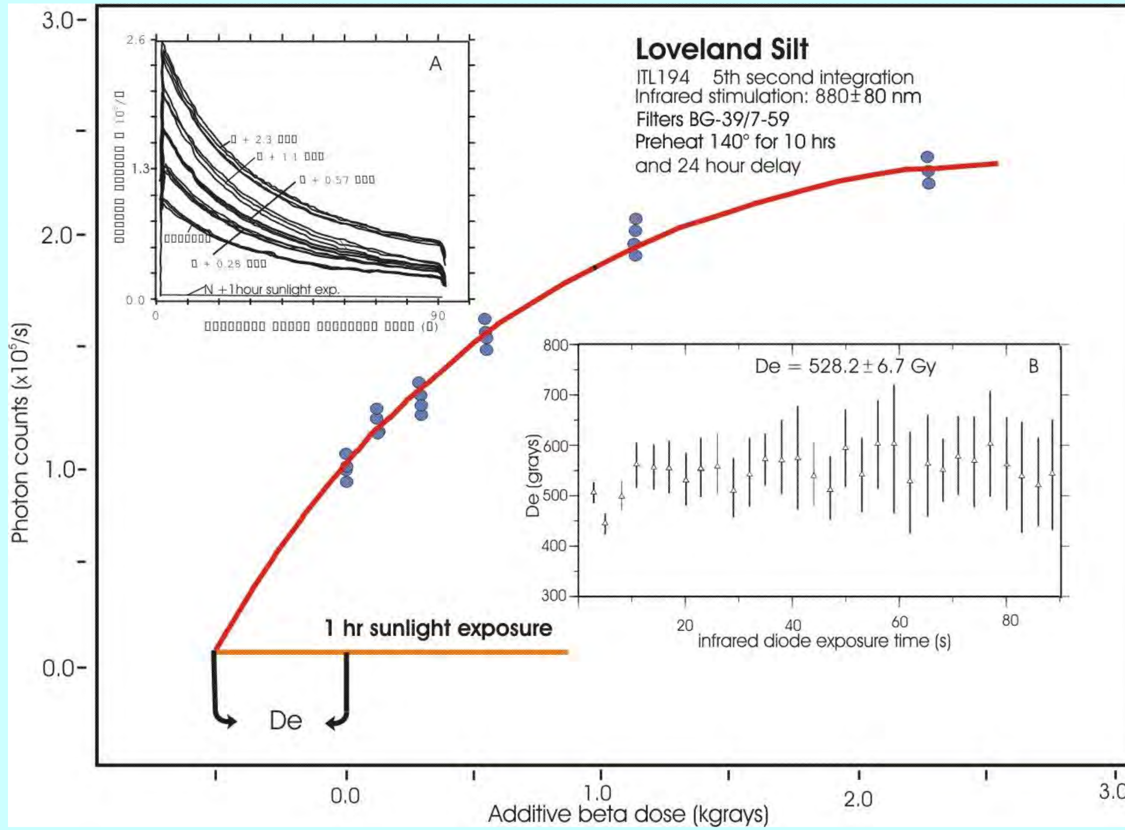
(From Aitken, 1998, *Optical Dating*)



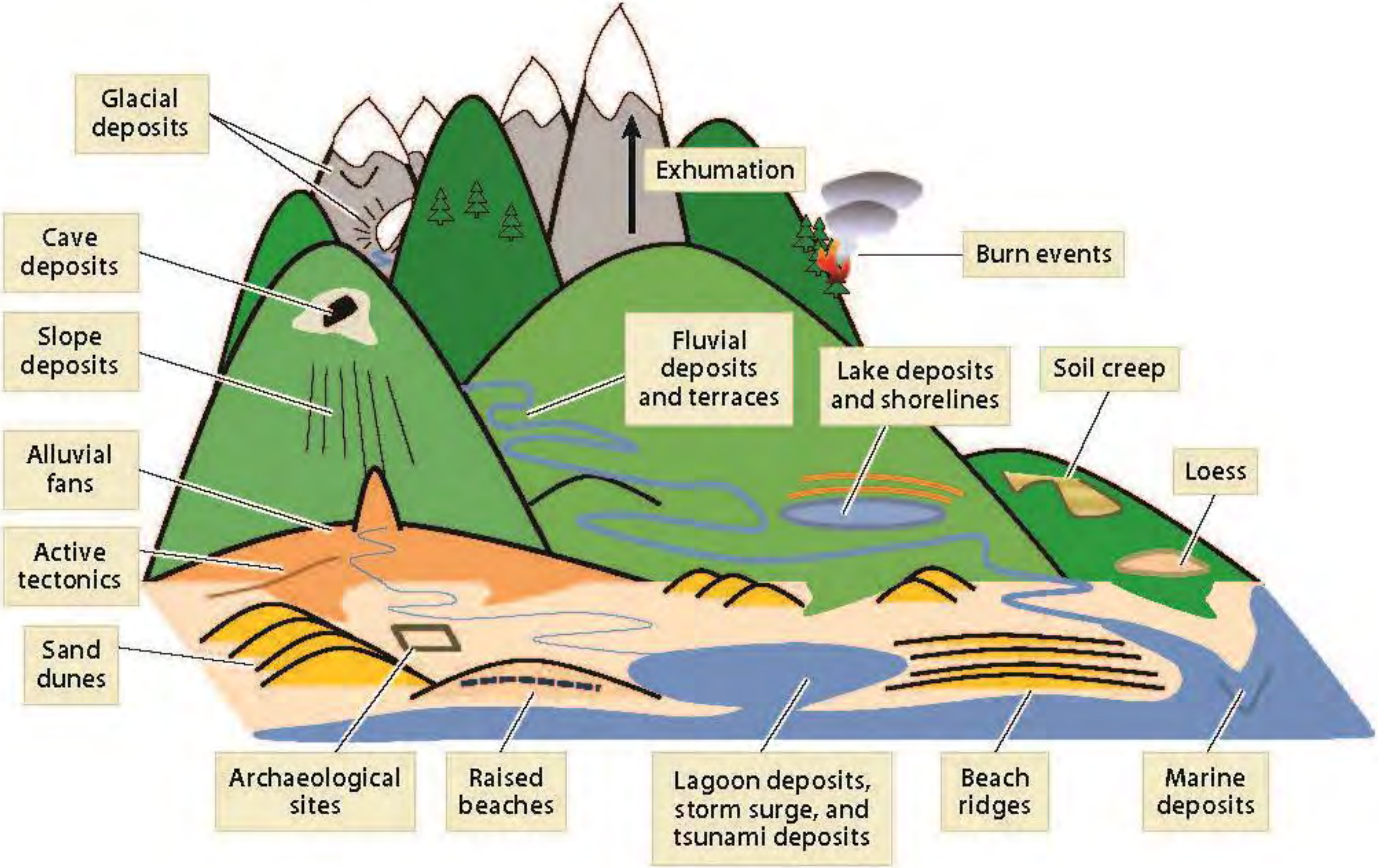
Radiocarbon dating: Exponentially decreasing signal with time based on radioactive decay



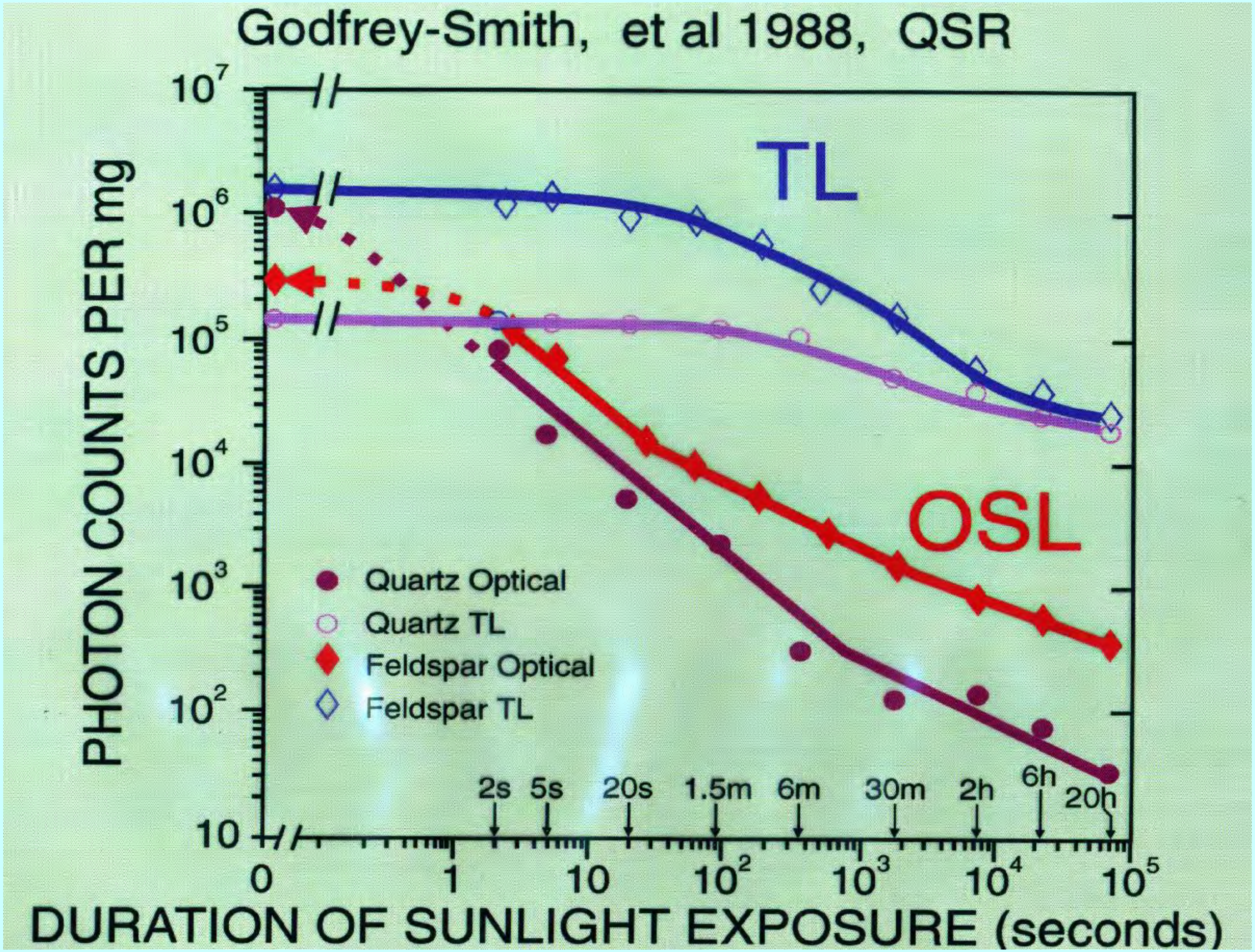
Luminescence dating: Exponential increasing signal with time based on radiation dosimetry



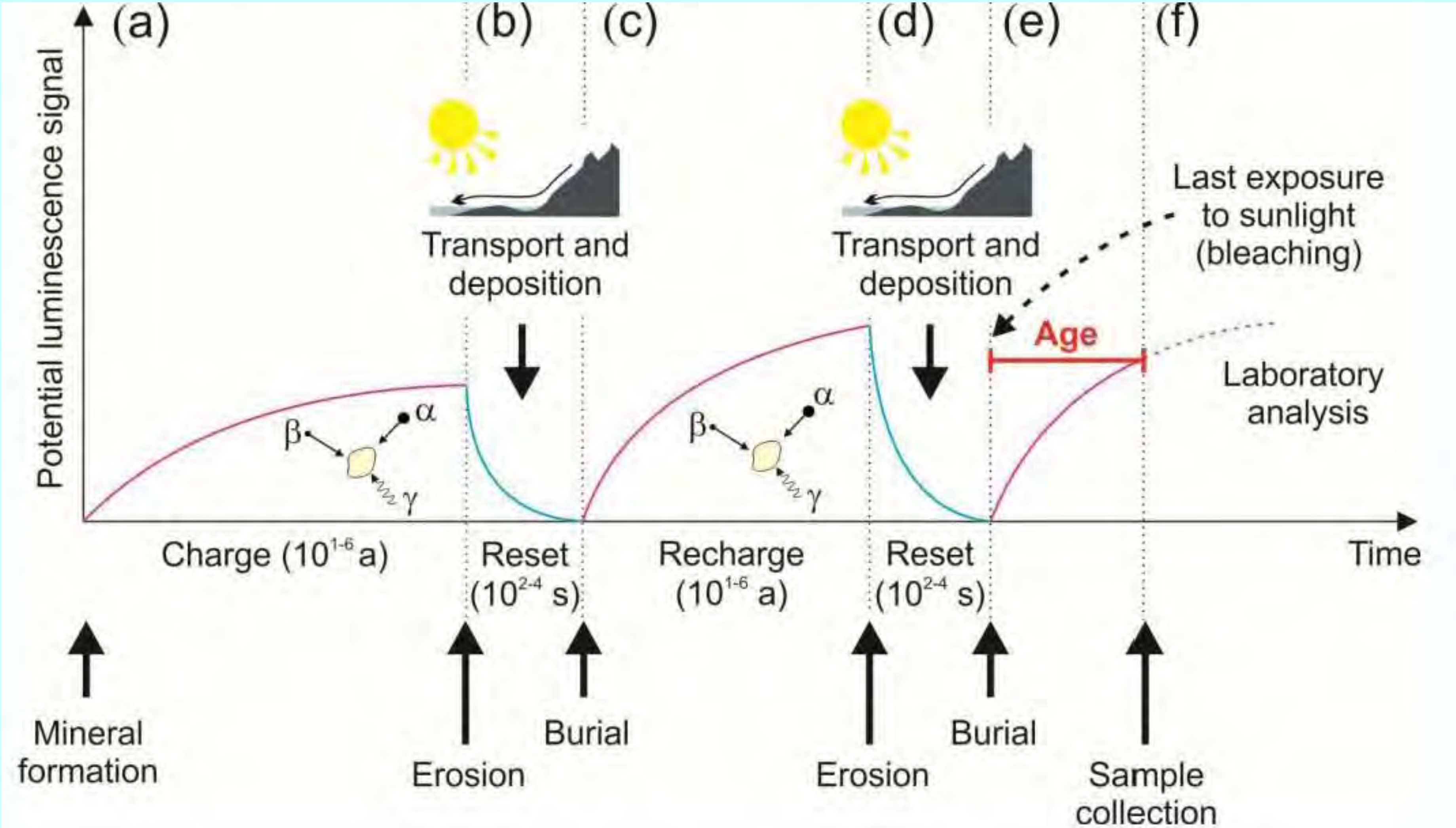
OSL dating has broad application across sedimentary environments



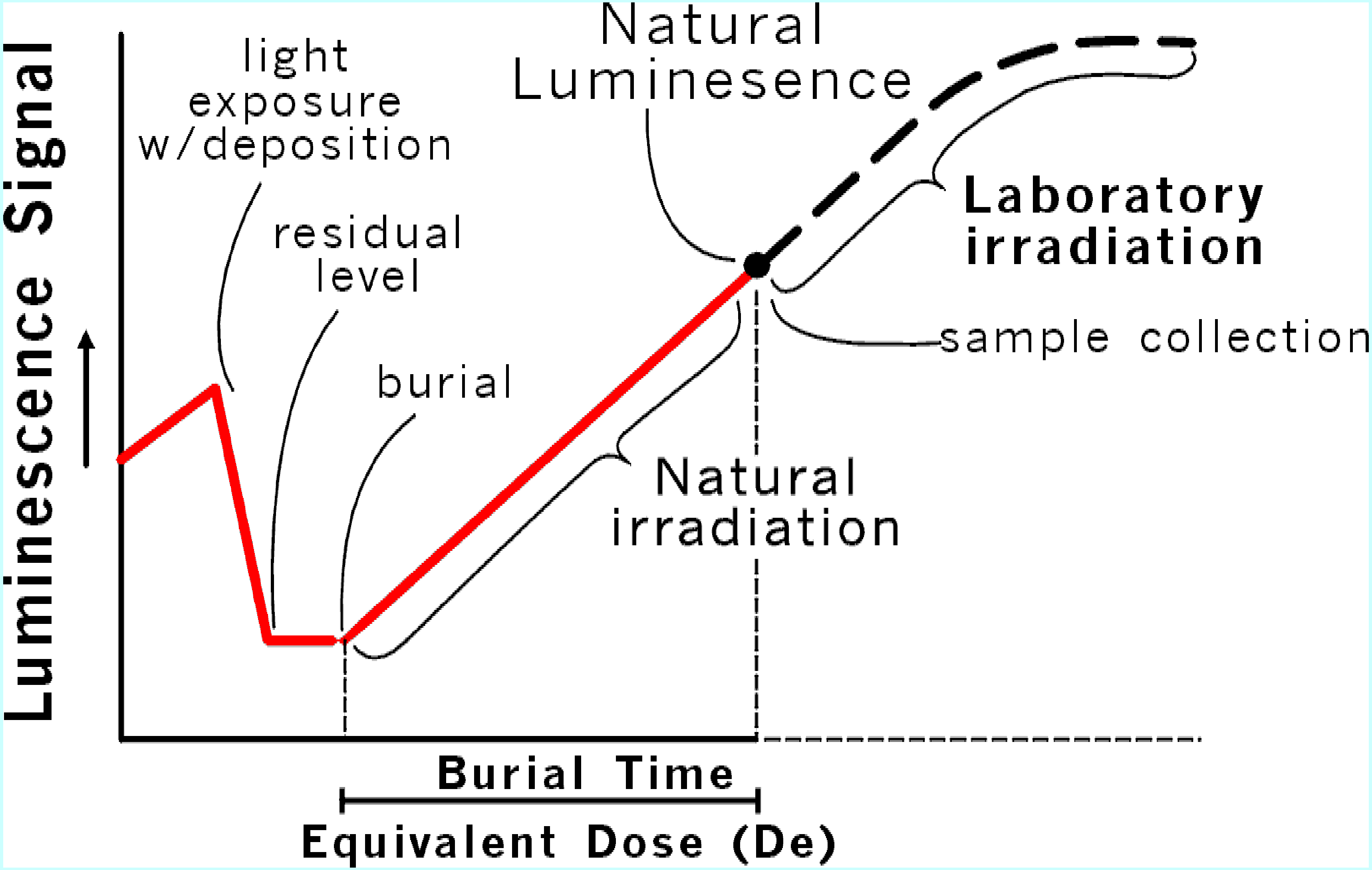
OSL signal is solar reset in minutes to seconds versus hours for thermoluminescence (TL)



Luminescence dates the time since mineral grains were last exposed to light or heat after deposition and burial



Luminescence Geologic Cycle



- The "natural" is the luminescence for the collected mineral grains and is calibrated in the lab to an equivalent dose (grays)

What material do we analyze with OSL dating ?

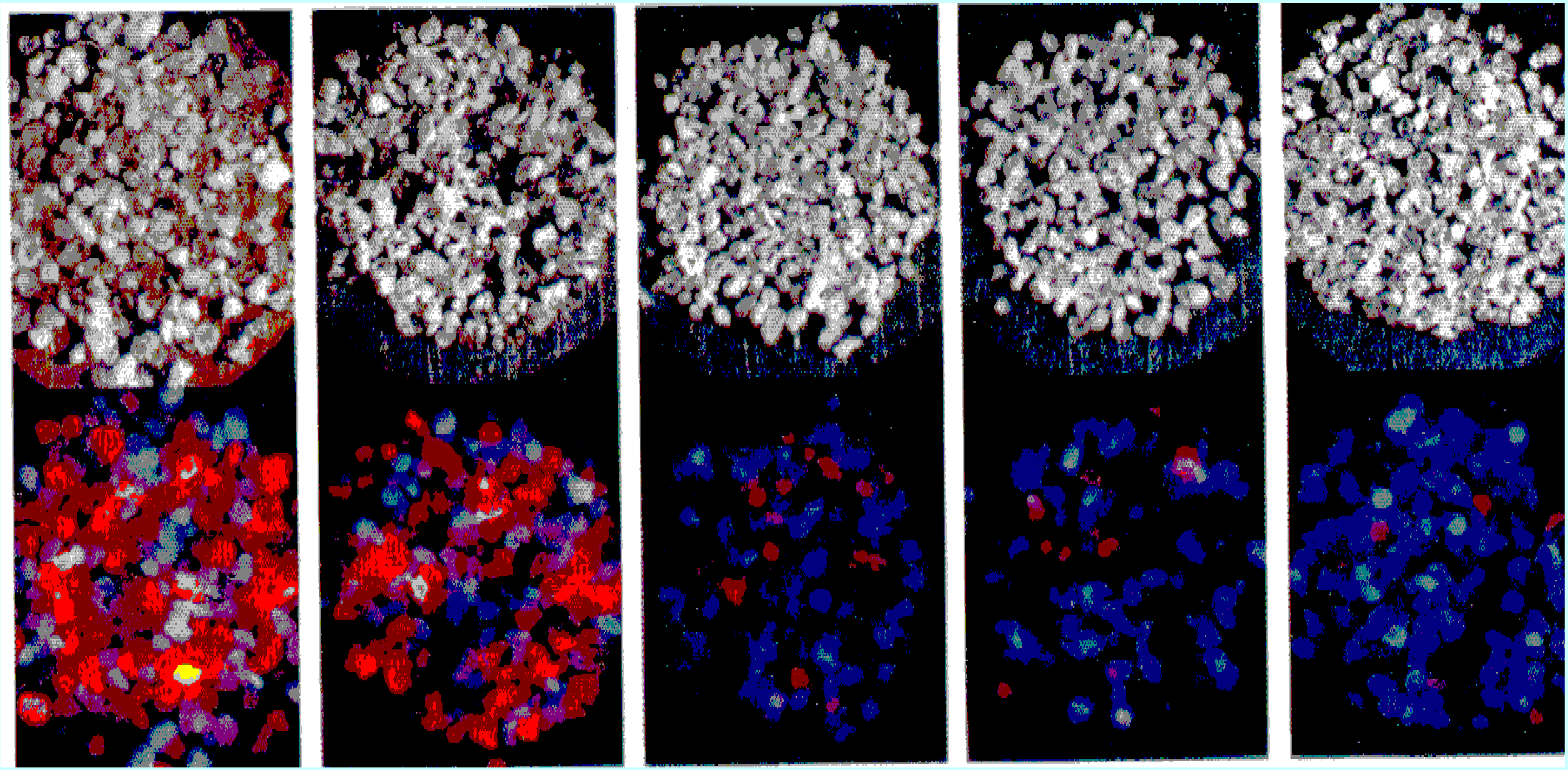
Mono-mineralogic sedimentary grains of quartz or feldspar < 500 microns

Quartz is often the mineral of choice because of its abundance and well known and stable luminescence characteristics.

Though k-feldspar also shows promise in many terrains

Luminescence Dating in a thumbnail….

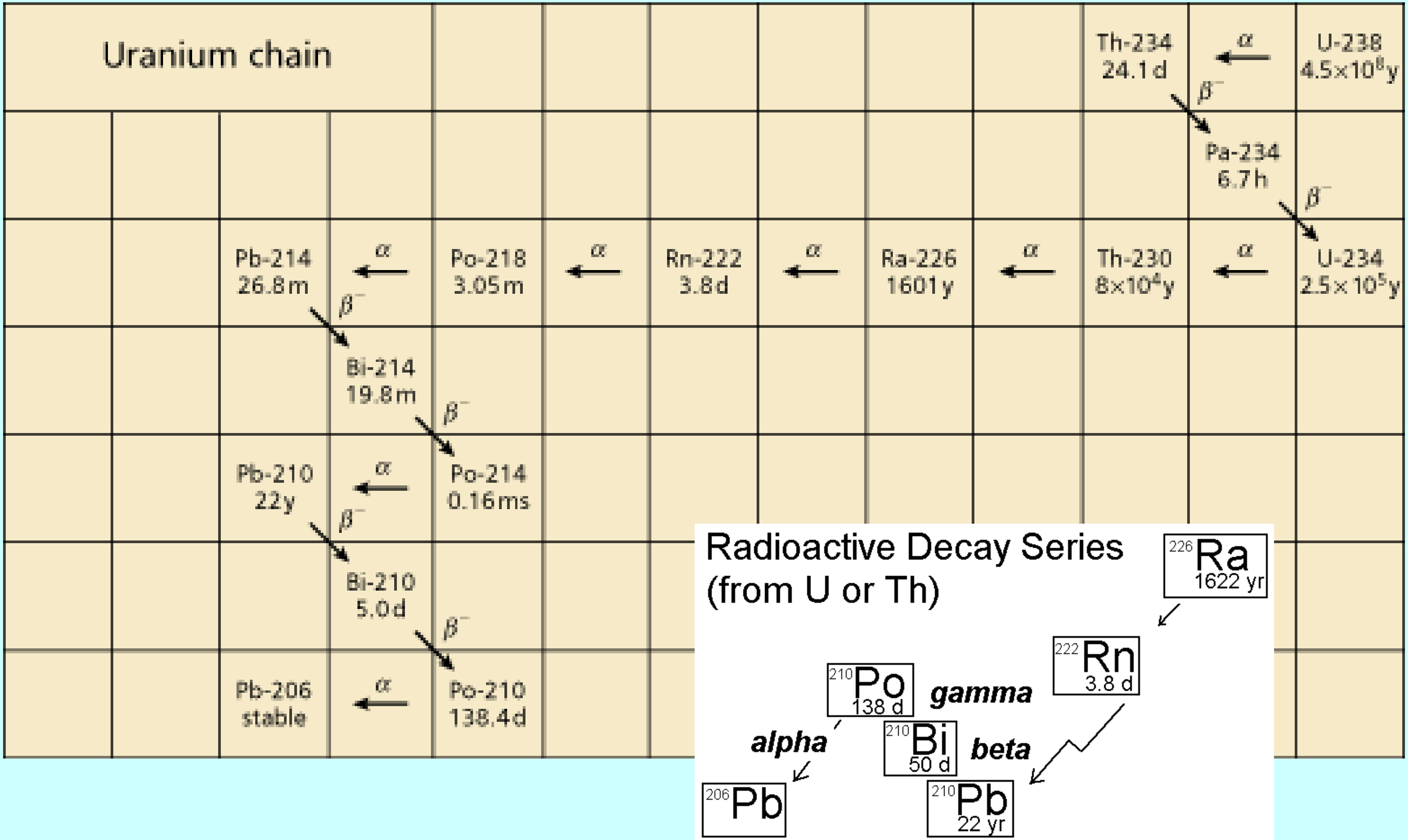
- Sunlight resets luminescence
- Ionizing radiation during burial results in free electrons
- Electrons are subsequently trapped in crystal charge defects
- Electrons are liberated in the lab as photons = Time



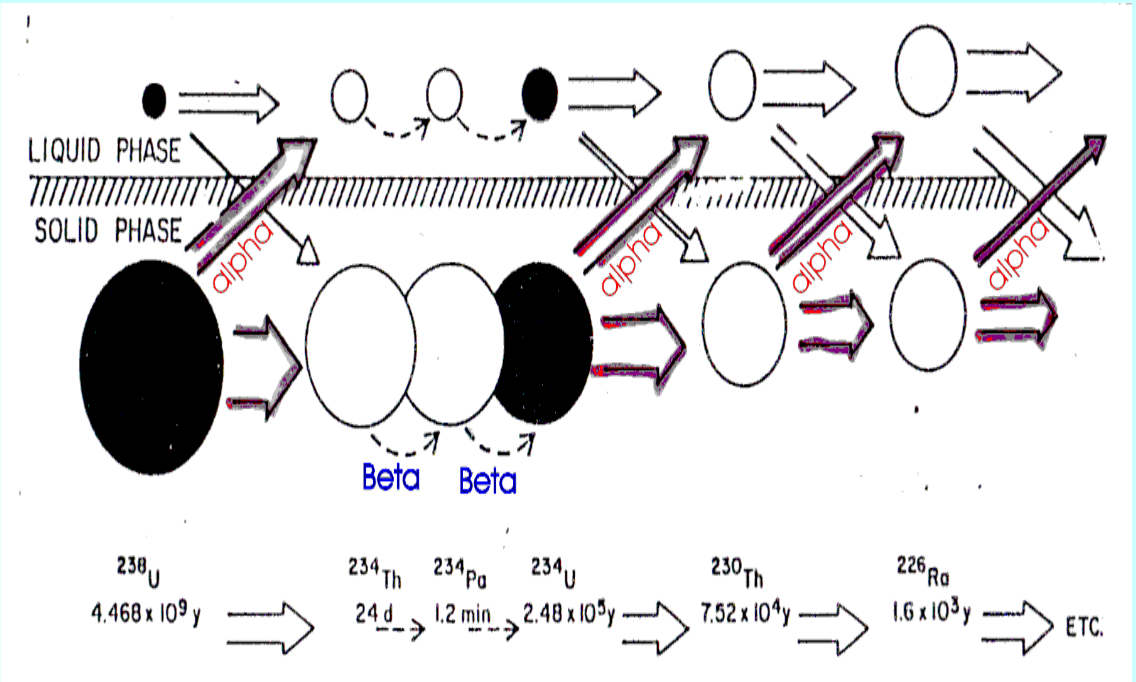
Quartz grains luminescence with heating

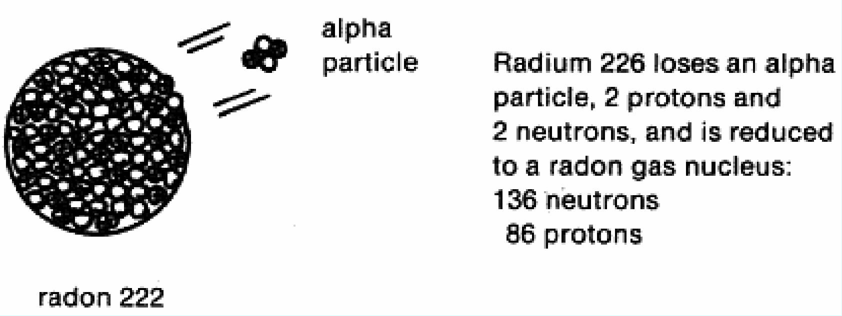
Hasimoto et al., 1986. Chemical Journal v. 20: 111+

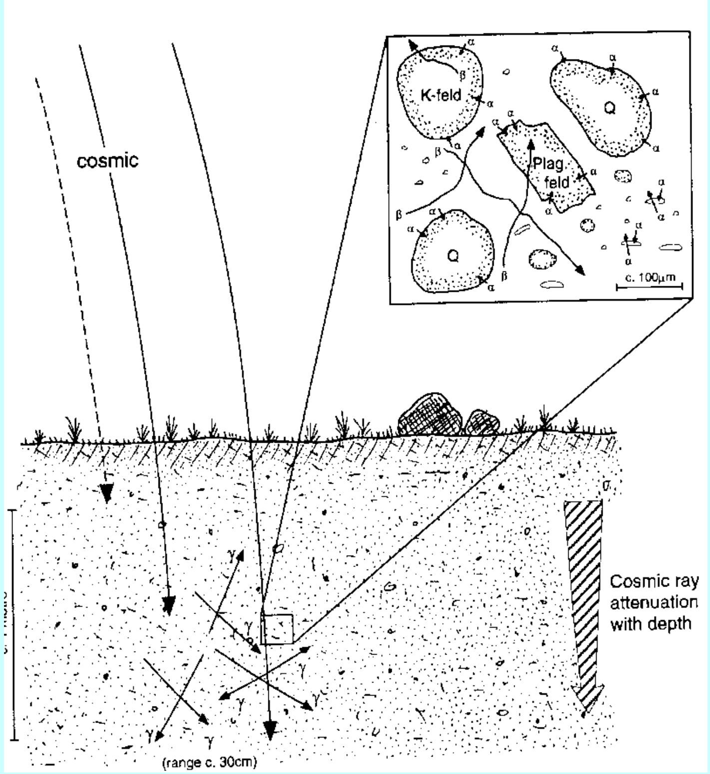
Uranium and Thorium decay series produce alpha, beta and gamma radiation/particles



Ionizing radiation from the decay of the U and the Th series, ^{40}K and a small component (0.10-0.15 grays/ka) from cosmic radiation produces free electrons which induces the luminescence signal during burial

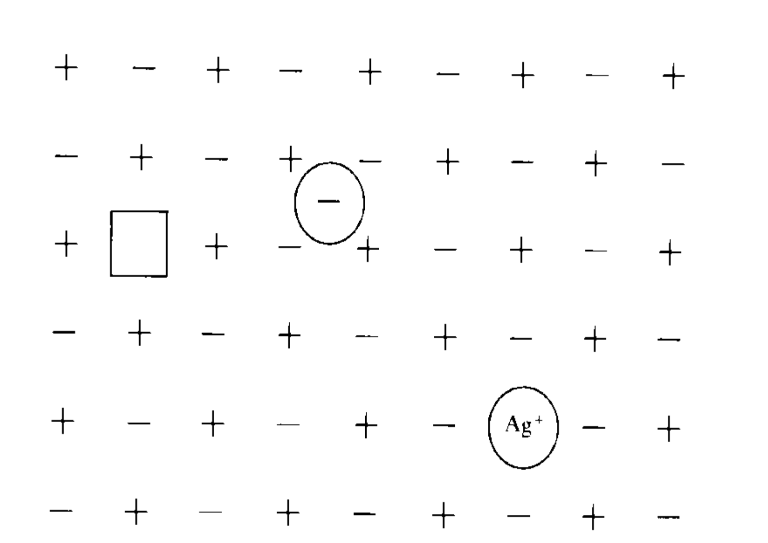






Ionizing radiation:
Alpha, beta, gamma radiation evict electrons from outer orbitals

Luminescence Process: Electrons trapped by charge defects in the crystal lattice of quartz



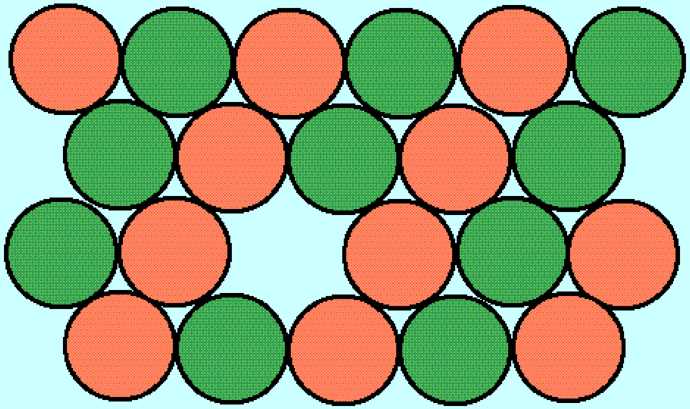
Simple types of lattice defects in an ionic crystal. (negative ion vacancy, negative ion interstitial, & substitutional impurity center) (Aitken, 1985)

Frenkel Vacancy – lattice vacancy where the atom leaves its structural site but is retained in an interstitial (nonlattice) position

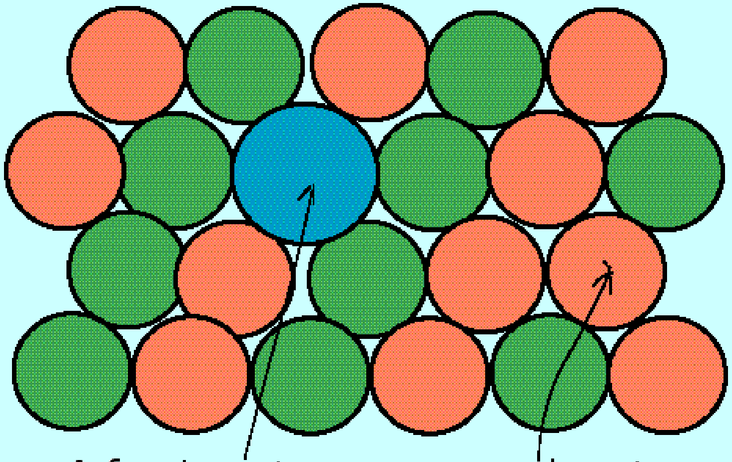
Schottky Vacancy-lattice vacancies of neighboring cation and anion

Substitutional Vacancy- An impurity atom replaces one of the original atoms in the crystal

Interstitial Vacancy- An impurity atom resides in a nonlattice position

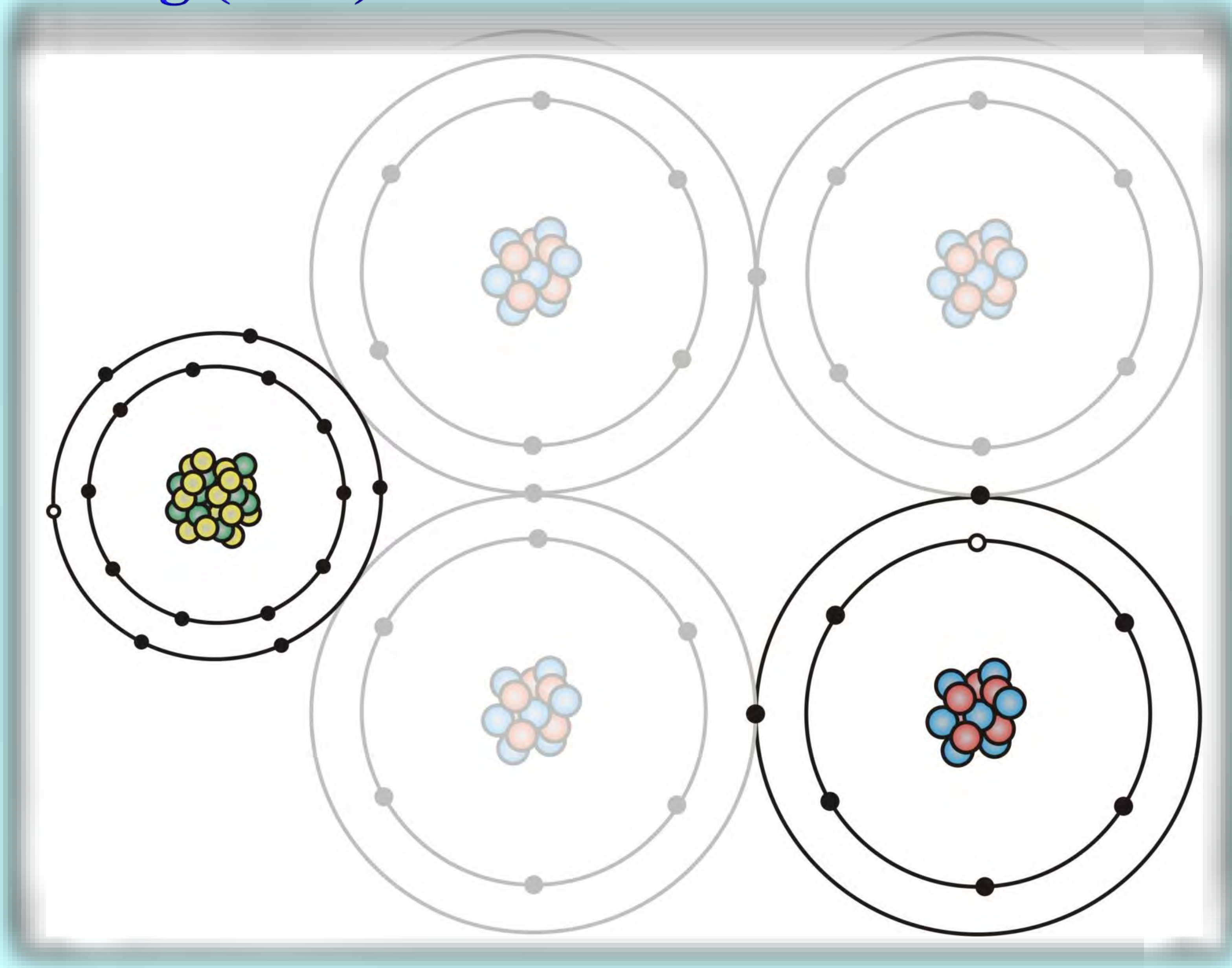


An empty lattice site is a vacancy

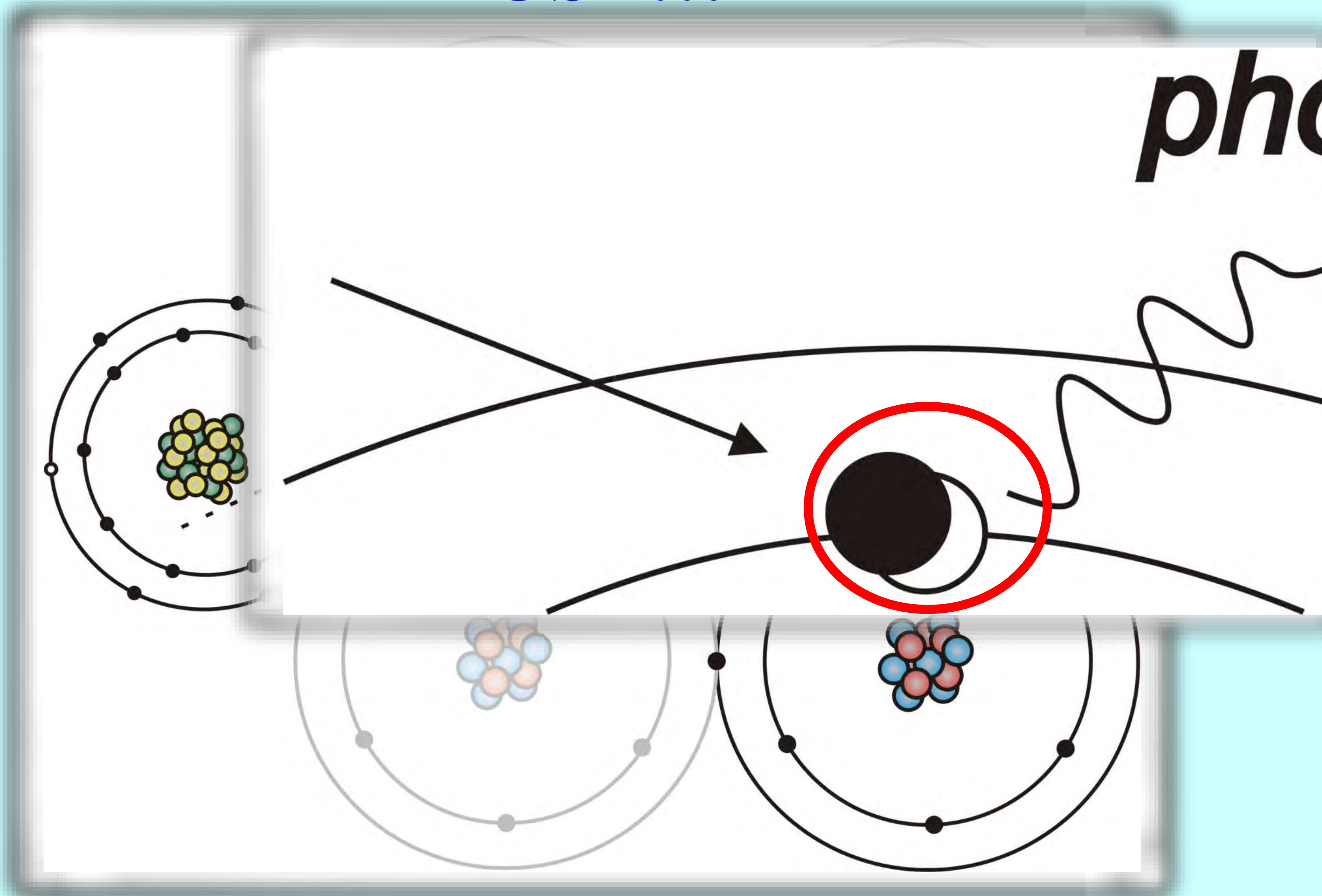


A foreign atom, or a regular atom out of place, is an impurity.

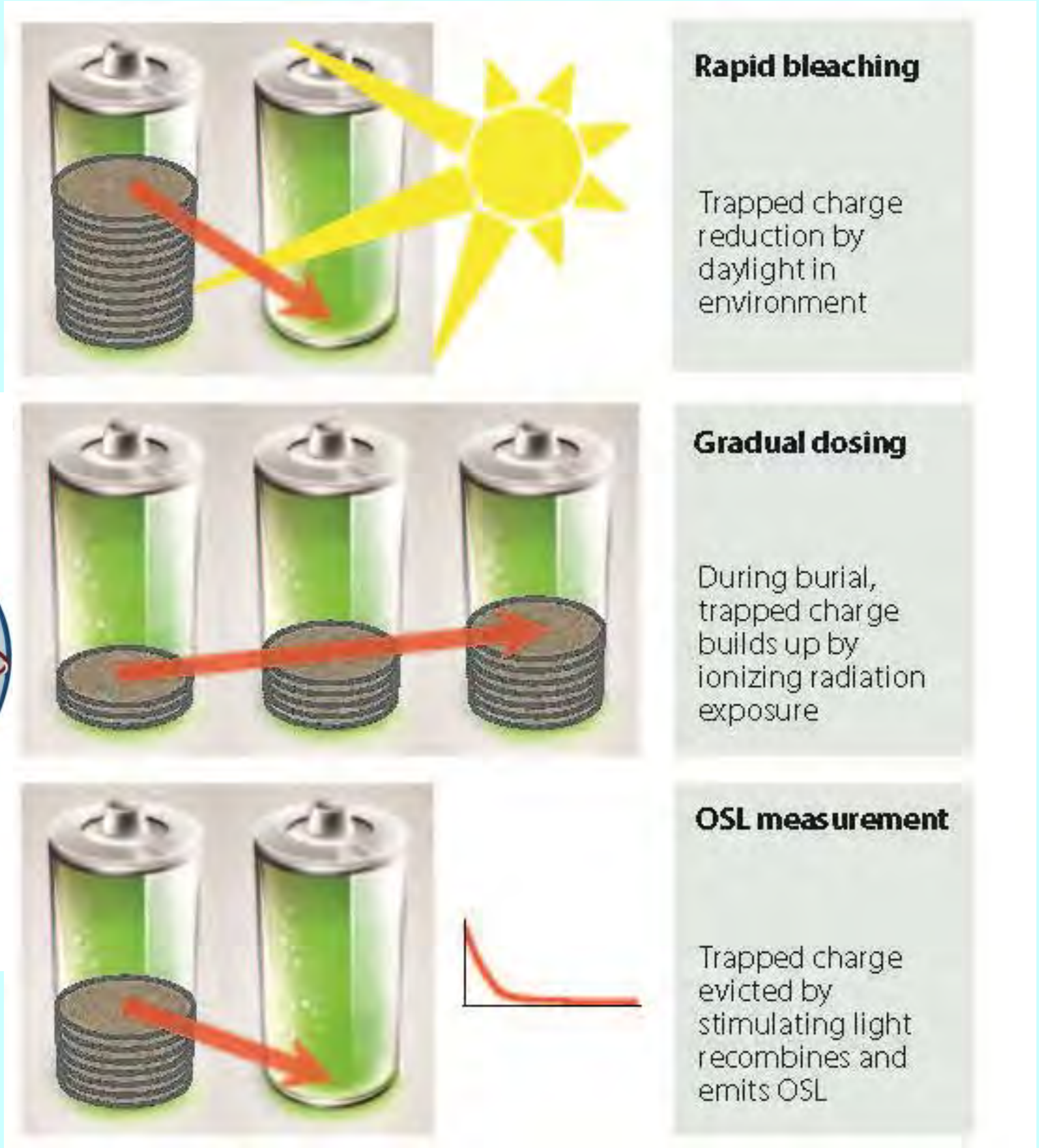
Ionizing (beta) radiation cause electron eviction



Quantify stored charge (electrons):Use OSL...



OSL dating quantifies stored charge (electrons) in crystal lattices and quantifying in terms of radiation induced equivalent dose



Calculating A Luminescence Age

$$\text{Luminescence Age} = \frac{\text{Equivalent Dose (De, Grays)}}{(aD_\alpha W + D_\beta W + D_\gamma W) + D_c}$$

Dose rate, Dr (Grays/ka)

W= water content factor

a= alpha radiation attenuation coefficient

D_α = alpha radiation contribution to dose rate

D_β= beta radiation contribution to dose rate

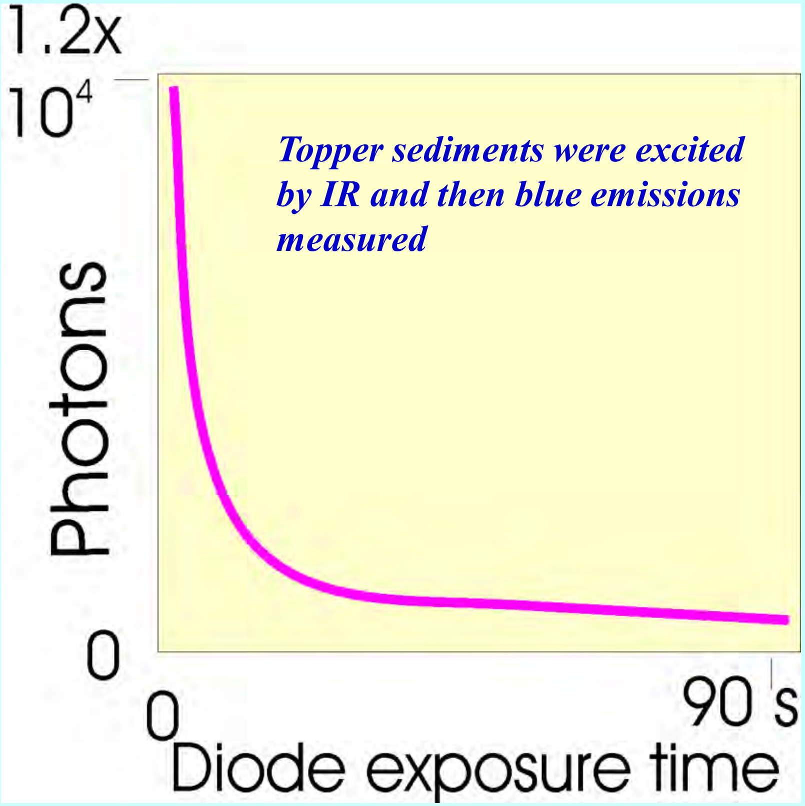
D_γ = gamma radiation contribution to dose rate

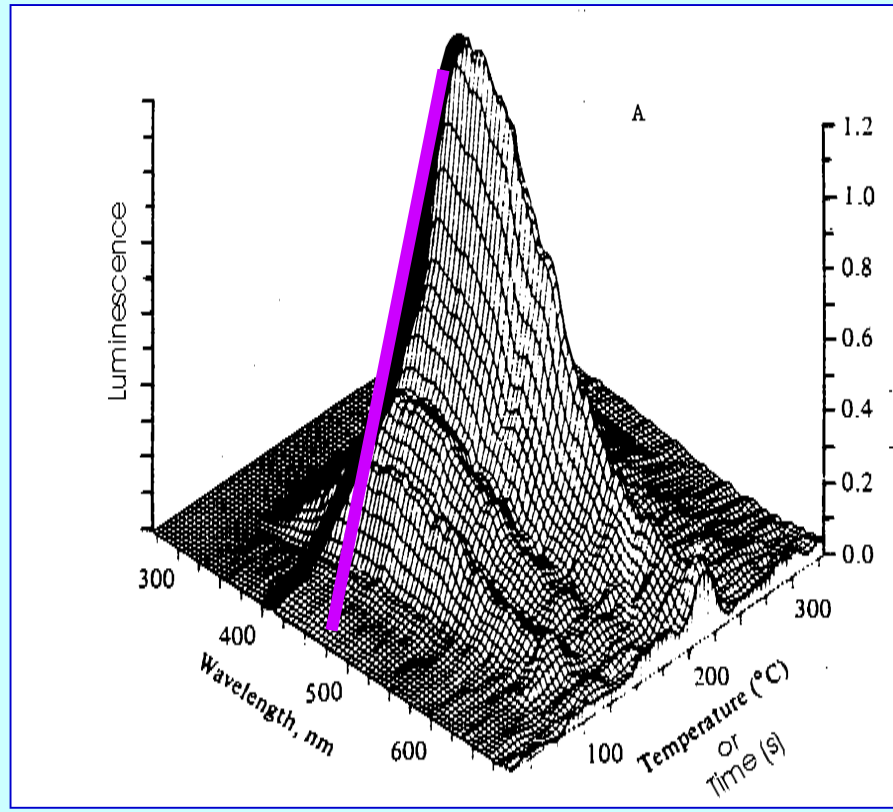
D_c= cosmic radiation contribution to dose rate

Radionuclide	Concentration	Alpha Contribution	Beta Contribution	Gamma Contribution
Th Series	1 ppm ^{232}Th	738 µGy/yr	28.6µGy/yr	51.4µGy/yr
U Series	1 ppm ^{238}U	2783	146.2	114.8
Potassium	1% K_2O		689.3	206.9
Rubidium	100 ppm Rb		46.4	

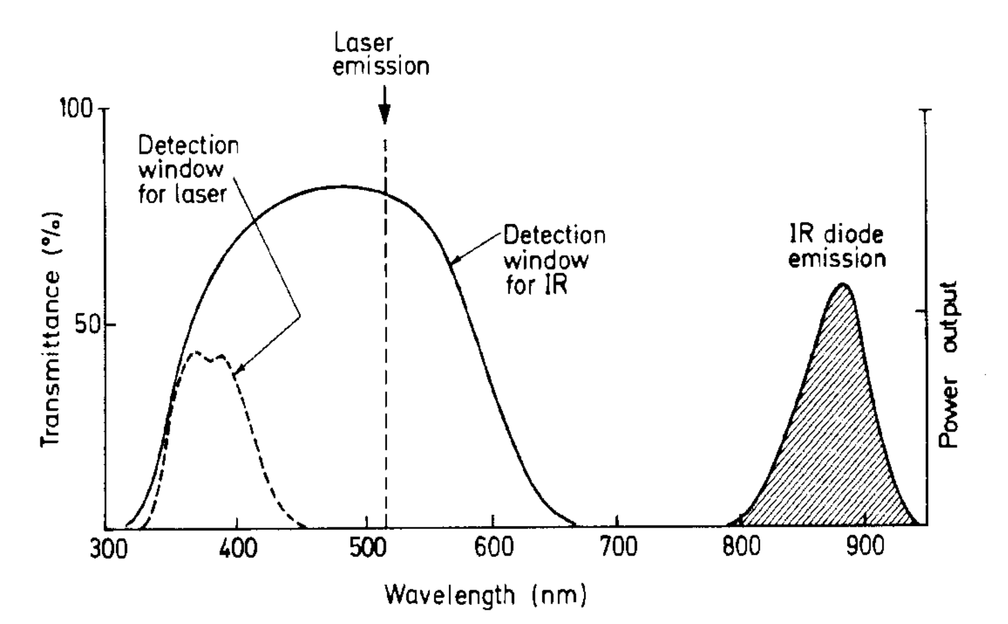
Evaluation of annual alpha, beta and gamma dose from U, Th, K and Rb content, Assuming secular equilibrium. Units are micrograys/year.

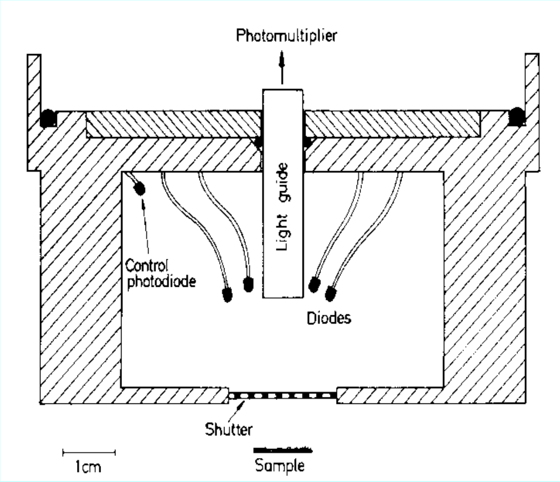
The luminescence signal is 3D, but in practice a specific wavelength of emission is measured





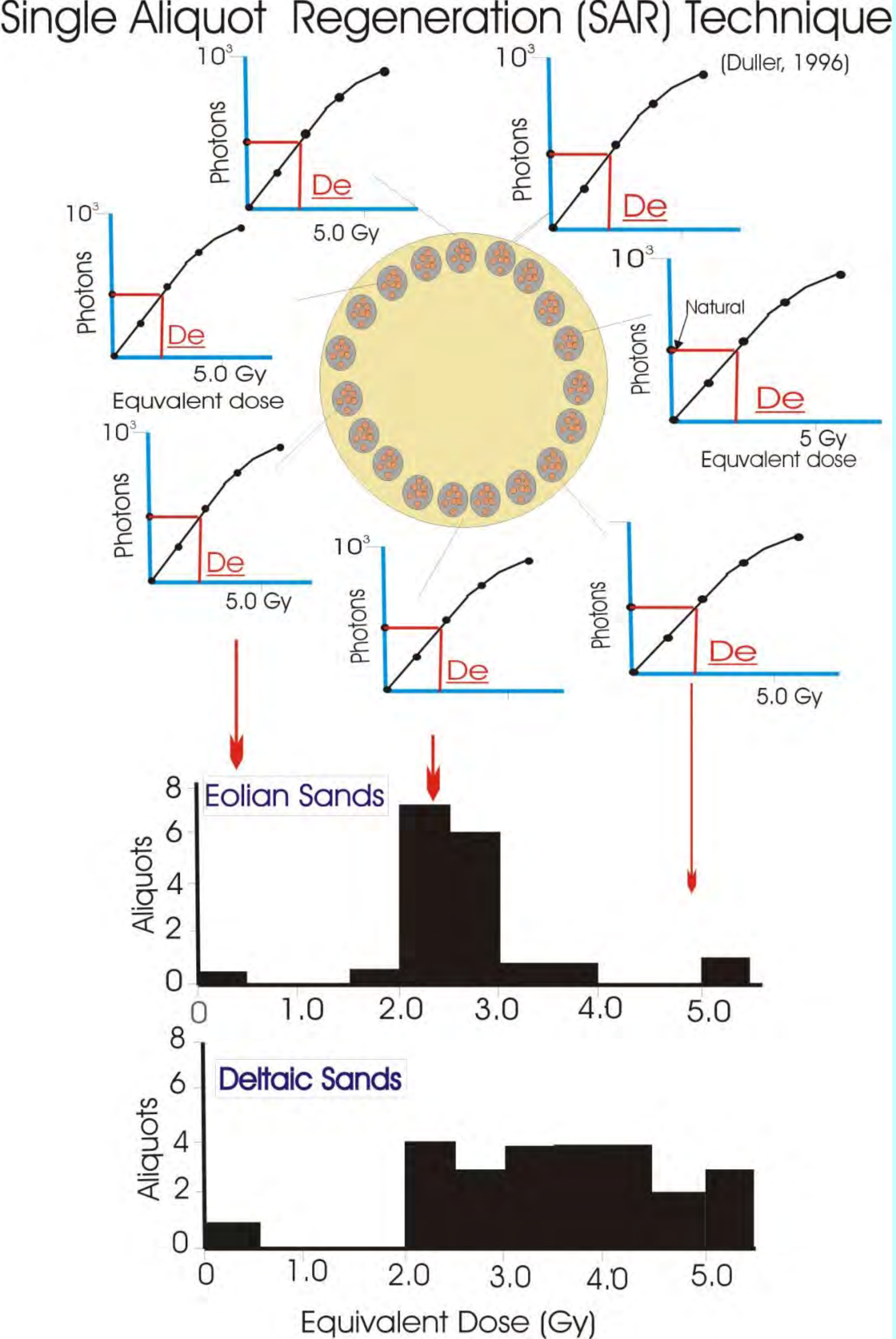
Wavelength of Excitation and Wavelength of Measurement





Excite by infrared (880 nm) and subsequent measurement of blue emissions (400 -500 nm)

Diode array, the source of infrared excitation with optics for measurement of light emission (blue) by a photomultiplier tube

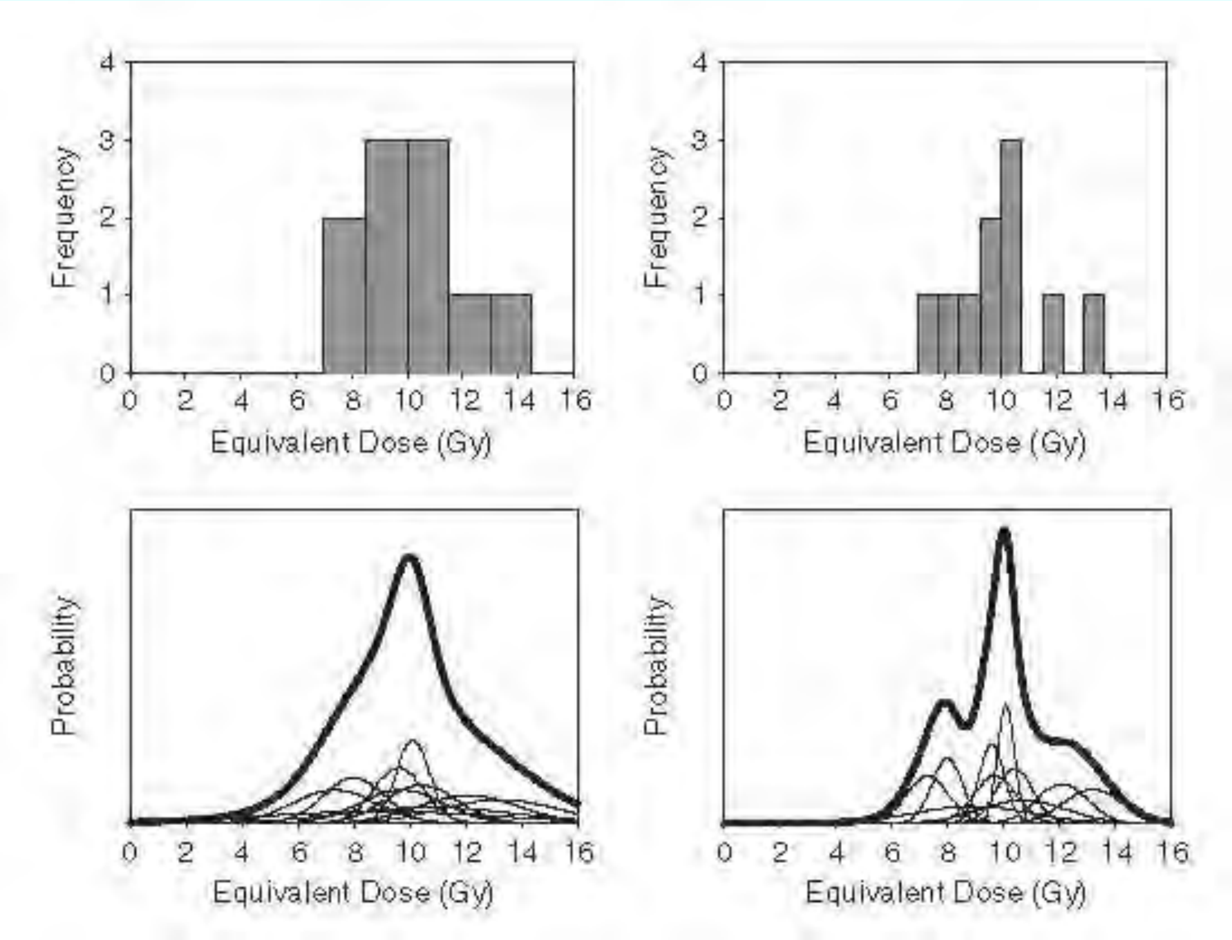


Single Aliquot Regeneration (SAR) Dating (Murray and Wintle, 2003; 2006)

1. Produces ages on a single disc with 10s to 100s of quartz grains
2. Best results with sediment that is solar reset uniformly
3. Most useful for dating sediments, < 100 ka old

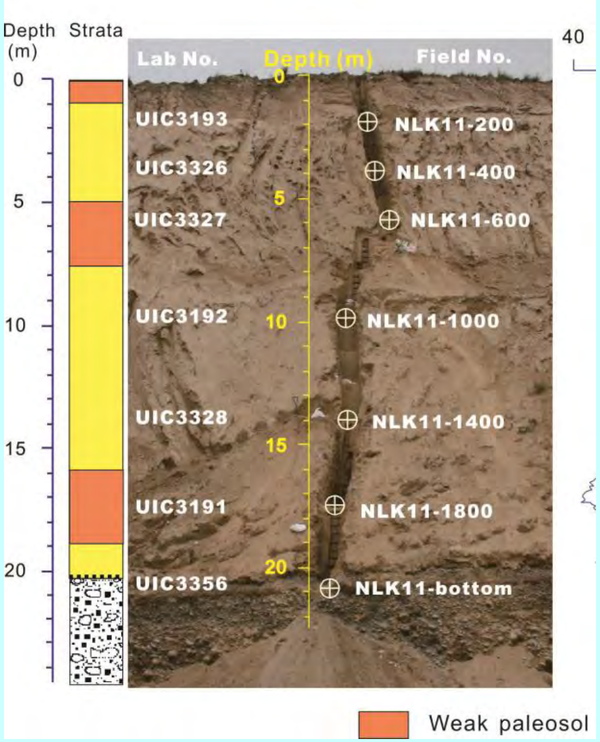
Single Grain Dating: A new frontier

Often single aliquot regeneration equivalent dose distributions are wider and have multiple peaks, outside statistical limits of a single, Gaussian population



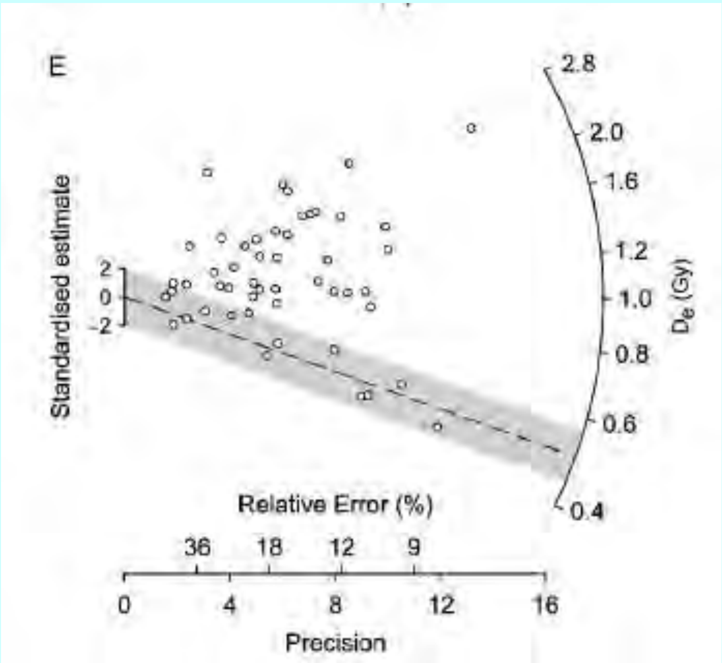
Thus, there may be **multiple-age grain populations**: the way to deconvolute these populations is to undertake single grain analysis.

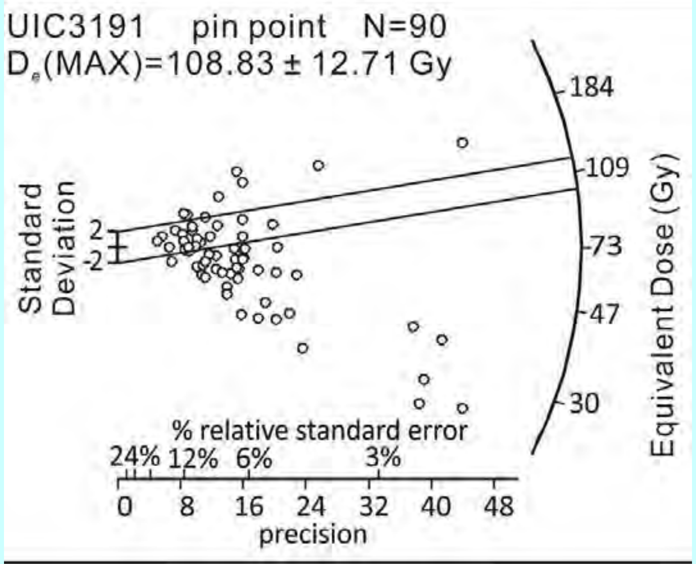
The youngest or oldest subpopulation
may yield an accurate age.



Fluvial sands; youngest population preferred

In eolian sediments pedogenically altered; oldest population preferred



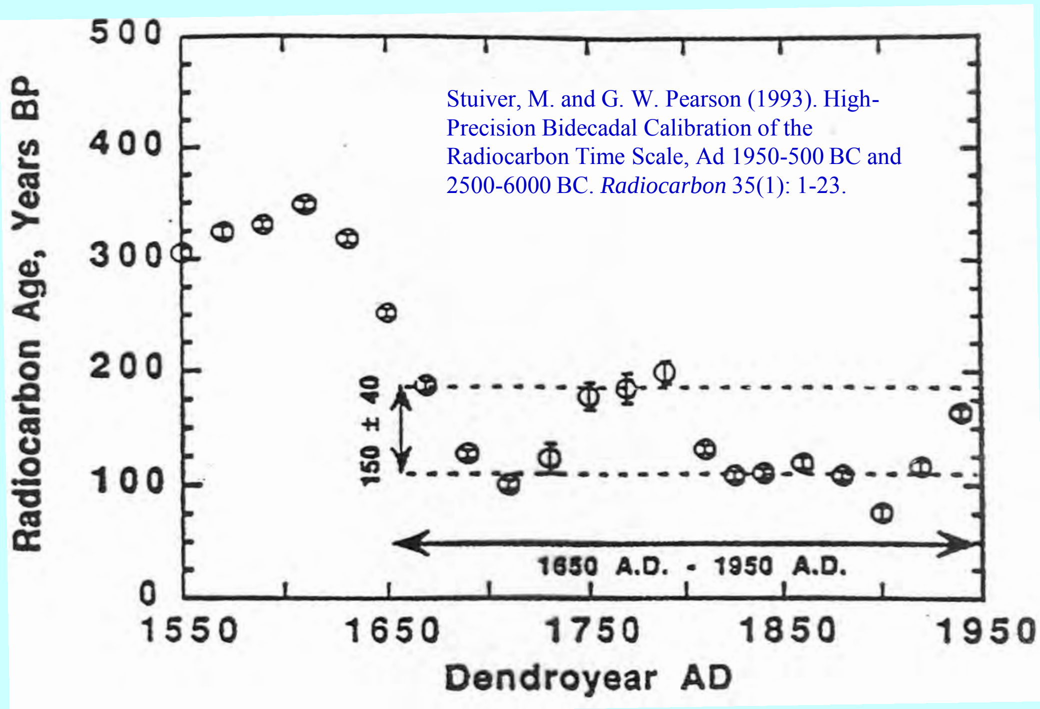


Sampling for OSL dating: Ponder, describe and understand sedimentologic and pedologic context

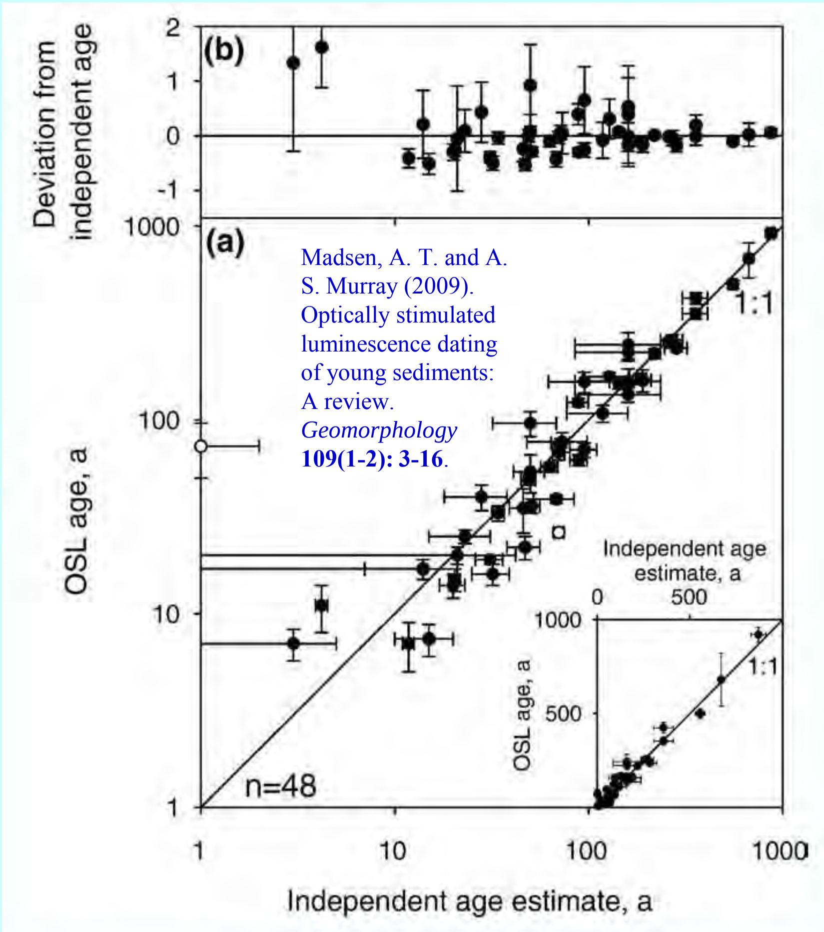
Sampling for OSL dating should be the last task.

Sample is a light-tight core of sediment

OSL has the resolution for dating deposits in the past 1000 years and supplies needed resolution for the plateau in ^{14}C ages in the past 400 years.



Stuiver, M. and G. W. Pearson (1993). High-Precision Bidecadal Calibration of the Radiocarbon Time Scale, Ad 1950-500 BC and 2500-6000 BC. *Radiocarbon* 35(1): 1-23.



Madsen, A. T. and A. S. Murray (2009). Optically stimulated luminescence dating of young sediments: A review. *Geomorphology* **109(1-2): 3-16**.

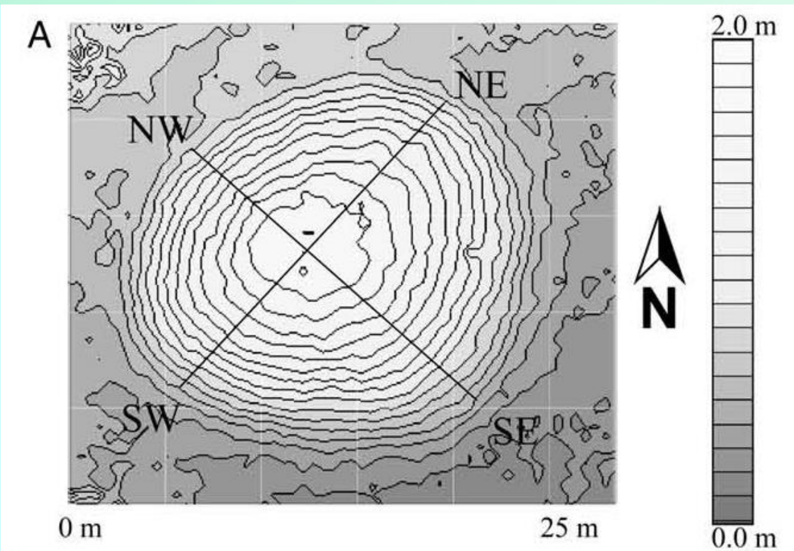
Fig. 7. a) Summary of OSL ages and associated independent age control from all sites discussed in this paper (the inset displays the same data on a linear scale). b) The deviation from independent age control, expressed as the ratio between the OSL age (minus the independent age), and the independent age.

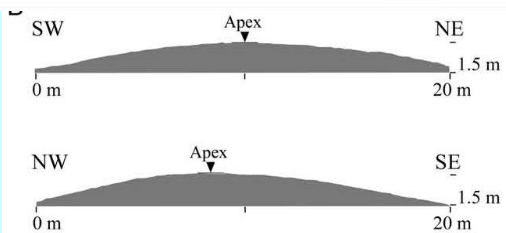
The eolian sediments are most suitable for OSL dating because of the "long" light exposure.

OSL dating of eolian sedimentary sequences in the past decade has revolutionized our knowledge of these environmental archives.

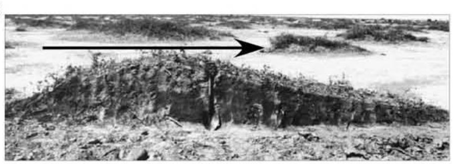
Relict nebkhas (pimple mounds) record prolonged late Holocene drought in the forested region of south-central United States

Christopher L. Seifert [a], Randel Tom Cox [a,*], Steven L. Forman [b], Tom L. Foti [c], Thad A. Wasklewicz [d], Andrew T. McColgan [a] *Quaternary Research* v. 71, 329-4339, 2009

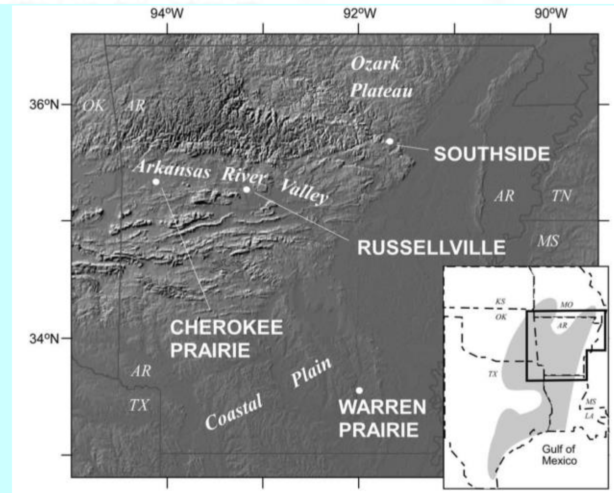


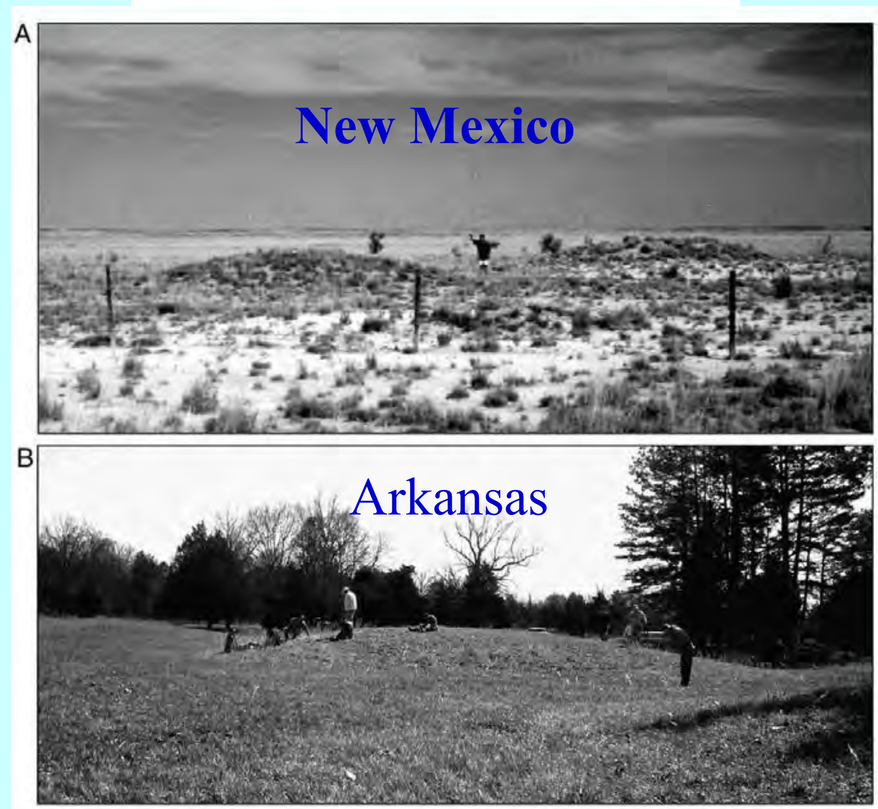


C



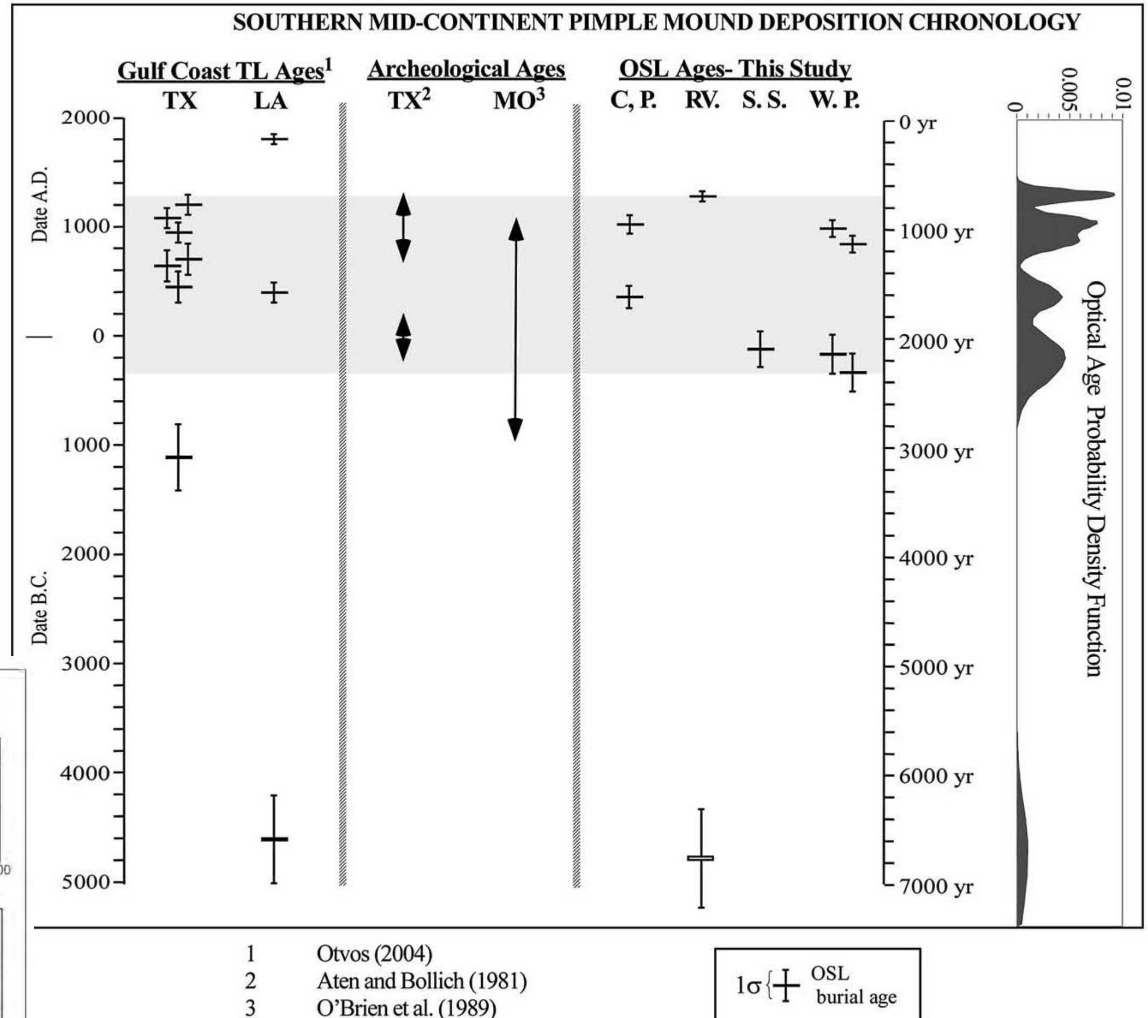
Nebkha in Mali, West Africa

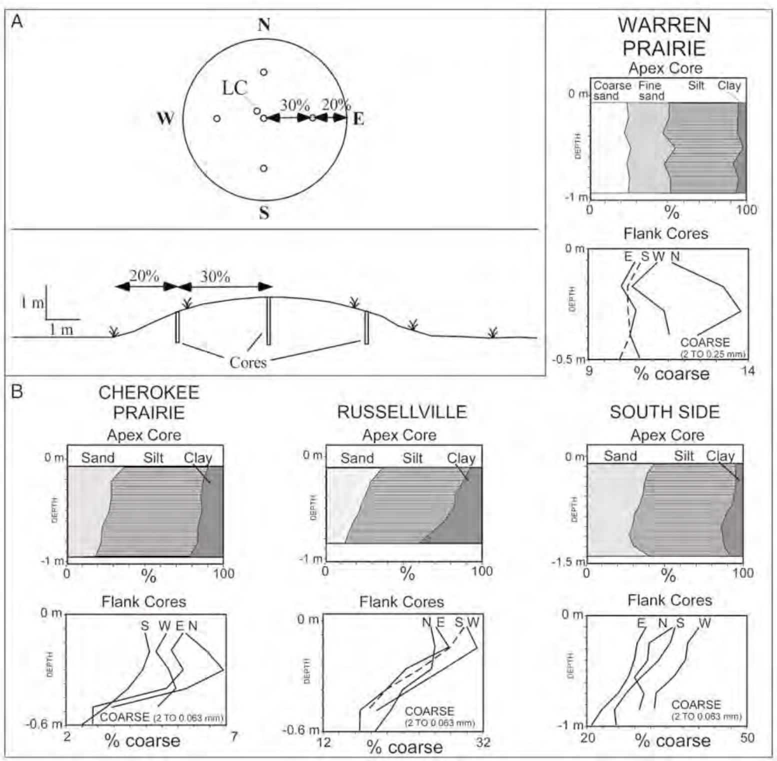




Nebkha Dunes formed ca. 800 to 1600 years ago, during the Medieval Climate Anomaly, with winds from the NW.

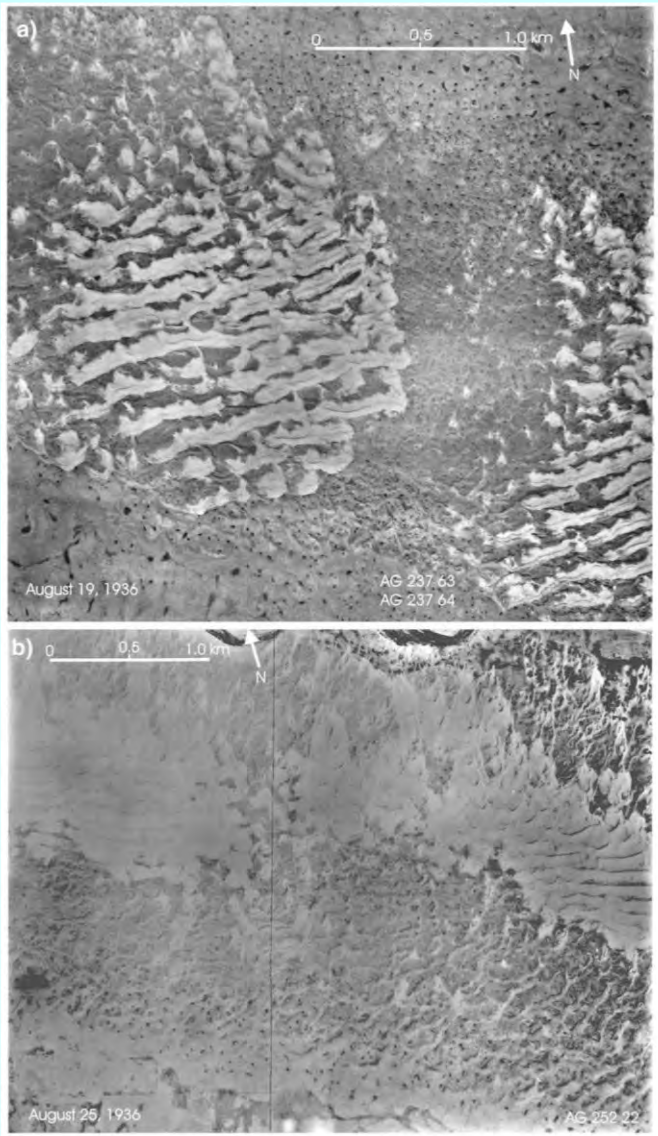
Analogous landforms from west Texas and eastern New Mexico have mean annual precipitation of < 350 mm.

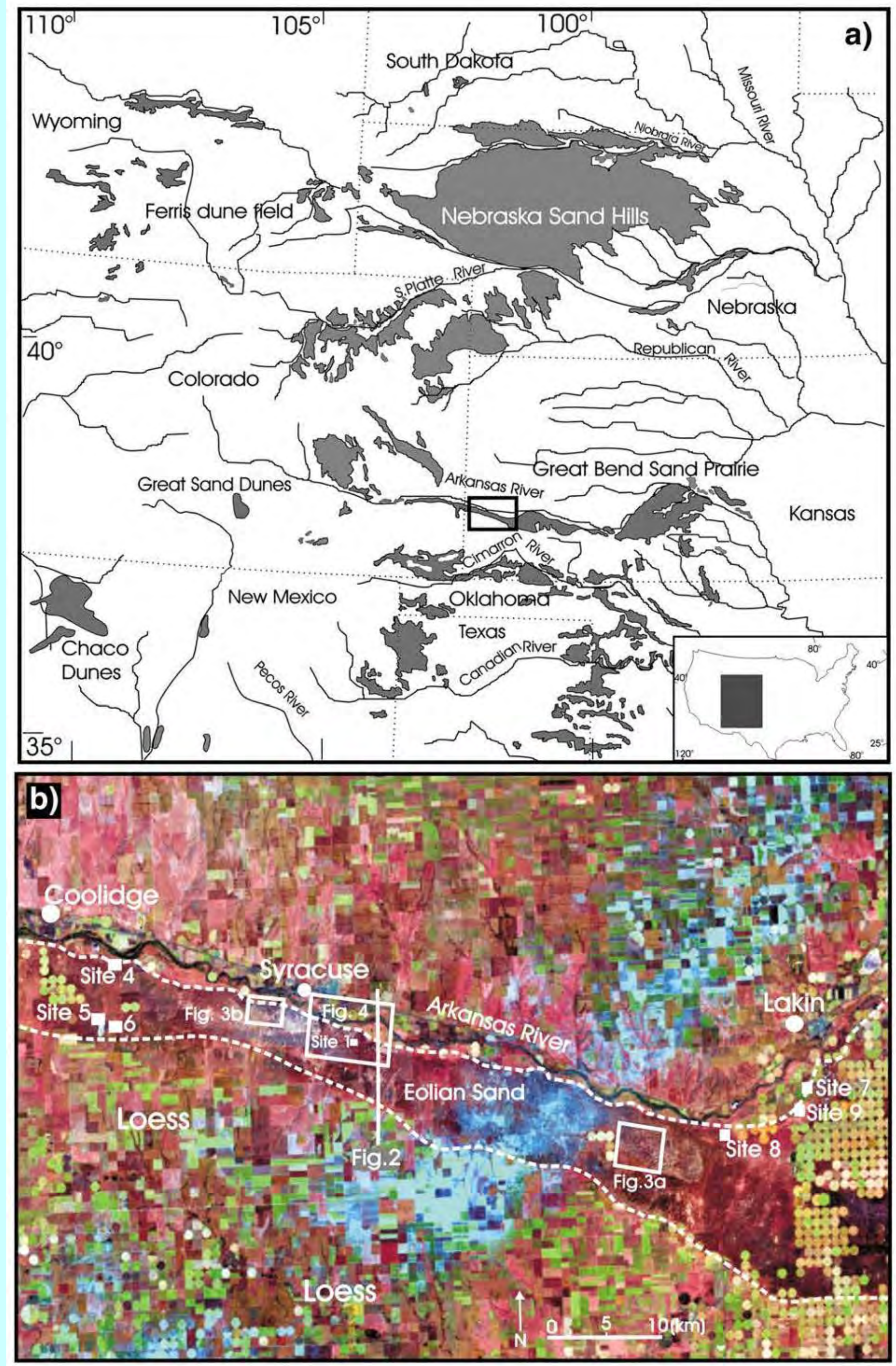


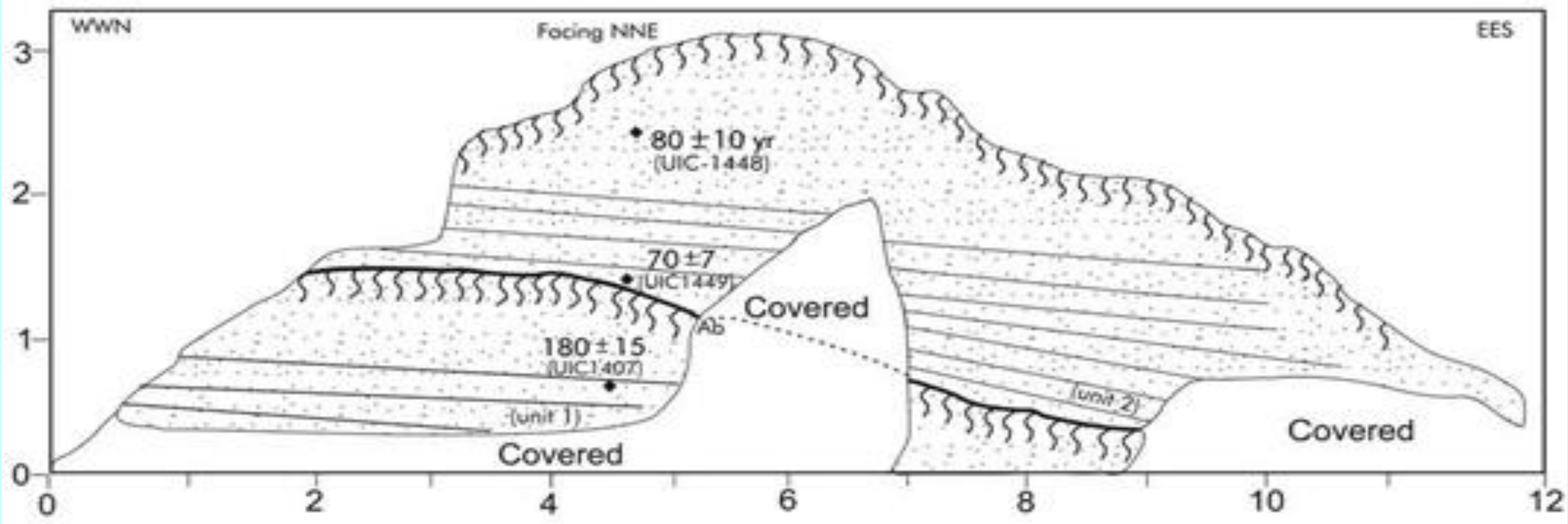


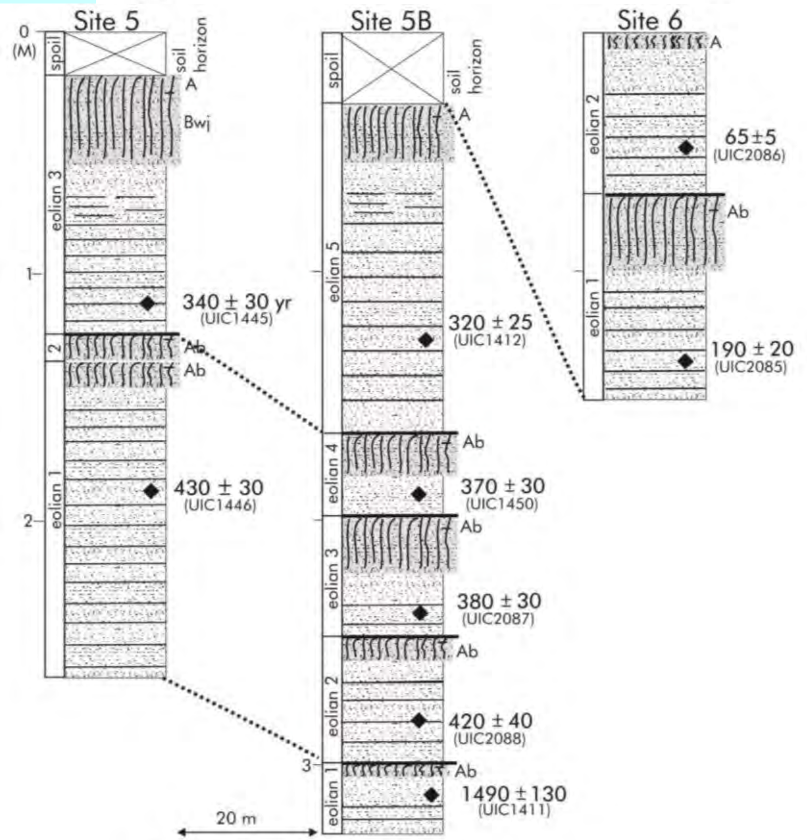
These landforms reflect an extreme ***megadrought***,
beyond historic climate variability

Forman, S.L., Marín, L., Gomez, J. and Pierson J., Late Quaternary eolian sand depositional record for southwestern Kansas: Landscape sensitivity to droughts. *Paleogeography, Paleoclimatology, Paleoecology 265, 107-120.*



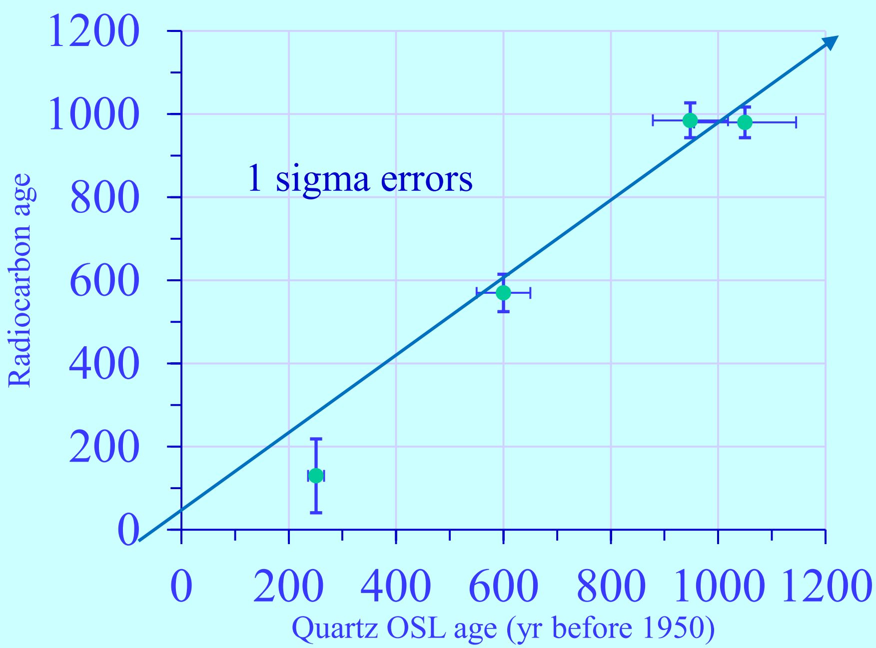




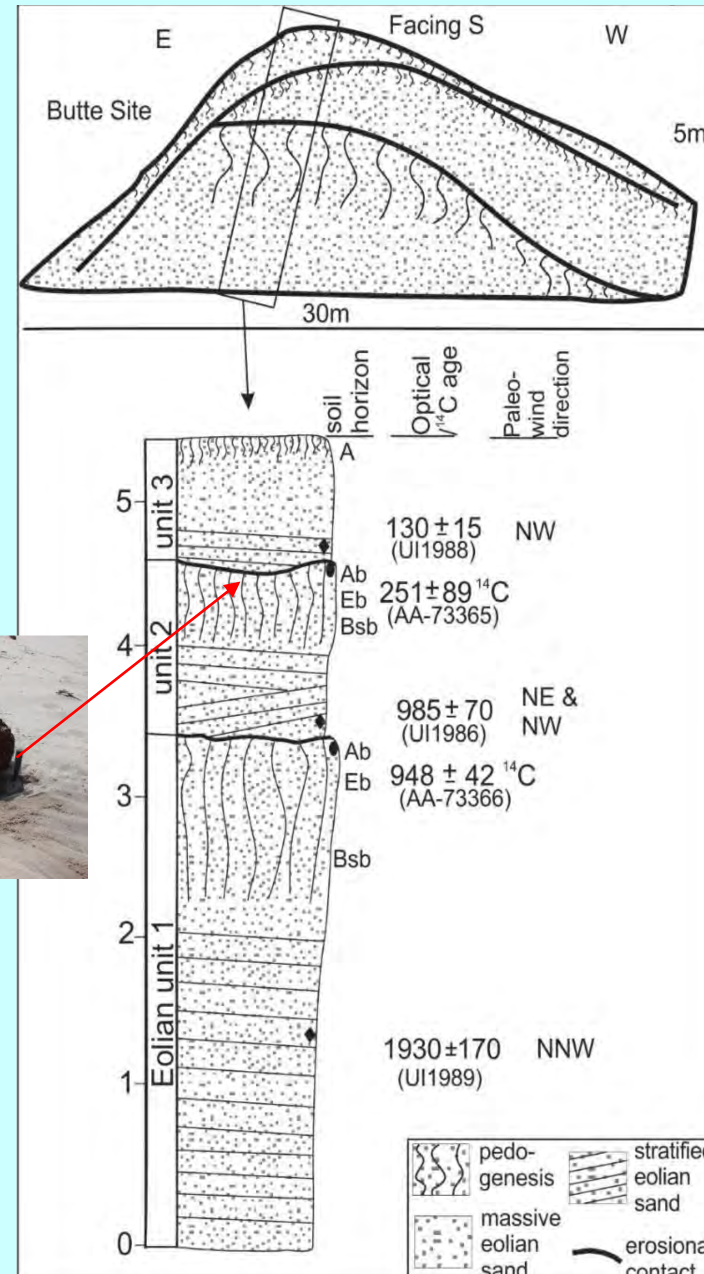


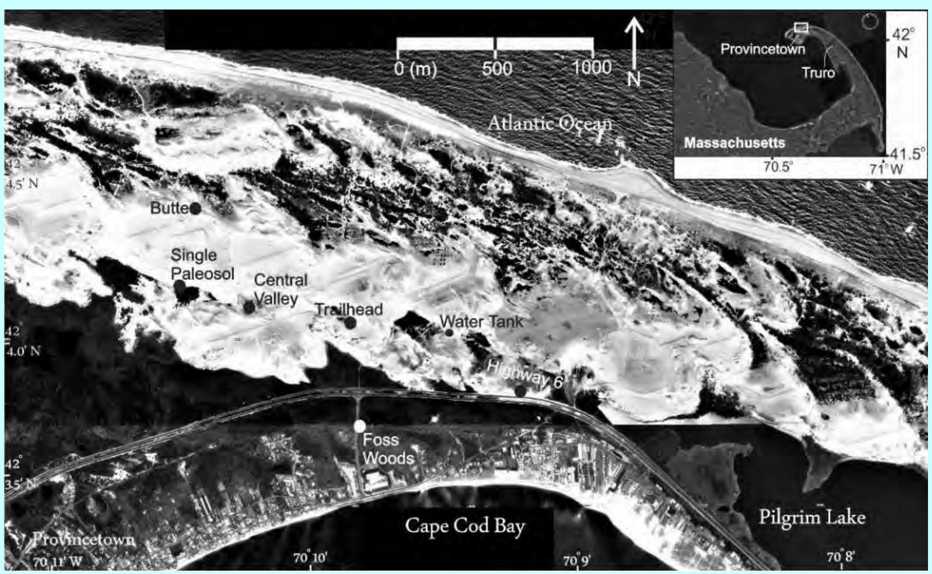
OSL dating provides chronologic resolution for 1930s Dust Bowl Drought deposits and older eolian deposits

Recent test of concordance between ^{14}C and OSL ages on quartz: Cap Cod Dunefield, MA



Forman, S. L., 2015. Episodic eolian sand deposition in the past 4000 years in Cape Code National Seashore, Massachusetts USA in response to possible hurricane/storm and anthropogenic disturbances. *Frontiers in Earth Sciences.*

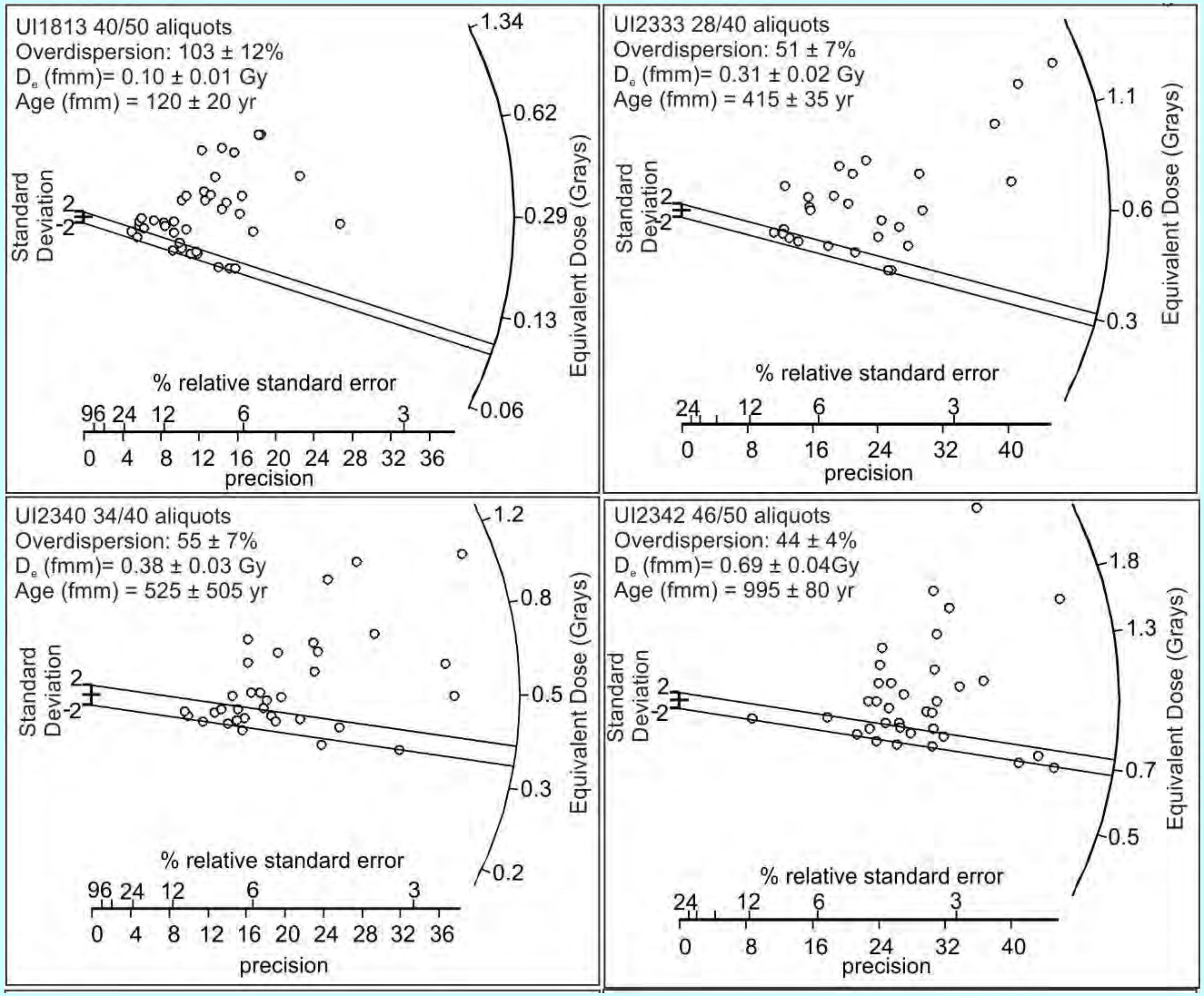




Even though the sediments are composed of eolian quartz grains many aliquots were not fully solar reset because of short transport of grains and preferentially in the winter and with snow.

Equivalent dose values show high overdispersion > 40%.

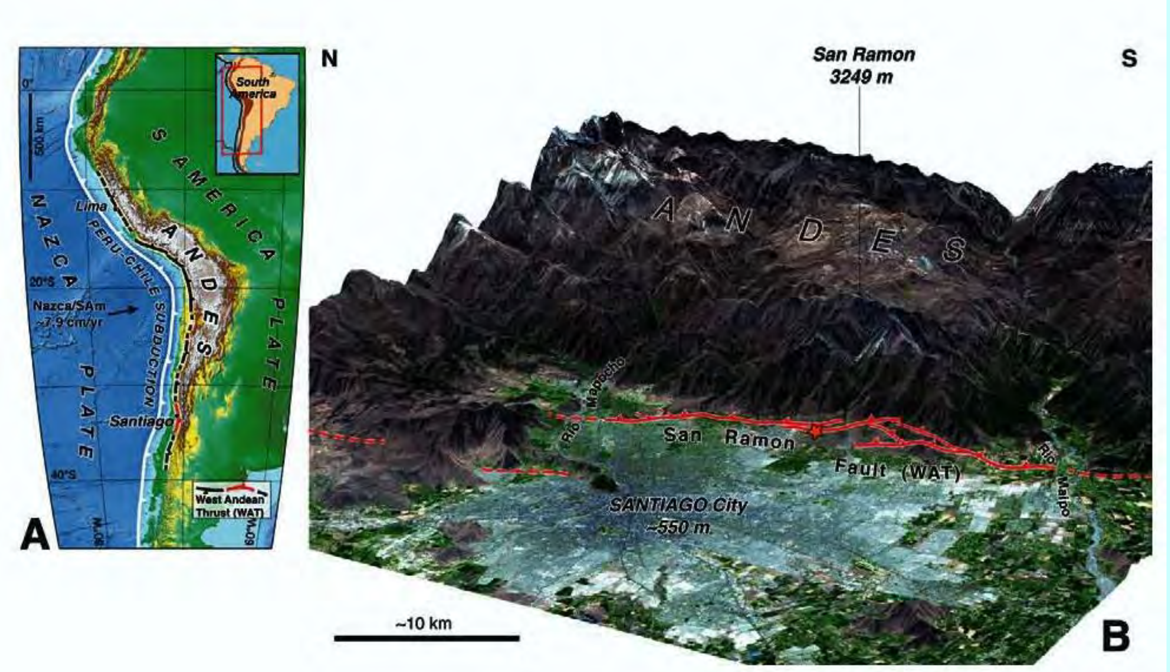
We used a Finite Mixture Model on the equivalent dose data to evaluate the lowest population of equivalent doses (Galbraith and Green, 1990).

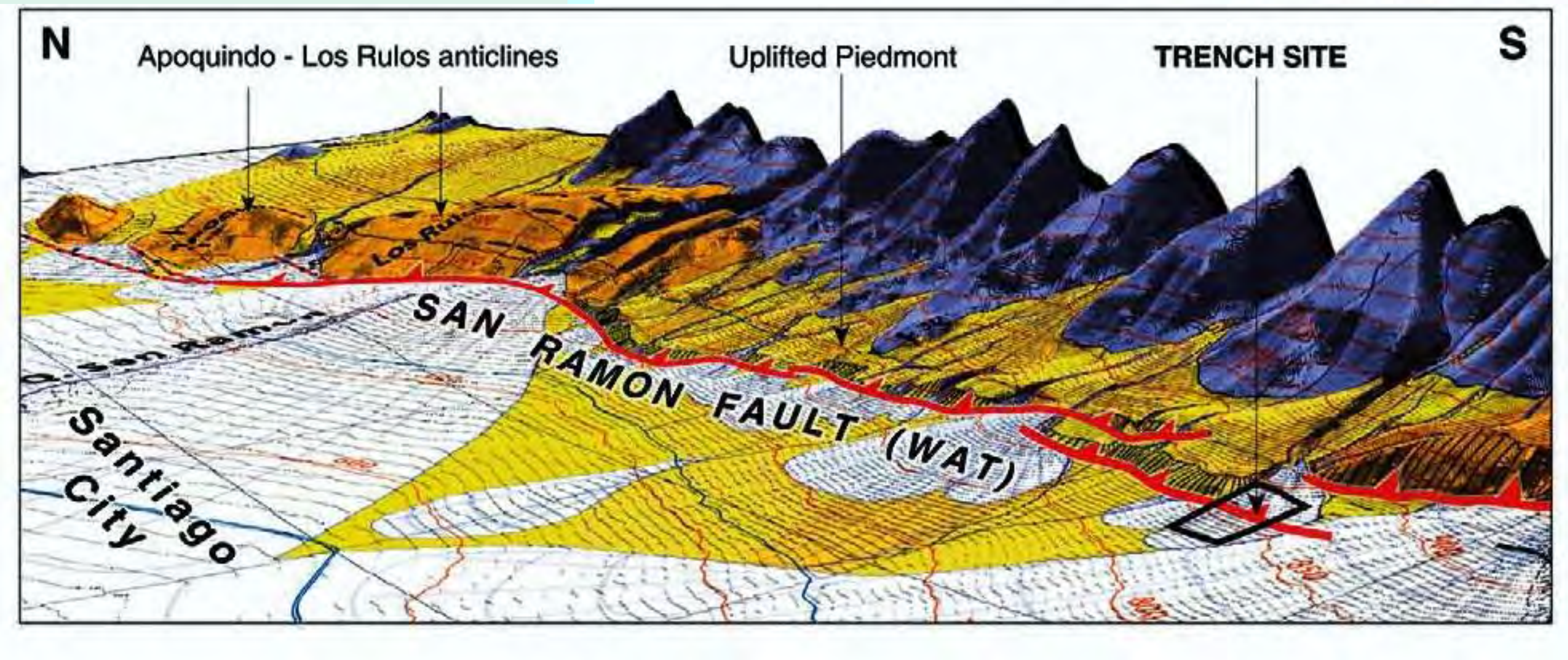


Forman, S. L., 2015. Episodic eolian sand deposition in the past 4000 years in Cape Code National Seashore, Massachusetts USA in response to possible hurricane/storm and anthropogenic disturbances. *Frontiers in Earth Sciences,*

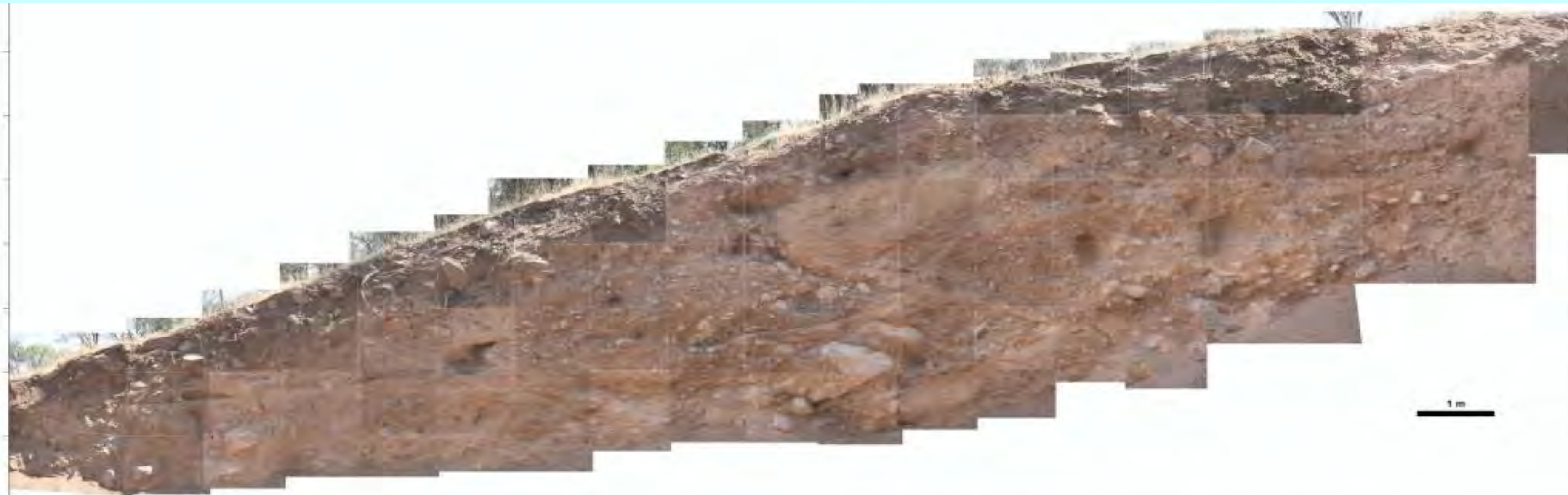
Geochronology is key in unraveling activity of fault zones, especially South American thrust faults, Like the San Ramon, on the edge of Santiago

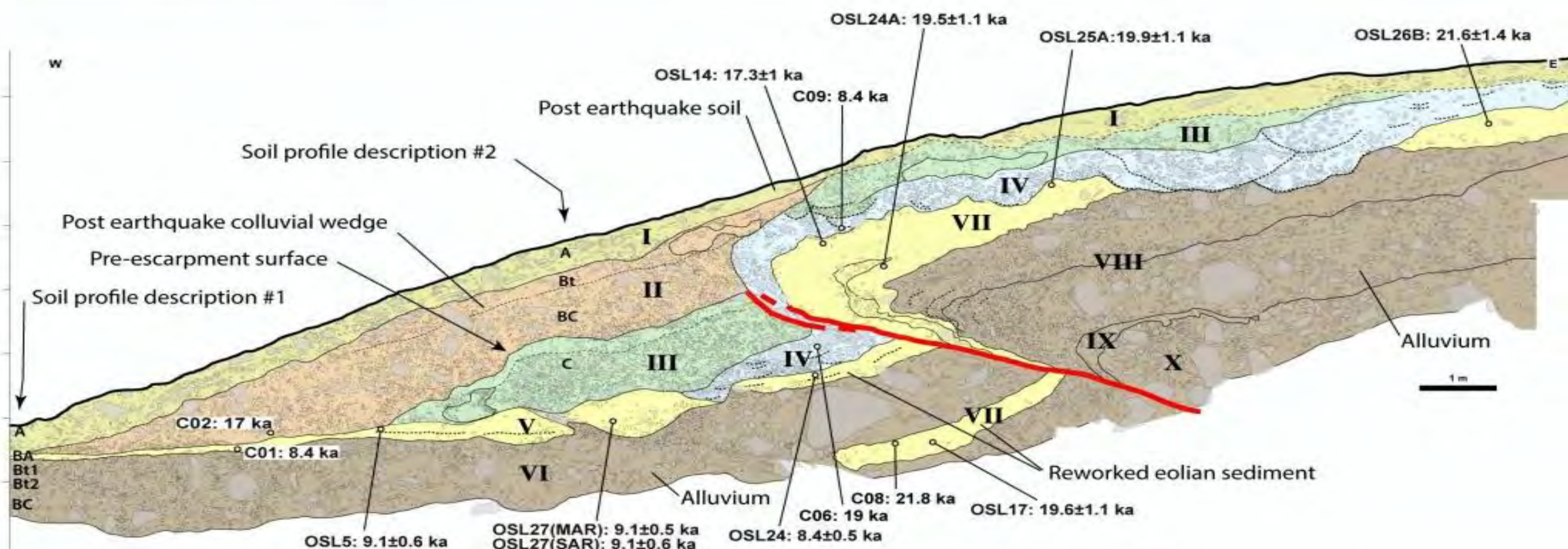
Vargas G., Klinger Y., Rockwell T., Forman S.L., Rebolledo S., Lacassin R., Armijo R. 2014. Probing large intraplate earthquakes at the west flank of the Andes. Geology v.



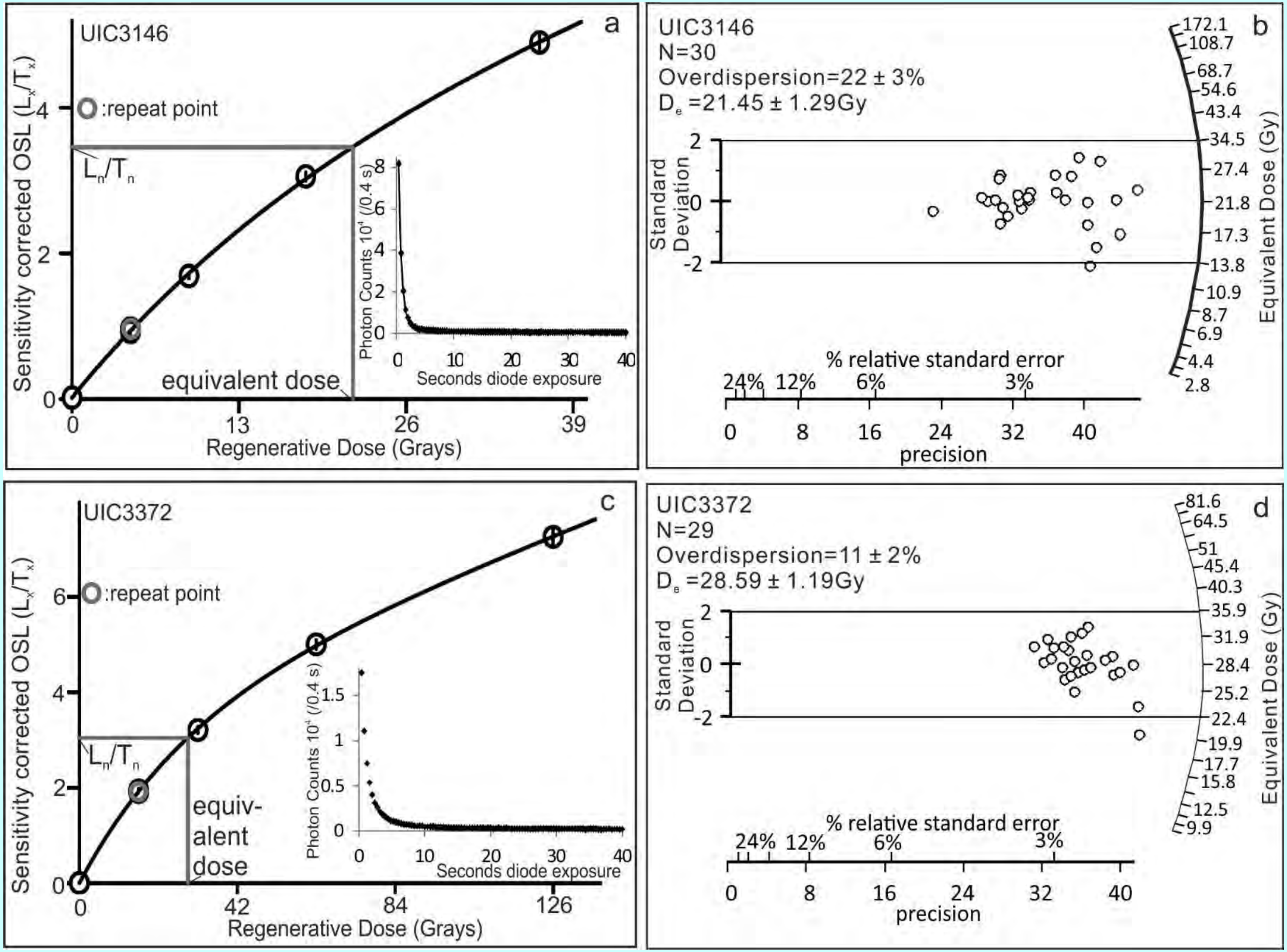


After study of the trench stratigraphy, careful sampling for OSL dating we deciphered to thrust events ca. 9 and 18 ka.





Dating quartz grains from the top of buried soils and from reworked loess provided credible OSL ages in agreement with radiocarbon ages



Reconstruction sequence of events with measured deformation and OSL ages.

Two thrust fault events of ~4.8 m ca. 18 and 9 ka.

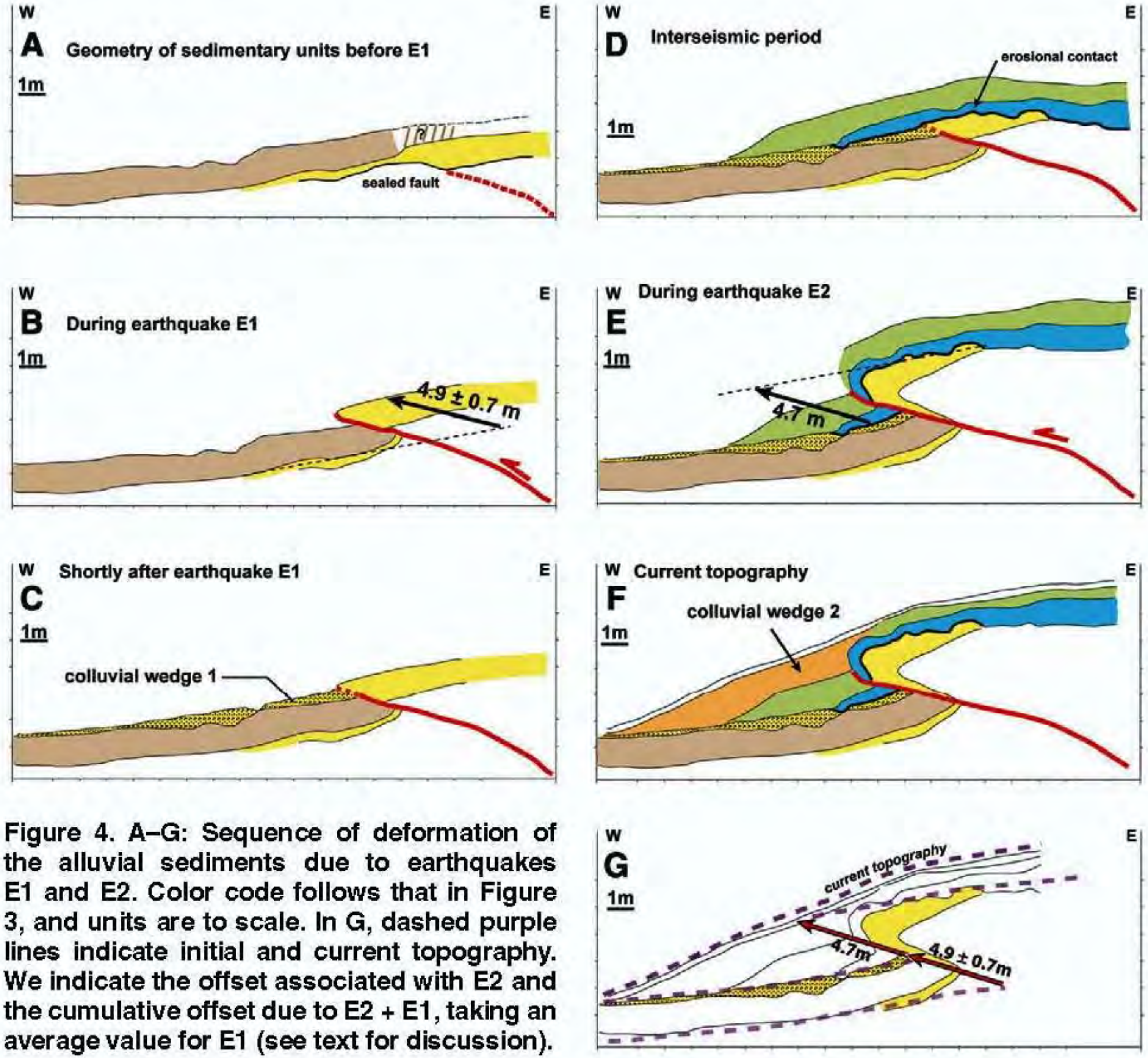
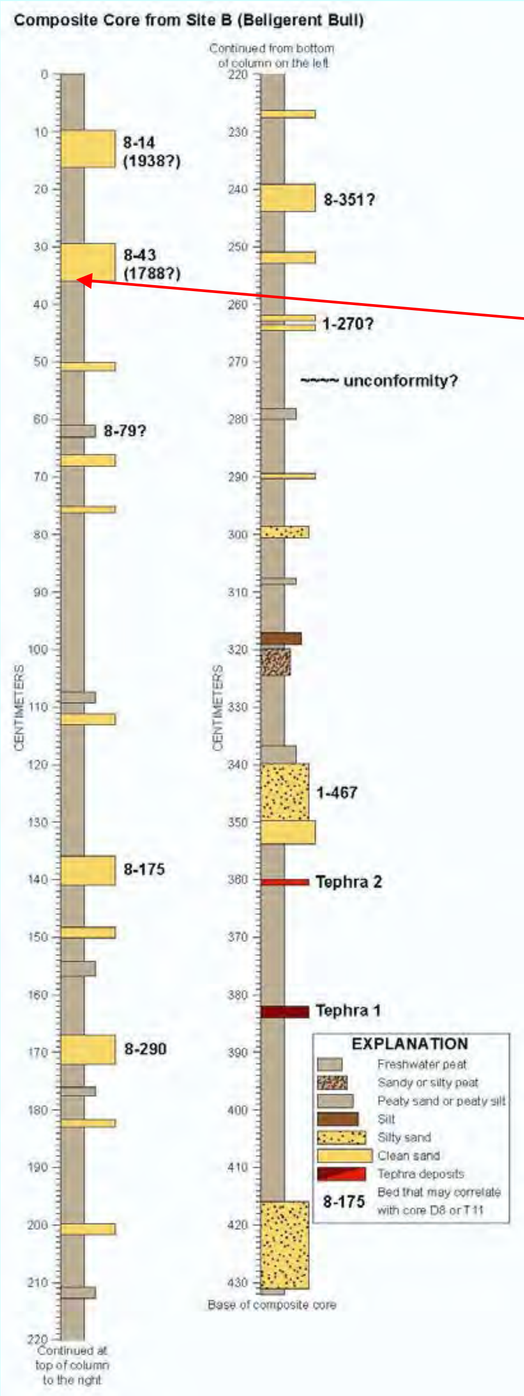
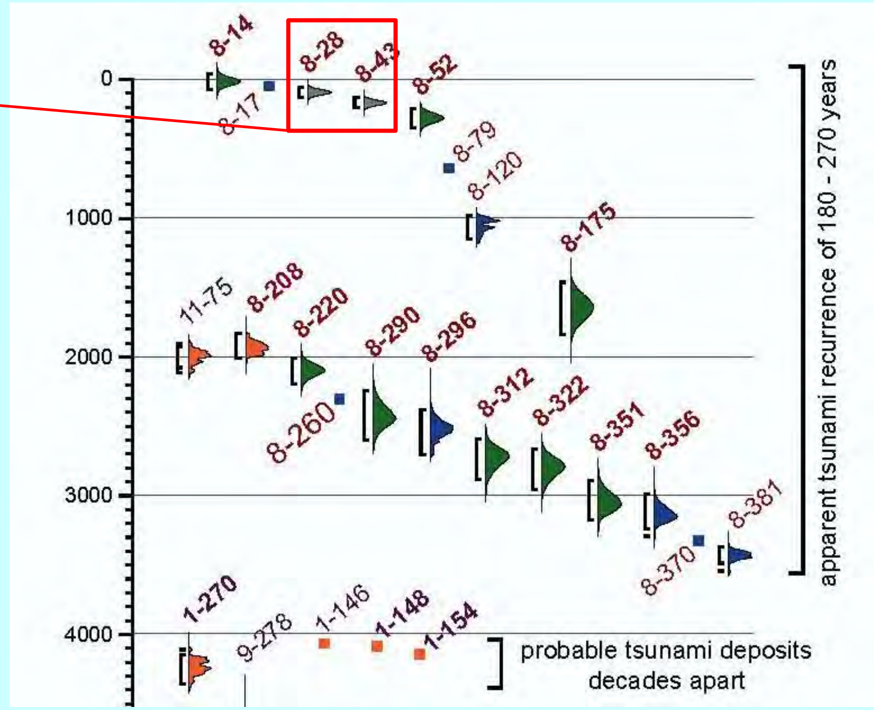
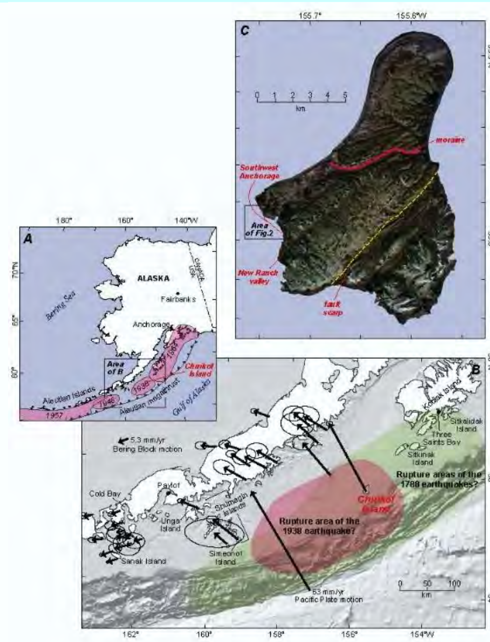


Figure 4. A–G: Sequence of deformation of the alluvial sediments due to earthquakes E1 and E2. Color code follows that in Figure 3, and units are to scale. In G, dashed purple lines indicate initial and current topography. We indicate the offset associated with E2 and the cumulative offset due to E2 + E1, taking an average value for E1 (see text for discussion).

On going research: OSL dating of paleo-tsunami deposits, Aleutian Islands, Alaska and western Chile



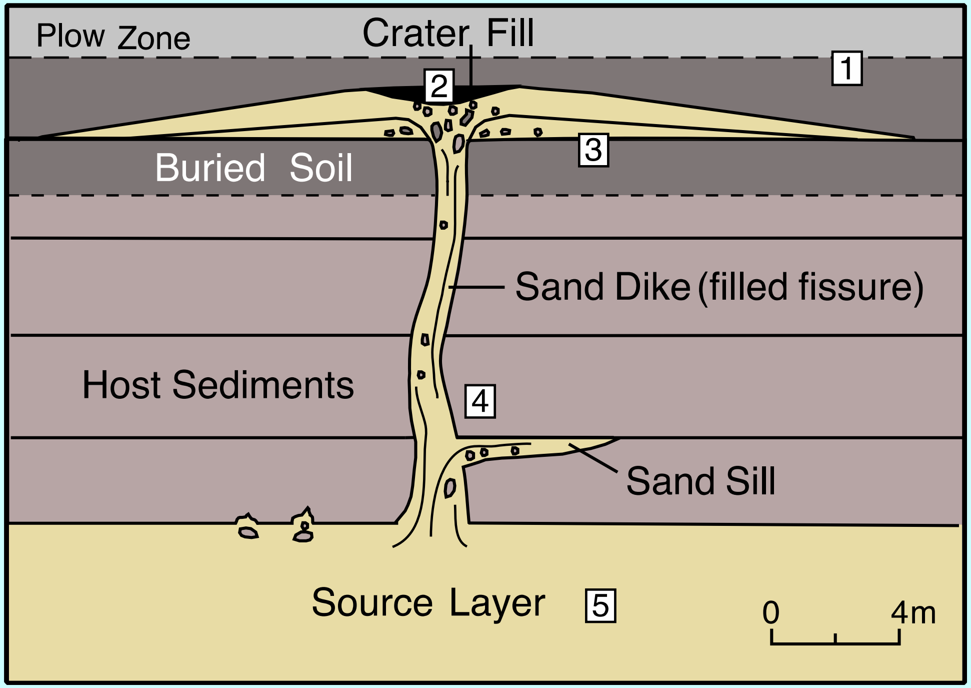




We are going through a "blind" calibration exercise by dating historic or well ^{14}C-dated tsunami events.

✧ OSL dating can now provide well-constrained ages of liquefaction features for estimating timing of paleoearthquakes

Vertical Profile Through Sand Blow



Sample

1 **Post sand blow sediment**

2 Cater fill?

3 **Buried soil (for sure!)**

4 **Host sediment**

5 **Source Layer**

Modified from Tuttle & Hartleb, 2012

With OSL dating there is always sediment to sample for dating and the opportunity for duplicate or triplicate dating of the event horizon

What have we learned that will lead to better science?

OSL is an experiment-based dating technique dependent on the luminescence properties of quartz and other minerals at a specific site or terrain.

Age range is from a few decades to 10^5 to 10^6 years. Precision is currently between 4 to 8%, but it is decreasing.

Always sample sediment with a known depositional setting and maximizing for light exposure and minimizing for depositional or post-depositional mixing.

It is wise to focus sampling on event horizons; burial of surface by sand blow material. New sampling approaches a-tuned to micro-stratigraphy of the buried soil are needed. Care in the field leads to better ages in the laboratory.

The laboratory aspects of OSL dating are more tractable with automation, better numeric treatments and now for us three Riso OSL systems.

There is an endless frontier for "geoluminescence" dating linked to the "paleosciences."

2010-11 Canterbury Earthquake Sequence: hidden faults, liquefaction, rock fall, economic impact, government response

Pilar Villamor

on behalf of many scientists and engineers

GNS SCIENCE
TE PŪ AO

This presentation: The Canterbury Earthquake Sequence

- What happened
  - Background
  - The Earthquake Sequence

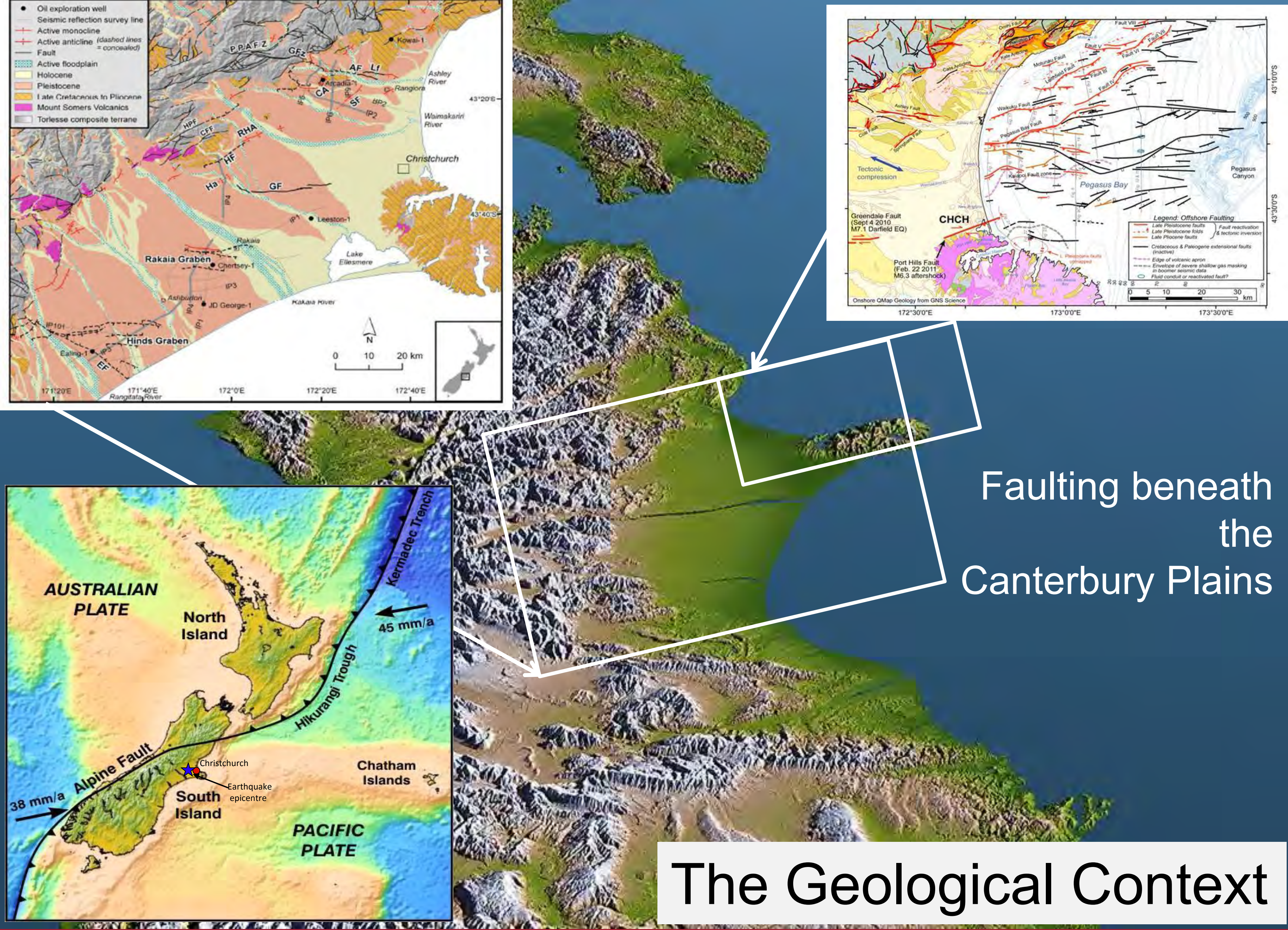
- The “surprise? factor(s)” (moderate hazard area)- Wellington was supposed to be the one!
  - Hidden faults and a direct hit
  - Long –lasting sequence of events (different from main shock-aftershock): Difficult to forecast
  - Extensive monitoring (seismic, GPS..etc)
  - Extreme ground motions: 2500 return period shaking in February: Building damage and Rock fall risk
  - Liquefaction damage (50% total losses: poor land use planning, no risk-based)
  - Maintaining confidence in the insurance market (looses 50 % higher than models used by insurance companies prior to this events - Hey what about liquefaction and rock fall damage?).

This presentation: The Canterbury Earthquake Sequence

- Other
    - Damage and losses: CBD, residential
    - Science response
    - Government response
    - Recovery

- LIQUEFACTION AND THE SEDIMENTARY ENVIRONMENT

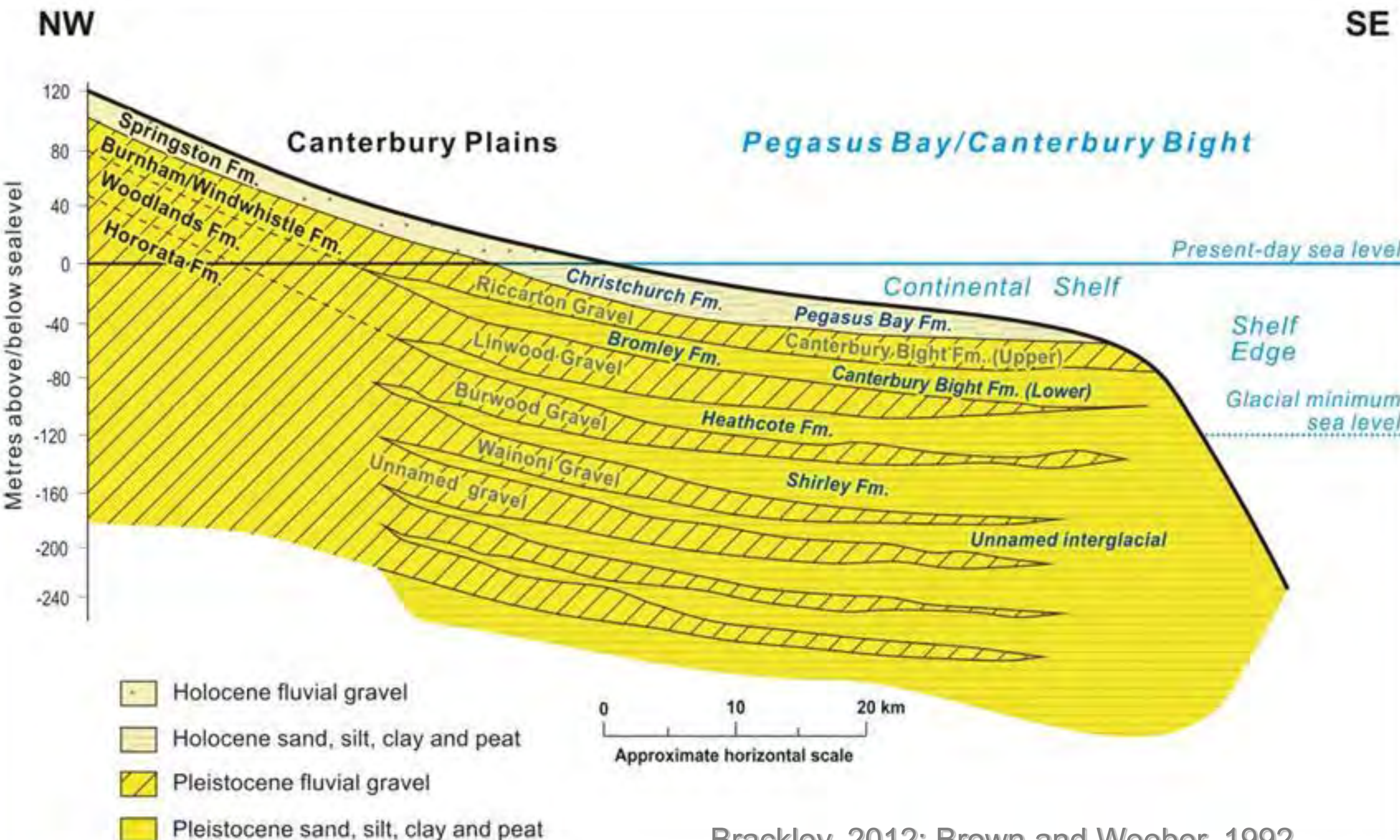
Population : 366,000



Faulting beneath the Canterbury Plains

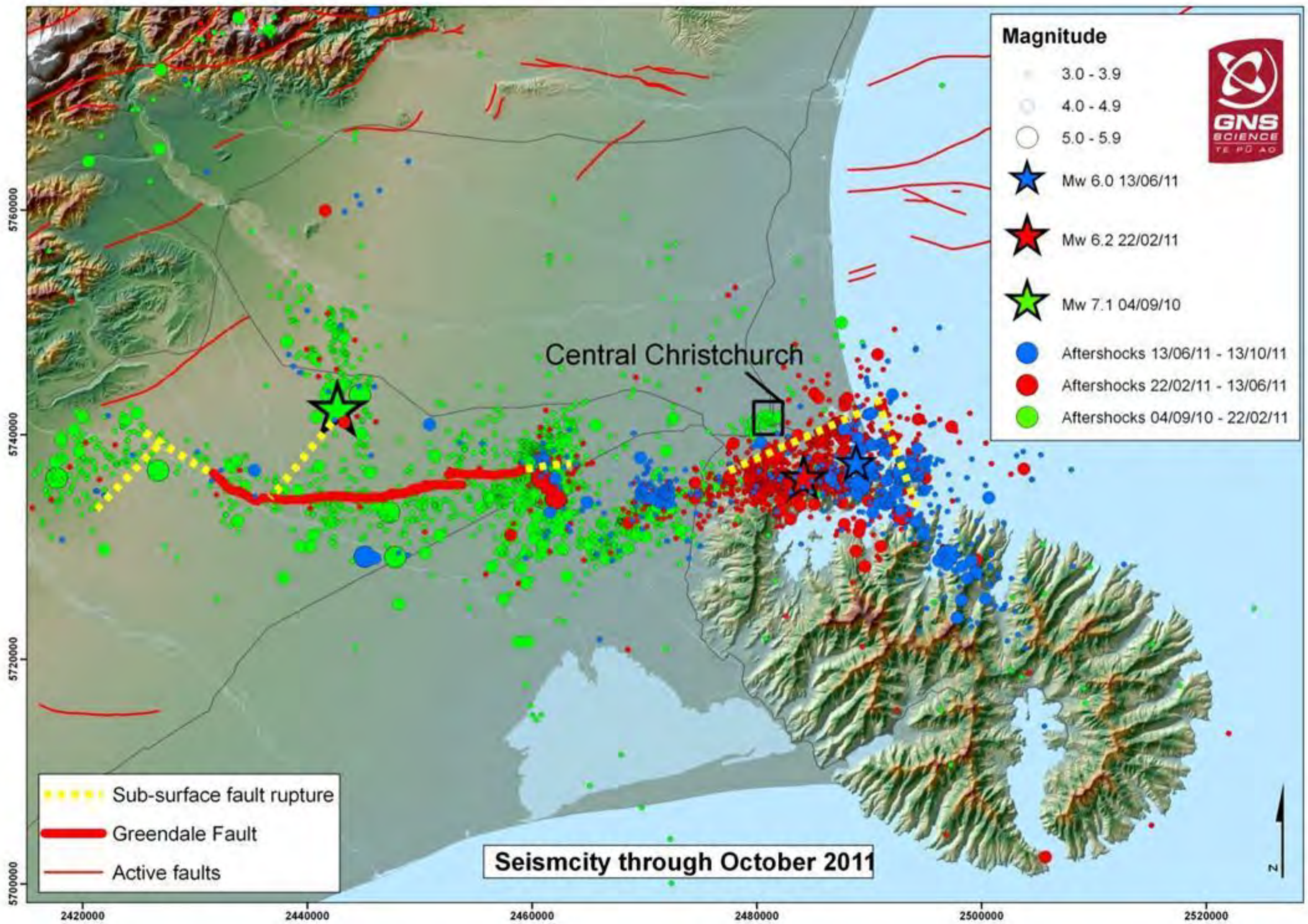
The Geological Context

Geological Cross-Section in Canterbury Region



Brackley, 2012; Brown and Weeber, 1992

The Earthquake sequence



Long-lasting sequence of events

	4 September 2010	22 February 2011	13 June 2011	23 December 2011
Mag (M_w)	7.1	6.2	6.0	5.9
Epicentre[1]	30 km W	10 km SE	10 km SE	10 km E
Time[2]	4:36 am	12.51 pm	2.20 pm	3.18 pm
Max PGA[3]	0.6g (0.3g CBD)	2.2g (0.8g CBD)	2.2g (0.4g CBD)	0.96g[4] (0.25g CBD)
Casualties	0 fatalities	185 fatalities	0 fatalities	0 fatalities
Building Damage	To older concrete & URM	All pre-1970's & several modern buildings with eccentric design	Further residential damage in Port Hills & already damaged CBD buildings	Minor, but several instances of progressive failure
Liquefaction	Widespread in eastern suburbs	Extreme damage in many eastern Christchurch suburbs	Further damage in eastern Christchurch suburbs	Minor damage in eastern Christchurch suburbs
Cost[5]	4-5 billion	15-20 billion	c. 1.5 billion	c. 26 million

- Long and evolving impacts – more like an extended volcanic eruption
- On-going social impacts – psycho-social issues, confidence, domestic violence
- Progressive degradation of the built environment

Not only hidden but COMPLEX!!!

Mw 7.1

Complex rupture of several faults – mainly strike-slip with smaller reverse faults

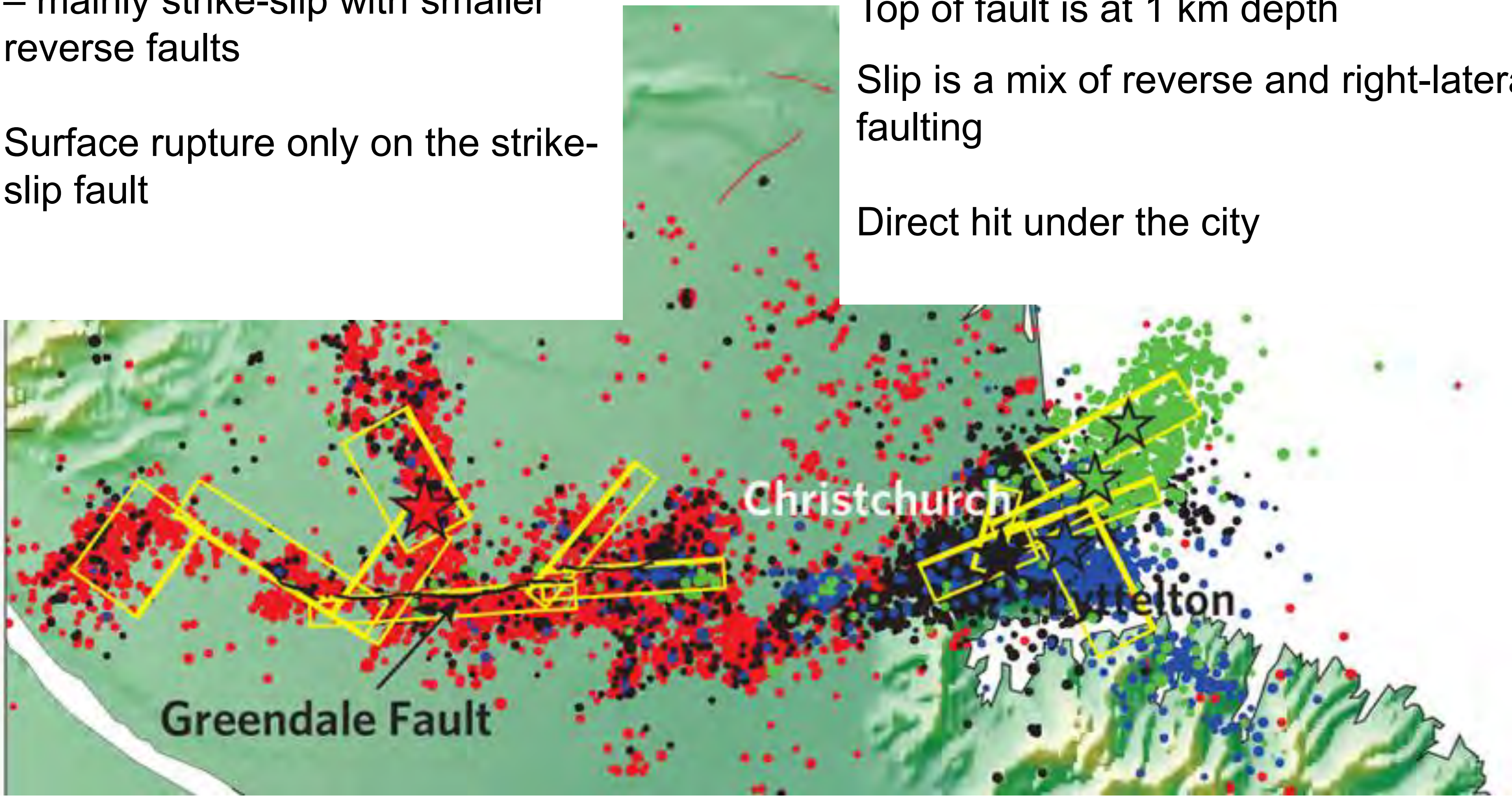
Surface rupture only on the strike-slip fault

Mw 6.3 and 6.0

Top of fault is at 1 km depth

Slip is a mix of reverse and right-lateral faulting

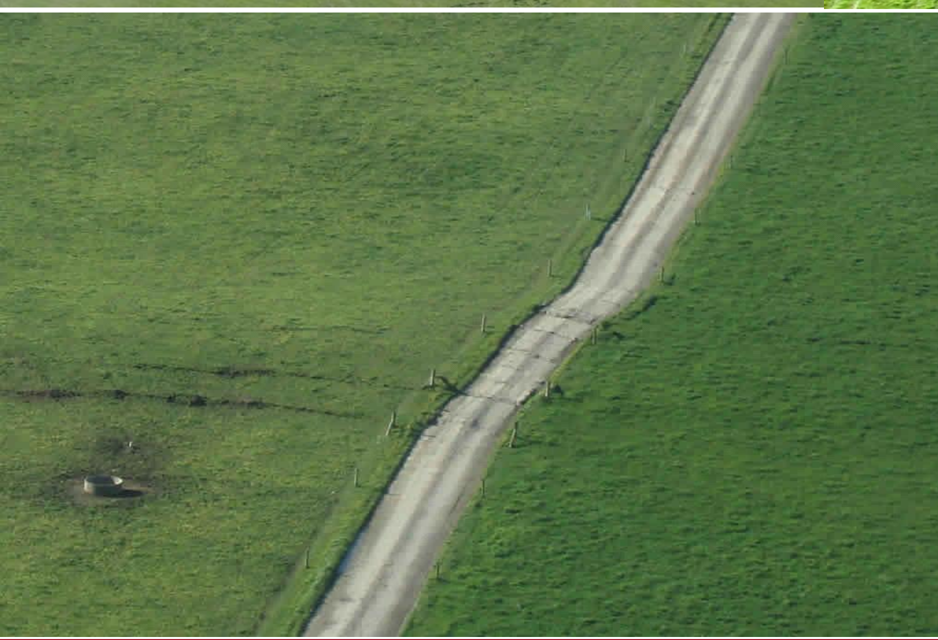
Direct hit under the city



Reyners et al., 2013

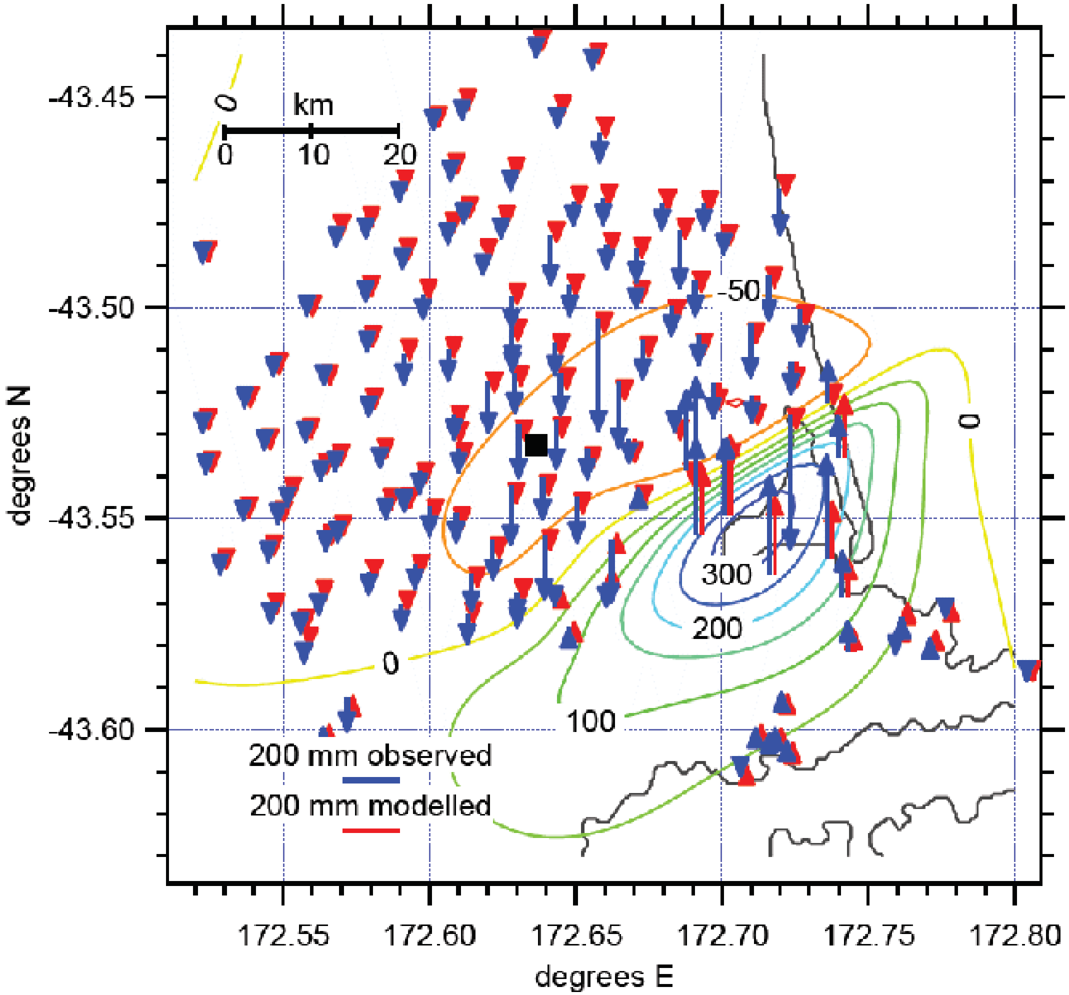
The Hidden Faults

Greendale Fault (4 Sept 2010) was not previously mapped and was only 30 km away from a big city



Photos: Richard Jongens

Christchurch Fault (22 Feb 2011)- "surface expression"



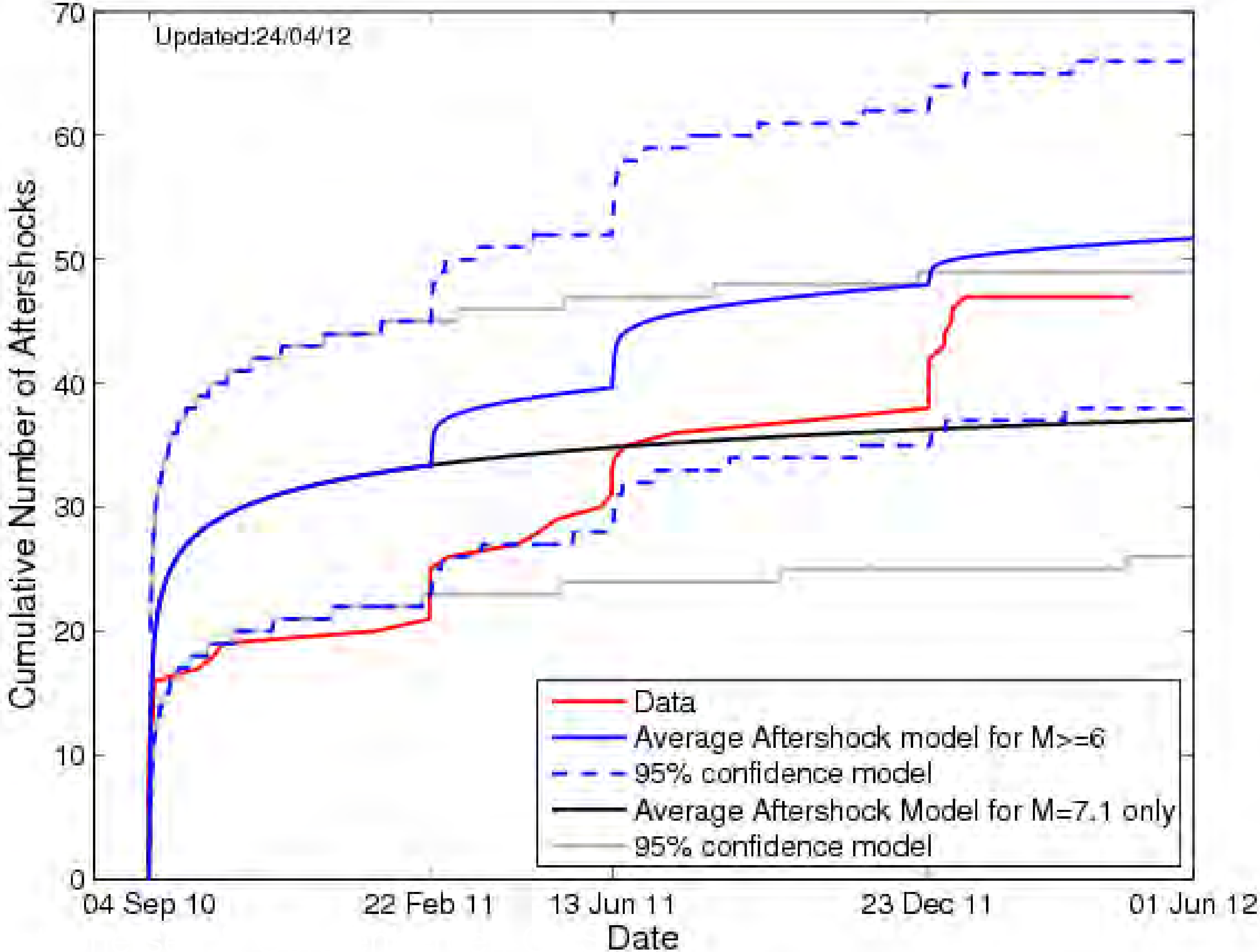
Beavan et al., 2012

GPS and CSK DInSAR data

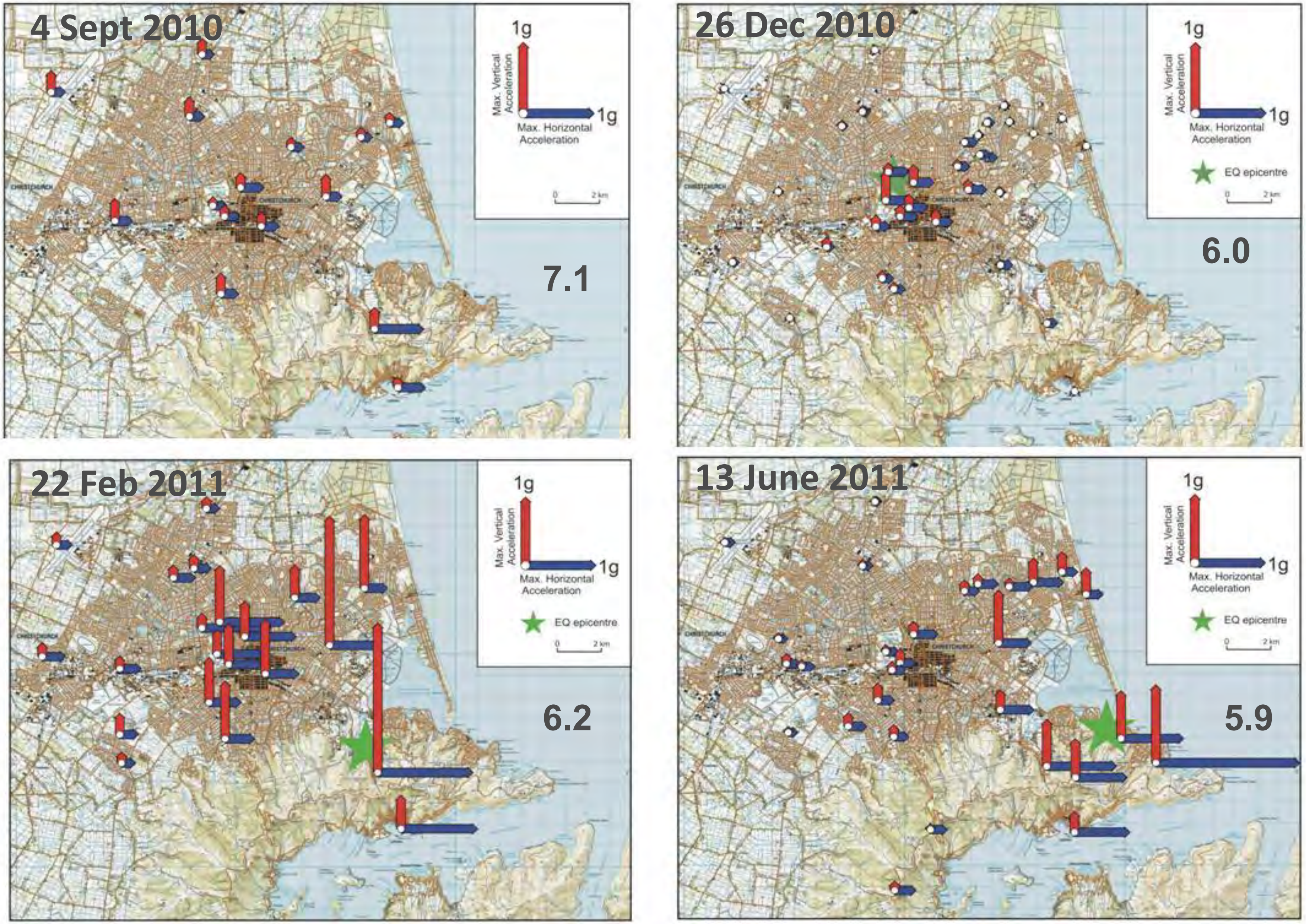
MORE FLOODS IN THE CITY!!

Subsidence

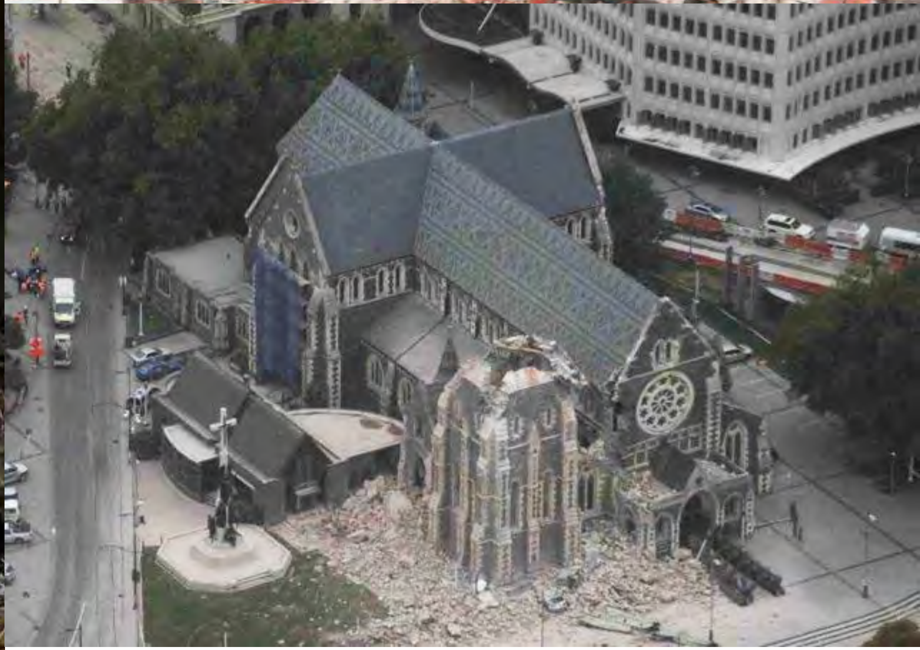
Long-lasting sequence of events: Difficult to forecast



The Impacts - Ground Motion (10% in 50 yr code level = 0.3 g)

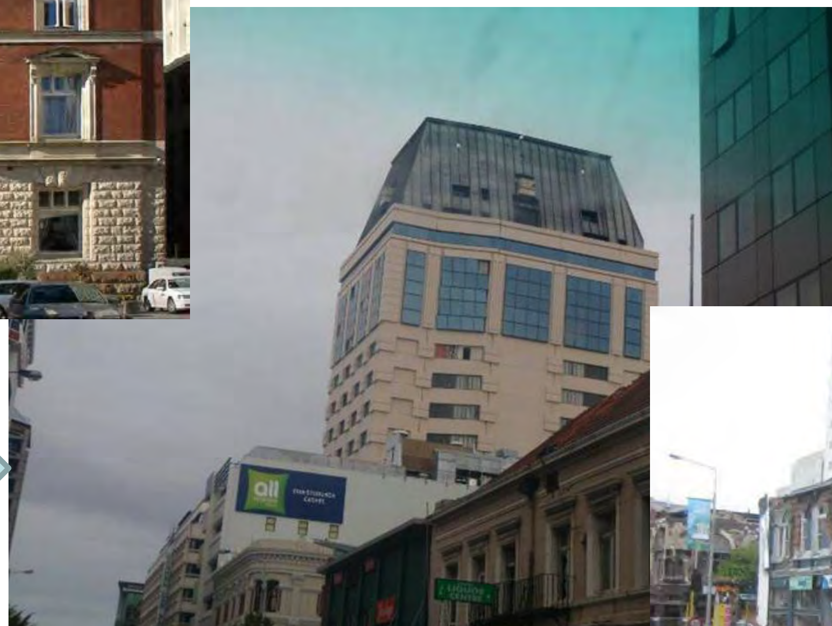


Strong ground shaking CBD



Commercial Building Performance

Good – careful retrofit



Bad – eccentric configuration

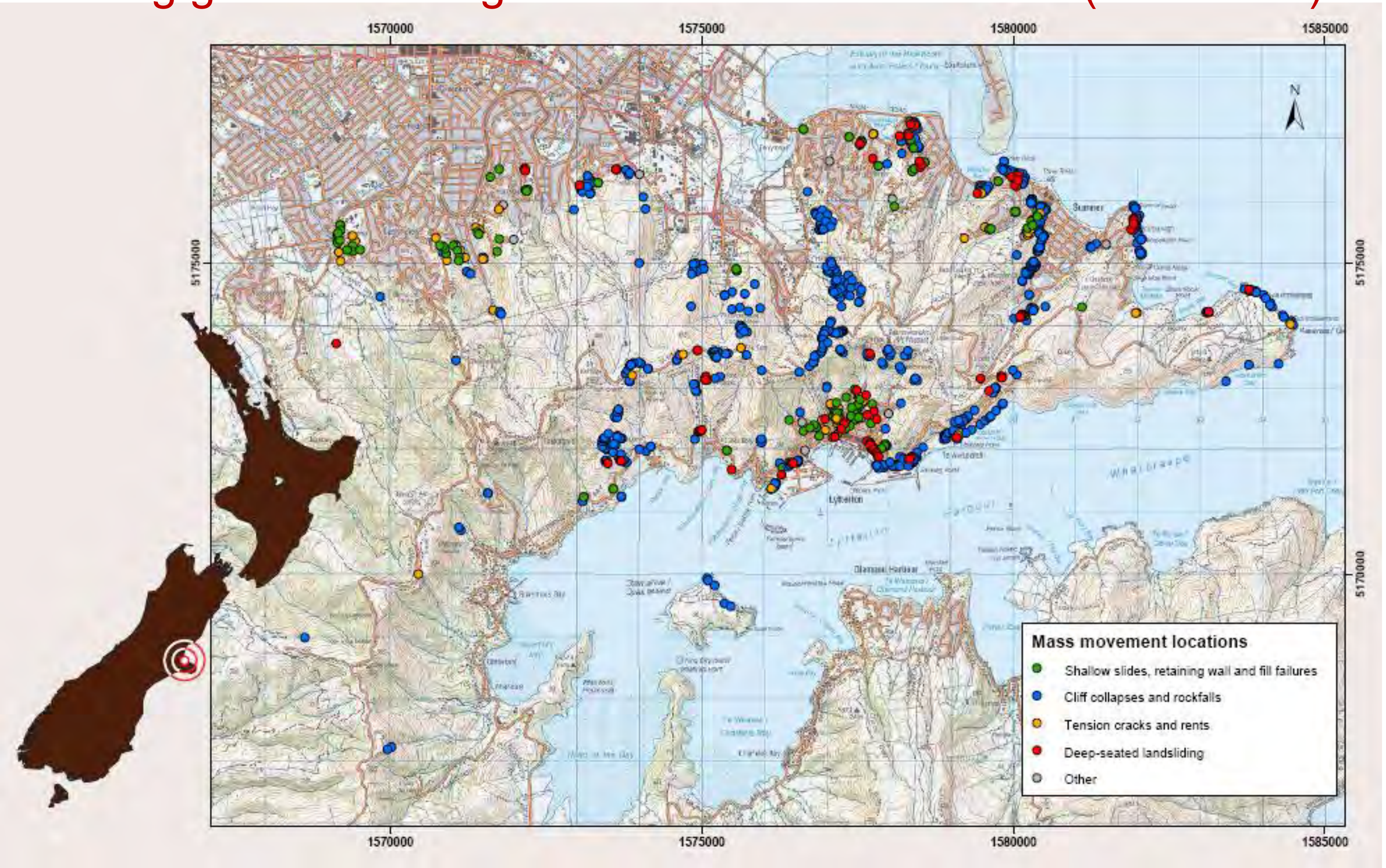
As Expected – not up to code

22 February 2011 Eq. was a 2500 year return period event

RESIDENTIAL- Strong Ground motion

- Mainly timber framed- good repose to shaking
- URM did not

Strong ground shaking: Landslides and Rock falls (residential)



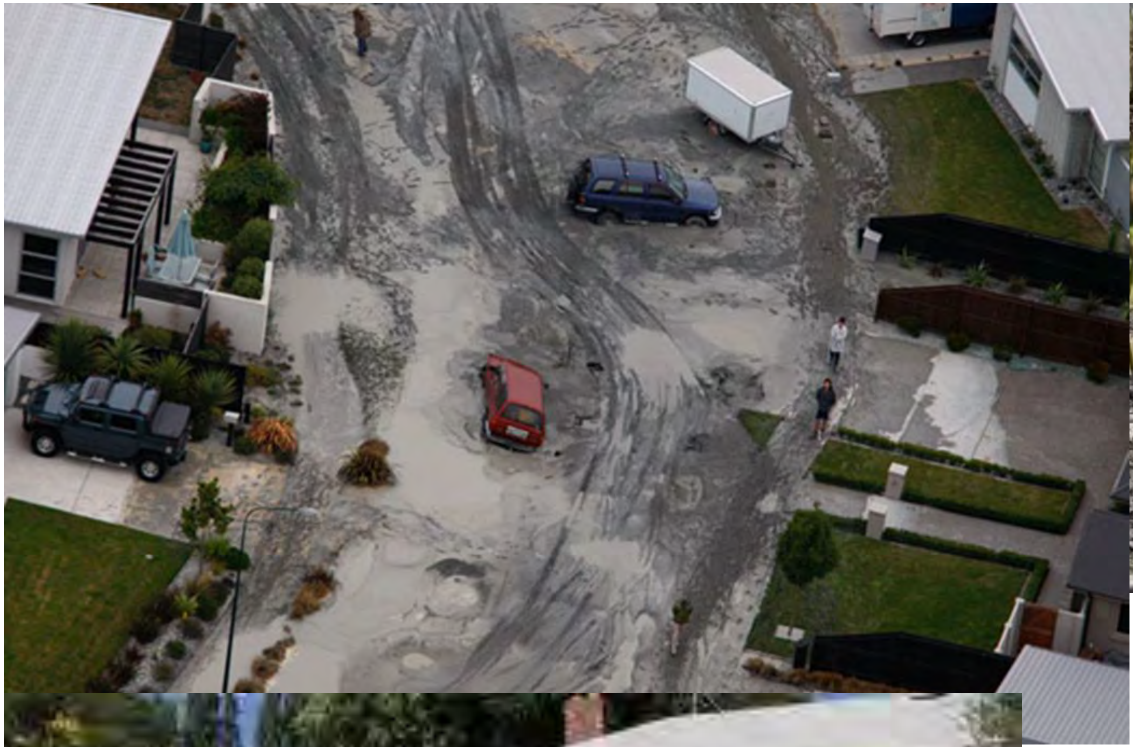
Slide from Chris Massey (GNS Science)

Landslides and Rock falls

22 Feb 2011 earthquake impacts: Rock fall and life risk

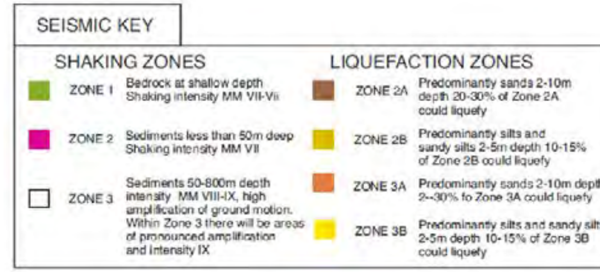
- **5 fatalities from falling rock**
- **100 homes damaged by falling rocks**
- **4 fatalities from falling rock outside:**
  - 2 people on park tracks
  - 1 person in garden
  - 1 person working
- **1 fatality from falling rock inside**
- **Occurred midday**
  - Not many people were home

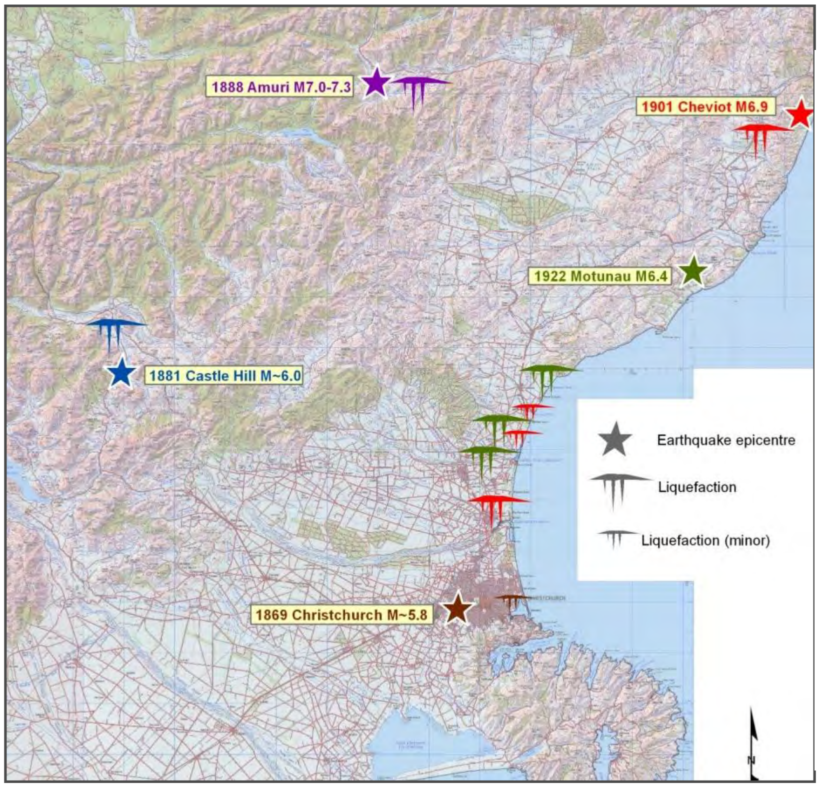
Slide from Chris Massey (GNS Science)



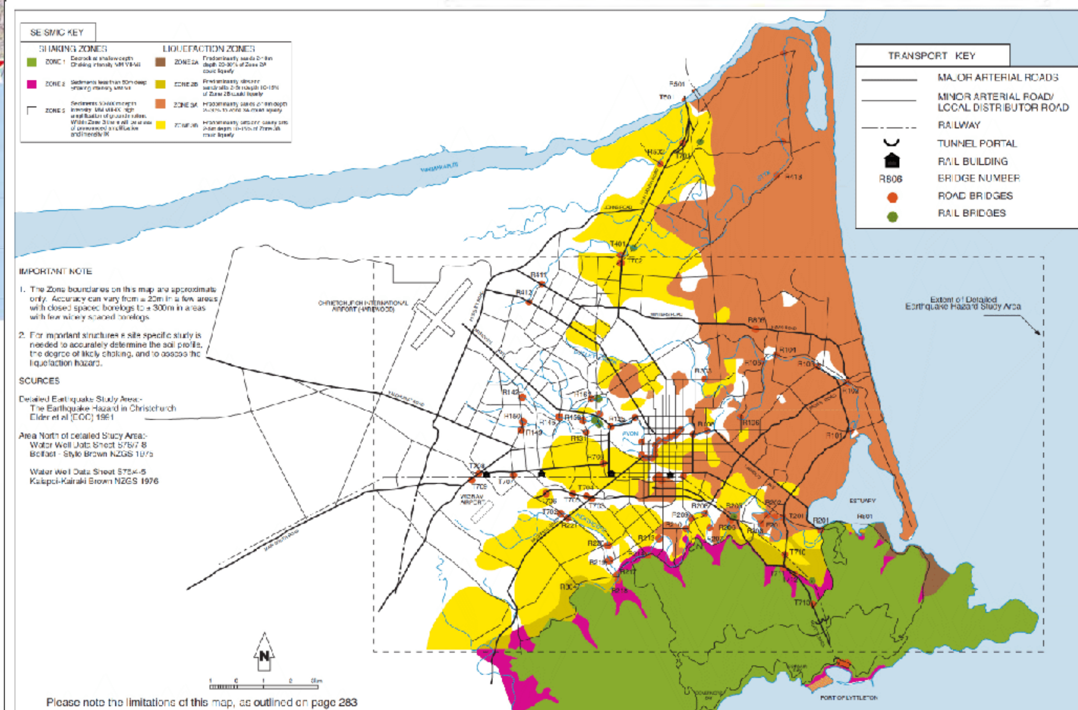
Liquefaction

Historical Earthquake-Induced Liquefaction and susceptibility maps





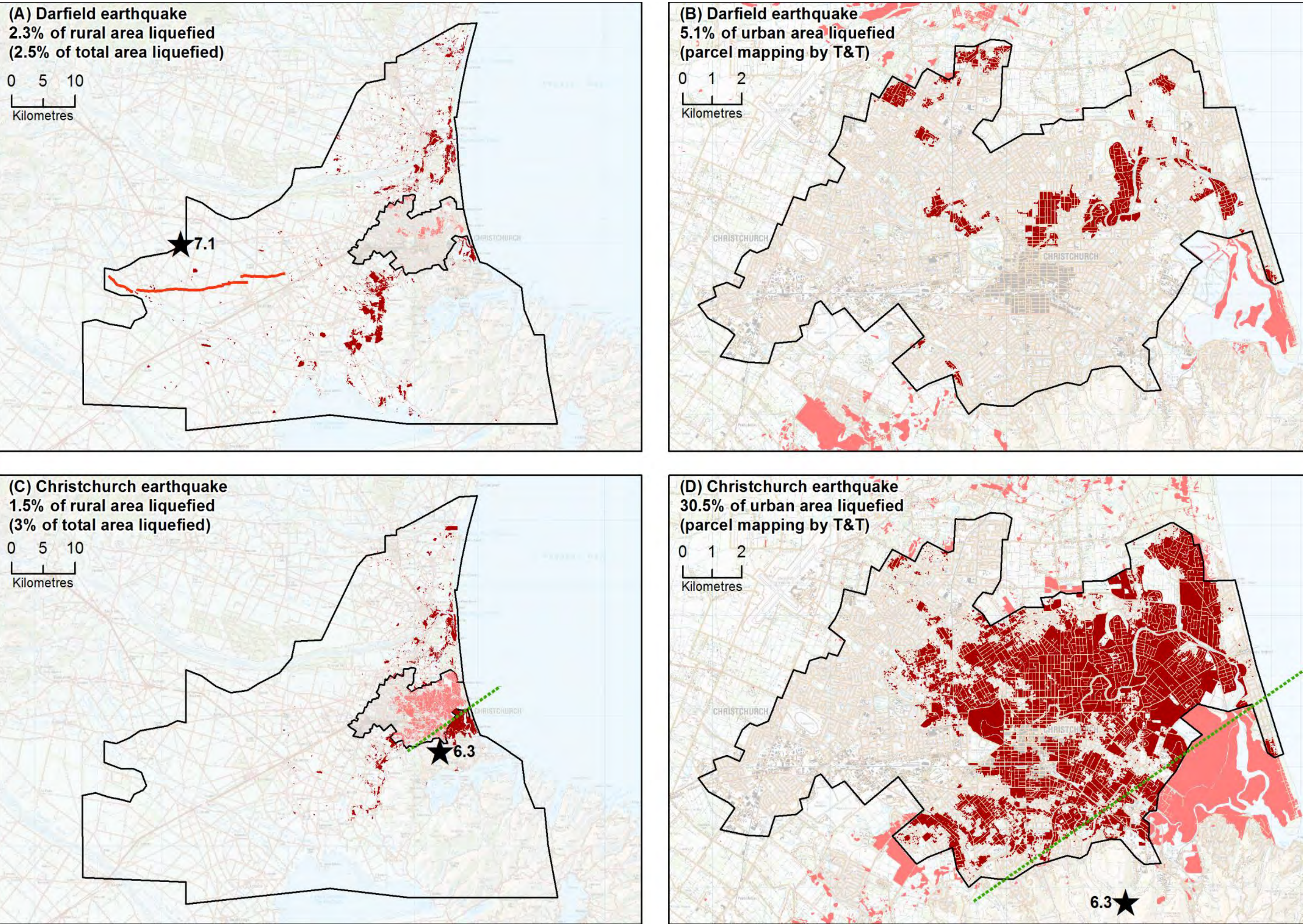
Brackley, 2012



Risk and Realities, 1997

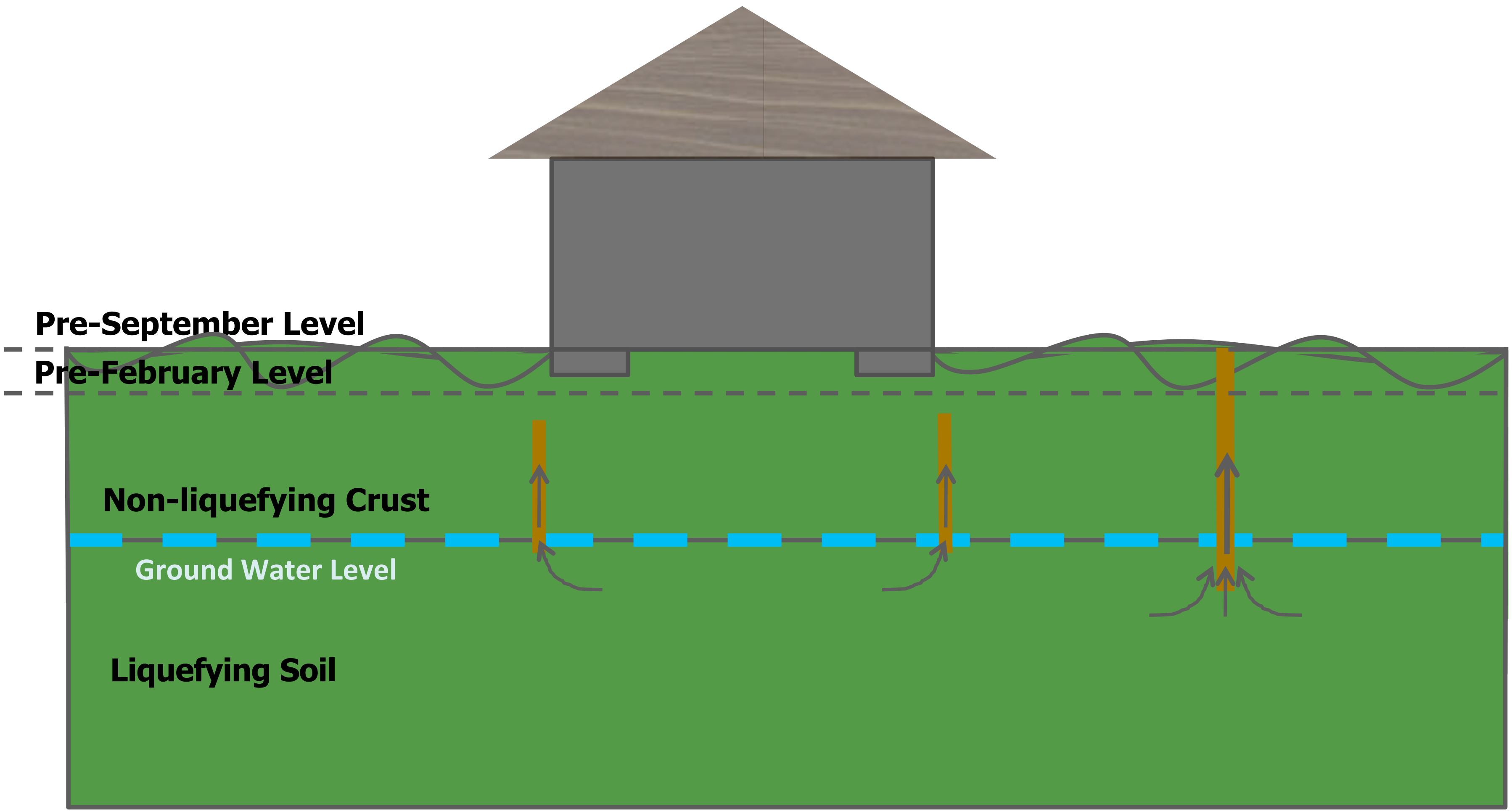
Liquefaction extent and recurrence

Brackley 2012; Townsend et al in prep.



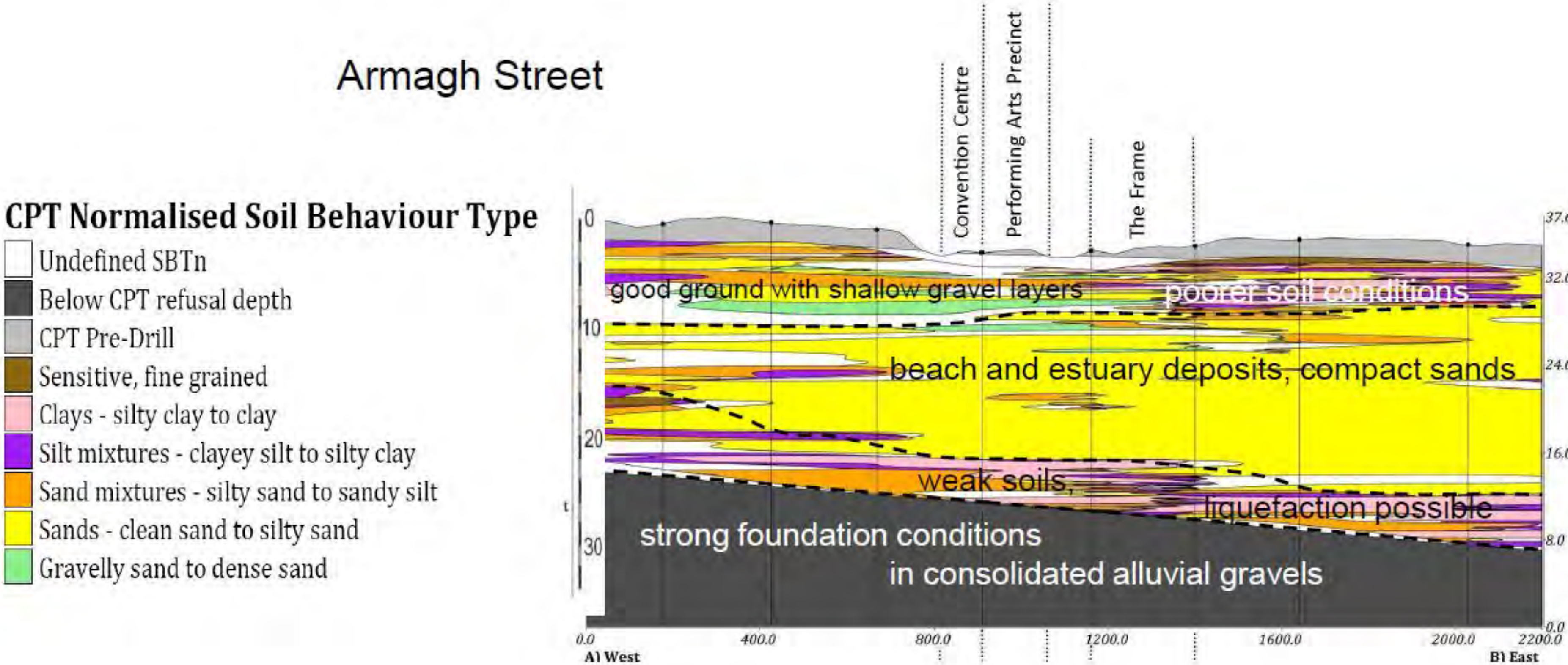
Crust Thinning – Simplified Example

Ground Settlement, Liquefaction & Structures Sinking into Ground
September Earthquake
February Earthquake



Slide courtesy of Sjoerd van Ballegooy (Tonkin & Taylor) & EQC

Subsurface conditions in central Christchurch well known and not especially difficult for rebuilding



Christchurch urban geological mapping after Begg & Jones in prep. using Leapfrog 3D modelling software

Canterbury Geotechnical Database

- ~20,000- CPT, SPT , SCPTs
- Water level model
- MASW shear wave velocity

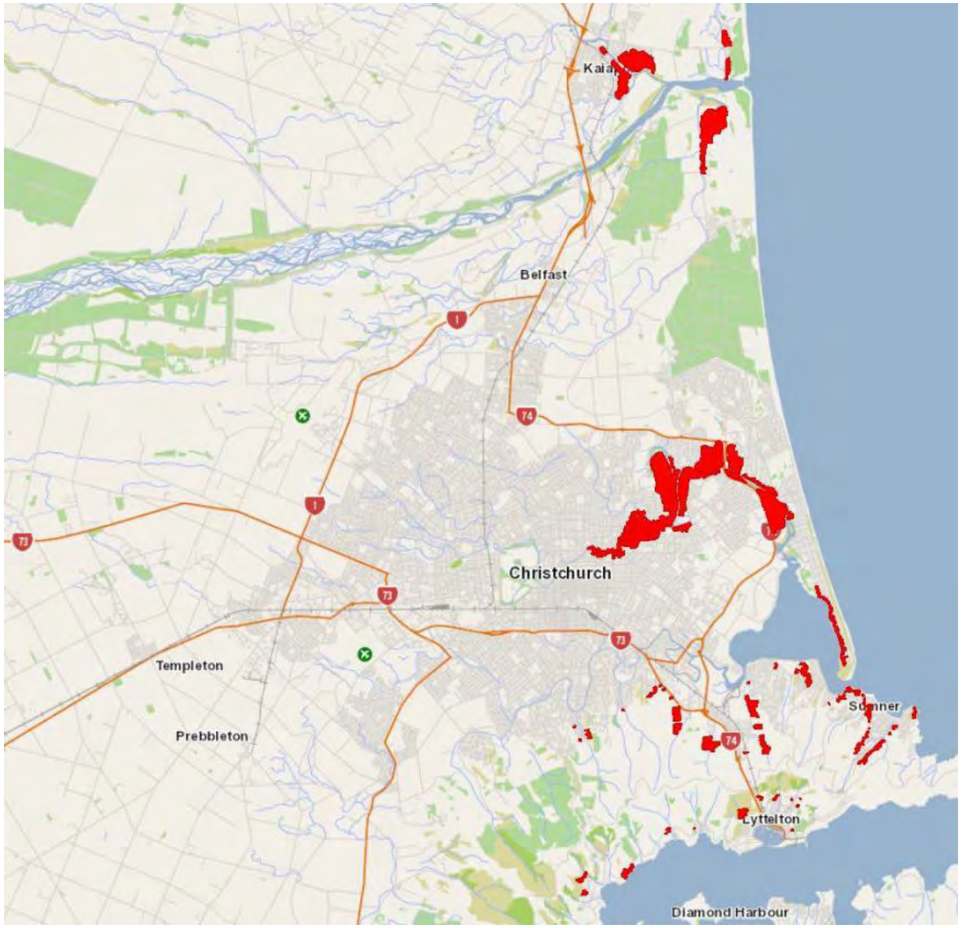
The damage in Christchurch resulting from liquefaction is changing the way New Zealand considers land-use planning towards a risk-based approach

Risk (Impacts) = Hazard x Consequences

Reducing Future Risk – The Residential Red Zone

Residential Red Zone – as at 24 Sep 2012

- In total 190,000 homes have been zoned
- 7,861 properties in flatland
- c. 600 properties in Port Hills
- c. 4% of total homes
- Value c. NZD 3-4 billion
- Flatland zoning due to likely future land damage
- Port Hills zoning due to future life risk



Economic Features of the earthquake sequence in the NZ context

A large (for NZ) natural hazard event in a small economy

- 10% of NZ's 4.5 million people directly impacted
- Total loss estimates c. $40-50b NZD – about ~ 15% GDP
- NZ's economy about the same size as Munich-Re or IBM annual revenue

Events such as this have the possibility of irreparably damaging the economy of small or developing nations. Insurance is critical for NZ

Regional economy is strong (based on agriculture)

- Port, airport, road and rail networks had very little downtime
- 95% of businesses are still operating albeit with downturn in tourism, education, and hospitality
- Some migration away from Canterbury especially initially, now about 9,000 persons, but 30,000 new workers needed for rebuild – communities remained largely intact
- Early government support for local business continuity and workforce

A city cannot operate in isolation from its hinterland. Supply chains and infrastructure are critical. There was no need for widespread evacuation in Christchurch and this is a key tipping-point in regional economic resilience

Insurance Perspectives - Recent major earthquake events

USD billion (at 2011 prices)

Event Date	Country	Economic Losses	Economic losses as %GDP	Insured Losses	Insurance Industry Contribution
11 March 11	Japan	300	5.4%	35	17%
27 Feb 11	Chile	30	18.6%	8	27%
22 Feb 11	NZ	15	10%	12	80%
12 Jan 10	Haiti	8	121%	0.1	1%
04 Sept 10	NZ	6	5.3%	5	81%
06 April 09	Italy	4	0.2%	0.5	14%
23 Oct 11	Turkey	0.75	0.1%	0.03	4%
04 April 10	Mexico	0.95	0.09%	0.2	21%

Source: Swiss Re *sigma* catastrophe database

Big events in small countries can have a major economic impact without risk transfer.

Government Response and Recovery Actions

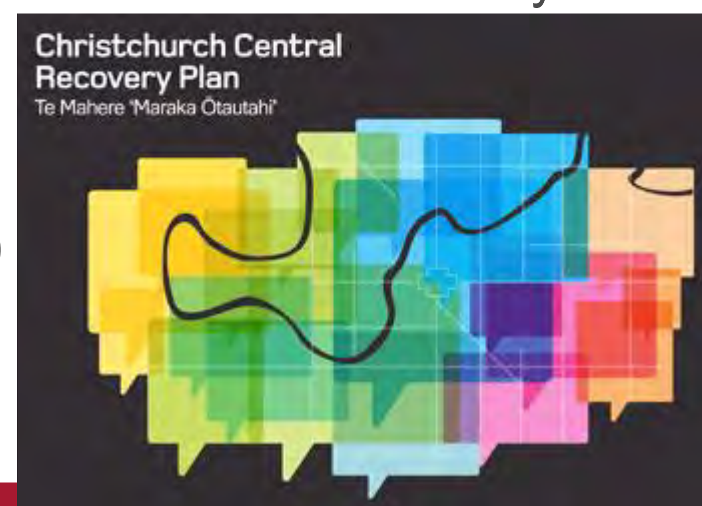
1. Following the Darfield earthquake a Regional Civil Defence Emergency was declared

2. Following the Feb 2011 Christchurch earthqua the first-ever National Civil Defence Emergency was declared (23 Feb – 30 Apr 2011)

- *CBD cordon*
- *Police and military enforcement*
- *National Controller has wide powers under a command and control structure*

3. Government passed special legislation and enacted several Recovery measur

- *Canterbury Earthquakes Recovery Act*
- *Special Cabinet Committee to manage Executive Government response*
- *Canterbury Earthquake Recovery Authority (CERA) – a new govt. dept. with 5yr life*
- *Canterbury Earthquake Recovery Fund in Budget*



Operational Response

- Wage and Salary Subsidy to maintain economic confidence – NZD 250 million
- Earthquake Commission expanded from 22 to 1500 staff
- Formation of Stronger Christchurch Infrastructure Rebuild Team (SCIRT)
- Coordinated Demolition Programme for CBD Buildings
- Coordinated land and building assessment
- Land Zoning and Government coordinated clearance of red zone residential land
  – future liquefaction and rockfall risk
- Investigation into large building collapses -
- Technical guidance & engineering solutions
  - Published guidance on house repairs in conjunction with Insurance Industry
  - Increase seismic requirements by 35% to account for heightened seismic activity
  - Ground improvements where there is potential for further liquefaction
  - Improving foundation requirements

Government Spending on Recovery

- **Canterbury Earthquake Recovery Fund → NZ$5.5 billion**
  - Funding for restoration of infrastructure
  - Includes funding for buyout of red-zoned properties
- **The Earthquake Commission → NZ$7.124 billion, drawn from the National Disaster Fund and backed by a Crown guarantee (residential only)**
  - The Commission sustains a first loss of up to NZ$1.5 billion for each event before NZ$2.5 billion reinsurance attaches
- **Accident Compensation Corporation (personal injury insurance) → $181 million**
- **Total Crown spending → NZ$12.852 billion**
- **Approximately 25% of total economic losses**
- **Insurance industry covers commercial losses**

Canterbury Earthquakes
Main points

- Complexity of “intraplate events”
- Impacts of a floating Mw 6+ earthquake under a major city
- Impacts of a long lasting sequence
- Science and Engineering informing response and recovery
- NZ (small country) and insurance

The Canterbury Earthquakes: links between liquefaction and the sedimentary environment

Pilar Villamor, Monica Giona, Peter Almond, Tish Tuttle, Carol Smith
with contributions from many others.

Lincoln University
Te Whare Wānaka o Aoraki
CHRISTCHURCH • NEW ZEALAND

GNS SCIENCE
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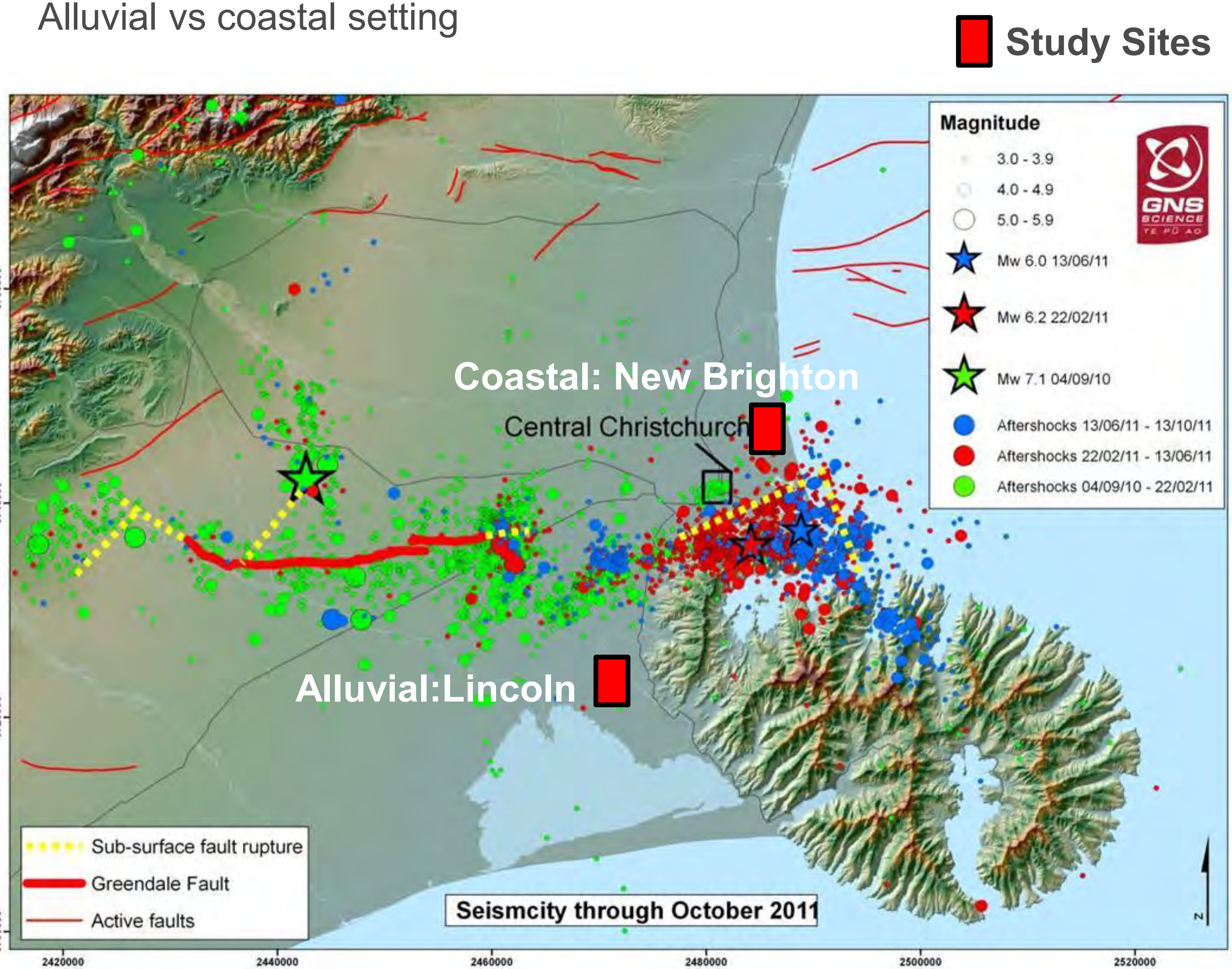
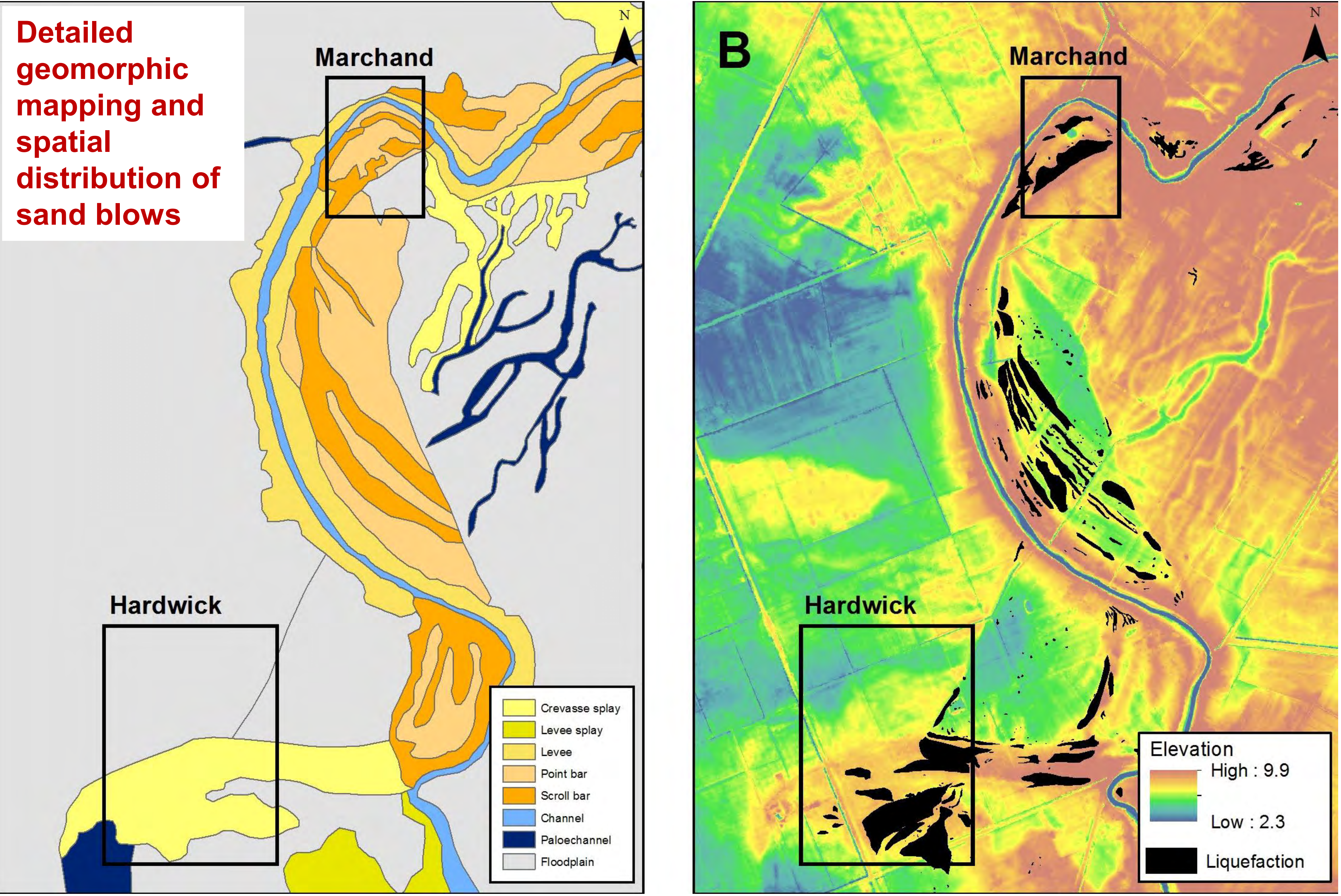
M. TUTTLE & ASSOCIATES
Specializing in Paleoseismology and Seismic Hazard Assessment

Alluvial vs coastal setting

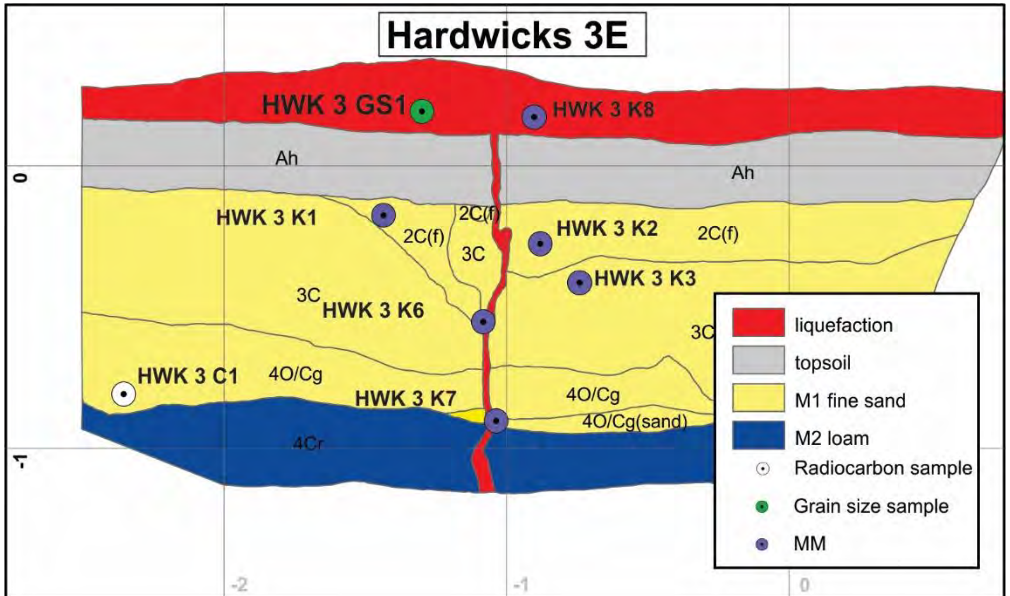


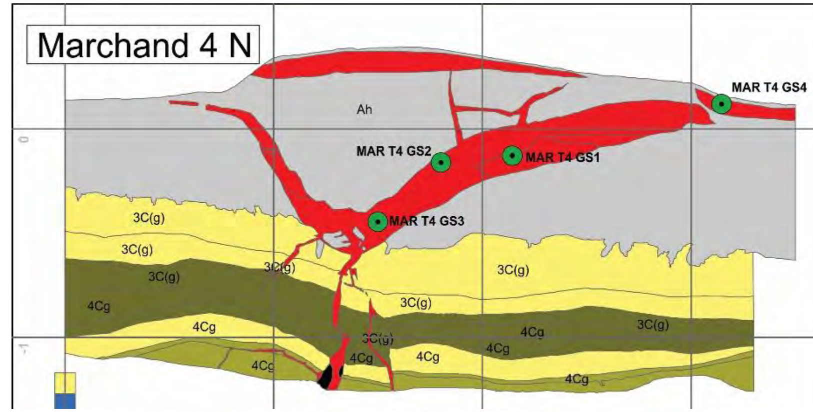
Detailed geomorphic mapping and spatial distribution of sand blows



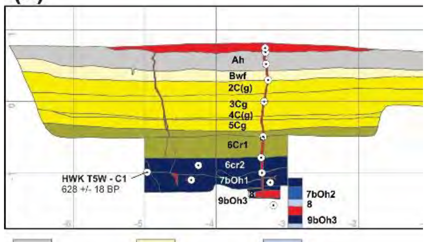
Aligned parallel to point bars, leeves, old channels; mainly ejecting on topographic highs.

-Small dikes and sand blows
-Blisters



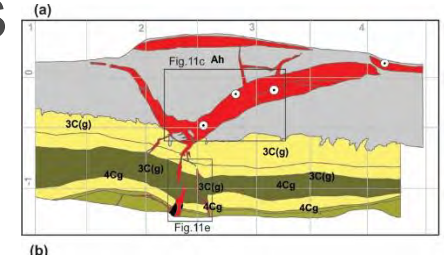


(a)

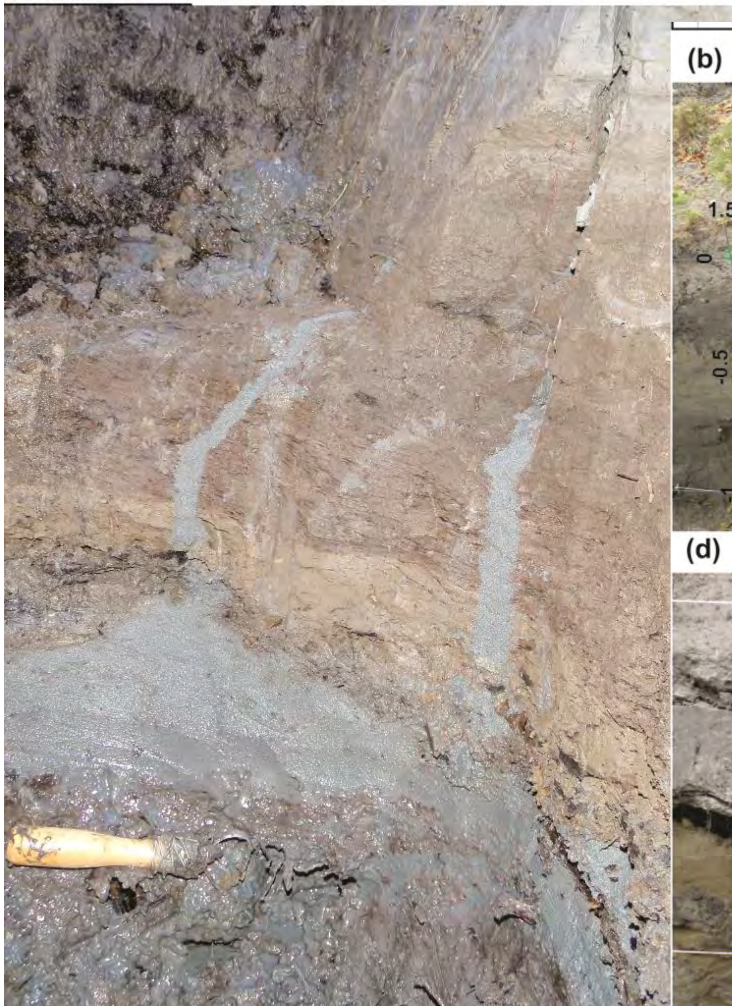


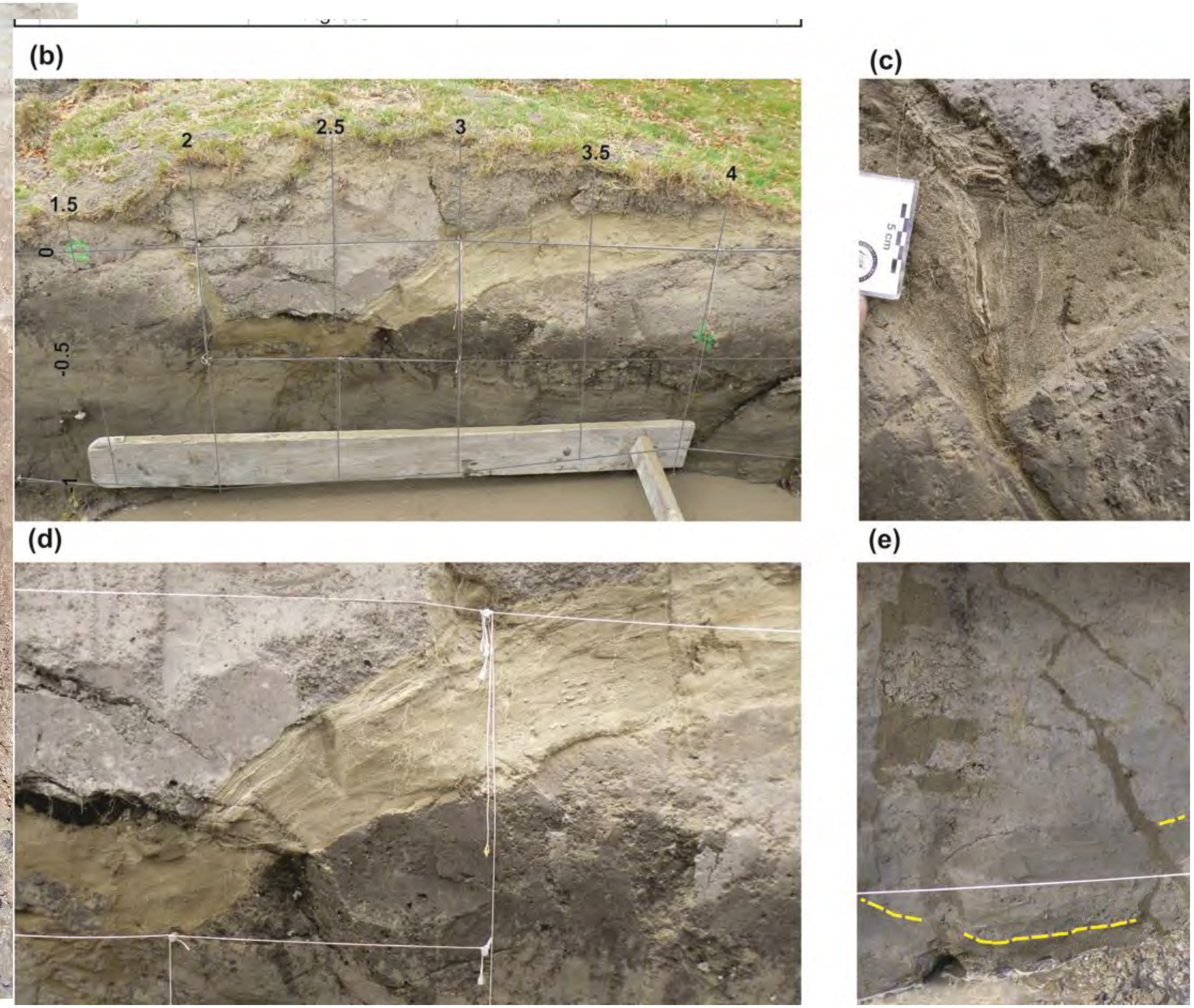
-Small dikes and sand blows

-Blisters

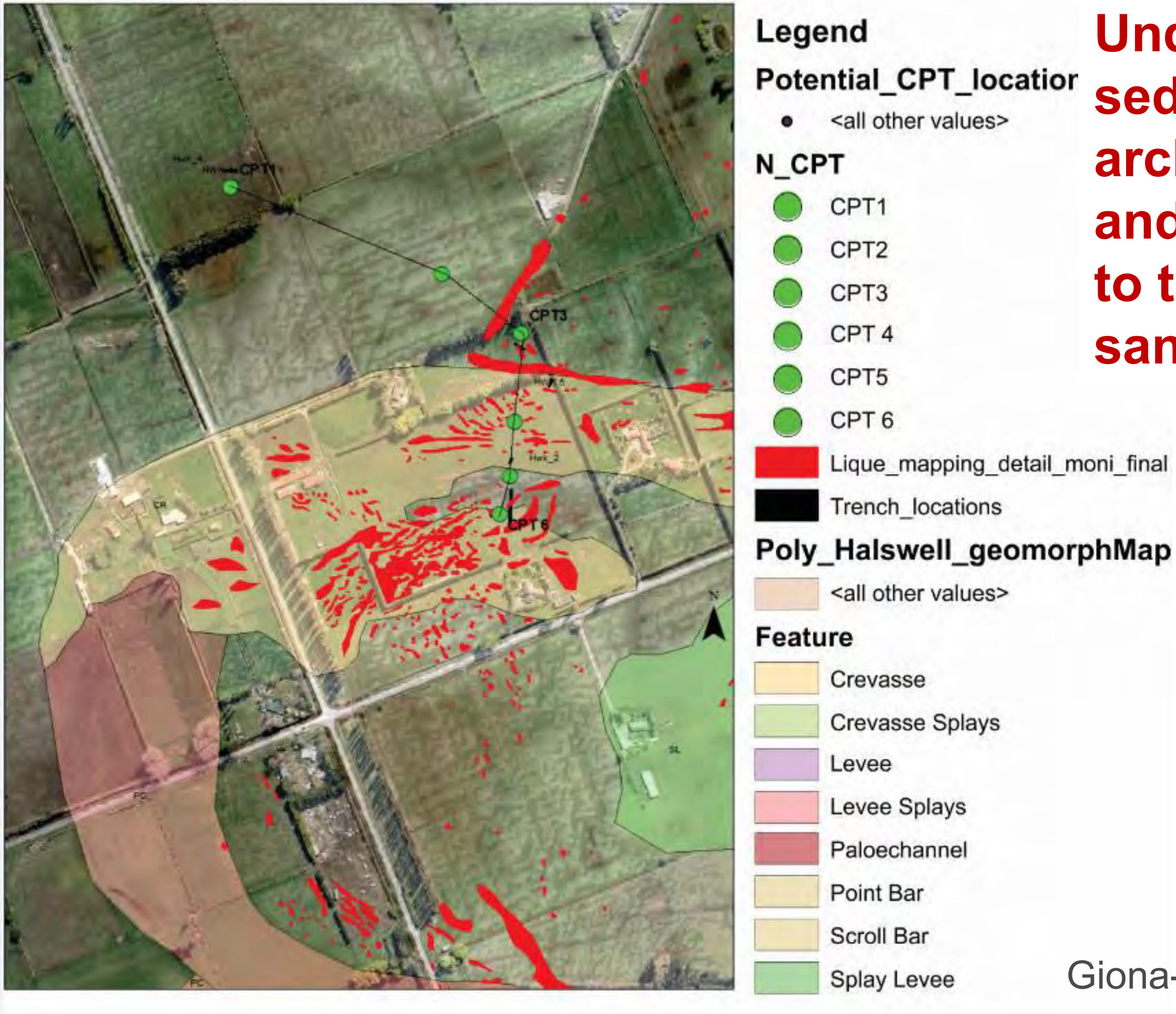


(b)

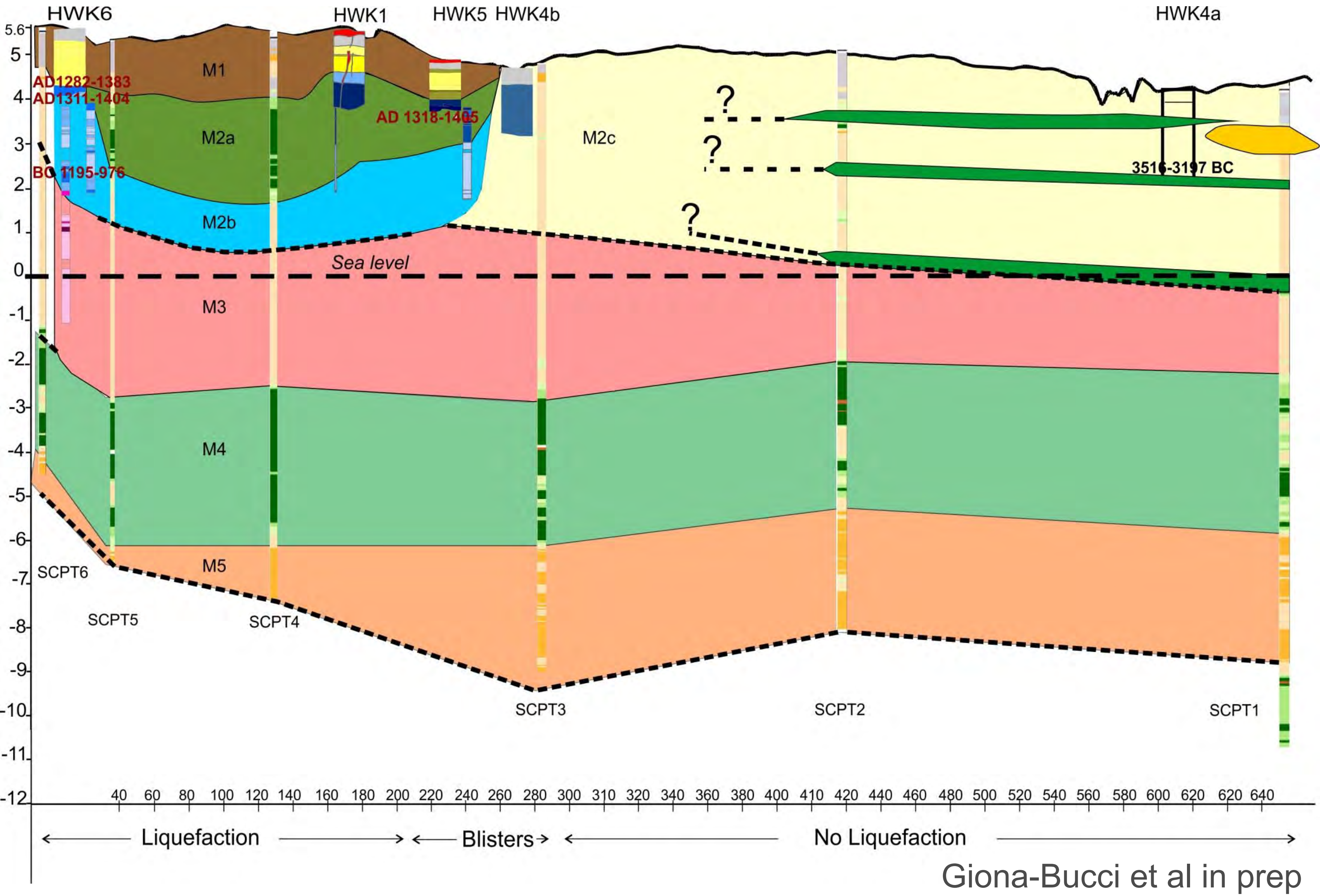




Understanding sediment architecture and its relation to the source sand



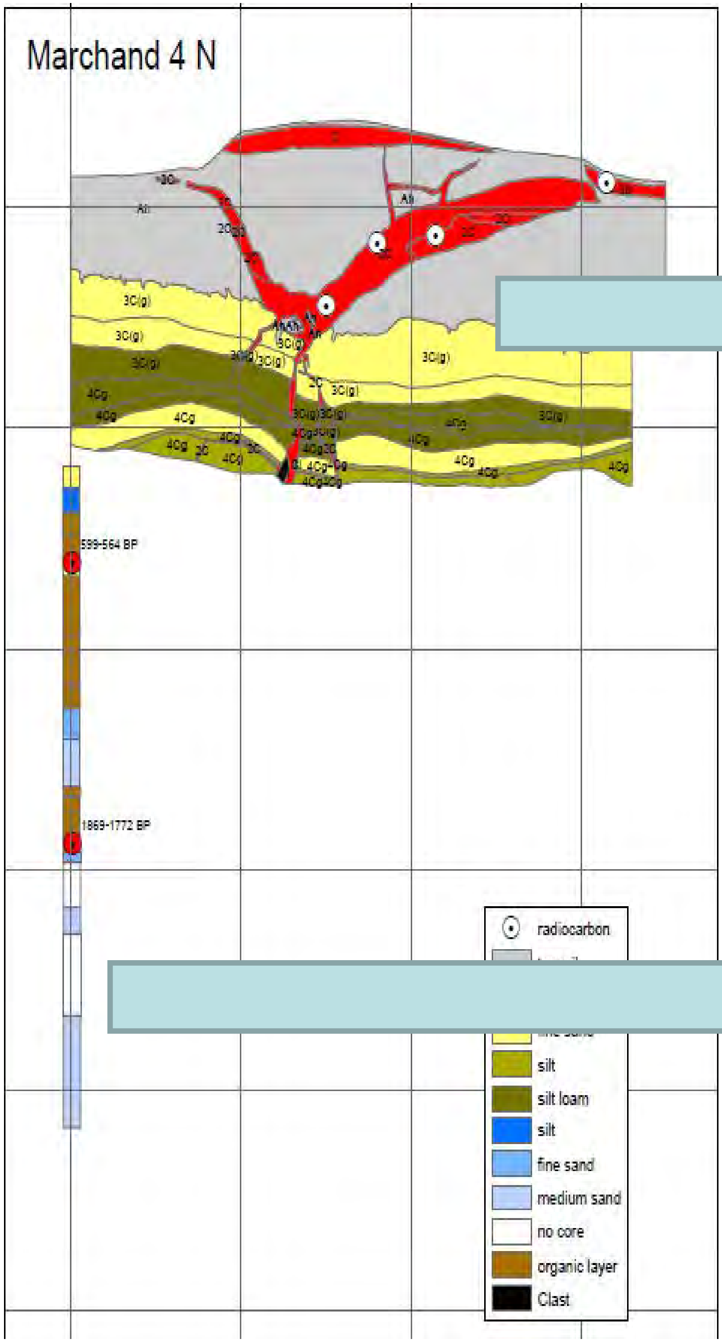
Giona-Bucci et al in prep

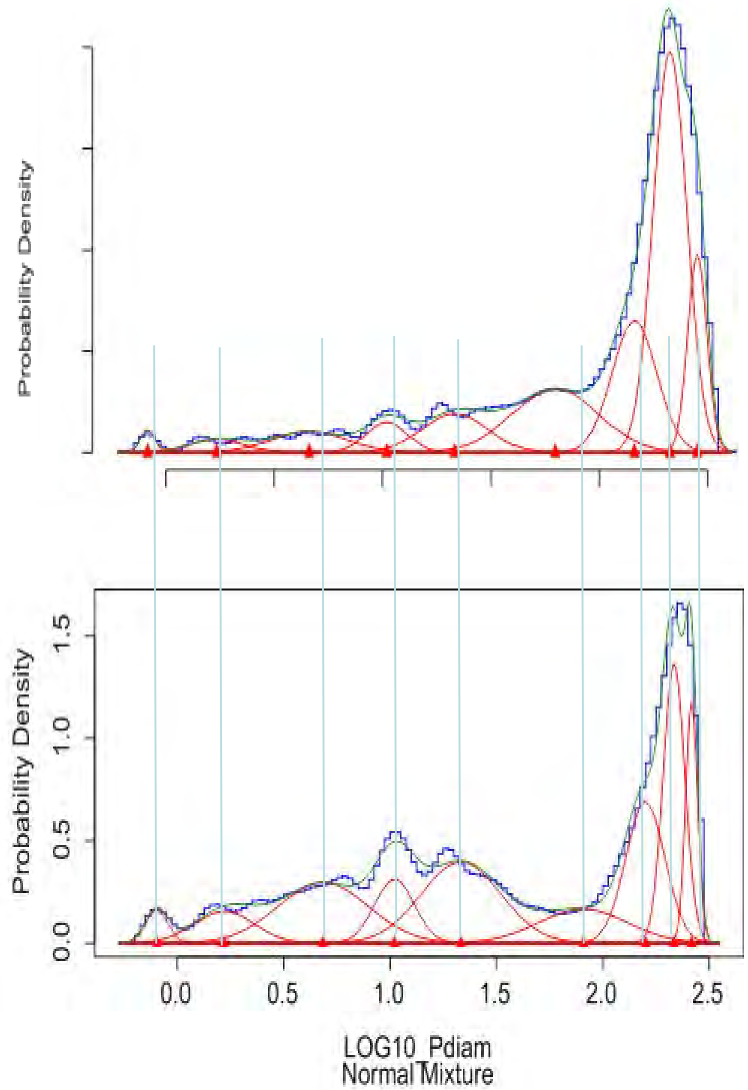


Giona-Bucci et al in prep

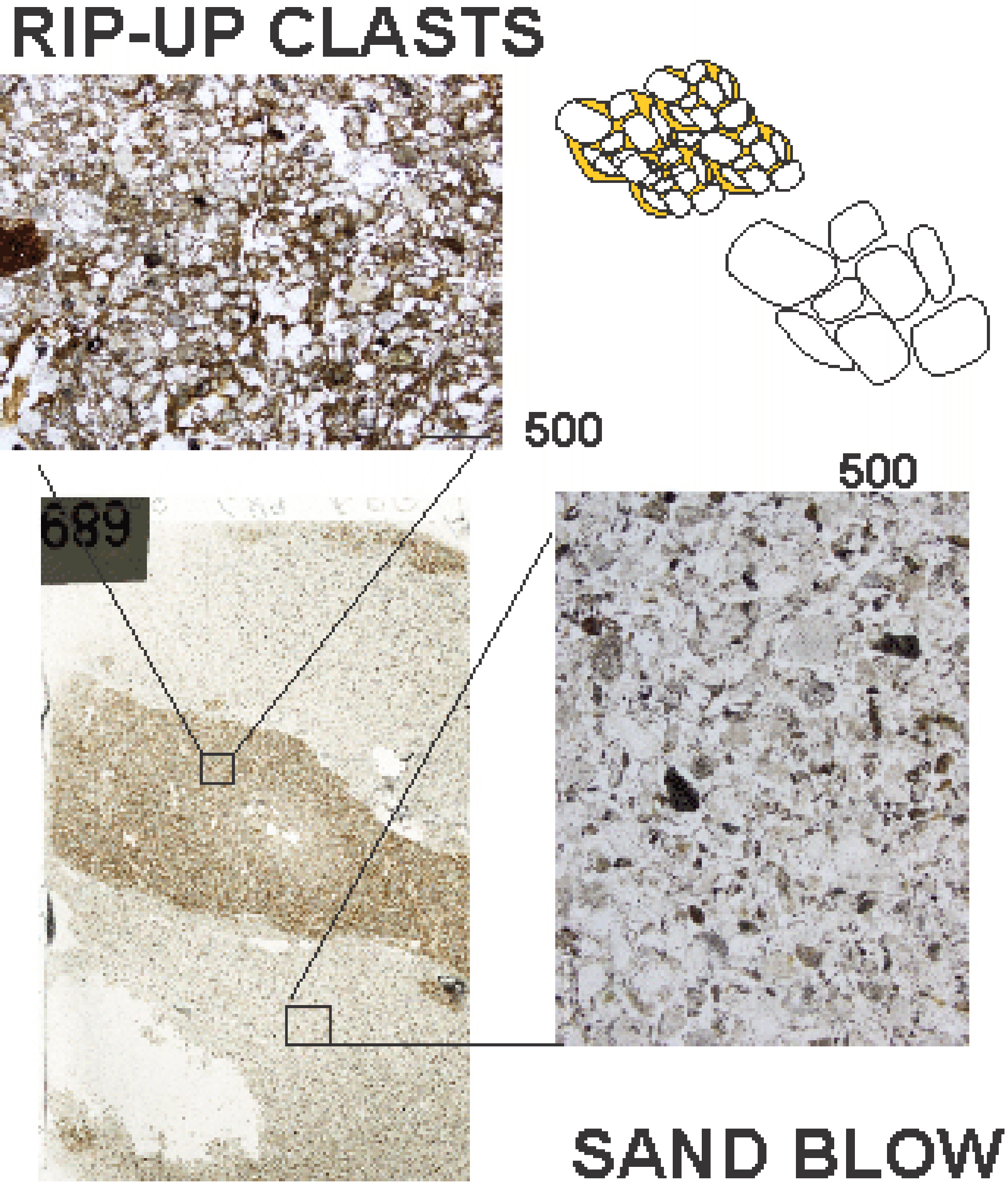
What is the source layer: Grain Size Analysis

Matching (polymodal) distributions





Giona-Bucci et al in prep

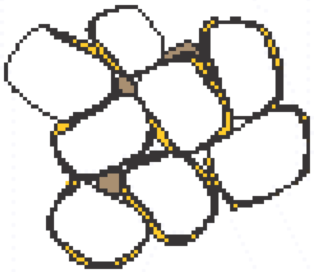


What is the source layer: Micromorph analysis

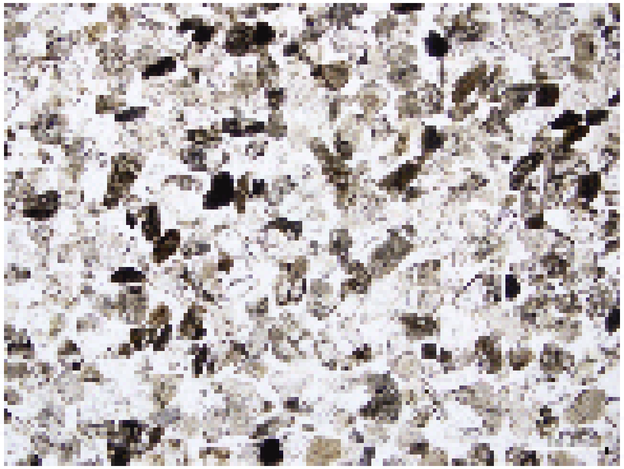
Sand blow: Single grain structure, simple packing voids, no micromass, no organic fragments, evidence of silt coating, grains look moderatly sorted

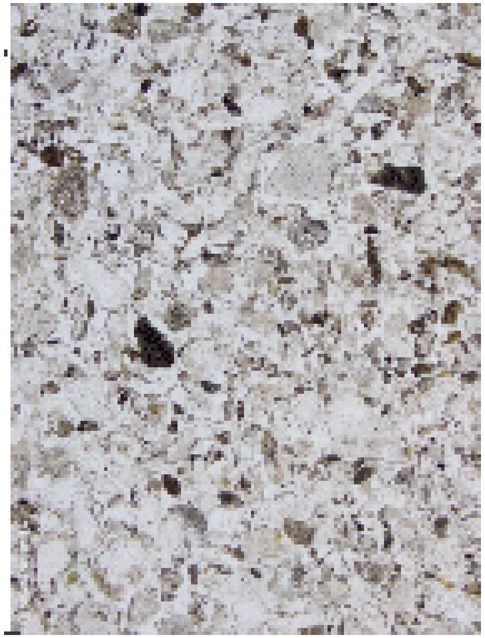
Rip up clasts come from buried A horizon, grains are finer than the liquefaction grains. Very packed grain structure, presence of micromass, organic pedofeatures and organic fragments, related distribution close porphyric.

PALEO-SAND BLOW



The paleodike is characterized by a intergrain microaggregate structure with common clay coatings and common presence of micromass.
presence of common organic pedofeatures and common organic fragments.





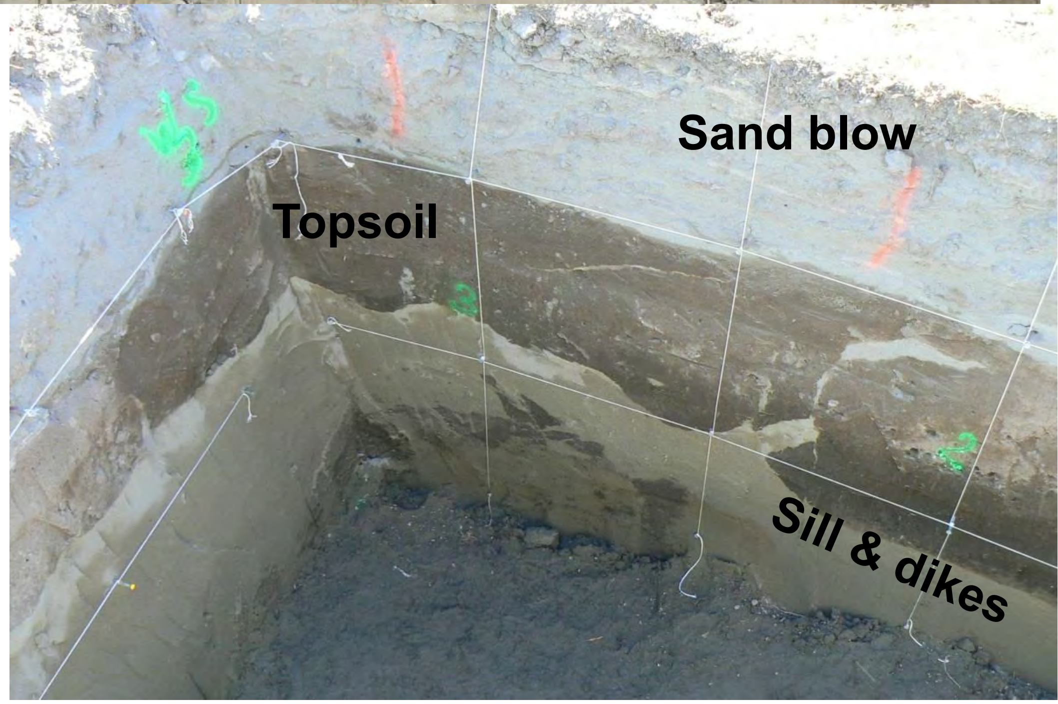
Modern Dike

Costal setting

DUNE SYSTEM (ongoing research)

- Sand blows different shape- not aligned along fissures
- Interdune depression is more susceptible to liquefaction
- Possible source layer: dune sand or river sand?

Coastal dunes:
Larger sand blows and dikes



Liquefaction and sedimentary environment

Preliminary findings, Alluvial vs Costal:

- Alluvial: sand blows aligned along geomorphic features (channel, leeves, point bars). Ejecta occurs along ridges (micro lateral spreading?). Smaller dikes and blows. Depths of sources ranging from 5 to ~ 1m and from variable sources: point bar, channel deposits. Strong control by variable water table.

- Coastal: random spatial distribution Ejecta associated with to low topography, or interdune, Why? Where and what is the source? – Work in progress.

Liquefaction during Canterbury Earthquakes informing susceptibility and paleoliquefaction

- Refined spatial distribution of ground failure

Understanding the liquefaction process in association with the different elements within each sedimentary environment

- Paleoliquefaction

Within each sedimentary environment, better understanding of what are we looking for (e.g. small vs large; ground deformation or not), where is it likely to be located (e.g. in alluvial - ridges of point bars), what are the methods that we need to investigate, good locaiton for dating potential.

THANKS!

ALSO THANKS TO:
Collaborators from GNS Science and Canterbury University
Provision of slides and talk preparation : K. Berryman, C.Massey, R.Van Dissen, S. Van Ballogey an many others
Land access: land owners (Hardwick and Marchand families, Christchurch City Council)
International flight sponsor: ISRN, France.

Recent Advances in Paleoliquefaction Back-Calculation Procedures

Russell A. Green and Brett Maurer

Outline

- Commonly used back-calculation procedures
  - Magnitude-bound curve procedure
  - Site-specific geotechnical analysis
- Newly proposed back-calculation procedures
  - Back-calculated regional probabilistic magnitude-bound curves
  - Updated site-specific geotechnical analysis

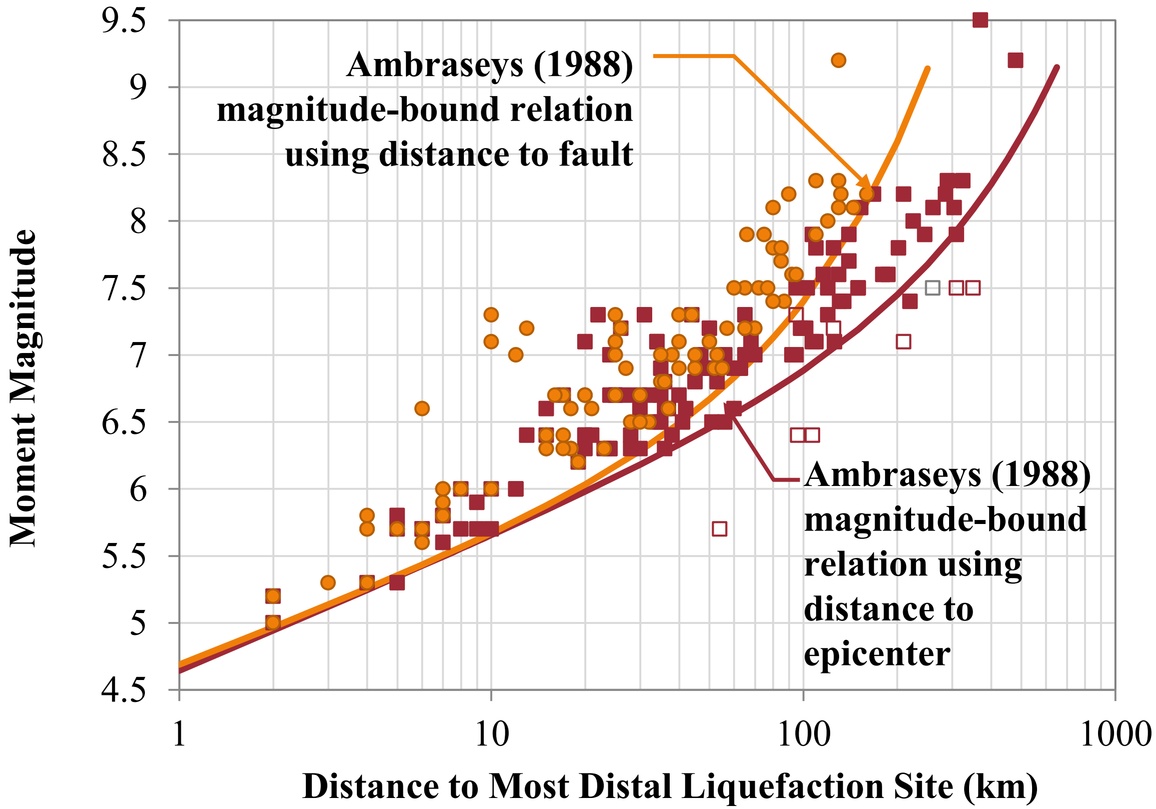
Commonly Used Back-Calculations Procedures

- Magnitude-Bound Curves
  - Most commonly procedure used (simple to use; does not require detailed geotechnical characterization of paleoliquefaction sites)
  - Provides lower-bound estimate of paleo-magnitude
- Site-Specific Geotechnical Analysis
  - Requires detailed geotechnical characterization of paleoliquefaction sites
  - Provides best estimate of paleo-magnitude

Magnitude Bound Curve Procedure

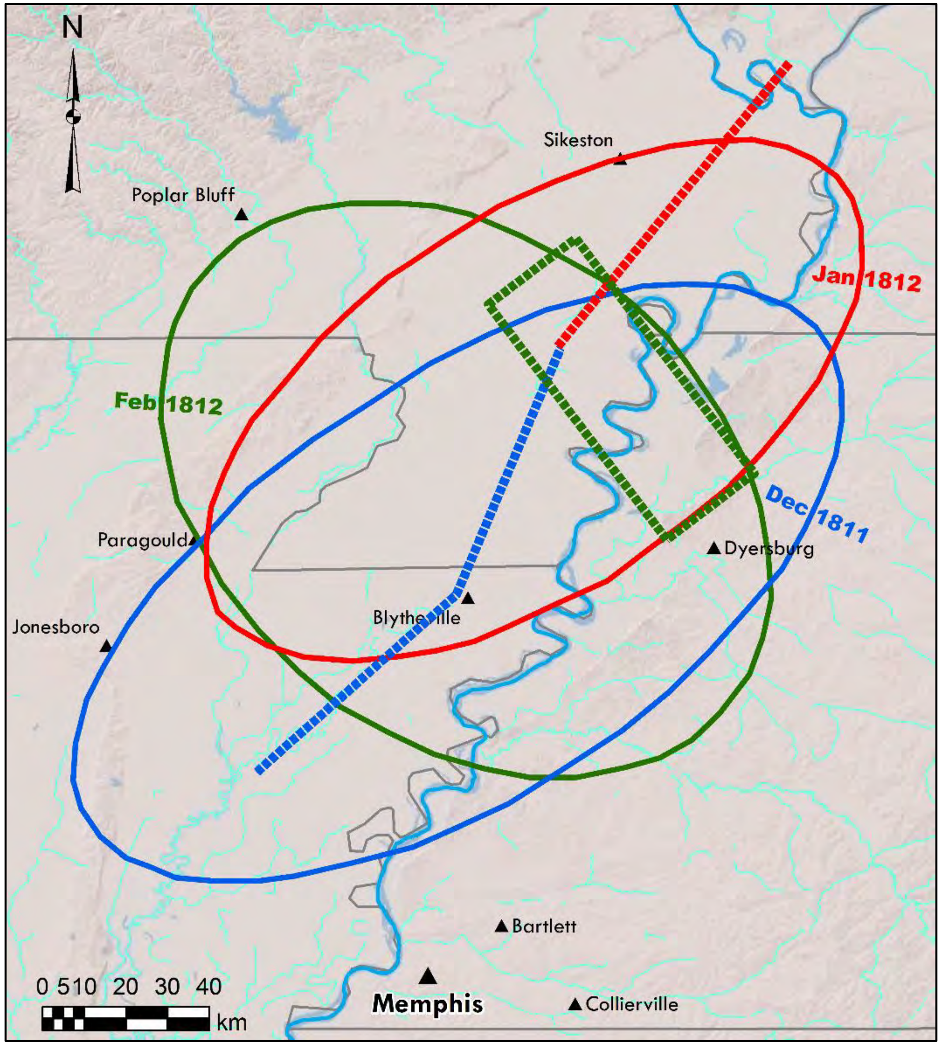
Magnitude Bound Curves

Worldwide Data

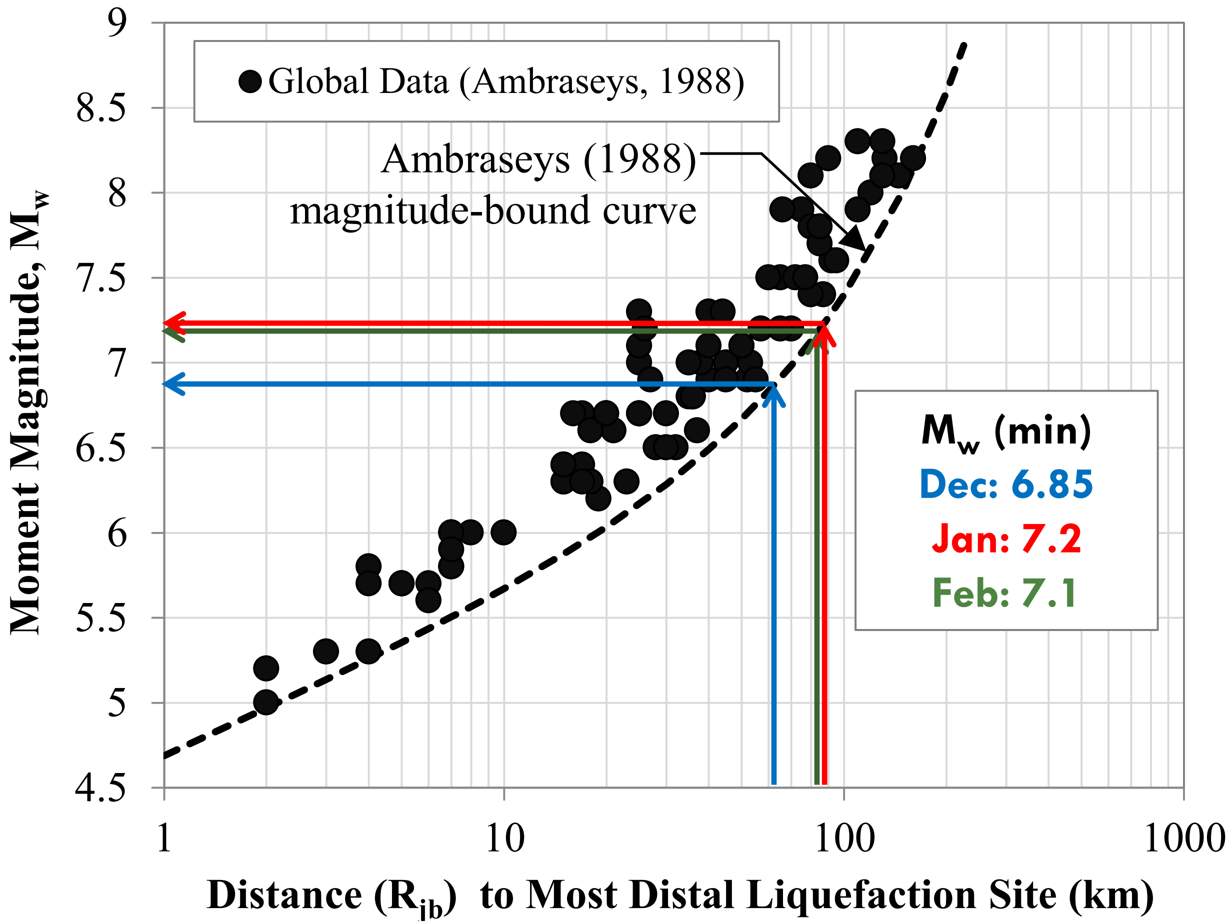


- Epicentral distance to most distal liquefaction feature for shallow/moderate depth earthquakes (focal depth < 50 km)
- Epicentral distance to most distal liqeufaction feature for moderate/deep earthquakes
- Distance from fault to most distal liqeufaction feature for all depth earthquakes

Magnitude Bound Curve Procedure



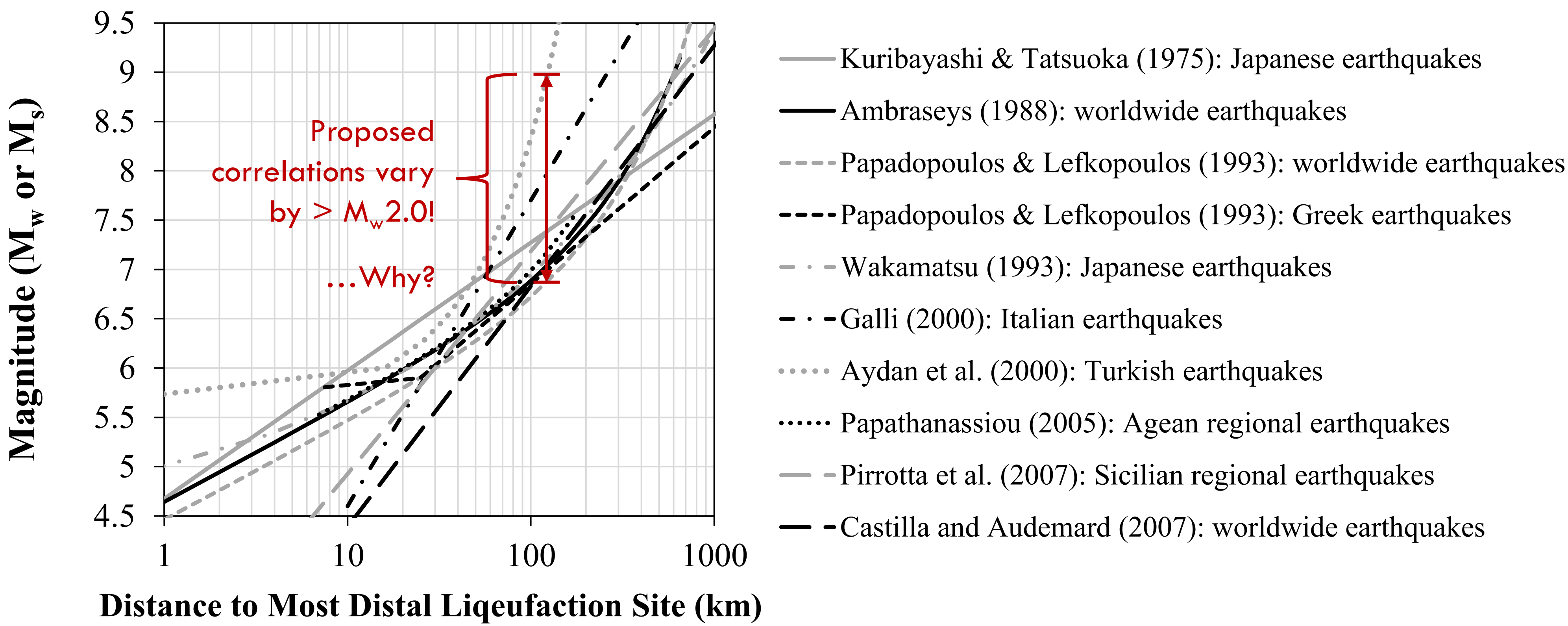
CEUS-SSC (2012) Preferred Rupture Scenario



(Based on Tuttle 2001 and Tuttle et al. 2002)

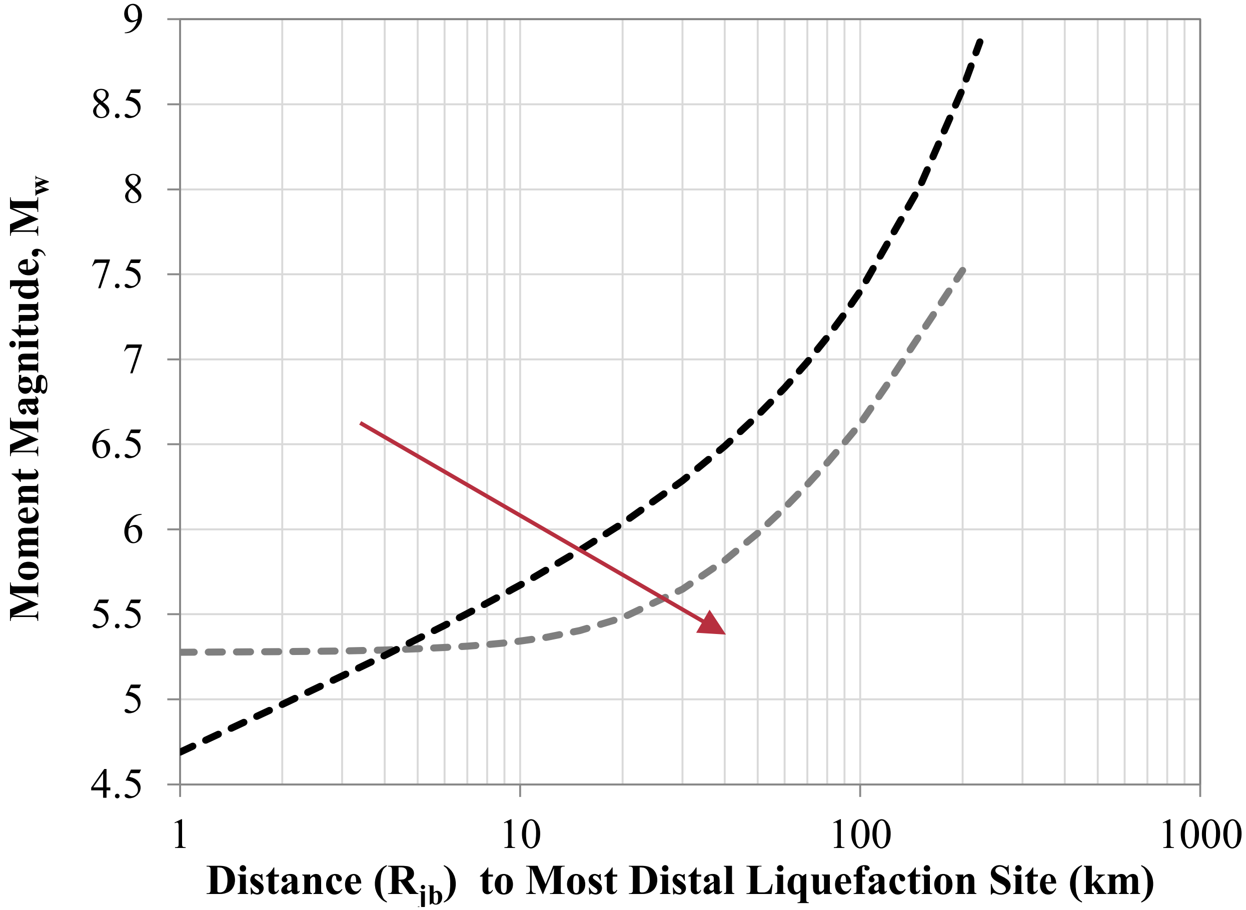
Limitations of Magnitude Bound Curve Procedure

Magnitude bound curves proposed in literature



(Olson et al. 2005a)

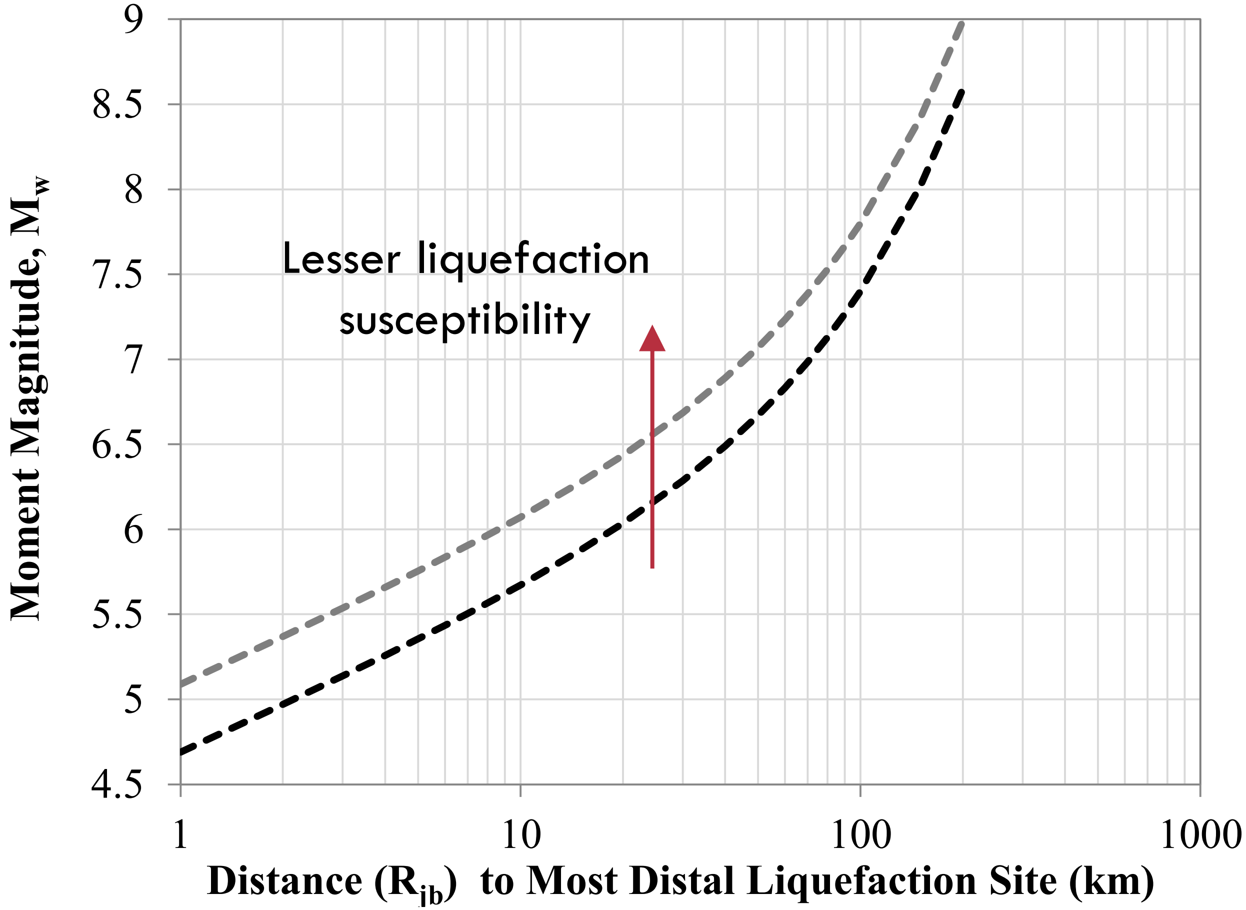
Limitations of Magnitude Bound Curve Procedure



The curve shape is a function of energy attenuation & site response

(Olson et al. 2005b)

Limitations of Magnitude Bound Curve Procedure

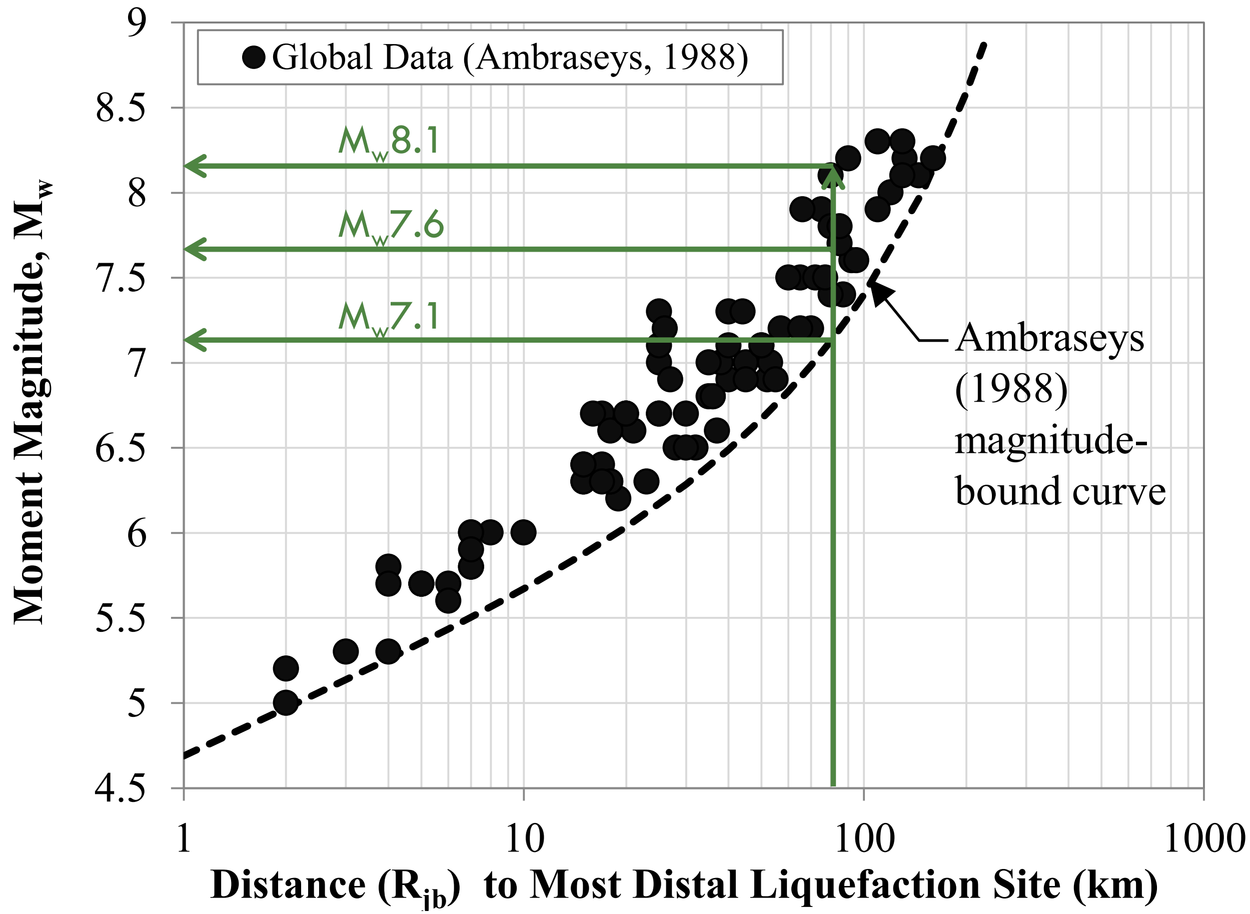


The curve position is a function of liquefaction susceptibility

(Olson et al. 2005b)

Limitations of Magnitude Bound Curve Procedure

Magnitude of paleo-earthquake???

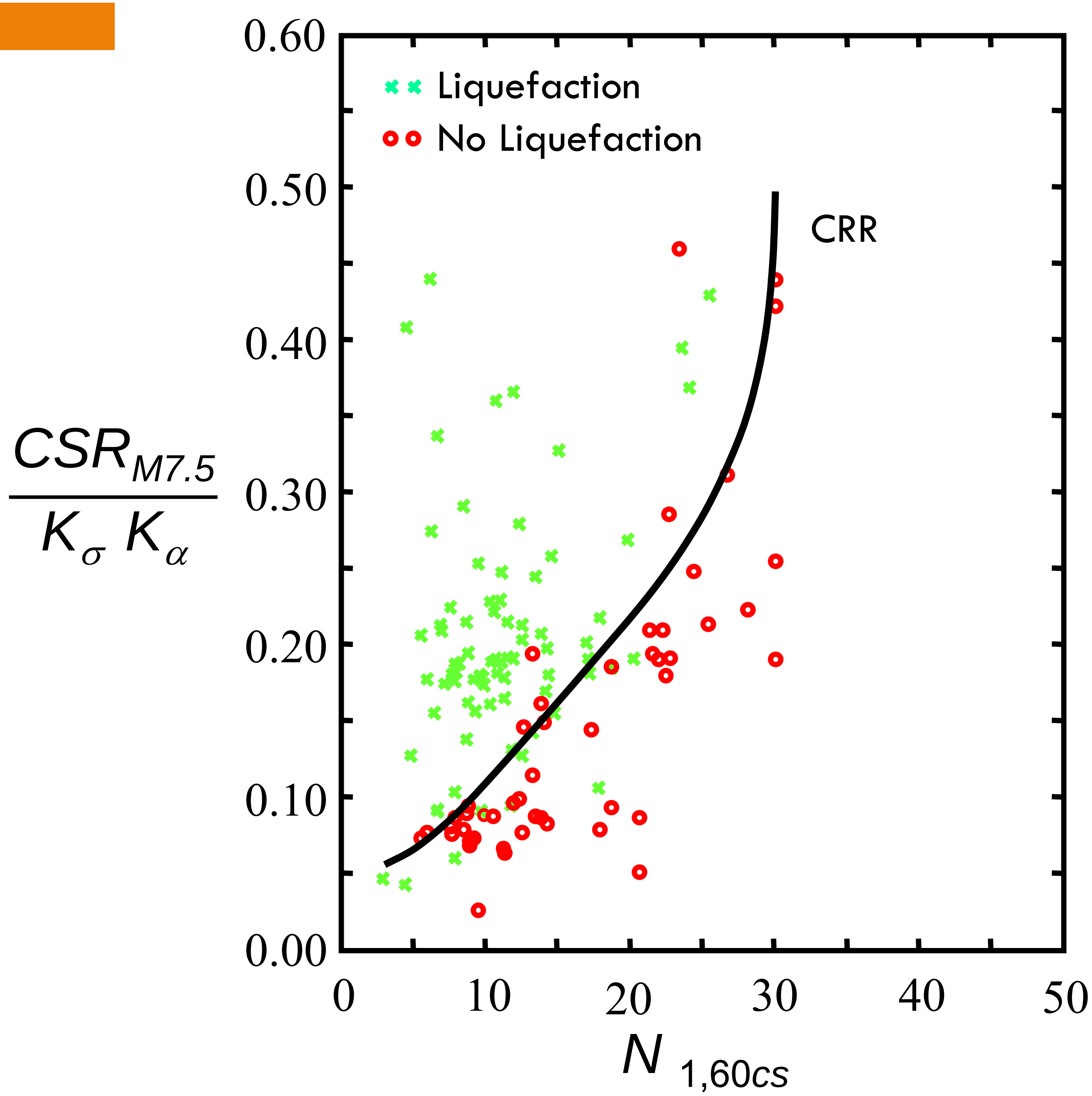


Site-Specific Geotechnical Analysis

Site-Specific Geotechnical Analysis

- Simplified Chart developed using post-earthquake field observations

Level Ground & σ'_{vo} = 1 atm



Site-Specific Geotechnical Analysis

- Seismic Demand: Normalized CSR

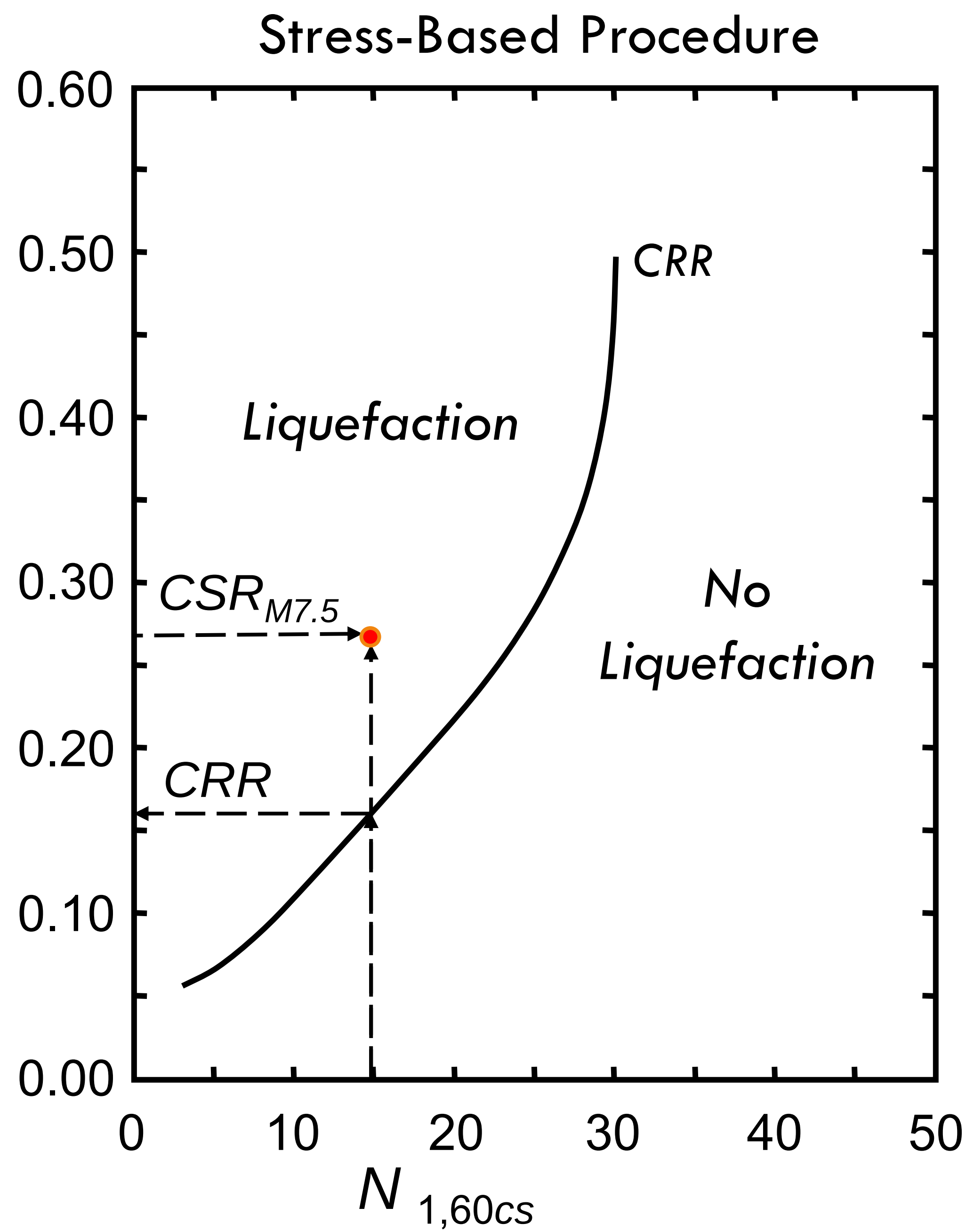
$$CSR_{M7.5} = 0.65 \frac{a_{max}}{g} \frac{\sigma_v}{\sigma'_{vo}} r_d \frac{1}{MSF}$$

Site-Specific Geotechnical Analysis

Factor of Safety Against Liquefaction:

$$FS = \frac{CRR}{CSR_{M7.5}}$$

$$\frac{CSR_{M7.5}}{K_{\sigma}\, K_{\alpha}}$$



Site-Specific Geotechnical Analysis

Steps: Site-Specific Geotechnical Analysis:

I. The "critical" strata within the profile is assumed to have a factor of safety against liquefaction of 1.0:

$$FS_{liq} = \frac{CRR}{CSR_{M7.5}} = 1.0 \quad (1)$$

II. Substituting for CRR and $CSR_{M=7.5}$, the minimum a_{max} to induce liquefaction (for level ground: $K_{\alpha} = 1$) is expressed as :

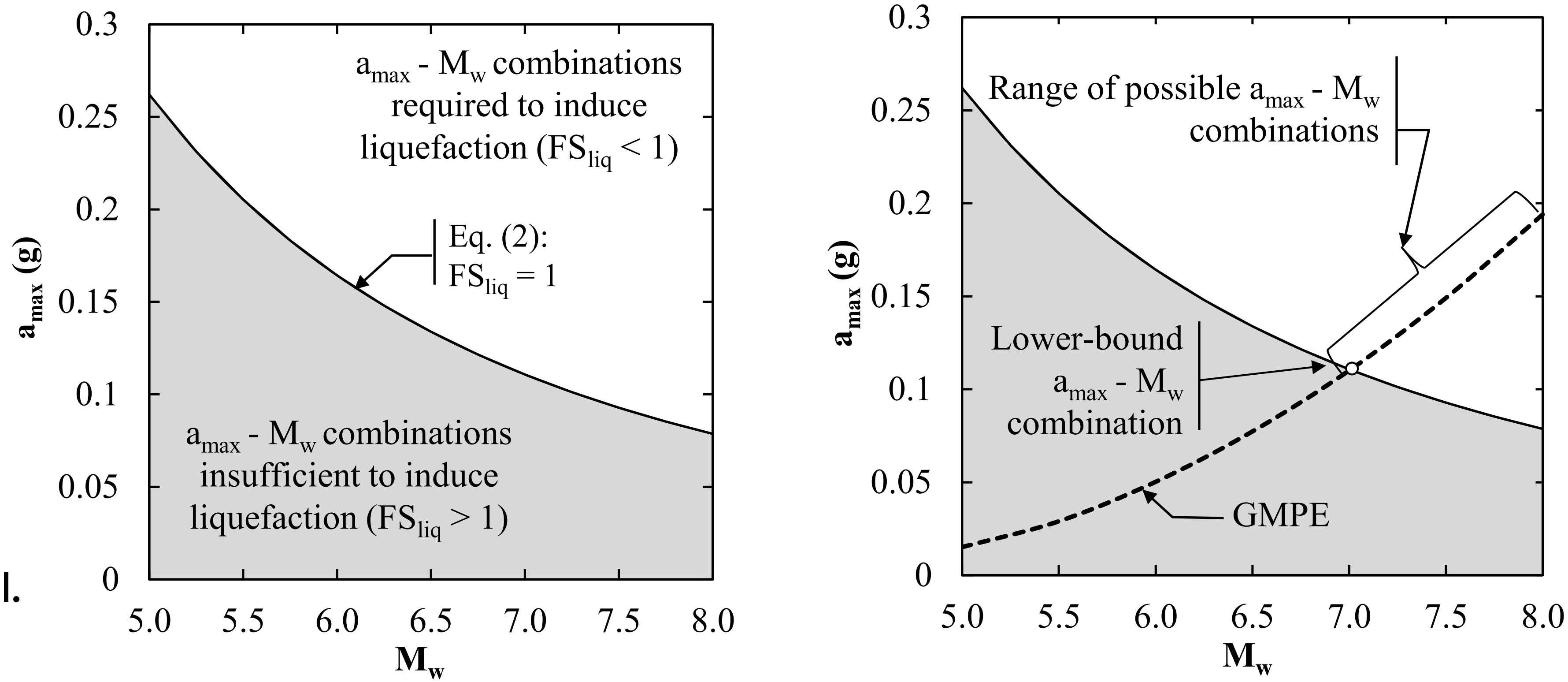
$$a_{max} = CRR(N_{1,60cs})MSF(M_w)K_{\sigma}\frac{g\sigma'_{vo}}{0.65\sigma_v r_d} \quad (2)$$

(Green et al. 2005)

Site-Specific Geotechnical Analysis

III. The boundary given by Eq. (2) identifies combinations of a_{max} – M_w sufficient to trigger liquefaction.

IV. A ground motion prediction equation (GMPE) is used to define credible a_{max}–M_w combinations for a given site-to-source distance



(Green et al. 2005)

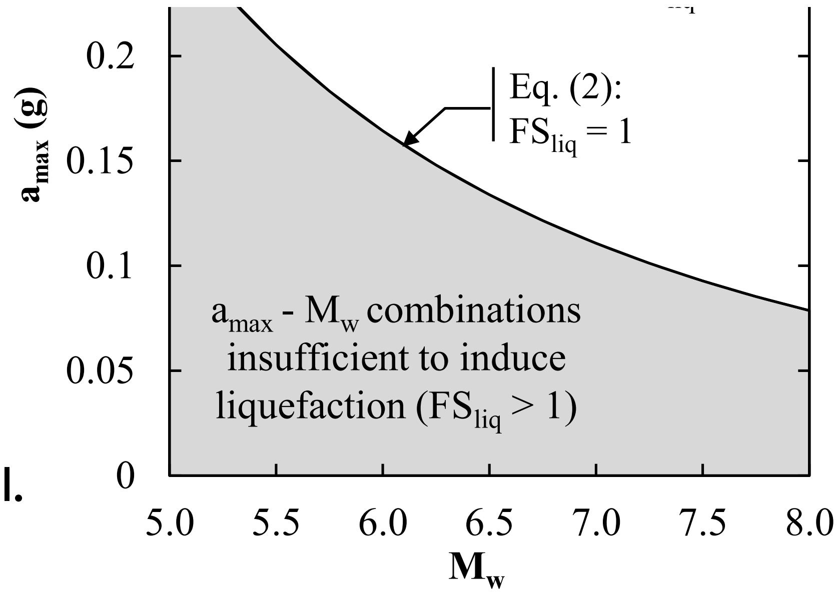
Determination of lower-bound a_{max} – M_w combination for paleoliquefaction investigation site

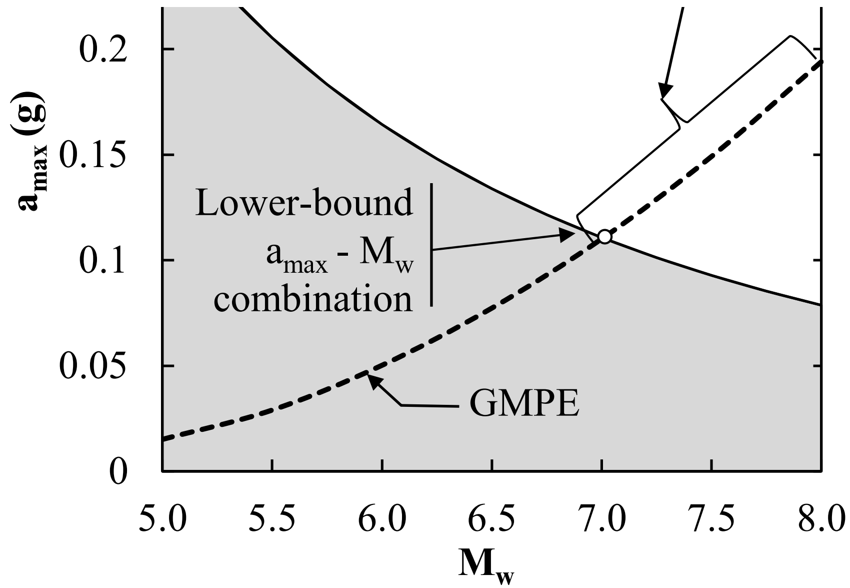
Site-Specific Geotechnical Analysis

III. The boundary given by Eq. (2) identifies combinations of a_{max} – M_w sufficient to trigger liquefaction.

IV. A ground motion prediction equation (GMPE) is used to define

Requires a priori knowledge of the source location





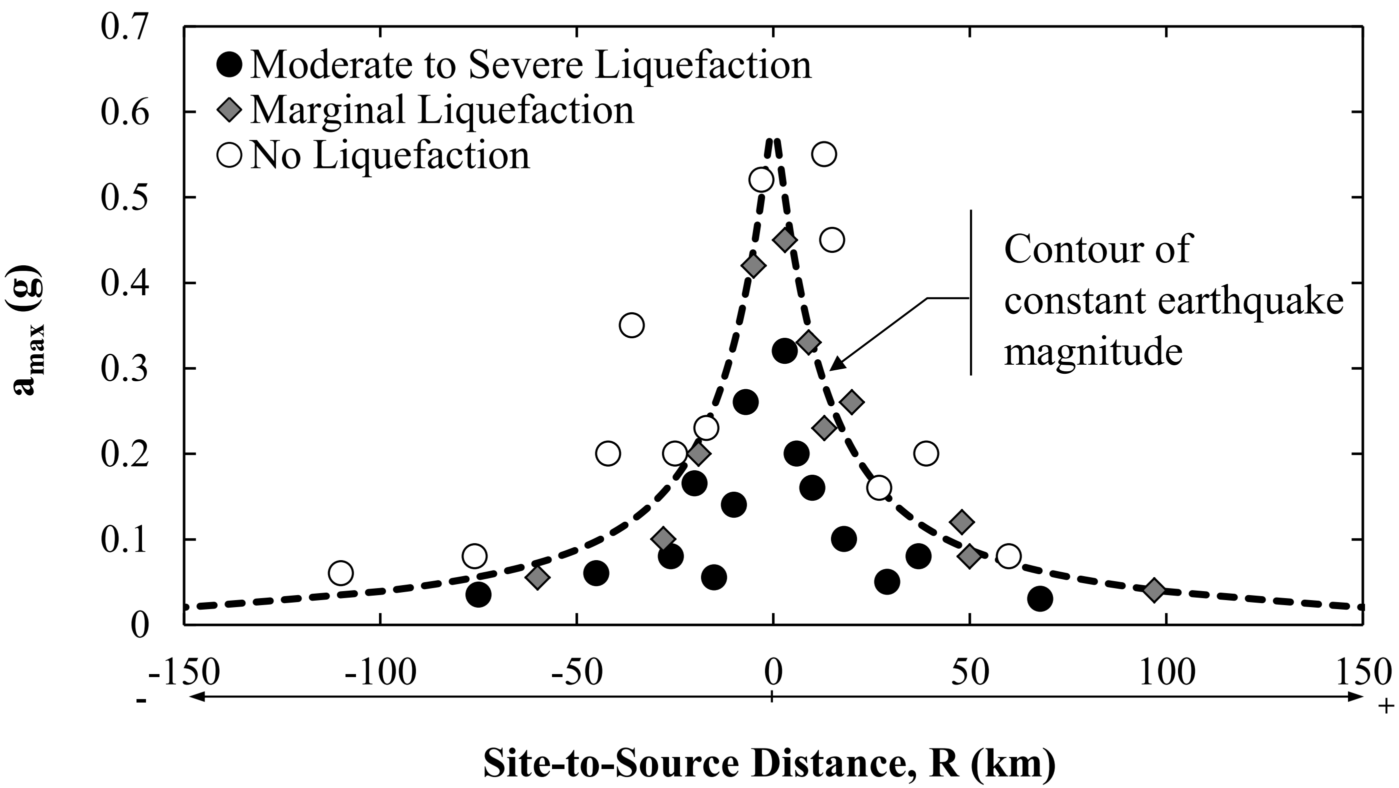
(Green et al. 2005)

Determination of lower-bound a_{max} – M_w combination for paleoliquefaction investigation site

Site-Specific Geotechnical Analysis

V. To obtain a best-estimate of the causative earthquake M_w, individual back-analyses are incorporated from many sites.

VI. Causative M_w is that which best segregates liquefaction data from non-liquefaction data



Regional assessment of back-calculated data

(Green et al. 2005)

Newly Proposed Back-Calculations Procedures

- Back-calculated probabilistic magnitude-bound curves
  - Region-specific magnitude-bound curves
  - Probabilistic estimates of paleo-magnitudes
- Updated Site-Specific Geotechnical Analysis
  - Provides both source locations and paleo-magnitudes

Back-Calculated Probabilistic Magnitude Bound Curves

Back-Calculated Probabilistic Magnitude Bound Curves

- Back-calculates magnitude-bound curves using liquefaction triggering mechanics in conjunction with ground motion prediction equations.
- Using the total probability theorem to integrate over uncertainties, the probability that a site liquefies in an earthquake of magnitude (M) at site-to-source distance (R) is:

Using Stress-based liquefaction triggering mechanics:

$$P(\tau \geq \tau_t | EQK{:}\, M, R) = \int_{a_{max}} \int_{r_d} P(\tau \geq \tau_t | a_{max}, r_d)\, f(a_{max}|M, R)\, f_{r_d}(r_d) \cdot dr_d \cdot da_{max}$$

Using Strain-based liquefaction triggering mechanics:

$$P(\gamma \geq \gamma_t | EQK{:}\, M, R) = \int_{a_{max}} \int_{r_d} \int_{\frac{G}{G_{max}}} P\left(\gamma \geq \gamma_t \middle| a_{max}, r_d, \frac{G}{G_{max}}\right) f(a_{max}|M, R)\, f_{r_d}(r_d)\, f_{\frac{G}{G_{max}}}\left(\frac{G}{G_{max}}\right) d\frac{G}{G_{max}} \cdot dr_d \cdot da_{max}$$

(Maurer et al. 2015b)

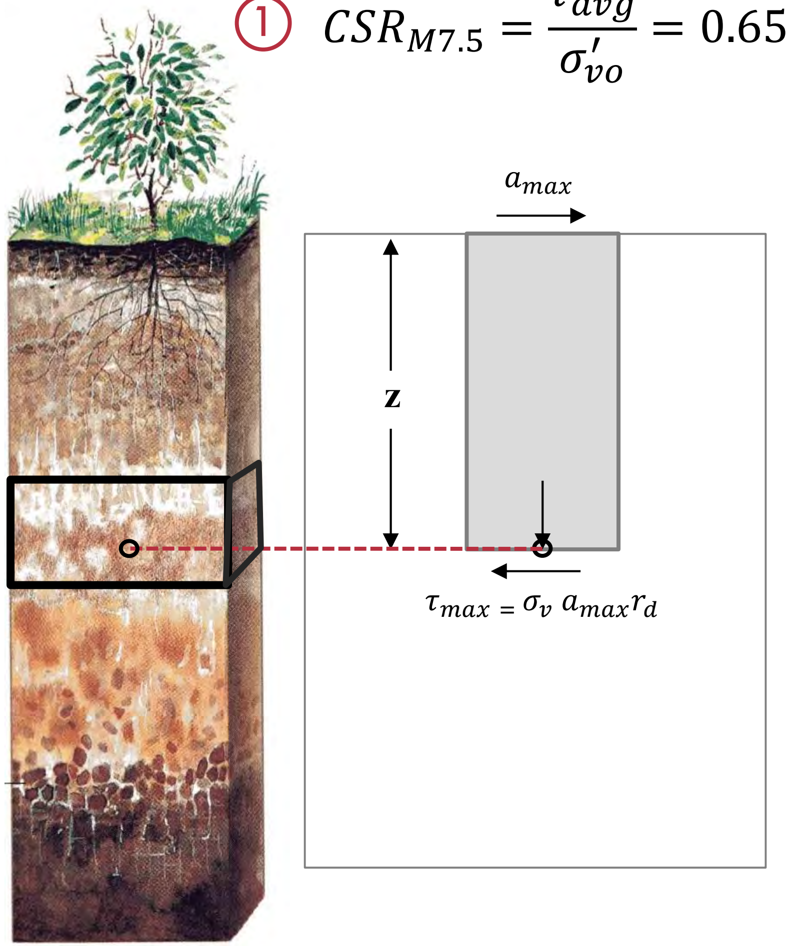
Back-Calculated Probabilistic Magnitude Bound Curves

Using Stress-based liquefaction triggering mechanics:

$$P(\tau \geq \tau_t | EQK: M, R) = \int_{a_{max}} \int_{r_d} P(\tau \geq \tau_t | a_{max}, r_d)\, f(a_{max}|M, R)\, f_{r_d}(r_d) \cdot dr_d \cdot da_{max}$$

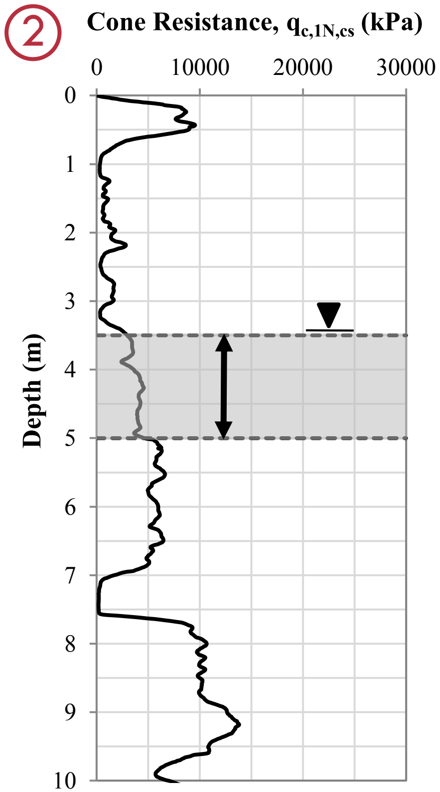
① $$CSR_{M7.5} = \frac{\tau_{avg}}{\sigma'_{vo}} = 0.65 \frac{\tau_{max}}{\sigma'_{vo}} = 0.65\ \frac{a_{max}}{g} \frac{\sigma_v}{\sigma'_{vo}} r_d \frac{1}{MSF}$$

Normalized Cyclic Stress Ratio (CSR) induced in soil stratum



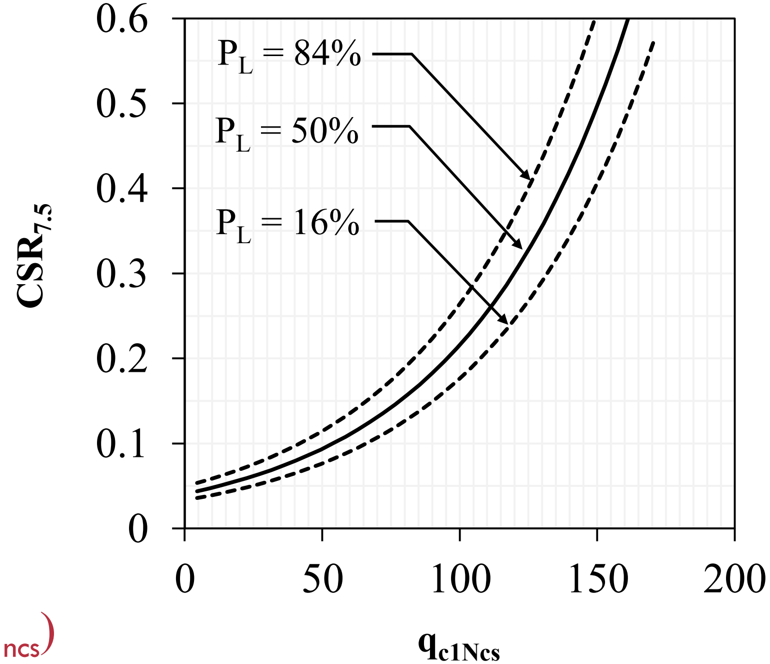
(Maurer et al. 2015b)

②



Cyclic Resistance Ratio (CRR) = $f\,(q_{c1ncs})$

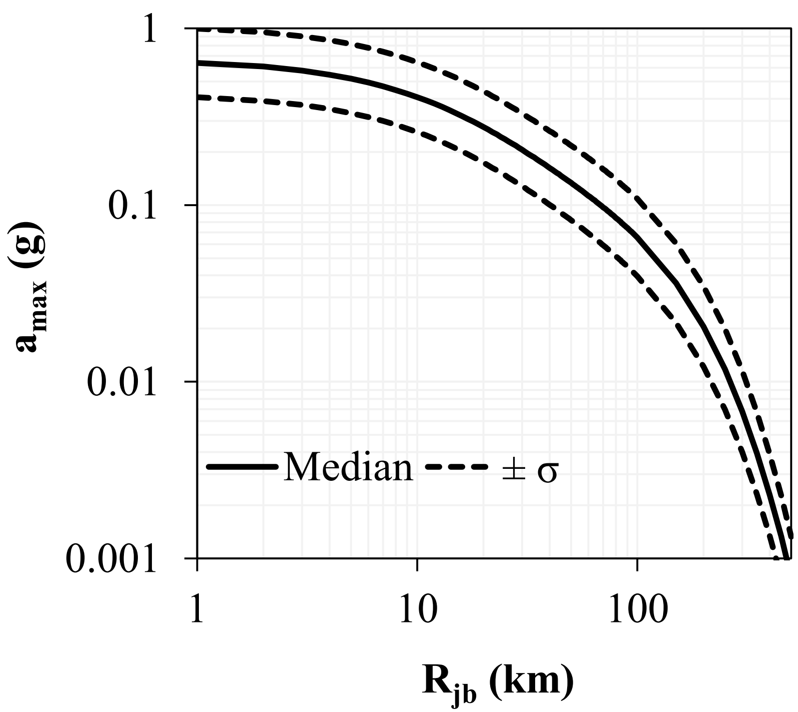
③ Every combination of CSR and CRR has a probability of liquefaction associated with it

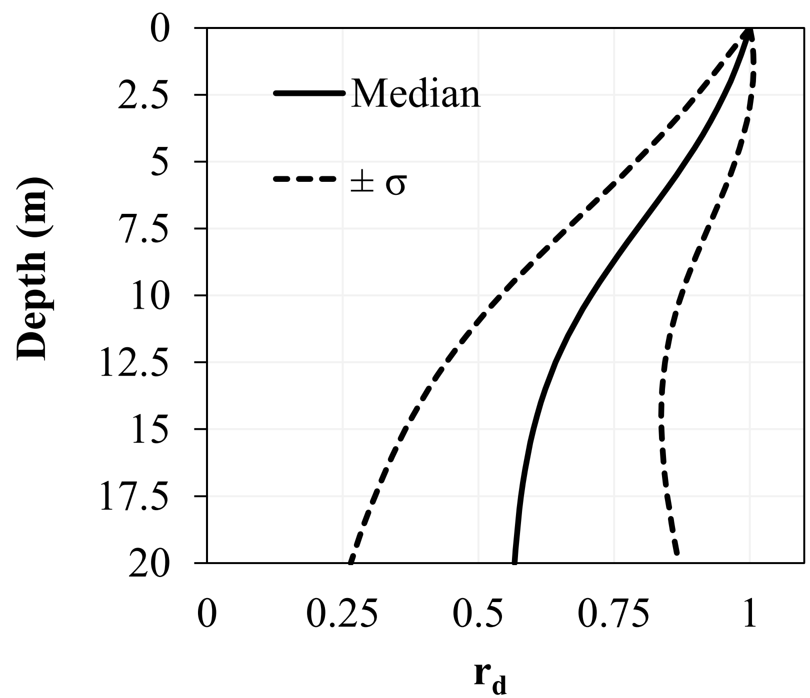


Back-Calculated Probabilistic Magnitude Bound Curves

Using Stress-based liquefaction triggering mechanics:

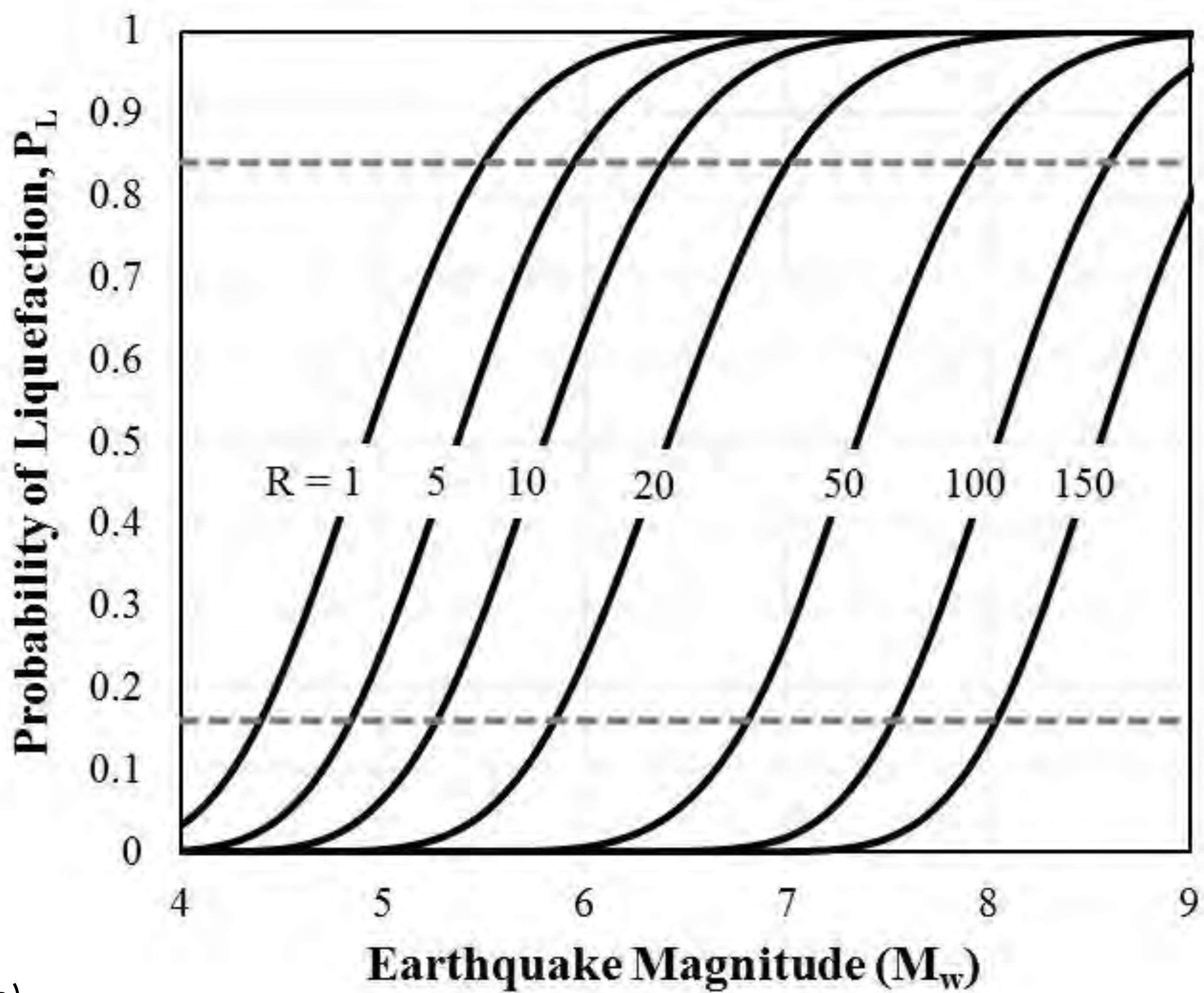
$$P(\tau \geq \tau_t | EQK{:}\, M, R) = \int_{a_{max}} \int_{r_d} P(\tau \geq \tau_t | a_{max}, r_d)\, f(a_{max}|M,R)\, f_{r_d}(r_d) \cdot dr_d \cdot da_{max}$$





(Maurer et al. 2015b)

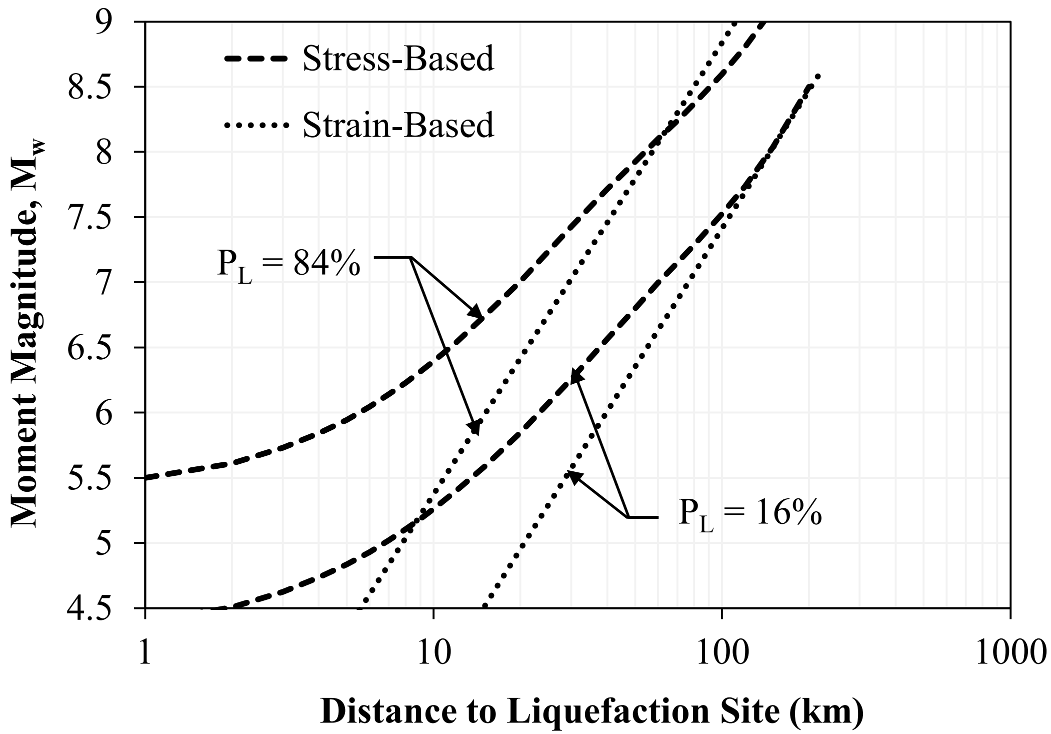
Back-Calculated Probabilistic Magnitude Bound Curves

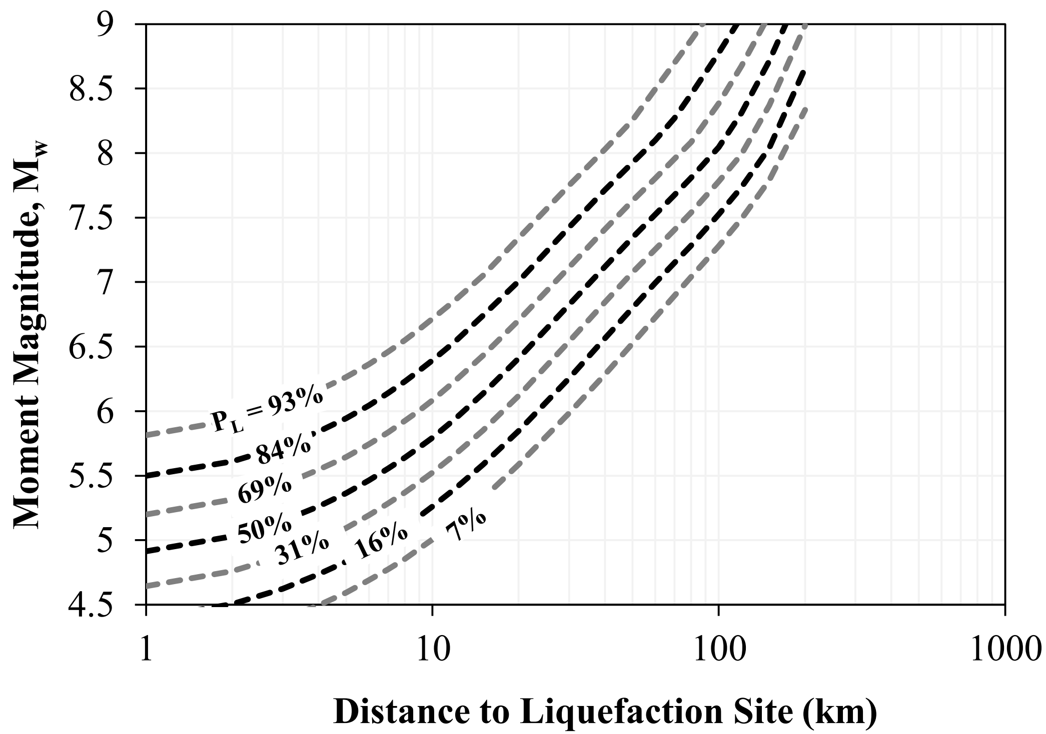


(Maurer et al. 2015b)

Back-Calculated Probabilistic Magnitude Bound Curves

Combining results from the stress-based and strain-based frameworks…

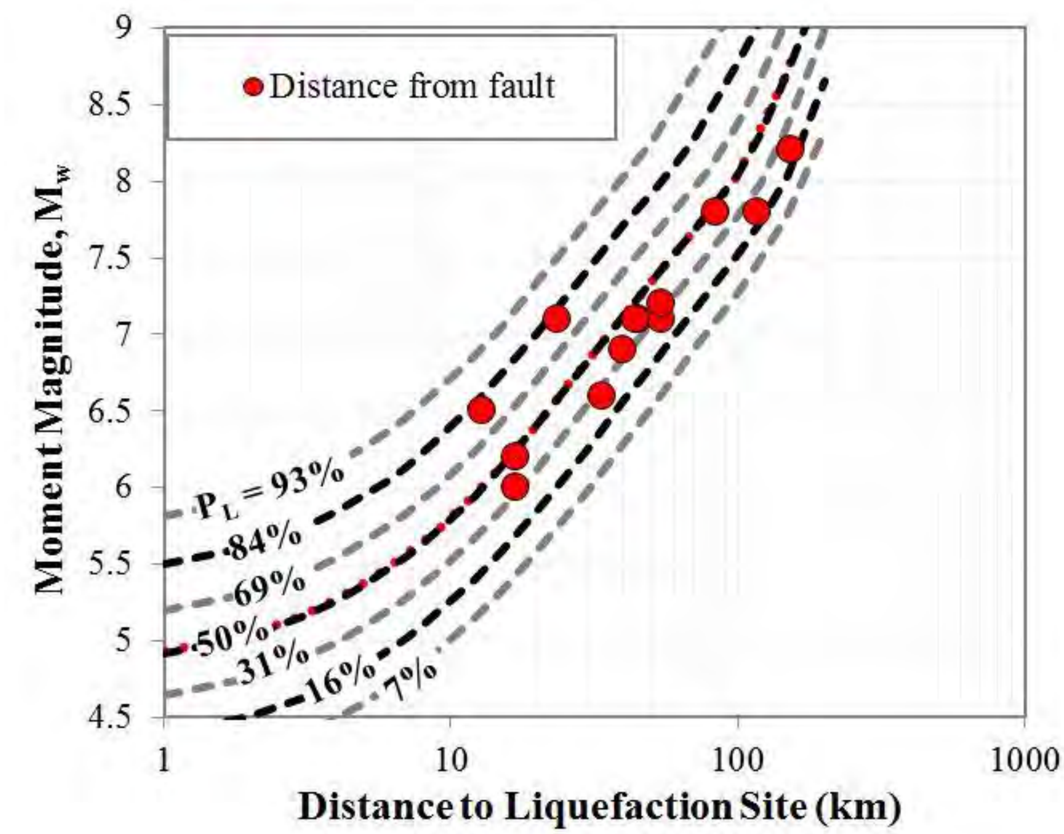


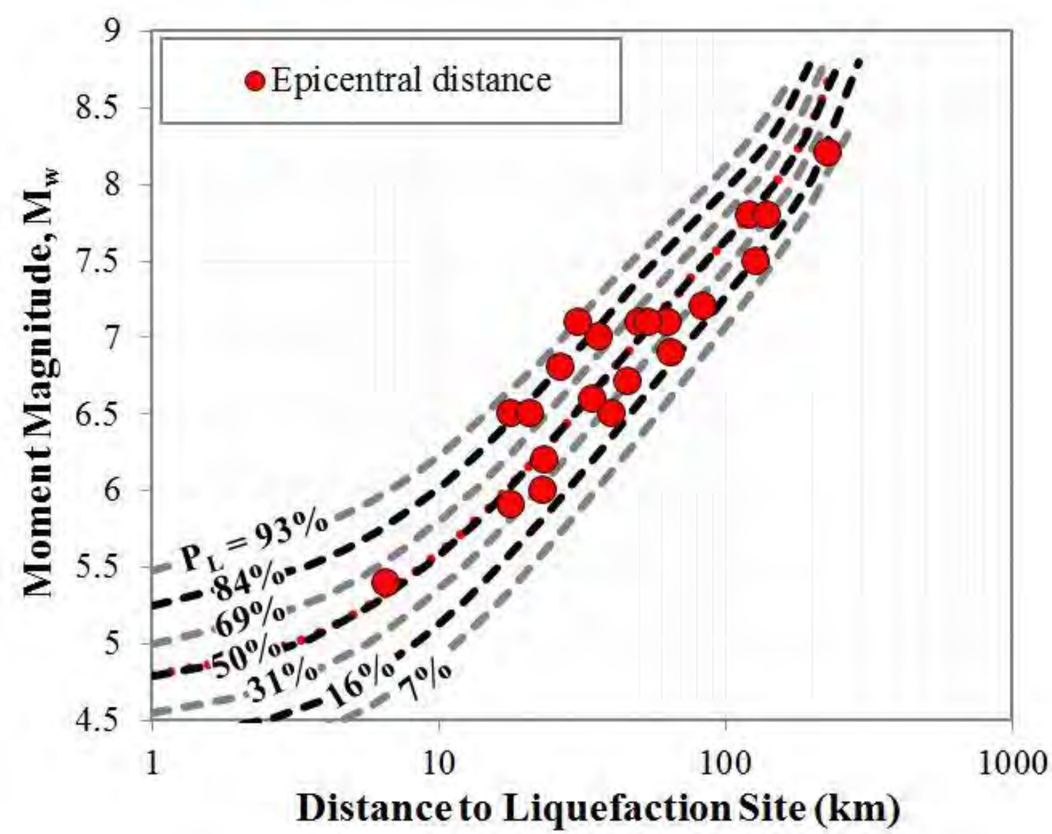


(Maurer et al. 2015b)

Back-Calculated Probabilistic Magnitude Bound Curves

Curves developed for shallow crustal earthquakes in New Zealand: Comparison with historical data from New Zealand

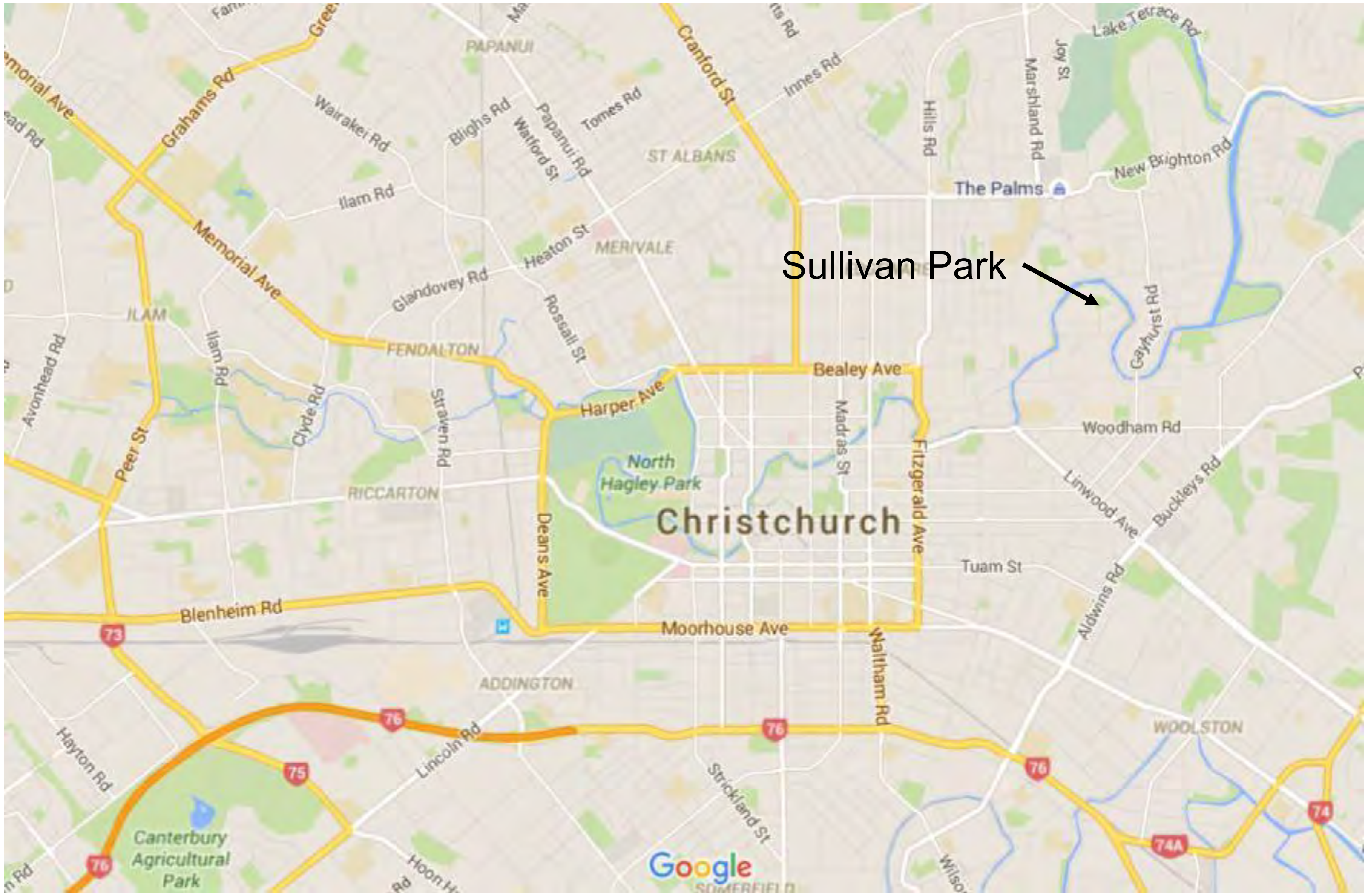




(Maurer et al. 2015b)

Back-Calculated Probabilistic Magnitude Bound Curves

Example application: Sullivan Park



Back-Calculated Probabilistic Magnitude Bound Curves

Example application: Sullivan Park

Age of paleoliquefaction feature: AD 1660 – 1803 and ca. 1905 (Bastin et al., 2015).

Back-Calculated Probabilistic Magnitude Bound Curves

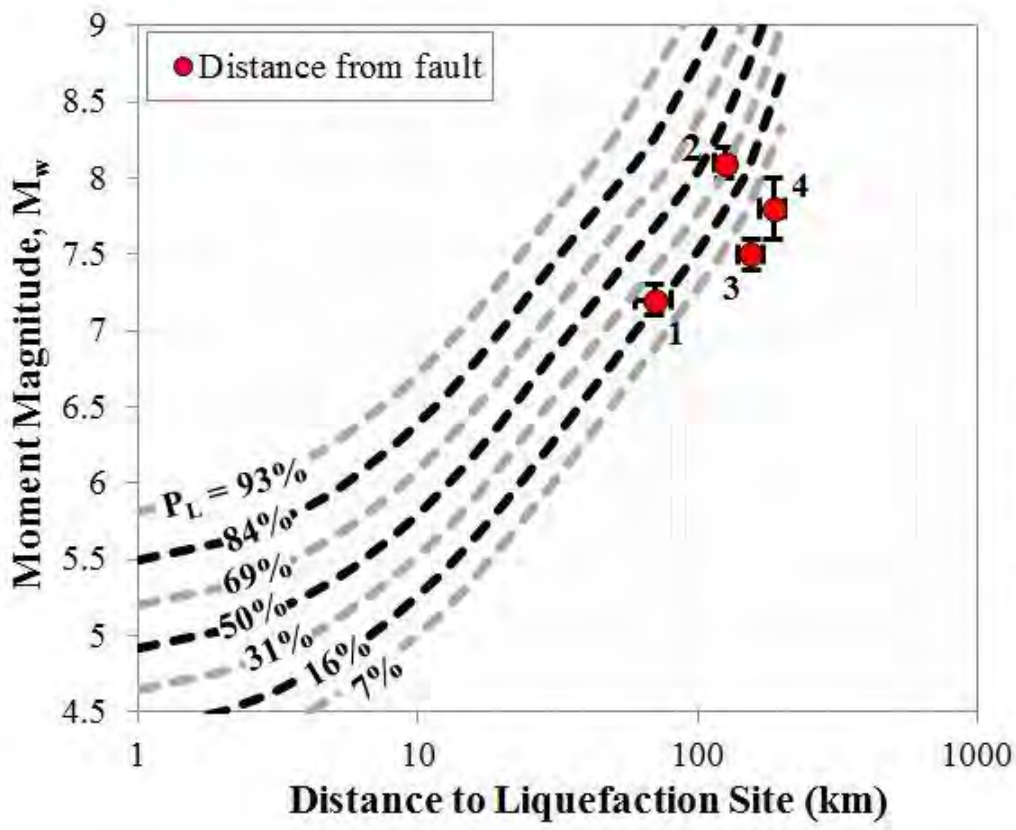
Year	Earthquake	Estimated M_w	Plotted M_w	Estimated R_{epi} (km)[a]	Plotted R_{epi} (km)	Estimated R_{jb} (km)[b]	Plotted R_{jb} (km)	Reference
1400-1500	Porter's Pass[1]	7.1 - 7.3	7.2	-	-	60 - 80	70	Howard et al. (2005)
1717	Alpine Fault[2]	8.0 - 8.2	8.1	-	-	115 - 135	125	Sutherland et al. (2007)
1848	Marlborough[3]	7.4 - 7.6	7.5	-	-	140 - 170	155	Mason & Little (2006)
1929	Murchison[4]	7.6 - 8.0	7.8	-	-	166 - 206	186	Carr & Berrill (2004)
1855	Wairarapa[5]	8.0 - 8.3	8.2	311 - 351	331	-	-	GeoNet (2014)
1869	Christchurch[6]	4.7 - 4.9	4.8	1.7 - 11.7	6.7	-	-	Downes & Yetton (2012)
1870	L. Ellesmere[7]	5.6 - 5.8	5.7	19.4 - 54.4	34.4	-	-	Downes & Yetton (2012)
1888	N. Canterbury[8]	7.0 - 7.3	7.1	82 - 122	102	-	-	Doser & Robinson (2002)
1901	Cheviot[9]	6.8 - 7.0	6.9	62 - 90	75	-	-	Berrill et al. (1994)
1913	Westport[10]	6.65 - 6.95	6.8	185 - 235	215	-	-	Fairless & Berrill (1984)
1922	Motunau[11]	6.4 - 6.6	6.5	53 - 83	63	-	-	Doser & Robinson (2002)
1929	Arthur's Pass[12]	6.9 - 7.1	7.0	81 - 126	101	-	-	Doser & Robinson (2002)

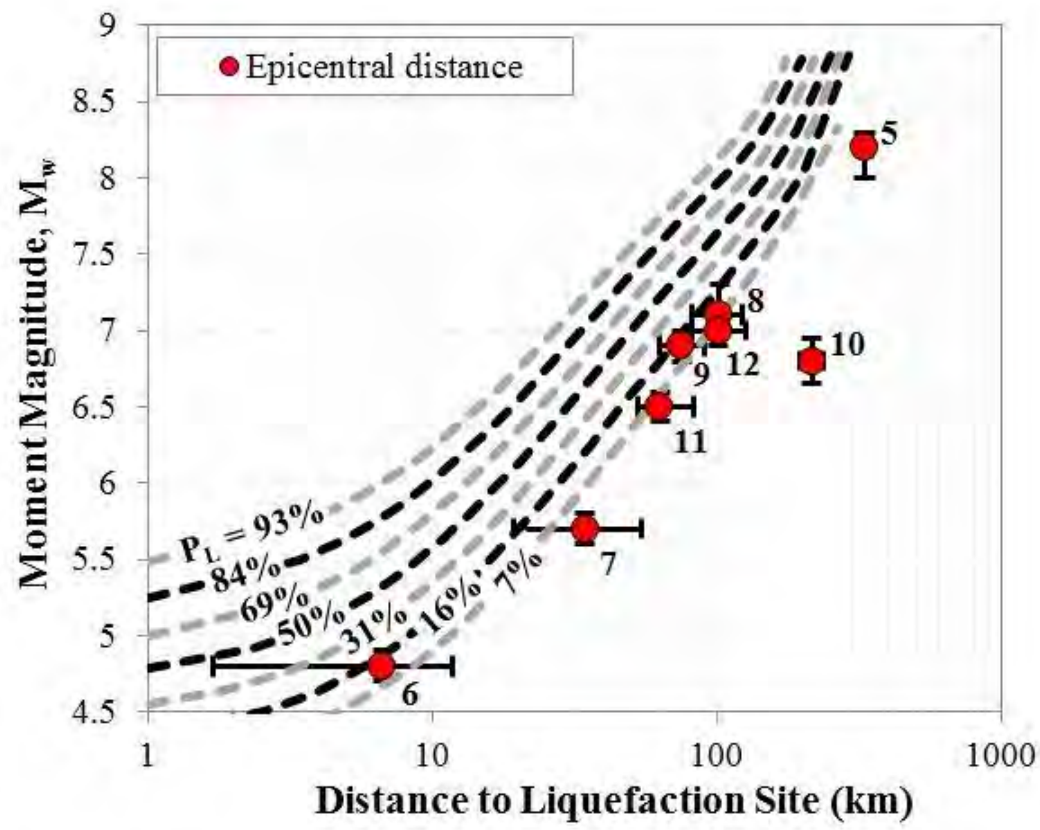
[a] Site-to-source distance from earthquake epicenter (R_{epi}) to Sullivan Park, Christchurch
[b] Site-to-source distance from fault (R_{jb}) to Sullivan Park, Christchurch
[1] Event identification number

(Maurer et al. 2015b)

Back-Calculated Probabilistic Magnitude Bound Curves

Example application: Sullivan Park





(Maurer et al. 2015b)

Back-Calculated Probabilistic Magnitude Bound Curves

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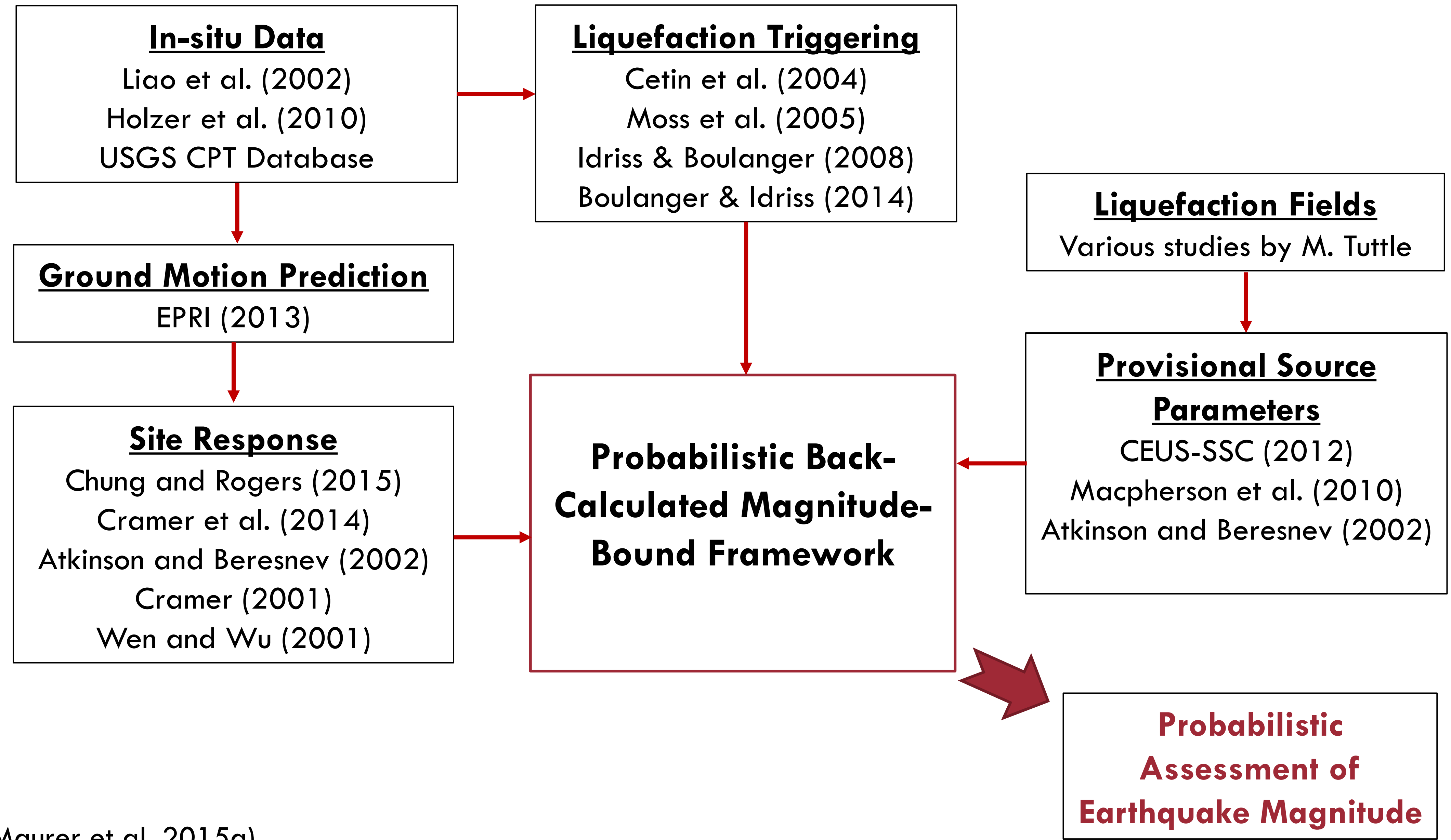
[a] Site-to-source distance from earthquake epicenter (R_{epi}) to Sullivan Park, Christchurch
[b] Site-to-source distance from fault (R_{jb}) to Sullivan Park, Christchurch
[1] Event identification number

(Maurer et al. 2015b)

Back-Calculated Probabilistic Magnitude Bound Curves

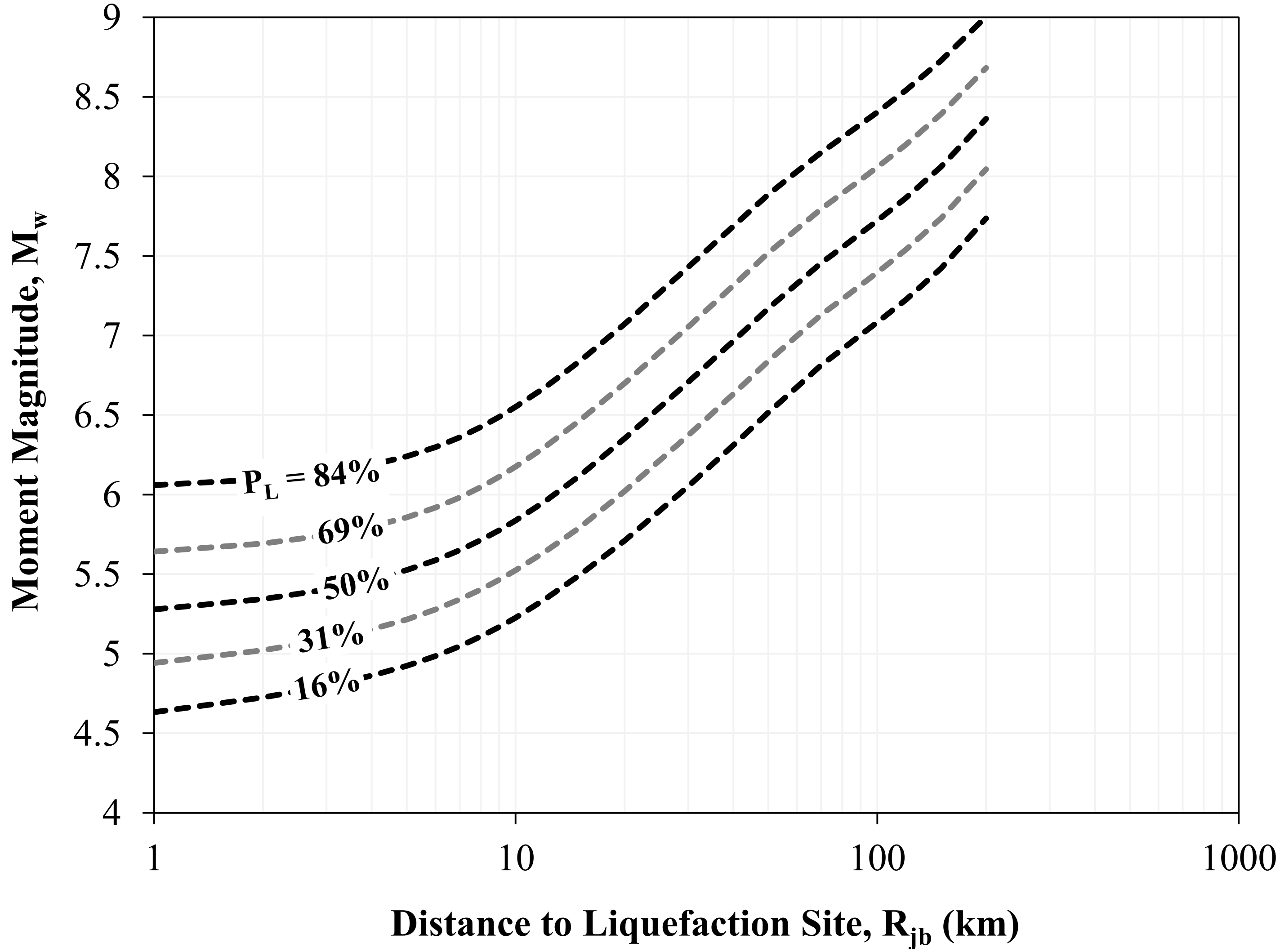
Application to the 1811-1812 New Madrid Earthquakes



(Maurer et al. 2015a)

Back-Calculated Probabilistic Magnitude Bound Curves

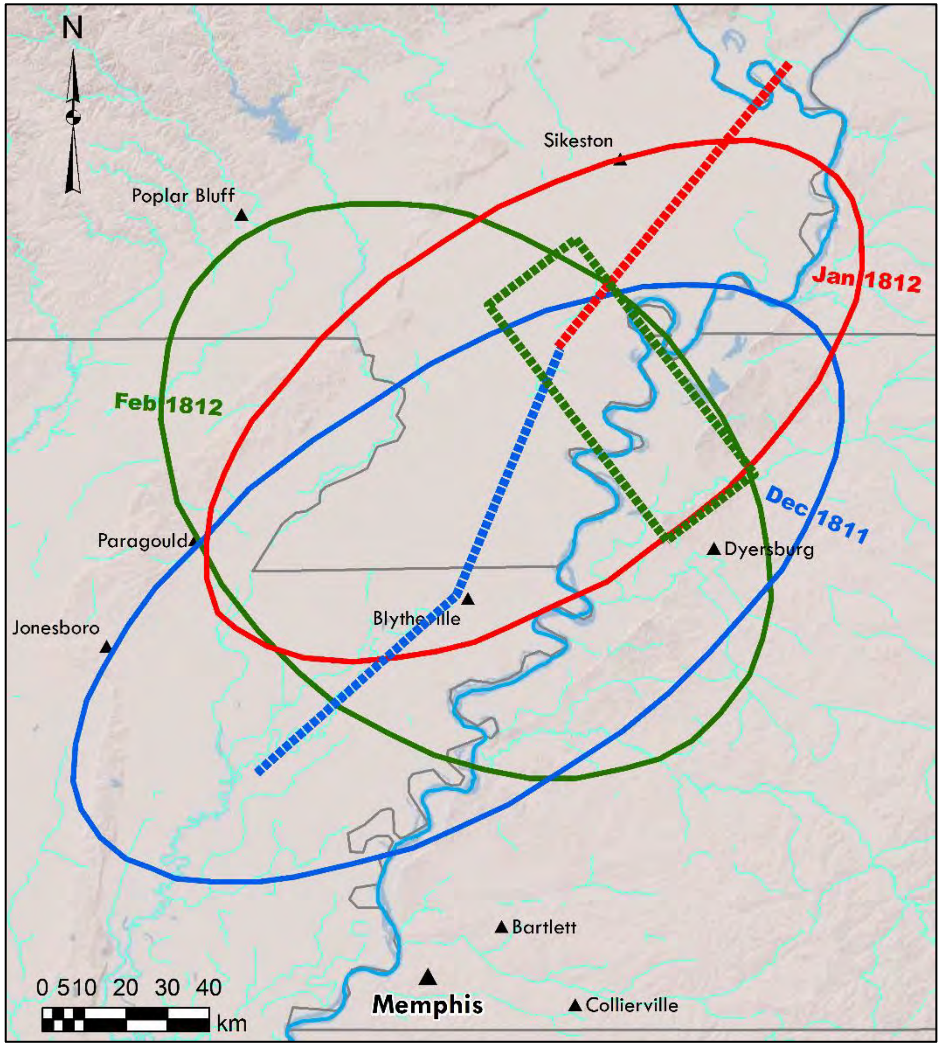
Application to the 1811-1812 New Madrid Earthquakes



(Maurer et al. 2015a)

Back-Calculated Probabilistic Magnitude Bound Curves

Application to the 1811-1812 New Madrid Earthquakes

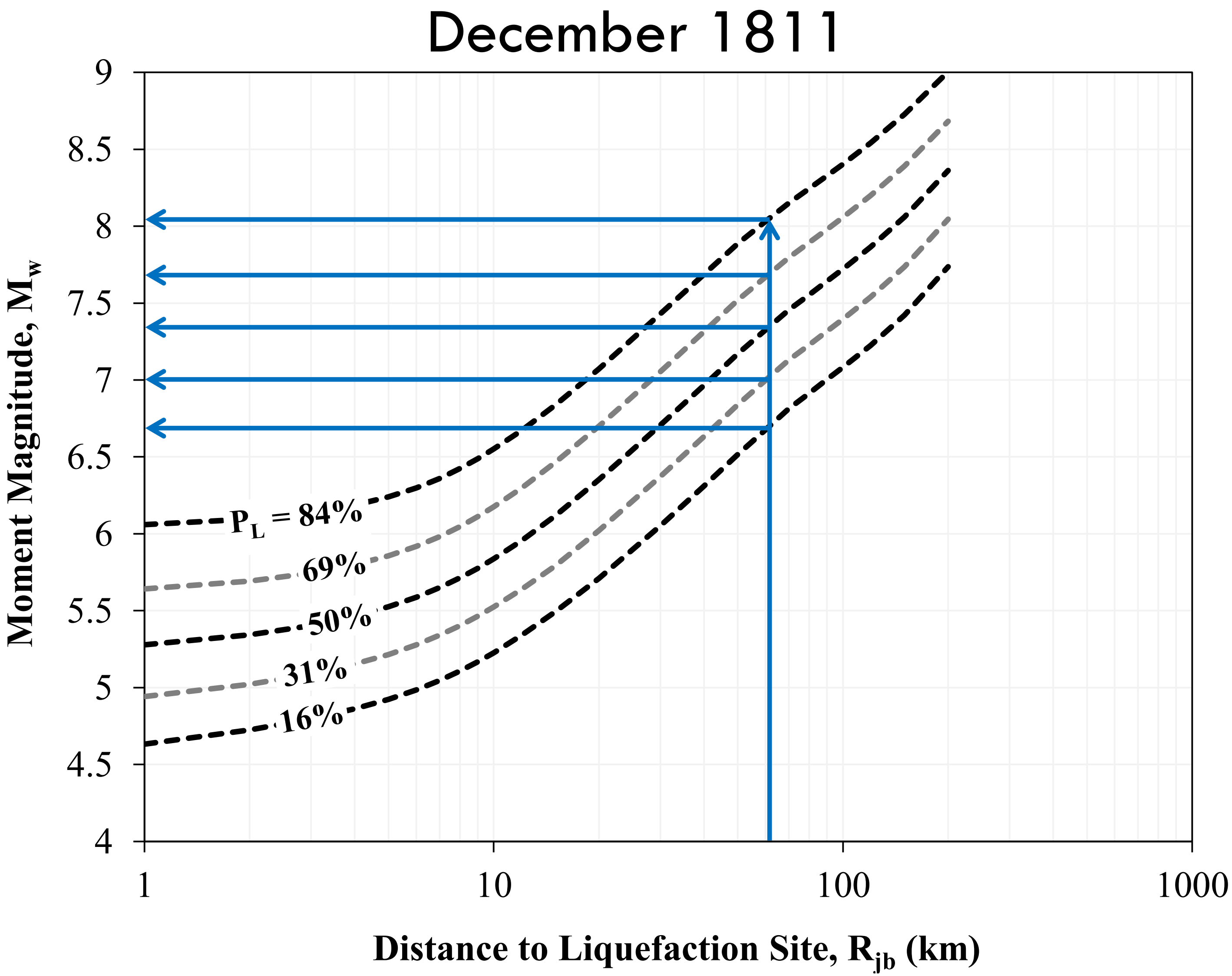


CEUS-SSC (2012) Preferred Rupture Scenario

(Maurer et al. 2015a)

Back-Calculated Probabilistic Magnitude Bound Curves

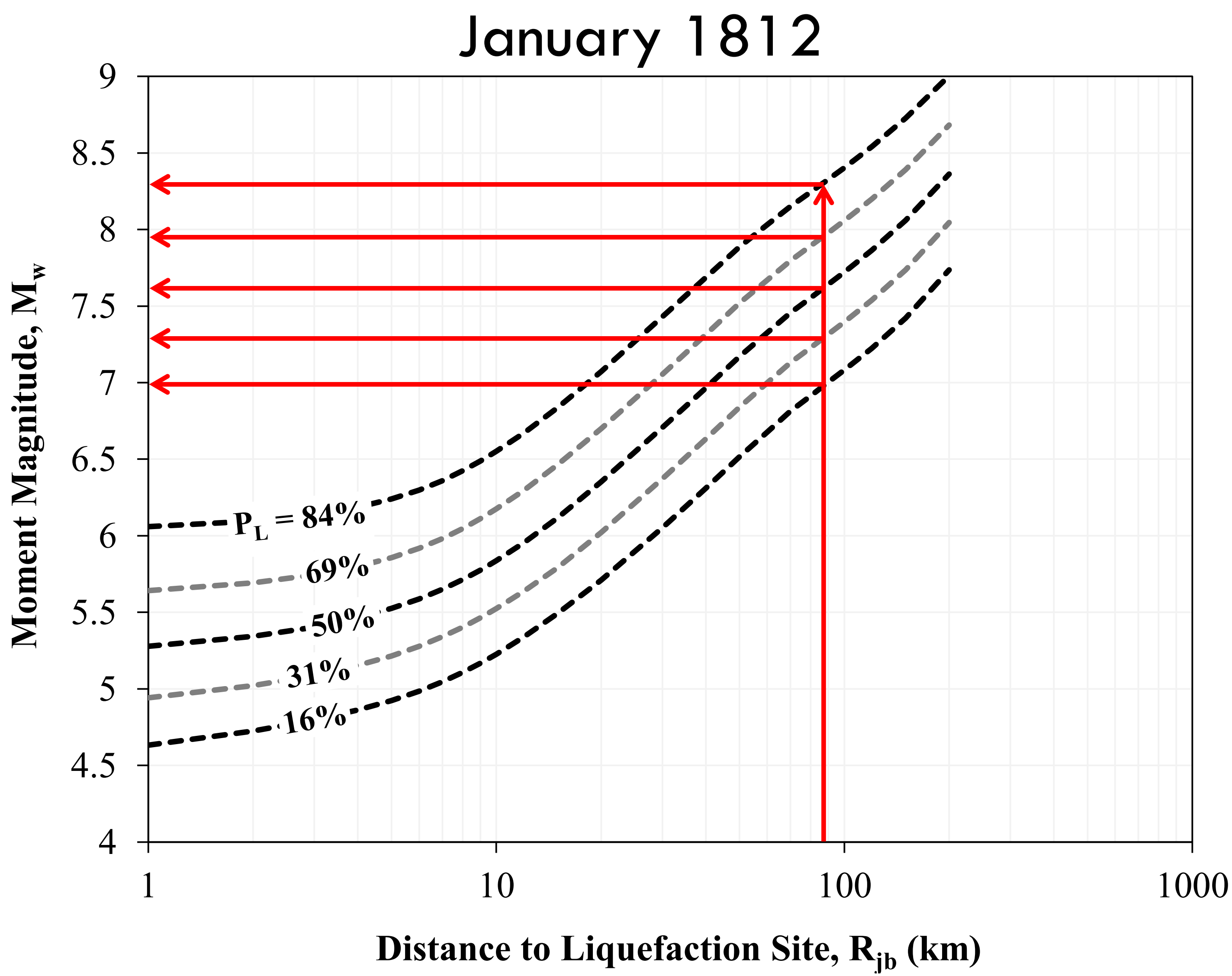
Application to the 1811-1812 New Madrid Earthquakes



(Maurer et al. 2015a)

Back-Calculated Probabilistic Magnitude Bound Curves

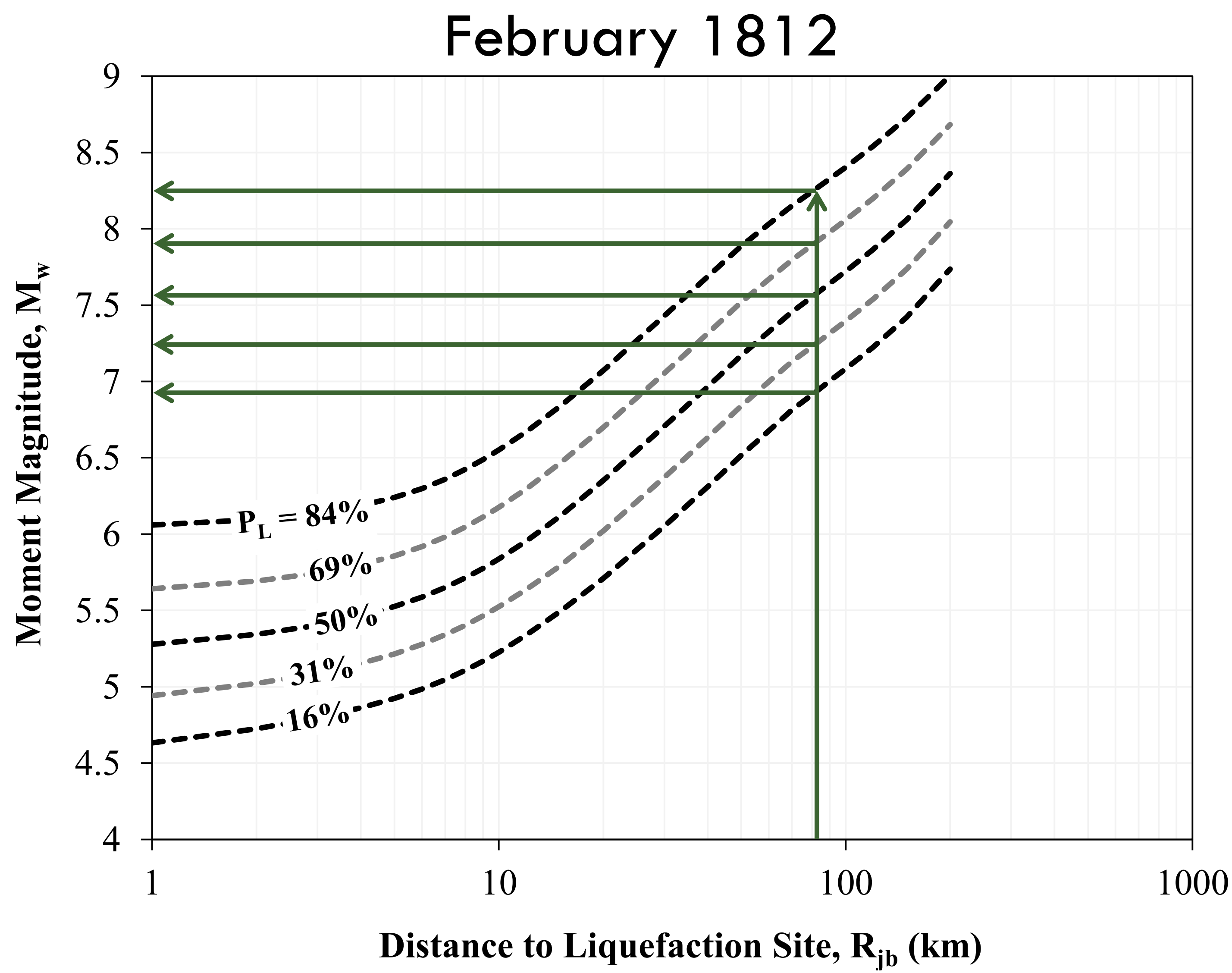
Application to the 1811-1812 New Madrid Earthquakes



(Maurer et al. 2015a)

Back-Calculated Probabilistic Magnitude Bound Curves

Application to the 1811-1812 New Madrid Earthquakes

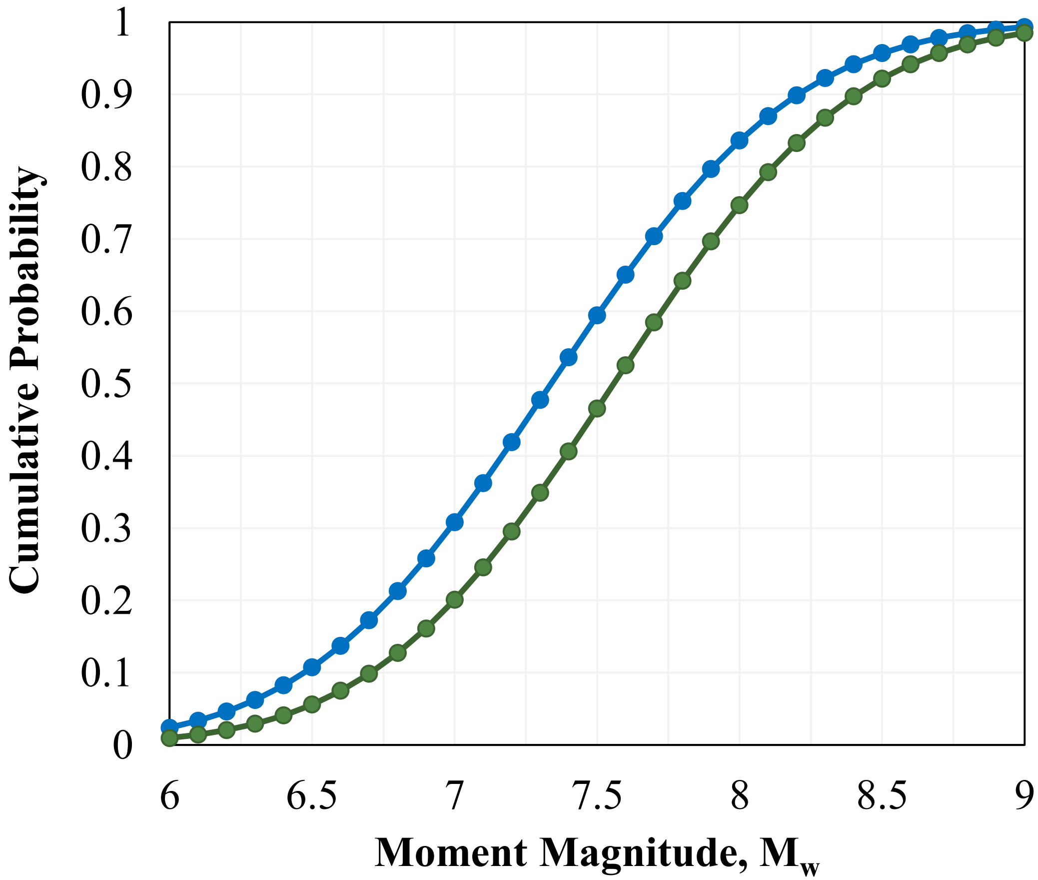


(Maurer et al. 2015a)

Back-Calculated Probabilistic Magnitude Bound Curves

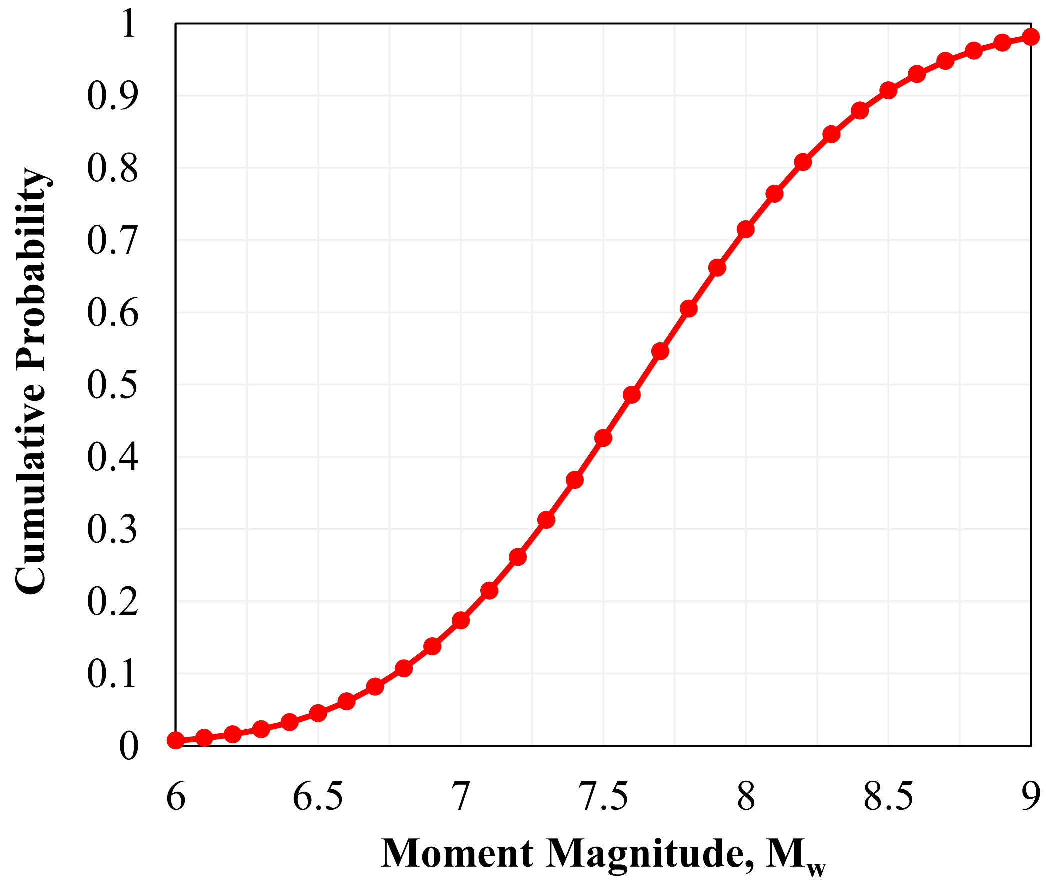
Application to the 1811-1812 New Madrid Earthquakes

Southern (Cottonwood) & Central (Reelfoot) Faults



	Dec 1811	Feb 1812
Median M_w	7.35	7.55

Northern Fault



	Jan 1812
Median M_w	7.62

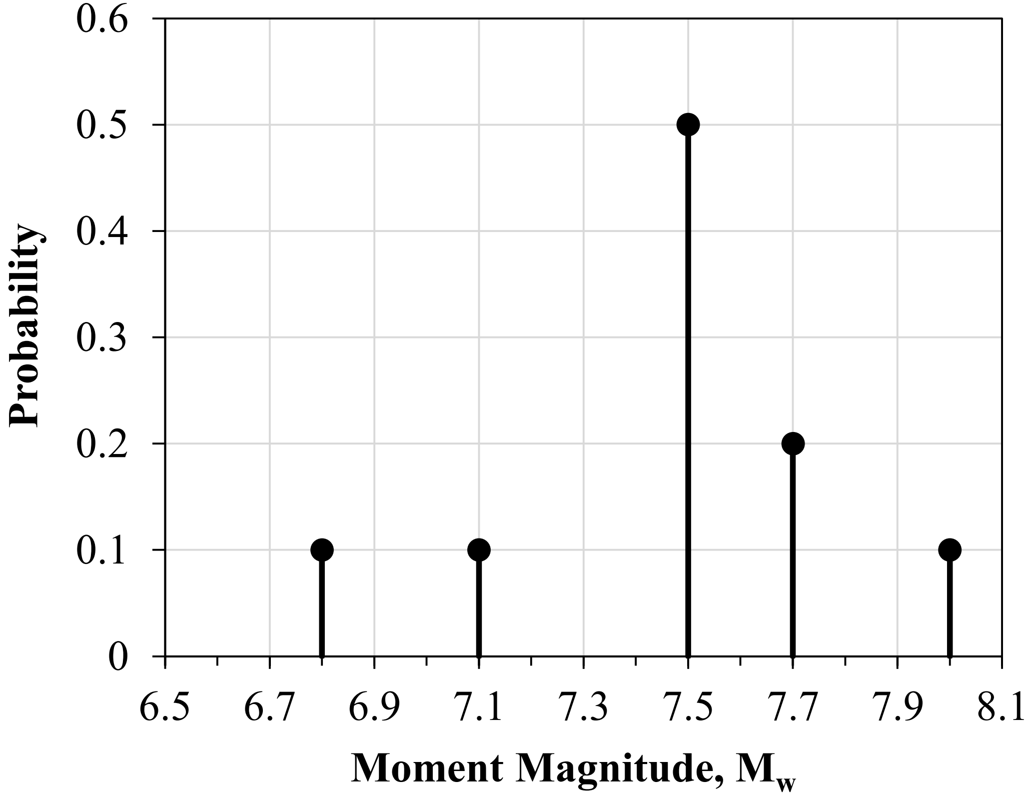
(Maurer et al. 2015a)

Back-Calculated Probabilistic Magnitude Bound Curves

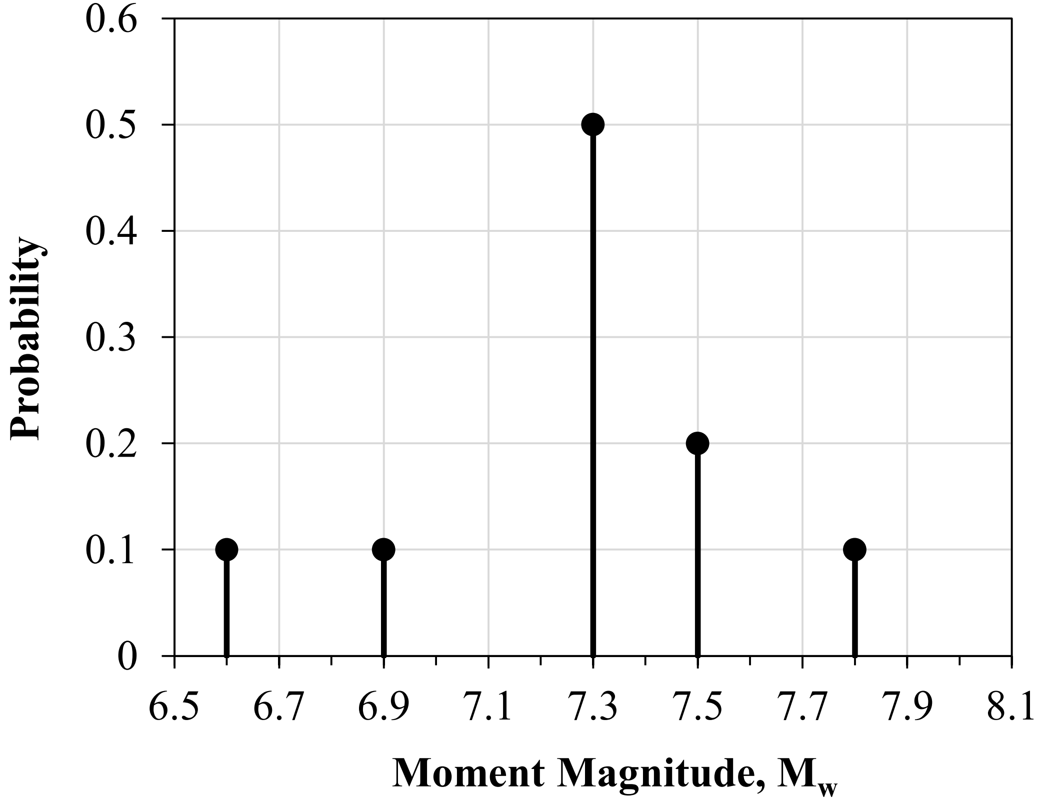
Application to the 1811-1812 New Madrid Earthquakes

2014 USGS NSHMP Rupture Magnitude Probabilities

Southern (Cottonwood) & Central (Reelfoot) Faults



Northern Fault

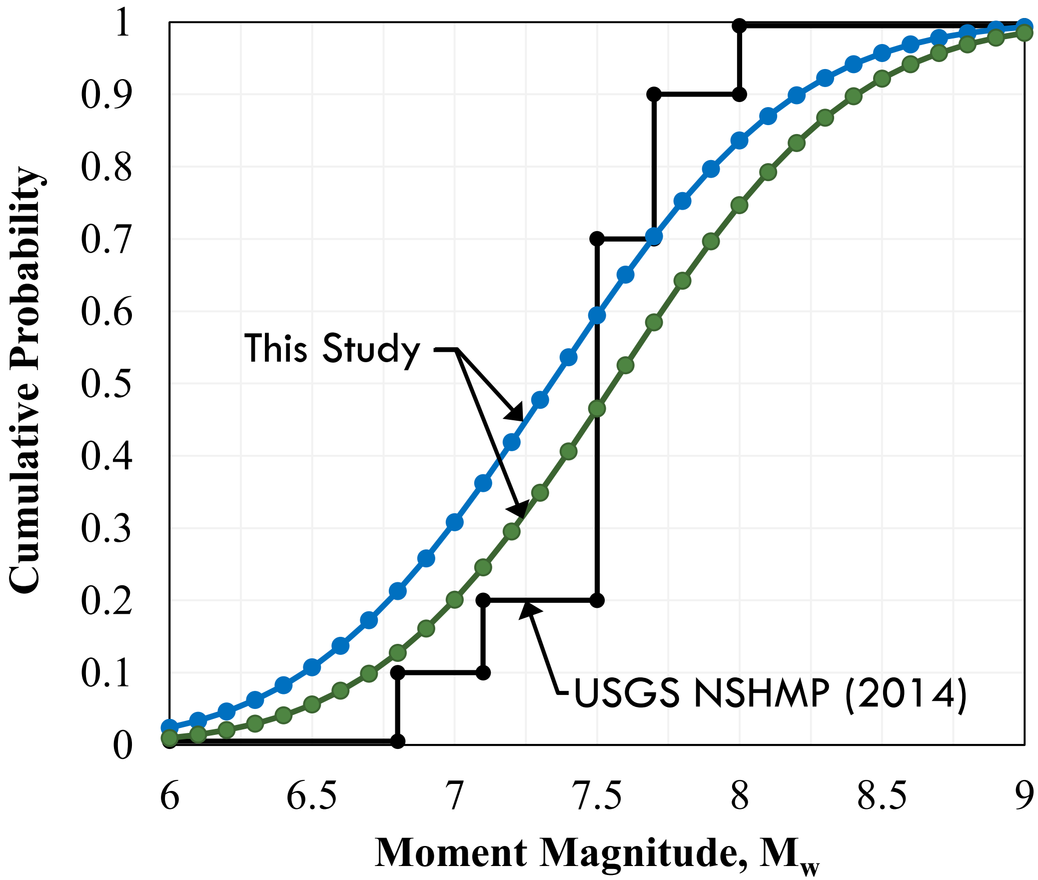


(Maurer et al. 2015a)

Back-Calculated Probabilistic Magnitude Bound Curves

Application to the 1811-1812 New Madrid Earthquakes

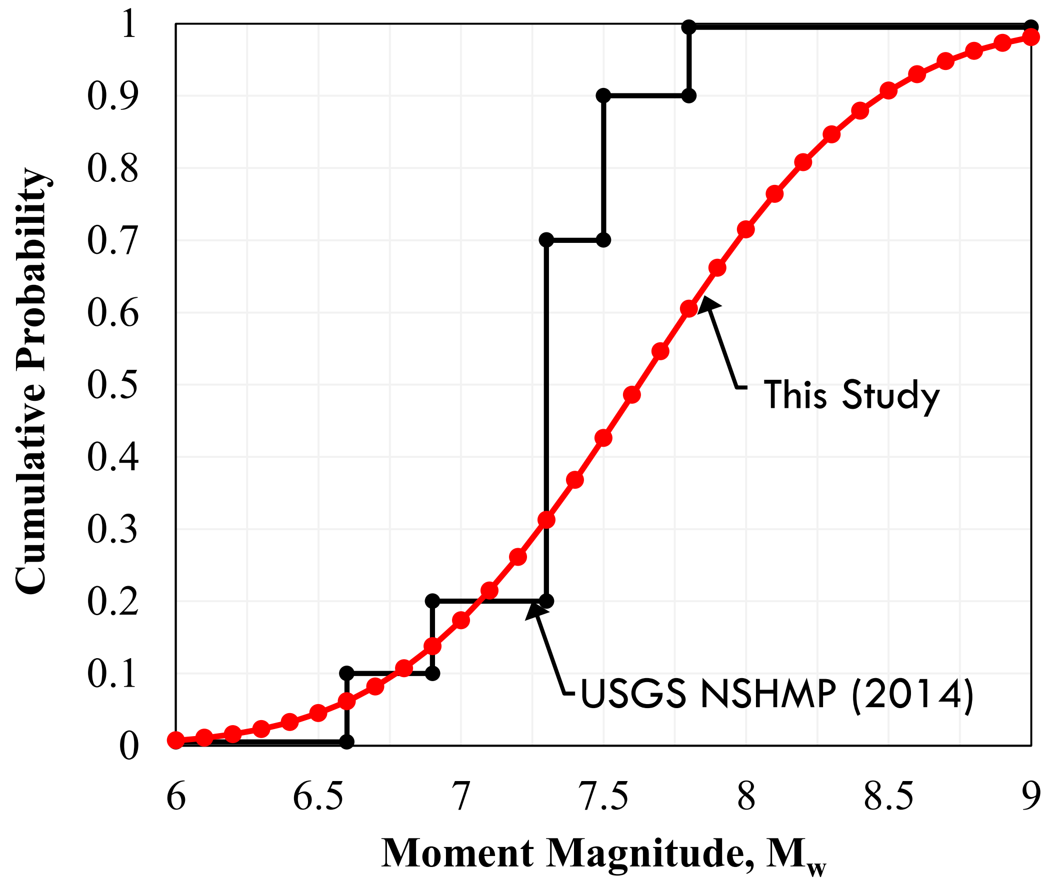
Southern (Cottonwood) & Central (Reelfoot) Faults



	Dec 1811	Feb 1812
Median M_w (This Study)	7.35	7.55
Median M_w (USGS, 2014)	7.5	7.5

(Maurer et al. 2015a)

Northern Fault



	Jan 1812
Median M_w (This Study)	7.62
Median M_w (USGS, 2014)	7.3

Back-Calculated Probabilistic Magnitude Bound Curves

Future Work

- Expand framework to account for other uncertainties not currently considered
- Develop probabilistic magnitude bound curves for various regions in the world
- Application to other paleoearthquakes

Updated Site-specific Geotechnical Analysis

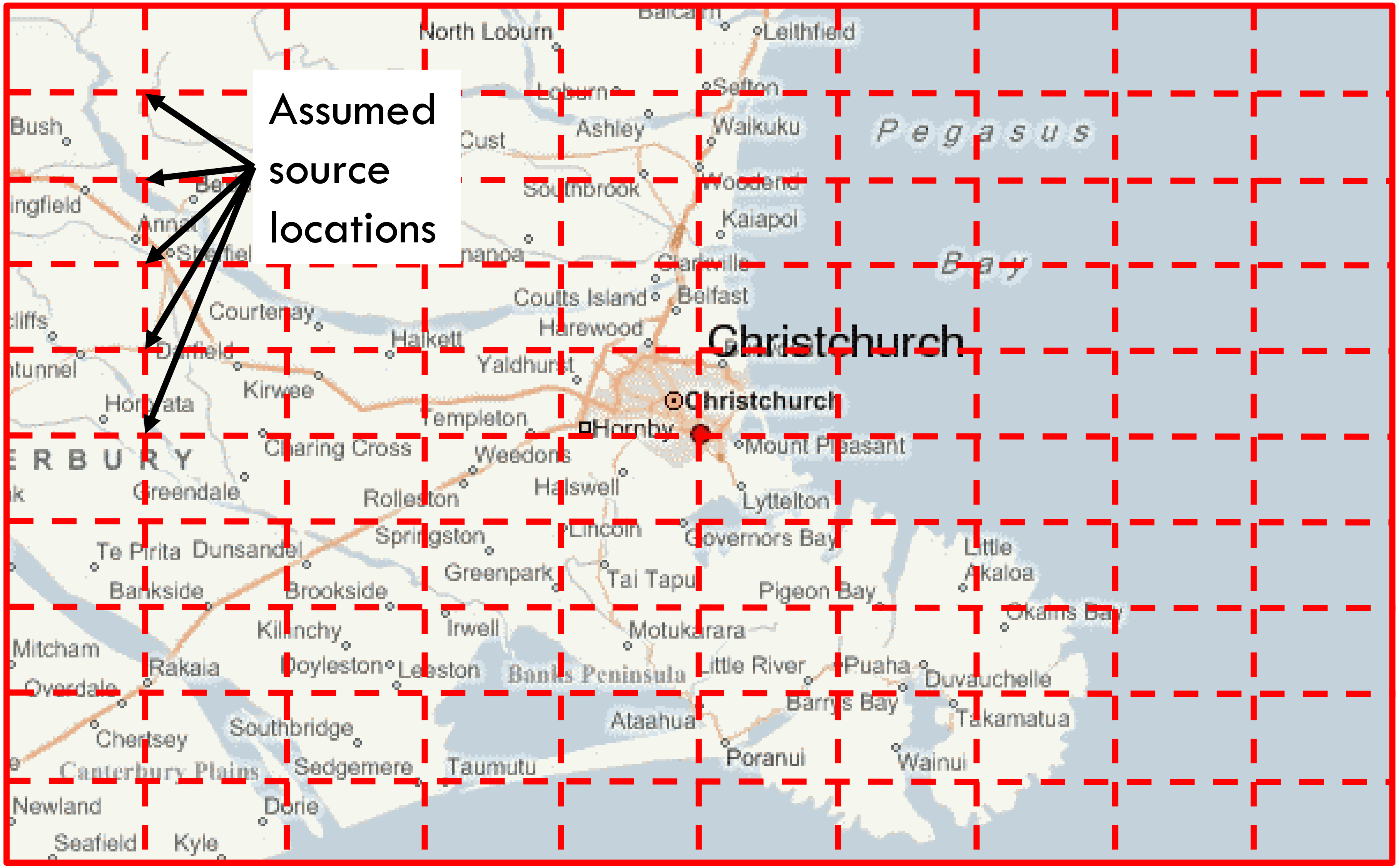
(a priori knowledge of causative source location not required)

Updated Site-Specific Geotechnical Analysis

Application to the Darfield and Christchurch Earthquakes

Updated Site-Specific Geotechnical Analysis

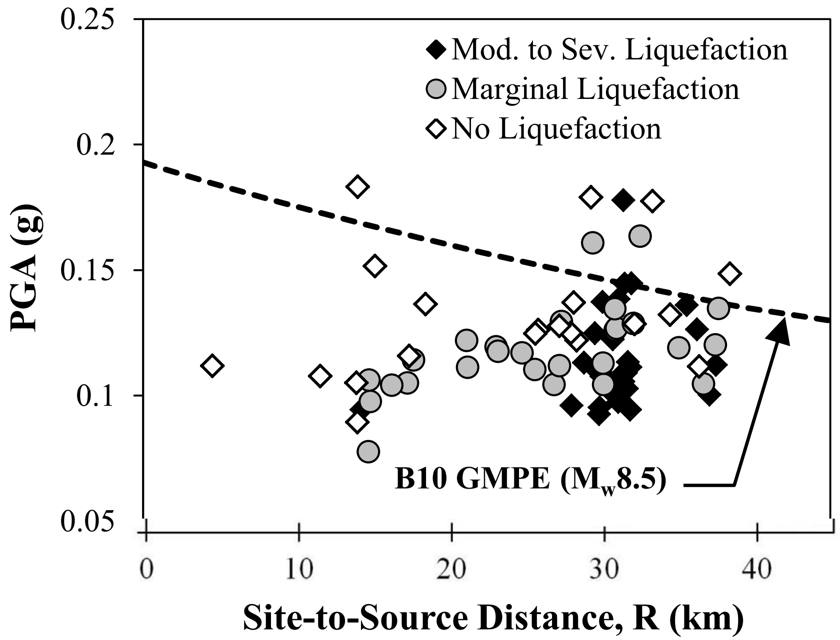
Application to the Darfield and Christchurch Earthquakes

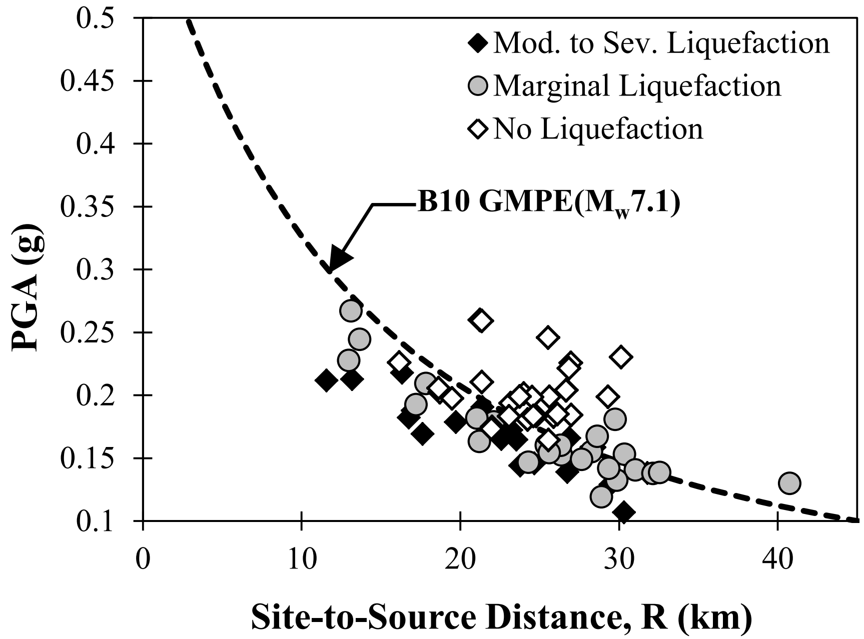


Updated Site-Specific Geotechnical Analysis

Application to the Darfield and Christchurch Earthquakes

For each assumed source location, determine M_w that is most consistent with field observations





(Green et al. 2013)

Updated Site-Specific Geotechnical Analysis

Application to the Darfield and Christchurch Earthquakes

$$E_f = \sum_{i=1}^{n} S_i$$

$$\text{where}\quad S_i = \left|\ln(a_{max,LIQ,i}) - \ln(a_{max,GMPE,i})\right| \ \text{if} \begin{Bmatrix} a_{max,LIQ,i} > a_{max,GMPE,i} \text{ at liquefaction sites} \\ a_{max,LIQ,i} < a_{max,GMPE,i} \text{ at non-liquefaction sites} \end{Bmatrix}$$

$$\text{else}\quad S_i = 0$$

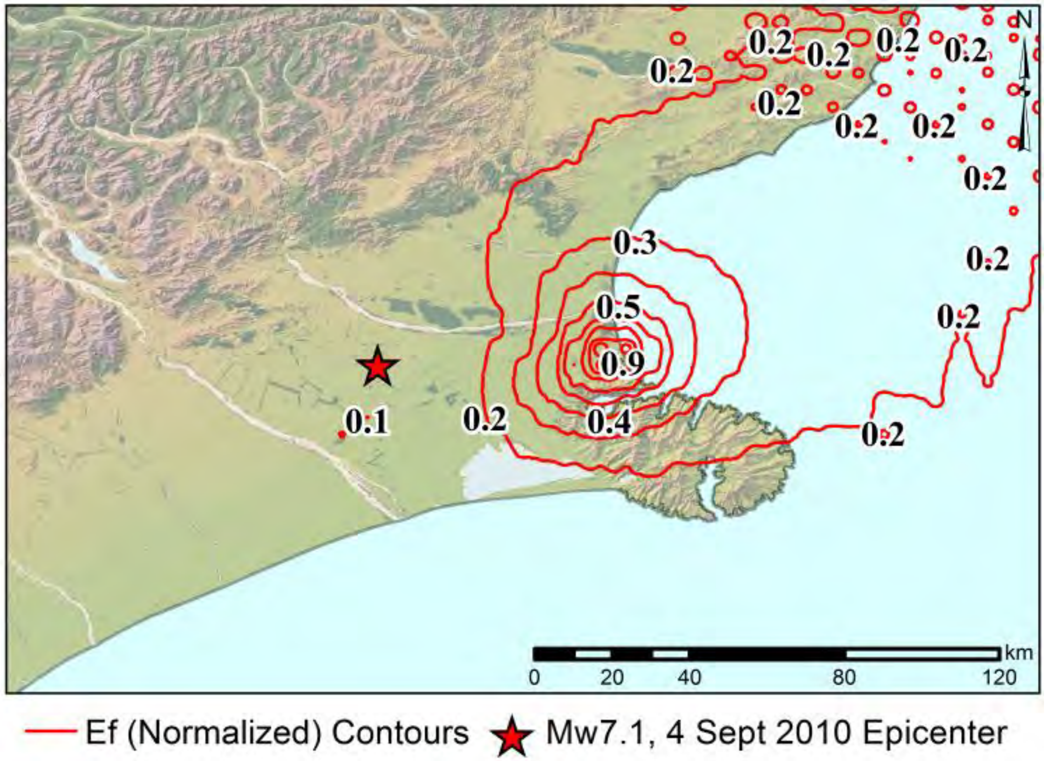
E_f is an index to assess how well the different sets of data points (i.e., liquefaction and no liquefaction) separate for the assumed source location and earthquake magnitude.

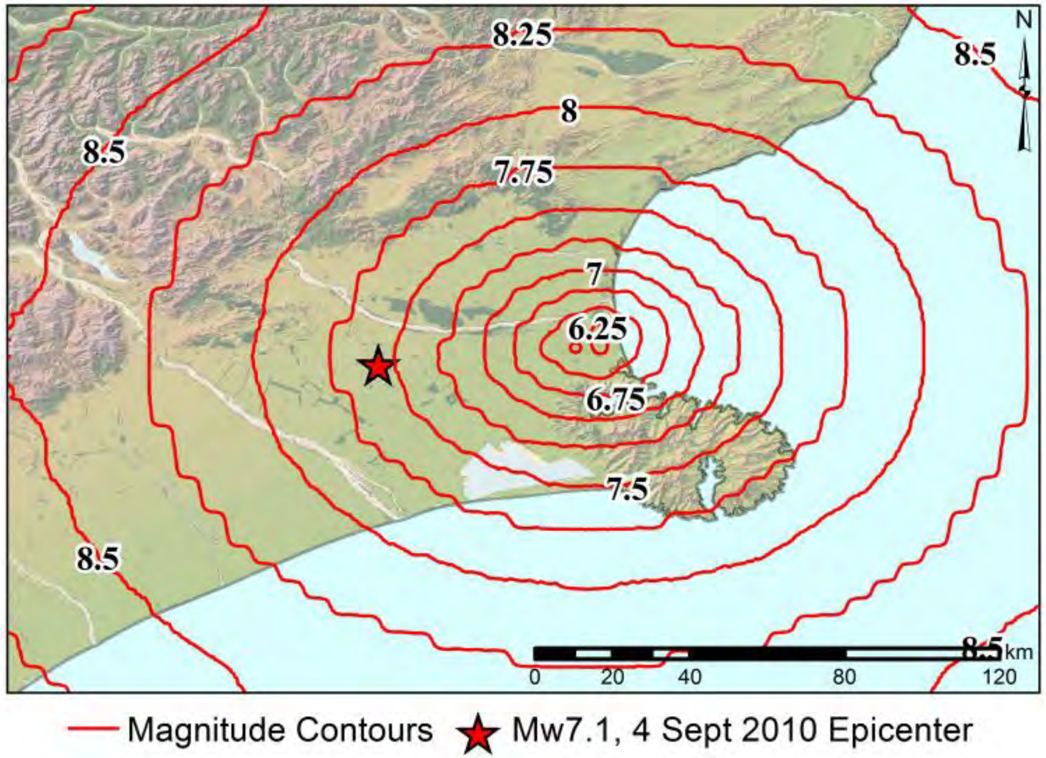
(Green et al. 2013)

Updated Site-Specific Geotechnical Analysis

Application to the Darfield and Christchurch Earthquakes

M_w7.1, 2010 Darfield Earthquake





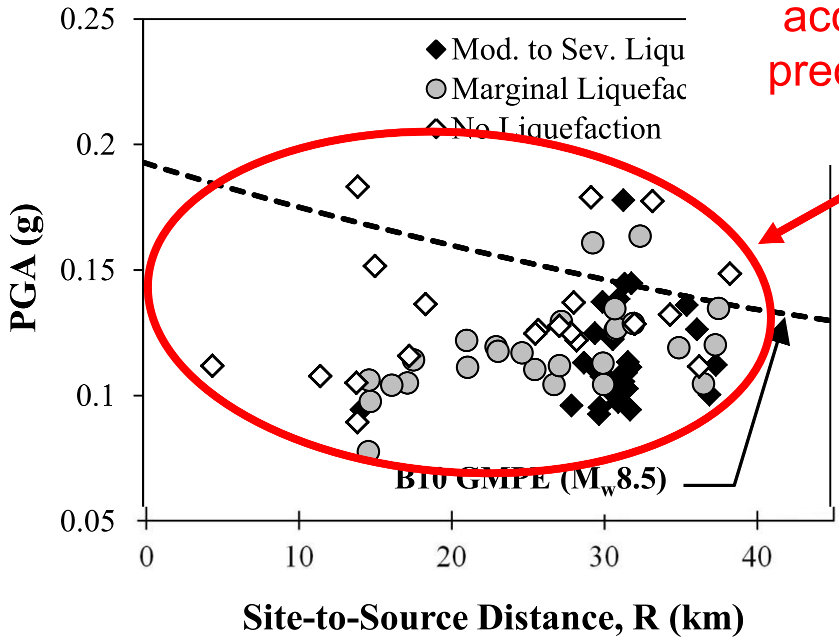
(Green et al. 2013)

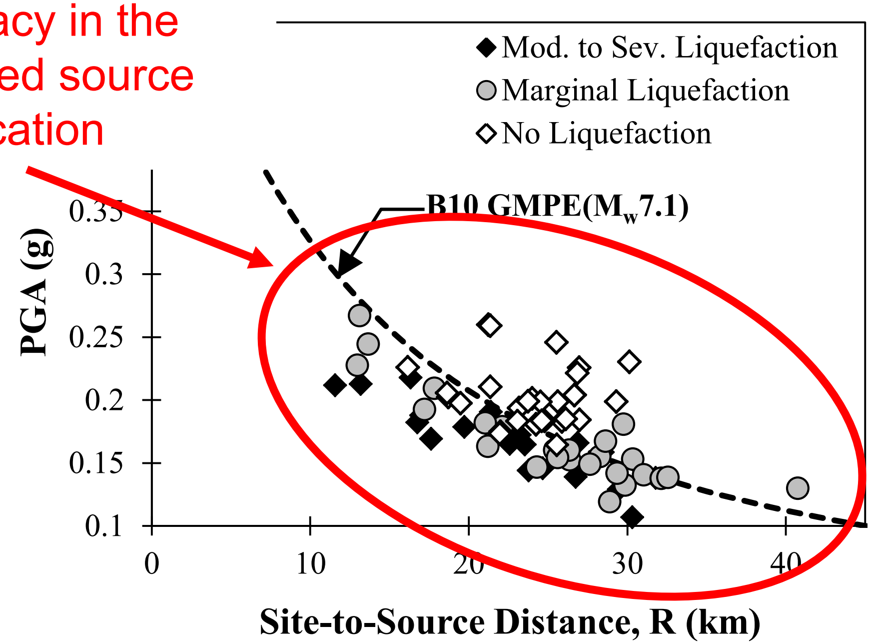
Updated Site-Specific Geotechnical Analysis

Application to the Darfield and Christchurch Earthquakes

For each assumed s[...] etermine M_w that is most consis[...] ɔservations

Size of the "point cloud" reduces as source distance increases from the liquefaction sites, which decreases the accuracy in the predicted source location



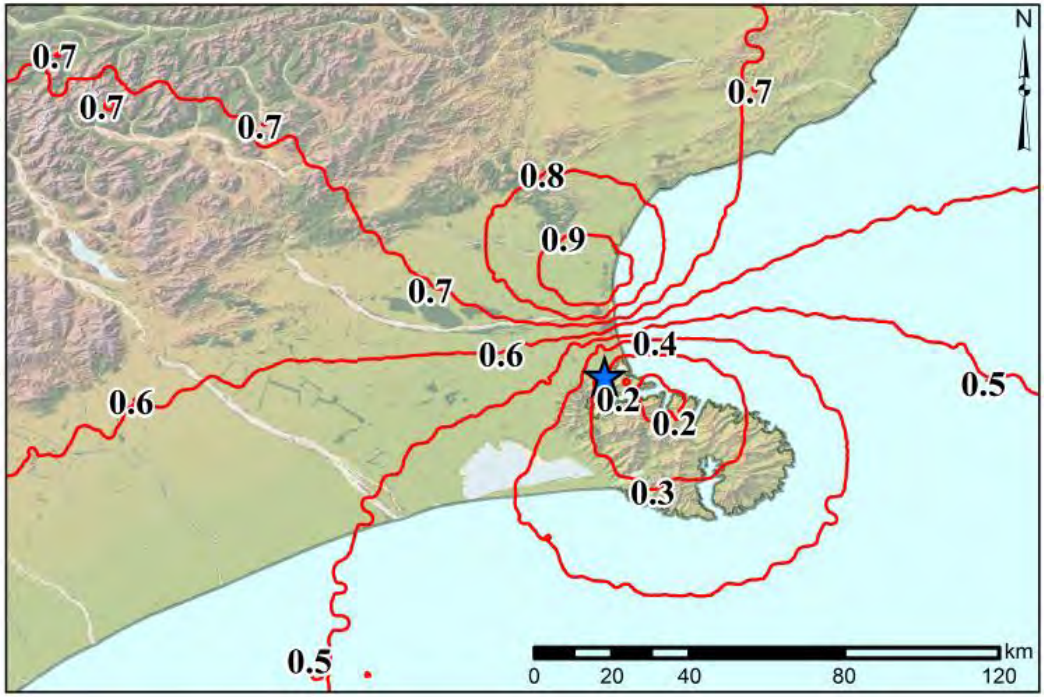


(Green et al. 2013)

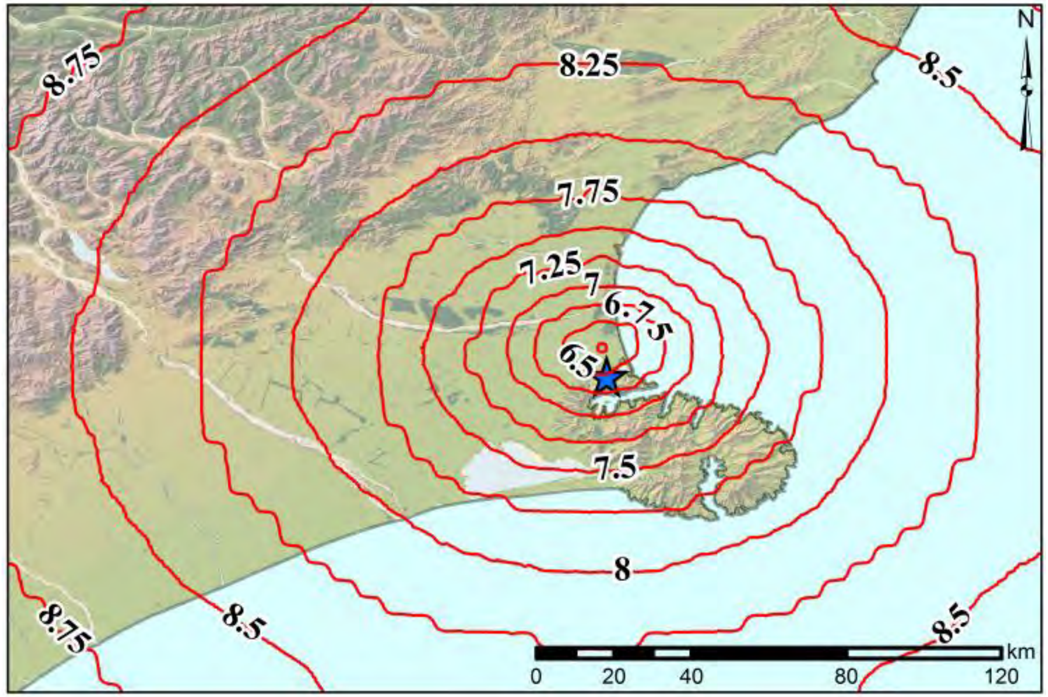
Updated Site-Specific Geotechnical Analysis

Application to the Darfield and Christchurch Earthquakes

M_w6.2, 2011 Christchurch Earthquake



Ef (Normalized) Contours ★ Mw6.2, 22 Feb 2011 Epicenter



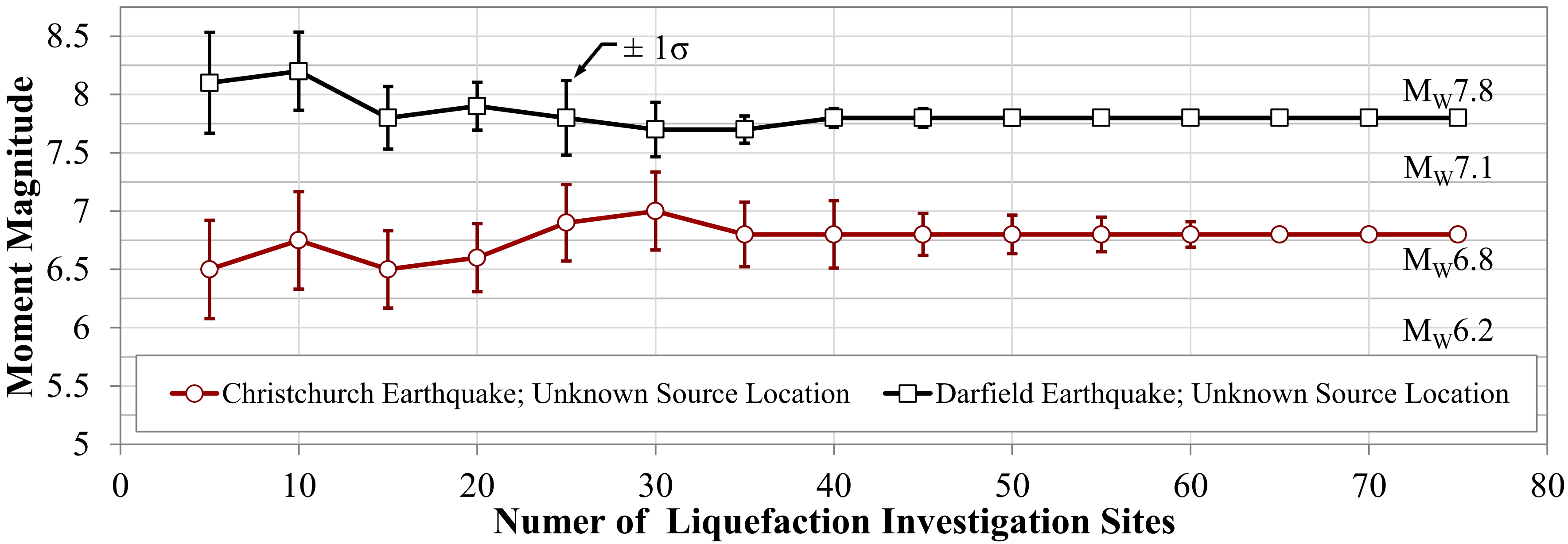
Magnitude Contours ★ Mw6.2, 22 Feb 2011 Epicenter

(Green et al. 2013)

Updated Site-Specific Geotechnical Analysis

Application to the Darfield and Christchurch Earthquakes

Influence of number of sites used in the analysis

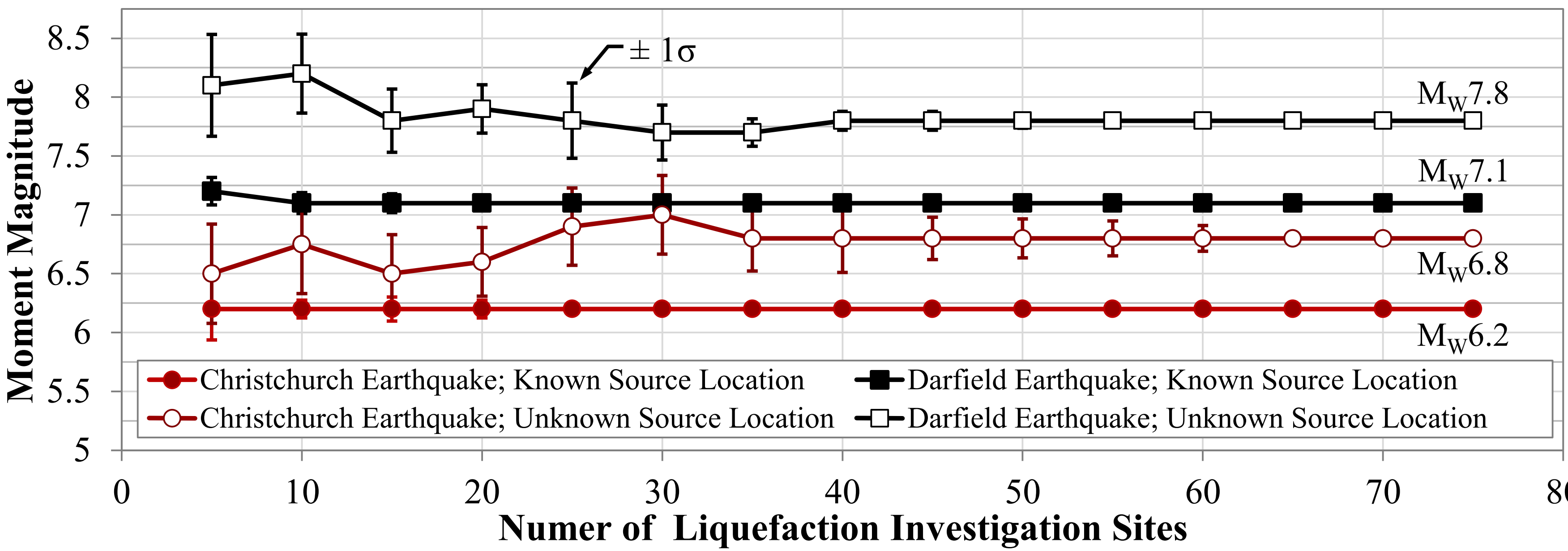


(Green et al. 2013)

Updated Site-Specific Geotechnical Analysis

Application to the Darfield and Christchurch Earthquakes

Influence of number of sites used in the analysis



Targeted field studies to refine estimated location of source location will improve back-calculated magnitude

(Green et al. 2013)

Updated Site-Specific Geotechnical Analysis

Application to the 1886 Charleston, SC, Earthquake

Photo by C.C. Jones (from USGS Photographic Library)

Updated Site-Specific Geotechnical Analysis

Application to the 1886 Charleston, SC, Earthquake

Photo by C.C. Jones (from USGS Photographic

Photo by J.K. Hiller (from USGS Photographic Library)

Updated Site-Specific Geotechnical Analysis

Application to the 1886 Charleston, SC, Earthquake

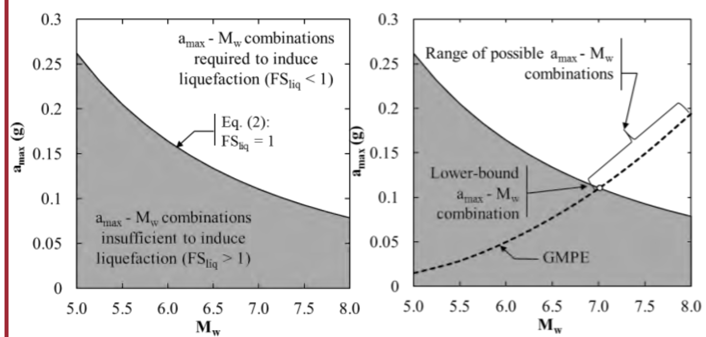
In-situ Data
Boller (2008)
Geiger (2010)
Hasek et al. (2008)
Gassman & Talwani (2002)
Williamson & Gassman (2014)
USGS CPT Database

Liquefaction Triggering
Robertson & Wride (1998)
Moss et al. (2005)
Idriss & Boulanger (2008)
Boulanger & Idriss (2014)

Aging Effects
Leon et al. (2006)
Hayati & Andrus (2009)
Heidari & Andrus (2010)
Maurer et al. (2014)

Ground Motion Attenuation
Toro et al. (1997)
Somerville et al. (2001)
Silva et al. (2003)
Atkinson (2011)

Site-Specific Geotechnical Paleoliquefaction Framework



Provisional Source Parameters
(1) **Unknown location**

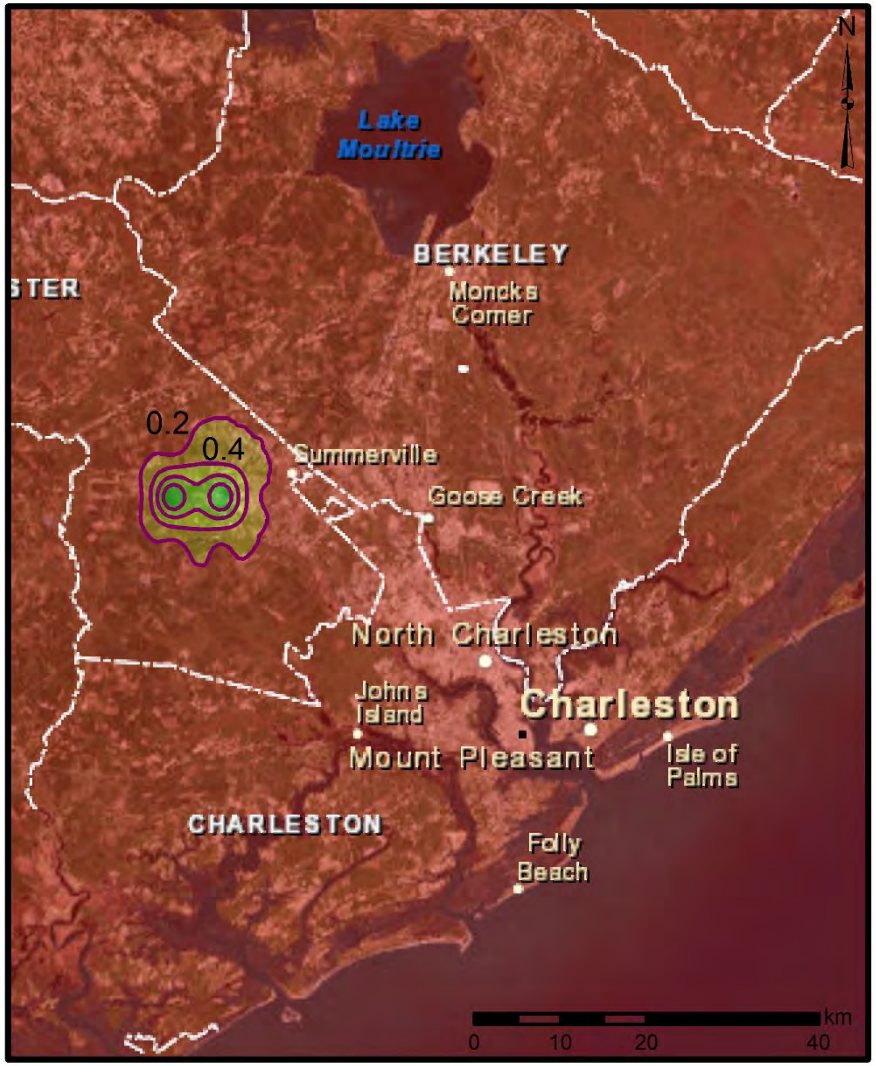
Site Response
Silva et al. (2003)
Andrus et al. (2006)
Chapman et al. (2006)

Best-estimate earthquake magnitude and source location

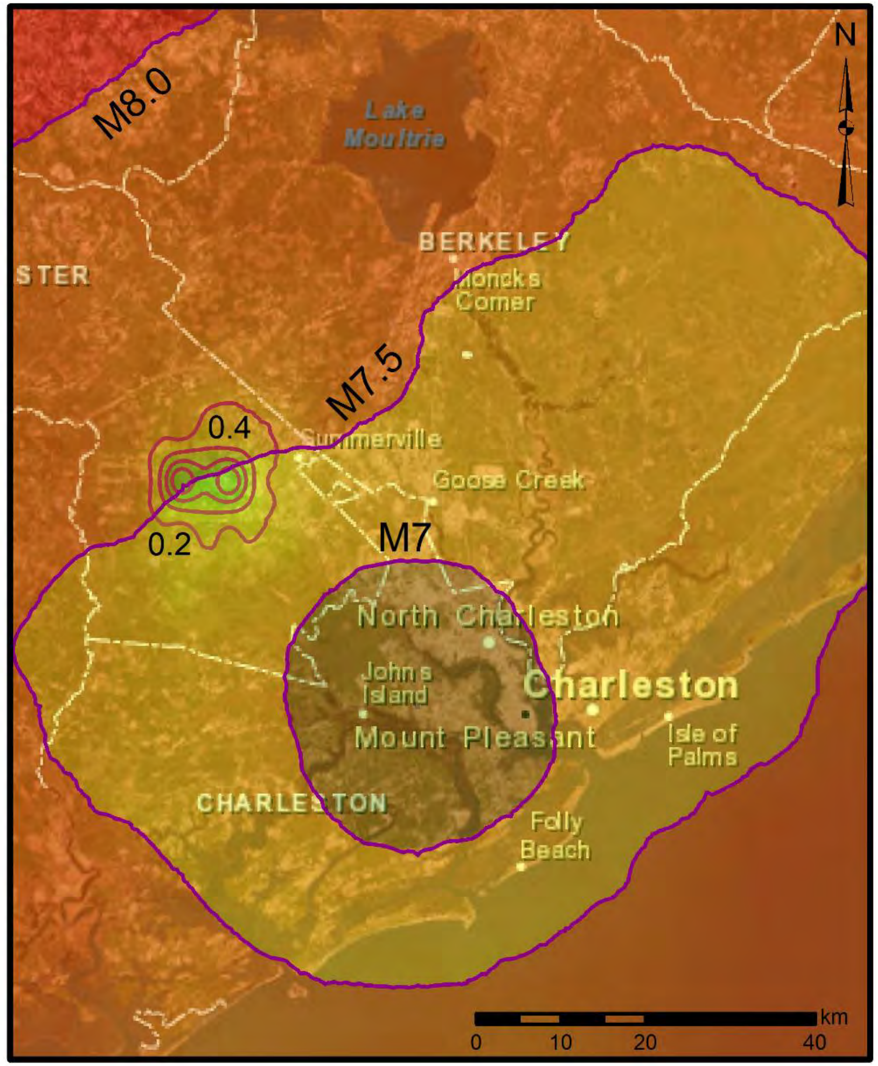
(Maurer et al. 2014)

Updated Site-Specific Geotechnical Analysis

Application to the 1886 Charleston, SC, Earthquake



Most likely (i.e., best fit) location of the 1886 Charleston earthquake



Corresponding rupture magnitudes

(Maurer et al. 2014)

Updated Site-Specific Geotechnical Analysis

Future Work

- Develop probabilistic framework for the updated site-specific geotechnical analysis procedure
- Validation of procedure using data from modern earthquake data
- Application to other paleoearthquakes

Conclusions

- Commonly used procedures for estimated paleo-magnitudes have limitations
- Newly proposed procedures are very promising

Questions?

2011 Christchurch, NZ
(Photo by George Kuek)

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The USGS Seismic Hazard Maps

Chuck Mueller, USGS

and members of the USGS NSHM Project

Paleoliquefaction Workshop (NRC)

Blytheville, Arkansas

13 Nov 2015

USGS Hazard Models & Maps

- ✓ Future ground shaking for a specified risk level
- ✓ Best, current science => generalized models for earthquakes & ground motions
- ✓ Consensus <= workshops, review, feedback
- ✓ Strong collaboration with engineering community
- ✓ 48-States, Alaska, Hawaii, US Territories, *etc.*
- ✓ Applications: building codes, insurance, emergency planning, land-use planning, military facilities, research priorities, *etc.*

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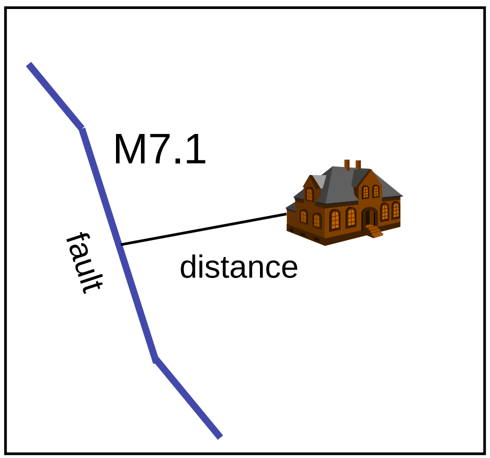
One Way to Think About Seismic Hazard …

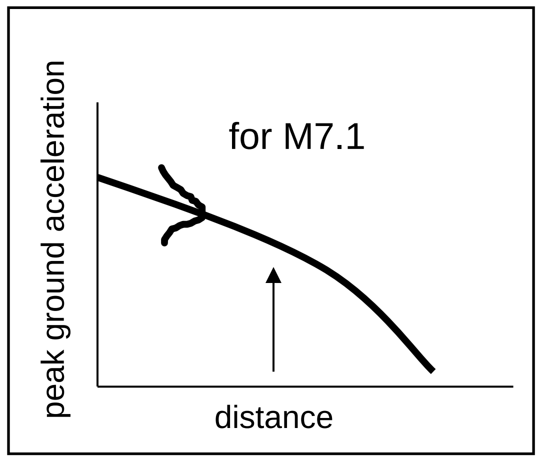
Given:

- A fault near a building site, capable of a magnitude 7.1 earthquake
- Ground shaking *vs* distance for a M7.1 earthquake, with statistical uncertainty



earthquake source

+



shaking *vs* distance

➡

PGA = 0.3 g

ground motion for design
(say, median + 1 σ)

But suppose …

- The size and timing of the earthquake are uncertain
- The fault can generate other earthquakes with uncertain sizes and rates
- There are other faults
- There are earthquakes that can't be associated with faults
- There are alternative ground motion estimates
- *and so on ...*

How do we quantify the hazard?

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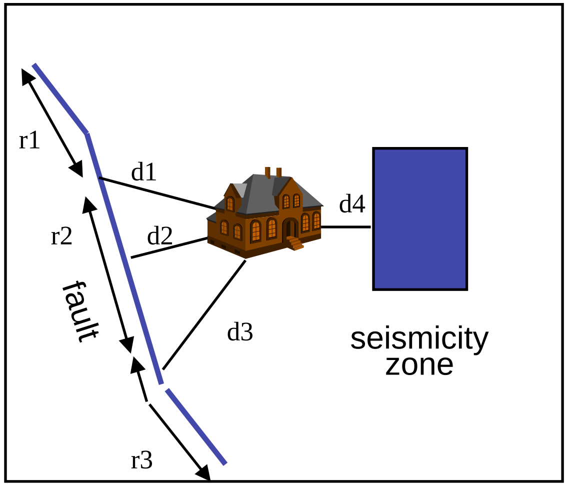
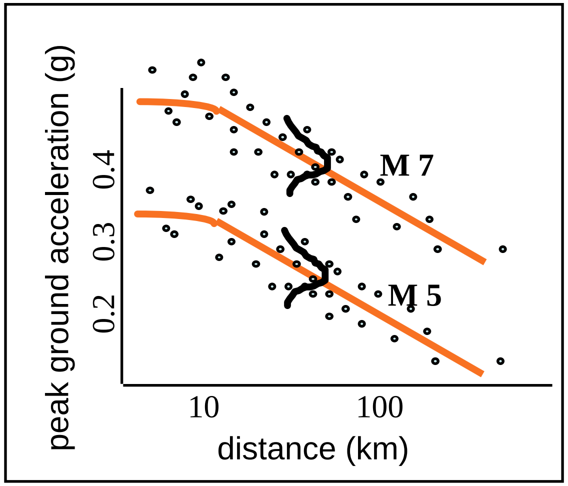
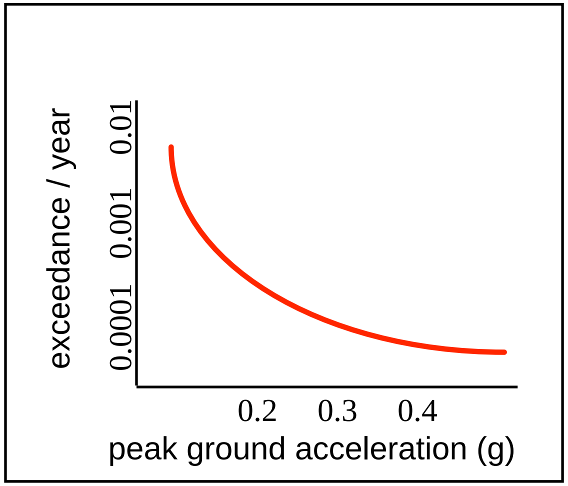
Probabilistic Methodology (PSHA)

First: consider one site …







sources: distances, sizes, rates (uncertainties, logic trees)

ground motions: expected shaking (uncertainties, logic trees)

hazard curve: rates of exceeding ground motion levels; sum over sources and alternative models (exceedances are additive!)

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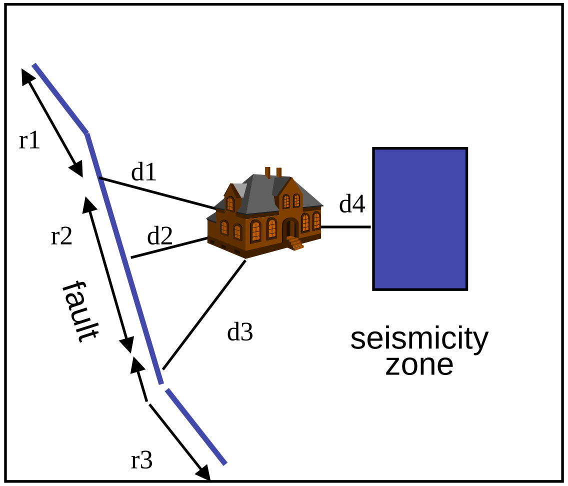
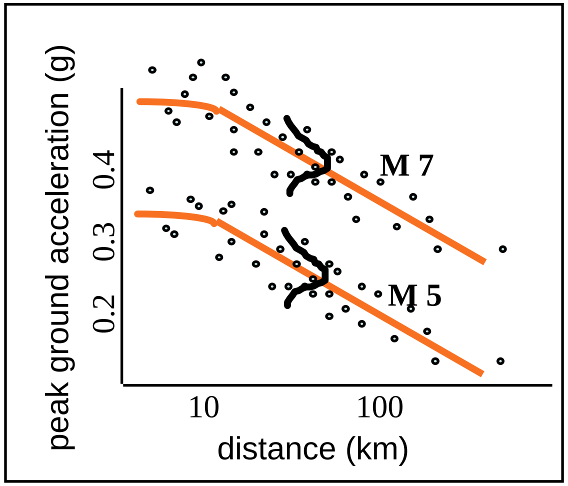
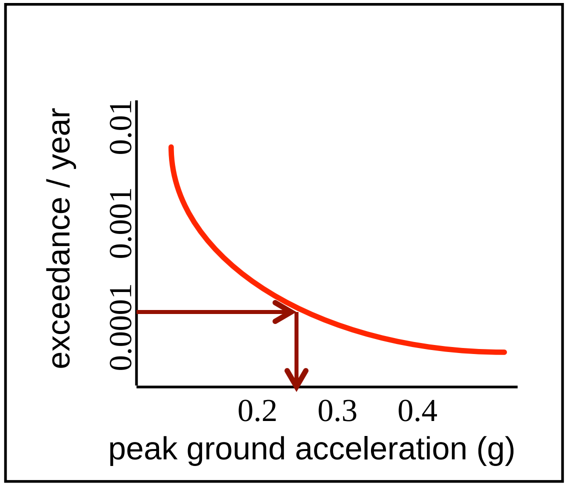
Probabilistic Methodology (PSHA)

First: consider one site …







sources: distances, sizes, rates (uncertainties, logic trees)

ground motions: expected shaking (uncertainties, logic trees)

hazard curve: rates of exceeding ground motion levels; sum over sources and alternative models (exceedances are additive!)

Then: make a hazard curve for each site on a grid, select a risk level (say, 10% probability of exceedance in 50 years - generally an engineering or societal decision), and map the corresponding “probabilistic” ground motions.

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annual rate of exceeding ground motion U
at a site

=

annual rate of earthquake occurring

×

probability of having ground motion
greater than U
when earthquake occurs

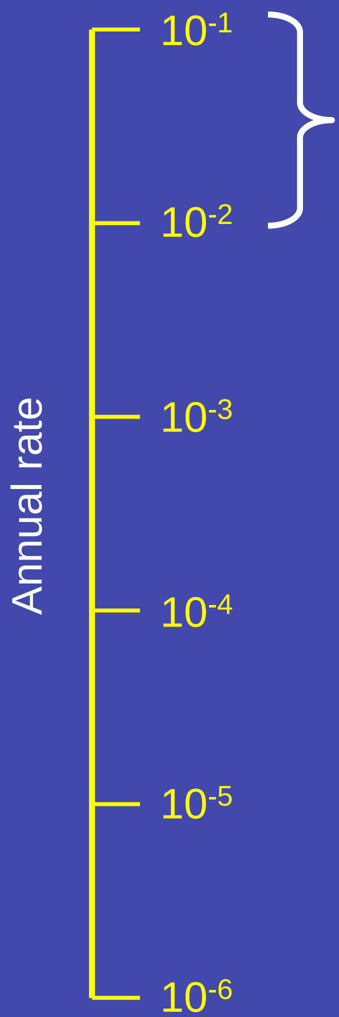
Good Things About PSHA:

- Accounts for multiple-sources
- Accounts for rates of seismic activity
- Accounts for uncertainties & alternative models (logic trees)

Engineers design for ground motions, not earthquakes

Cost/Benefit: When does seismic hazard analysis make sense?

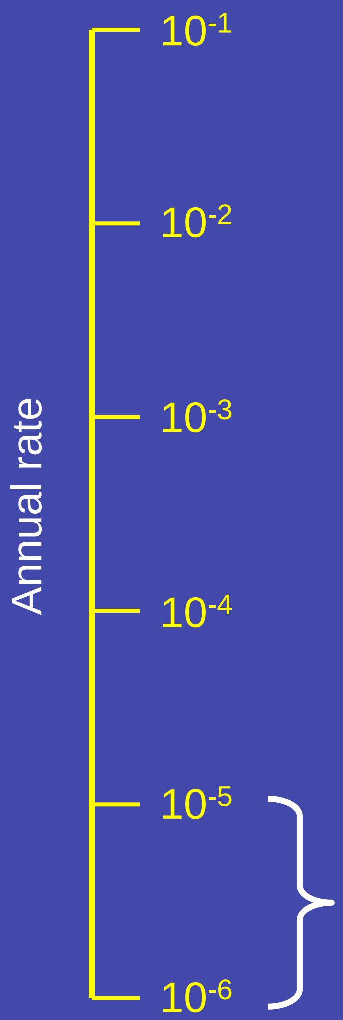
(after McGuire, 2004)



At these high rates, some kind of mitigation is probably needed.

Cost/Benefit: When does seismic hazard analysis make sense?

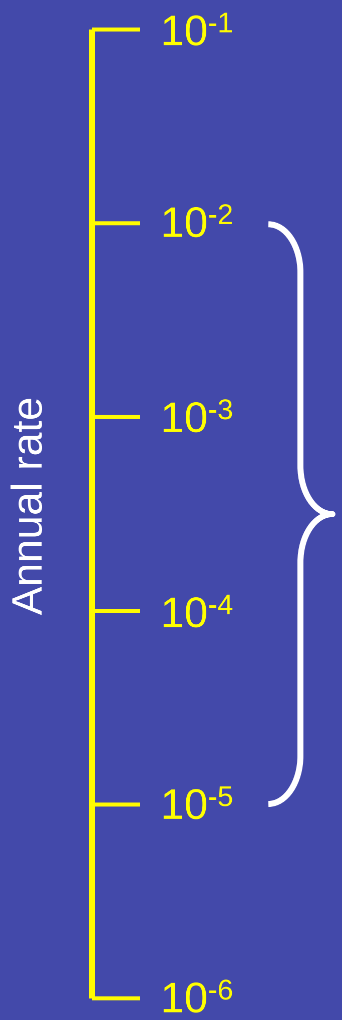
(after McGuire, 2004)



At these low rates, many perils are tolerated. For example, the average individual fatality risk from extreme weather in the CEUS is ~5×10^{-6}/yr, yet people choose to live in flood- & wind-prone places. (an exception: nuclear facilities)

Cost/Benefit: When does seismic hazard analysis make sense?

(after McGuire, 2004)



PSHA can help balance risk and mitigation costs. Uncertainties are large and any analysis is approximate, but we have enough data to do this.

A major development for the 2014 NSHM:

Central and Eastern US Seismic Source Characterization for Nuclear Facilities (CEUS-SSC) Project

- ✓ Sponsored by NRC/DOE/EPRI
- ✓ Dozens of experts; SSHAC Level 3
- ✓ Results compared with 2008 NSHM
- ✓ USGS adapted/adjusted CEUS-SSC models for 2014 update

Catalog-based (“background”) sources in the CEUS

A few key ideas (for natural earthquakes)

- Most eqks in the CEUS can't be associated with specific active faults.
- Repeat times of large eqks are long (but the history of seismology is short).
- Tests show that past eqks are pretty good predictors of future eqks.
- In places where we have a lot of data, we invariably see similar kinds of "recurrence" relationships between the numbers of small and large eqks ("exponential", "Gutenberg-Richter").

=> A defensible forecasting model for hazard can be developed from an eqk catalog, even if it is short and only contains small eqks.

Catalogs

Step 1: Combine authoritative source catalogs

- NCEER91, USGS ComCat, SLU, CEUS-SSC, *etc*
- Uniform moment magnitude (convert)
- Uniform record format

Step 2: Delete duplicates, explosions, mining-related eqks

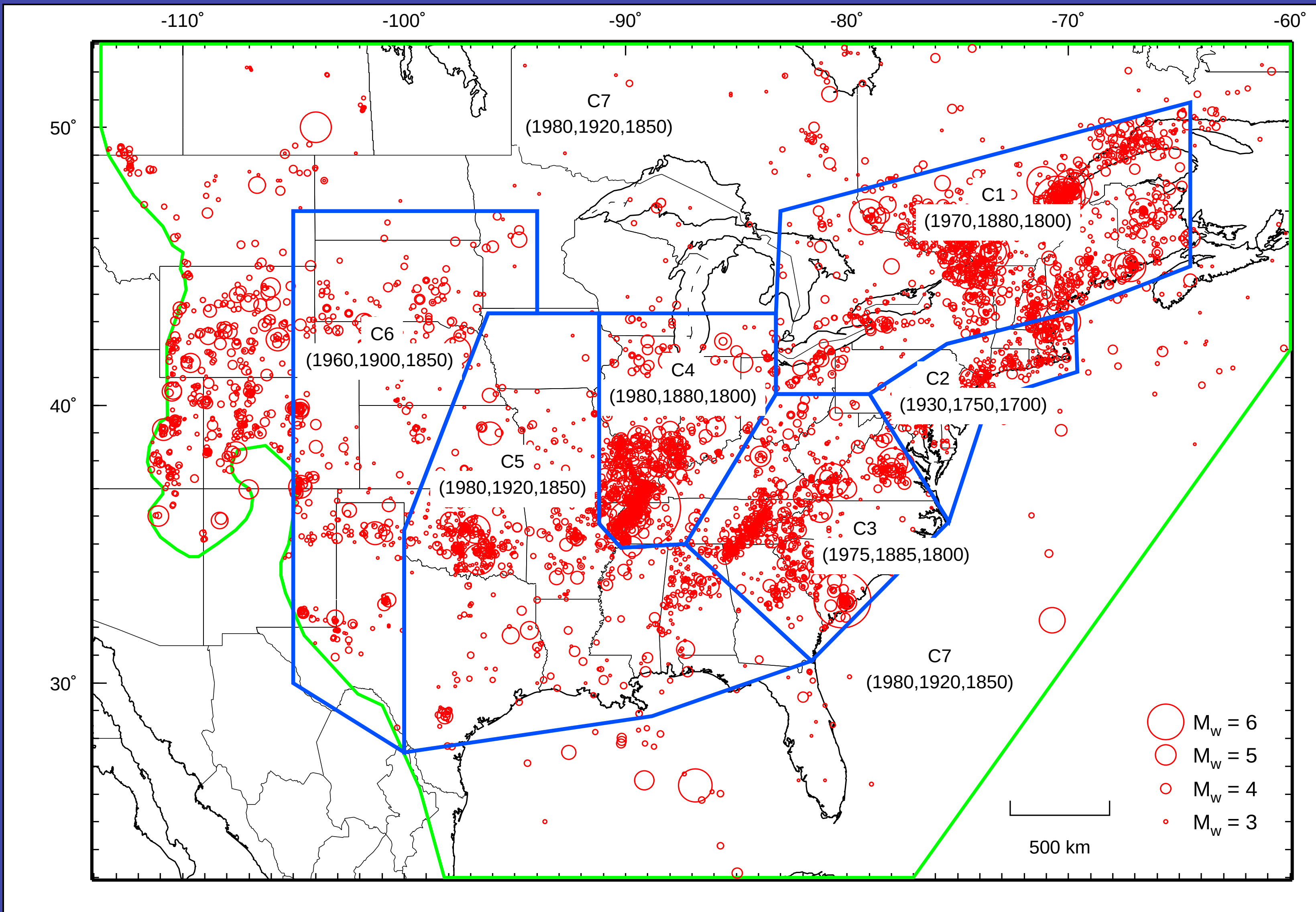
- Identify duplicates – keep one preferred record for each eqk
- Identify explosions & mining-related eqks

Step 3: Decluster

- Standard PSHA methodology assumes eqks are statistically independent
- Identify aftershocks in time/radius windows (Gardner & Knopoff, 1974)

Step 4: Separate out suspected induced eqks

Completeness: We want to count as many eqks as possible to define seismicity patterns, but if we over-assume the catalog coverage we get the rates wrong! The zonation reflects patterns of human settlement and seismic instrumentation.



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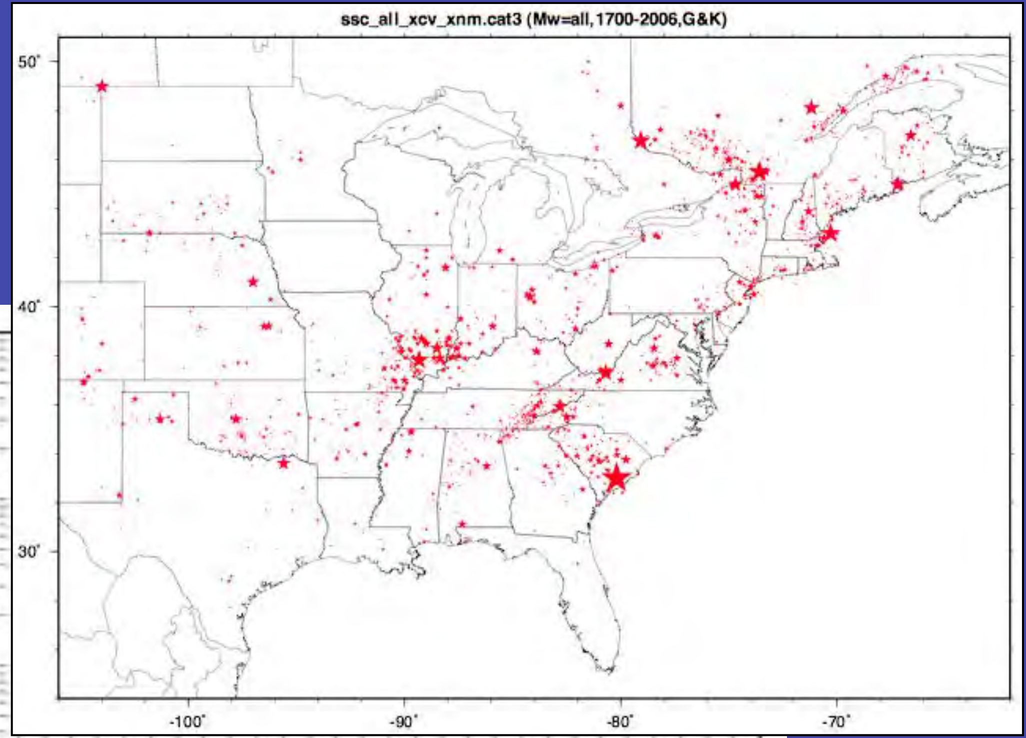
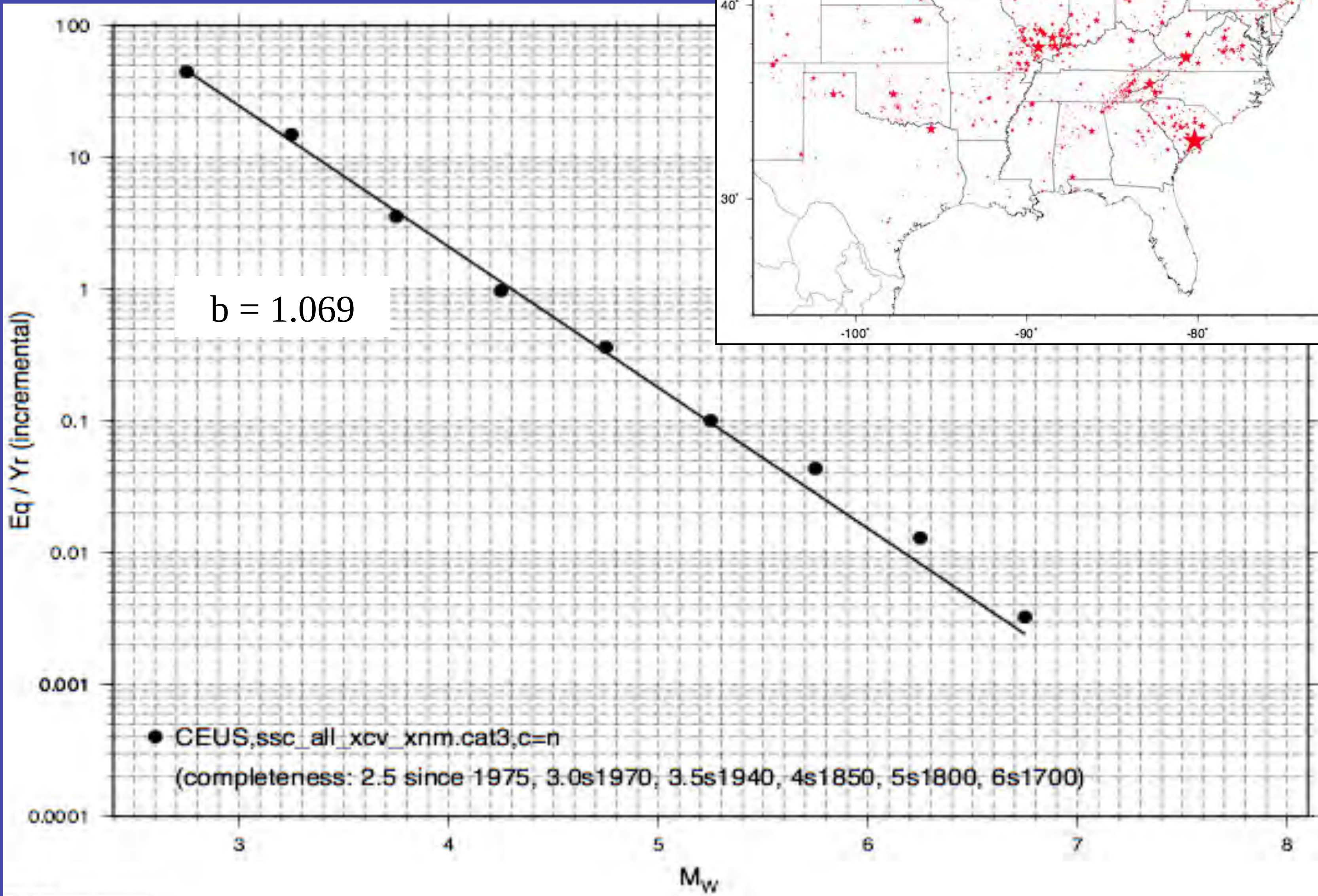
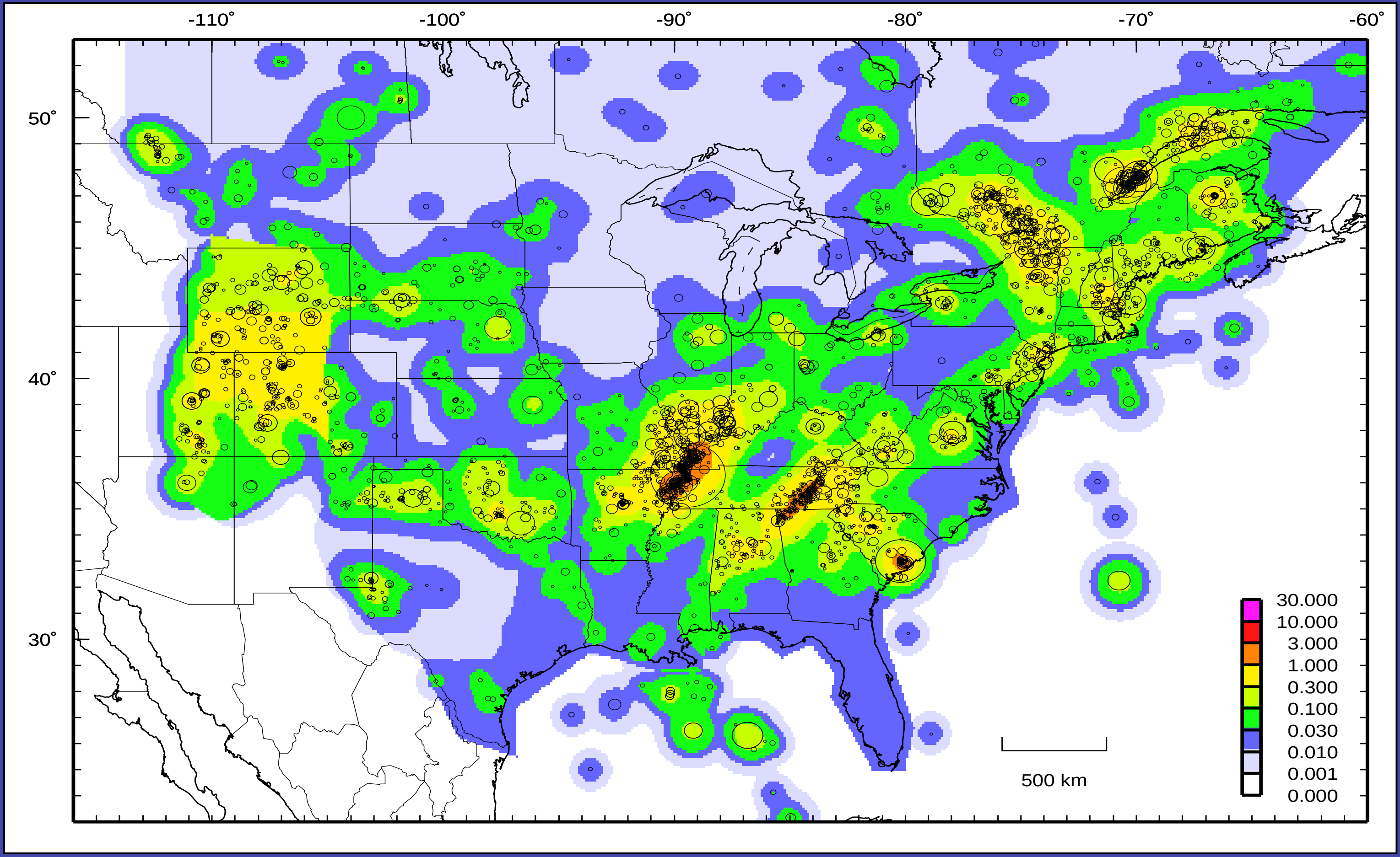
Recurrence: About one-tenth as many mag4 as mag3, one-tenth again as many mag5, and so on…





Then:

- ✓ Impose a grid (usually 0.1 degree x 0.1 degree)
- ✓ Count eqks in grid cells using completeness rules
- ✓ Apply recurrence models to estimate future rates
- ✓ Smooth the gridded rates (2-D gaussian or nearest-neighbor)



Repeating Large Magnitude Earthquake (RLME) sources in the CEUS

Updated:

- New Madrid
- Charleston
- Meers
- Cheraw

New:

- Charlevoix
- Wabash Valley
- Commerce Geophysical Lineament
- East Rift Margin
- Marianna

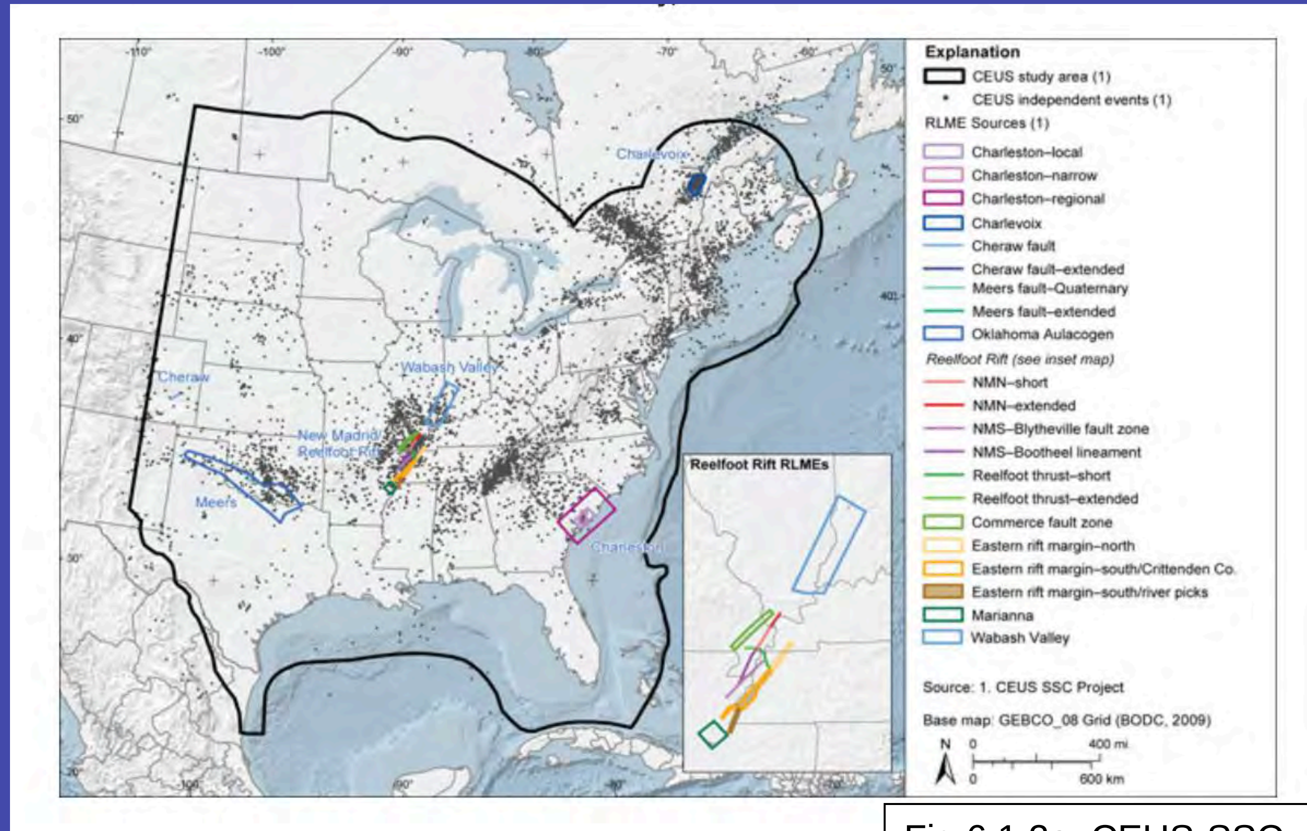


Fig 6.1.2a, CEUS-SSC

All 2014 models use results from CEUS-SSC

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- ✓ We need:
  - Fault locations
  - Earthquake sizes
  - Earthquake rates (slip rates, recurrence)
- ✓ All source models are informed by paleoseismic & paleoliquefaction data
- ✓ Some RLMEs have been observed historically (New Madrid, Charleston, Charlevoix), others not (Wabash Valley, Cheraw, Meers)
- ✓ No simple relationship between RLME and current seismicity (consider New Madrid & Cheraw)

Charleston

- 1886 earthquake

  M7.3 from Johnston (1996) (intensity data)

  M6.9 from Bakun & Hopper (2004) (intensity data)

  No tectonic fault Identified

- Paleoliquefaction => several large eqks since mid-Holocene

- 2014 Model:

  RLME with fixed-magnitude (characteristic) earthquakes distributed throughout a zone on vertical, strike-slip (virtual) faults.

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Location

2002:

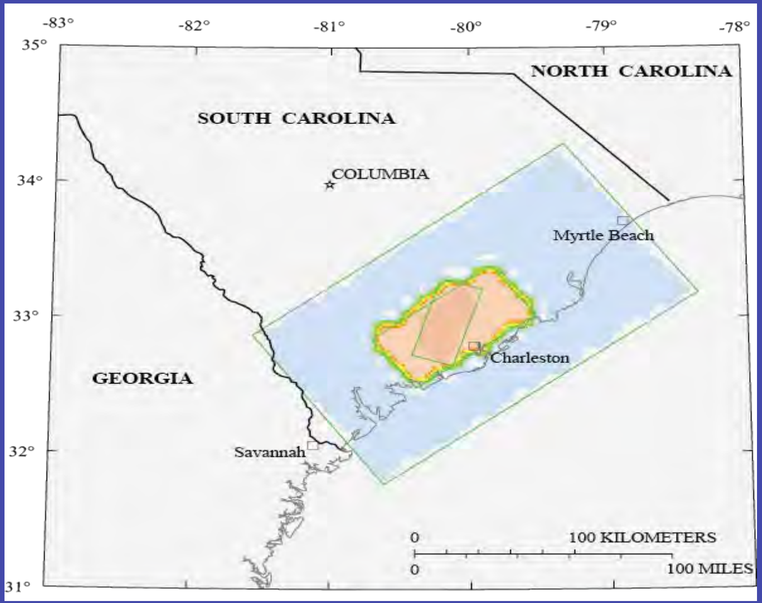
1) "Narrow" zone along proposed Woodstock fault (Talwani, 1982) and zone of river anomalies (Marple & Talwani, 1993)
2) "Broad" zone encompassing liquefaction (Obermeier et al, 1990)

2008:

Expand Broad zone offshore to enclose Helena Banks faults

2014 (based on CEUS-SSC):

1) "Narrow" zone (modified from USGS)
2) "Regional" zone (modified from USGS)
3) "Local" zone enclosing greatest 1886 shaking, greatest density of 1886 and prehistoric liquefaction features, several faults, Middleton Place–Summerville seismicity zone (new)



Logic-tree node for characteristic magnitude

Magnitude	Weight
6.7	0.10
6.9	0.25
7.1	0.30
7.3	0.25
7.5	0.10

The distribution encompasses estimates of:

- ✓ 7.3 by Johnston (1996)
- ✓ 6.9 by Bakun & Hopper (2004)

Logic-tree node for rates

- Alternative rates from alternative interpretations of liquefaction data
- Record back to mid-Holocene, but complete for only ~2000 years
- Combine alternative models:

2000 yrs, 4 eqks	**5500 yrs, 4 eqks**	**5500 yrs, 5 eqks**	**5500 yrs, 5 eqks**	**5500 yrs, 6 eqks**	**Simulation Weight**
0.0047	0.0047	0.0027	0.0019	0.0022	0.101
0.0031	0.0031	0.0019	0.0013	0.00015	0.244
0.0021	0.0021	0.0013	0.00092	0.0011	0.310
0.0013	0.0013	0.00088	0.00064	0.00078	0.244
0.00068	0.00068	0.00050	0.00034	0.00046	0.101
0.80	0.04	0.06	0.04	0.06	**Model Weight**

- Composite, weighted rate = 0.00210 eqks/yr (recurrence = 476 yrs)

Logic-tree node for clustering

- Paleoliquefaction evidence for repeating large earthquakes since the mid-Holocene.
- But, the lack of tectonic landforms suggests long-term quiescence.
- Thus, the modern activity is either unique or part of a short-term cluster. But, we can’t assume the cluster ended in 1886.

So…

Assume 0.9 weight for “in cluster” and 0.1 for “out of cluster”

0.00210 x 0.9 => 0.00189 eqk/yr (476 yrs => 529 yrs)

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Charlevoix

- Source of repeating large eqks

  Historical record (Lamontagne et al, 2008)

  Paleo record (Tuttle & Atkinson, 2010)

- Reactivation of old rift faults

  Parallel to Iapetan margin & St Lawrence seismic trend

  Possibly complicated by Devonian impact structure and/or post-glacial rebound

- 2014 Model:

  RLME with fixed-magnitude (characteristic) earthquakes distributed throughout a zone on vertical, strike-slip (virtual) faults.

Geometry

2008 and earlier:

Modeled as part of the CEUS background seismicity

2014 (based on CEUS-SSC):

Source zone encompassing local seismicity, mapped rift faults, and the impact structure

Logic-tree node for characteristic magnitude

Magnitude	Weight
6.75	0.2
7.0	0.5
7.25	0.2
7.5	0.1

The distribution:

- ✓ Peaks at M7, the preferred size of 1663 eqk from Lamontagne et al (2008) (intensity data)
- ✓ Accounts for uncertainty of M7 +/- 0.25
- ✓ Encompasses larger 1663 estimate from Ebel (2009)

Logic-tree node for rates

- Alternative rates from alternative interpretations of liquefaction and seismicity data
- Combine alternative models:

1663 & 1870	1663 & 1870 + 1 eqk in 6–7 kyr	1663 & 1870 + 2 eqks in 9.5–10.2 kyr	Simulation Weight
0.0093	0.0013	0.00098	0.101
0.0067	0.00084	0.00067	0.244
0.0042	0.00057	0.00047	0.310
0.0022	0.00037	0.00032	0.244
0.00077	0.00019	0.00018	0.101
0.2	0.6	0.2	**Model Weight**

- Composite, weighted rate = 0.00137 eqks/yr (recurrence = 730 yrs)
- No clustering branch

New Madrid

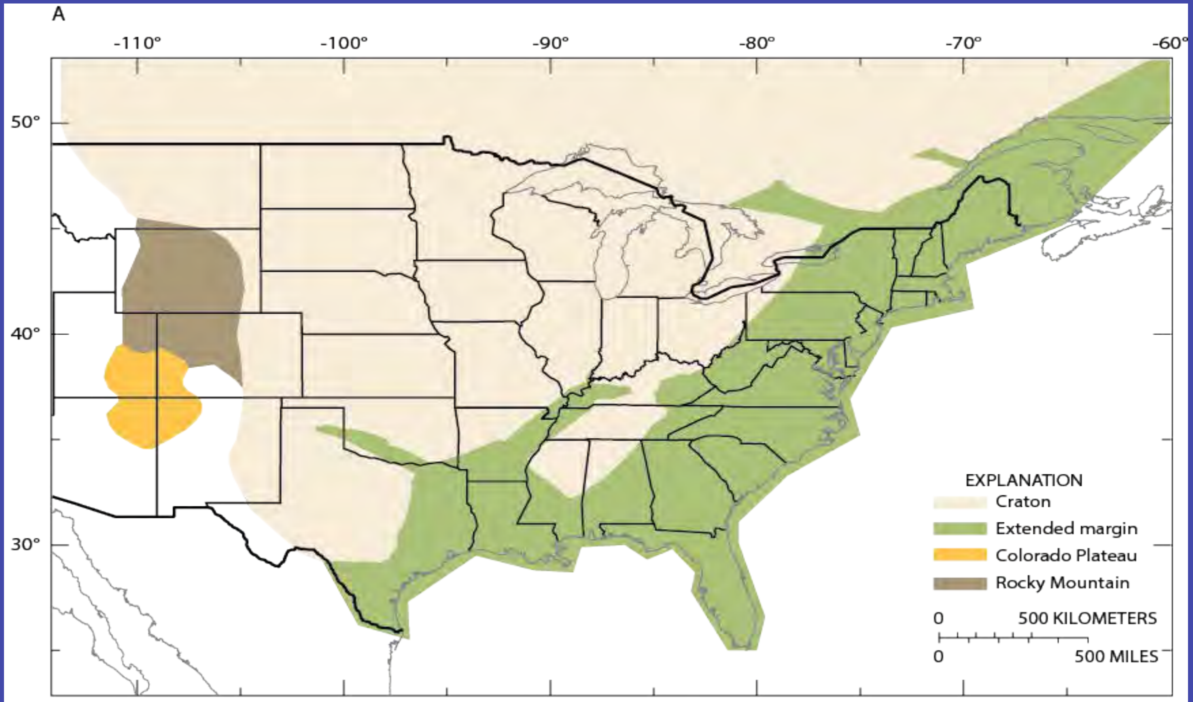
- ✓ RLME model primarily based on:
  - modern seismicity trends => locations
  - intensity data from 1811–1812 => magnitudes
  - paleoliquefaction data => rates
- ✓ Geodesy & seismic imaging => current high rate of seismicity is not sustainable long-term
- ✓ Origin of stresses?

2014 Model:

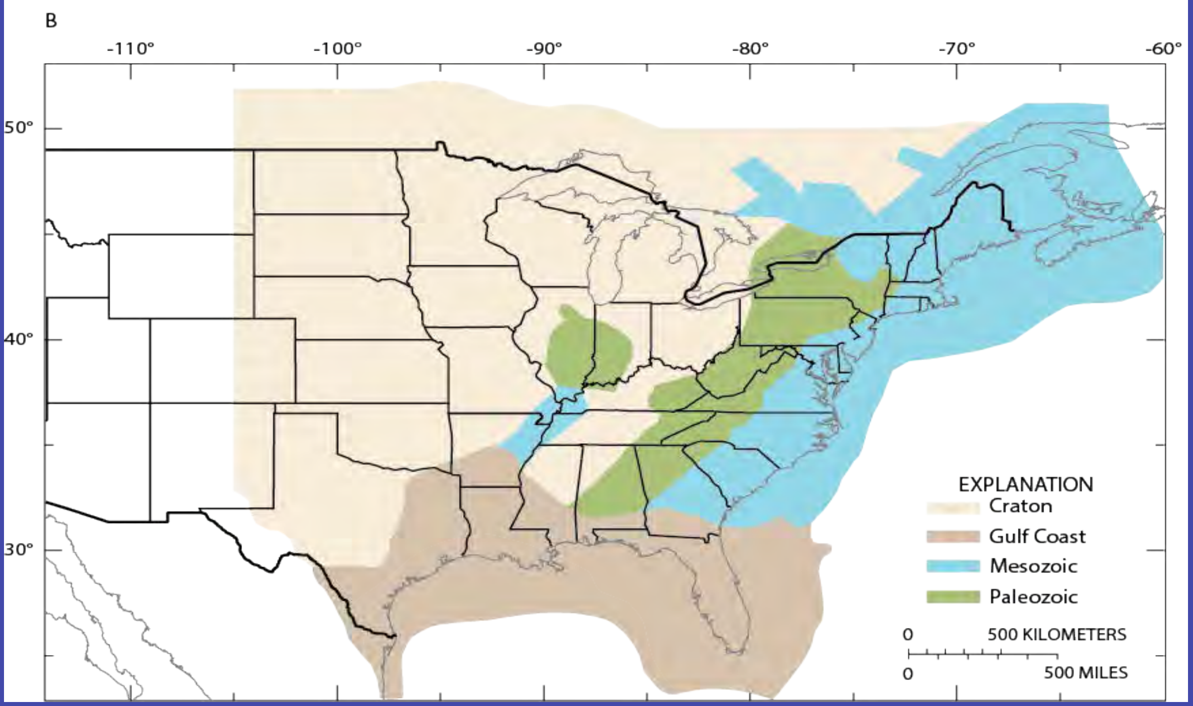
RLME: earthquakes distributed on several psuedo-faults, with clustering

M_{max} in the CEUS

Alternative m_{max} zonations (Petersen and others, 2014)



Based on 2008 USGS



Based on 2012 CEUS-SSC

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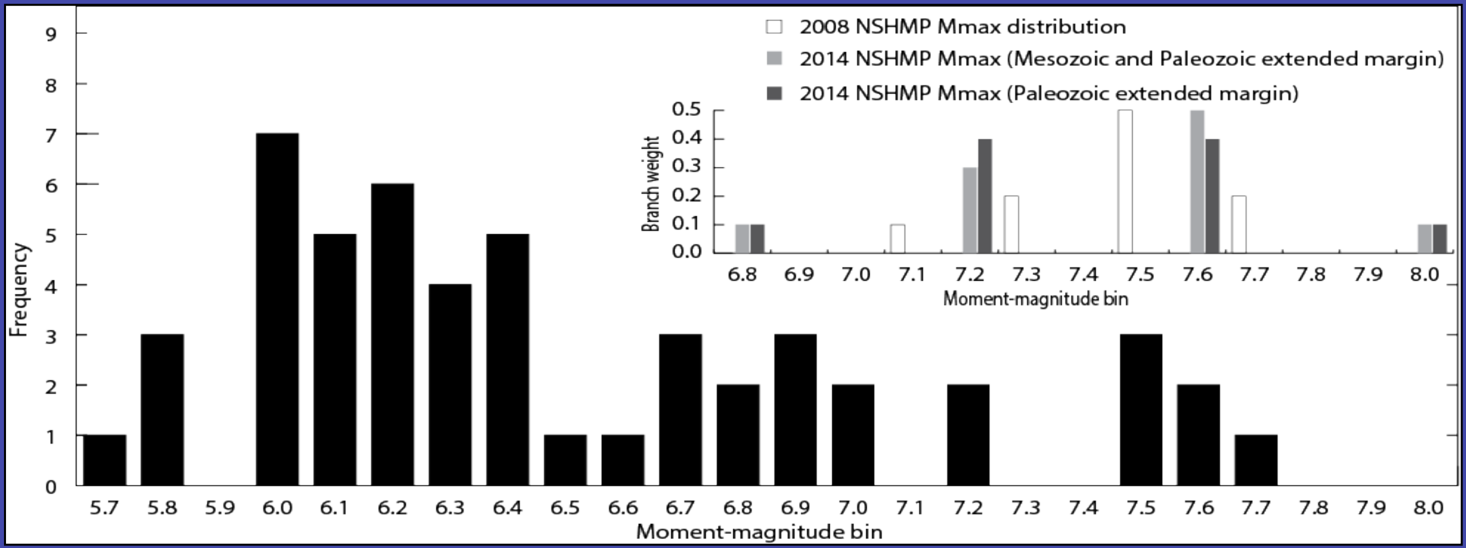
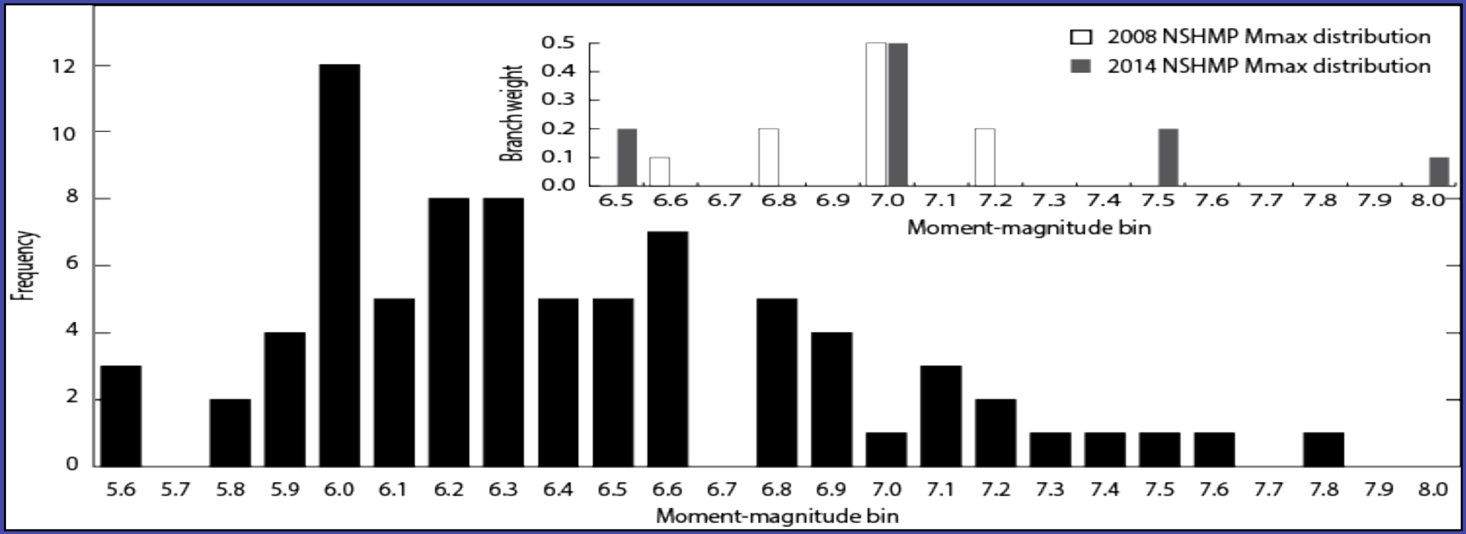
Mmax derived from analysis of large eqks in stable continental regions worldwide – CEUS tectonic analog (Wheeler, 2014).



SCR margins



SCR cratons

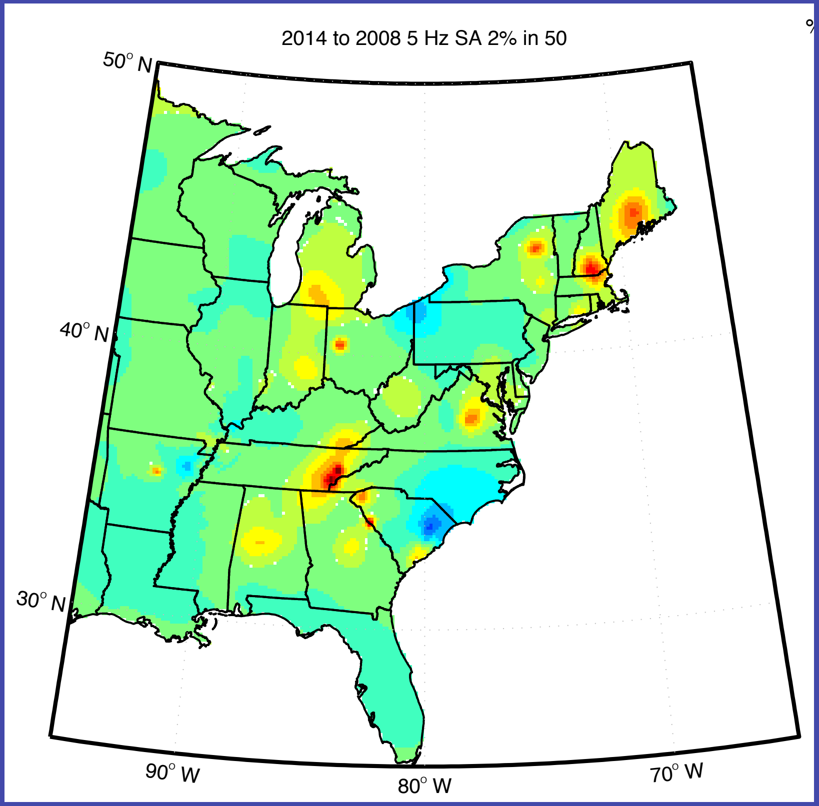
Ground Motion Models in the CEUS

Models and weights

GMM	Type	Kappa	Geometrical Spreading	Weight		
				RLME	GridSrc	>500km
Frankel et al. (1996)	Single corner	0.01	R^{-1}	0.06	0.06	0.16
Toro et al. (1997), Toro (2002)	Single corner	0.01	R^{-1}	0.11	0.13	0
Silva et al. (2002)	Single corner	0.01	R^{-1}	0.06	0.06	0
Campbell (2003)	Hybrid	0.01	R^{-1}	0.11	0.13	0.17
Tavakoli & Pezeshk (2005)	Hybrid	0.01	R^{-1}	0.11	0.13	0.17
Atkinson & Boore (2006’)	Dynamic corner	0.02	$R^{-1.3}$	0.22	0.25	0.3
Pezeshk et al. (2011)	Hybrid	0.02	$R^{-1.3}$	0.15	0.16	0.2
Atkinson (2008’)	Reference empirical	0.02	NA	0.08	0.08	0
Somerville et al. (2001)	Full waveform	0.01	NA	0.10	0	0

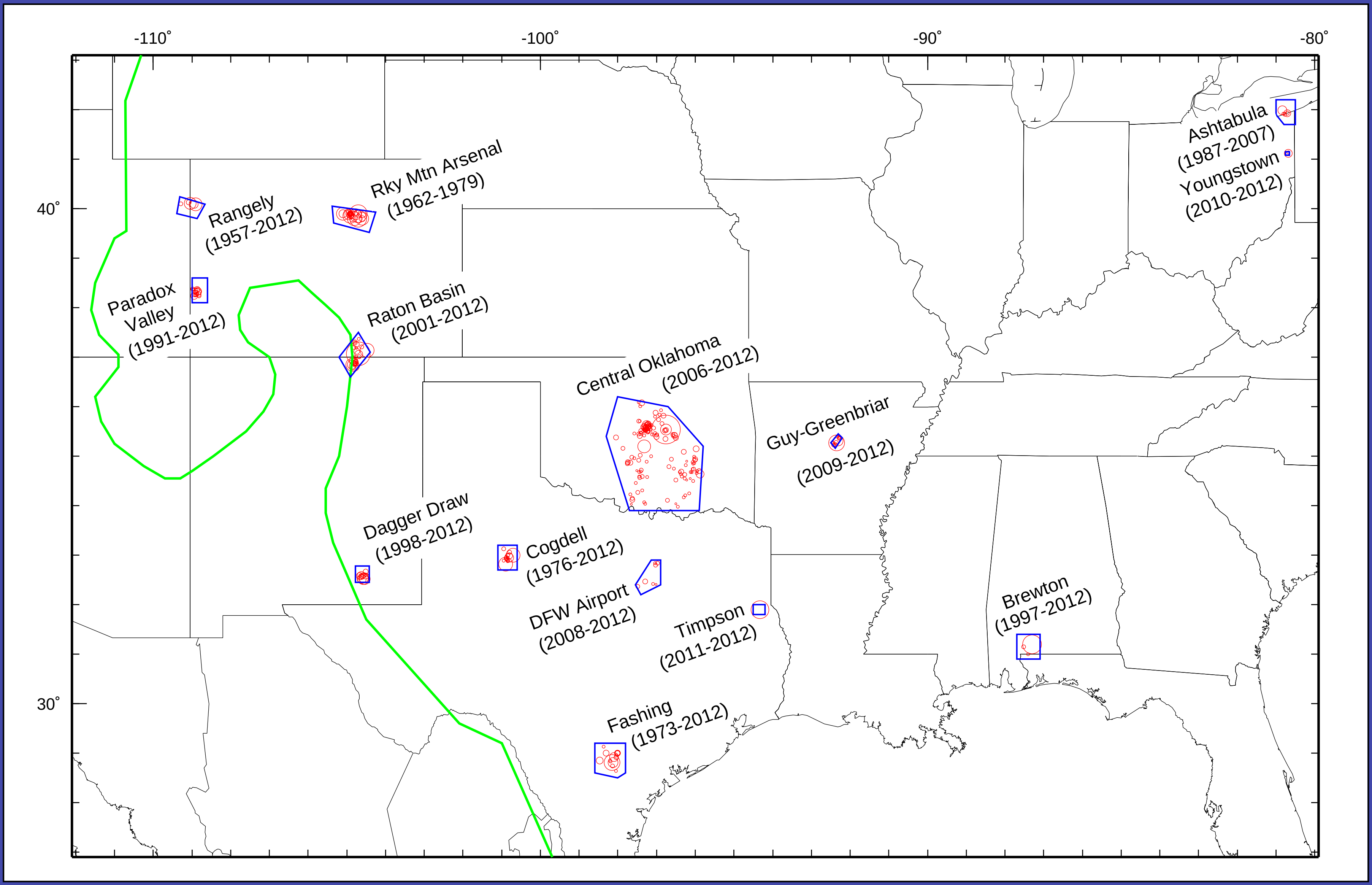
Most significant CEUS hazard changes for 2014

- Broad, regional decreases (~5-20%) primarily due to GMM changes (all frequencies)
- Local increases in some places due to adaptive smoothing and catalog additions (mid-high freq)
- Local changes due to updated fault models (all freq)



Treatment of induced seismicity

- Non-stationary, subject to commercial and policy decisions
- Not appropriate for long-term guidelines like building codes
- Don’t fit traditional PSHA
- We’re trying to develop short-term models; maybe this year predicts next year…?



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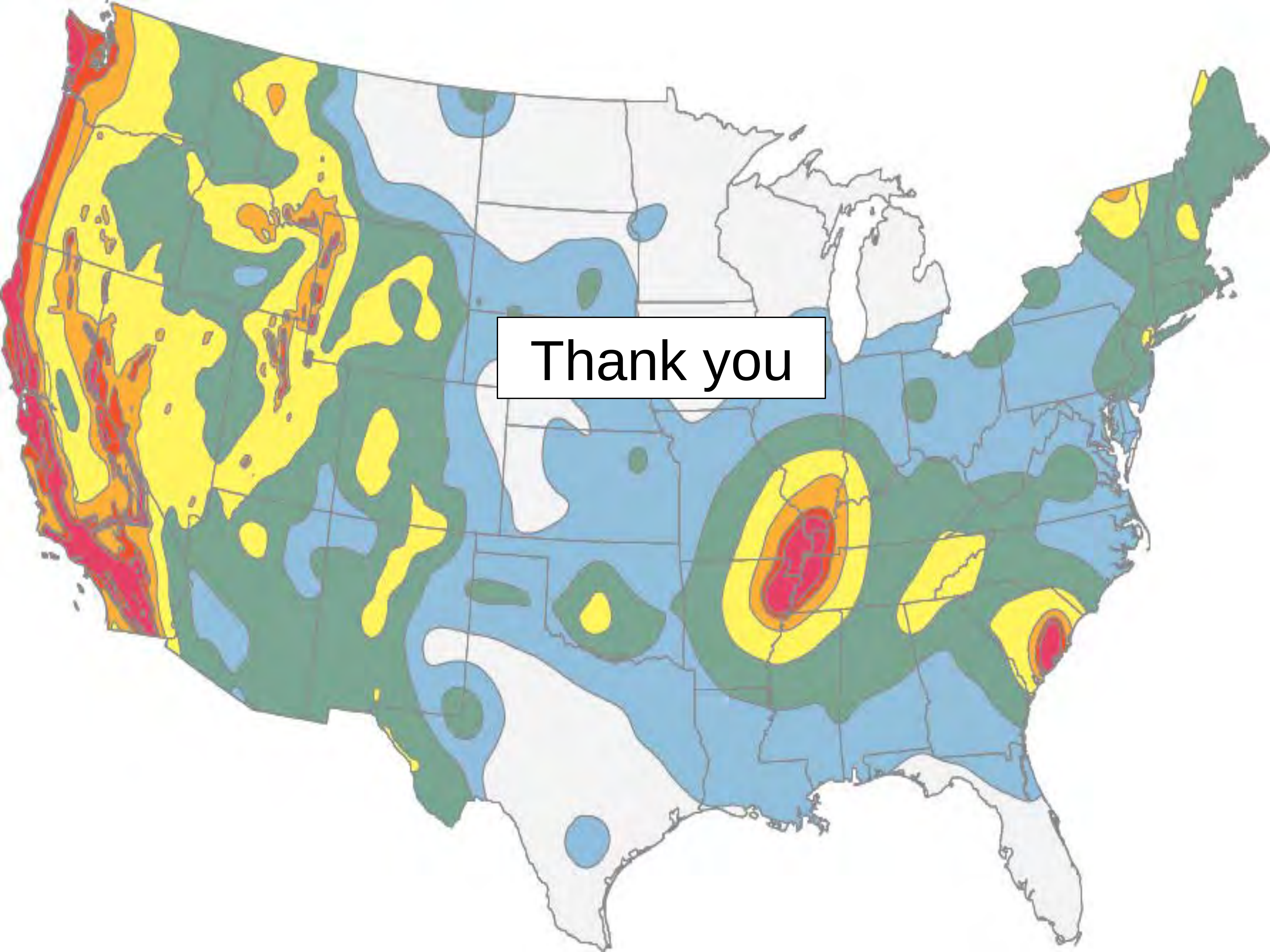
Thank you

NRC Training Workshop Wrap-Up:
Discussion and Recommendations

Participation of NRC Staff Members and Workshop Experts in Attendance

Facilitated by Lorraine Wolf, Auburn University
and Martitia Tuttle, M. Tuttle & Associates

Main Points

- ✧ Purpose of paleoliquefaction studies is to support PSHA
  - Identification of Recurrent Large Magnitude Earthquakes (RLME) sources and their characteristics
  - Provides critical information for evaluating nuclear power plant site safety
- ✧ Modern and historical analogs of eq-induced liquefaction
  - Valuable learning opportunities for interpreting past events
  - Serve as targets for paleoliquefaction studies
- ✧ Dating of liquefaction features
  - Well constrained ages of features are essential for correlating features across a region & for estimating timing, source areas, magnitudes, and recurrence times of paleoearthquakes
  - Poorly constrained ages can lead to large uncertainties of paleoearthquake characteristics

Recommendations for Research in Central and Eastern U.S.

- ✧ Studies of RLME source zones
  - New Madrid seismic zone and Marianna area – infrequent, high impact events; blind faults buried under basin sediments
  - Central Virginia seismic zone – any kind of surface deformation, including paleoliquefaction features, would be helpful
  - Eastern Tennessee seismic zone – is it a source of RLMEs?
  - Other potentially active zones (e.g., Charleston – need further, comprehensive evaluation
- ✧ Priorities
  - Central Virginia seismic zone – very high priority due to proximity to North Anna nuclear power plant and Washington D.C.; refine techniques for locating and dating sand dikes
  - Marianna area – more complete characterization of earthquake potential, timing, and related uncertainties; better understanding of relationship to Reelfoot Rift, NMSZ, and active seismicity

Recommendations for Research Cont’d

- ✧ Priorities
  - Eastern Tennessee seismic zone – did changing conditions over time (e.g., water table) affect the record of past earthquakes?
  - Modern earthquakes – positive and negative evidence (e.g., Christchurch earthquake induced liquefaction in some places and not in others)
  - New technology and data to identify active faults (e.g., LIDAR, potential field data - magnetic and gravity, ambient noise studies, high-resolution seismic data)
  - Drivers of seismicity – still big question