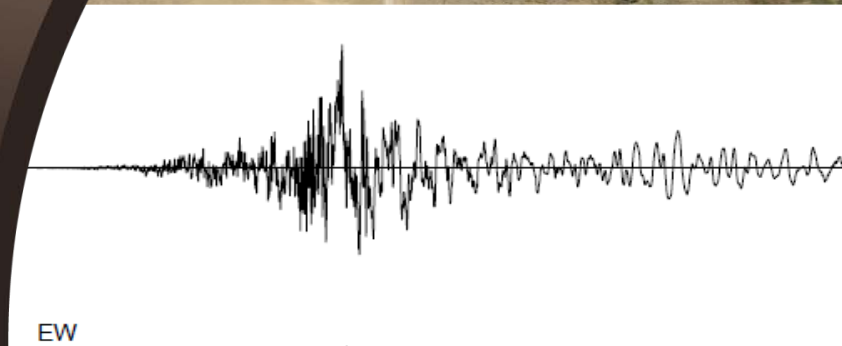
Best Practices in Dam and Levee Safety Risk Analysis

Seismic Hazard Analysis

13 July 2015



RECLAMATION
Managing Water in the West

US Army Corps of Engineers
BUILDING STRONG®

Outline

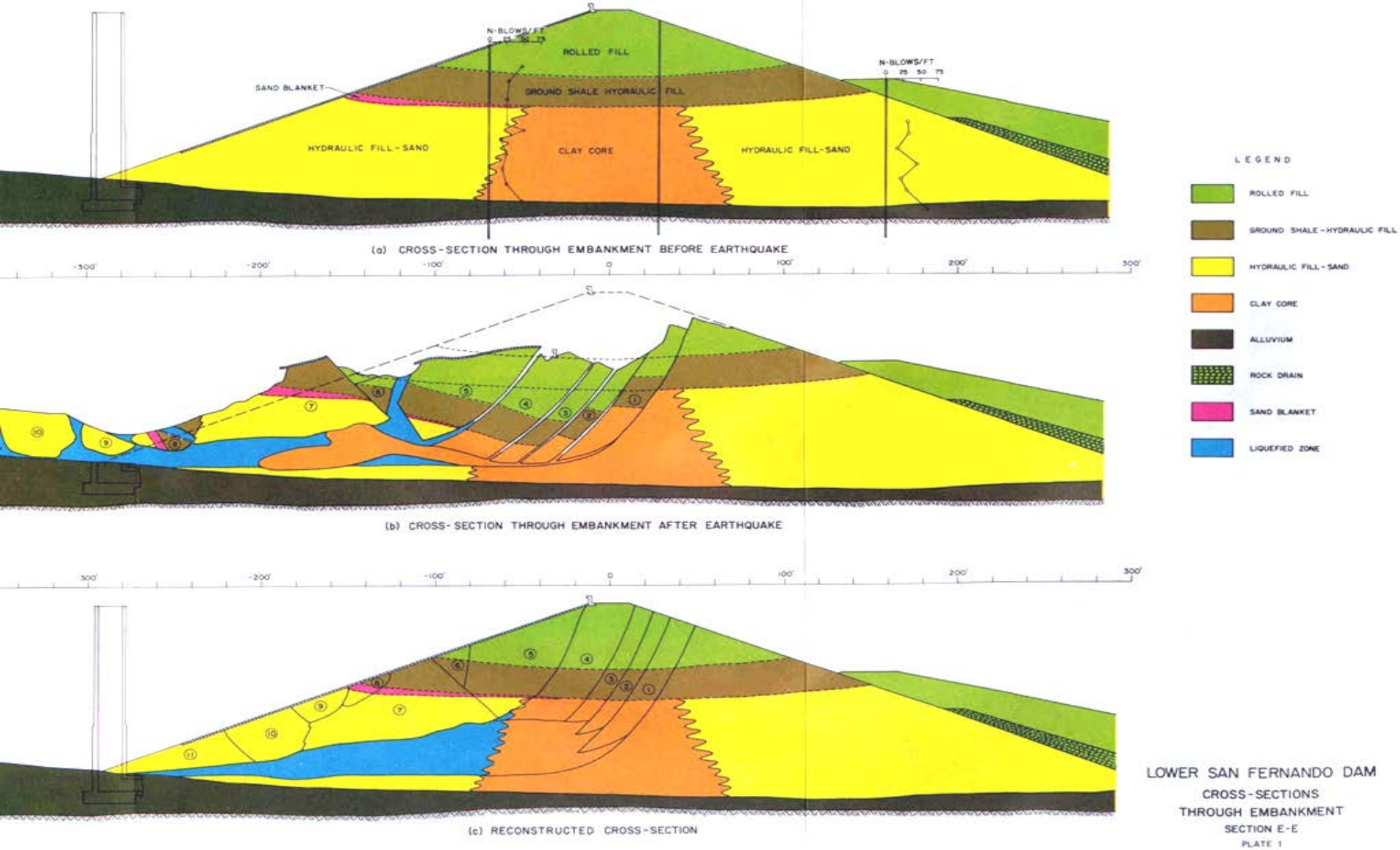
- Seismic Loading Failure modes
- Technical background: plate tectonics, types of faults
- Strong ground motion analysis
  - Seismic source characterization: fault source, areal sources
  - Attenuation (GMPEs)
  - De-aggregation plots
  - Site response: hazard curve, time histories, CMS
- Fault rupture hazard
- Summary and Conclusions

Seismic Failure Modes of Dams

- Sliding and cracking – concrete dams
- Liquefaction of foundation
- Embankment deformation and loss of freeboard
- Cracking of embankment leading to piping
- Fault displacement of dam foundation
- Overtopping from landslides into reservoir

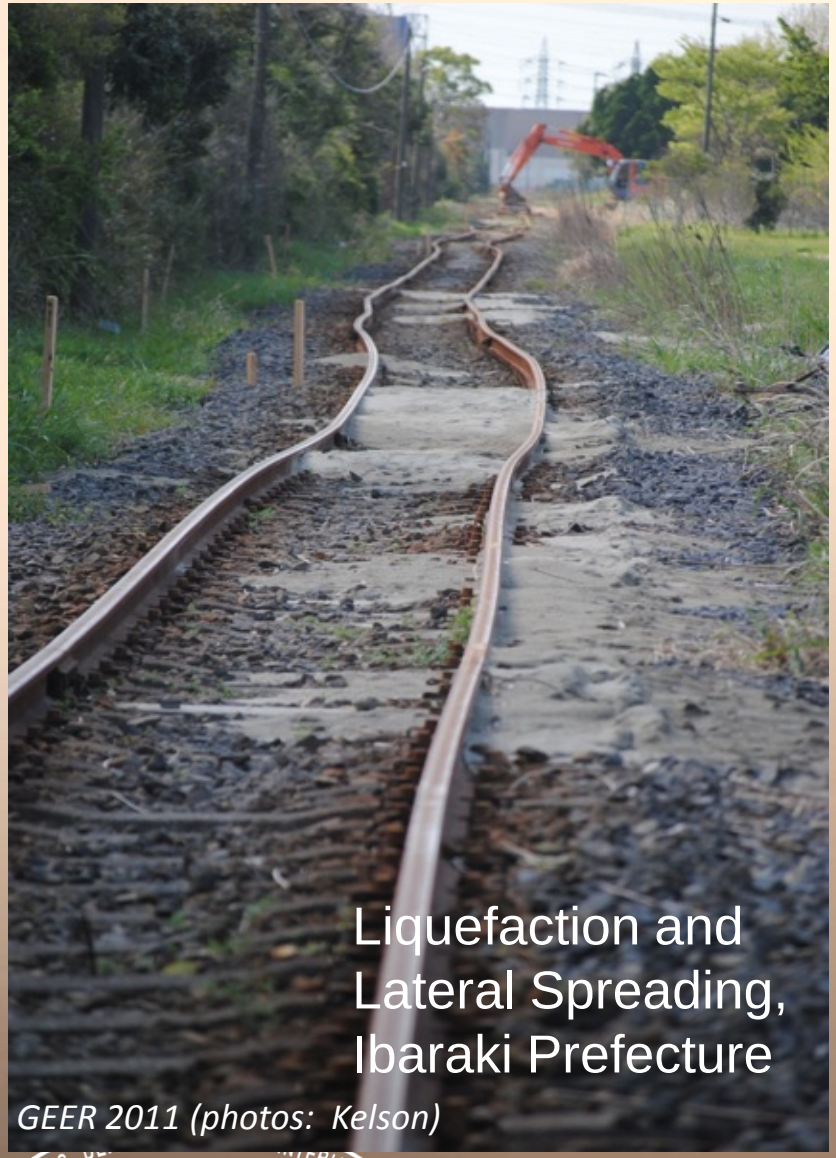
Lower Van Norman Dam February 9, 1971
M 6.6 earthquake at about 14 km = 0.5 g

Van Norman Dam pre and post earthquake cross sections



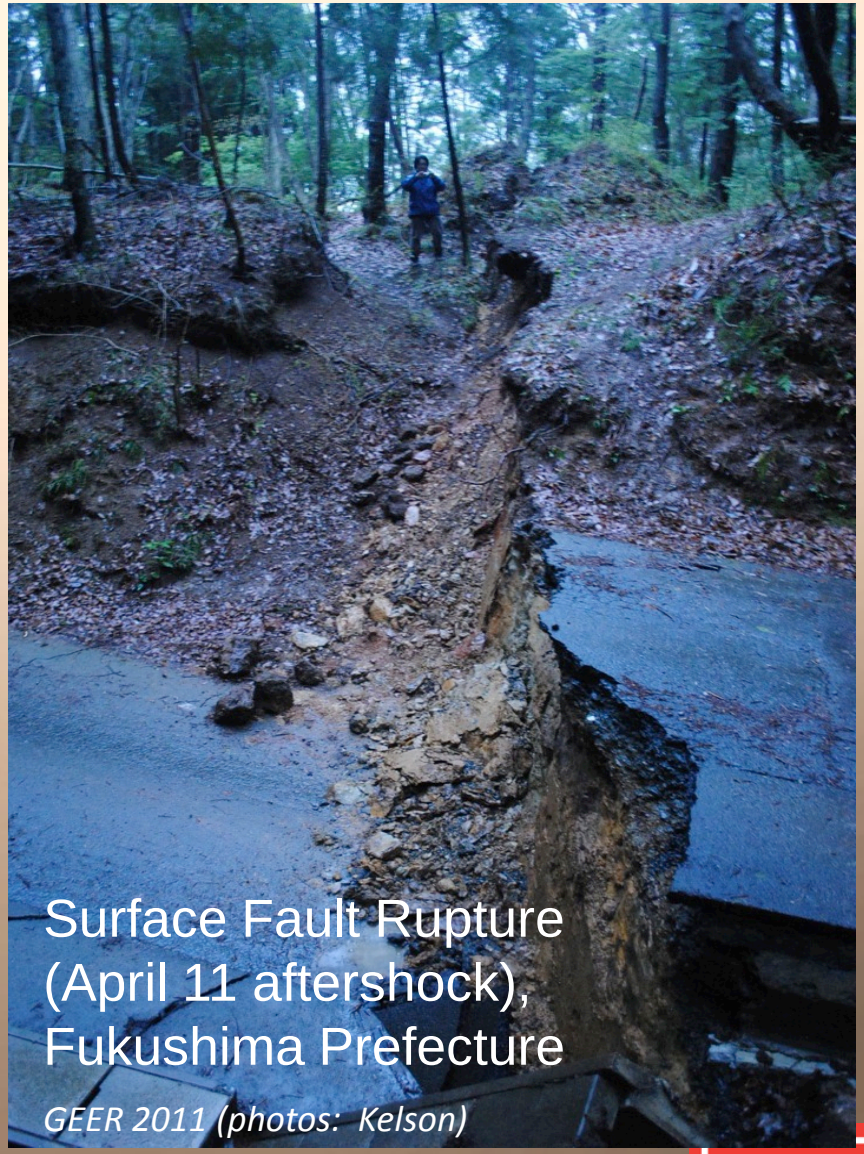
1999 **M**7.6 Chi-Chi Earthquake, Taiwan
Shih-Kang Dam “rupture”

2011 **M**9.0 Tohoku Earthquake, Japan



Liquefaction and Lateral Spreading, Ibaraki Prefecture

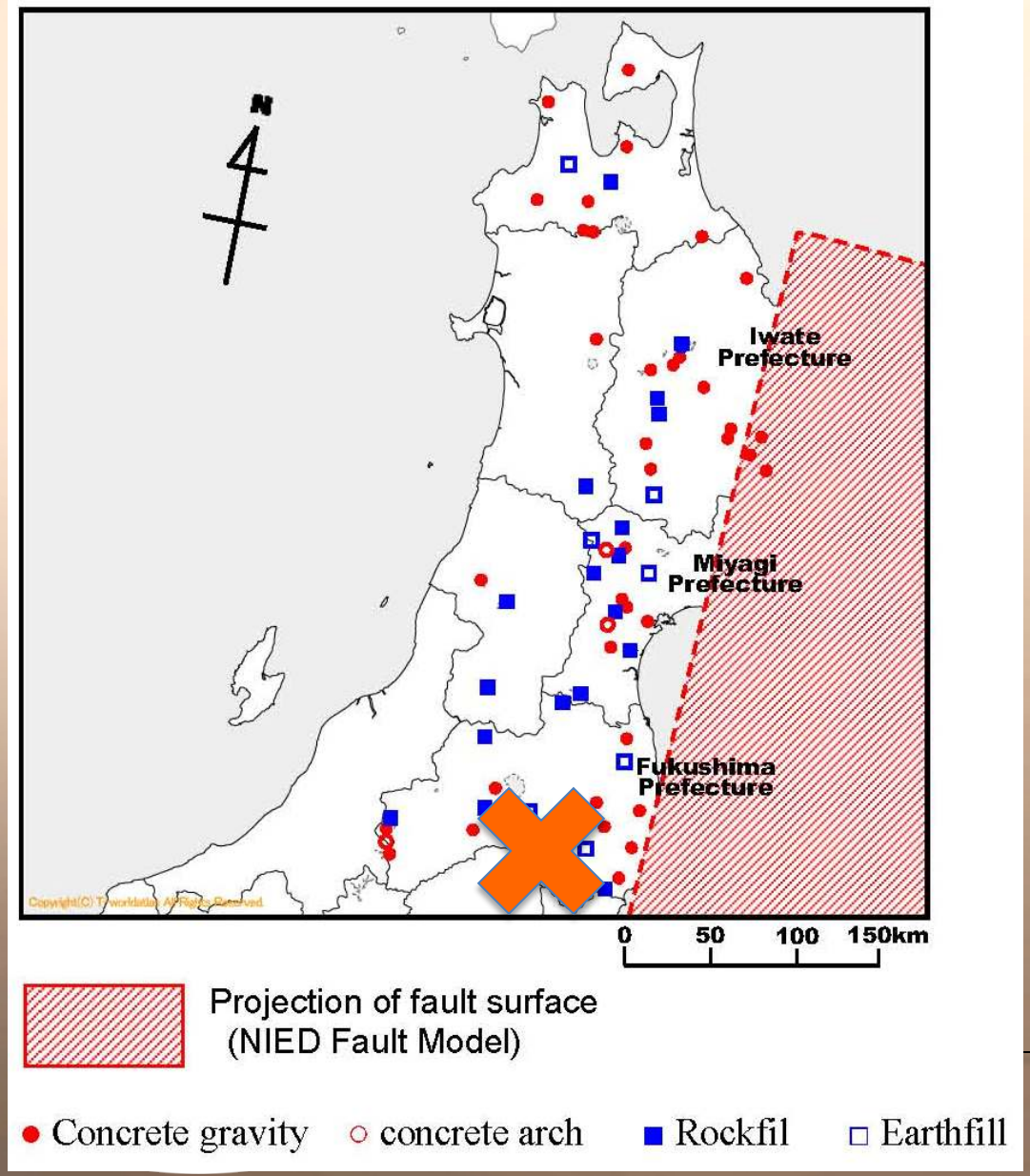
GEER 2011 (photos: Kelson)



Surface Fault Rupture (April 11 aftershock), Fukushima Prefecture

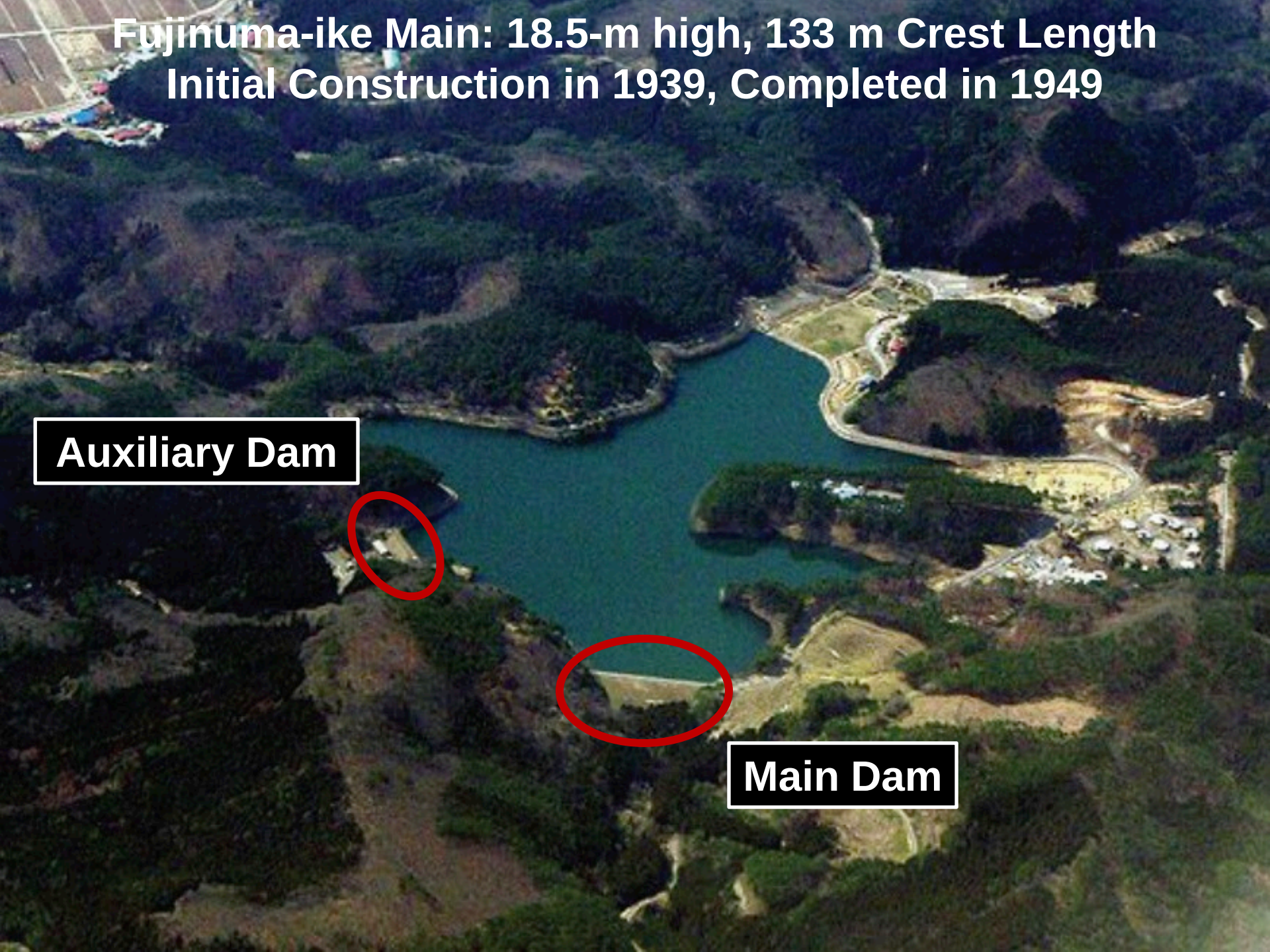
GEER 2011 (photos: Kelson)

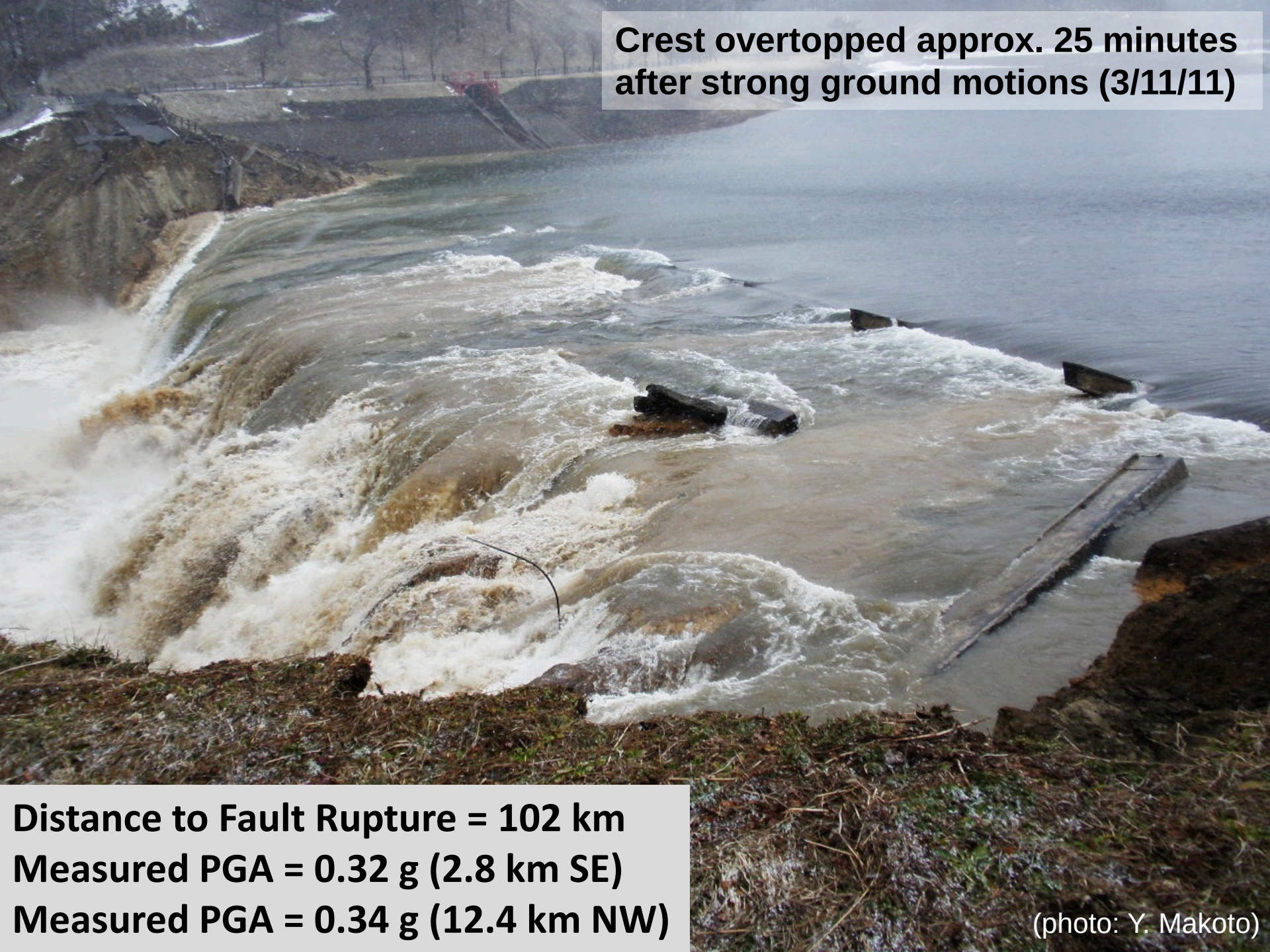
General Dam Performance



Dams generally performed well with minor or moderate cracking occurring at embankment dams.

Exception:
Fujinuma Dam
Non-regulated,
18.5 m-high earthfill
Irrigation dam


Fujinuma-ike Main: 18.5-m high, 133 m Crest Length
Initial Construction in 1939, Completed in 1949
Auxiliary Dam
Main Dam


Crest overtopped approx. 25 minutes after strong ground motions (3/11/11)
Distance to Fault Rupture = 102 km
Measured PGA = 0.32 g (2.8 km SE)
Measured PGA = 0.34 g (12.4 km NW)
(photo: Y. Makoto)

Fujinuma Dam – View of Breach of Main Dam from Left Abutment

(April 23, 2011)

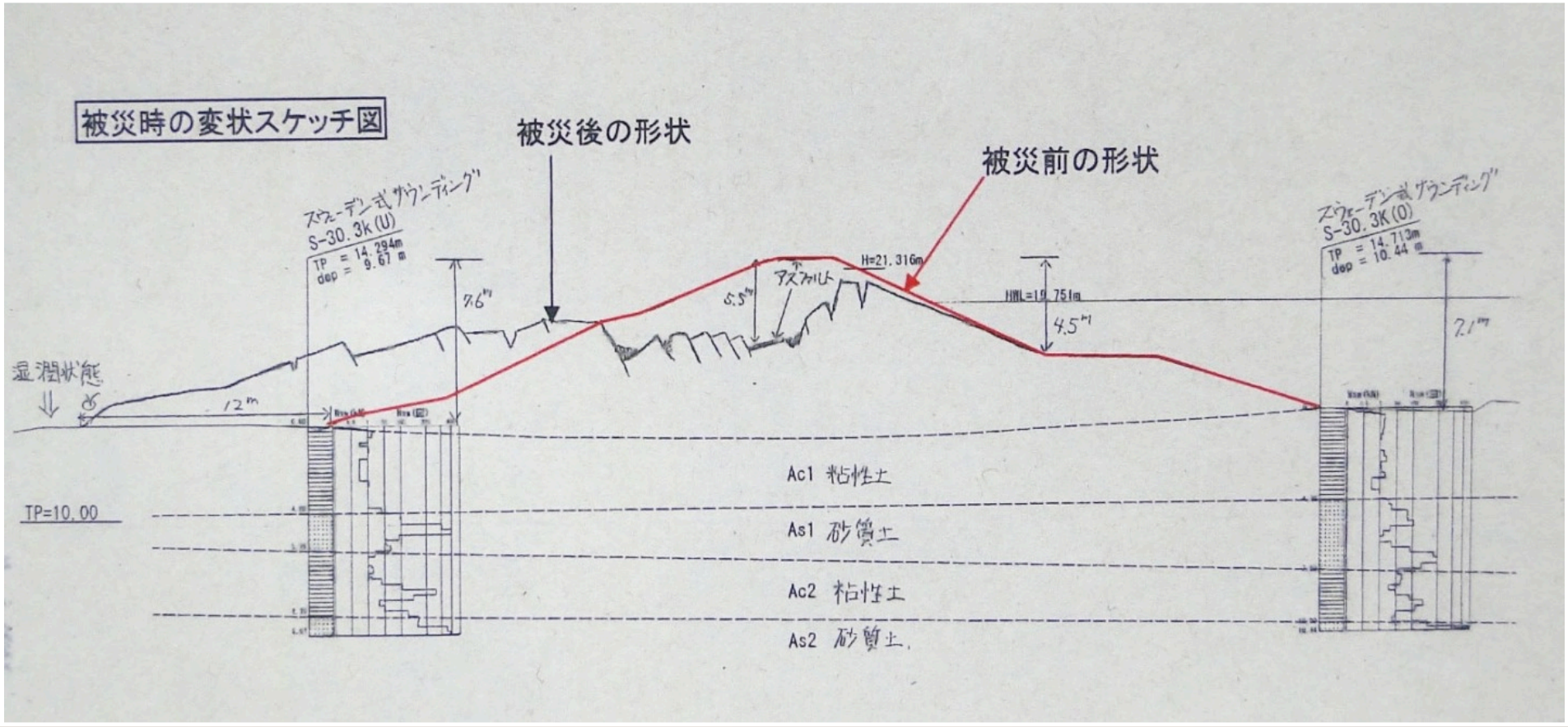
View of Upstream Side of Failed Auxiliary Dam
Rapid Drawdown Following Failure of Main Dam?

Photo: K. Kelson, April 23, 2011)

Collapse of Approach Road and Levee Fill on Naruse River Right Levee, River Kilometer 30.0

Drawing Depicting Major Levee Damage along Naruse River Due to Earthquake-Induced Foundation Liquefaction

(from MLIT, 2011)



Aerial View of Treated and Untreated Levee Reach along Naruse River Right Levee at River Kilometer 15.0 - 14.7

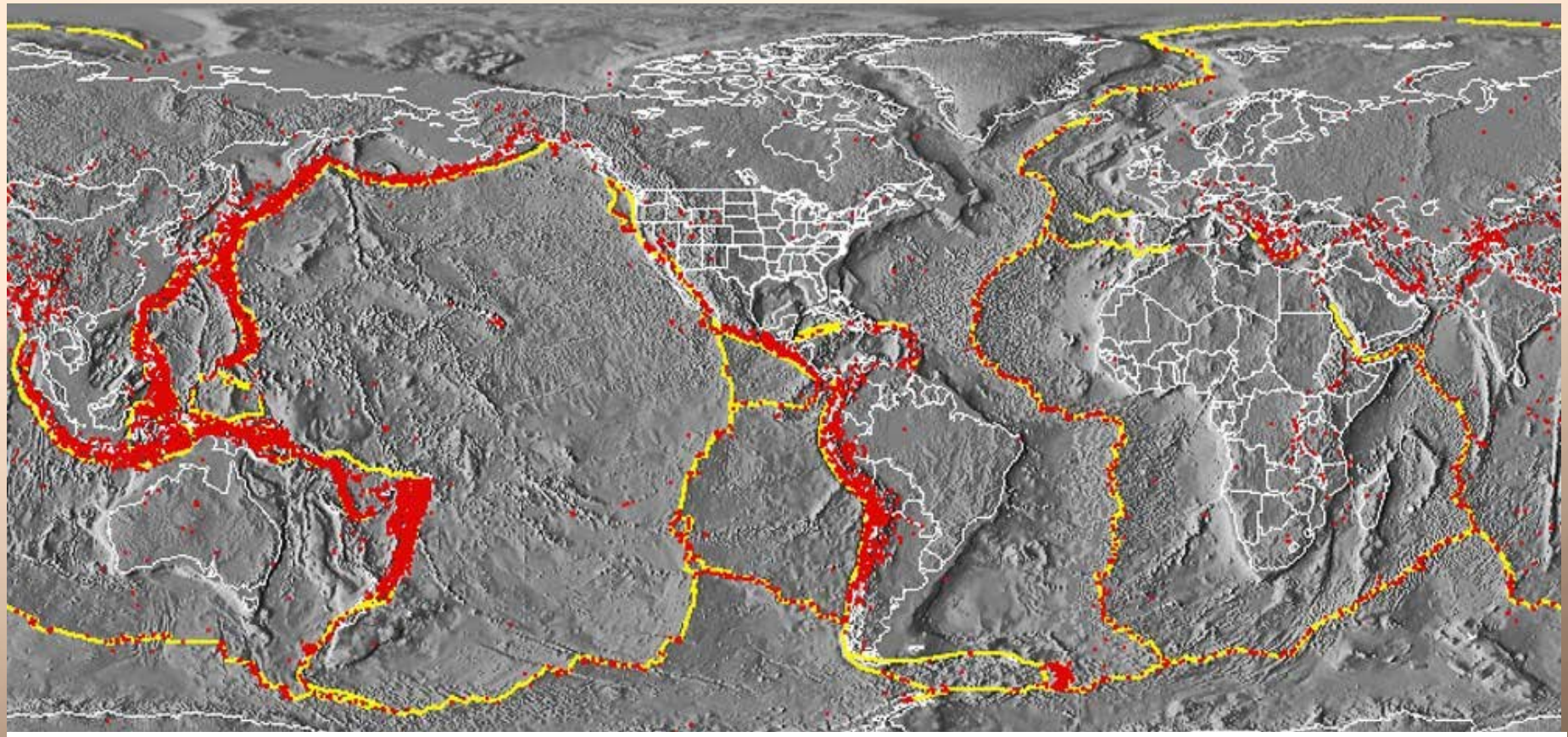
(adapted from Google Earth 2011)

View of Treated and Untreated Levee Reach along Naruse River Right Levee at River Kilometer 15.0 - 14.7

Right Levee Naruse River, Miyagi Prefecture

Eai River, Miyagi Prefecture

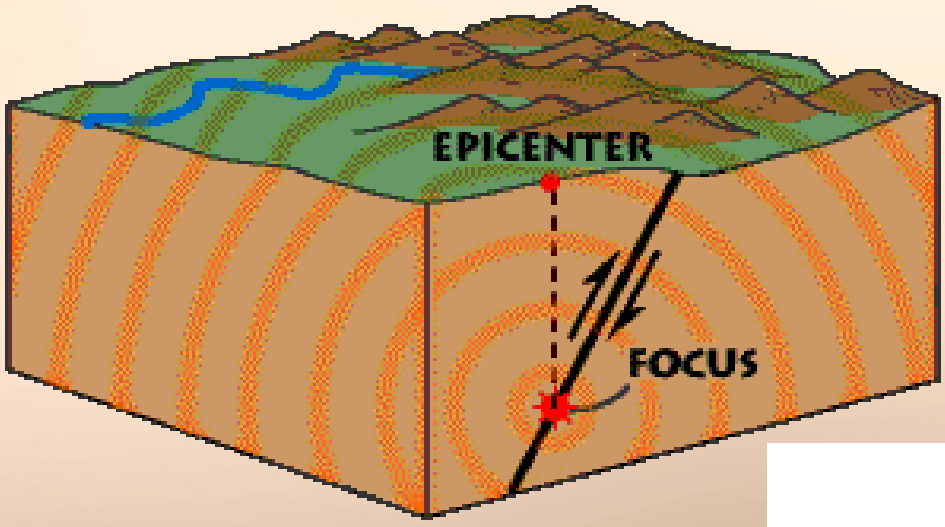
Earthquakes 101

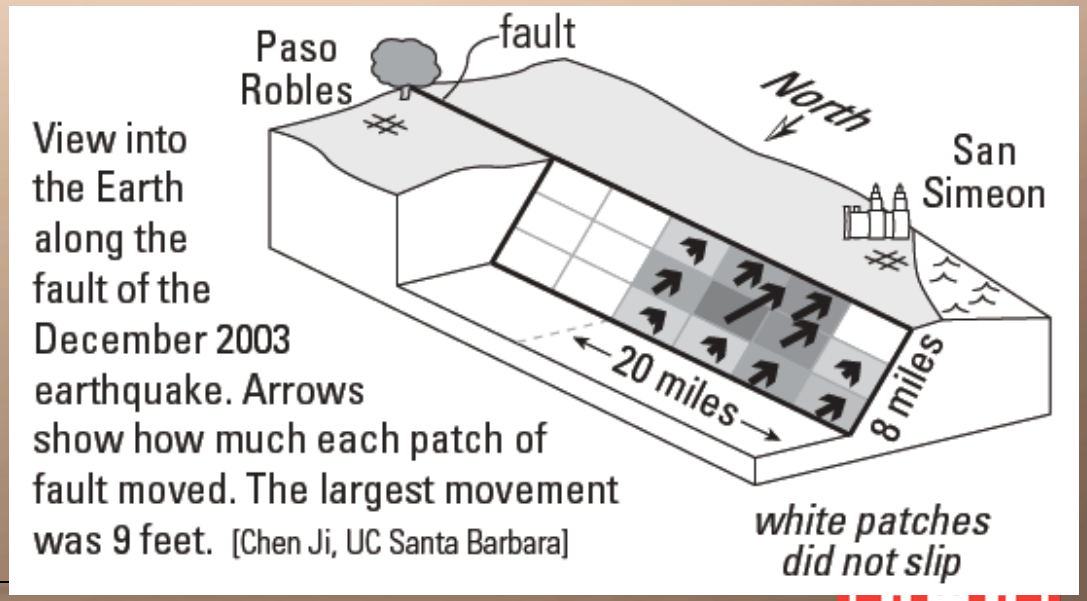


Earthquake!

- Release of energy and rupture of Earth's crust (measured via *magnitude*)
- Radiating waves felt at ground surface (measured via *intensity*)

Earthquakes 101





View into the Earth along the fault of the December 2003 earthquake. Arrows show how much each patch of fault moved. The largest movement was 9 feet. [Chen Ji, UC Santa Barbara]

Plate Tectonics

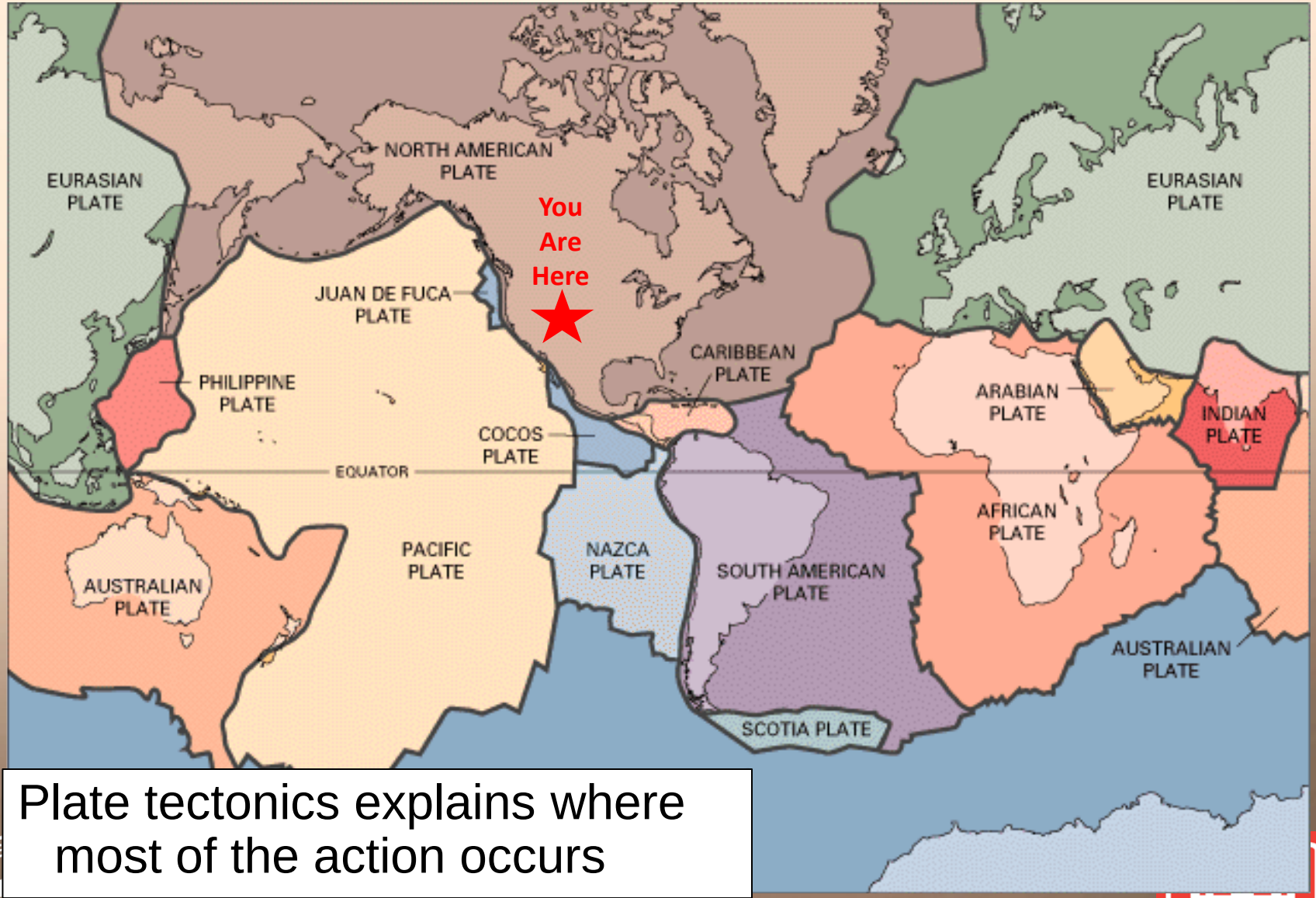
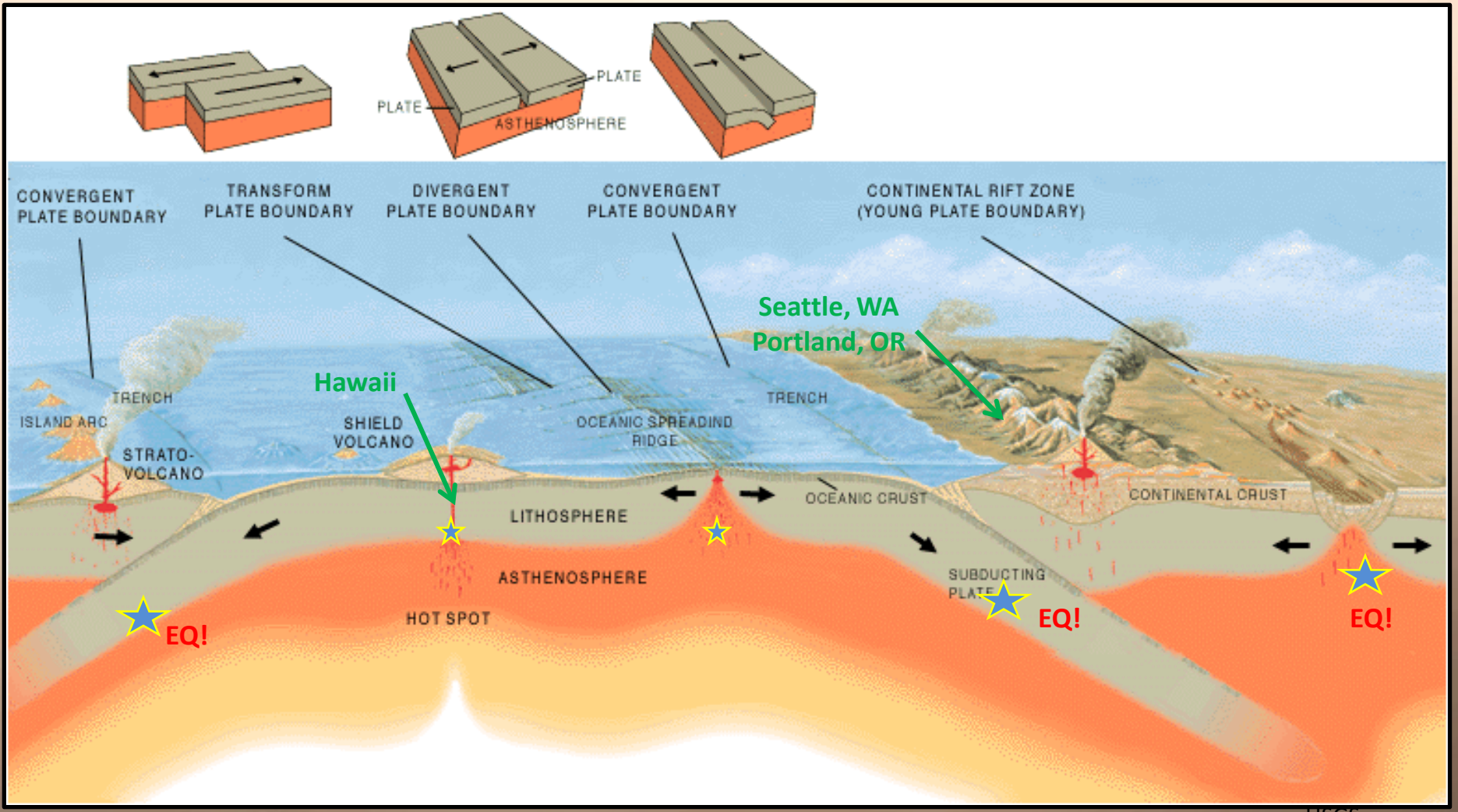


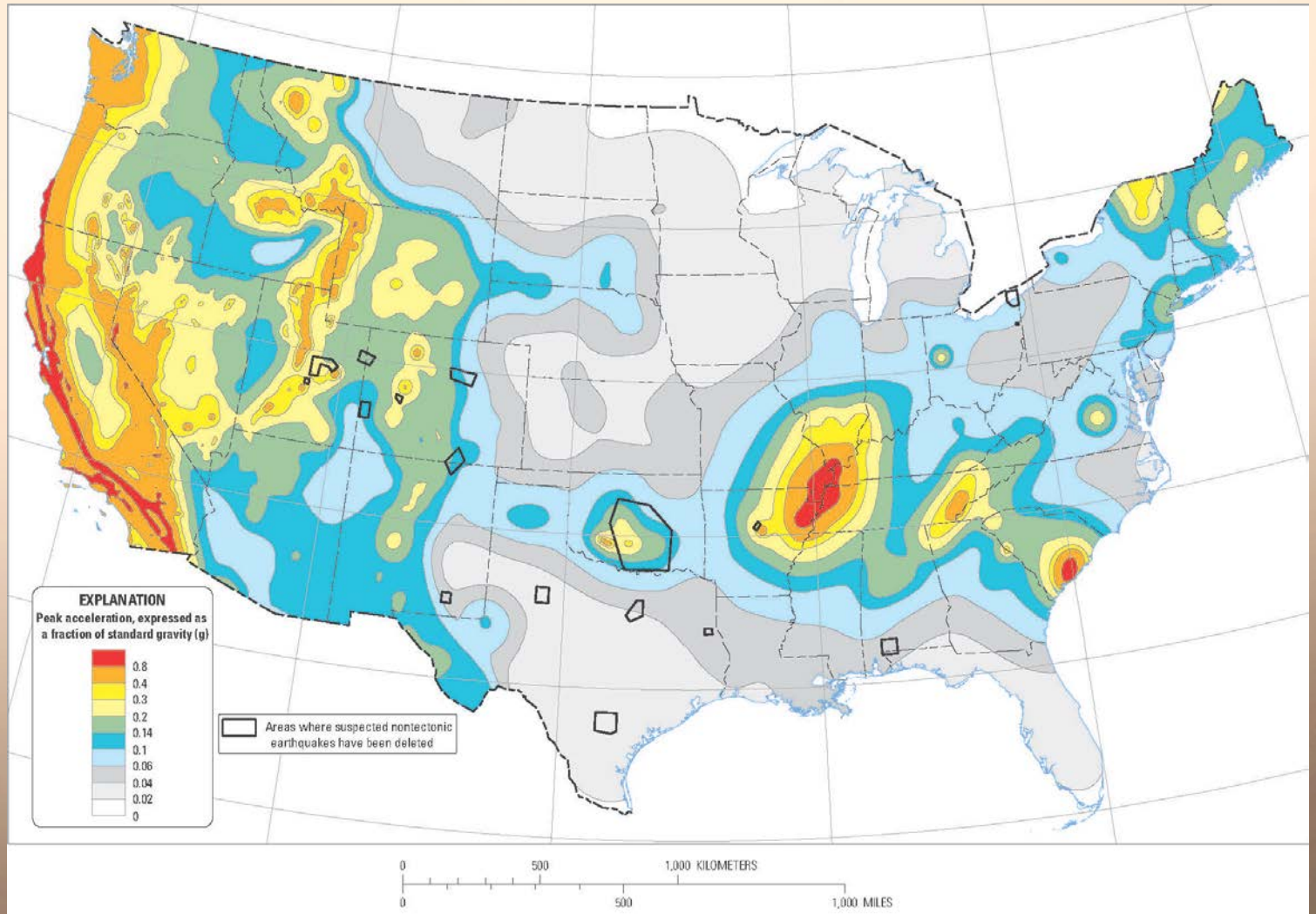
Plate tectonics explains where most of the action occurs

USGS

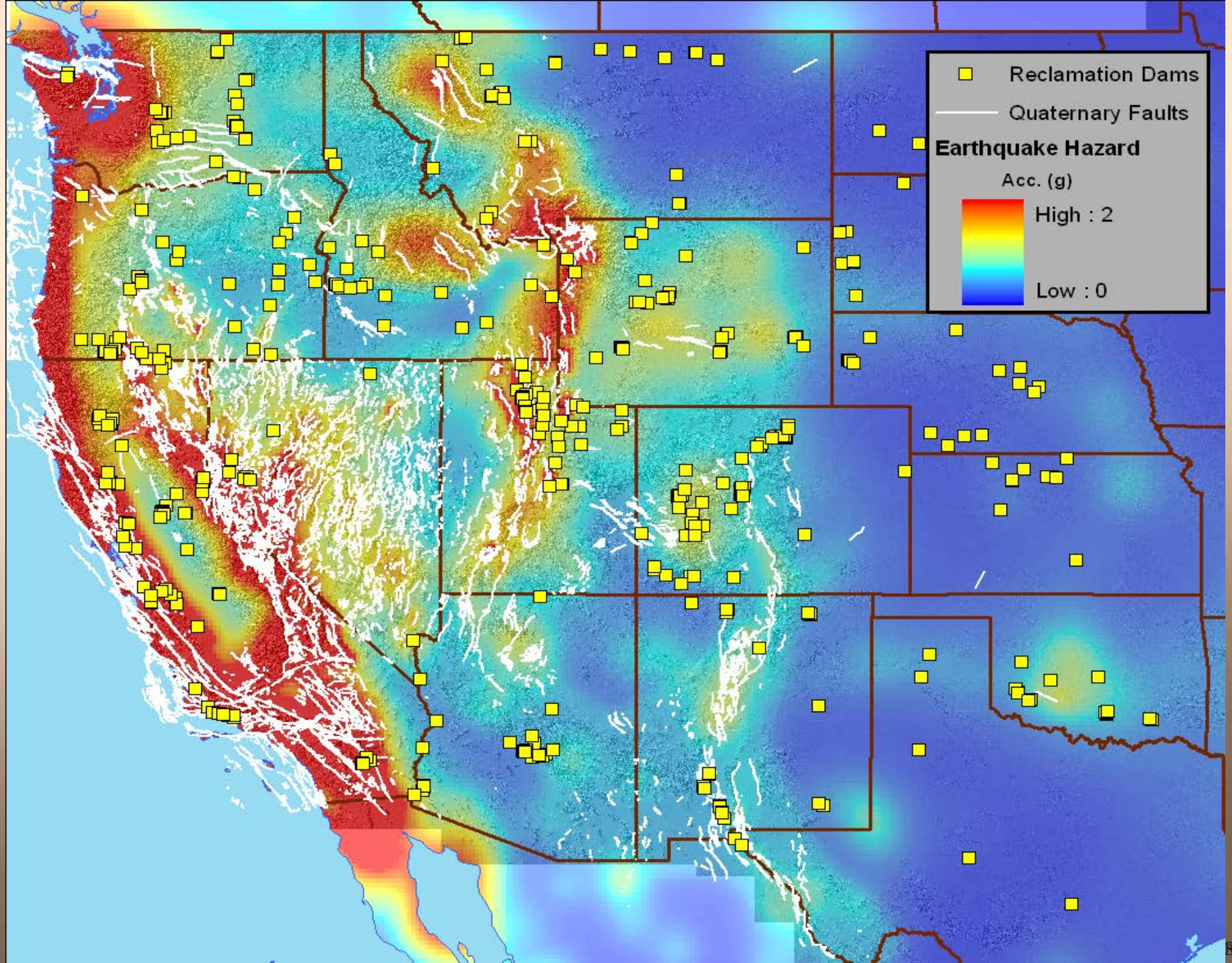
Plate Tectonics: The Process That Drives EQs



USGS (2014) NSHMP

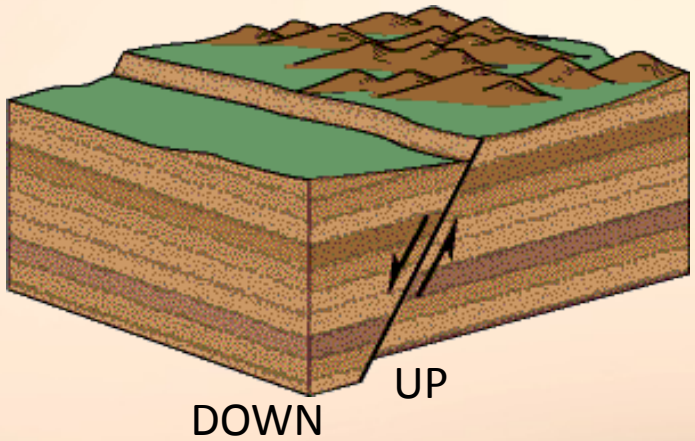


Two-percent probability of exceedance in 50 years map of peak ground acceleration

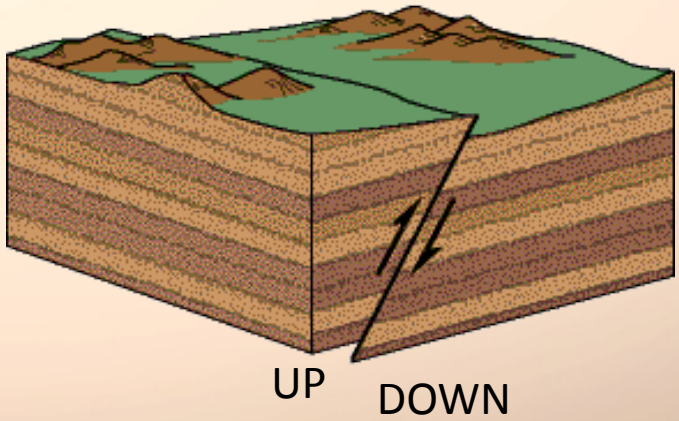

Reclamation Dams
Quaternary Faults
Earthquake Hazard
Acc. (g)
High : 2
Low : 0

Types of Faults

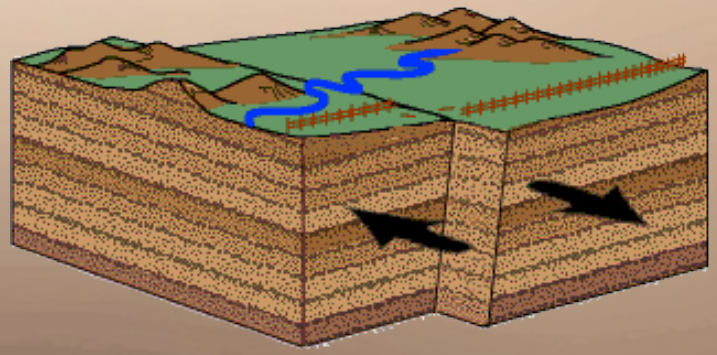
Normal



Reverse

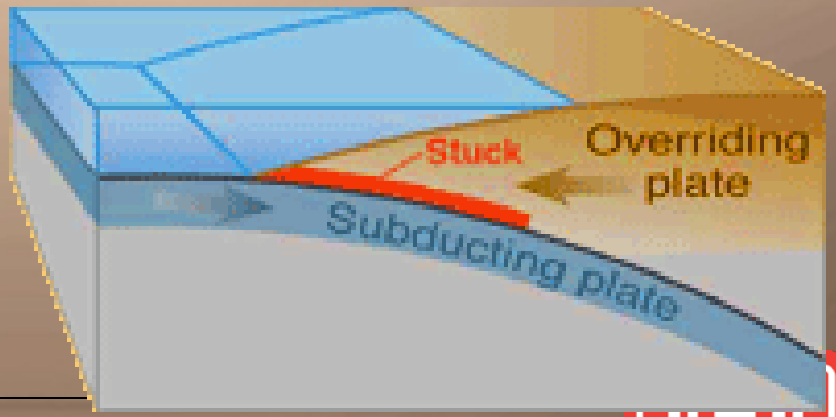


Strike-Slip

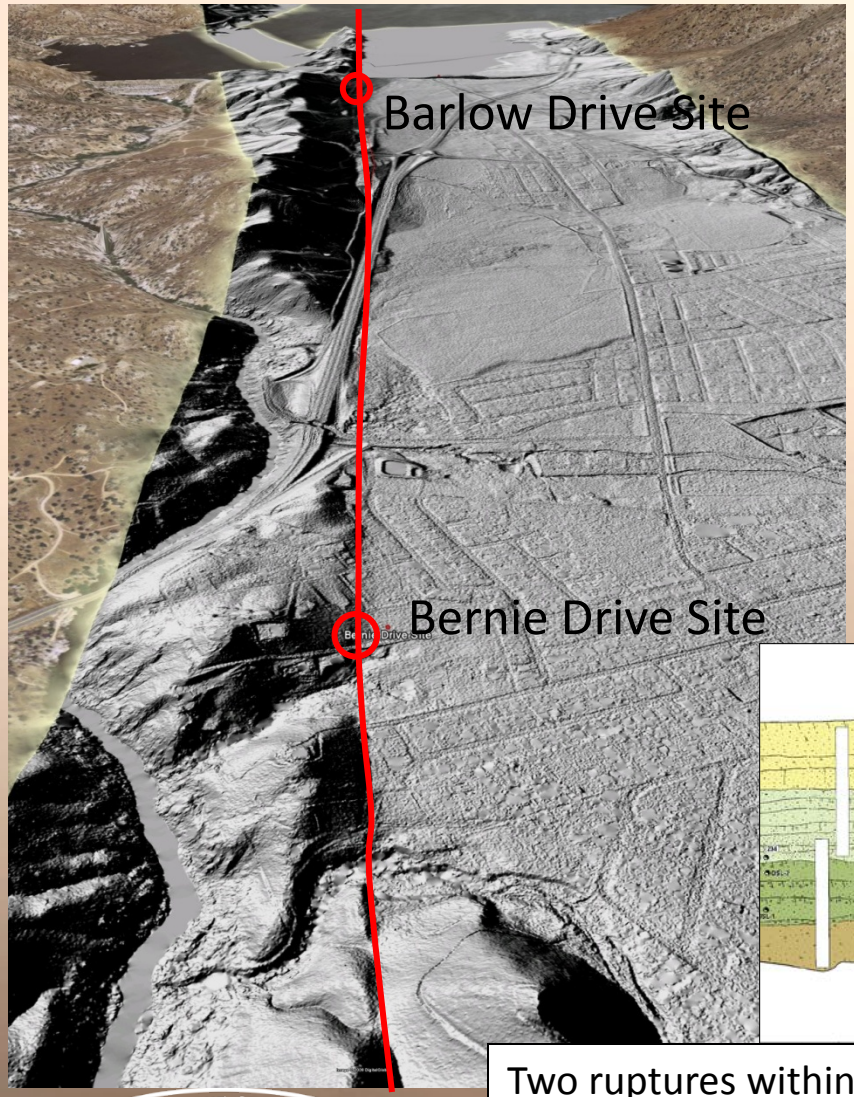


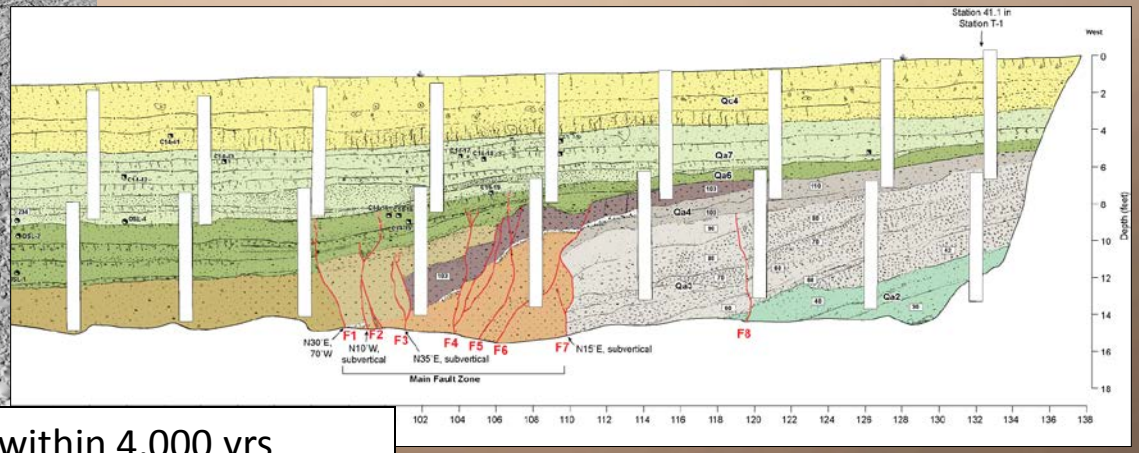
Subduction Zone

(special case of reverse)



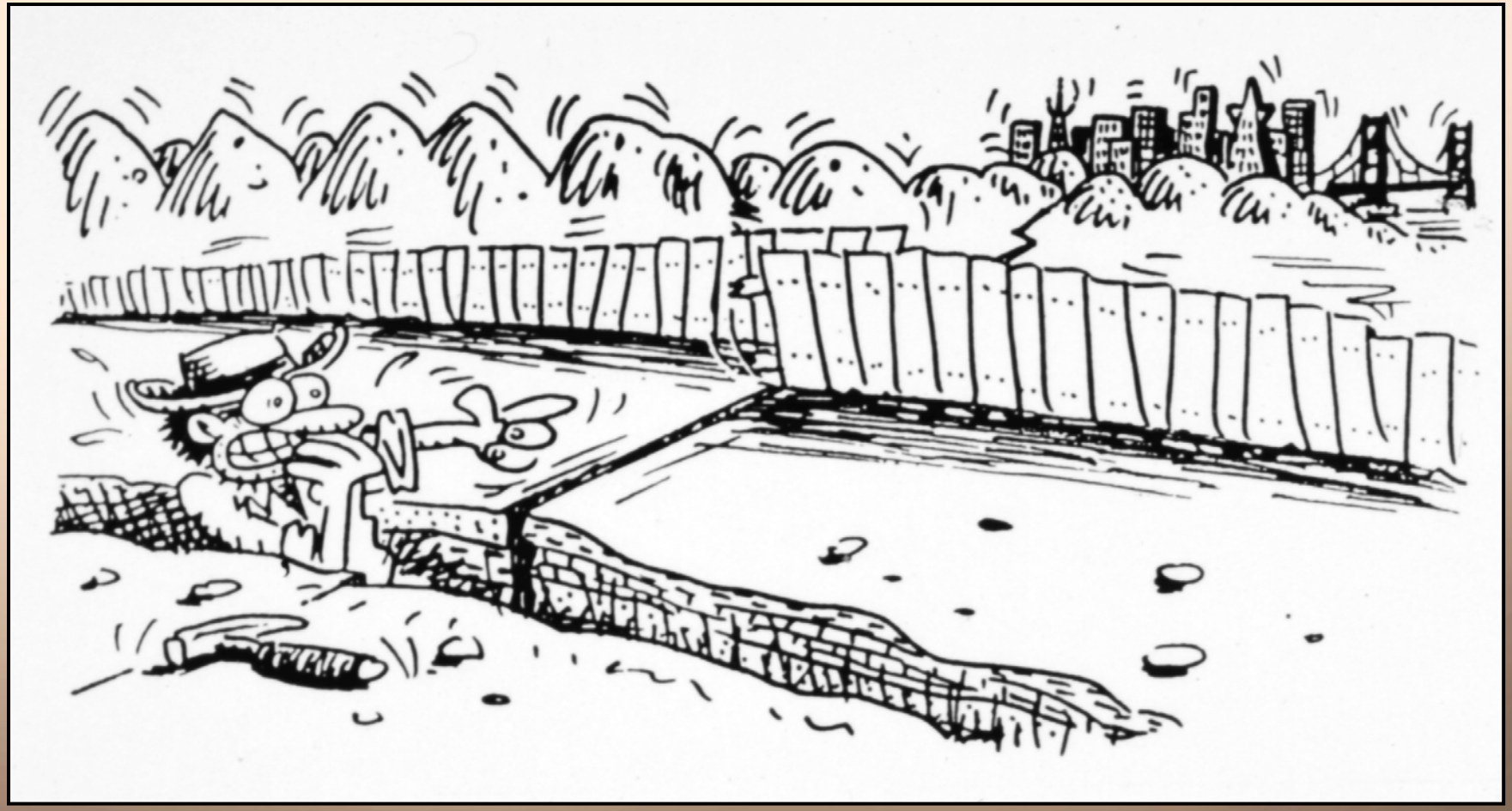
Normal Fault Rupture





Two ruptures within 4,000 yrs
Holocene slip rate 0.2-0.4 mm/yr
East-down normal displacement

Strike-slip Faulting



Example: Strike-slip Faulting

Narrow zone of surface faulting from two well-defined, linear segments of strike-slip ruptures: (a) right lateral offset from the 1906 San Francisco earthquake northwest of Olema (Lawson, 1908) and (b) right-lateral offset from the 1999 Kocaeli earthquake (Turkey). (from Bray and Kelson, 2006)

Example: Strike-slip Faulting

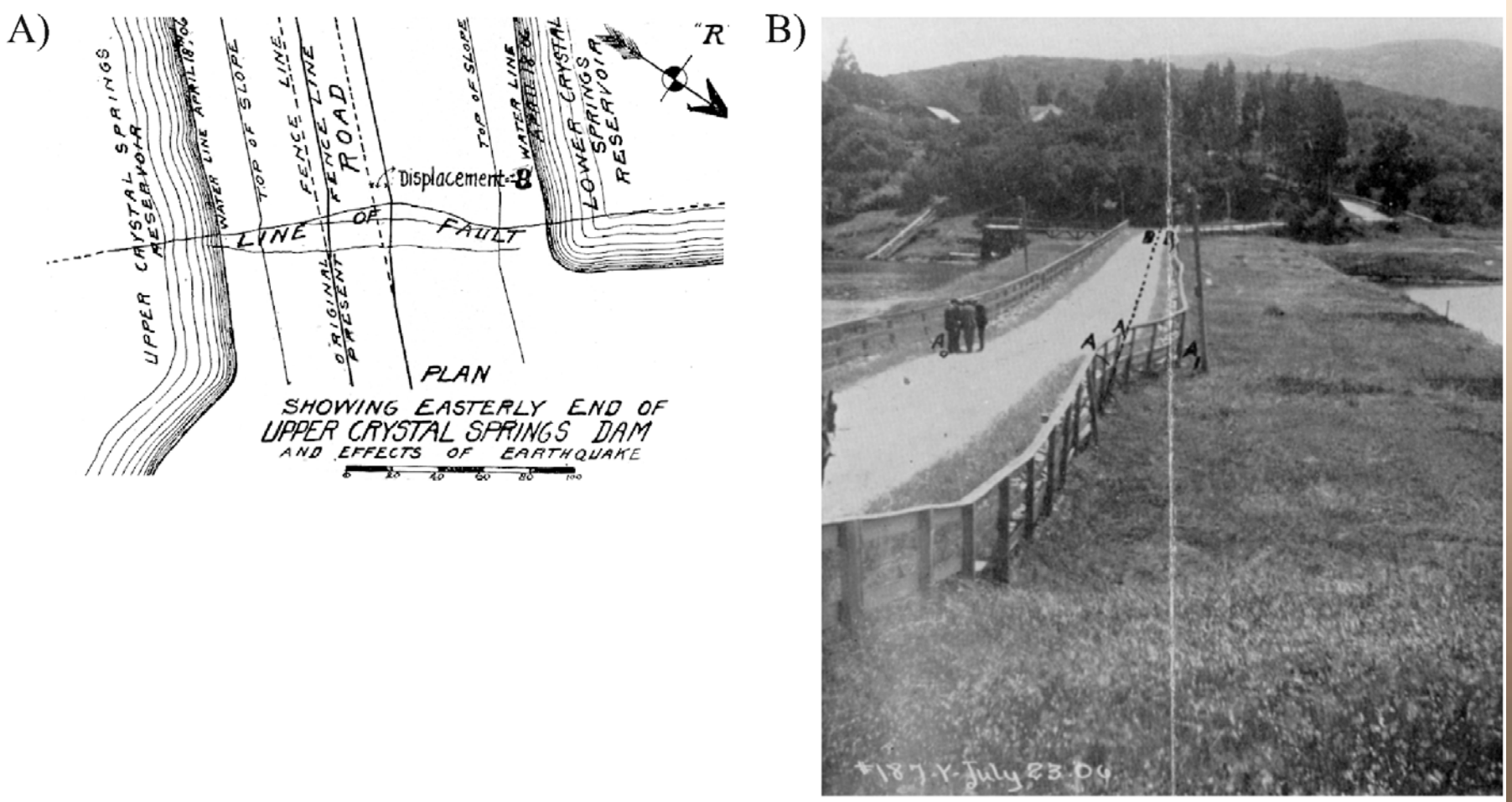


Figure 6. (a) Map of fault-trace across old dam between Upper and Lower Crystal Springs Lakes (Schussler, 1906). (b) Photograph looking southwest across dam crest, showing fence line offset (Schussler, 1906). (from Bray and Kelson, 2006)

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Example: Strike-slip Faulting

Photo: K. Kelson Sep 2, 2014

Example: Strike-slip Faulting

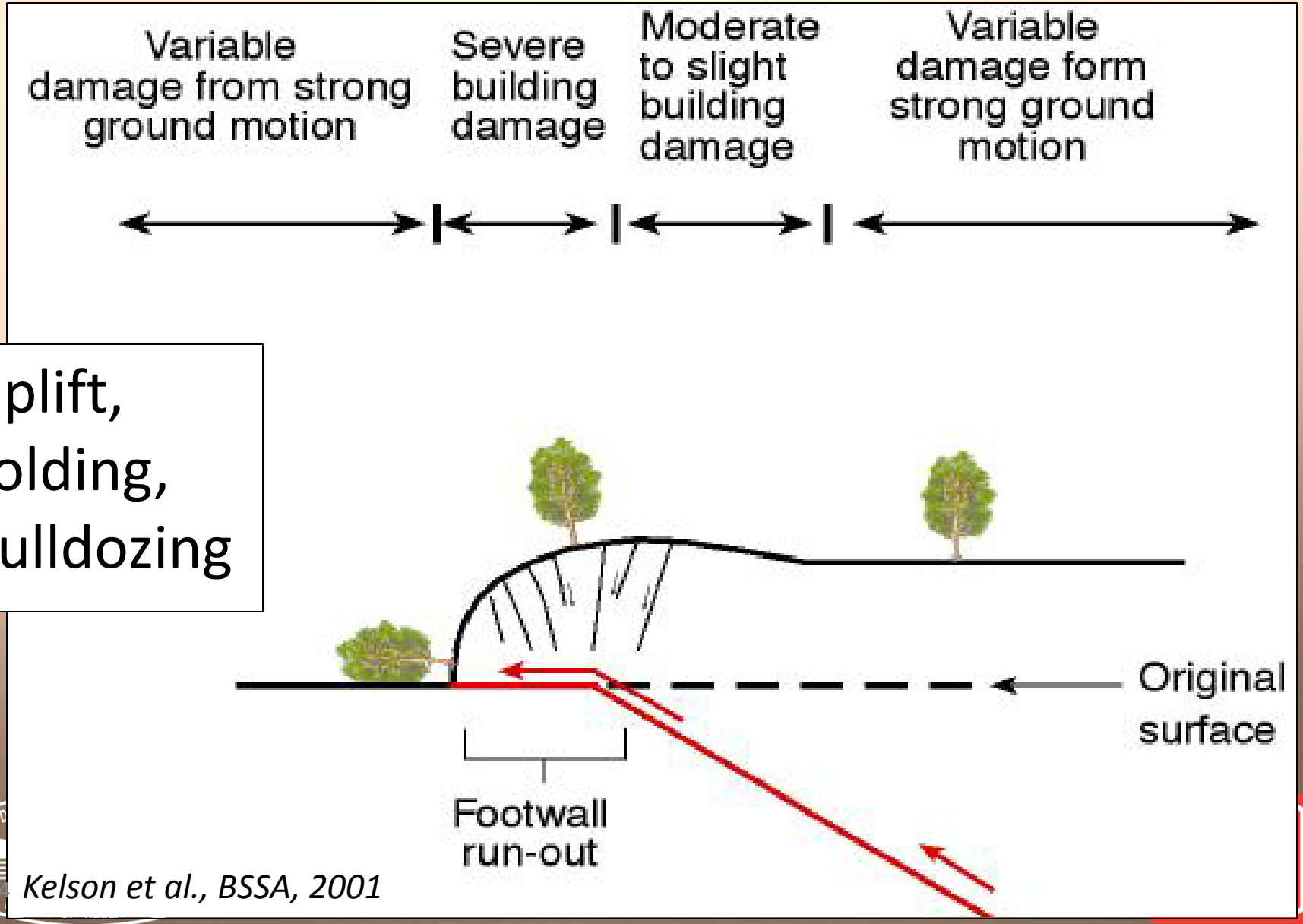
Example: Strike-slip Faulting

Maximum RL Offset
40 to 45 cm
Aug 25, 2014

Photo: K. Kelson Aug 25, 2014

Reverse Fault Rupture

Primary Fault Rupture

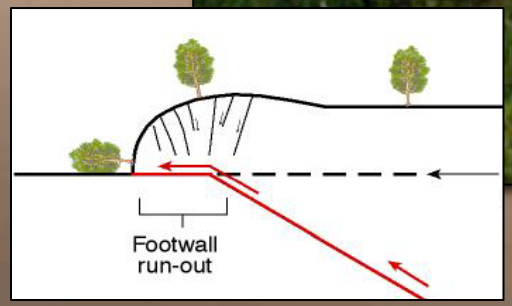


Uplift, Folding, Bulldozing

Kelson et al., BSSA, 2001

Primary Fault Rupture

Photo: K. Kelson; Oct. 11, 1999



Purpose of Seismic Hazard Studies

Develop probabilistic earthquake loadings for dam stability analyses

- Identify earthquake sources
- Characterize activity rates and magnitudes
- Estimate ground motion exceedance rates
- Develop probabilistic time-histories

Assess potential for surface fault rupture, and characterize for mitigation

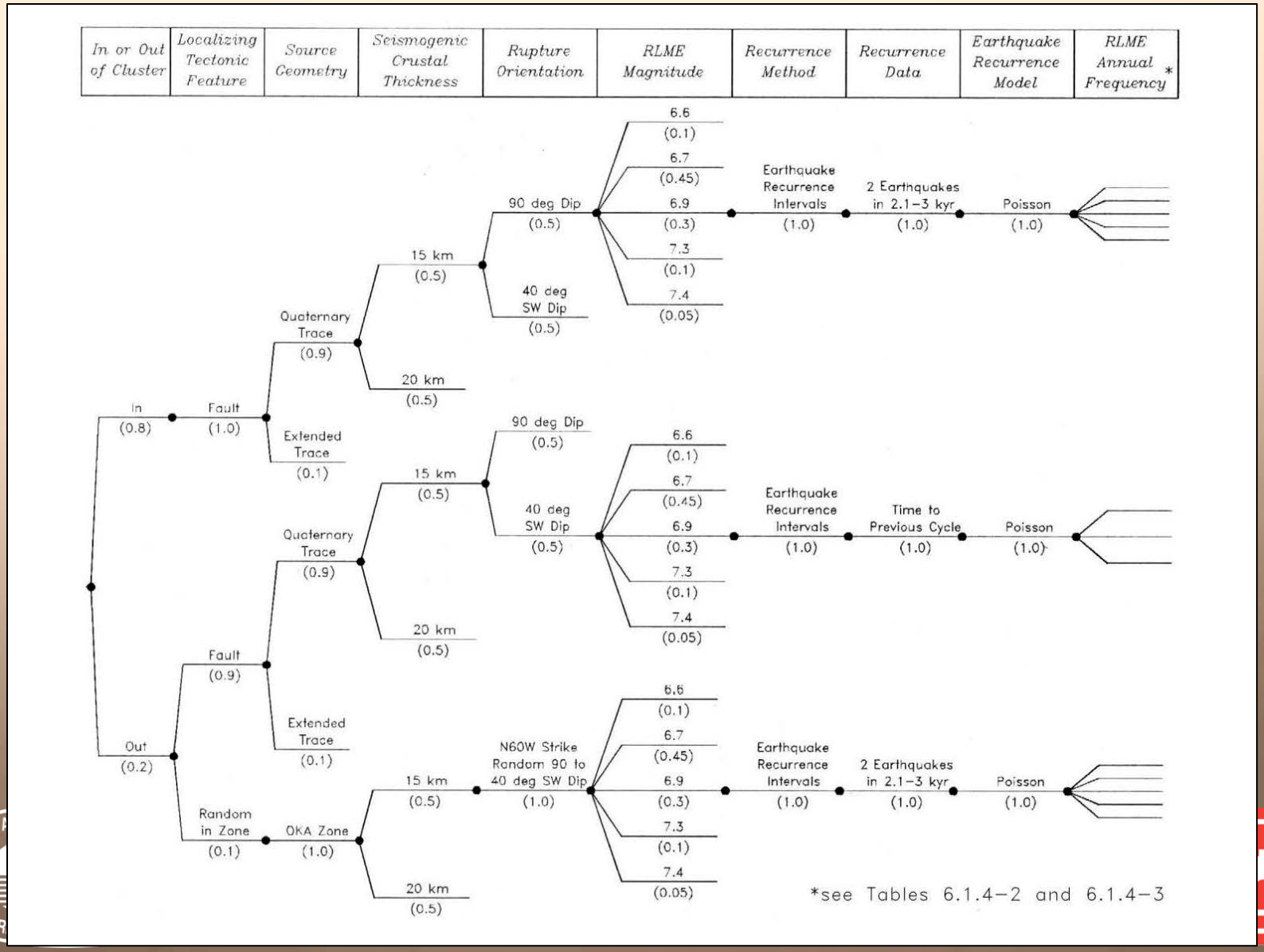
Ground Motion Analysis

- Seismic source characterization
- Development of hazard curves
- Development of uniform hazard spectra (UHS)
- Development of target response spectra
- Development of scenario ground motion time histories

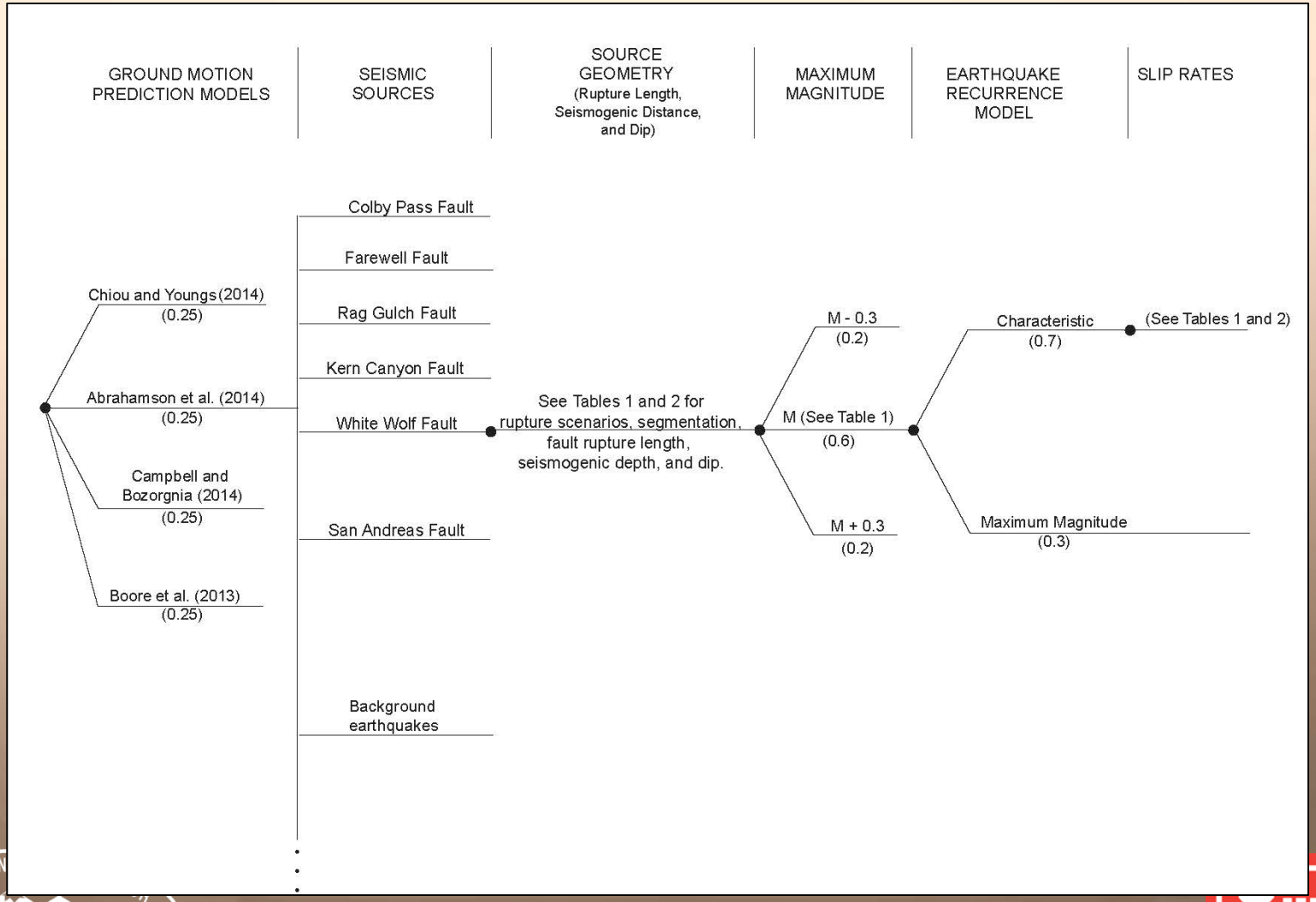
Fault Sources

- Geologic, geomorphologic, paleoseismologic data
- Develop rate of earthquake activity, inferred from
  - Slip rate and simple fault model and/or
  - Site-specific rupture chronology
- Fault model properties
  - Geometry (location, length, dip, down-dip extent)
  - Sense of slip (strike slip, normal, reverse)
  - Segmentation – rupture scenarios
  - Maximum magnitude
  - Recurrence model – distribution of magnitude

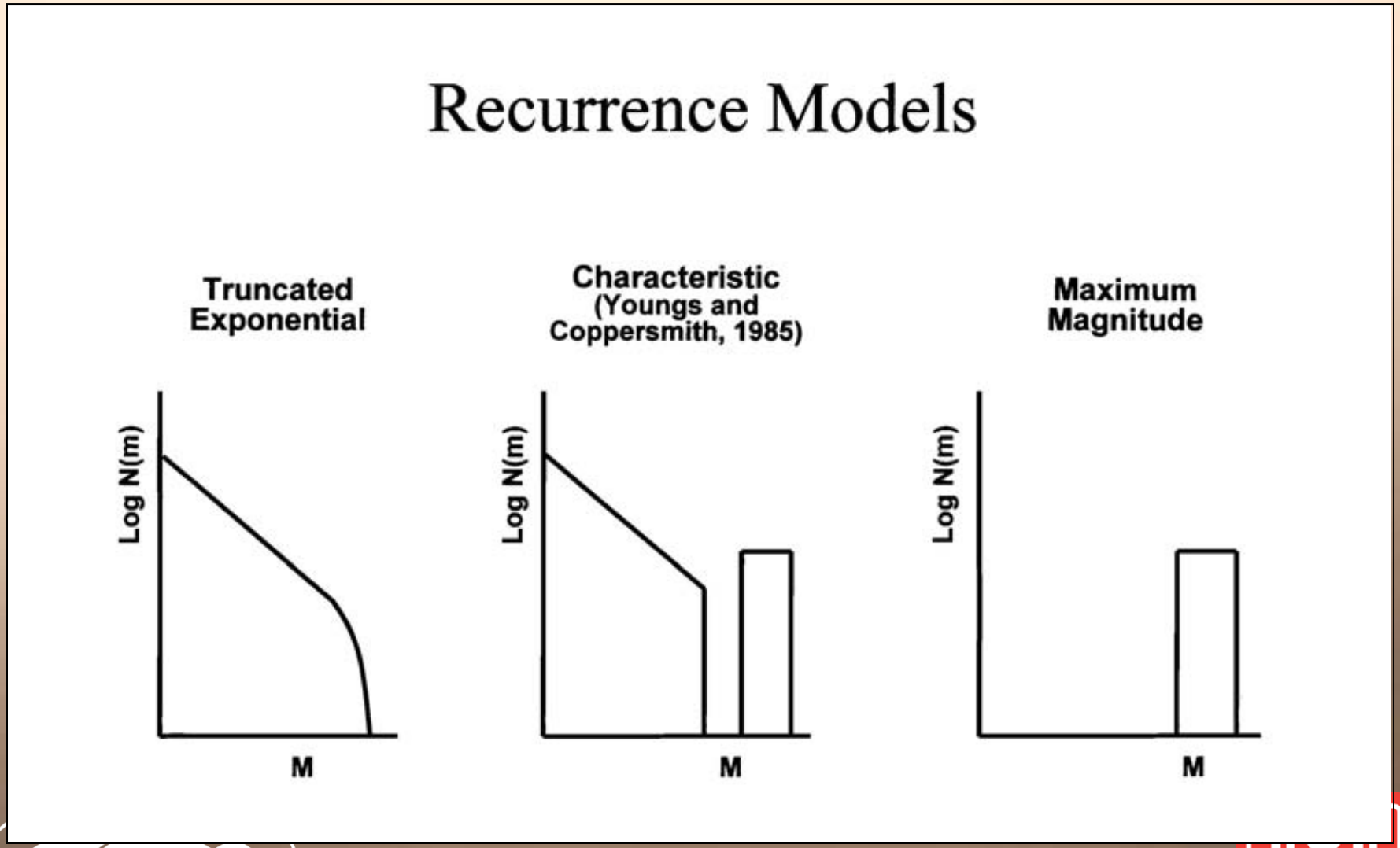
Source Characterization Logic Tree



Source Characterization Logic Tree



Earthquake Recurrence Models

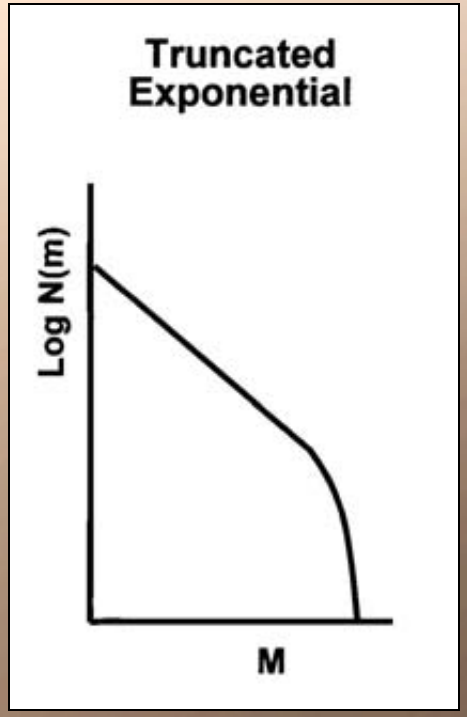


Areal Source Zones (Background Seismicity)

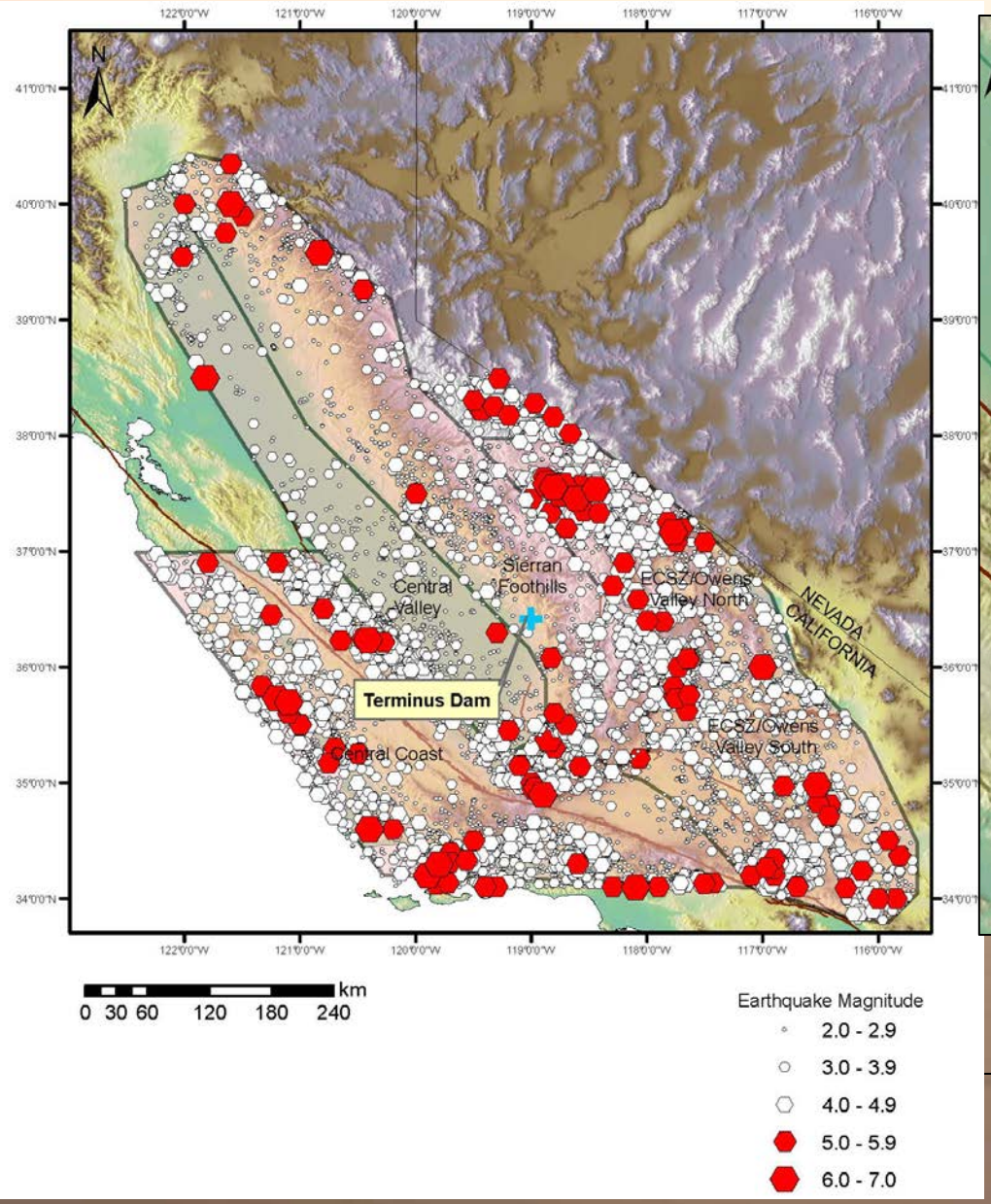
- Accounts for earthquakes on unidentified faults
- Maximum magnitude
  - Western US, usually assume M ~ 6.5
  - CEUS usually assume M ~ 8

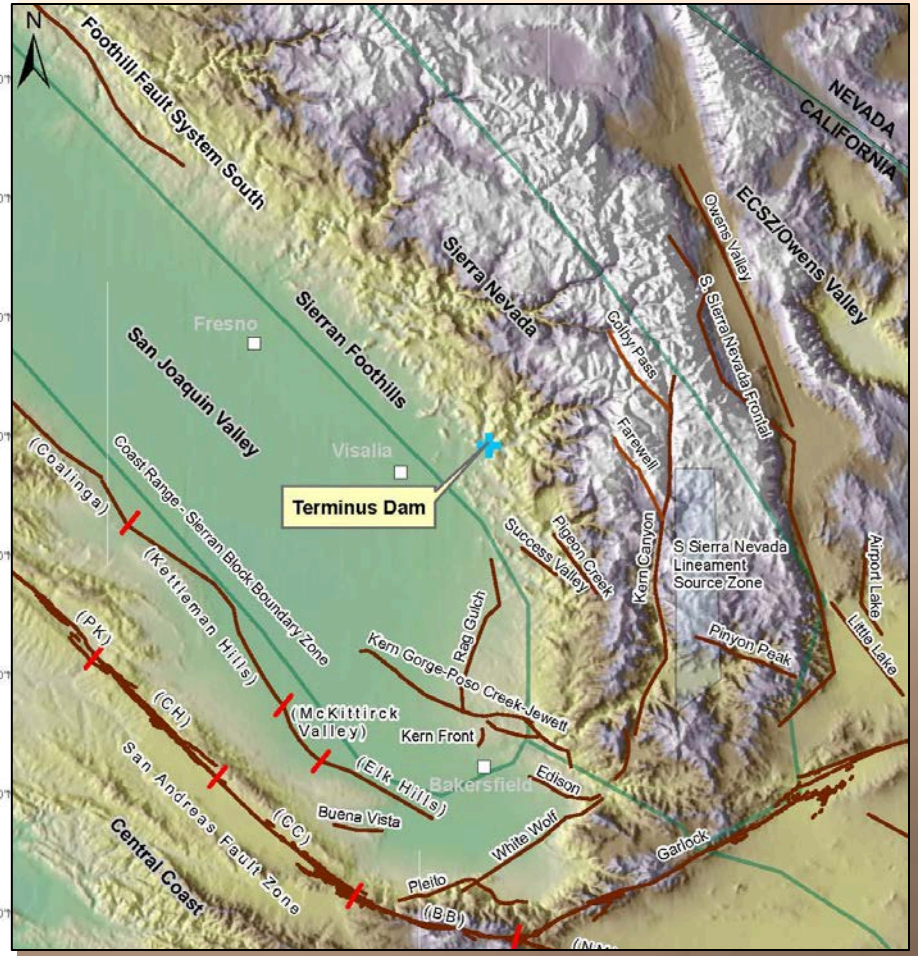
    (New Madrid Seismic Zone, now M7?)

- Rate of activity from historical seismicity

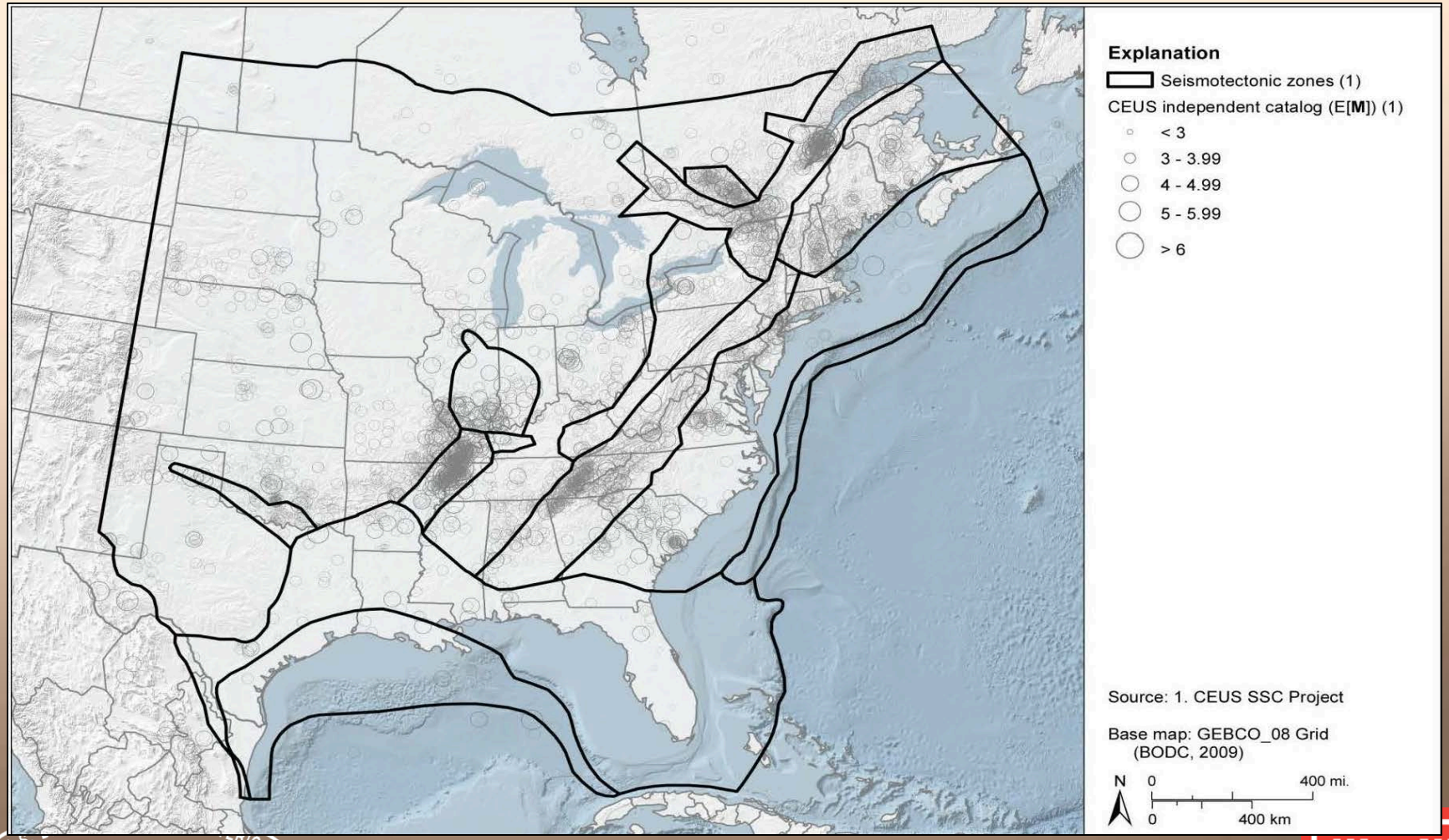


Background Seismicity Zones: Example





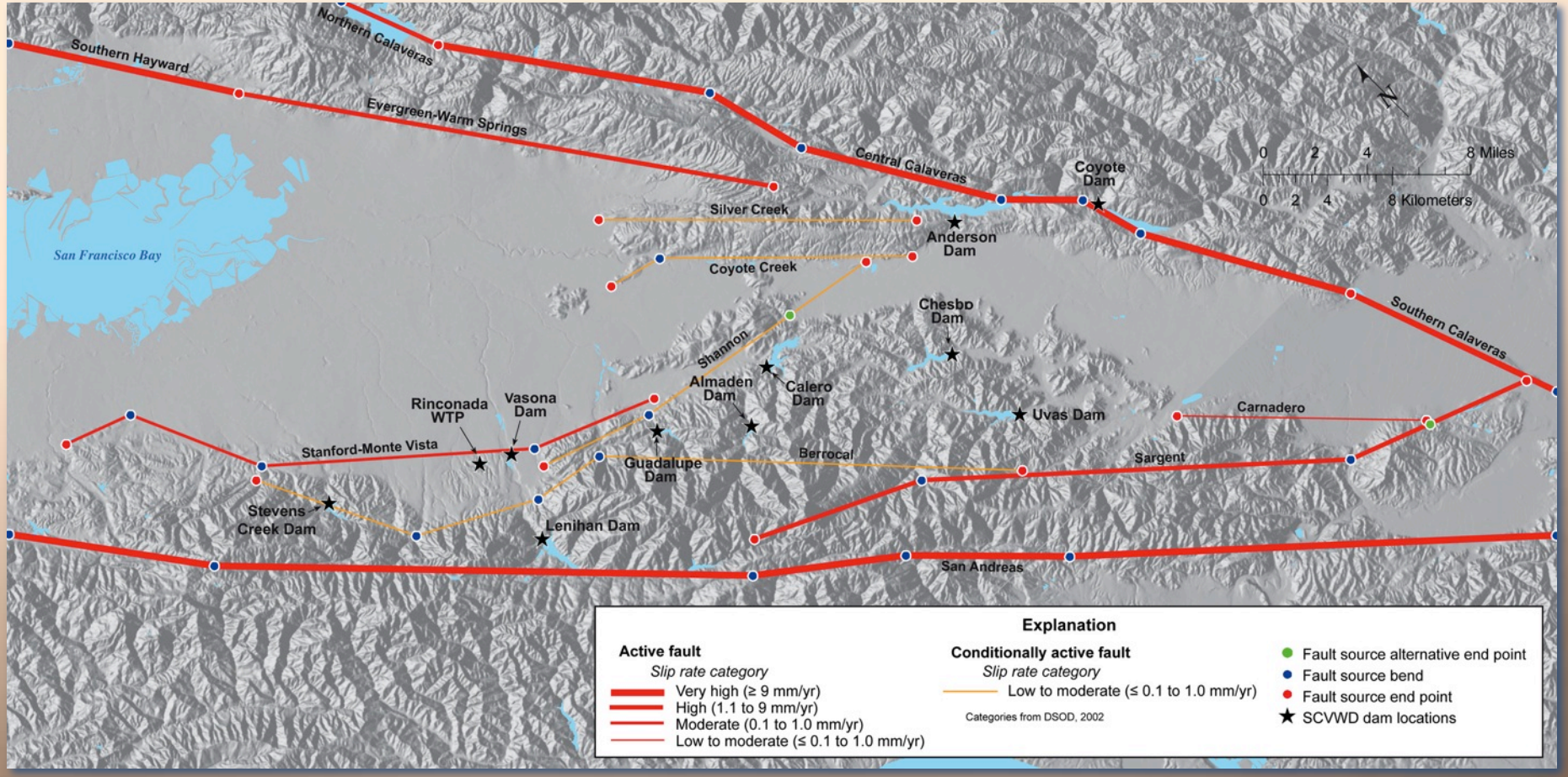
Regional Seismotectonic Zones in the Central and Eastern US



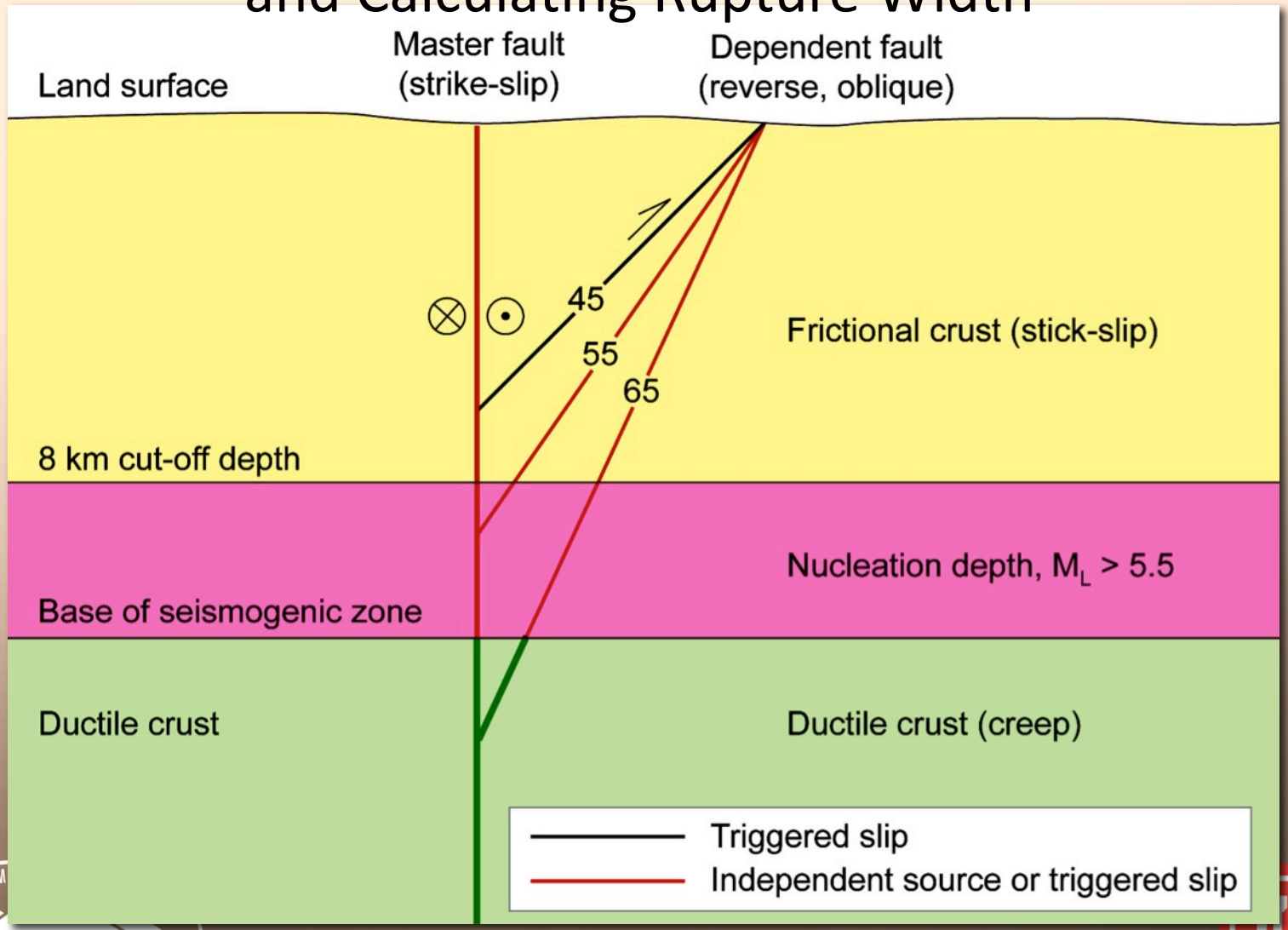
Scenario-based DSHA

- Goal: Estimate range, center, and body of values
- Deterministic SHA required by state regulation, but PSHA process still used to estimate Mmax
- Consider all reasonable fault geometries to evaluate the range of magnitudes
- Interpret likely Mmax from range of cases
- DSHA ground motions derived from Mmax

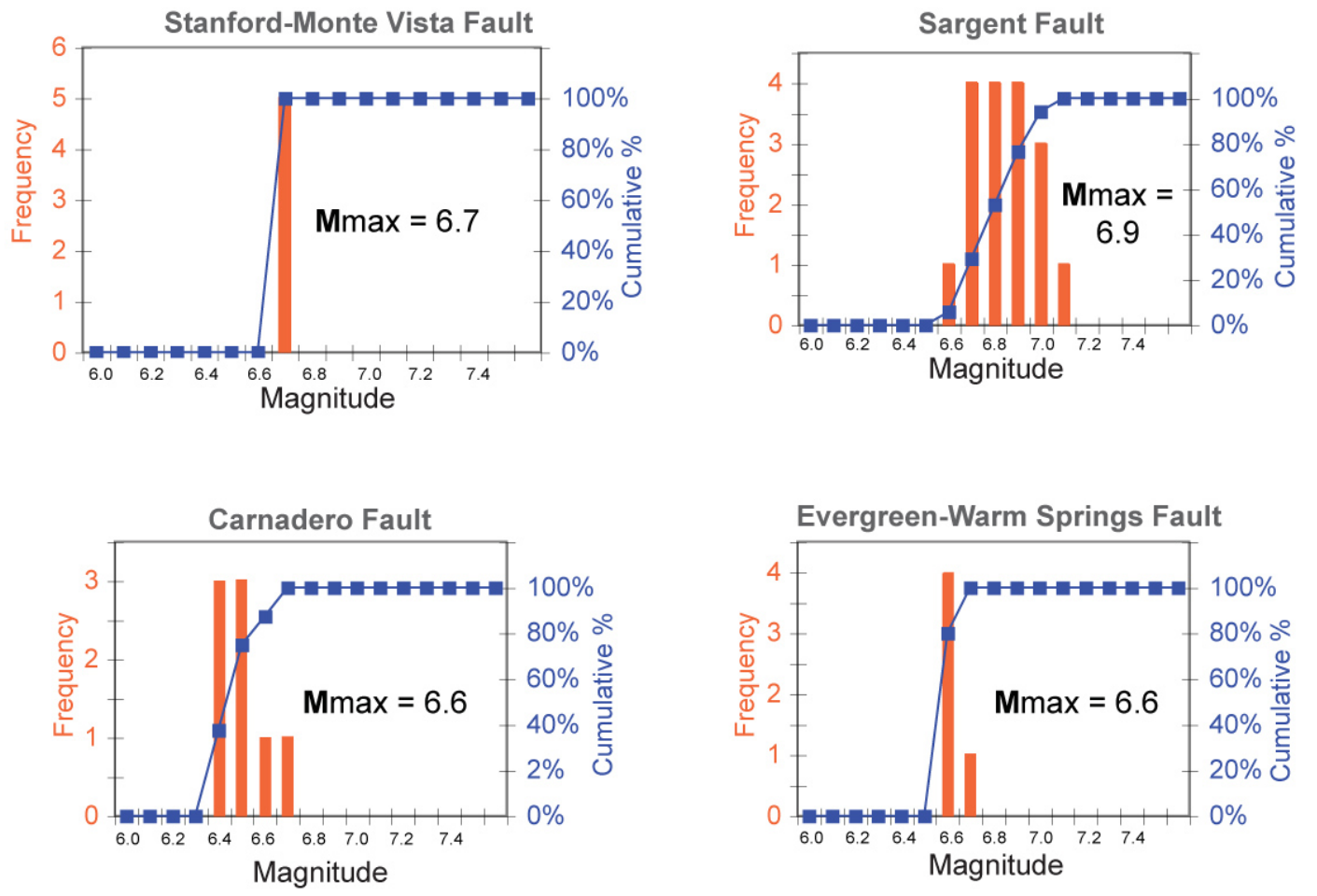
Seismic Source Model



Criteria for Assessing Seismogenic Potential and Calculating Rupture Width



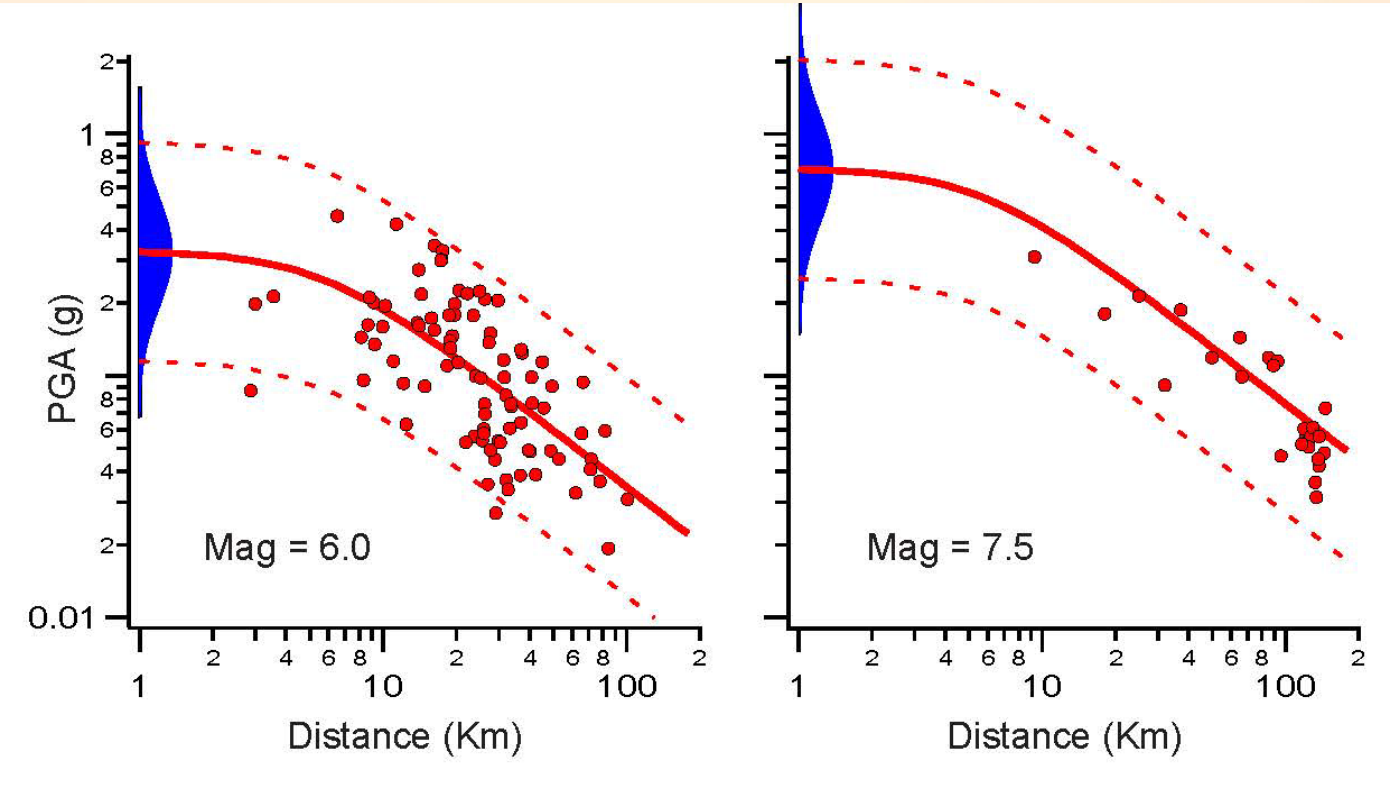
Mmax calculations for Active faults



Mmax = Median magnitude + one standard deviation

Ground Motion Prediction Equations (GMPE)

Examples of GMPEs for two magnitudes, with schematic uncertainties



Typical current practice:

- USGS (2014) for screening and regional analyses
- NGA-West2 or NGA-East for site-specific analyses

Site Response

Ground motion prediction eqns depend on site conditions

- Soil column response - characterized by shear wave velocity (V_S30) – shear wave velocity in upper 30 m
- Shallow basin response – characterized by depth to 1.0 or 2.5 km/s layer depth

Determined by geophysical exploration

Site Class	Generalized Description	V_s^{100} (ft/s)	V_s^{30} (m/s)
A	Hard Rock	>5,000 ft/s	>1,520 m/s
B	Rock	2,500 to 5,000 ft/s	760 to 1520 m/s
C	Very Dense Soil/Soft Rock	1,200 to 2,500 ft/s	360 to 760 m/s
D	Stiff Soil	600 to 1,200 ft/s	180 to 360 m/s
E	Soft Clay Soil	<600 ft/s	<180 m/s
F	Requires Site Response Analysis		

Probabilistic Seismic Hazard Analysis

Determine rates at which specific peak ground motions are exceeded (PHA, PHV)

- Include contributions from all potential earthquake sources
- Incorporate rate and magnitude of all earthquake sources

Technical Input

- Paleoseismic and historical seismicity data
- Empirical relationships between ground motion and earthquake magnitude and distance (attenuation relationships)
- Site Response

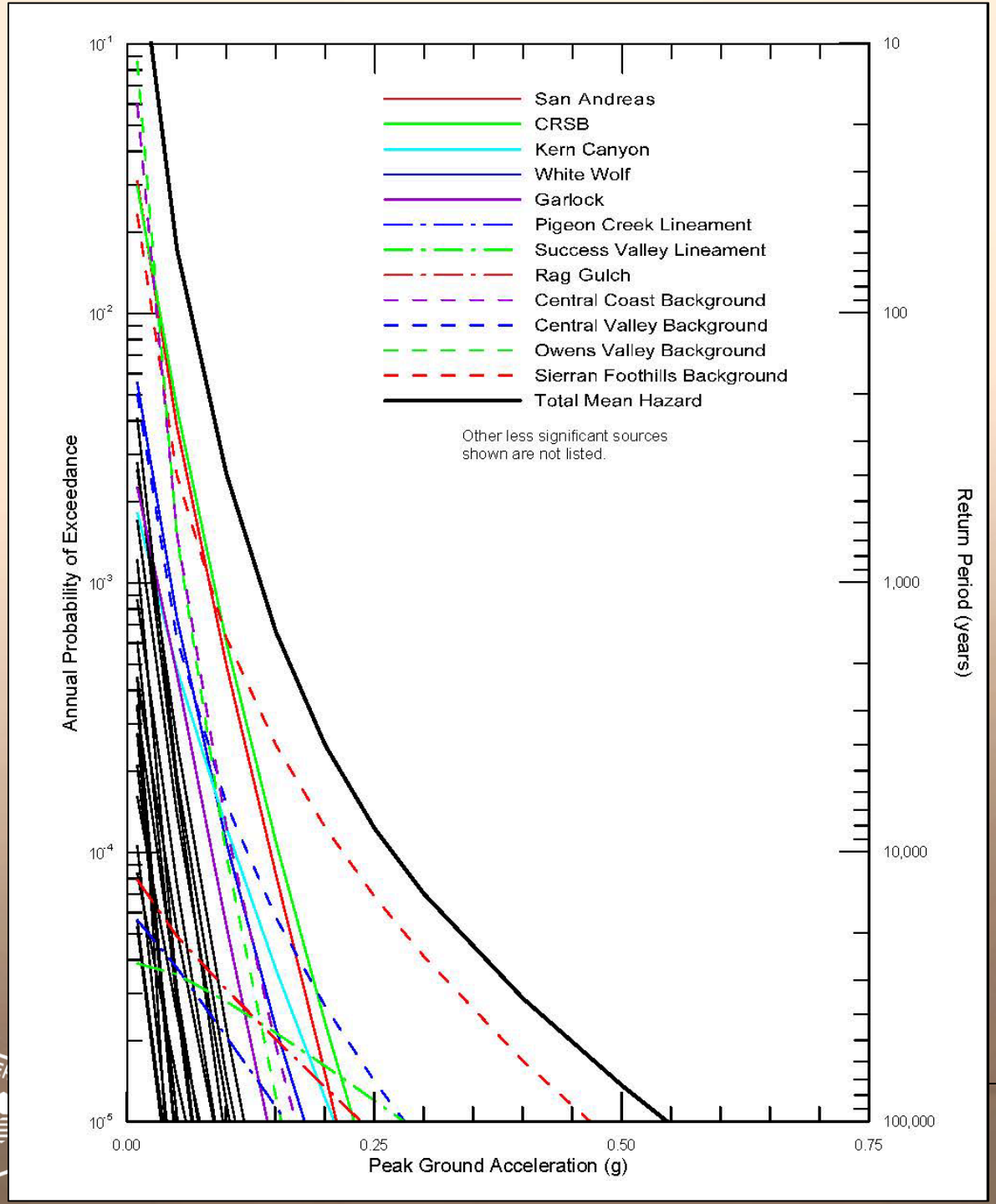
PSHA Fundamental Premise

$$Rate(loading) = Rate(EQ) \times \Pr(loading \mid EQ)$$

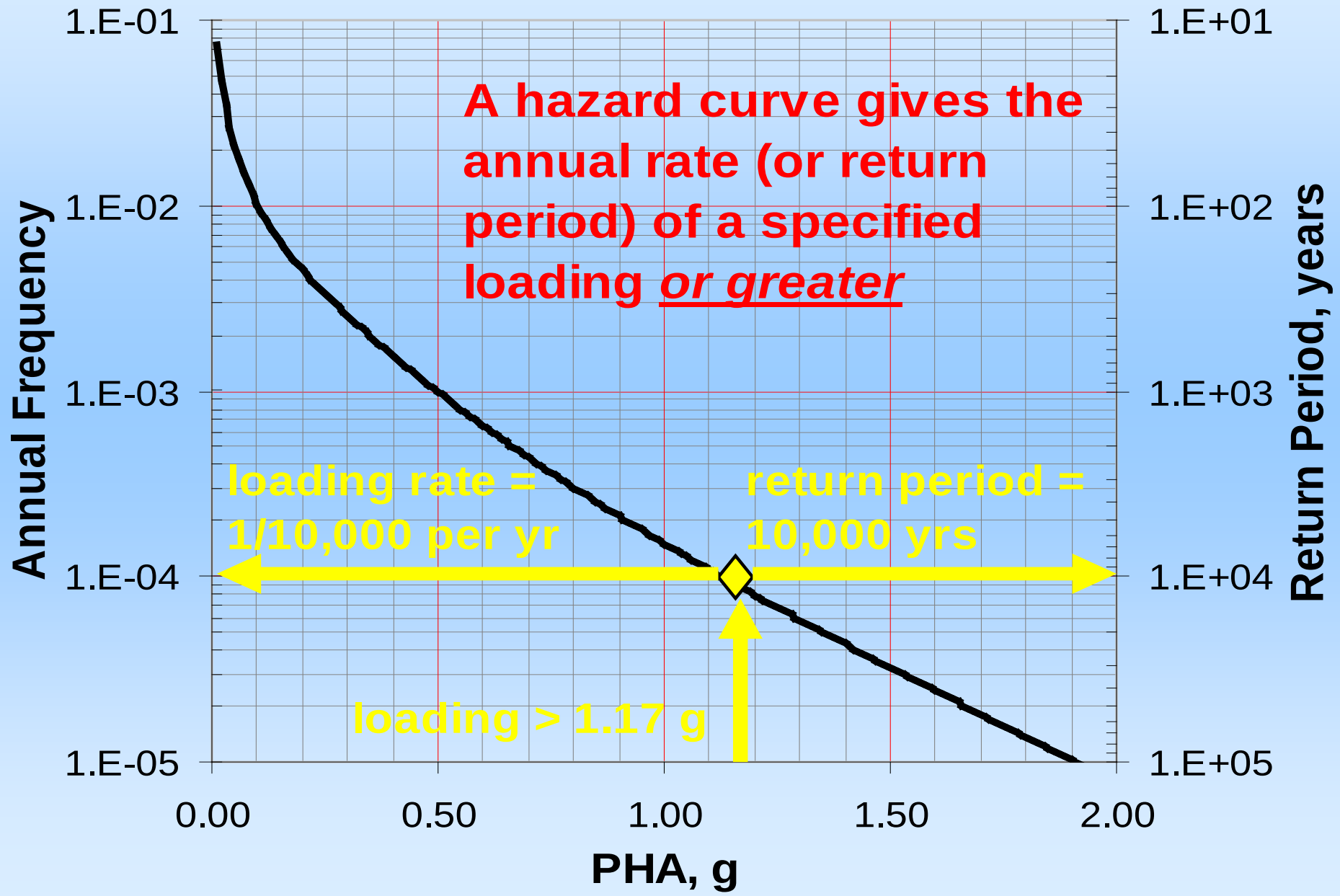
- Loading rate ≤ Earthquake rate
- Loading return period ≥ Earthquake return period
- Earthquake rate ≈ loading rate, for loadings ≈ 0. This means the y-intercept of hazard curve provides a good estimate of the total earthquake rate.

PSHA Principles

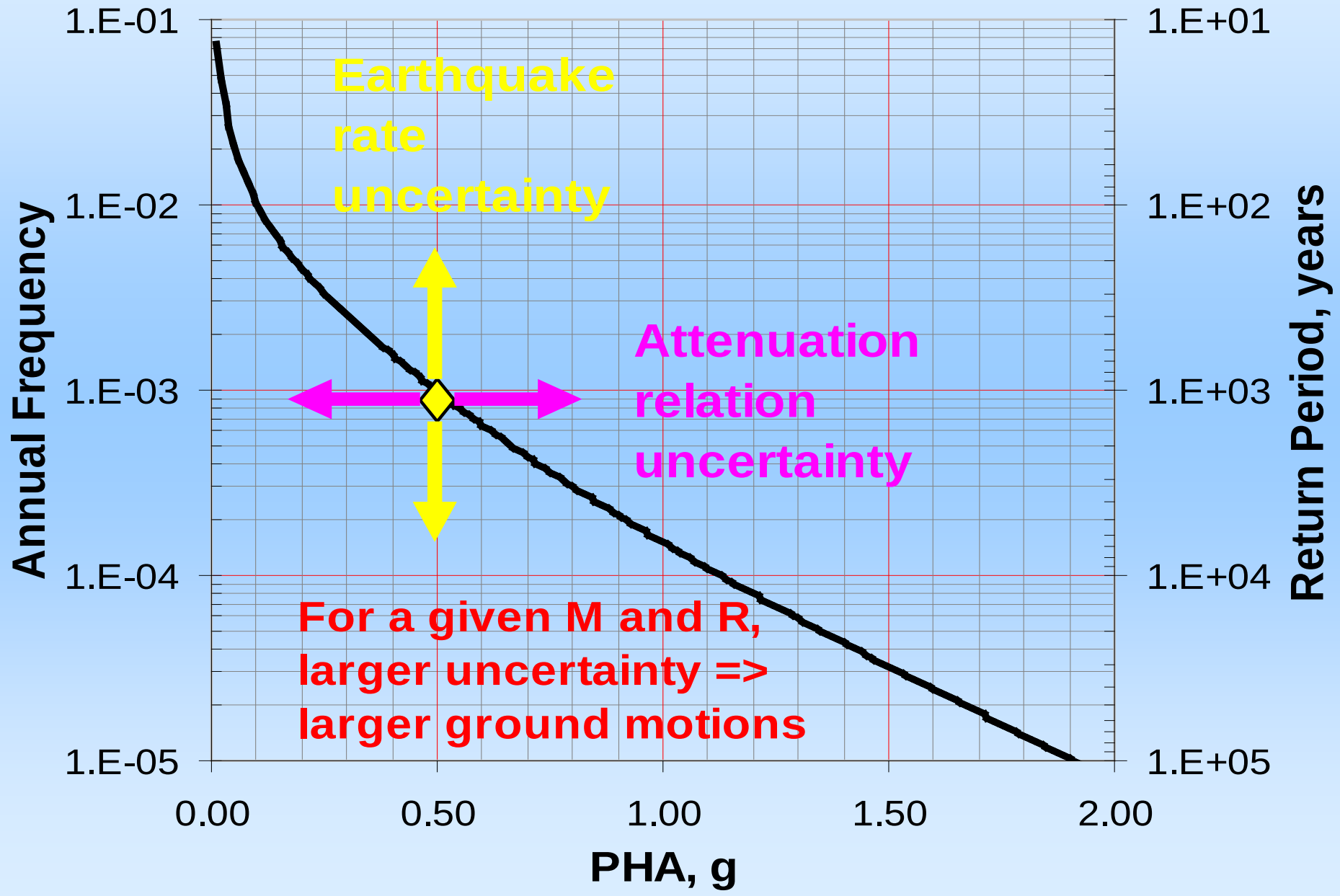
- For multiple independent earthquake sources, the total loading rate is just the sum of the rates of the individual sources
- Rates are additive
- Loadings are not additive
  - Loading considering all sources is determined from the total loading rate (total hazard curve)
  - Loading for all sources ≠ sum of individual loadings

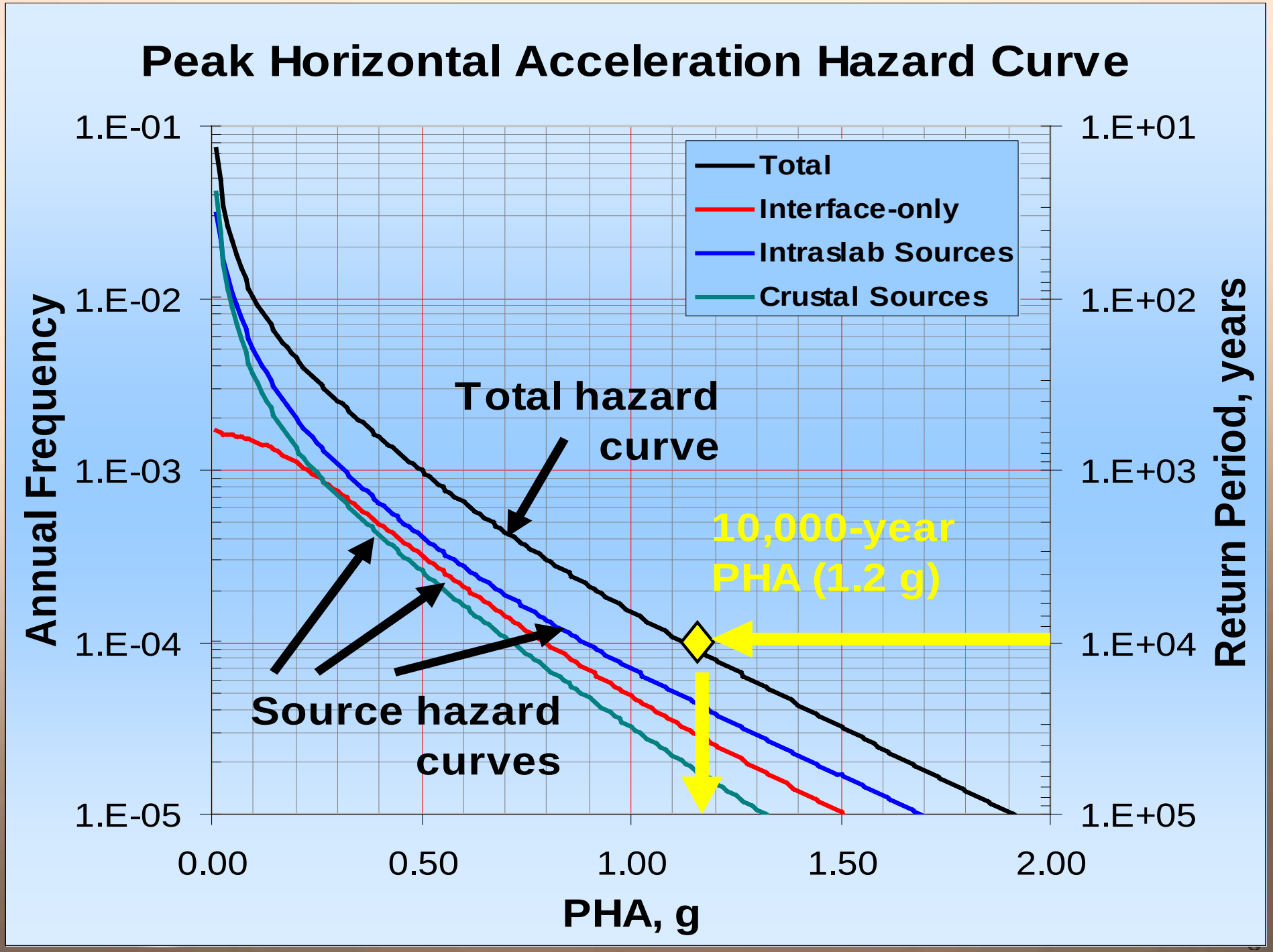

San Andreas
CRSB
Kern Canyon
White Wolf
Garlock
Pigeon Creek Lineament
Success Valley Lineament
Rag Gulch
Central Coast Background
Central Valley Background
Owens Valley Background
Sierran Foothills Background
Total Mean Hazard
Other less significant sources shown are not listed.
Annual Probability of Exceedance
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Return Period (years)
10
100
1,000
10,000
100,000
0.00
0.25
0.50
0.75
Peak Ground Acceleration (g)

Peak Horizontal Acceleration Hazard Curve

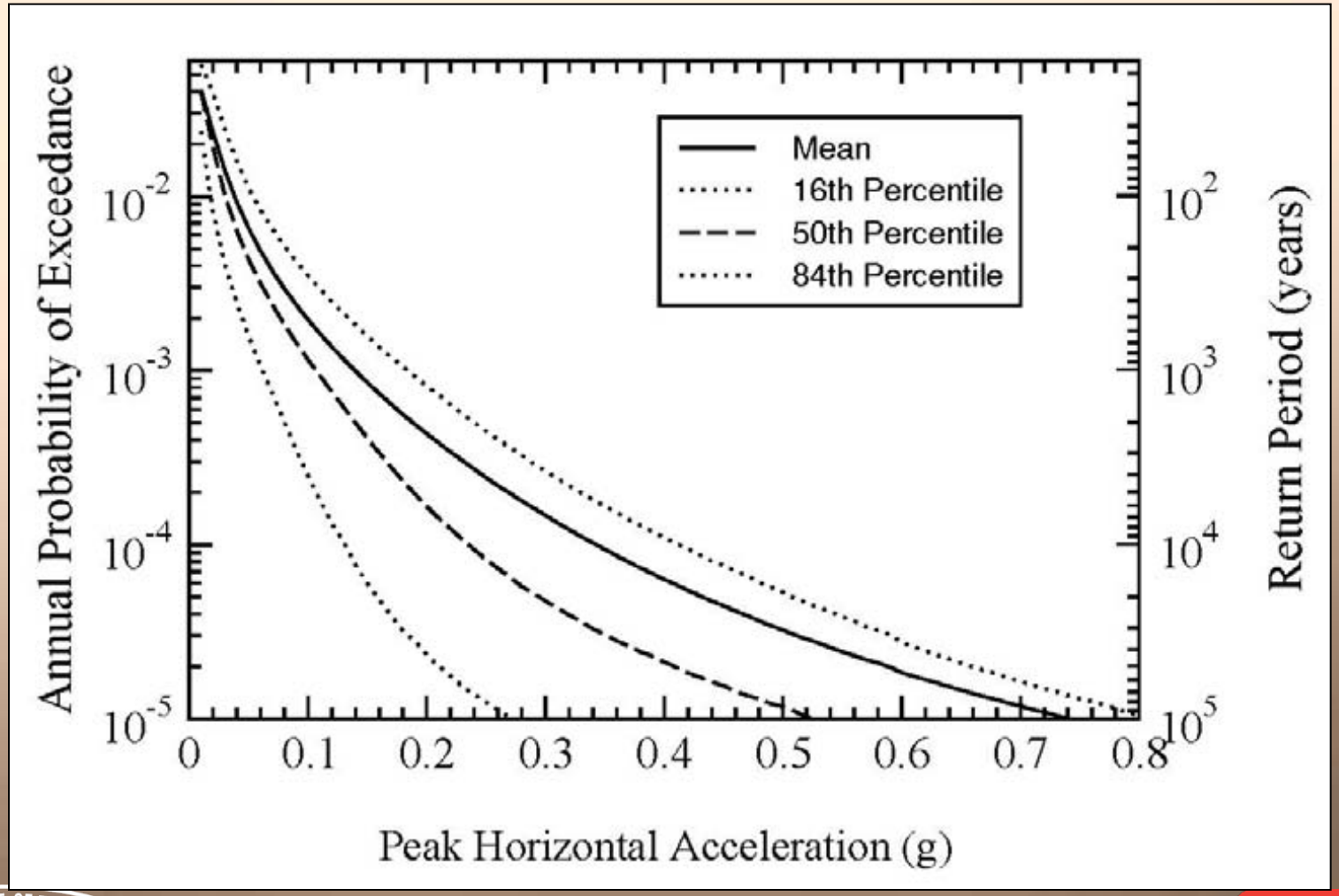


Peak Horizontal Acceleration Hazard Curve




Peak Horizontal Acceleration Hazard Curve
Total
Interface-only
Intraslab Sources
Crustal Sources
Total hazard curve
10,000-year PHA (1.2 g)
Source hazard curves
Annual Frequency
Return Period, years
PHA, g
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E+01
1.E+02
1.E+03
1.E+04
1.E+05
0.00
0.50
1.00
1.50
2.00

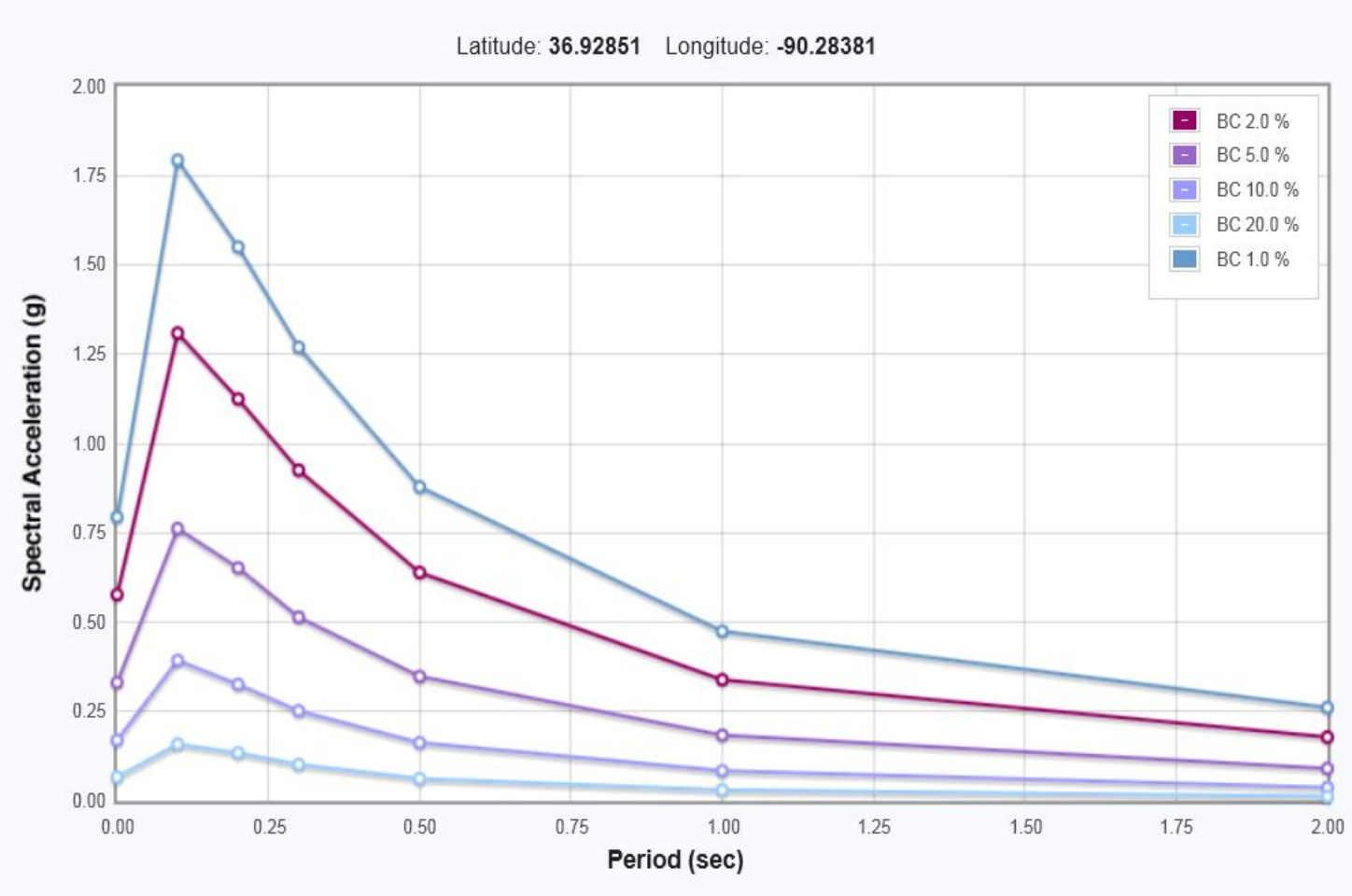
Seismic Hazard Curve



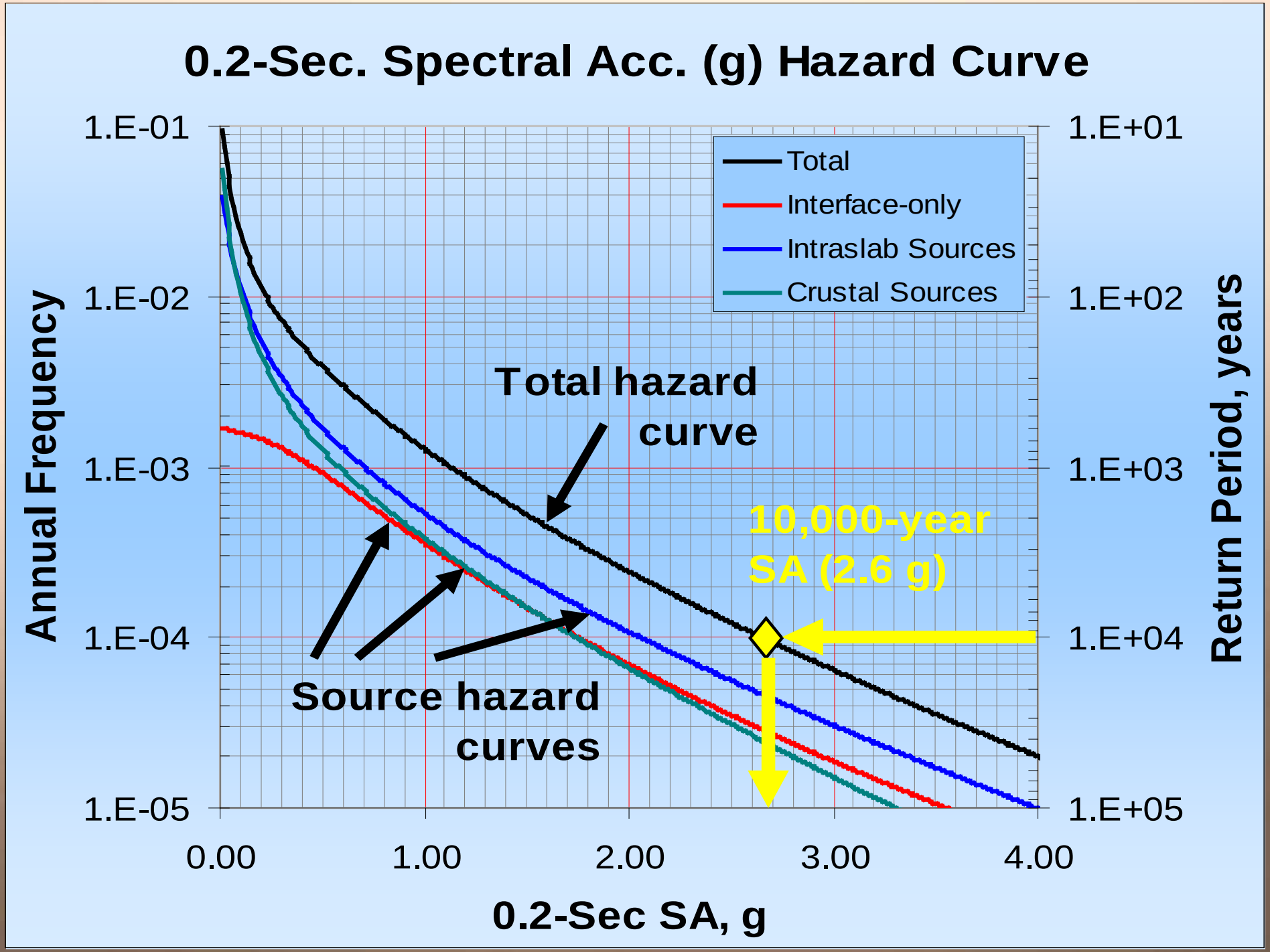
Uniform Hazard Spectrum

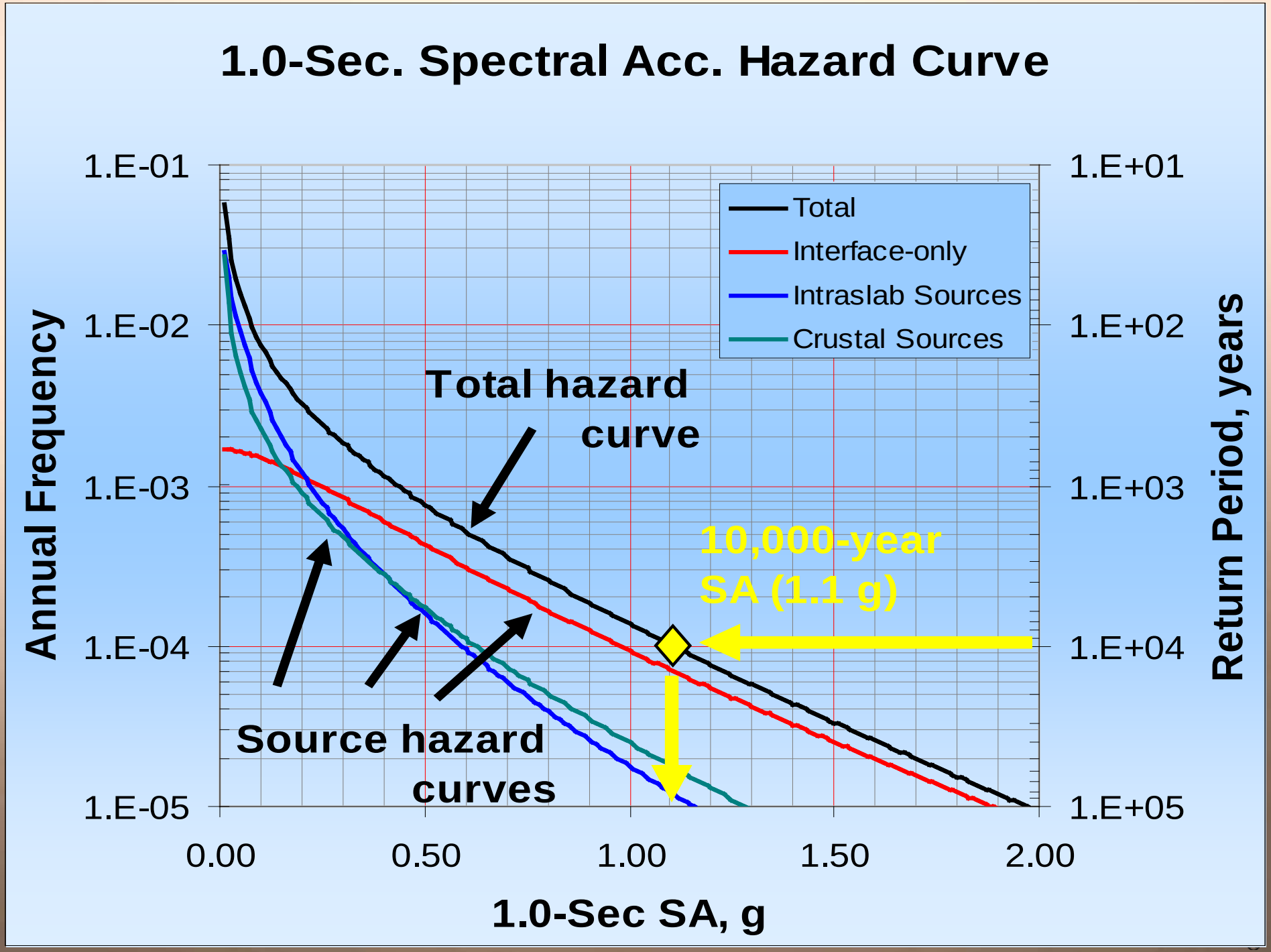
- Provides the response spectral acceleration at a specified return period as function of spectral response period
- Same hazard, e.g. 1 in 10,000, for all response periods (uniform)
- Determined by reading values from a hazard curve for a given response period

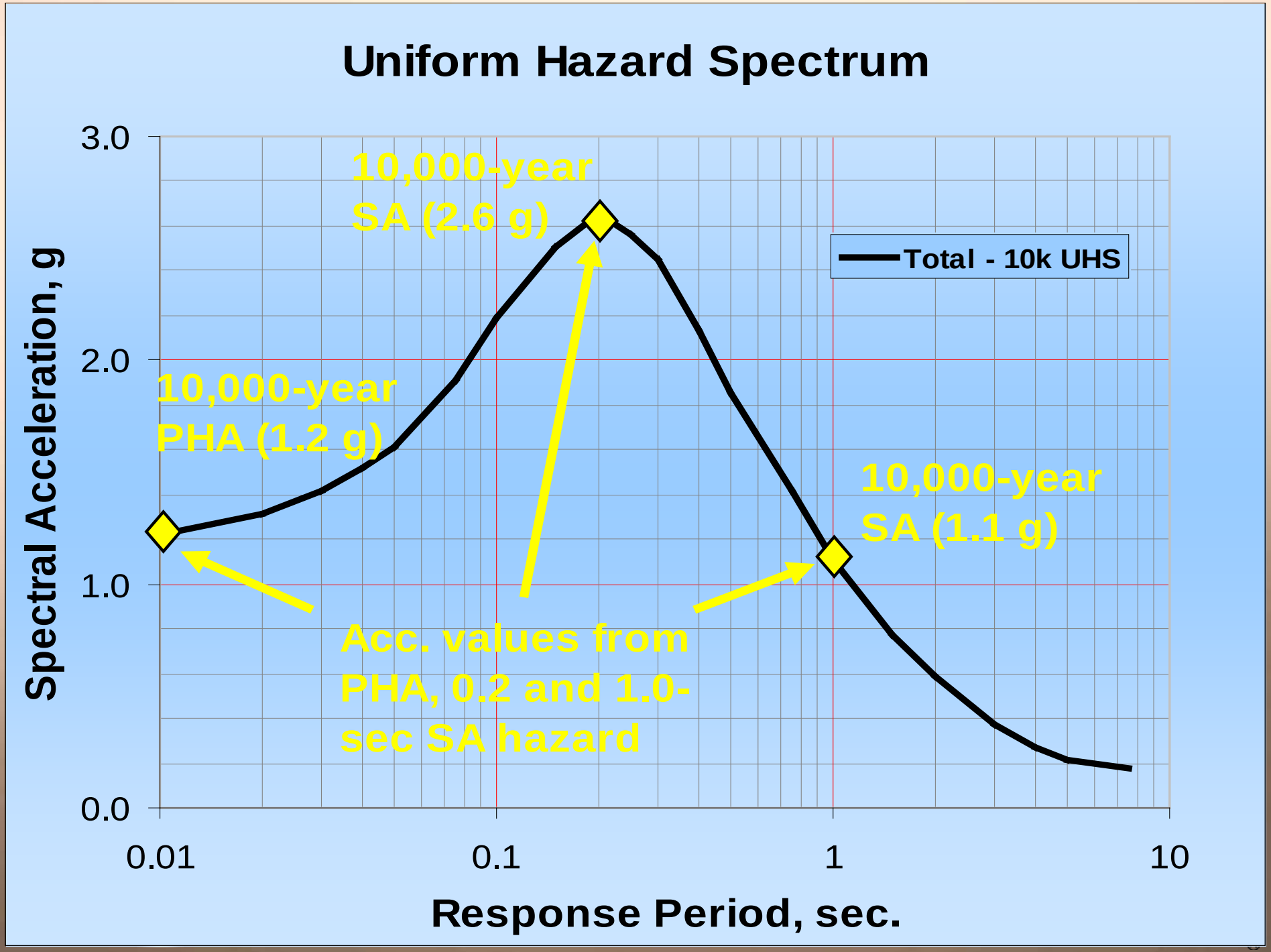
Uniform Hazard Spectra



http://geohazards.usgs.gov/hazardtool/application.php


0.2-Sec. Spectral Acc. (g) Hazard Curve
Total
Interface-only
Intraslab Sources
Crustal Sources
Total hazard curve
10,000-year SA (2.6 g)
Source hazard curves
Annual Frequency
Return Period, years
0.2-Sec SA, g
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E+01
1.E+02
1.E+03
1.E+04
1.E+05
0.00
1.00
2.00
3.00
4.00


1.0-Sec. Spectral Acc. Hazard Curve
Total
Interface-only
Intraslab Sources
Crustal Sources
Total hazard curve
10,000-year SA (1.1 g)
Source hazard curves
Annual Frequency
Return Period, years
1.0-Sec SA, g
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E+01
1.E+02
1.E+03
1.E+04
1.E+05
0.00
0.50
1.00
1.50
2.00


Uniform Hazard Spectrum
3.0
2.0
1.0
0.0
Spectral Acceleration, g
0.01
0.1
1
10
Response Period, sec.
Total - 10k UHS
10,000-year
SA (2.6 g)
10,000-year
PHA (1.2 g)
10,000-year
SA (1.1 g)
Acc. values from
PHA, 0.2 and 1.0-
sec SA hazard

Target Spectra and Conditional Mean Spectra (CMS)

- For risk analyses, realistic scenario earthquakes must be generated at a range of specified return periods, and this requires generating target response spectra
- UHS is not a realistic target response spectrum
  - Not the response spectrum of any actual earthquake
  - Actual earthquakes often have a peak at one spectral period, but the level tends to diminish away from the peak period
  - Unlikely for an actual earthquake to have peaks at all spectral response periods
  - UHS sets the envelope of the set of target spectra for a specified return period
- Conditional Mean Spectra (CMS) are a type of target response spectra developed to produce realistic scenario earthquakes

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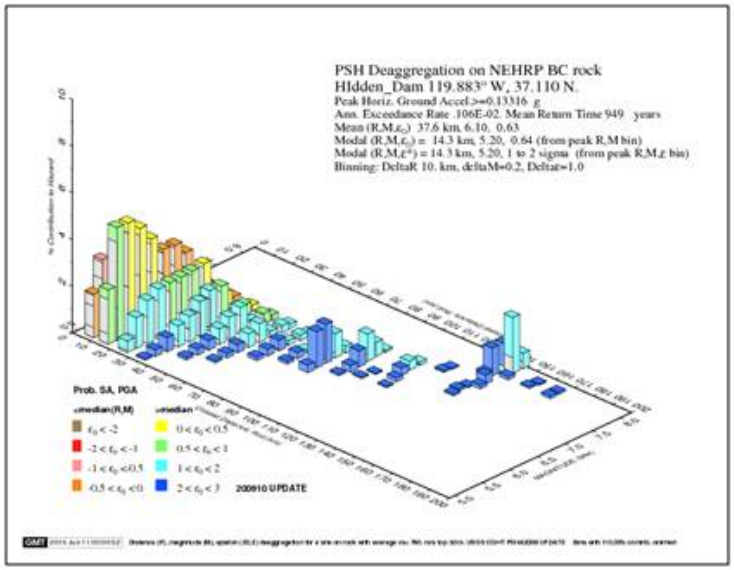
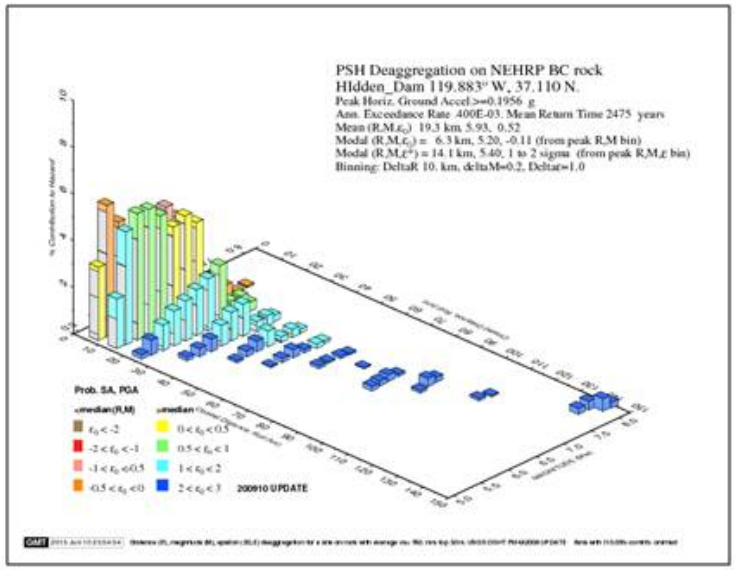
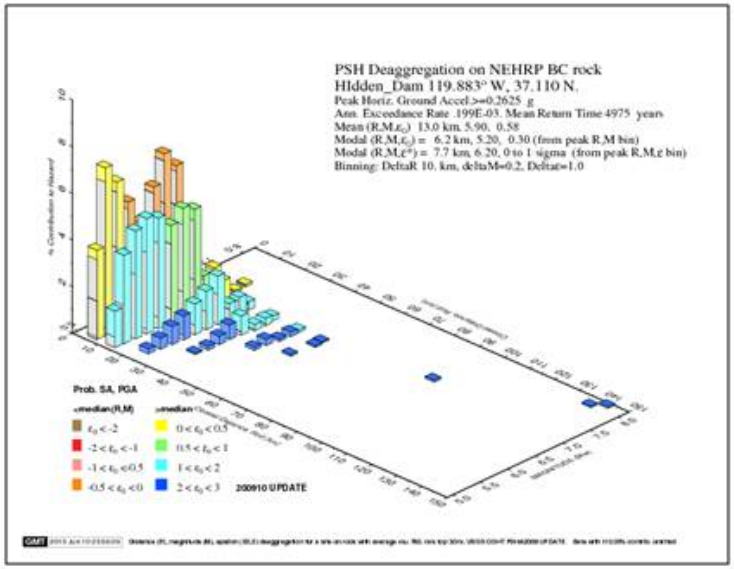
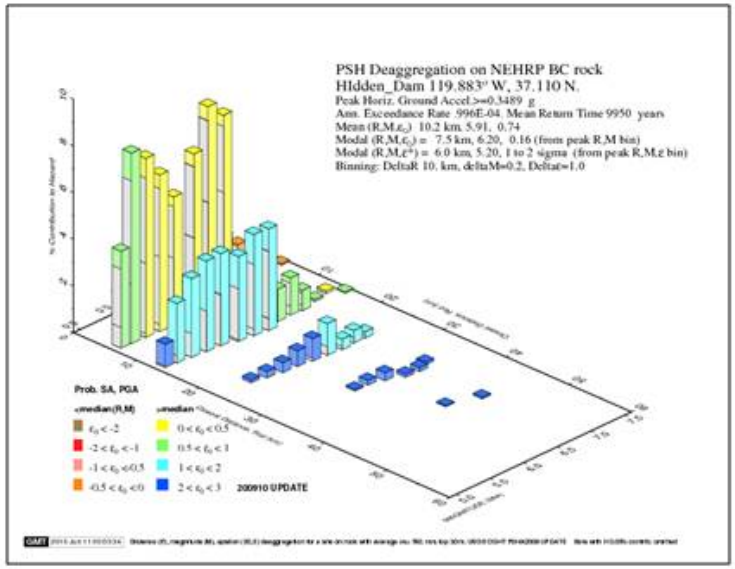
Seismic Source De-aggregation









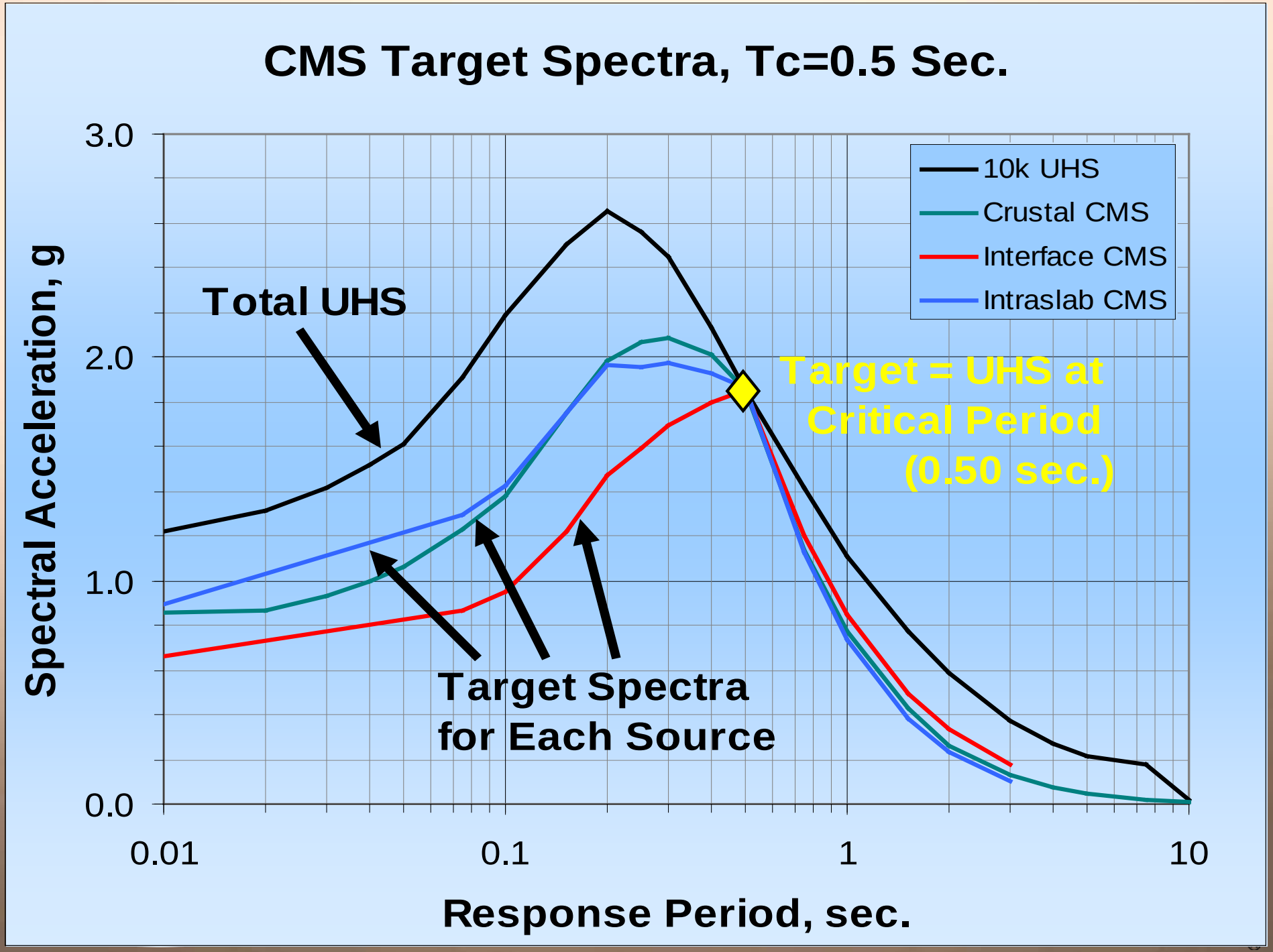
Conditional Mean Spectra

Response spectrum obtained from actual earthquakes conditioned on the peak response occurring at a specified target spectral period

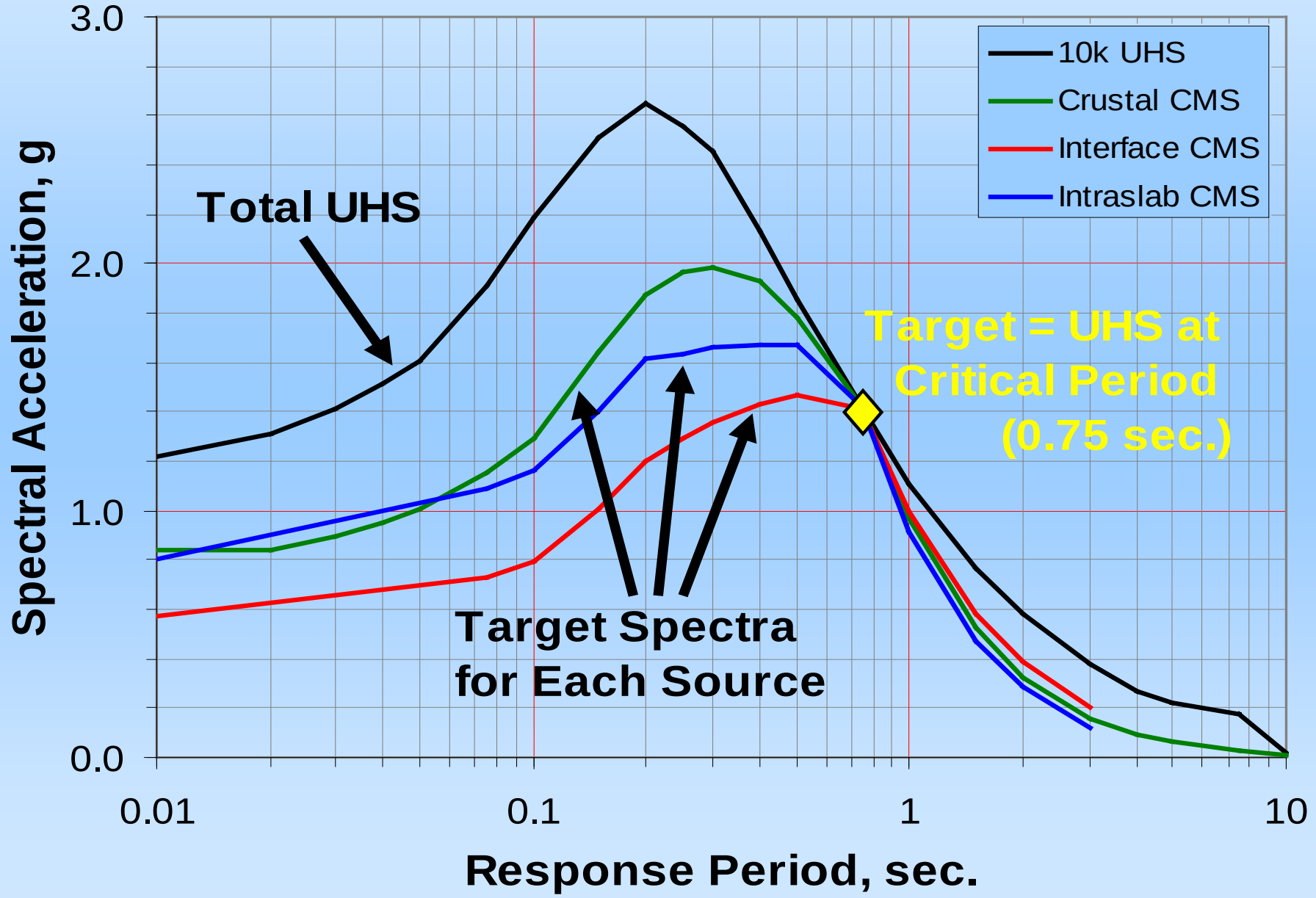
- Typically chosen as the critical period of a structure (as known or approximated)

Critical period for a particular structure is rarely known

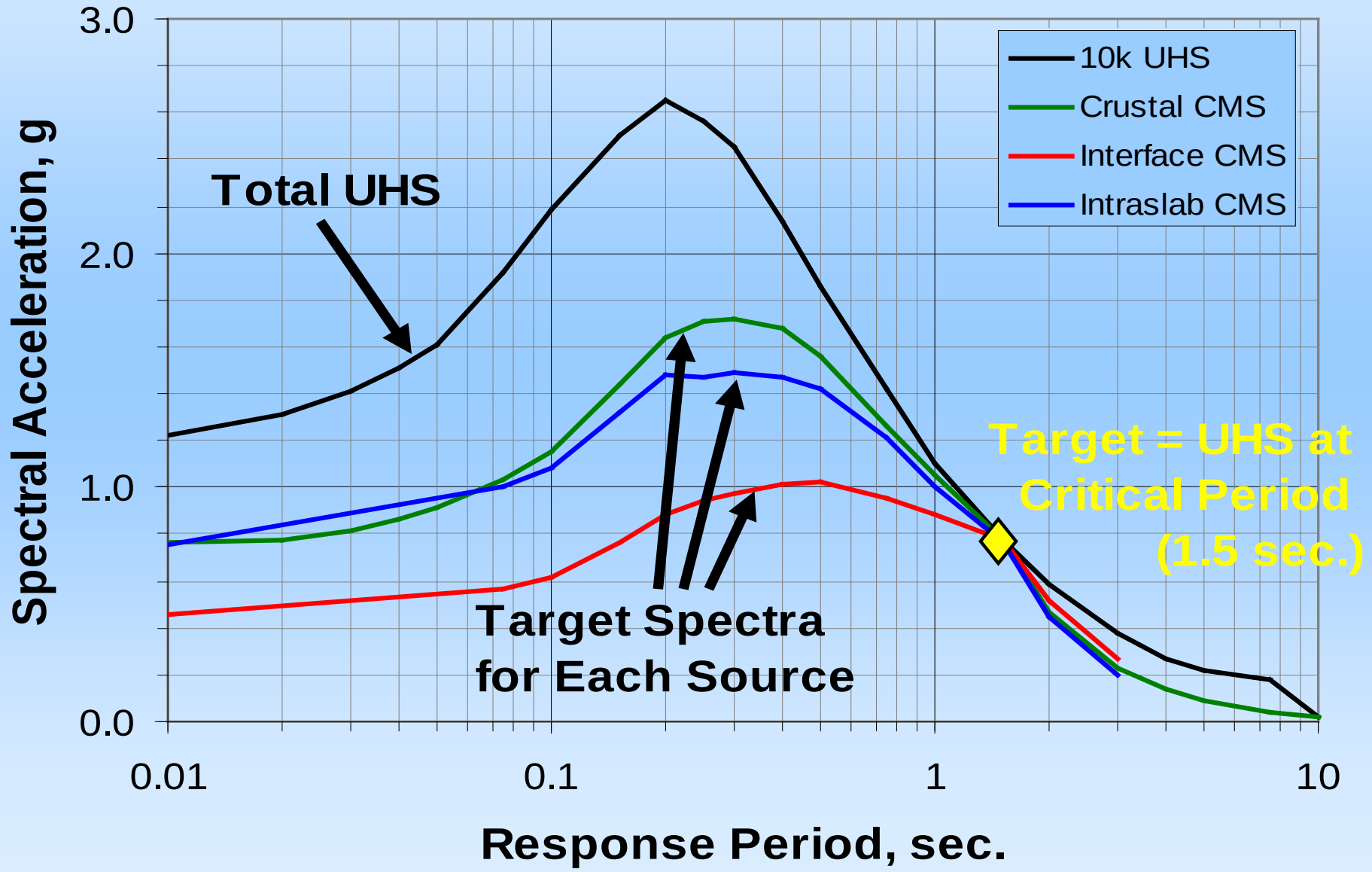
- Structures may have nonlinear behavior
- Many potential critical periods need to be considered


CMS Target Spectra, Tc=0.5 Sec.
Spectral Acceleration, g
3.0
2.0
1.0
0.0
0.01
0.1
1
10
Response Period, sec.
10k UHS
Crustal CMS
Interface CMS
Intraslab CMS
Total UHS
Target = UHS at
Critical Period
(0.50 sec.)
Target Spectra
for Each Source

CMS Target Spectra, Tc=0.75 Sec.



CMS Target Spectra, Tc=1.5 Sec.

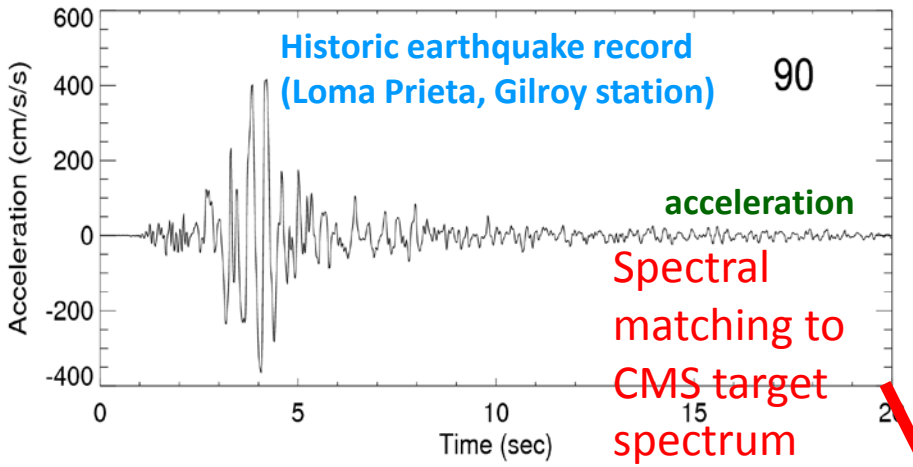


Time Histories

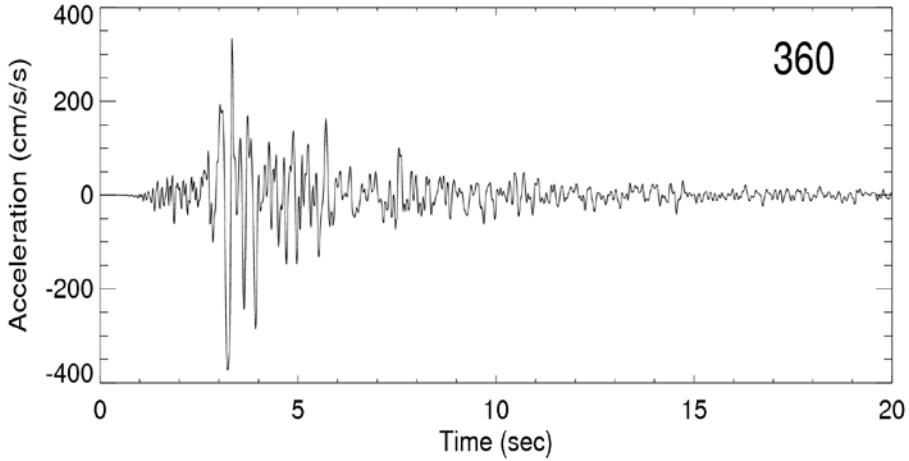
- For dynamic analyses, ground motion time histories (velocity or acceleration) are developed for a set of return periods (typically 1,000 to 50,000 years)
- Suites of time histories are developed for each return period to represent the intrinsic variability in potential ground motions of future earthquakes.
- Time histories are used for dynamic analyses using programs such *FLAC*, *SHAKE,* or *LS-DYNA*

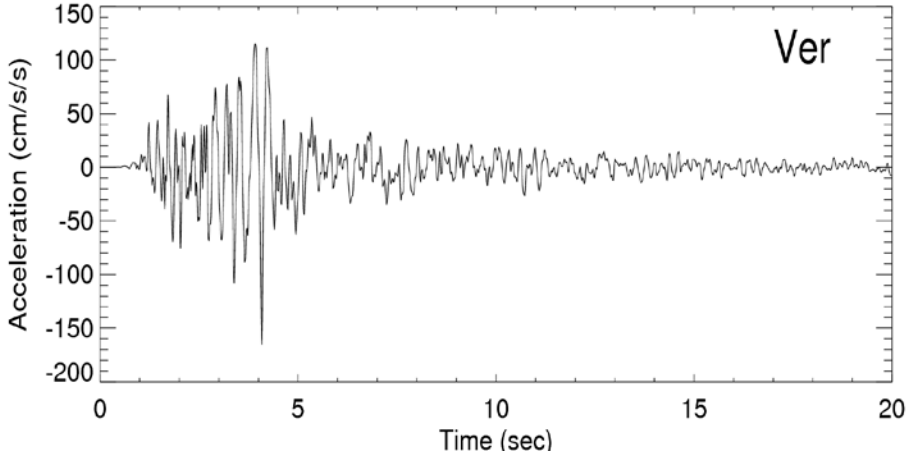
Time History Development

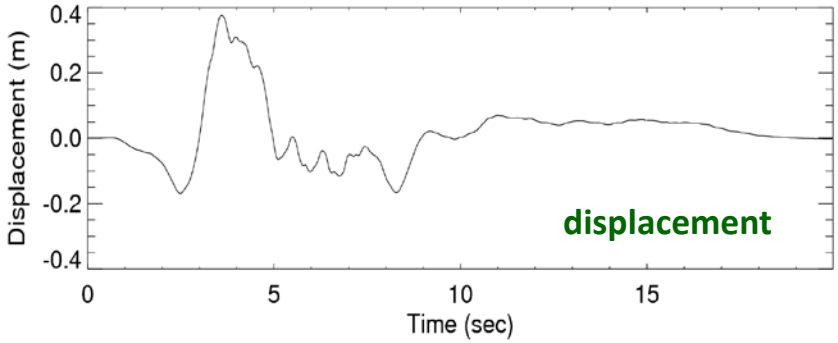
- A PSHA does not necessarily provide all important earthquake characteristics for engineering analyses, for example -
  - Duration of shaking
  - Timing and phasing of peak ground motions
- This limitation is partly addressed by selecting records of historical earthquakes at similar magnitudes and distances, and then modifying those records to be consistent with the hazard calculated from the PSHA
- In order to do this, the total hazard must be disaggregated to find the magnitude and the distance of the primary contributing earthquake scenarios

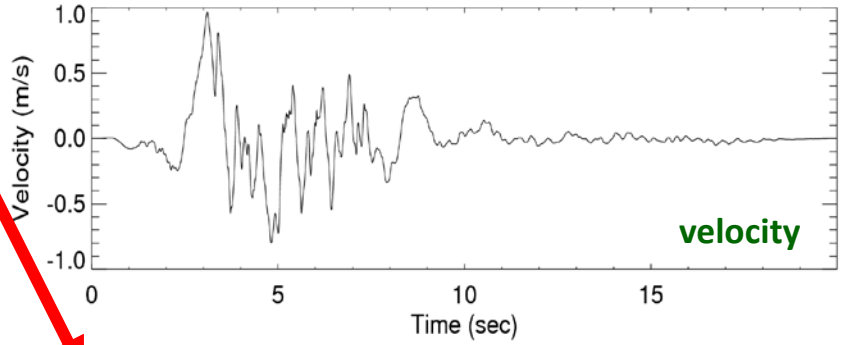


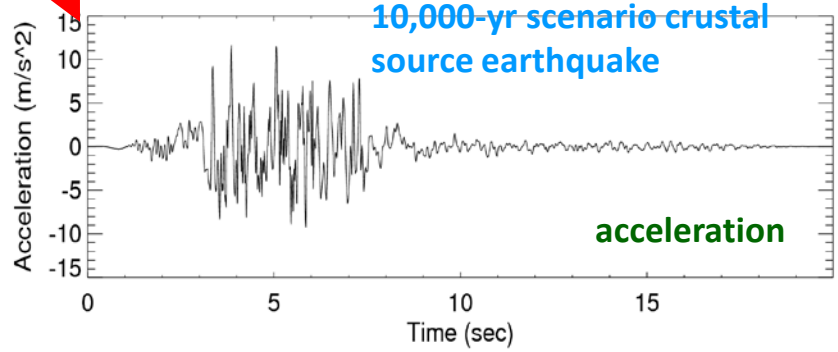
Spectral matching to CMS target spectrum

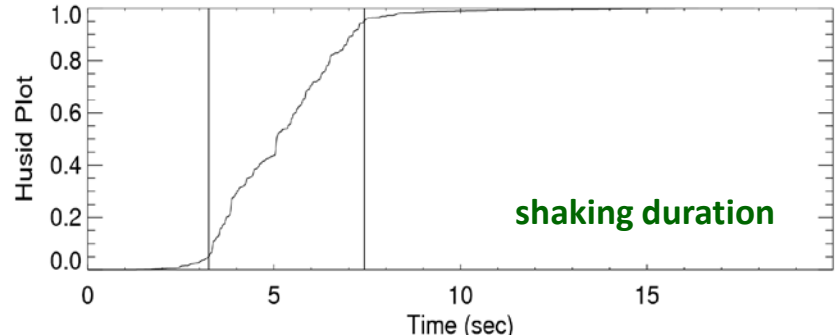


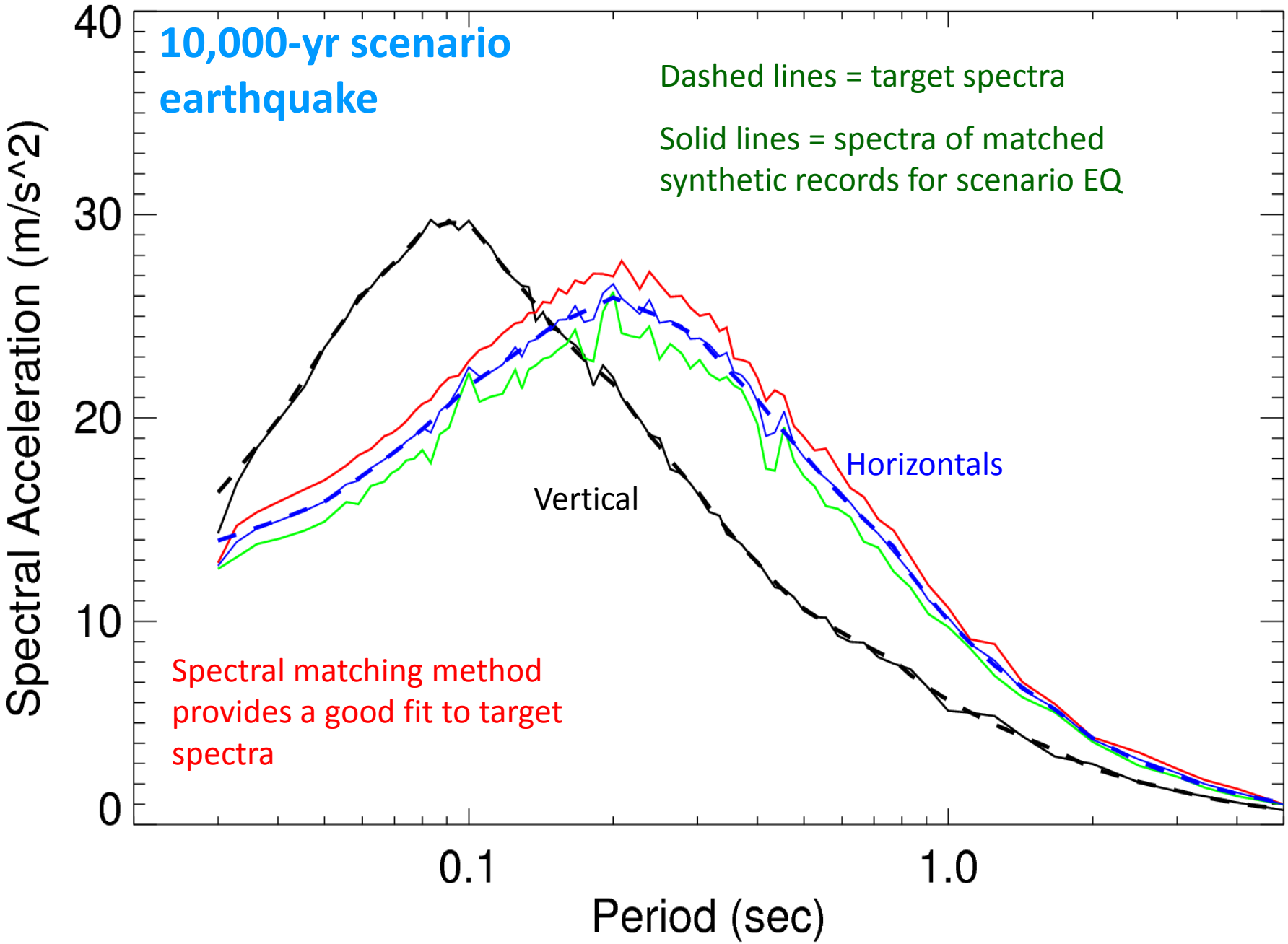






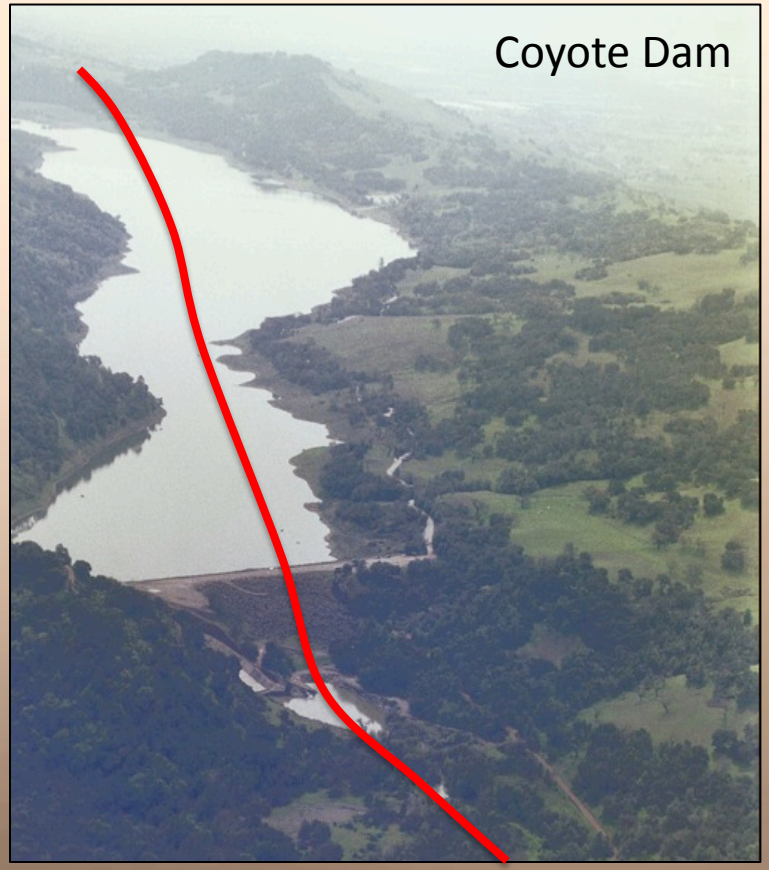





10,000-yr scenario earthquake
Dashed lines = target spectra
Solid lines = spectra of matched synthetic records for scenario EQ
Horizontals
Vertical
Spectral matching method provides a good fit to target spectra
Spectral Acceleration (m/s^2)
Period (sec)
0
10
20
30
40
0.1
1.0

The Other Seismic Loading: Surface Fault Rupture

Dams in the US have been built across active faults, sometimes knowingly.



Lake Isabella Auxiliary Dam

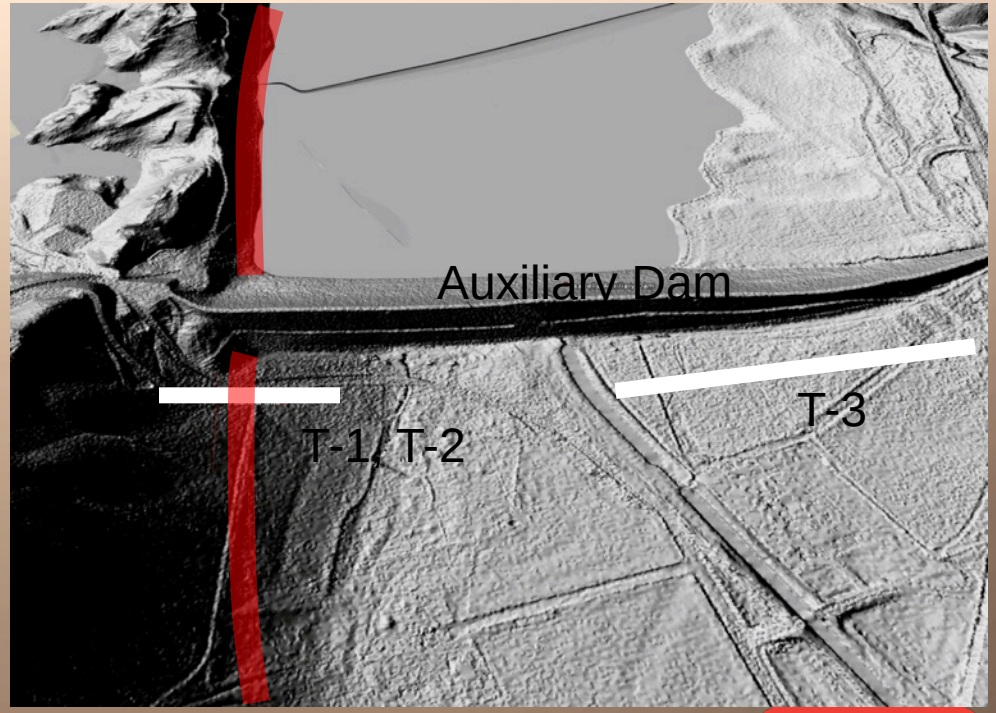
Lake Isabella Auxiliary Dam

Active: Multiple Holocene surface ruptures

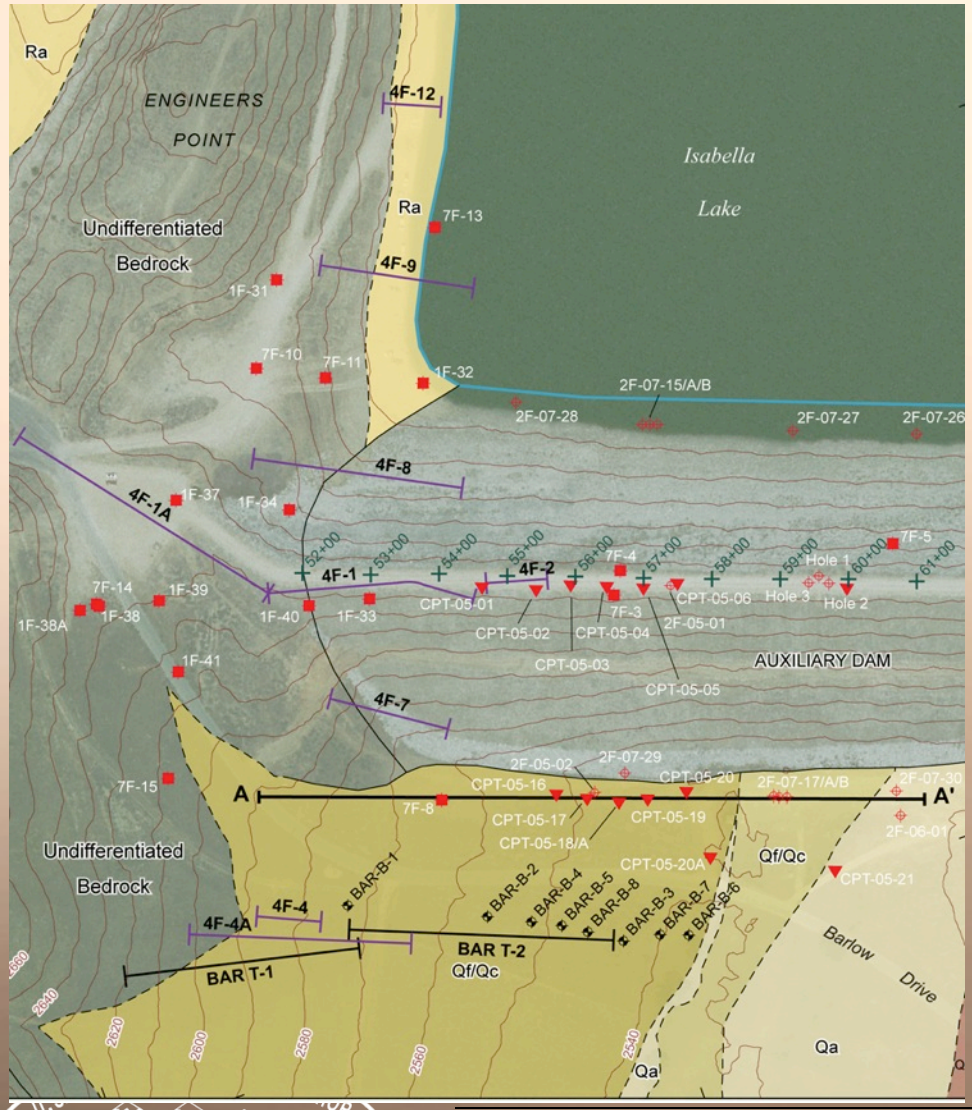
- Maximum magnitude: M_w7.5 (distance = 0 km)
- East-down fault displacement
- About 45 m wide beneath right abutment
- Estimated max displacement: 2.1 m **(6.8 ft)**

Fault Rupture Characterization

- Active Fault Strand Location
- Width of Surface Deformation
- Amount of Surface Deformation
  - Primary Fault Rupture
  - Secondary Deformation
- Sense of Slip



Fault Characterization: Kern Canyon Fault



Local Site Data

Two paleoseismic trenches (16-ft-deep, 350-ft-long)

Eight shallow soil borings up to 40 ft deep

Multiple geotechnical boreholes on dam crest and abutment

Dam construction trenches (USACE)

USGS geophysical data

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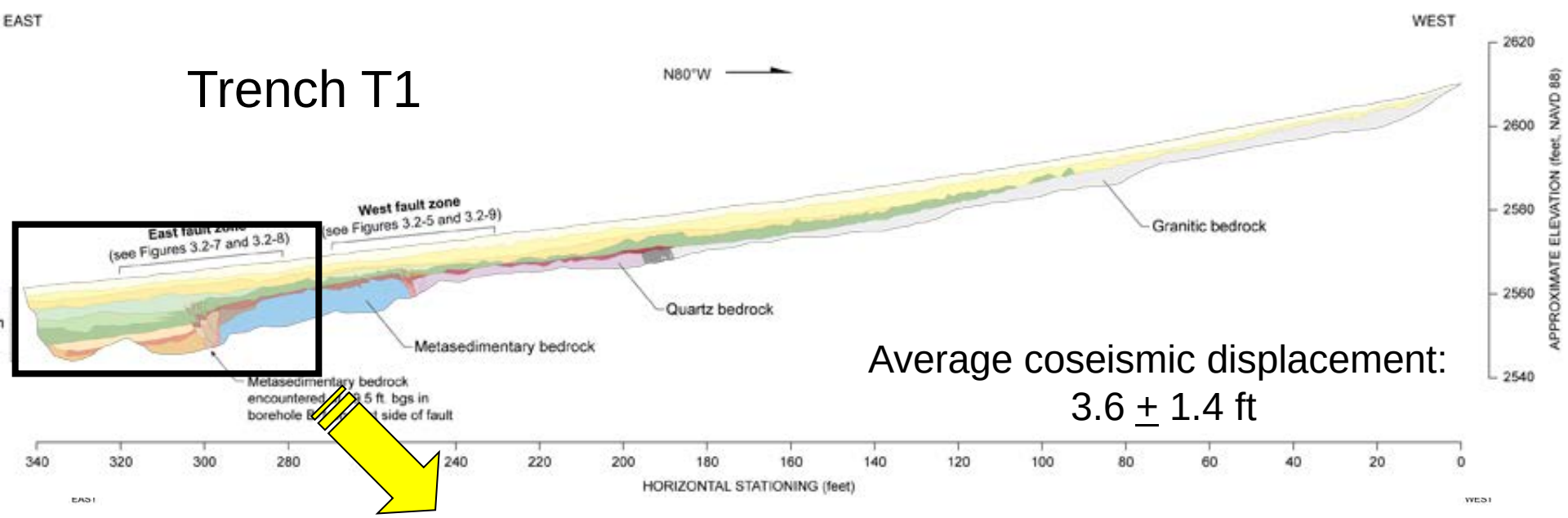
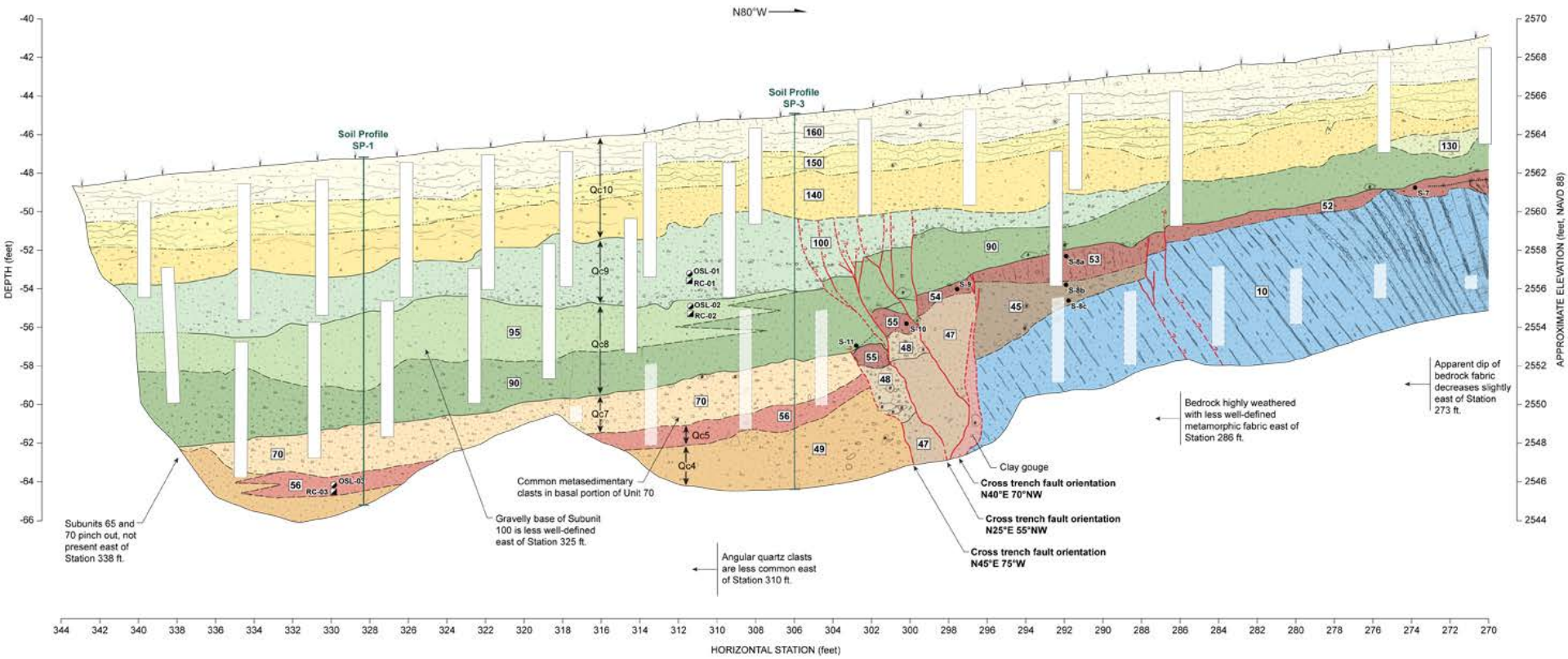
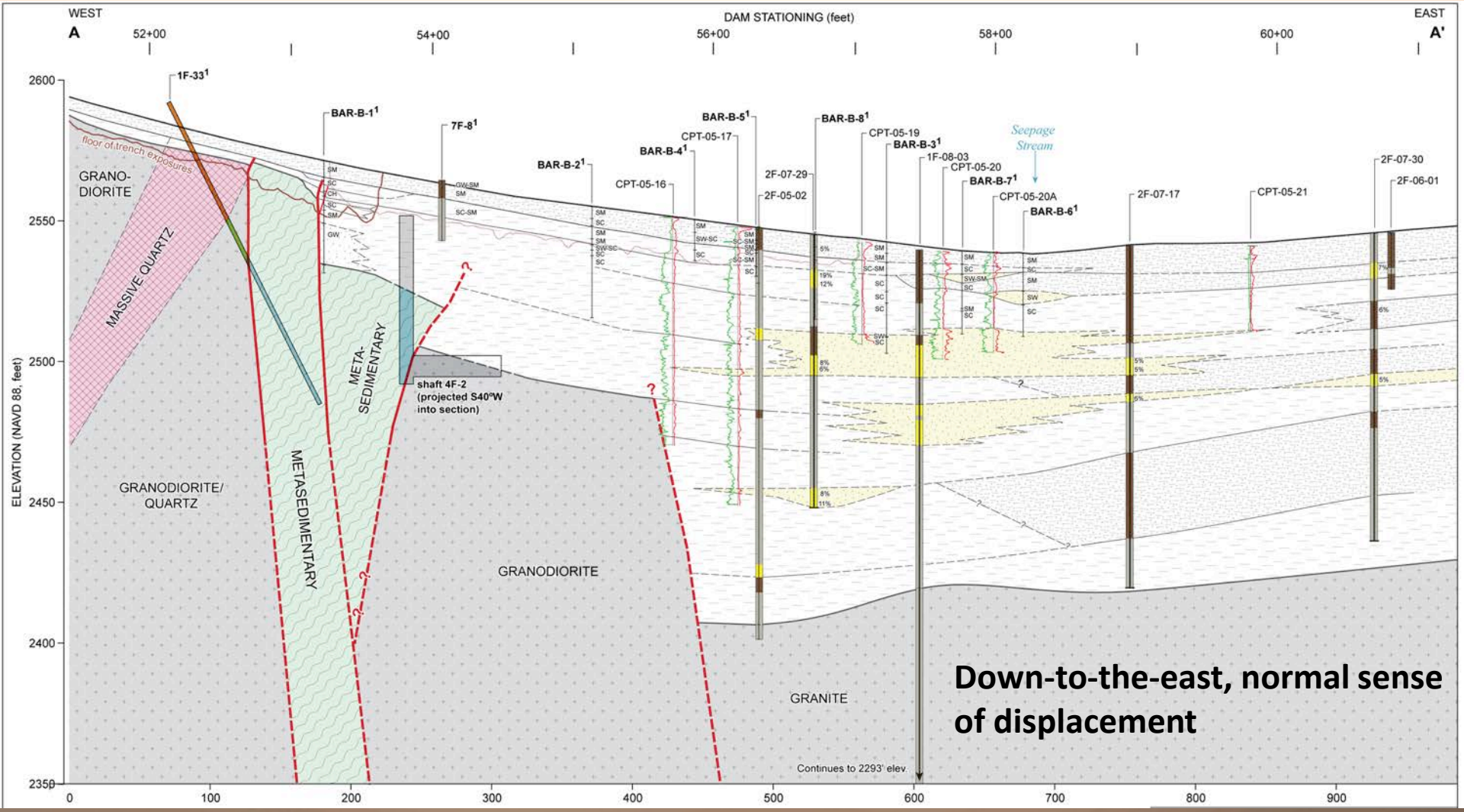
Trench T1



Average coseismic displacement:
3.6 ± 1.4 ft

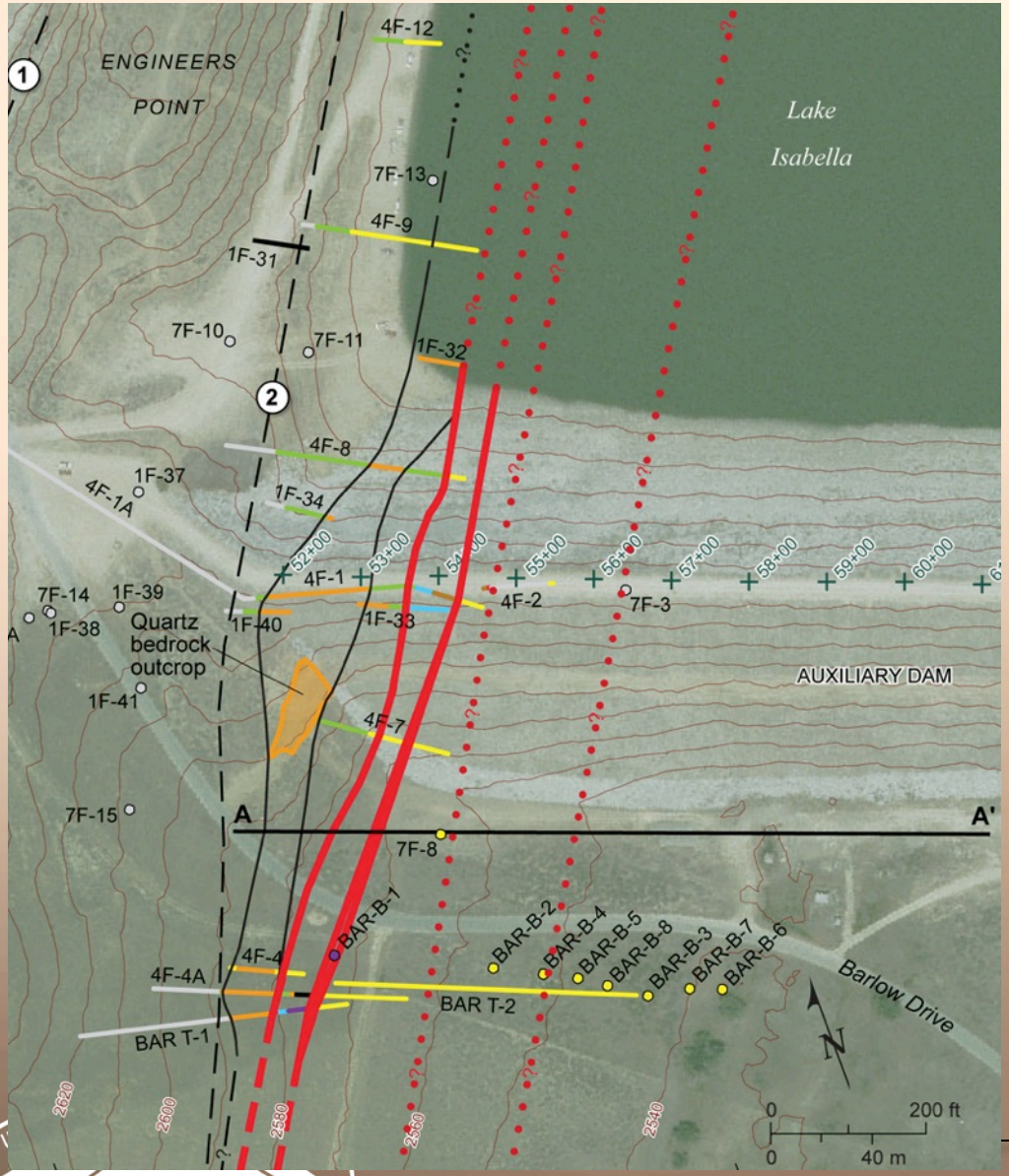


Four fault strands (two active), slightly asymmetric tectonic basin



Down-to-the-east, normal sense of displacement

Fault Characterization: Kern Canyon Fault

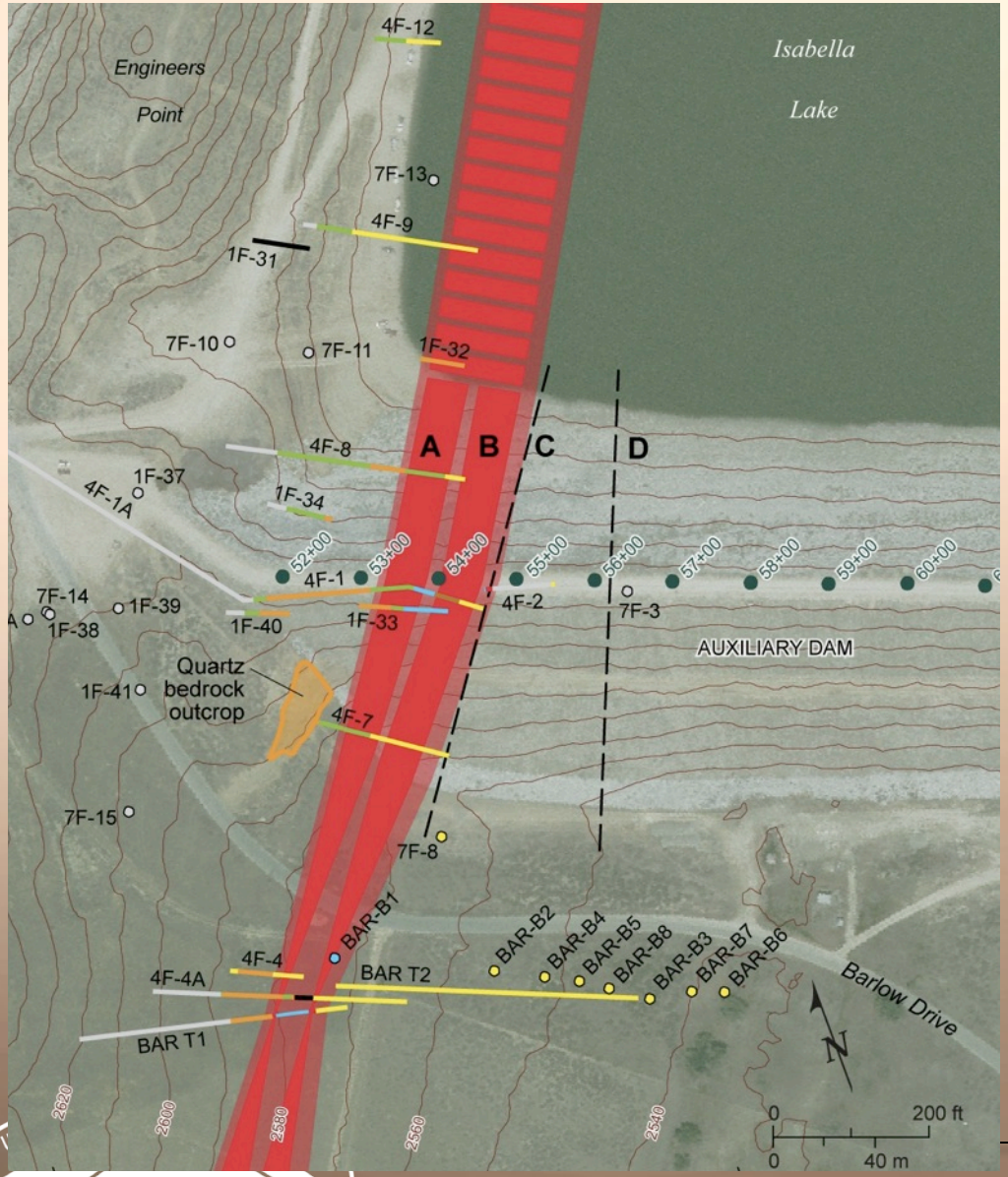


Two active fault strands, 50 ft apart

Secondary deformation between two primary strands

Tectonic displacement in 150-ft-wide zone

Fault Characterization: Kern Canyon Fault



Two primary zones (Fault A and Fault B)

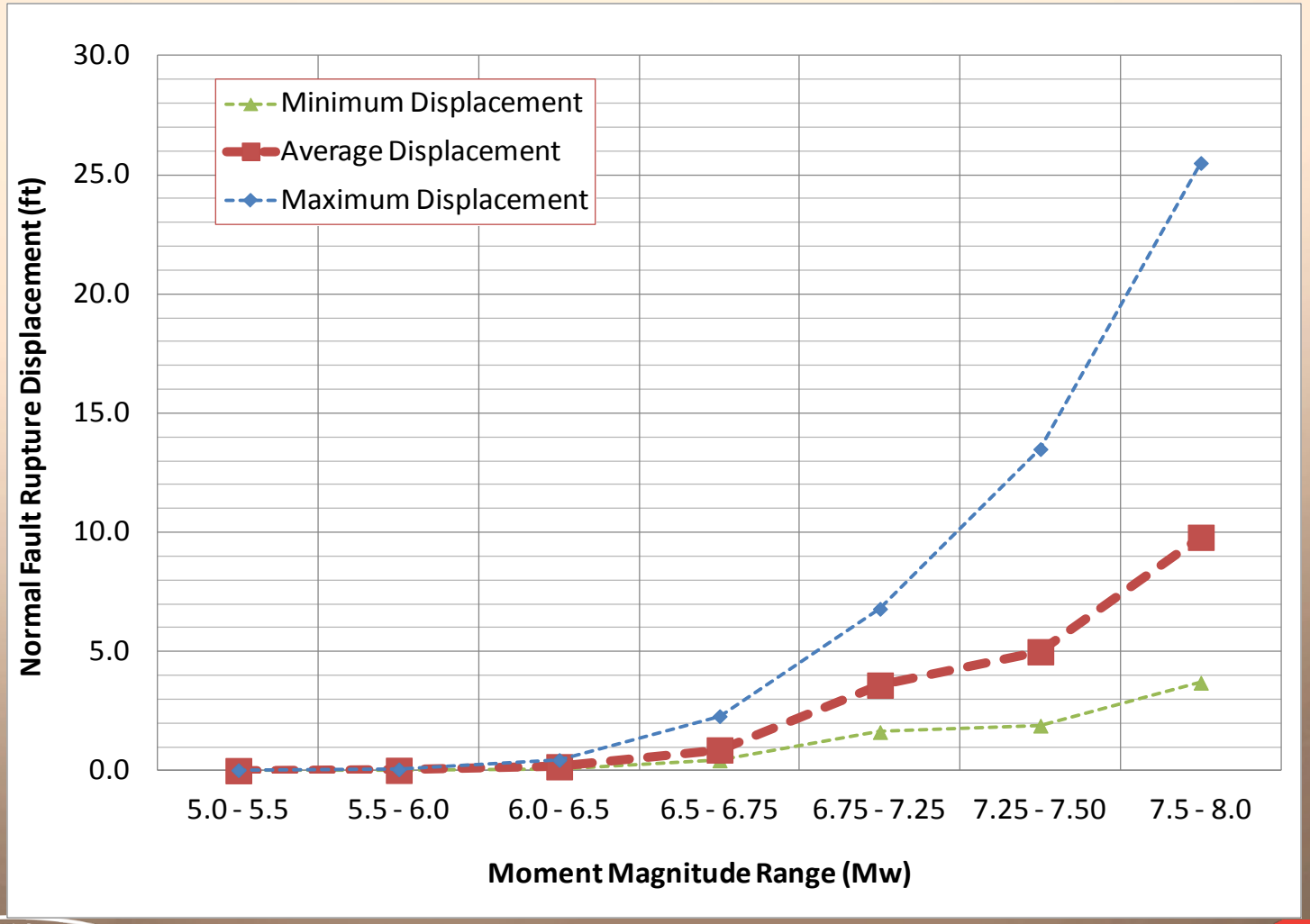
Secondary zones of faulting and tilting

Zone of deformation: 45 m (150 ft) wide

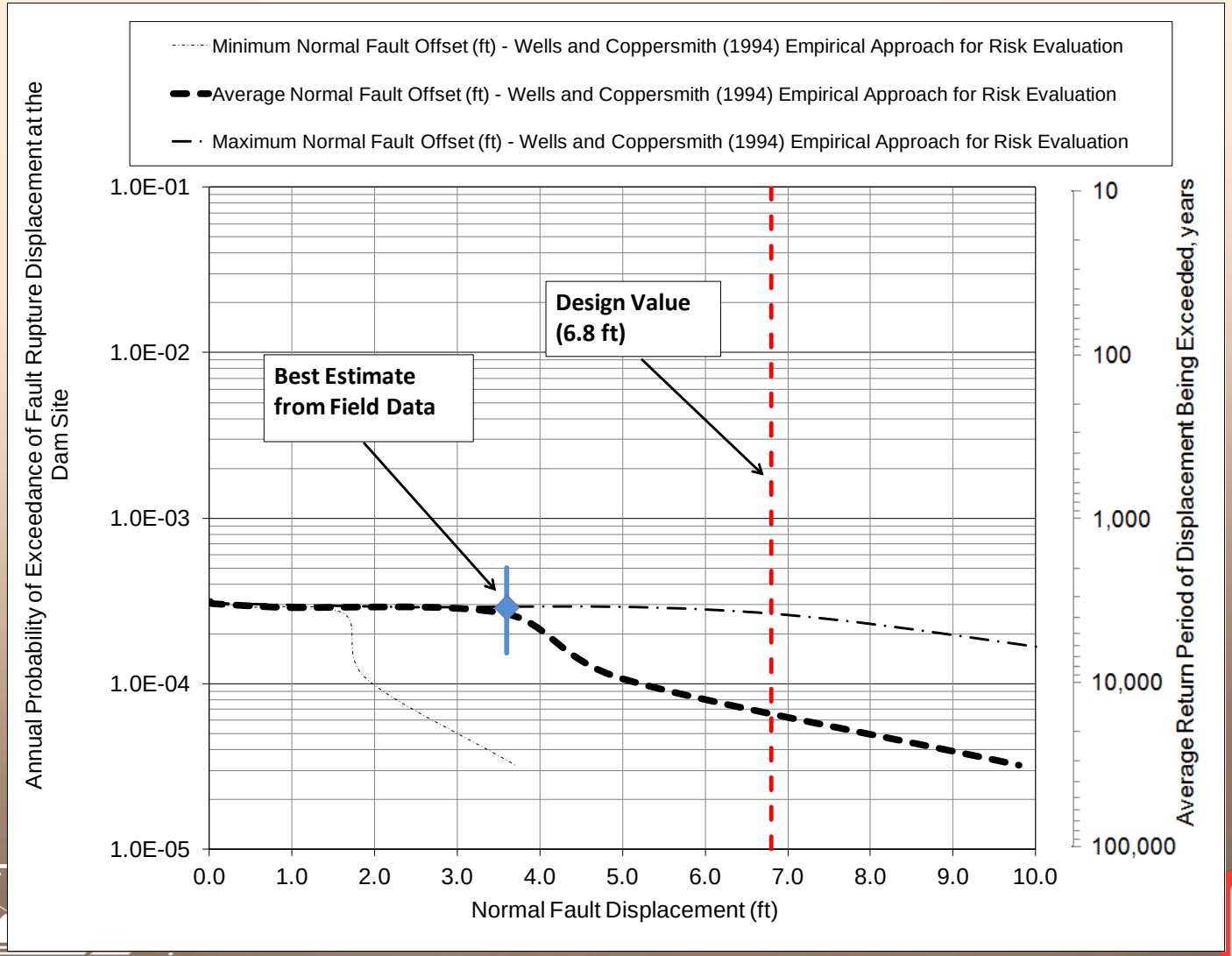
East-down displacement

Probable maximum displacement of about **2.1 m (6.8 ft)**

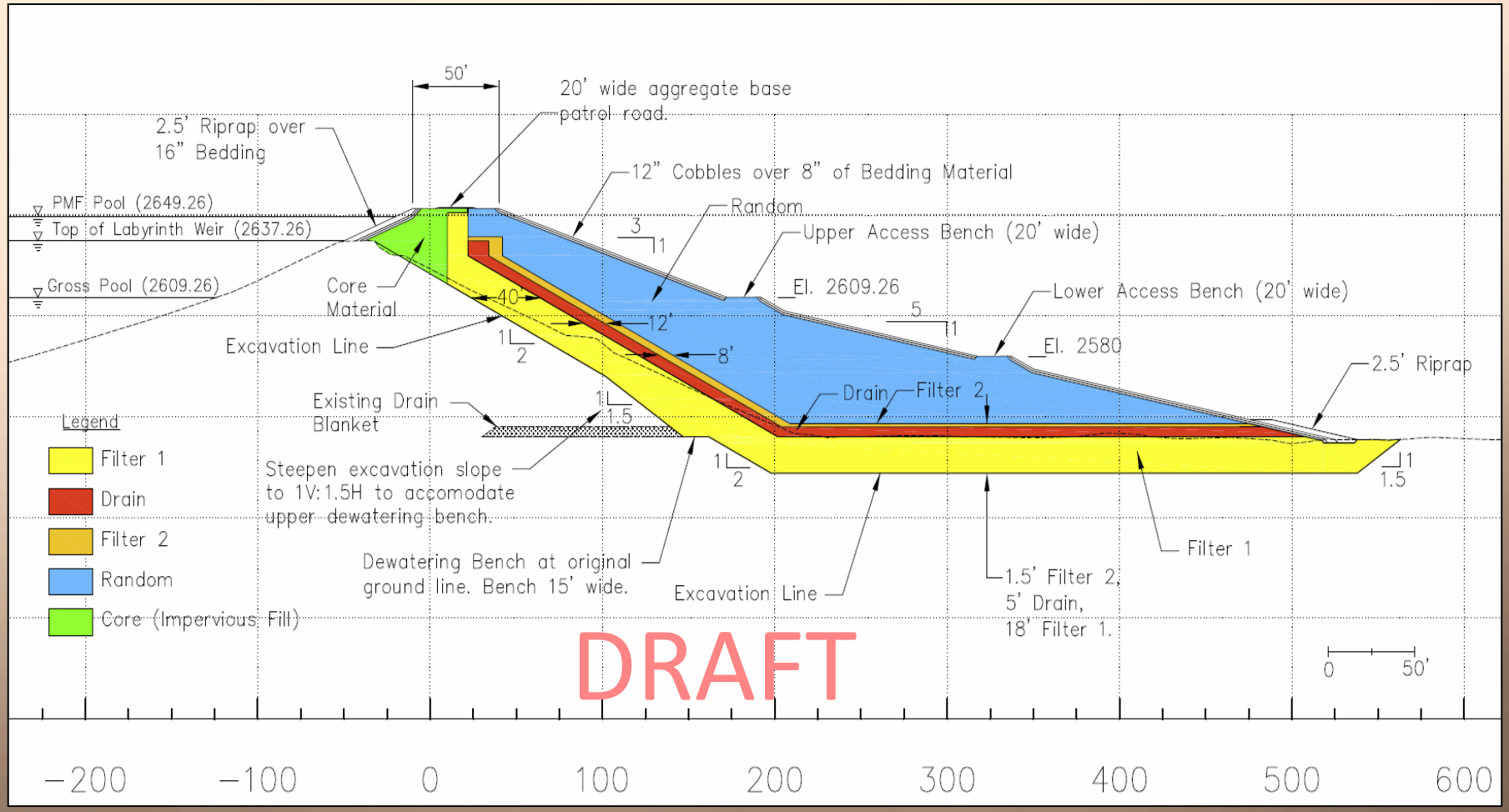
From Characterization to Design



From Characterization to Design



From Characterization to Design



Summary

- Seismic loading failure modes
- Technical background: plate tectonics, types of faults
- Strong ground motion analysis
  - Seismic source characterization: fault source, areal sources
  - Attenuation (GMPEs)
  - De-aggregation plots
  - Site response: hazard curve, time histories, CMS
- Fault rupture hazard
- Summary and Conclusions