Basin and Range Province Seismic Hazards Summit III

Utah Geological Survey and Western States Seismic Policy Council

Day 1

Keynote

Technical Session 1 – Perspectives and User Needs: *Moderator: William Lund, Utah Geological Survey*

Technical Session 2 – M_{max} Issues in the Basin and Range Province: *Moderator: Ivan Wong, URS Corporation*

Keynote

EARTHQUAKE EARLY WARNING IN THE INTERMOUNTAIN WEST

Keith D. Koper, Director
University of Utah Seismograph Stations
January 13, 2015

The following is a PDF version of the author's PowerPoint presentation.

Earthquake Early Warning in the Intermountain West

Keith D. Koper, Director
University of Utah Seismograph Stations

January 13, 2015

UUSS
UNIVERSITY OF UTAH
SEISMOGRAPH STATIONS
quake.utah.edu

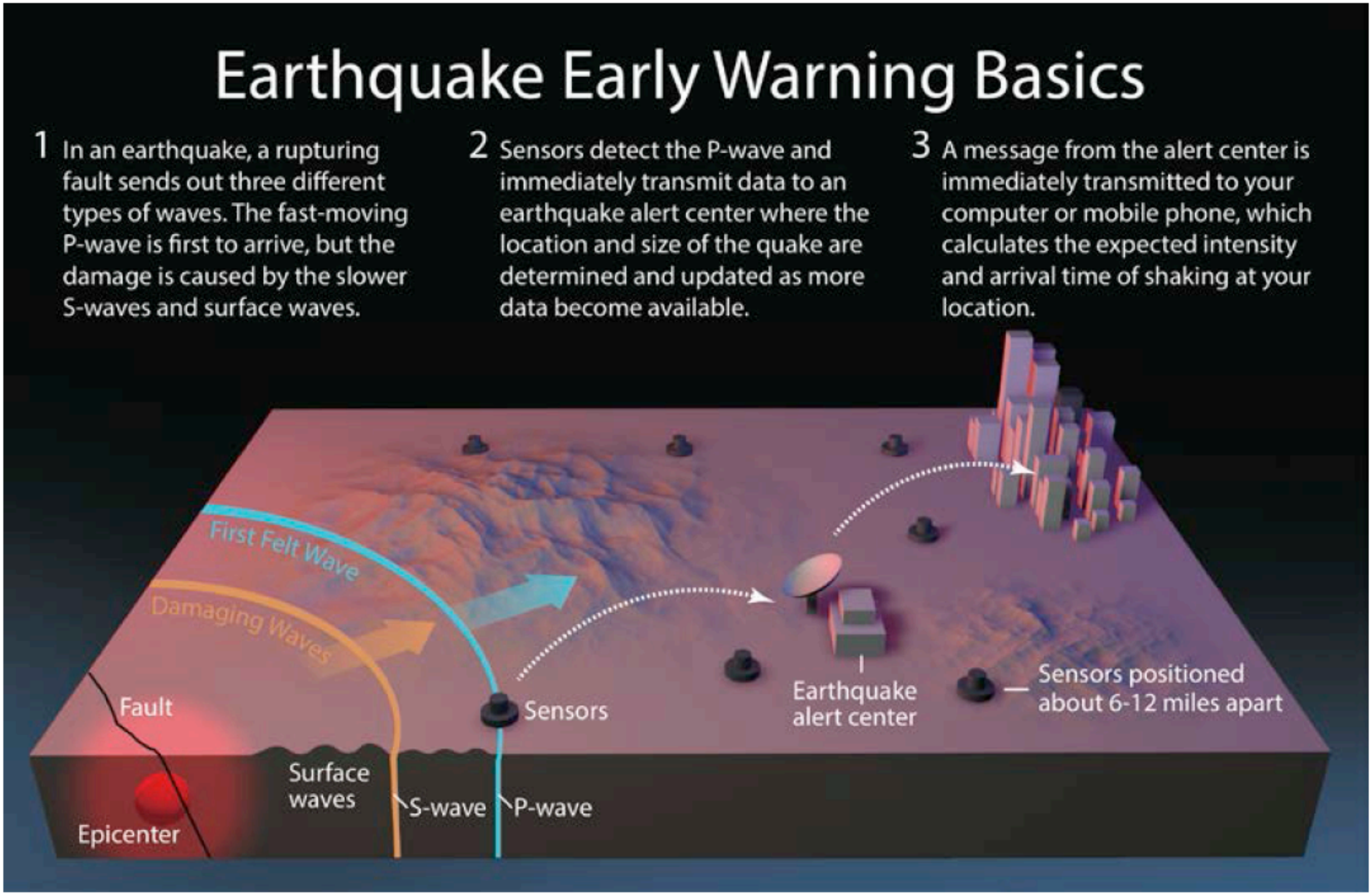
Talk Outline

1. Earthquake Early Warning (EEW) Overview

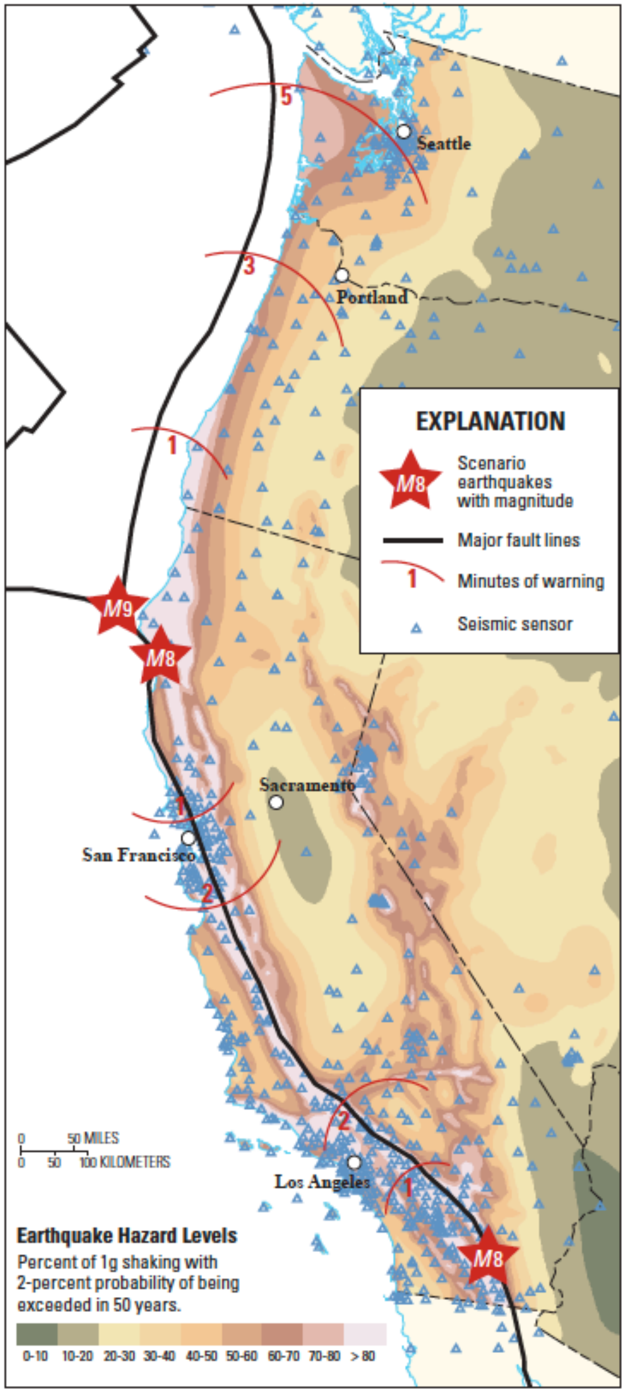
2. Recent Developments in EEW

3. EEW in the Intermountain West (?)

Surface rupture from the 1934 magnitude 6.6 Hansel Valley, Utah, earthquake [Utah Seismic Safety Commission, 2009].



(*Givens et al.*, USGS, 2014)



How Warning Can Increase Safety and Prevent Damage

Even a few seconds of warning can enable actions that protect people and property. In the time between receipt of an alert and arrival of damaging shaking, the following actions can be taken:

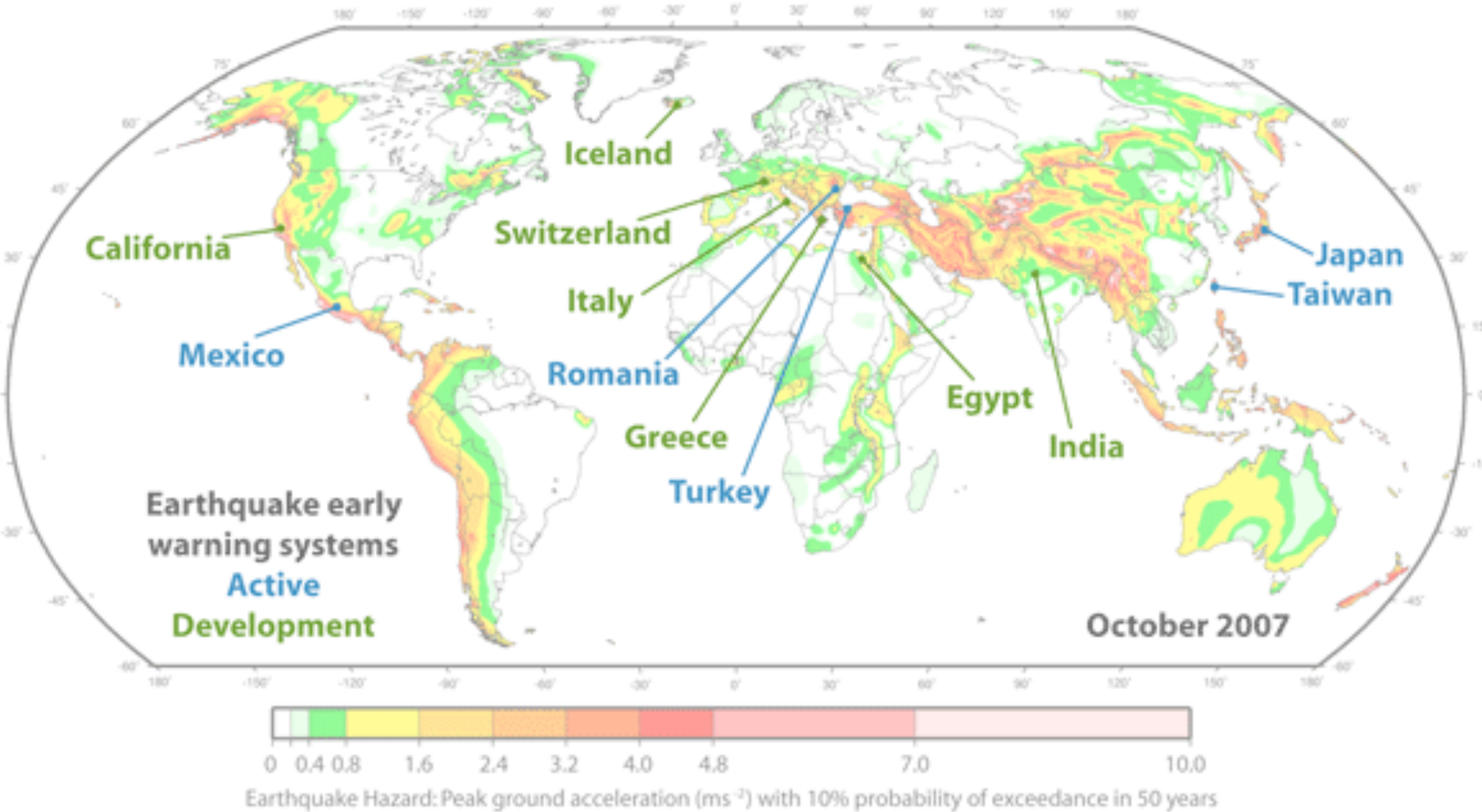
Human Responses

- Public: Citizens, including schoolchildren, drop, cover, and hold on; turn off stoves, safely stop vehicles.
- Businesses: Personnel move to safe locations.
- Medical services: Surgeons, dentists, and others stop delicate procedures.
- Emergency responders: Open firehouse doors, personnel prepare and prioritize response decisions.

Automated responses

- Businesses: Open elevator doors, shut down production lines, secure chemicals, place sensitive equipment in a safe mode.
- Transportation: Automatically slow or stop trains to prevent derailment.
- Power infrastructure: Protect power stations and grid facilities from strong shaking.

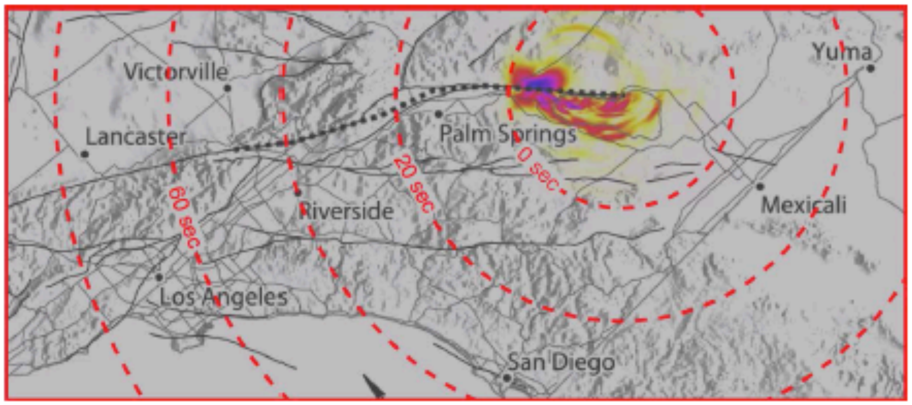
(*Burkett et al.*, USGS, 2014)



(R. Allen, UC-Berkeley)

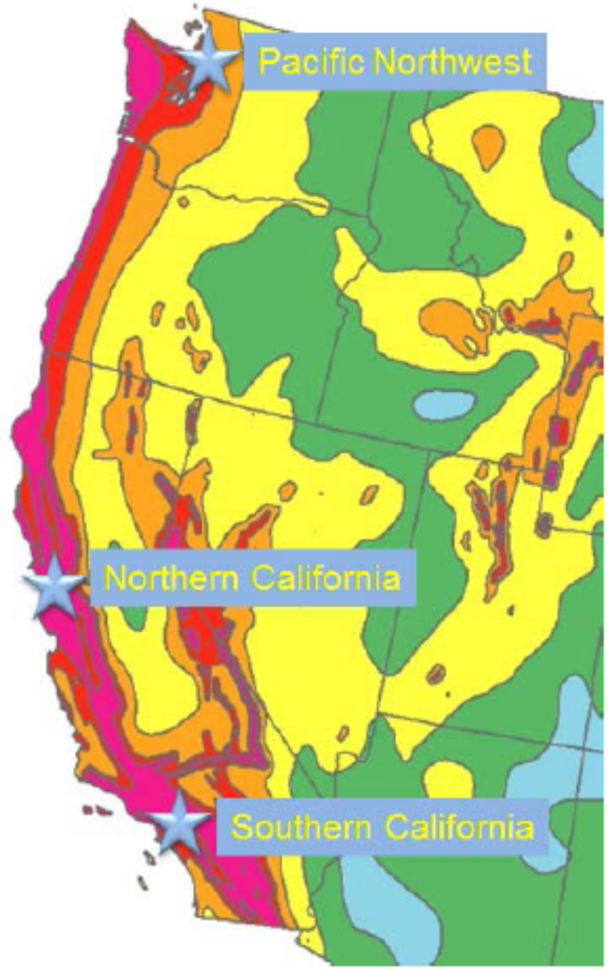
USGS
science for a changing world

Technical Implementation Plan for the ShakeAlert Production System—An Earthquake Early Warning System for the West Coast of the United States



Open-File Report 2014–1097

U.S. Department of the Interior
U.S. Geological Survey



http://www.shakealert.org/

Investment in ShakeAlert Development

(Through FY14, courtesy of D. Given, USGS)

USGS

(2002-2015)

- External coops R & D for EEW
  - Phase I & II (2002-2012) $2,093,851
  - Phase III (2012-2015) $1,575,000
- ARRA California (2009-2011) $4,426,110
  - Network equipment upgrades
- MultiHazards Project (2008-2014) $2,342,150
  - San Andreas sensors, digital upgrades, production computers, personnel

TOTAL $10,437,111

Moore Foundation

(2012-2014, no renewal)

- Caltech $1,996,888
- UC Berkeley $2,040,889
- Univ. of Washington $1,848,351
- USGS $ 594,406

TOTAL $6,480,534

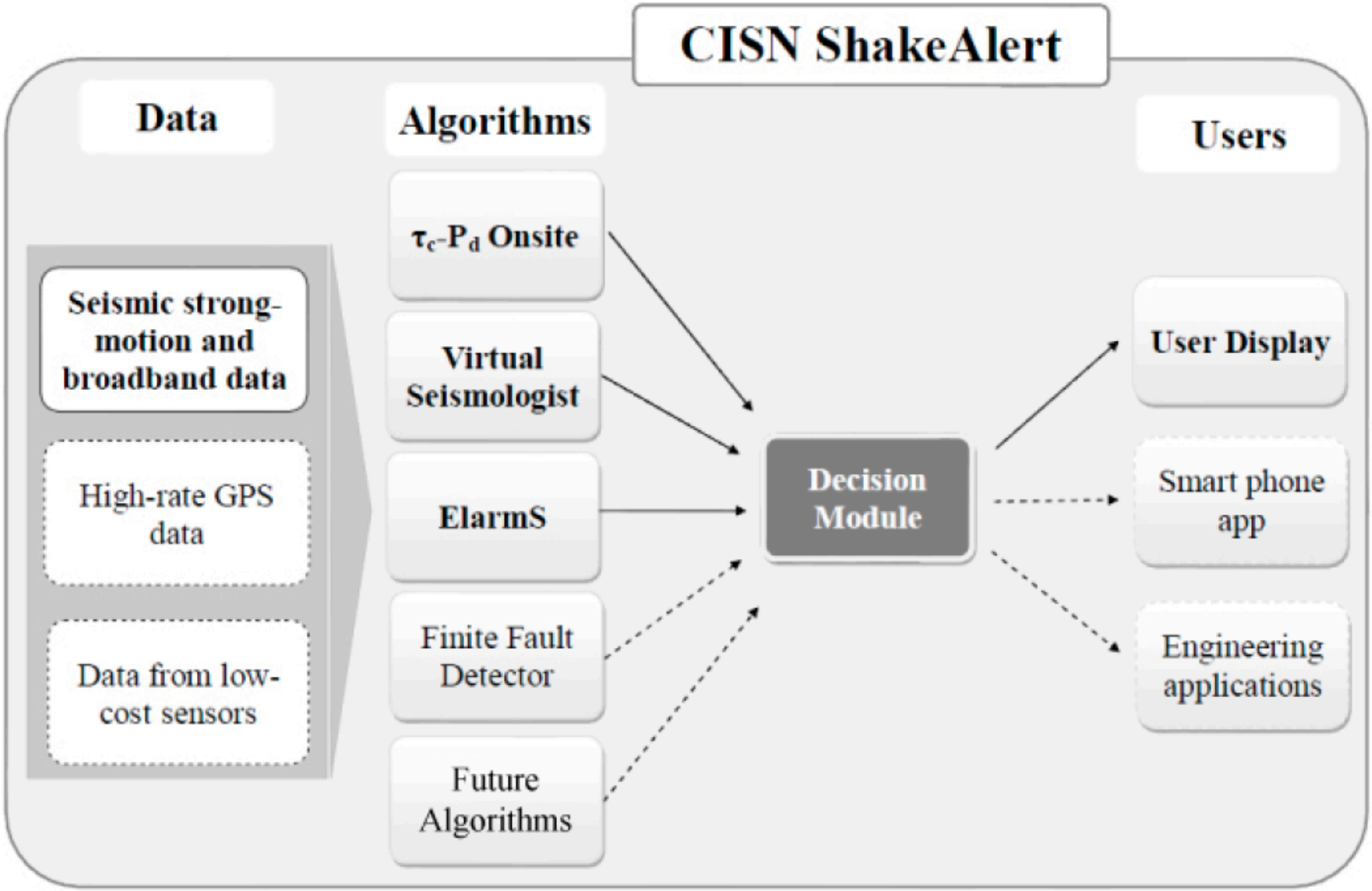
FY14 – Federal Omnibus Budget Bill

- $850,000 for EEW
- <u>"The Committees support efforts to continue developing an earthquake early warning prototype system on the West Coast."</u>

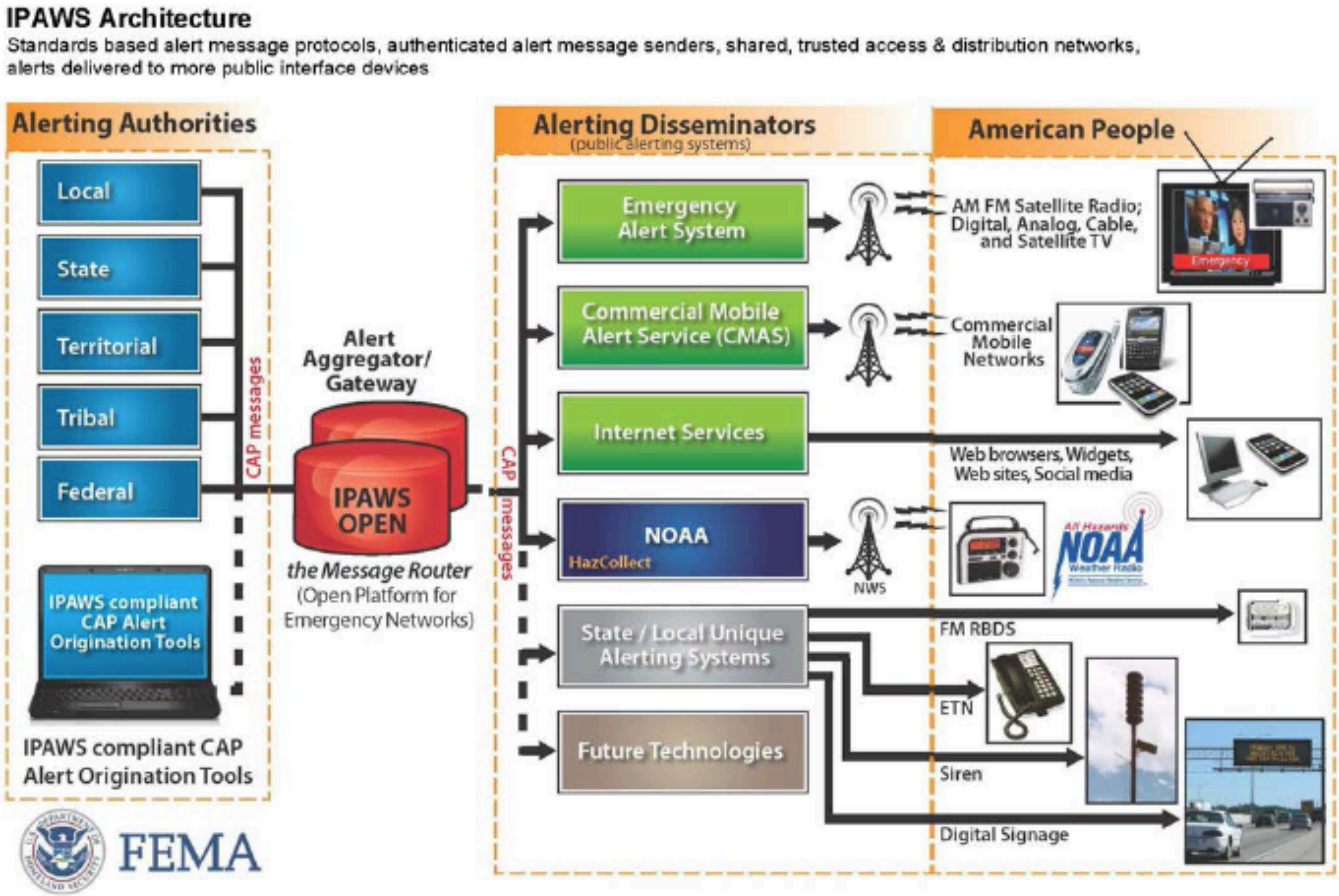
City of Los Angeles – UASI funding

- To Caltech **$5,600,000**
  - 125 new & upgraded stations
  - 40 RT-GPS stations
  - System infrastructure upgrades

+ $5 million in FY15 "Cromnibus"



(*Given et al.*, USGS, 2014)



(*Given et al.*, USGS, 2014)

On your screen: ShakeAlert

1. Real-time tracking of seismic waves from quake's epicenter.
2. Real-time tracking of the fault rupture (updates intensity).
3. Your current location tracked by GPS.
4. Seconds remaining before seismic waves reach you.
5. Expected intensity of quake at your current location.
6. Estimated magnitude of quake.
7. Intensity scale.

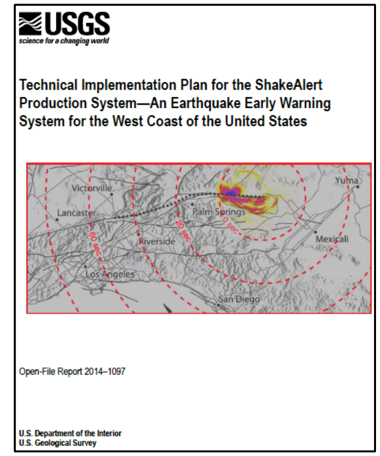
A user of ShakeAlert receives a message like this on the screen of his computer. The message alerts the user to how many seconds before the shaking waves arrive at their location and the expected intensity of shaking at that site. The shaking intensity follows the Modified Mercalli scale; an intensity of VI, as shown here, would mean the shaking is felt by everyone, people find it difficult to stand, and structures may suffer some damage. The warning message also displays a map with the location of the epicenter, the magnitude of the quake, and the current position of the P and S waves. In this example, the alert is for the ShakeOut scenario earthquake (Perry and others, 2008).

Table 4. Summary Cost of an Earthquake Early Warning (EEW) system (in millions of dollars)

	California	Pacific Northwest	West Coast Total
Construction costs	23.1	15.2	38.3
Annual M&O	11.4	4.7	16.1

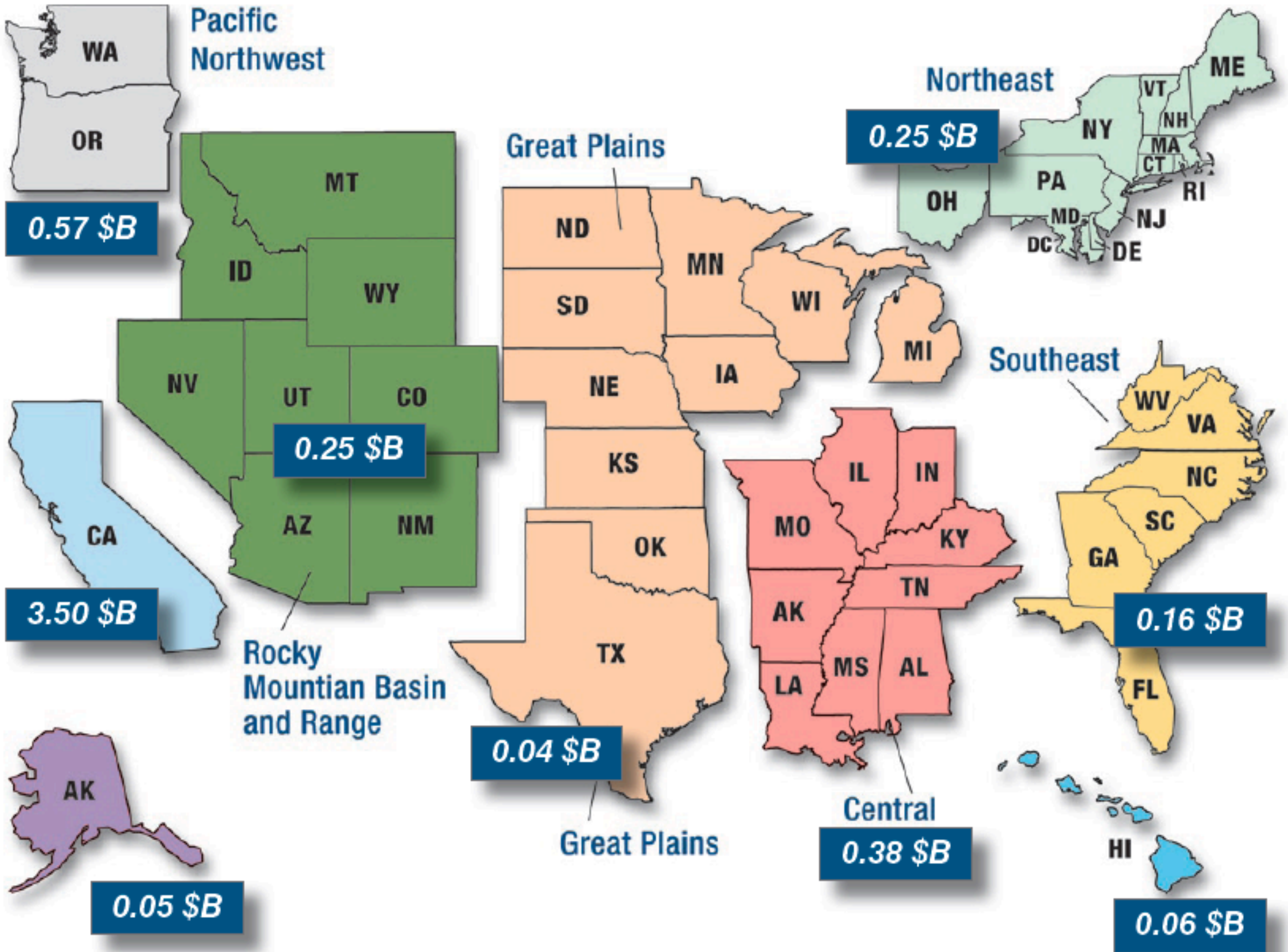
Table 5. Capital Cost of an Earthquake Early Warning (EEW) system (in thousands of dollars)

	California	Pacific Northwest	West Coast Total
Equipment			
Seismic	7,768.0	4,632.0	12,400.0
GPS	2,400.0	2,496.0	4,896.0
Installation			
Construction, material	3,512.0	2,208.0	5,720.0
Construction, labor	2,195.0	1,380.0	3,575.0
Permitting	1,097.5	690.0	1,787.5
Telemetry			
New	878.0	552.0	1,430.0
Upgrade	165.6	36.0	201.6
Microwave	2,500.0	1,500.0	4,000.0
Telemetry study	100.0	50.0	150.0
USGS overhead (12%)	*2,473.9*	*1,625.3*	*4,099.2*
Total	23,090.0	15,169.3	38,259.3



Roll-Out to Other Regions

The scope of this plan is limited to implementation of a system for the West Coast which accounts for three-quarters of the national earthquake risk. However, as EEW technology is proven and matures, ShakeAlert will be propagated to other regions with significant seismic risk. A strategy to extend EEW to the other regions of the United States will need to evaluate the cost/benefit in other areas, and focus first on those population centers with highest risk; which include New York City, Salt Lake City/Provo, Anchorage, San Juan PR, Memphis, St. Louis, Boston, and Washington, D.C. All of the investment in development work for a West Coast system is transferrable at minimal cost to the ANSS regional seismic networks that now provided enhanced reporting of earthquakes in the intermountain west and the central and eastern United States.



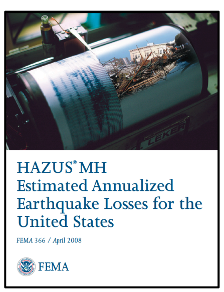


Figure E-1. Comparison of U.S. Regional Seismic Risk by Annualized Earthquake Losses (AEL).

Annualized Casualties by State

Rank	State	Day Time			Night Time		
		Minor	Life Threatening	Fatal	Minor	Life Threatening	Fatal
1	California	1891	63	122	1276	19	36
2	Washington	260	9	17	127	2	4
3	Oregon	188	7	13	85	2	3
4	Utah	86	3	6	59	2	3
5	Tennessee	89	3	5	62	1	3
6	South Carolina	64	2	4	51	1	2
7	Missouri	67	2	4	62	2	3
8	Nevada	59	2	4	33	1	1
9	Illinois	45	1	2	48	1	2
10	Arkansas	38	1	2	33	1	2
11	Alaska	28	1	2	17	0	1
12	New York	45	1	2	45	1	2
13	Kentucky	31	1	2	25	1	1
14	Georgia	32	1	1	17	0	1
15	Hawaii	21	1	1	17	0	1
16	New Mexico	15	0	1	13	0	1

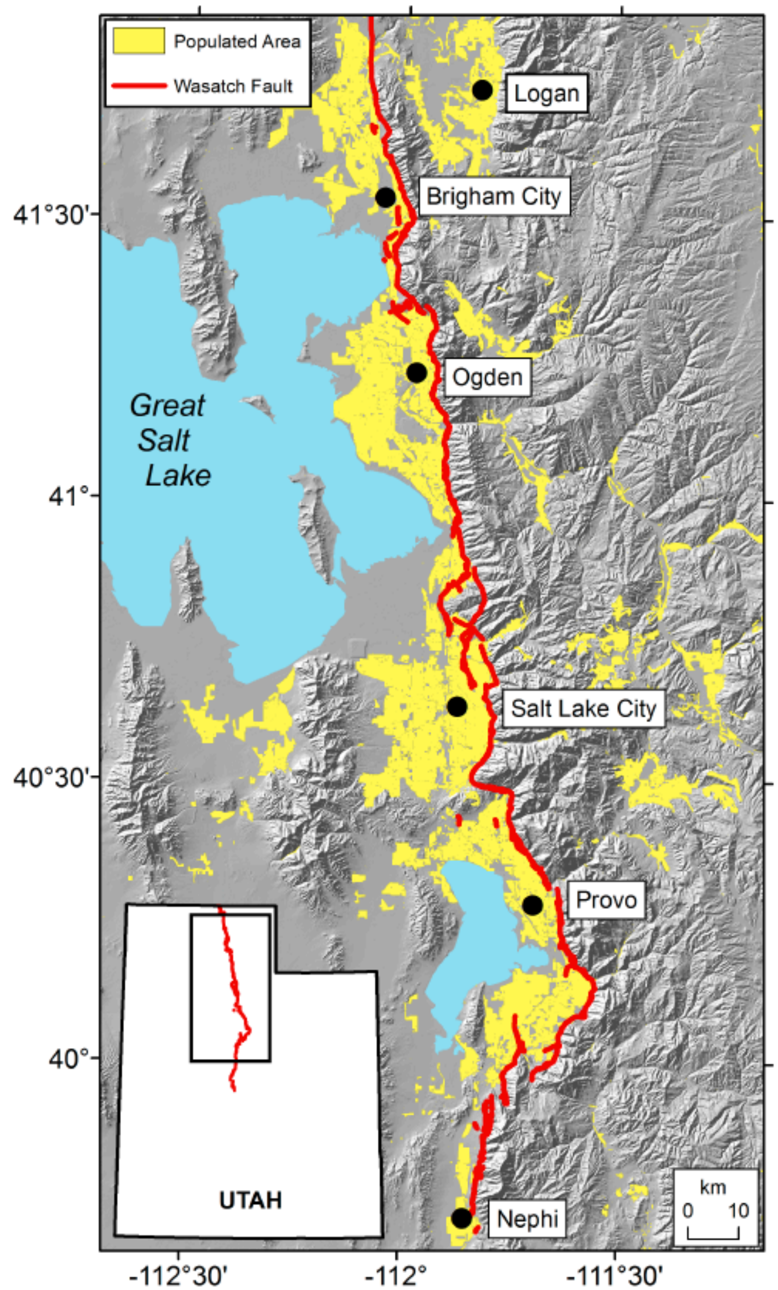
FEMA 366, April 2008

State Ranking of Utah in Measures of Earthquake Risk[1]

	National Ranking	Regional[2] Ranking
Annualized Earthquake Loss	6	1
Annualized Earthquake Loss Ratios	5	1
Estimates of Debris	5	1
Displaced Households	6	1
Annualized Shelter Requirements	5	1
Casualties	4	1

[1] Data from *FEMA 366 HAZUS-MH Estimated Annualized Earthquake Losses for the United States* (2008).

[2] The Rocky Mountain Basin and Range seismic region in *FEMA 366* includes: MT, ID, WY, NV, UT, CO, AZ, and NM.

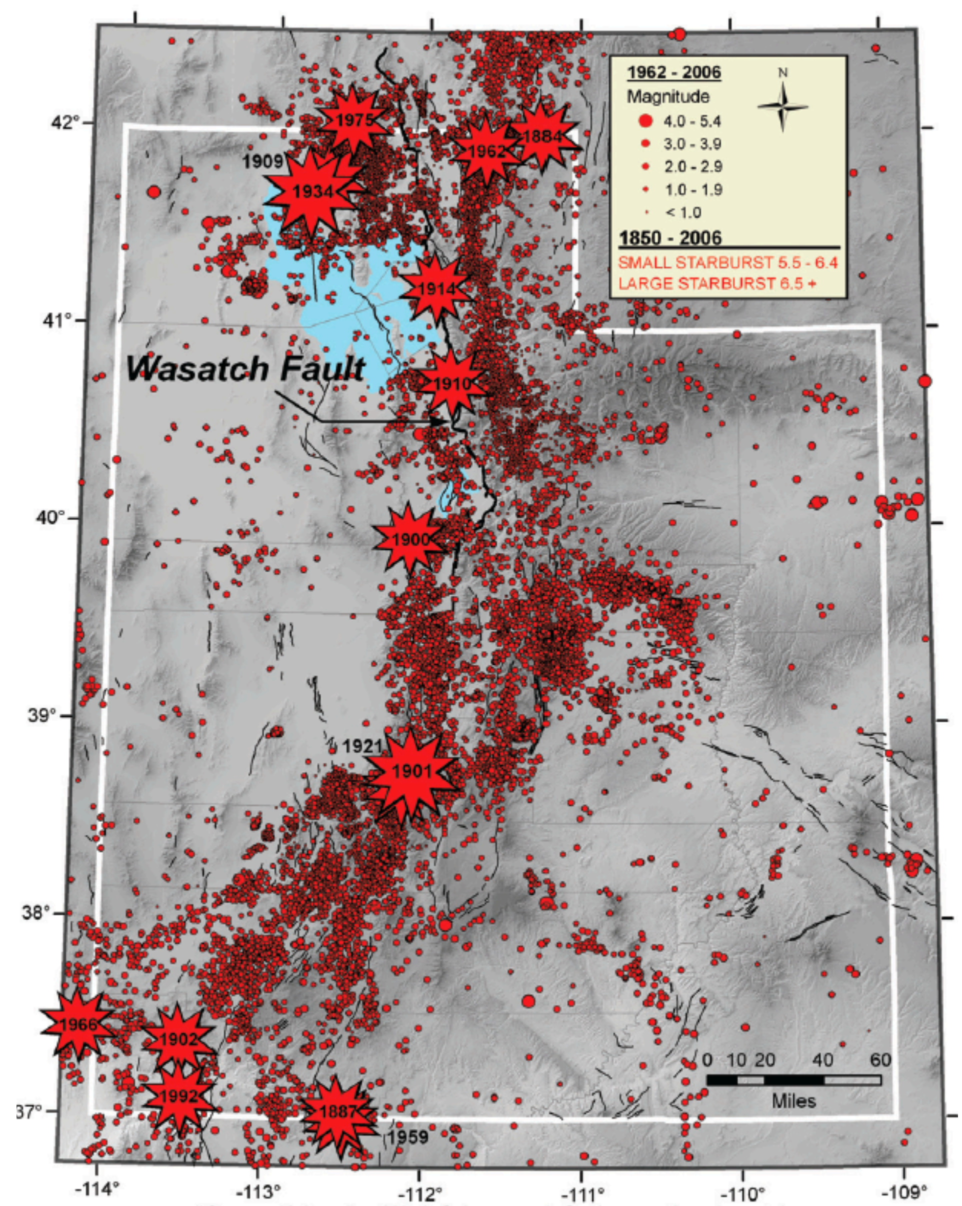


Historical quakes of about magnitude (M) 5.5 and larger in the Utah region*		
1884	M 6	Bear Lake Valley
1887	M 5.5	Kanab
1900	M 5.5	Eureka
1901	M 6.5	Richfield
1902	M 6	Pine Valley
1909	M 6	Hansel Valley
1910	M5.5	Salt Lake City
1914	M 5.5	Ogden
1921	M 6	Elsinore (two events)
1934	M 6.6	Hansel Valley
1959	M 5.7	Utah-Arizona Border
1962	M 5.7	Richmond
1966	M 6.0	Utah-Nevada Border
1975	M 6.0	Utah-Idaho Border
1992	M 5.9	St. George

*sizes of shocks before 1934 are approximate

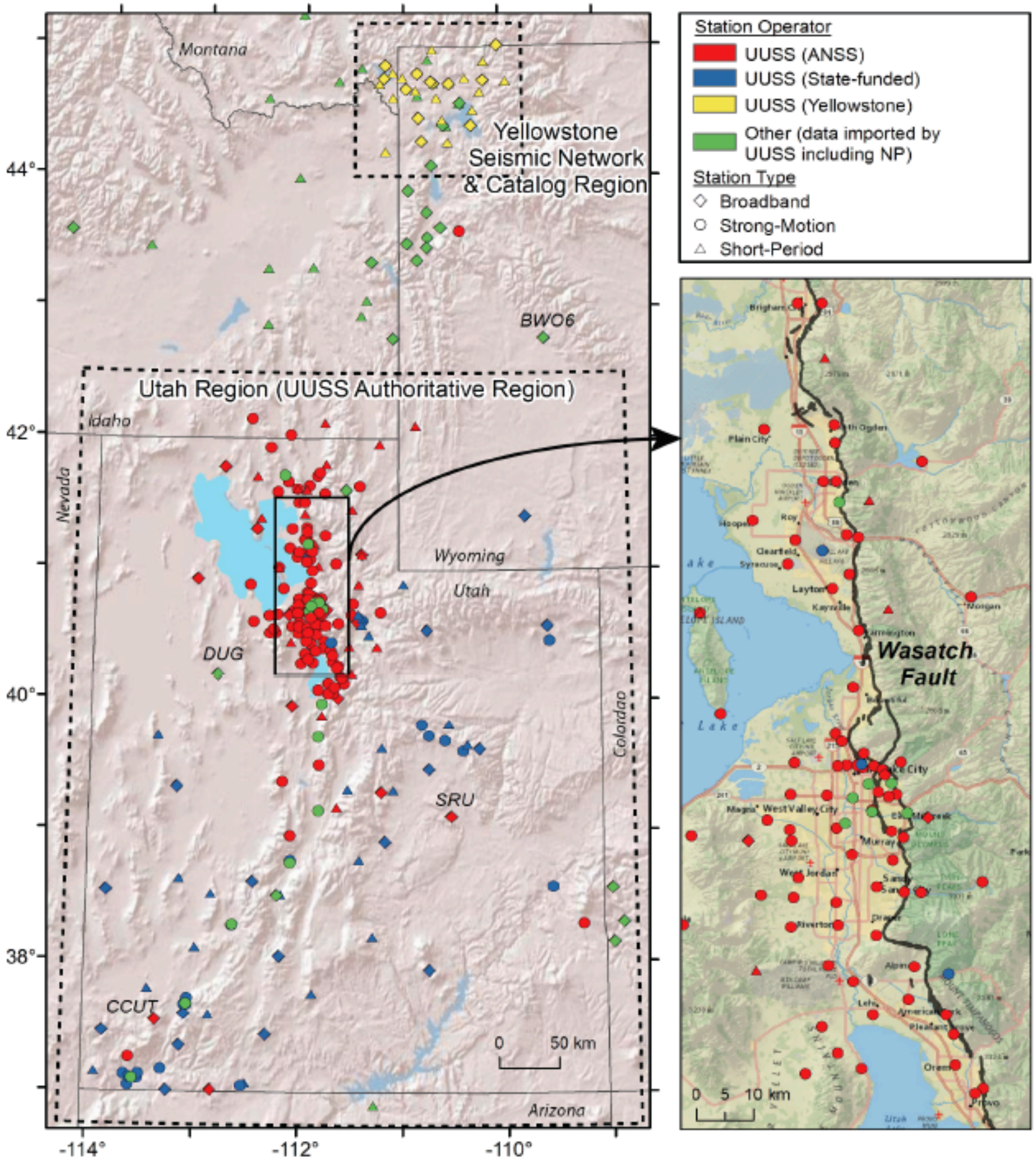
[Utah Seismic Safety Commission, 2008]

Earthquakes in the Utah region



*Source: University of Utah Seismograph Stations earthquake catalog

UUSS Station Map



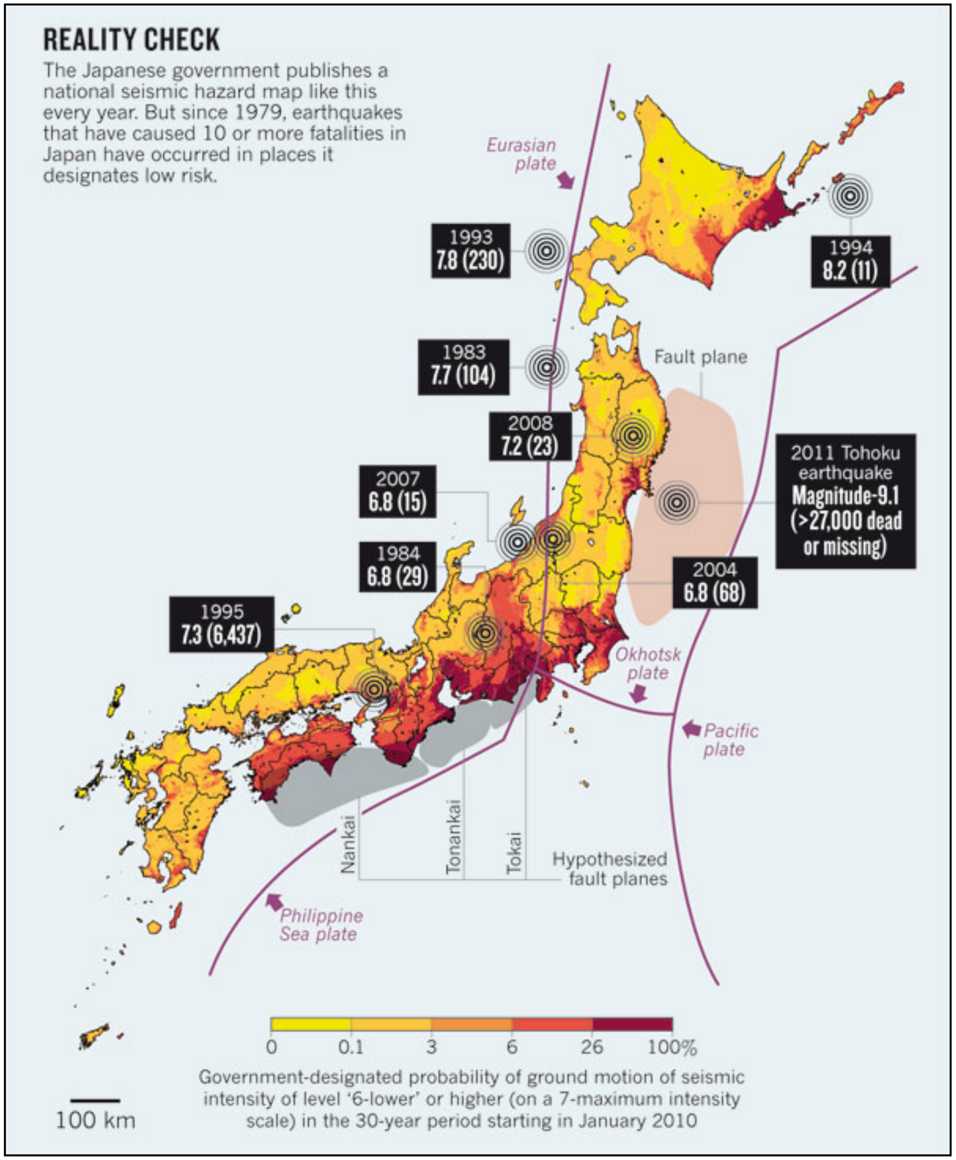
Current annual UUSS budget for seismic monitoring of Utah:
$1.6 million (State + Federal)

Estimated annual costs for O&M of a Utah EEW system:
$4.7 million (PNW value)

Estimated capitalization costs for a Utah EEW system:
$15 million (PNW value)

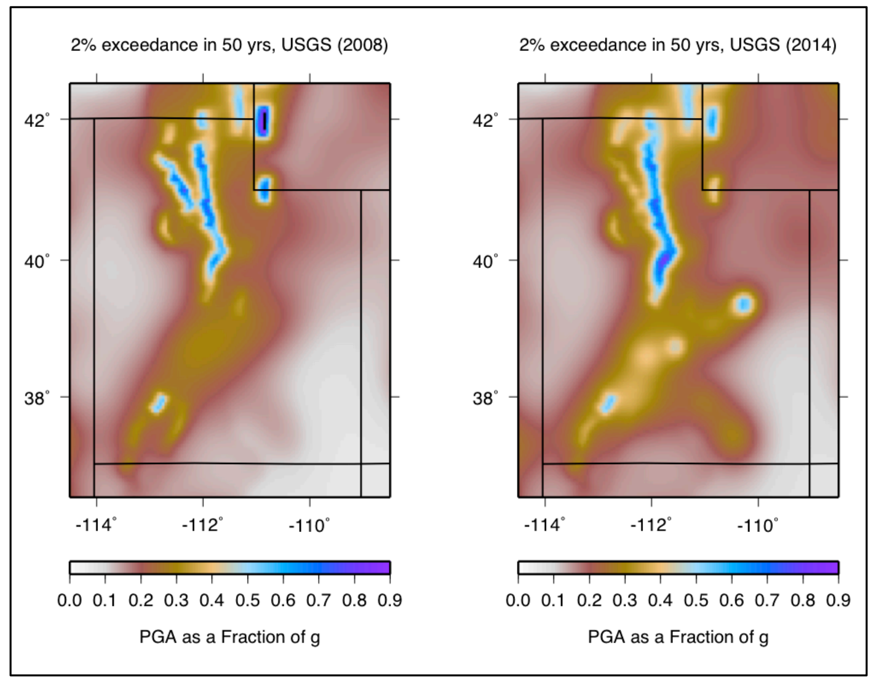
10-20 km spacing of seismometers needed near all high-risk areas (Given et al., 2014).

OBSs in Great Salt Lake ??



(*Geller*, 2011, Nature)

Is EEW more important than continued hazard map refinement ?



2008 2014

Technical Session 1 – Perspectives and User Needs

Moderator: William Lund, Utah Geological Survey

Basin and Range Province Earthquakes—Low Probability High Consequences: *Ivan Wong, URS Corporation*

What Emergency Managers Need from Geoscientists: *Bob Carey, Utah Division of Emergency Management*

What Engineers Need from Geoscientists: *George Ghusn, Jr., BJG Architecture + Engineering*

One City's Perspective on What Local Governments Need from Geoscientists: *David Dobbins, City Manager, City of Draper, and David Simon, Simon Associates, LLC*

The USGS National Seismic Hazard Maps in the Basin and Range Province—Thirty-Five Years in the Making: *Mark Petersen, Kathleen Haller, and Yuehua Zeng, U.S. Geological Survey*

Data and Tools for Seismic Hazard Investigations: *Steve Bowman, Utah Geological Survey*

BASIN AND RANGE PROVINCE EARTHQUAKES: LOW PROBABILITY AND HIGH CONSEQUENCES

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More than 12 million people live within the Basin and Range Province of the western United States. The vast majority of those people are concentrated in the nine largest metropolitan areas including Salt Lake City and Provo-Orem in Utah; Reno-Sparks and Las Vegas in Nevada; Albuquerque, New Mexico; Boise-Nampa, Idaho; El Paso, Texas; and Phoenix and Tucson, Arizona (table 1 and figure 1). Although the Denver-Aurora-Lakewood, Colorado area is outside the Basin and Range Province, it could be impacted by a large earthquake in the province. Some of these metropolitan areas, such as Salt Lake City, Phoenix, and Denver are some of the fastest growing in the United States. The vast majority of these large metropolitan areas, as well as many small and mid-sized cities (e.g., Jackson, Wyoming, and Missoula, Montana), are situated in valleys in the hanging walls of Quaternary active normal faults. Seismically active seasonal attractions such as Yellowstone and Grand Teton National Parks are visited by about 3 million people each year. Paleoseismic and seismological studies indicate that the faults in these areas are capable of generating moment magnitude (M) 6.5 and larger surface-faulting earthquakes (Wong and Olig, 1998). Large areas in the Basin and Range Province also exhibit moderate to high rates of background seismicity.

Given these large population centers are in the near-field of active faults, the consequences of a large earthquake could be devastating. For example, a large M 7 earthquake on the Salt Lake City segment of the Wasatch fault zone could result in about 2000 deaths, 6000 to 9000 seriously injured, $32 billion in economic losses to buildings and lifelines, and 56,000 structures destroyed based on 2012 HAZUS estimates (URS and FEMA, 2011).

The earthquake hazards in the Basin and Range Province are concentrated along the major seismic zones including the Intermountain seismic belt, Sierra Nevada-Great Basin boundary zone, and the Rio Grande rift (extending into central Colorado), but the widespread distribution of Basin and Range normal faults poses a hazard to the whole population within the province. For example, the seismic hazard in central Colorado, including the Denver metropolitan area, may be under-estimated because the late-Quaternary faults in the northernmost portion of the Rio Grande rift in central Colorado have not been properly accounted for in seismic-hazard analyses. It is only been in the past few years that the potential seismic hazard from these faults has been revealed.

The earthquake threat includes strong ground shaking, liquefaction, landsliding, surface-fault rupture, and in rare cases, tsunami and seiche. Of course, strong ground shaking is the most significant hazard due to its widespread potential impact. Because many of these metropolitan areas are in valleys adjacent to lakes, rivers, and mountain ranges, the seismic hazards are not only greater in number, but are also often accentuated. For example, the Salt Lake City metropolitan area will not only be impacted by strong ground shaking, liquefaction, surface faulting, and landsliding if a large earthquake were to rupture the central Wasatch fault zone, but its proximity to the Great Salt Lake brings also a seiche and tsunami hazard.

The level of seismic hazard in the Basin and Range Province varies over a factor of 10 based on the 2014 U.S. National Seismic Hazard Maps (Petersen and others, 2014; figure 1) due in large part to fault recurrence intervals which span from about a thousand years to more than 100,000 years, and the wide range in rates of background seismicity (e.g., southern Arizona to Yellowstone) (table 1). However, because the National Seismic Hazard Maps are time-independent, they may give an incorrect depiction of the real-time hazard. There are areas such as the El Paso metropolitan area where the elapsed time since the most recent earthquake on the adjacent East Franklin Mountains fault is probably at its mean recurrence interval (McCalpin, 2006), and so despite the relatively low time-independent hazard (table 1), the time-dependent hazard may be significantly higher. Note the National Seismic Hazard Maps also do not account for the effects of the near-surface geology and basin geometry, which can significantly amplify the levels of ground shaking.

The range in seismic risk in the Basin and Range Province probably varies over an order of magnitude based on factors which impact vulnerability, such as population, age, and type of infrastructure, and effectiveness of seismic-hazard-mitigation efforts. Despite the potential earthquake risk in the Basin and Range Province, the public's perception is that the seismic hazard and risk are low because the large earthquakes that have occurred in the province historically have been in generally unpopulated areas (e.g., 1954 M 7.1 Dixie Valley-Fairview Peak, Nevada, 1959 M 7.3 Hebgen Lake, Montana, and 1983 M 6.9 Borah Peak, Idaho).

In summary, state-of-the-practice probabilistic seismic hazard analyses, e.g., National Seismic Hazard Maps may give an incorrect depiction of the hazard today because they are time-independent and do not account for the most recent earthquake on faults. The paleoseismic chronology along potentially dangerous faults near urban areas, are the key to developing an accurate hazard assessment. I recommend that the USGS begin developing time-dependent hazard maps for the U.S. and convince the building code community that such maps are more accurate. I also recommend that the USGS National Earthquake Hazards Reduction Program (NEHRP) emphasize the need to perform paleoseismic investigations of faults near urban areas even in areas where the perceived time-independent probabilistic hazard is less than high.

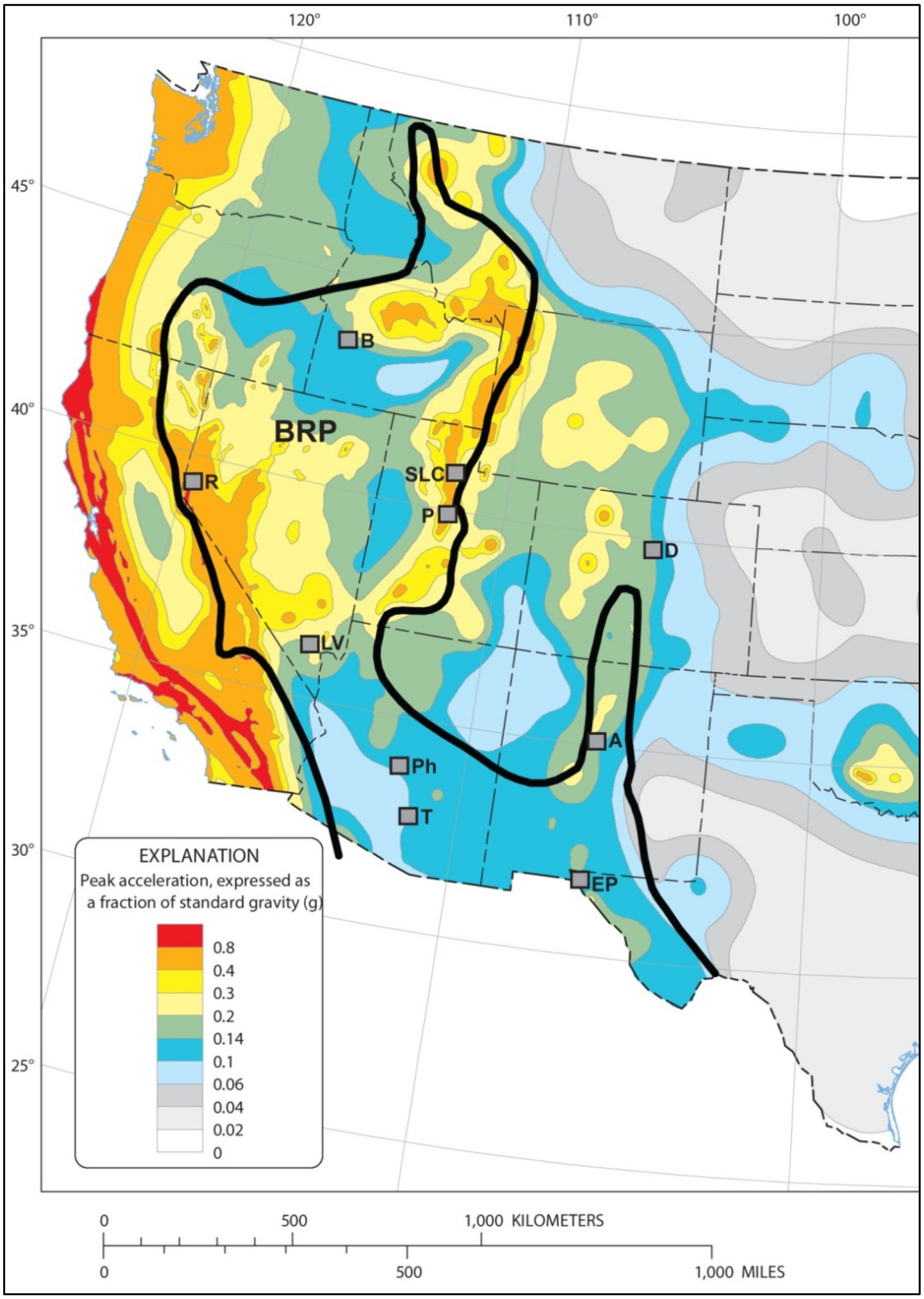

Figure 1. *2014 USGS National Seismic Hazard Map 2% probability of exceedance in 50 years for peak horizontal acceleration and the Basin and Range Province. Major metropolitan areas are indicated with gray boxes (B – Boise, …..).*

Table 1. *Basin and Range Province metropolitan areas at risk.*

Metropolitan Area	Population	Year Established	2014 USGS Time-Independent 2%/50 B/C PGA (g's)
Salt Lake City, UT	1 million	1847	0.68
Reno-Sparks, NV	425,000	1868	0.68
Provo-Orem, UT	527,000	1849	0.63
Las Vegas, NV	1.9 million	1905	0.24
Albuquerque, NM	1 million	1706	0.19
El Paso, TX	831,000	1854	0.13
Boise City-Nampa, ID	617,000	1908	0.13
Denver, CO	2.9 million	1858	0.12
Tucson, AZ	1 million	1775	0.12
Phoenix, AZ	4.2 million	1861	0.08

REFERENCES

McCalpin, J.P., 2006, Quaternary faulting and seismic source characterization in the El Paso-Juarez metropolitan area; collaborative research with the University of Texas at El Paso. Program Element II—Evaluate Urban Hazard and Risk: Final Technical Report Contract 03HQGR0056 National Earthquake Hazards Reduction Program, U.S. Geological Survey.

Petersen, M.D., Moschetti, M.P., Powers, P.M., Mueller, C.S., Haller, K.M., Frankel, A.D., Zeng, Y., Rezaeian, S., Harmsen, S.C., Boyd, O.S., Field, N., Chen, R., Rukstales, K.S., Luco, N., Wheeler, R.L., Williams, R.A., and Olsen, A.H., 2014, Documentation for the 2014 update of the United States National Seismic Hazard Maps: U.S. Geological Survey Open-File Report 2014-1091, http://pubs.usgs.gov/of/2014/1091/.

URS Corporation and FEMA Region VIII, 2011, HAZUS analyses of fifteen scenario earthquakes in the State of Utah: unpublished report.

Wong, I.G., and Olig, S.S., 1998, Seismic hazards in the Basin and Range Province—Perspectives from probabilistic analyses, *in* Lund, W.R., editor, Western States Seismic Policy Council, Proceedings Volume, Basin and Range Province Seismic-Hazards Summit: Utah Geological Survey Miscellaneous Publication 98-2, p. 110-127.

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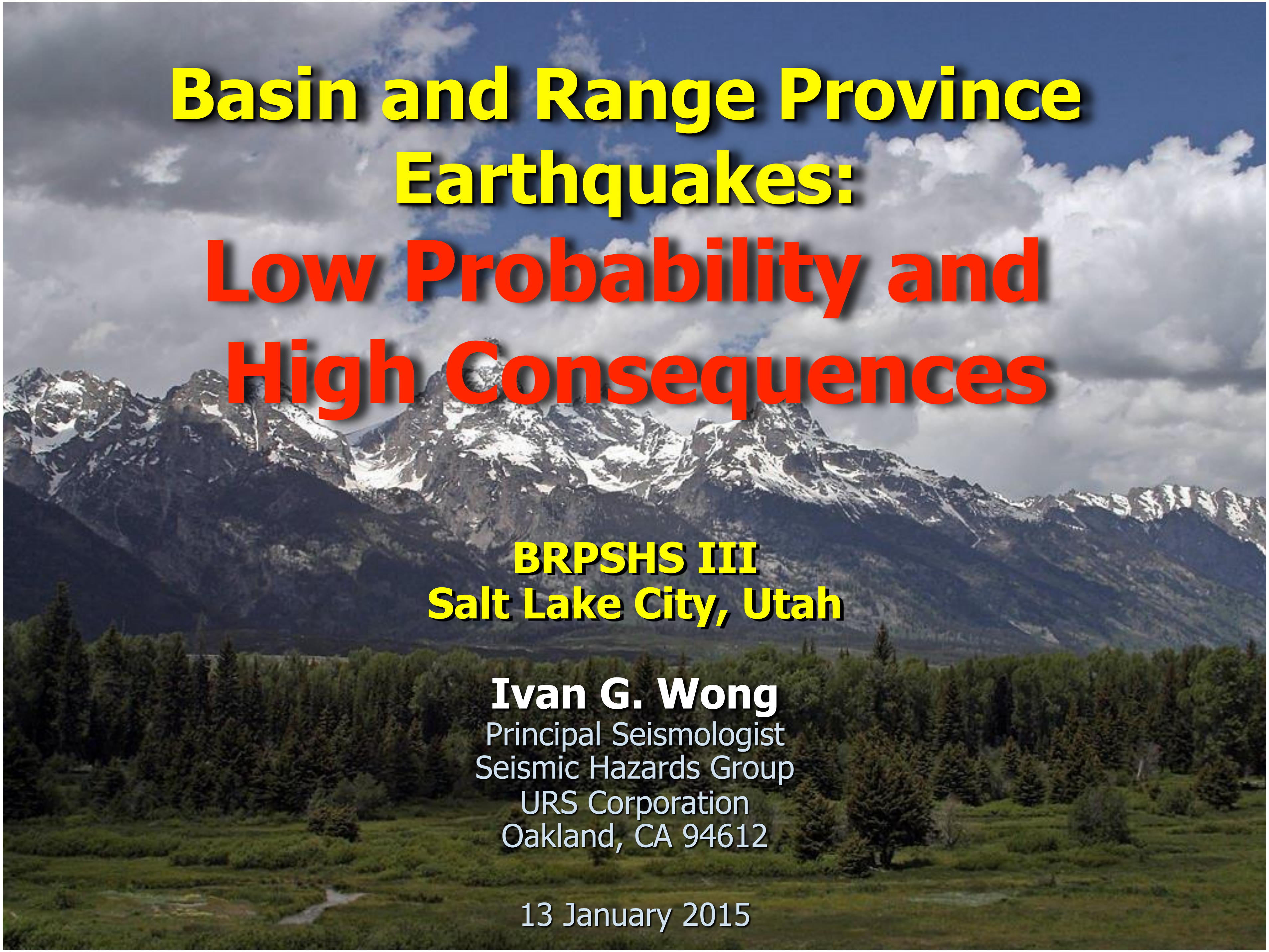
Basin and Range Province
Earthquakes:
Low Probability and
High Consequences
BRPSHS III
Salt Lake City, Utah
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13 January 2015

Introduction

- More than 12 million people live within the Basin and Range Province (BRP) of the western U.S. The vast majority of those people are concentrated in the 9 largest metropolitan areas including:
  - Phoenix, Arizona (4.2 million)
  - Las Vegas, Nevada (1.9 million)
  - Albuquerque, New Mexico (1 million)
  - Salt Lake City, Utah (1 million)
  - Tucson, Arizona (1 million)
  - El Paso, Texas (831,000)
  - Boise City-Nampa, Idaho (617,000)
  - Provo-Orem, Utah (527,000)
  - Reno-Sparks, Nevada (425,000)

Introduction (cont.)

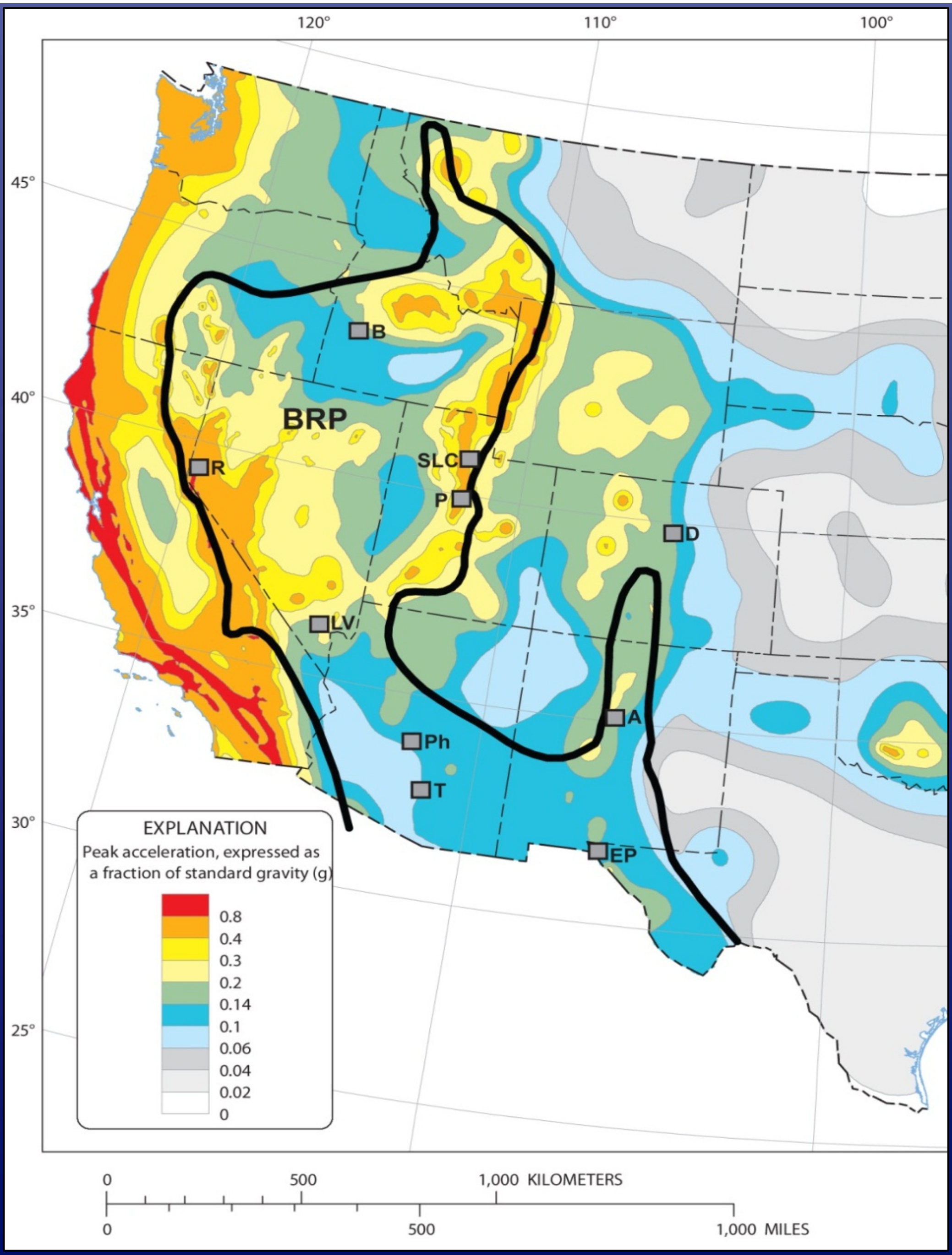
- Although the Denver-Aurora-Lakewood, Colorado area (2.9 million) is located outside the BRP, it could be impacted by a large earthquake in the province.
- Some of these metropolitan areas such as Salt Lake City, Phoenix, and Denver are some of the fastest growing areas in the U.S.
- The vast majority of these large metropolitan areas as well as many small and mid-sized cities (e.g., Jackson Hole, Wyoming and Missoula, Montana) are situated in valleys located in the hanging walls of Quaternary active normal faults.
- Seismically active seasonal attractions such as Yellowstone and Teton National Parks are visited by about 3 million people each year.

Introduction (cont.)

- Paleoseismic and seismological studies indicate that the active faults in these BRP urban areas are capable of generating moment magnitude (**M**) 6.7 larger surface-faulting earthquakes.
- It is also recognized that most BRP faults have long recurrence intervals of thousands to tens of thousands of years, i.e., infrequent earthquakes. (Slip rates range from < 0.01 to > 1 mm/yr).
- Large areas in the BRP also exhibit moderate to high rates of background seismicity.
- Given these large population centers are located in the near-field of active faults and background earthquakes, the consequences of a large earthquake could be devastating.

BRP Seismic Hazard

- The level of seismic hazard in the BRP varies over a factor of 10 based on the 2014 U.S. National Seismic Hazard Maps due to in large part to the range in fault recurrence intervals (1,000 to 100,000 yrs) and the wide range in background seismicity rates (e.g., southern Arizona to Yellowstone).



BRP Seismic Hazard (cont.)

- This range in hazard does not account for the effects of the near-surface geology and basins, which can significantly amplify the levels of ground shaking.
- However, the range in seismic risk probably varies over an order of magnitude based on the factors that impact vulnerability such as population, age and type of infrastructure, and effectiveness of seismic hazard mitigation efforts.

Earthquake Hazards

- Hazards include strong ground shaking, liquefaction, landsliding, surface fault rupture and in rare cases, tsunami and seiche.
- Of course, strong ground shaking is the most significant hazard due to its widespread potential impact.
- Because many of these metropolitan areas are located in valleys adjacent to lakes, rivers, and mountain ranges, the seismic hazards are not only greater in number but accentuated. For example, Salt Lake City has a tsunami and seiche hazard.

Hazard Versus Risk

- SEISMIC HAZARD = Effect of an earthquake that results in an unacceptable consequence (damage and loss)
- SEISMIC RISK = The probability of loss or damage
= Hazard x Vulnerability x Exposure
- Vulnerability is usually expressed as a damage or loss function
- High hazard does not necessarily equate to high risk nor does low hazard equate to low risk.
- Risk can be as high or higher in intraplate areas e.g., BRP as along plate boundaries because of higher vulnerability

Exposure

- The size of the impacted population is a significant factor.
- Some communities are more vulnerable than others due to less earthquake-resistant design and/or construction.

Dangerous Buildings

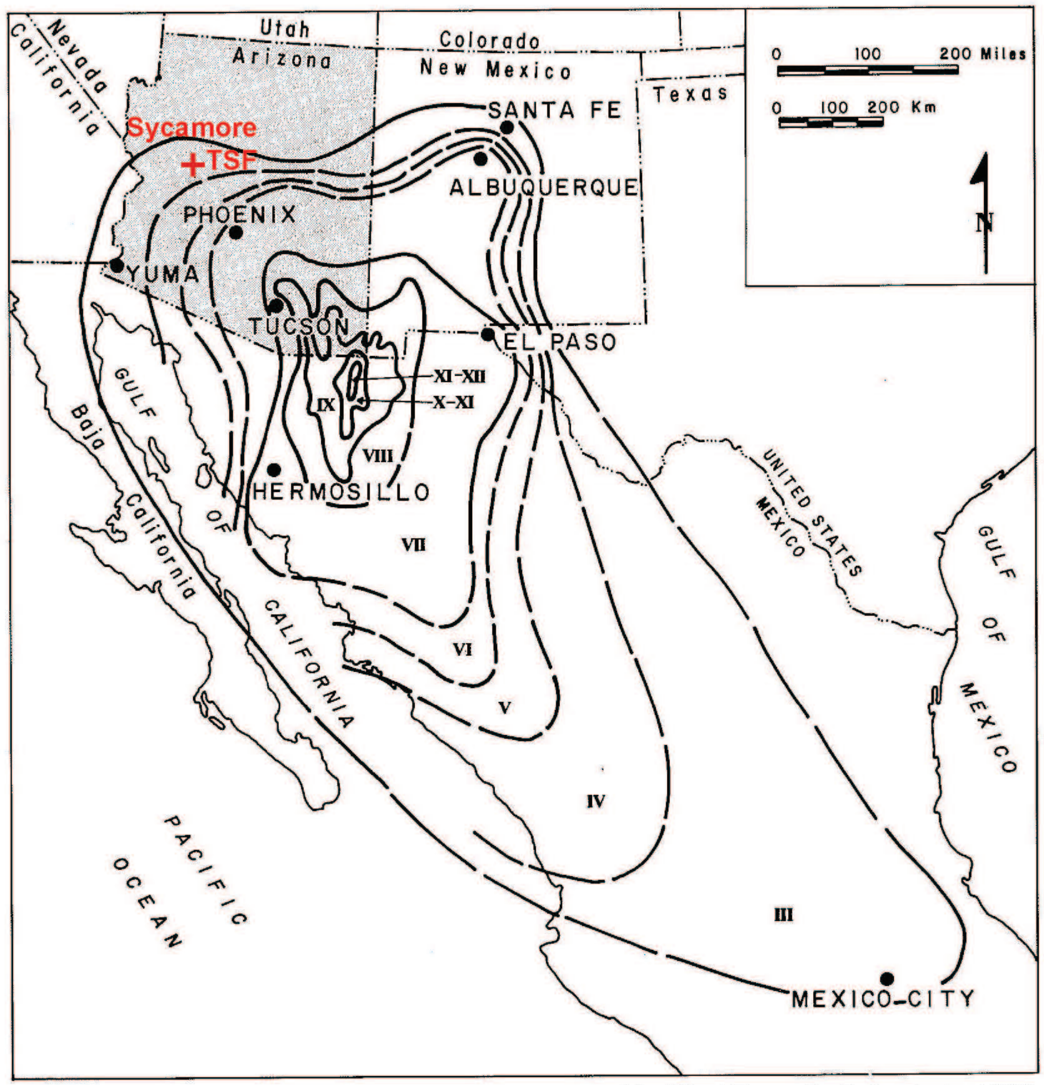
- URM (unreinforced masonry), e.g., adobe
- Soft-story buildings
- Nonductile concrete buildings
- Concrete tilt-ups

Time-Dependent Versus Time-Independent Hazard

- Time-independent (real-time) probabilistic seismic hazard analyses, e.g., National Seismic Hazard Maps do not incorporate the timing of the most recent earthquake on a fault.
- Hence the Maps may not accurately portray the probabilistic hazard TODAY.
- Will a fault pose the same level of hazard if it had a large earthquake last year or if it last ruptured 10,000 years ago?
- Should a fault be considered more dangerous if the elapsed time since its last large earthquake is equal to or greater than its mean recurrence interval?

Paleoseismic Record

- The 1887 earthquake ruptured the Pitaycachi, Teras, and Otates faults (75 km).
- Mean recurrence intervals are 100-200 kyr, 15-26 kyr, and 30-42 ky, for the three faults.
- The penultimate earthquake on the Pitaycachi fault is more than 100 ka.



Modified From DuBois et al., 1982

1887 M 7.5 Sonora, Mexico Earthquake

Largest Historical BRP Earthquakes

- Despite the potential earthquake risk in the Basin and Range Province, the perception of hazards and risk are low due to the fact that the largest earthquakes that have occurred historically have been located in generally unpopulated areas.

1872 **M** 7.4 Owens Valley, California

1887 **M** 7.5 Sonora, Mexico

1915 **M** 7.3 Pleasant Valley, Nevada

1932 **M** 7.1 Cedar Mountain, Nevada

1954 **M** 7.1 and 7.2 Dixie Valley – Fairview Peak, Nevada

1959 **M** 7.3 Hebgen Lake, Montana

1983 **M** 6.9 Borah Peak, Idaho

Background Earthquakes

1901 **M** 6.6 Richfield, Utah

1906 **M** 6.2 Socorro, New Mexico

1906 **M** 6.2 Flagstaff, Arizona

1912 **M** 6.2 Flagstaff, Arizona

1925 **M** 6.6 Clarkston Valley, Montana

1934 **M** 6.6 Hansel Valley, Utah

1962 **M** 5.8 Cache Valley, Utah

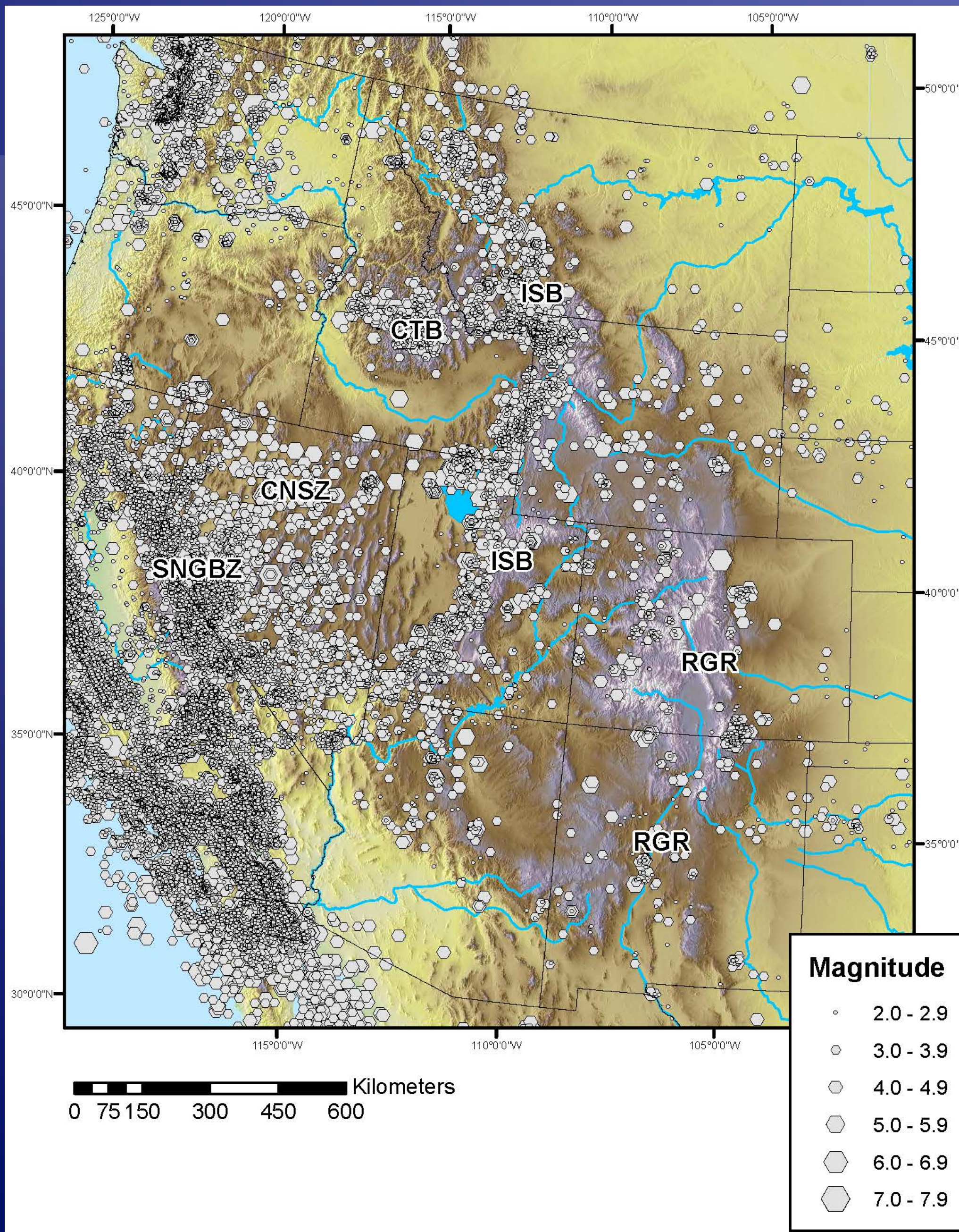
1975 **M** 6.0 Pocatello Valley, Idaho

1992 **M** 5.5 St. George, Utah

2008 **M** 6.0 Wells, Nevada

Seismicity

- The earthquake hazards in the Basin and Range Province are concentrated along several major seismic zones.
- The widespread distribution of Basin and Range normal faulting poses a hazard to the whole population within the province.



BRP Metropolitan Areas at Risk

Metropolitan Area	Population	Year Established	2014 USGS Time-Independent 2%/50 B/C PGA (g's)
Salt Lake City, UT	1 million	1847	0.68
Reno-Sparks, NV	425,000	1868	0.68
Provo-Orem, UT	527,000	1849	0.63
Las Vegas, NV	1.9 million	1905	0.24
Albuquerque, NM	1 million	1706	0.19
El Paso, TX	831,000	1854	0.13
Boise City-Nampa, ID	617,000	1908	0.13
Denver, CO	2.9 million	1858	0.12
Tucson, AZ	1 million	1775	0.12
Phoenix, AZ	4.2 million	1861	0.08

Site Effects

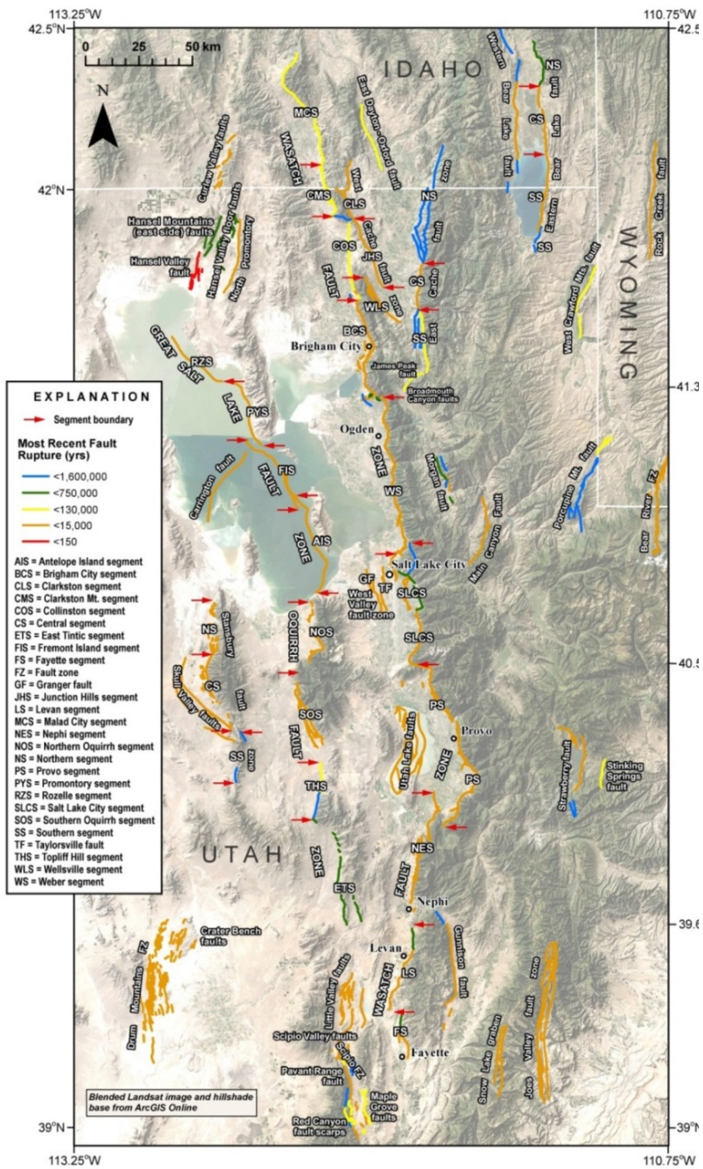
- All the metropolitan areas are located in sedimentary basins and hence amplification (or deamplification) effects will impact strong ground shaking.
- Amplification will result from the velocity gradient in the soil/soft sediments, velocity contrasts such as the sediment/rock interface, and basin effects particularly basin edge effects.
- The amplification is strain and frequency-dependent.
- At low levels of input ground motions, the amplification can be a factor of two or more. At high levels of shaking where nonlinear effects are most pronounced, the amplification can be up to a factor of two.

Near-Fault Effects

- Many of the metropolitan areas are situated in the hanging walls of normal faults. Ground motions are amplified in the hanging wall as compared to the footwall.
- Although the empirical evidence is scarce, theoretically rupture directivity along normal faults should also pose an additional hazard updip along the fault e.g., 1994 Northridge.
- Some cities and towns such as Salt Lake City are located between antithetic faults. That should mean that ground motions will be amplified.
- Along strike-rupture directionality along normal faults may also result in amplified ground shaking depending where the location is with respect to where rupture is initiated.

Paleoseismic Record

- The mean recurrence intervals of the central segments of the Wasatch fault ranges from 1,100 to 1,500 years.
- The MRE ranges from 300 to 2,500 years ago.
- Mmax ranges from **M** 7.0 to 7.3 for single segments.
- Numerous other hazardous faults.



Wasatch Front Region

Wasatch Front

- The Salt Lake City metropolitan area will not only be impacted by strong ground shaking, liquefaction, surface faulting and landsliding if a large earthquake were to rupture the central Wasatch fault but its proximity to the Great Salt Lake brings also a seiche and tsunami hazard.
- Based on 2012 HAZUS estimates (Utah DEM) a large **M** 7 earthquake on the Salt Lake City segment of the Wasatch fault could result in about
  - 2,000 deaths
  - 6,000 to 9,000 seriously injured
  - $32 billion in economic losses to buildings and lifelines
  - 56,000 structures destroyed
- 80% of the casualties will be caused by URMs.

WGUEP

EARTHQUAKE PROBABILITIES FOR THE WASATCH FRONT REGION IN UTAH, IDAHO, AND WYOMING

Submitted to

U.S. Geological Survey
under the
National Earthquake Hazards Reduction Program
Awards G11AP20010, G11AP20004, G13AP00003, and G13AP00002

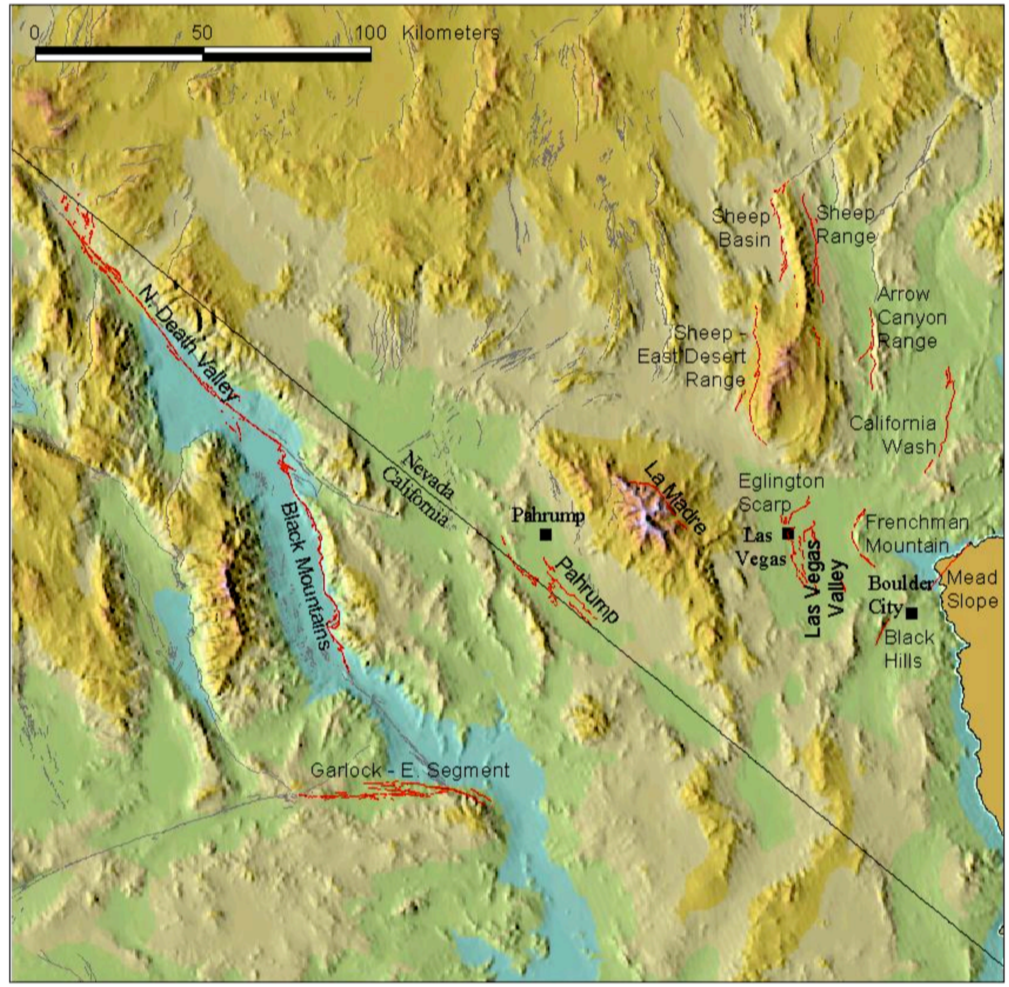
Prepared by

Working Group on Utah Earthquake Probabilities

9 January 2015
Rev. 0

Las Vegas Faults

- There are a number of regional faults that can produce large earthquakes that can impact Las Vegas.
- The LVFS is composed of several subparallel sets of faults including the Eglington, Decatur, Valley View, Cashman Field, Whitney Mesa, and West Charleston faults.
- What is the earthquake potential of each of the faults of the LVFS and collectively if they were to all rupture coseismically in a large earthquake?



Active Faults Around Las Vegas

Las Vegas, Nevada

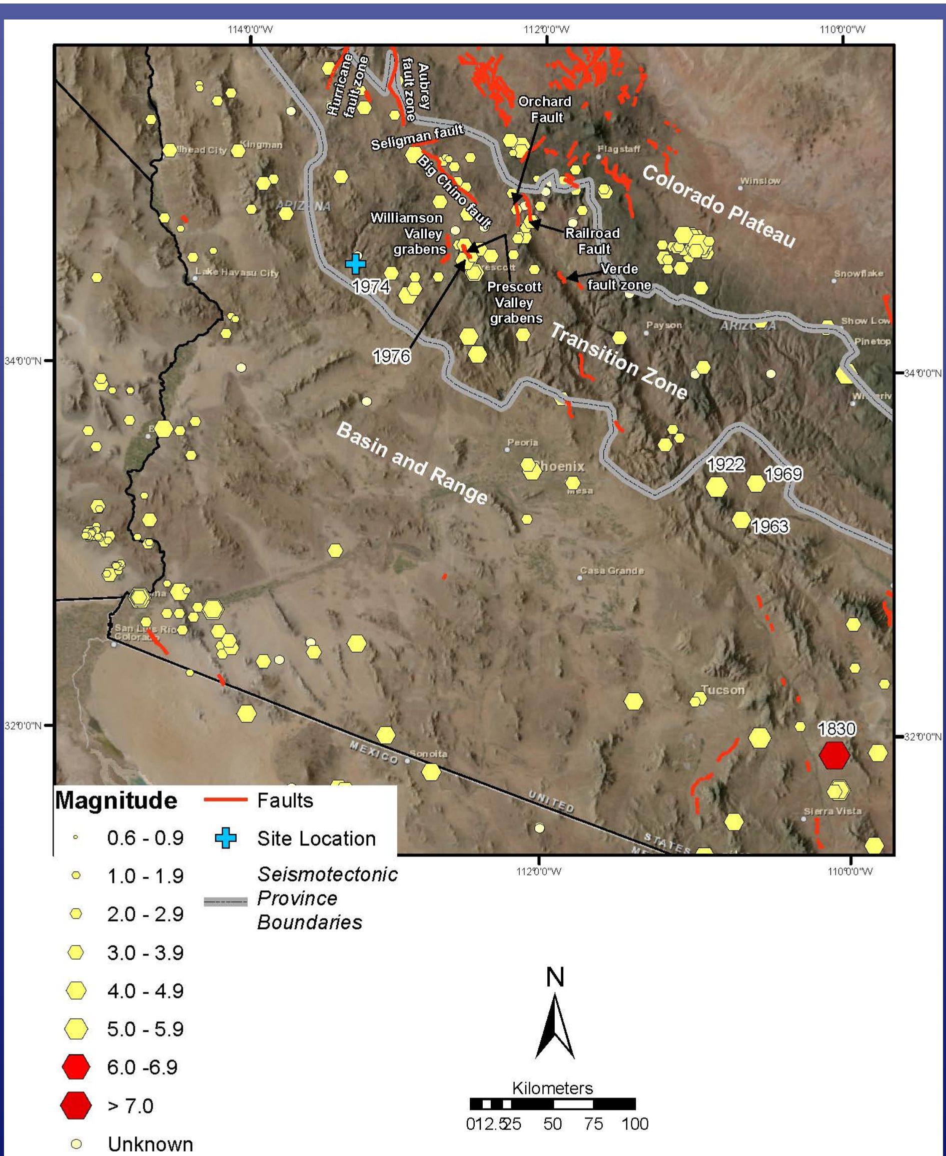
Las Vegas is situated in a deep alluvial basin where near-surface site response and basin effects on ground motions are likely significant.

M 7.0 Scenario (Price et al.,2009)

- 2,300 Fatalities
- 60,000 building with extensive to complete damage
- $25 billion in total economic loss

Active Faults

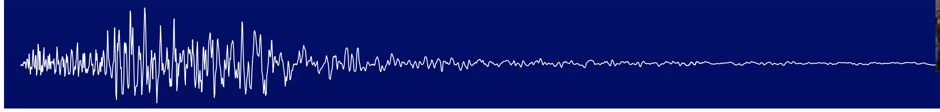
- There are few known active fault in southern Arizona.
- The Santa Rita fault south of Tucson is probably the most significant fault.
- The fault has generated **M** 7 earthquakes in the past.
- The MRE is 60 to 100 kya.
- 4-5 m of vertical slip in 200-300 ka.
- Think time-dependent.



Historical Seismicity (1830-2012) and Quaternary Faults in Southern Arizona

Phoenix/Tucson, Arizona

- If a large earthquake were to occur in southern Arizona, it would be a perfect example of a low probability high consequence event.
- Although the impression of Phoenix and to a lesser extent, Tucson as modern cities with modern infrastructure, there is a significant amount of vulnerable adobe buildings.



Paleoseismic Record

- There have been 4 large earthquakes along the east Franklin Mountains fault (McCalpin, 2006).
- The MRE occurred 13 to 17 ka.
- The mean recurrence interval is 14 to 19 kyr.
- The Mmax is **M** 7.
- Think time-dependent.

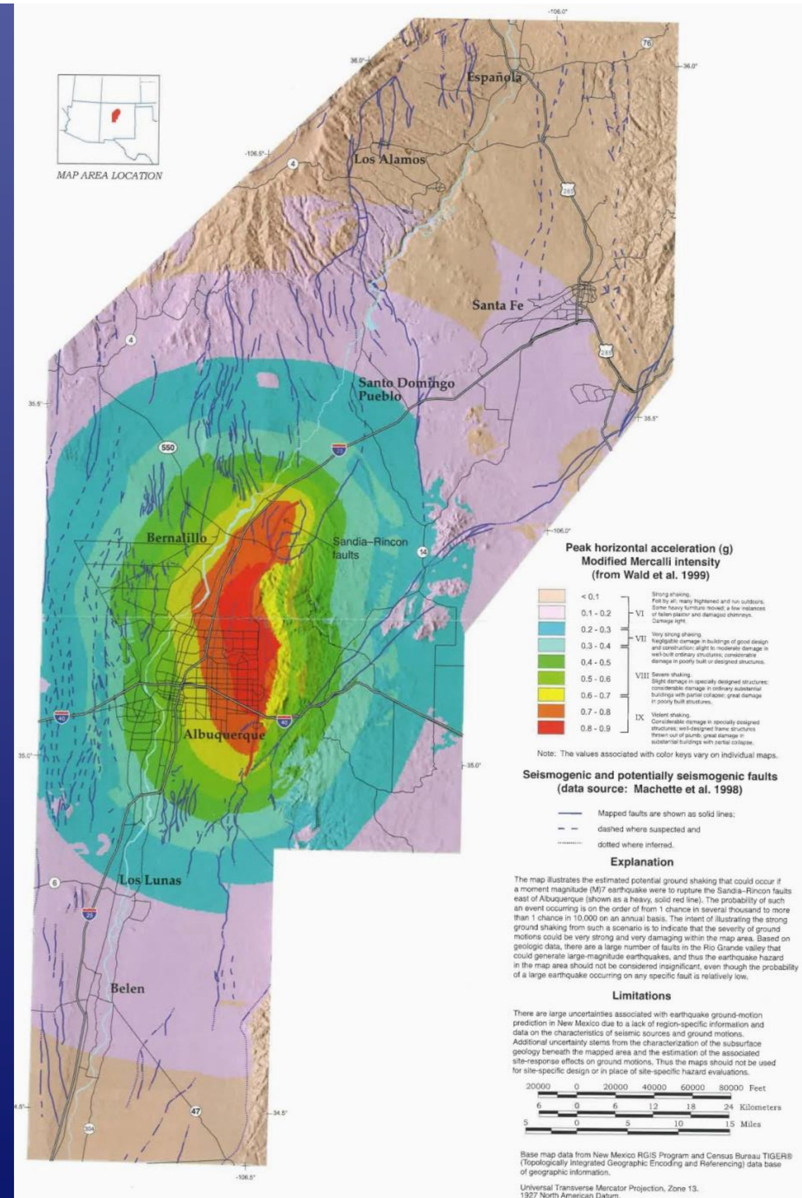
East Franklin Mountains

El Paso, Texas

- El Paso is an old city (1854) where adobe construction is abundant.
- The downtown area contains some of the oldest and historic neighborhoods.
- A large portion of the population are vulnerable.
- 22% of the population is below the poverty line.
- The city like Albuquerque straddles the Rio Grande.

Active Faults

- Although the historical record would suggest a low to moderate level of seismic hazard, there are numerous active faults in the Rio Grande rift of New Mexico, e.g., Sandia Rincon fault.
- To date, 24 know surface-rupturing earthquakes have been identified in the RGR.
- This would translate to a <u>minimum</u> composite recurrence interval of 400 years.



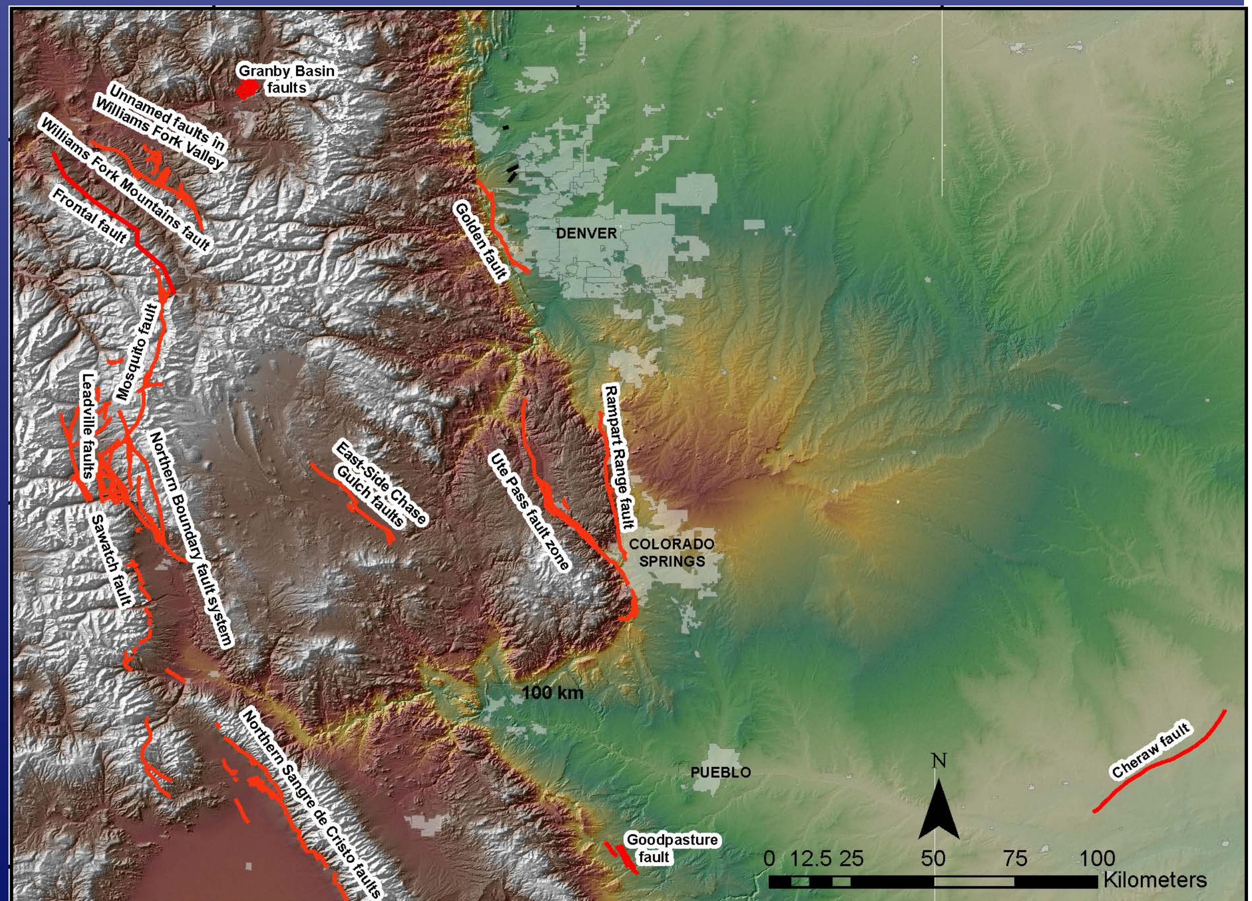
Albuquerque-Belen-Santa Fe Corridor

Albuquerque, New Mexico

- Albuquerque like all the cities and towns in New Mexico are characterized by the traditional adobe construction (URM).
- Because the city straddles the Rio Grande, soft soil amplification and basin effects on ground shaking can be significant plus a liquefaction hazard exists.

Denver Metropolitan Area

- The seismic hazard in central Colorado including the Denver metropolitan area may be under-estimated because the late-Quaternary faults in the northernmost portion of the Rio Grande rift have not been properly accounted for in seismic hazard analyses.



Summary

- State-of-the-practice probabilistic seismic hazard analyses, e.g., National Seismic Hazard Maps may give an incorrect depiction of the real-time hazard.
- The paleoseismic chronology (dates of past events) along potentially dangerous faults near urban areas are the key to developing an accurate hazard assessment, not slip rates.
- I recommend that the USGS begin developing real-time hazard maps for the U.S. and convince the building code community that such maps are more accurate.
- I recommend that the USGS in NEHRP emphasize the need to perform paleoseismic investigations of faults near urban areas even where the <u>perceived</u> probabilistic hazard is less than high because the faults have low slip rates.

WHAT EMERGENCY MANAGERS NEED FROM GEOSCIENTISTS

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bcarey@utah.gov

The average emergency manager does not have a working geologic background when he or she takes the position. Most of the time, the earthquake program is "other duties as assigned." The person holding this position is handicapped even further by the lack of program funding and, in some cases, support. Add the lack of earthquake activity, and it's amazing that some earthquake programs even exist. So how does an emergency manager build a credible earthquake program?

It starts with a credible message. This message has to be crafted to resonate with a target audience, whether it is with policy makers, stakeholders, or the general public. To craft this credible message, experts are needed—geoscientists.

In most states, this may include the state emergency management agency, the state geological survey, the state seismic safety commission, a university or college, and a variety of engineering and geologic associations. These organizations all will have a hand in developing a credible message and then speaking with one voice. A consensus among all the state earthquake program agencies will reassurance the public that the earthquake hazards and risks are real when the geoscientists and other geoscience professionals are all on the same page.

State geological surveys are one of the agencies where relevant earthquake information can be found. The geoscientists with these surveys are responsible for the identification of earthquake-related hazards, the mapping of those hazards, and analyzing how those hazards may affect the build environment. Emergency managers need to develop and nurture a relationship with these geoscientists.

For states with a seismic network, a state university may aid in developing a credible message. Accurate monitoring of seismic activity is invaluable. Since most seismic activity is below one's perception, the university seismic monitoring program can provide meaningful information to the public about the potential risk from a future earthquake. Additionally, the university can provide historic information on earthquakes to assist the emergency manager in developing public information.

The emergency manager working with geoscientists along with other related agencies and organizations, can develop earthquake scenarios which may provide the basis for such activities as developing natural hazard ordinances, future growth planning, response planning, and strengthening building codes to name but a few.

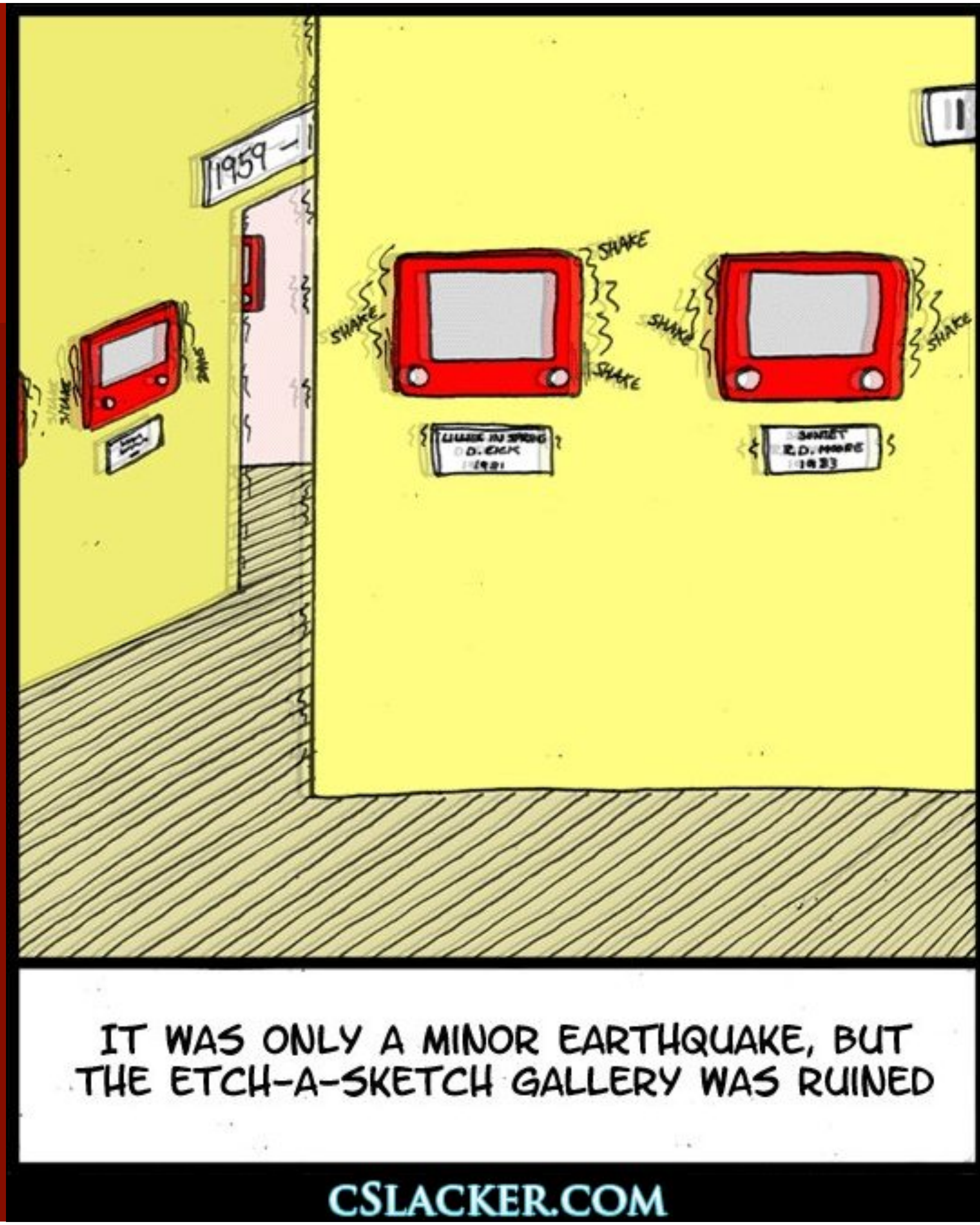
Currently, communities are being urged to become more disaster resilient. This can only be accomplished if the emergency manager, local stakeholders, government officials, and the community work together to find solutions to their disaster issues. And it will be the geoscientists that provide the science needed to insure the most accurate findings are used.

The following is a PDF version of the author's PowerPoint presentation.

What Emergency Managers Need from Geoscientists

BASIN AND RANGE PROVINCE
SEISMIC HAZARDS SUMMIT III
January 12 – 17, 2015

Utah Department of Natural Resources Building, Auditorium
Salt Lake City, Utah


1959 –
SHAKE
SHAKE
SHAKE
SHAKE
SHAKE
SHAKE
IT WAS ONLY A MINOR EARTHQUAKE, BUT THE ETCH-A-SKETCH GALLERY WAS RUINED
CSLACKER.COM

Emergency Managers

- Little working geologic knowledge
- Position may be "other duties as assigned"
- Little to no program funds
- Lack of significant earthquake activity

What Do EM’s Need

- A point of contact
- Simple and concise information
- Develop simple message
- Everyone on the same page
- Develop a partnership

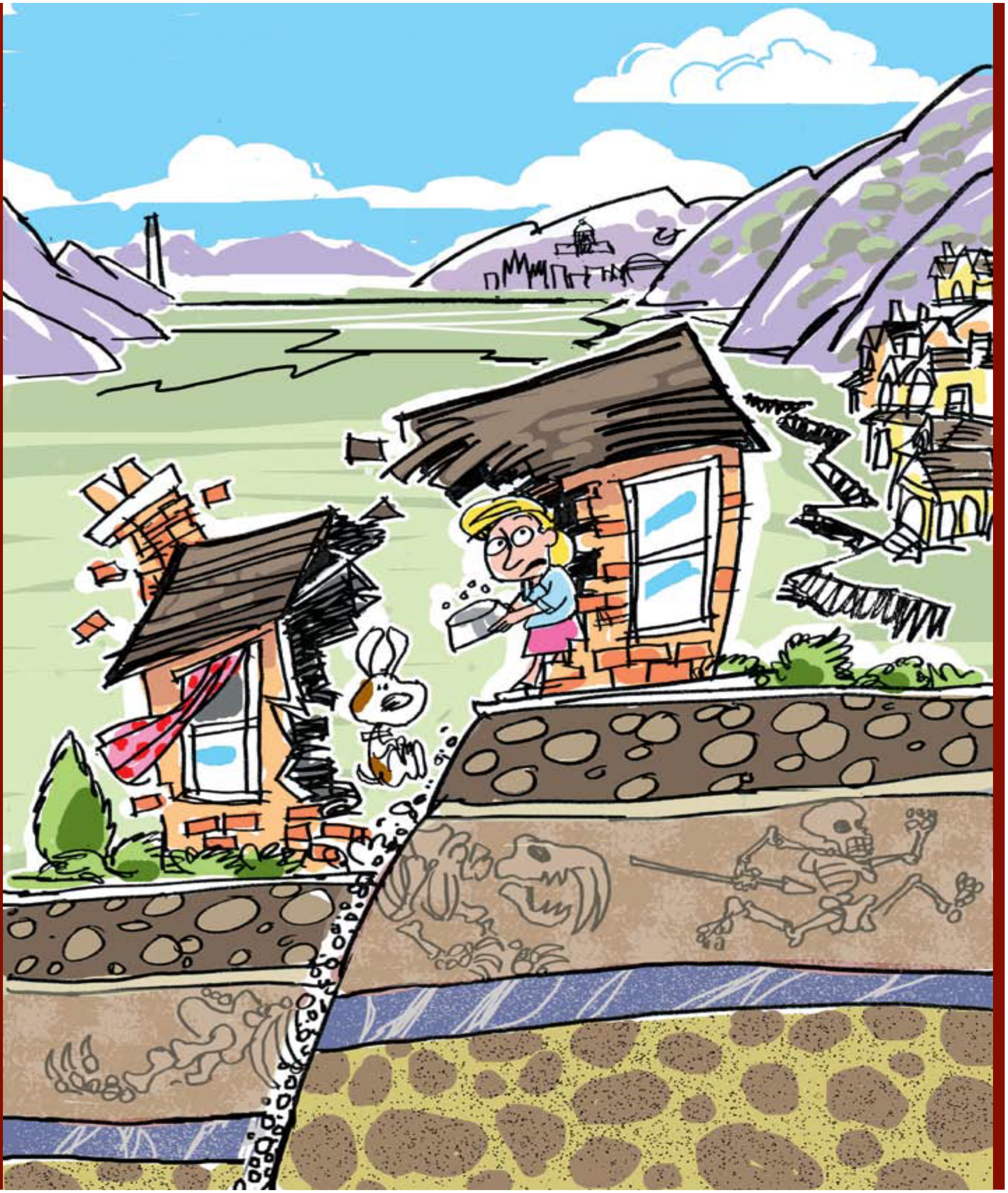
Three Amigos

Utah Earthquake Program

- Utah Geological Survey
- University of Utah Seismograph Stations
- Utah Division of Emergency Management

- Utah Seismic Safety Commission
- Utah Structural Engineers Association
- Utah Chapter EERI

Keep It Simple



Speaking with One Voice

Developing a Partnership

How We Helped Each Other

- Response, Recovery, Mitigation and COOP Planning
- Exercise, Training and Preparedness
- Earthquake Geologic Hazards Mapping
- LiDAR
- Earthquake ShakeMap Scenarios
- Traveling Earthquake Display

Recreational Opportunities

Recreational Opportunities

WHAT ENGINEERS NEED FROM GEOSCIENTISTS

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gghusn@bjginc.com

What do engineers need from geoscientists? The short answer is easy to use, stable, reasonable, and general ground accelerations.

Civil and structural engineers responsible for seismic design of structures must use code-dictated procedures for the vast majority of buildings and other structures. The ground accelerations are based on U.S. Geological Survey mapping of "pseudo accelerations," the maps show the probabilistic geometric mean acceleration response of an oscillator at certain periods (0.2 second - S_s, and 1 second - S_1, typical) with 5% damping. The latest version of the mapping includes the concept of "risk-targeting" instead of hazard mapping, which combines the assumed distribution of potential of building collapse versus ground motion with the probabilistic evaluation of ground motions.

This presentation's focus is the engineer's perspective on the needs listed above. But it is very difficult to discuss engineering needs without a brief introduction into how engineers actually use the values from the maps. The map values, S_s and S_1, are based on the location of the structure. Next, an engineer assigns an appropriate Site Class (one of six from A to F, from rock to progressively softer soil) to determine the two modification factors F_a and F_v. The default Site Class is D, which is used in lieu of any site-specific geotechnical information. In many instances, a geotechnical report is prepared for the site. However, such reports are primarily to identify bearing capacity and soil friction values, as well as identify challenging soil conditions, such as expansive clays. These site-specific reports usually contain seismic recommendations, but they are usually based on the default site class. Seismic characterization of a site is expensive and the default can be used in almost any condition except where Site Classes E and F occur. The final step is to find S_{ds} and S_{d1}, which are the design pseudo accelerations:

$$S_{ds} = 2/3\ F_a\ S_s$$

$$S_{d1} = 2/3\ F_v\ S_1$$

The "2/3" factor is reported to be based on an expected factor of safety of collapse in modern building of 1.5. In other words, we expect the building to be subject to collapse at 50% more than the design loads. As the building code is built on the idea of collapse prevention (not damage prevention), this aligns the design parameters with the expected performance of the structure based on code objectives. It should be noted that in the design of bridges, the "2/3" factor is not used—bridges are designed under a special bridge code.

The procedure described above is typical for the majority of buildings—those that are relatively short (say less than 5 stories), and that do not have special functions or configurations. Taller structures, and those with specific configurations requiring more involved analysis use either a response spectrum or specific earthquake ground motions (time histories).

The current ease of use is about as simple as possible. The current maps are digitized and available on the internet. The mapped values for a specific location in longitude and latitude are a few mouse clicks away. About the only way to make this easier is to incorporate longitude and latitude mapping within the hazard map utility—this would save the step of using Google Earth to find the coordinates of the site.

The stability of values over time has been an issue. While research produces better understanding of seismic sources and resulting ground motions almost continuously, design parameters should be relatively stable over time. Building projects take time to develop, design, and construct, and resources are always limited. While it may be the best available science at any given time, the design ground motion can change more slowly than the science because there are significant factors of safety in the actual design of a structure—not just in the ground motion. There is always a tendency to increase the design accelerations to increase safety. However, note that modern structural design emphasizes ductility in the structure—damage tolerance without collapse. Thus, the factor of safety to actual collapse can be much higher than the 1.5 assumed.

The design accelerations used have to be reasonable for the design of typical structures. While special structures demand special considerations, including site-specific studies, ordinary structures need reasonable design parameters that allow economic and safe designs. This is not a technical issue, but a judgment issue. How safe is safe enough cannot be set in an equation. When geoscientists incorporate a factor of safety in mapping design values, it has to be considered in context with all of the other factors of safety in the design of the structure. Compounding factors of safety does not make for a reasonable design.

Design specifications should be based on the expected ground acceleration and additional factors should be minimized in generating the mapping. The current practice of using targeted risk-based design accelerations is including too much building information in the design parameters. This current mapping, using a “fragility curve” to assign the probability of collapse versus the ground motion, may be misleading. Every structural material and system has its own design parameters and factors of safety against collapse. Unfortunately, all too often these do not provide consistent factors of safety and are highly material dependent. A single fragility curve for a location cannot accurately represent all the different building types and materials in use today.

For the vast majority of building projects, a straightforward design ground motion is needed without any assumptions about the structure other than response frequency. The design ground motion should be at a reasonable design level and apply in all directions. This type of design parameter mapping is relatively transparent for evaluating the overall factor of safety for a building. The geoscientist community should recognize that the remainder of the design process adds multiple safety factors against collapse.

The following is a PDF version of the author's PowerPoint presentation.

What Engineers Need From Geoscientists

George Ghusn, Jr., SE
BJG Architecture & Engineering

The Information We Need

- Surface acceleration in each orthogonal direction for largest earthquake at building site over next 50 years(buildings) to 75 years (bridges).
- Magnitude of ground displacement in each orthogonal direction.
- Date and Time of earthquake (date only would be OK)

Thanks!

Ok, So That's Not Happening

- Design Engineers need easy to use, reliable, stable and general *design* ground accelerations.
- How do we actually use the seismic mapping?

What Engineers Do with The Map

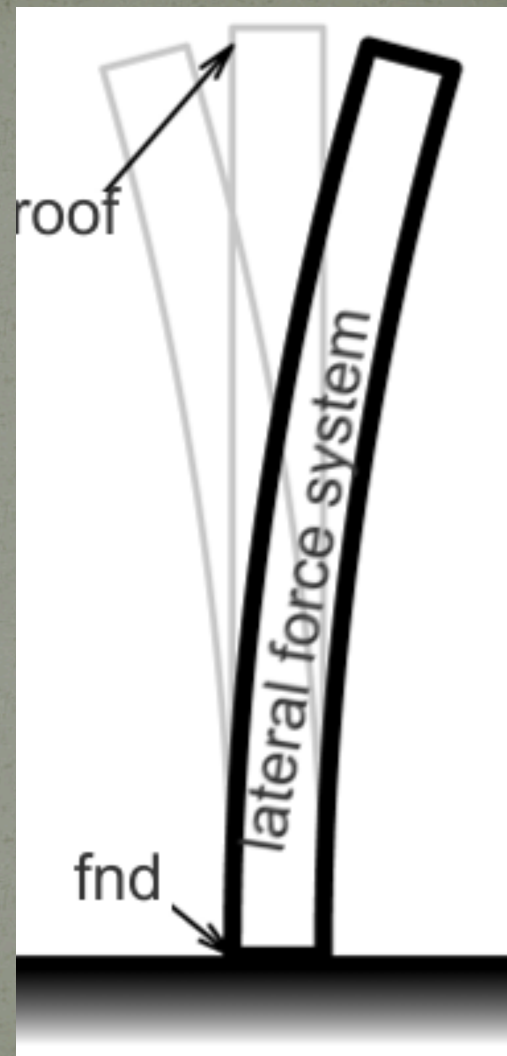
- Determine Ss and S1 values from the USGS Web App. Ss is 0.2s period and S1 is at 1s period.
- The building site is assigned a site class from A to F (rock to soft soil)
- Based on the Ss and S1 values and the site class, modification factors are selected (Fa and Fv) and applied to Ss and S1. Then Sds and Sd1 are calculated by multiplying by 2/3.
- The Web App does all this work and gives us Sds and Sd1, the key design parameters.

Analysis Methods

- **Most buildings are short and "regular" enough to use the pseudo-static method: The Sds value is used to develop a lateral force on the building that is *statically* applied to a model of the structure. This represents an envelope of forces expected in an earthquake.**
- More complicated structures may use the dynamic method –modal superposition which uses the response spectrums.
- The most sophisticated analysis uses step by step time history analysis and can model nonlinear responses.

Pseudo Static Forces

- The Sds value is divided by a response factor, R, which represents the expected seismic performance of a structural system.
- Cs = Sds/R * I
- The lateral seismic force (V) becomes Cs *Weight
- "I" is an additional safety factor (I>1.0) for important structures.

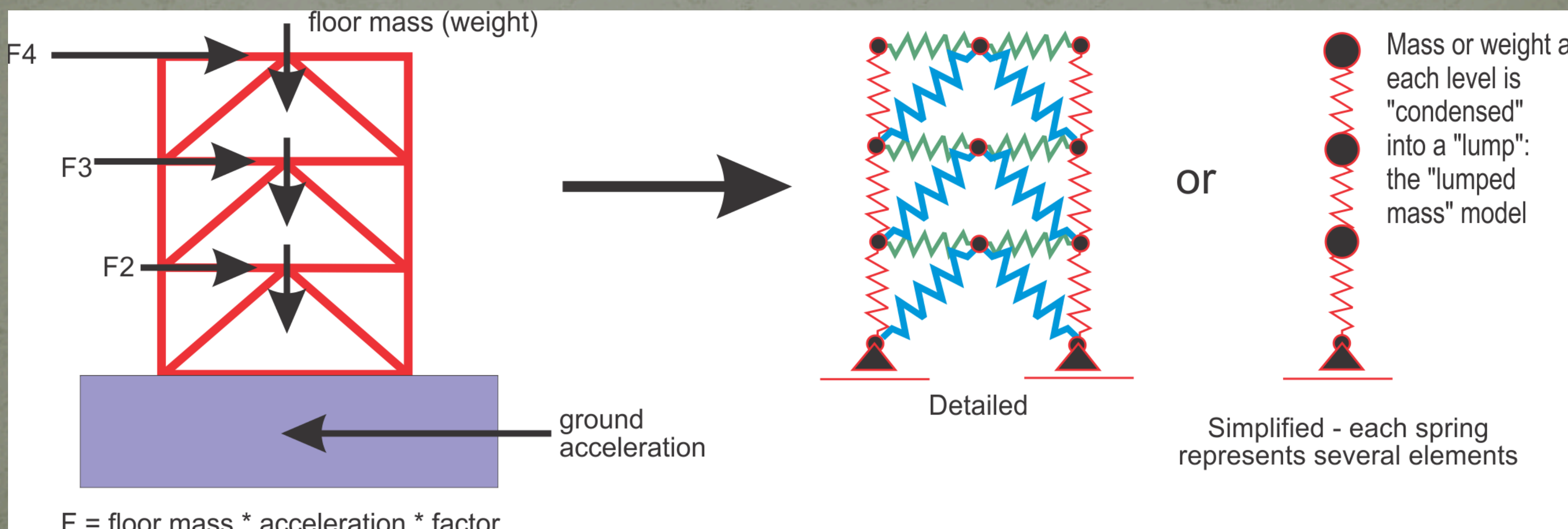


Example: Pseudo Static Forces

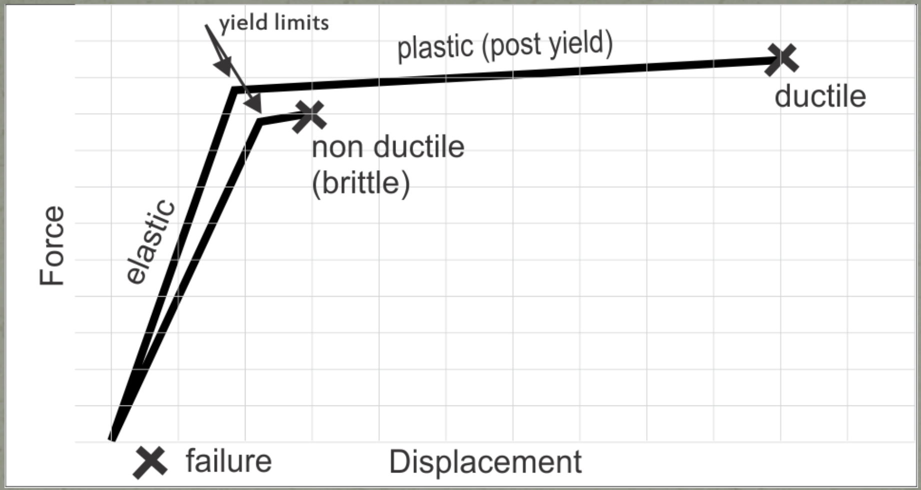
Assume Ss = 1.0 g, Site Class D
Then Sds = .67g.
For a typical wood shear wall building, R = 6.5
Thus ***V = 0.103 g * I * W***
R values range from 1.5 (worst performance)
to 8 (best performance).
Typical is 5-7 for systems used in seismically active areas.

Structural Modeling

- Only structural elements are assigned loads.
  - Gypsum board and other wall materials are neglected.
  - These materials will carry lateral forces but only for a few cycles.



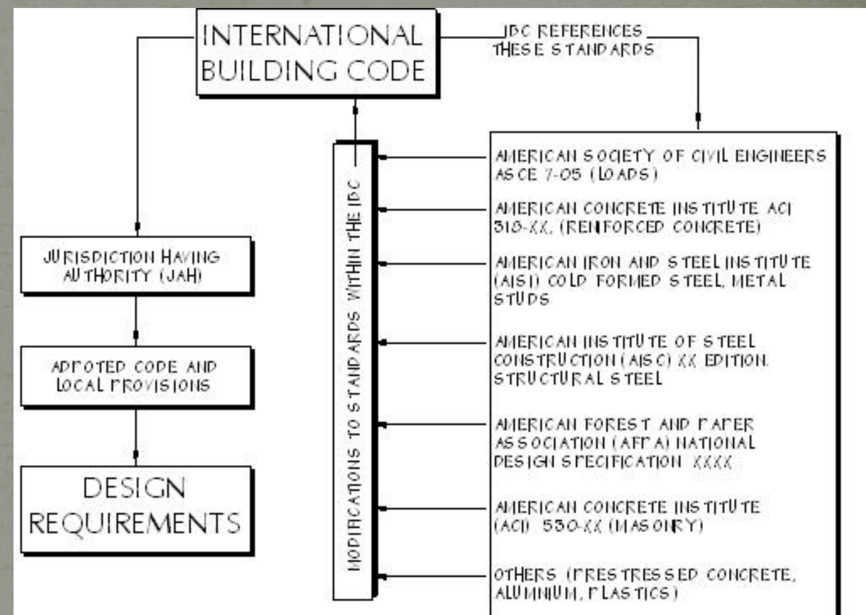
Design Forces Are Only The Beginning



- Structural seismic design is based on preventing collapse at forces *exceeding the design force*.
  - Ductility is the ability to perform non-linearly and absorb energy, accept damage and fail “gracefully”.
  - Ductility is the principal concept behind the material design provisions.

But Wait… That's Not All

- Each of the structural materials for buildings has specific design criteria for ductile performance under seismic loads.
- The material design requirements add significant additional factors of safety to the final structure.
  - Structures are designed for large overloads with damage but without collapse.
  - In some cases the calculated seismic load does not control the design.



A Design Example

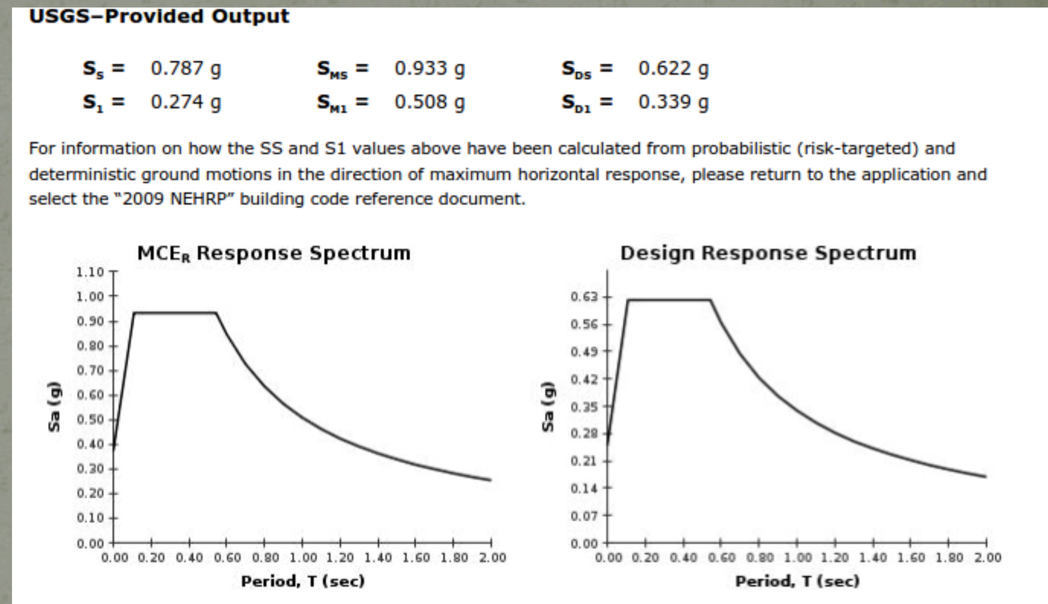
- University of Nevada Earthquake Engineering Laboratory Building – 2013
- Structural Systems:
  - North-South: Special Steel Moment Frames
  - East –West: Special Concentric Braces
- Because the braces are designed using geometric parameters, not the seismic design force, the factor of safety to design seismic load is approximately 10.

Summary

- The actual design seismic force is typically much smaller than the mapped “acceleration”.
- The specific material and system design requirements are based on ductility and damage tolerance, so a building is typically capable of significantly more seismic force than the design force would indicate.
- The goal of the code is to prevent collapse, not damage.

Ease of Use

- With the modern USGS Web Application, this issue is largely addressed.
- The integration of mapping to get the longitude and latitude for a site is appreciated.
- The App generates the Ss, S1, Sms, Sm1, Sds, S1s and the response spectrums curves for a given location.

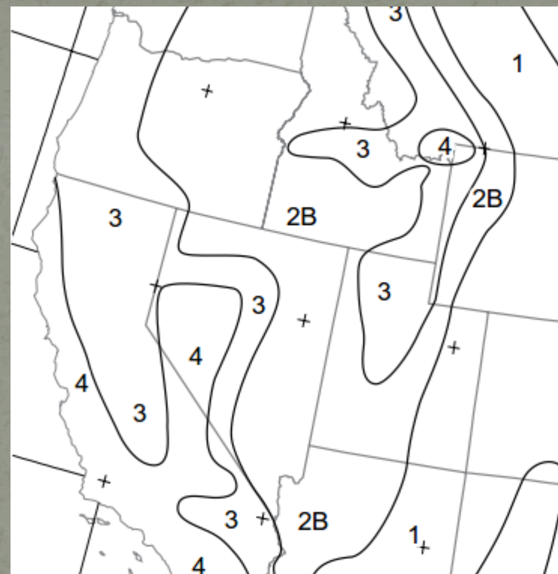


Stable and Reliable Map Values

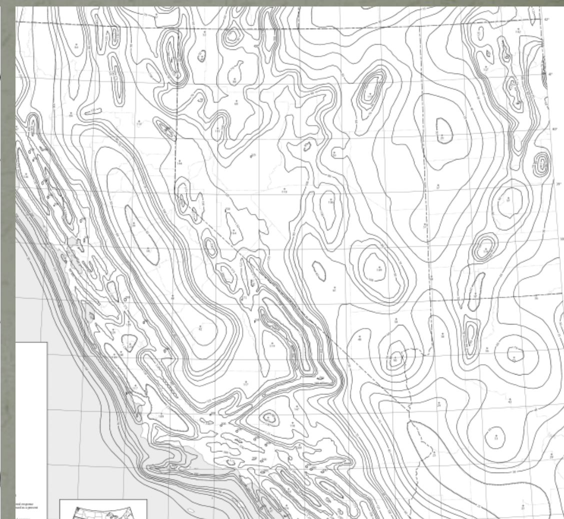
- For many years, until the 2000 IBC, the seismic hazard map was based on six zones (0, 1, 2A, 2B, 3 and 4) of increasing seismic design "acceleration". The last iteration of this map was used in the 1997 UBC and included "near fault" factors for areas close to known sources.
- With the 2000 IBC to the present (2012 IBC), the map uses contours of accelerations for both the 0.2 second and 1 second period.
- The new maps change with the source USGS map editions: 2002, 2008.

Maps Over Time

1985

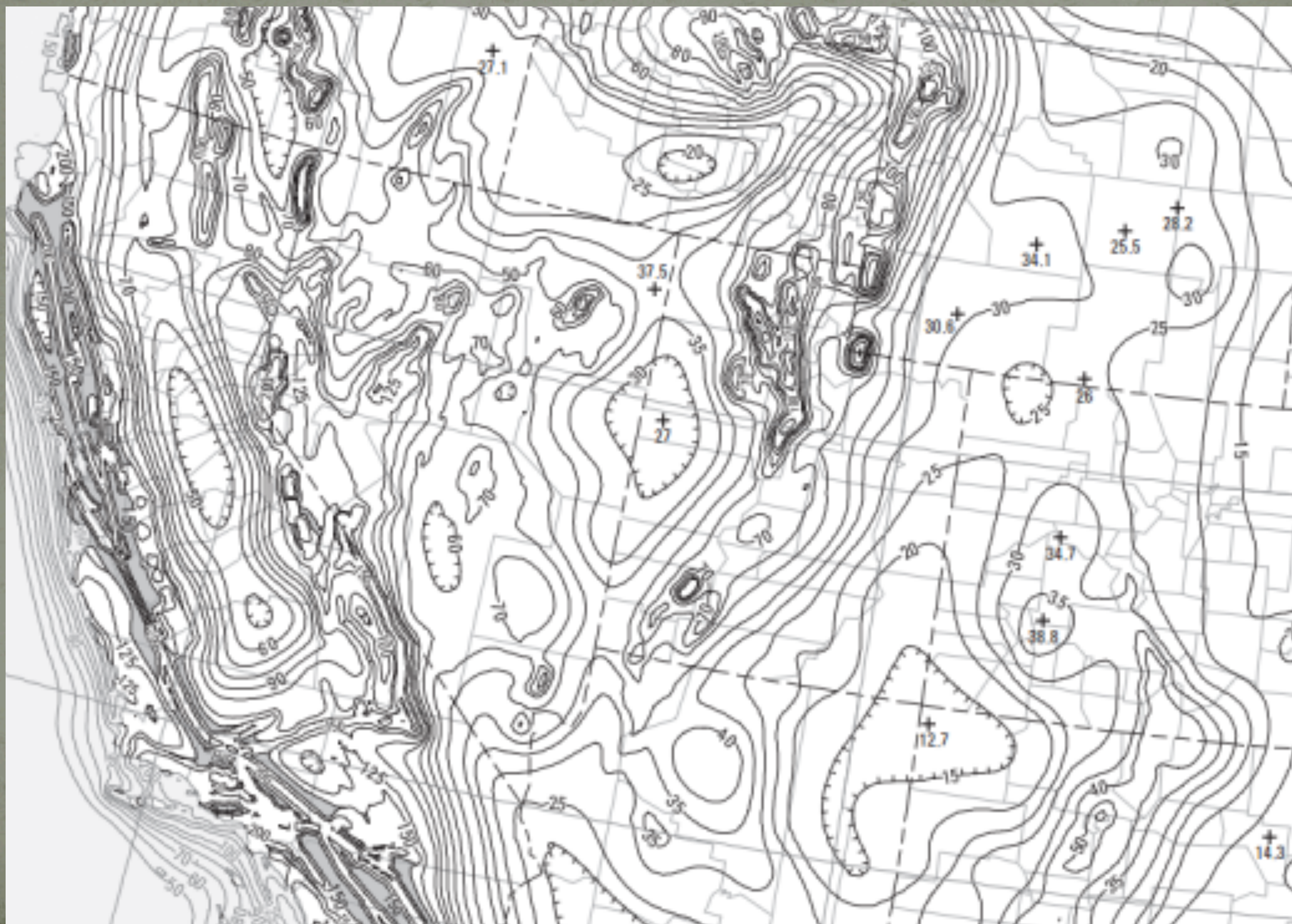


1988



2000

2012 IBC Map (current code)



Pros and Cons

- The modern detailed maps do not need additional factors for sources.
- The older mapping used large zones of equal design basis.
- The more detailed maps often have closely spaced contours– leading to very different design loads over a short distance. These same loads then do not remain the same over different editions of the code.
- Engineers are not fond of change.

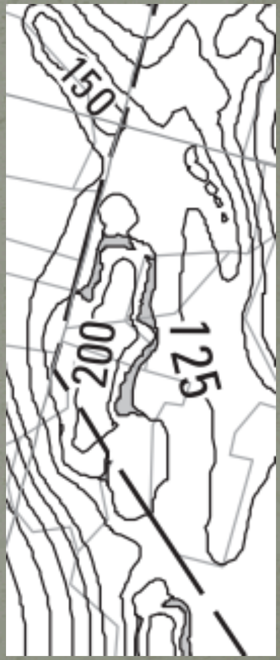
Changes For Reno 2006-2012 (Ss, site class D)

Reno Airport:
2006: 1.5g 2012: 1.978 g

SE Reno:
2006: 1.5 g 2012: 2.110g

SW Reno:
2006: 1.711g 2012: 2.309g

2006



2012

Other Changes 2006-2012 (Ss, site class D)

Fallon NV:
2006: 0.813g 2012: 0.787 g

Austin NV:
2006: 0.766g 2012: 0.705g

Ely NV:
2006: 0.372g 2012: 0.356g

Hinckley UT:
2006: 0.446g 2012: 0.398g

None of these changes would likely result in any difference in design of an actual structure

Design Issues with the Mapping

- The precision of the contours leads to the assumption of corresponding accuracy.
  - Where contours are closely spaced, neighbor structures may be designed for very different values based on assumed sources.
  - The current approach may not be conservative for some structures and overly conservative for others.
- Are the changes reliable enough to be implemented as a design standard?

Stability and Reliability

- Changes can result in existing structures being under-designed even though they are very new.
- Including structural "fragility" in defining the seismic hazard mapping is not a good idea for new construction.
  - Real factor of safety to collapse is unknown and likely far larger than anticipated.
- The level of precision does not match the accuracy. Why produce digital values with 1/1,000 g precision?

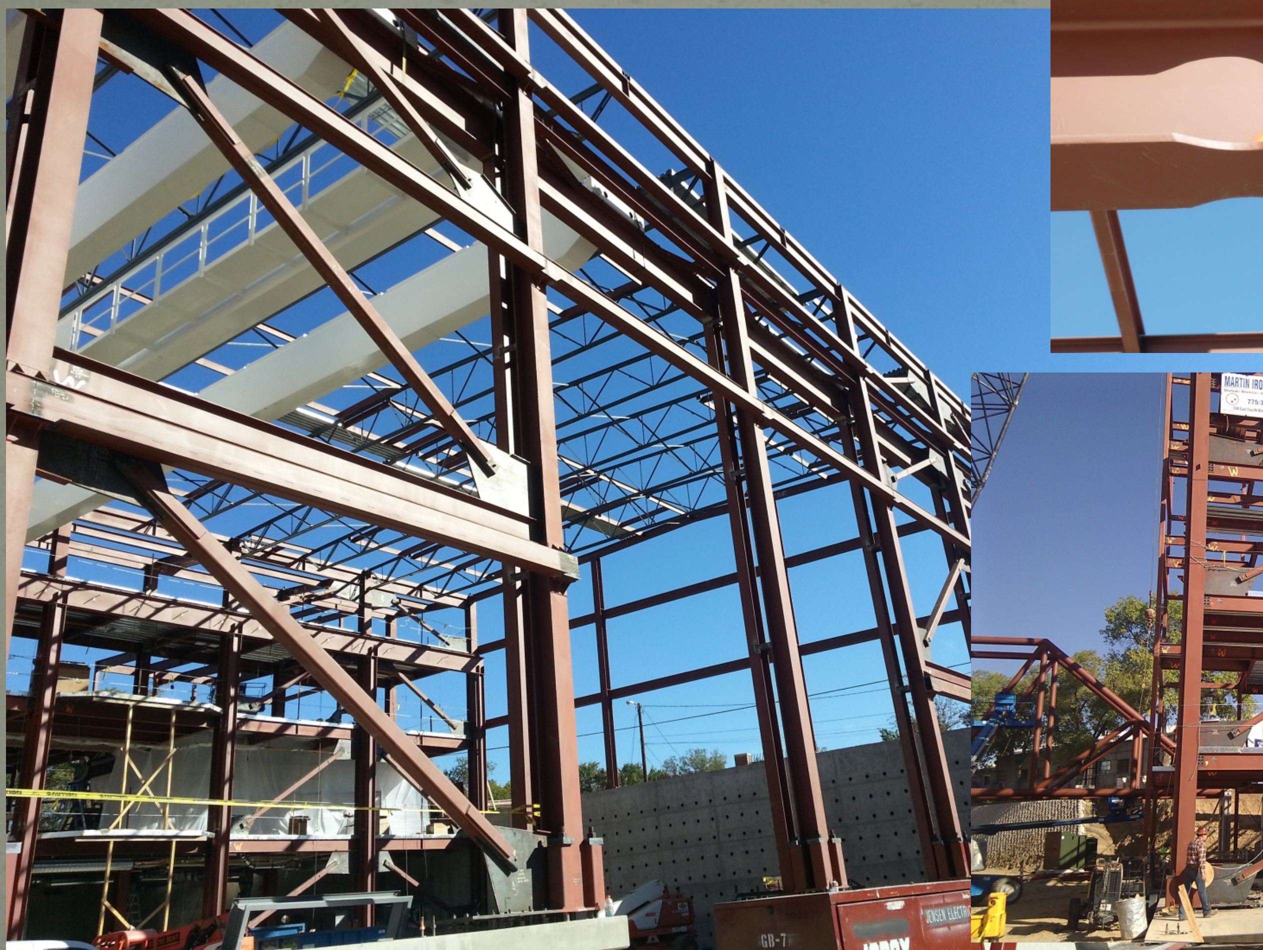
Seismic Forces Should Be Geologic

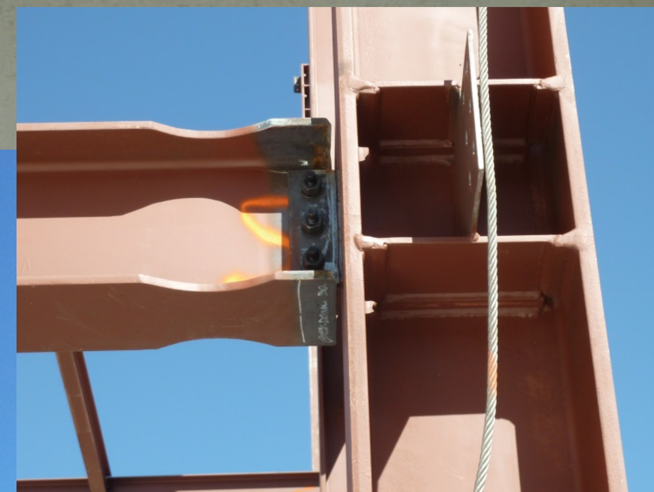
- The inclusion of structural fragility in hazard mapping adds assumptions about the structures to assumptions about the ground motion
  - Just keep it straightforward. Leave the structural stuff to the structural design process.
- There are factors of safety throughout the design process and materials specifications.
  - If everyone adds a factor of safety, then the design becomes unreasonable.
  - Safer is better up to the point where it impedes function or limits beneficial use.

So What's Ideal?

- The current system isn't ideal, but it works.
- Uncertainty in contour location is always a problem
- The boundaries of closely spaced contours might be better mapped as a single design value rather than the contours *for design purposes*.
  - Especially if the area is likely to be revised.
  - The mapped values are just a part of the overall design process and there are many compensating factors in the rest of the process.
  - Modern buildings have performed well despite changes in mapping and design procedure.

Thanks for this Opportunity





ONE CITY'S PERSEPECTIVE ON WHAT LOCAL GOVERNMENTS NEED FROM GEOSCIENTISTS

David Dobbins [1] and David Simon [2]
[1]City Manager, Draper City, 1020 East Pioneer Road, Draper, Utah 84020
[2]Simon Associates, LLC., 1981 East Curtis Drive, Salt Lake City, Utah 84010
Senior author's email address: david.dobbins@draper.ut.us

Draper City, Utah, ~10 miles south of Salt Lake City, is subject to geologic processes that impact public health, safety, and welfare, such as active faulting, landslides, liquefaction, rock falls, and debris flows.

Prior to 2003, Draper City "blindly" accepted reports from "professionals" without clear and concise prescriptive minimum standards and/or a formalized review process. In 2003, Draper City initiated a geologic review process via adoption of the Salt Lake County geologic-hazards ordinance, which included inconsistent review by City consultants.

After obtaining a comprehensive understanding of the value of the geologic review process, Draper City formed a panel of experts in 2007 to compose a geologic-hazard ordinance for the City. The purpose of the ordinance was three fold: (1) to reflect the most current standards of practice in the western United States, (2) to develop concise prescriptive minimum standards for evaluating geologic hazards such as slope stability, landslides, faulting, debris flow, rock fall, and liquefaction, and (3) to protect public health, safety, and welfare (not to add a bureaucratic layer to the development process). The current ordinance includes formalized, thorough reviews by City consultants.

Draper City did not appreciate being the guinea pig for establishing a geologic-hazard ordinance. Many cities refuse to undergo a similar process because the development community is so influential, and such ordinances are fraught with potential litigation. Although the process has been challenging and commenced with reluctance, Draper City found the rewards far overshadow the consequences of operating without regulation. The success of the City's review process is ultimately attributable to: (1) City leadership and willingness to leap into "regulation," (2) recognition that previous procedures were woefully inadequate and, (3) learning lessons from surrounding communities where geologic issues were ignored.

After working with geo-professionals for the past ten years and implementation of perhaps the most thorough geologic-hazard ordinance in Utah, we can now evaluate, as a municipality, what has worked and what we would like to improve on.

1. <u>Finding pragmatic solutions to difficult projects where "typical" approaches will not work.</u> The Hickory Ridge subdivision is an example where "typical" approaches were not feasible. The Hickory Ridge subdivision consists of about 45 lots, and is adjacent to the main trace of the Wasatch fault zone. Circa 2001, a fault investigation report was submitted, stamped, and sealed by the appropriate professional, for the proposed subdivision. The report was not peer reviewed.

   When development began circa 2006, we realized, to great dismay, that the consultant's report was inadequate. Active faults were identified in about 75% of the basement excavations and the lots were not of sufficient size to relocate structures.

   Draper City was told by the consulting firm that performance-based mitigation would work at the subdivision, and Draper City subsequently adopted a Protocol to the Geologic Hazard Ordinance, allowing building over an active fault if an engineering geologist, geotechnical engineer, and structural engineer stamped and sealed a report that complies with the Protocol. Mitigation is informally referred to as a "super-foundation," which increases the costs of a standard foundation system anywhere from $40,000 to $120,000. Will this approach work? We will find out after the next significant surface-faulting earthquake in Draper. The protocol was implemented to avoid costly litigation since the City had approved the subdivision, and any action to prohibit development would be challenged as a taking of property.

2. <u>Agreement.</u> We believe one of the major challenges when developing in geologically difficult areas, is that geologic and geotechnical professionals do not seem to agree on a standard of practice for development. Therefore, it has become the municipality's responsibility to establish regulations. To our wonder, some consultants have resisted regulations that establish a minimum standard of care.

3. Differing Objectives. Municipalities and developers have different objectives regarding development. A municipality's primary objective is to protect public health, safety, and welfare. The developer's objective is to get approval for the project in the most expeditious manner possible. The "need" or goal of a municipality is to try to balance these two objectives, which can at times be contentious.

4. Litigation. Complicating the development process is litigation, which, in Utah, has become more prevalent in the past five years. This appears to have been exacerbated by the 1998 North Salt Lake Springhill landslide, the 2005 Cedar Hills landslide, and the 2014 North Salt Lake Eagle Ridge Drive landslide.

   Litigation, and the efforts to avoid litigation, has caused cities to take on a consumer safety role. This is also driven by the perception of many homeowners, who assume the City has deemed their development is "safe" by issuing a building permit, which we know from prior examples is not necessarily true.

   Draper City currently spends about $400,000 annually on litigation, which the City Council detests. No politician likes litigation.

   State law for Utah development stipulates that a developer cannot be held liable for "arbitrary standards." This is a major source of contention between developers and municipalities. And nothing seems more arbitrary than an untrained bureaucrat or politician having to decide which expert geologist is correct when the developer's geologist says a landslide in the area of a proposed subdivision is "ancient," and therefore safe to build on, or the city's expert geologist who says the landslide is "young" and therefore unsuitable for development without proper mitigation.

5. Unifying Codes. Developers prefer codes that are inherently objective. Codes which clearly standardize A, B, and C. The International Building Code (IBC) or International Residential Code (IRC), for example, are codes with which a developer can objectively comply. If there is a disagreement in interpretation, the IBC has a board to assist with the interpretation, the International Code Council.

   Geologic-hazard ordinances are not viewed in the same light; they are viewed as subjective. Draper City is constantly trying to dispel this view point. In my opinion, the Draper City Geologic Hazard Ordinance, is as close to quantifying the process, as possible. After seven years, we will be revising and updating the Ordinance, making it easier to use (we hope) based on lessons learned. We also have produced check lists that are intended to help the consultant understand the ordinance. We realize that it is not likely, but public health, safety, and welfare would be better served if there was a nationally or internationally adopted geologic code, similar to the IBC or IRC. The IBC and IRC codes are used by nearly every city in Utah and are interpreted fairly consistently. If each city has to develop its own geologic-hazards ordinance, developers will not likely have the desired consistency and will look to the state legislature for resolution.

6. Geologic and geotechnical professionals. Local governments need to turn to the geologic and geotechnical professions for unanimous consensus on minimum standards to address geologic hazards. We would prefer our professionals tell us what has to be done. However, based upon our experience with adopting an ordinance, unanimous consensus seems unlikely. We found some professionals opposing our ordinance because they were representing developers who considered the ordinance too restrictive.

Our opinion is that the Draper City Geologic Hazard Ordinance works and works well. The reason our ordinance works is because we have established a clear and concise set of prescriptive minimum standards. Developers and their consultants now know the "rules."

Factors which contributed to the successful implantation of our geologic-hazard ordinance include: (1) a thorough and concise geologic-hazard ordinance, (2) an educated City Council, (3) review-consultants who understand City processes and can circumvent potential issues that could adversely impact the City, (4) preventing developers from controlling the development process, (5) implementing new data and making the hard decisions in regards to development, even if it involves halting approved developments, (6) working with developers to avoid geologically hazardous areas, and (7) advocating with the State legislature to assure a municipality's right to geologic and geotechnical review and the protection of public health, safety and welfare.

However, work still remains to be done, within Draper City and within the State of Utah, which includes:

1. Drafting of a unified, consistent geologic-hazard ordinance for all cities that possess property with potential geologic hazards.

2. Educating cities without an ordinance of the need and benefits of a prescriptive geologic-hazard ordinance.

In summary, the success of Draper City's geologic-hazard program has been, and continues to be, directly proportional to City/County official's, administrator's, and planner's ability to understand geologic processes. Challenges faced by municipalities during successful implementation of a geologic-hazard ordinance include the continued outrage by the development community (including likely litigation), resistance by consultants, and continued attempts by the development community to take control of the development process. Less resistance from the consulting community and implementation of a continuing education requirement would greatly contribute to achieving our mandate of protecting public health, safety, and welfare.

The following is a PDF version of the authors' PowerPoint presentation.

WHAT LOCAL GOVERNMENTS NEED FROM GEOSCIENTISTS
ONE CITY'S PERSPECTIVE

David W. Dobbins
David B. Simon, P.G.

SA
Simon Associates, LLC.

DRAPER CITY

Purpose

- History of geologic ordinances at Draper City
- Geologic Hazards
- Effectiveness of the ordinance
- Needs from the geoscience community
- Successes
- Flaws

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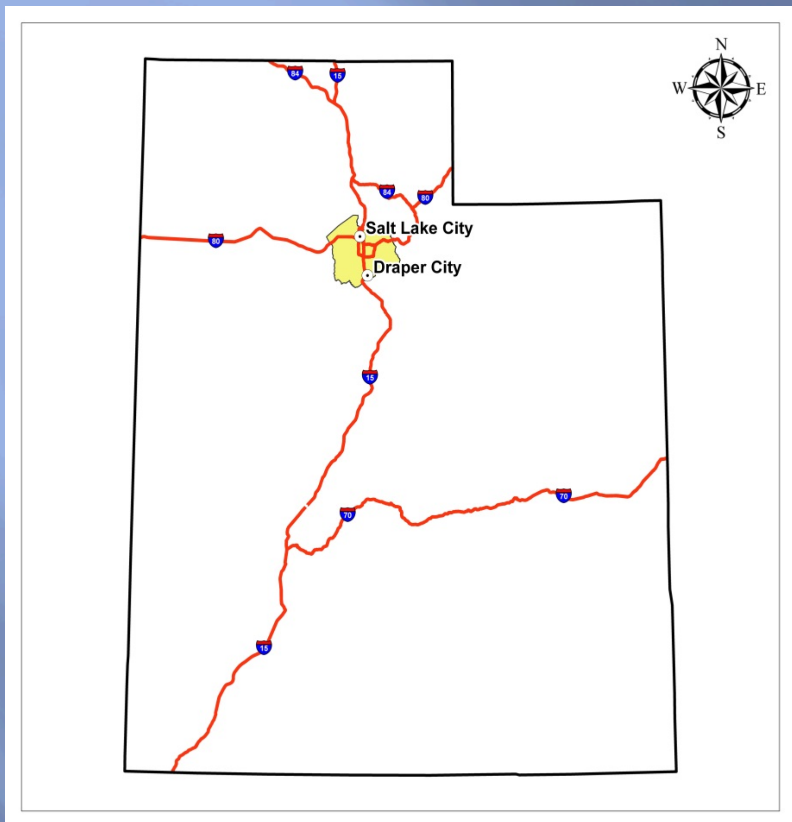
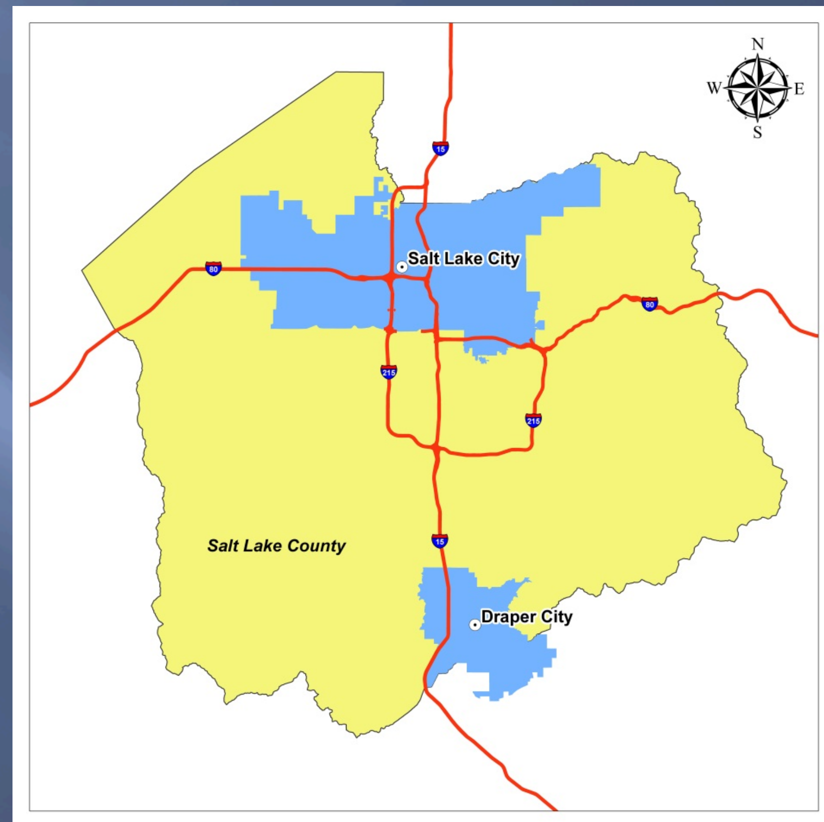
LOCATION MAP





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Draper City History & Facts

- **One of the fastest growing cities in Utah**
  - **500% since 1995**
  - **8,000 pop. 1995**
  - **40,000 pop. 2007**

- **In top three for home values ($500,000 average)**

- **Second highest household income in Utah ($115,000 per household)**

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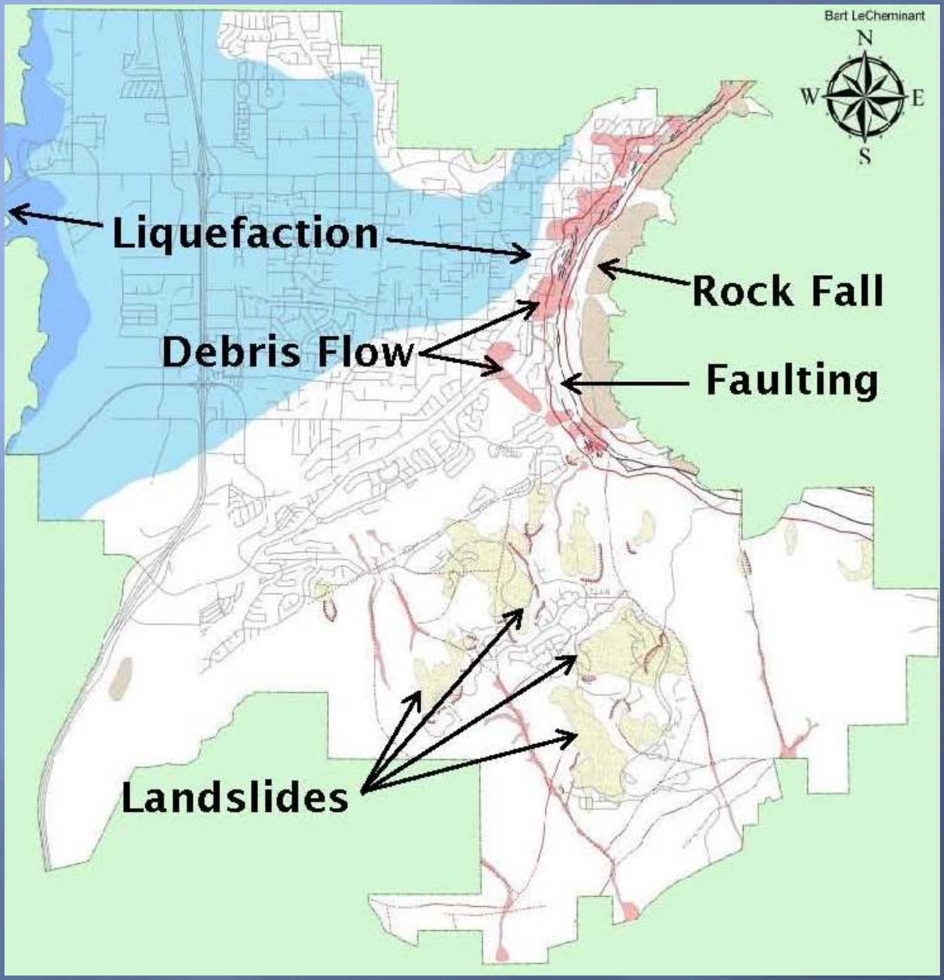
GEOLOGIC HAZARDS



Draper City is subject to geologic processes that could adversely impact public health, safety, and welfare.

- **Surface-fault-rupture**
- **Liquefaction**
- **Lateral spread**
- **Landslides**
- **Debris-flow**
- **Rock fall**

INITIAL IMPRESSION OF GEOLOGISTS

Geologists are “scientists” with an unnatural obsession with rocks and alcohol. Often too intelligent to do monotonous sciences like biology, chemistry, or physics, geologists devote their time to mud-worrying, volcano spotting, fault poking, skiing, bouldering, dust-collecting, and high-risk coloring.

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Anti-Regulatory Development Attitude When Draper City Entered into the Process

- **Utah is a "property rights" state.**
- **Many state legislators are developers, builders, real estate agents.**
- **Developers question a city's role/ rights in reviewing a private developer's consultant's work.**

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Regional Factors that Contributed to Regulatory Review

North Salt Lake Springhill Landslide
(circa 1998 – 2012)

(circa1998)

(2012)

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Regional Factors that Contributed to Regulatory Review

1998 Cedar Hills, Utah Landslide

reactivation of a historic landslide

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Regional Factors that Contribute to Regulatory Review

2014 North Salt Lake Eagle Ridge Landslide

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Draper City Review Process

- Prior to 2003 Draper City "blindly" accepted reports from "professionals" without clear and concise prescriptive minimum standards and/or a formalized review process.

- In 2003, Draper City initiated a geologic review process via adoption of the Salt Lake County geologic hazards ordinance, which included inconsistent review by City consultants.

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Draper City Review Process – cont.

- In 2007, Draper City initiated thorough geologic reviews, but this required "education" of City officials (including myself).
- The current success of the geologic review process required time, patience, and commitment by City leadership to support staff and the regulatory review process.
- Geologic reviews have had a greater success once City administrators understood the general geologic review processes, requiring the advice and coaching by the City's designated professional consultants.

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Draper City Review Process – cont.

- Revised Geologic Hazard Ordinance in 2006 – resulted in the most comprehensive geologic hazard ordinance in Utah and was used as the model ordinance by the Governor's Geologic Hazards Working Group.

- City now understands the best mitigation is avoidance.

  - Little Valley Landslide – traded open space with the developer.

  - Development on the Cherry Creek alluvial fan.

  - Stoneleigh Heights Phase III temporary hold until geologic issues could be adequately addressed

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LITIGATION

- Complicating the development process is litigation, which, in Utah, has become more prevalent in the past 5 years.

- Lawsuits are becoming a common way of getting approval.

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LITIGATION

- Litigation, and the efforts to avoid litigation, has caused Cities to take on a consumer safety role. This is also driven by the perception of a homeowner, who assumes the City is assuring everything is “safe” by issuing a building permit, which we know from prior examples is not necessarily true.

- Draper City currently spends about $400,000 annually on litigation, which the City Council detests. No Politician likes litigation.

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THE ORDINANCE

After obtaining a comprehensive understanding of the value of the geologic review process, Draper City, in 2007, formed a panel of experts to compose a geologic hazard ordinance for the City. The purpose of the ordinance was three fold:

1) to reflect the most current standards of practice in the western U.S.;

2) to develop concise prescriptive *minimum* standards for evaluating geologic hazards such as slope stability, landslides, faulting, debris flow, rock fall, and liquefaction, and;

3) to protect public health, safety, and welfare (*not to add a bureaucratic layer to the development process*). The current ordinance includes formalized, thorough reviews by in-house consultants.

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THE ORDINANCE

Draper City did not appreciate being the Guinea Pig for establishing an ordinance. Many cities refuse to undergo a similar process because the development community is so influential. Although the process has been challenging and commenced with reluctance, Draper City found the rewards far overshadow the consequences of operating without regulation. The success of the City's review process is ultimately attributable to:

1) City leadership and willingness to leap into "regulation;"

2) recognition that previous procedures were woefully inadequate, and;

3) learning lessons from surrounding communities where geologic issues were ignored.

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THE ORDINANCE

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PRAGMATIC SOLUTIONS

Finding pragmatic solutions to difficult projects where "typical" approaches were not feasible.

Our Hickory Ridge subdivision consists of about 45 lots, which, was adjacent to the main trace of the Wasatch fault zone. Circa 2001, a fault investigation report was submitted, stamped and sealed by the appropriate professional, for the proposed subdivision. The report was not peer reviewed.

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PRAGMATIC SOLUTIONS – CONT.

When development began circa 2006, we realized, to great dismay, that the consultant's report was inadequate. Active faults were identified in about 75% of the basement excavations and the lots were not of sufficient size to relocate structures.

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PRAGMATIC SOLUTIONS – CONT.

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PRAGMATIC SOLUTIONS – CONT.

The protocol was implemented to avoid costly litigation since the City had approved the subdivision and any action to prohibit development would be challenged as a taking of property.

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PRAGMATIC SOLUTIONS – CONT.

Mitigation is informally referred to as a “super-foundation,” which increases the costs of a standard foundation system anywhere from $40,000 to $80,000. Will this approach work? We will find out after the next significant surface-faulting earthquake.

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AGREEMENT

We believe one of the major challenges when developing in geologically challenging areas, is geologic and geotechnical professionals do not seem to agree on a standard of practice for development. Therefore, it has become the municipality's responsibility to establish regulations. To our wonder, some consultants have resisted regulations that establish the minimum standard of care.

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UNIFYING CODES

Developers prefer codes that are inherently objective and which standardize building practices. The IBC or IRC, for example, are codes which a developer can objectively comply. There is rarely a challenge to the code itself, but sometimes the interpretation of it is challenged and there are prescribed methods for obtaining an interpretation.

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UNIFYING CODES – CONT.

Geologic Hazard Ordinances are not viewed in the same light; they are viewed as being subjective. In our opinion, the Draper City Geologic Hazard Ordinance, is as close to quantifying the process, as possible. Draper City is constantly trying to dispel this view point.

After seven years, we will be revising and updating the Ordinance. Making it easier to use (we hope) based on lessons we have learned. We also have produced check lists that are intended to help the consultant understand the ordinance.

We realize that it is not possible, but it would be nice if there was a national or international adopted geologic code, like the IBC or IRC.

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UNIFYING CODES – CONT.

The IBC and IRC codes are used by nearly every city in Utah and are interpreted fairly consistently. If each city has to develop its own geologic hazards ordinance, developers will not likely have the desired consistency and will look to the state legislature for resolution.

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GEOLOGIC AND GEOTECHNICAL PROFESSIONALS

Local governments need to turn to our geologic and geotechnical professionals for unanimous consensus on minimum standards to address geologic hazards. *We would prefer our professional tell us what has to be done*. However, based upon our experience with adopting an Ordinance, unanimous consensus seems unlikely. This leaves it up to individual governmental agencies, often politicians or bureaucrats to decide what the minimum standard should be – not a good idea since some of whom believe the earth is only 7000 years old.

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SUMMARY

Our opinion is that the Draper City ordinance *works and works well*. The reason our ordinance works is because we have established a clear and concise set of prescriptive minimum standards. Developers and their consultants now know the "rules."

SUMMARY

The success of our geologic hazard program has, and continues to be, directly proportional to City/County officials, administrators, and planners ability to understand geologic processes. Other factors include:

- review-consultants who understand City processes and can circumvent potential issues that could adversely impact the City;
- making the hard decisions in regards to development, even if it involves halting approved developments;
- advocating with the State legislature to assure a municipality's right to geologic and geotechnical review and the protection of public health, safety and welfare.

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SUMMARY

Challenges faced by the municipalities during successful implementation of a geologic hazard ordinance include the continued outrage by the development community (including likely litigation), resistance by developers' Consultants, and continued attempts by the development community to take control of the development process.

Less resistance from the consulting community and implementation of a continuing education requirement would greatly contribute to achieving our mandate of protecting public health, safety, and welfare.

DRAPER CITY

SUMMARY

Work still remains to be done, within Draper City and within the State of Utah, which includes:

- Drafting of a unified, consistent geologic hazard ordinance for all cities that possess property with potential geologic hazards.

- Educating cities without an ordinance of the need and benefits of a prescriptive geologic hazard ordinance.

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Thank You

Questions?

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THE USGS NATIONAL SEISMIC HAZARD MAPS IN THE BASIN AND RANGE PROVINCE: THIRTY-FIVE YEARS IN THE MAKING

Mark D. Petersen, Kathleen M. Haller, and Yuehua Zeng
U.S. Geological Survey
1711 Illinois Street, Golden, Colorado 80401-1435
Senior author's email address: mpetersen@usgs.gov

The U.S. Geological Survey (USGS) updated the United States National Seismic Hazard Models in 2014 by incorporating the latest science and engineering data into a time-independent probabilistic framework. Previous versions of the conterminous United States hazard models were released in 1948, 1958, 1969, 1976, 1982, 1990, 1996, 2002, and 2008. The new models incorporate more detailed geologic information on fault locations, tectonic information on how earthquakes are generated, geodetic information on earthquake activity rates, recorded earthquakes since 2008, and ground-shaking information for various fault types. These maps are based on the best available earthquake science as determined from several topical and regional workshops and from advice provided by a Steering Committee composed of hazard experts. The new hazard models incorporate the latest methods, data, and input models in developing the hazard assessment.

Several different methods are required for seismic-hazard analysis: probabilistic analyses, conversion of slip rates or seismicity rates to earthquake rates, testing, and uncertainty. Probabilistic methods are used to combine input source and ground-motion models using a logic-tree framework. Testing procedures help the analyst determine optimal input parameters as well as assessments of the reliability of these maps in assessing future ground motions. Uncertainty analyses are currently being developed at the USGS to provide additional information on the range of potential hazard. All of these methods require uniformly processed data to develop and test the models.

New data from the Basin and Range Province have become available from the geology, geodesy, seismology, and engineering communities since 2008, when the last maps were released. This information is processed more uniformly than data applied in previous map versions. For example, recent working groups have uniformly processed geologic trenching information, geodetic strain-rate data, earthquake catalogs, and ground-shaking records. Working groups involving several experts worked collaboratively to process and assess the data.

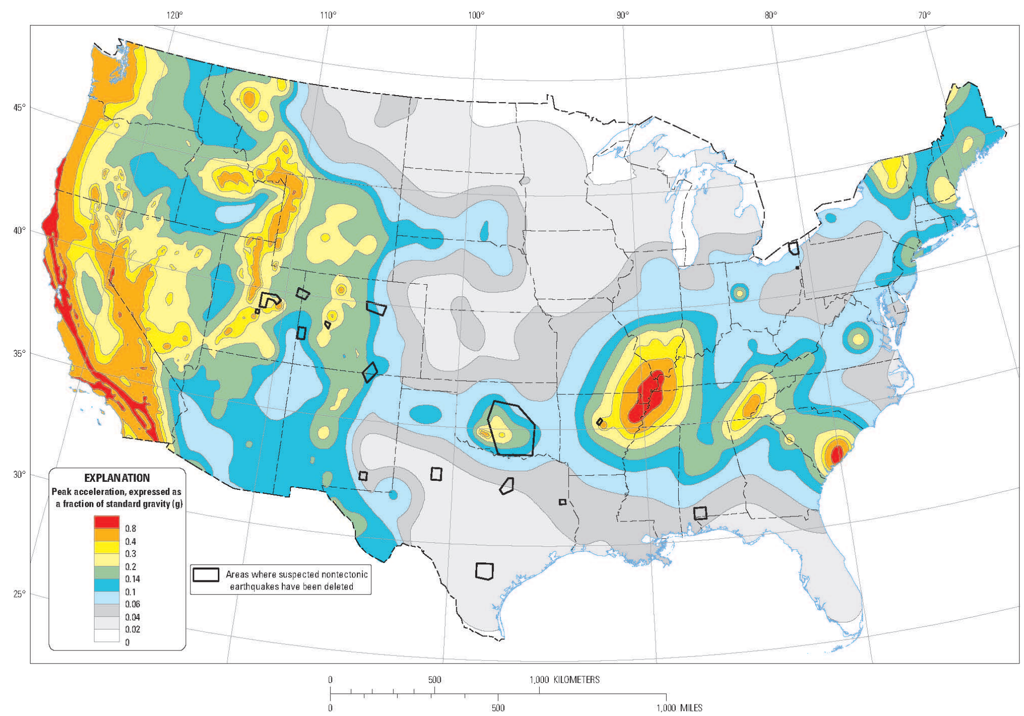
Seismic-hazard-input models use the locations and rates of past earthquakes and shaking intensities to estimate characteristics of future ground shaking. For example, new paleoseismic trench and geologic mapping studies are used to forecast alternative locations of future ruptures along faults such as the Salt Lake City segment of the Wasatch fault, new geodetic strain-rate information is combined with geologic data to assess how often earthquakes will rupture along modeled faults such as those found in central Nevada, and new seismic-shaking data are compiled to estimate how strong the ground will shake on the hanging wall of faults such as the Carson Range fault. The earthquake source models are constrained by regional seismic, geodetic, and geologic moment rates, while the ground-motion models are constrained by source, path, and site characteristics. They predict best estimates of the input or output parameters, and also give uncertainties related with each prediction. These uncertainties are critical for assessing probabilistic seismic hazard.

The new hazard models indicate changes of less than +/- 30% across the Basin and Range Province compared to the 2008 models. These changes are due to addition of new faults, change in seismicity modeling methods, incorporation of combined geodetic and geologic models, and modification of ground-motion models for normal and strike-slip faults.

The following is a PDF version of the authors' PowerPoint presentation.

The National Seismic Hazard Maps in the Basin and Range Province—~~Thirty-Five~~ 67 Years in the Making

Mark Petersen, Kathy Haller, and Yuehua Zeng (and NSHMP)
U.S. Geological Survey



2% probability of exceedance in 50 years : peak ground acceleration, uniform firm rock site condition Vs30=760m/s

PERCEIVED RISK

Slovic et al., (1981) Proc. R. Soc. Lond.

Table 1. Ordering of perceived risk for 30 activities and technologies (*22*). The ordering is based on the geometric mean risk ratings within each group. Rank 1 represents the most risky activity or technology.

Activity or technology	League of Women Voters	College students	Active club members	Experts
Nuclear power	1	1	8	20
Motor vehicles	2	5	3	1
Handguns	3	2	1	4
Smoking	4	3	4	2
Motorcycles	5	6	2	6
Alcoholic beverages	6	7	5	3
General (private) aviation	7	15	11	12
Police work	8	8	7	17
Pesticides	9	4	15	8
Surgery	10	11	9	5
Fire fighting	11	10	6	18
Large construction	12	14	13	13
Hunting	13	18	10	23
Spray cans	14	13	23	26
Mountain climbing	15	22	12	29
Bicycles	16	24	14	15
Commercial aviation	17	16	18	16
Electric power (non-nuclear)	18	19	19	9
Swimming	19	30	17	10
Contraceptives	20	9	22	11
Skiing	21	25	16	30
X-rays	22	17	24	7
High school and college football	23	26	21	27
Railroads	24	23	29	19
Food preservatives	25	12	28	14
Food coloring	26	20	30	21
Power mowers	27	28	25	28
Prescription antibiotics	28	21	26	24
Home appliances	29	27	27	22
Vaccinations	30	29	29	25

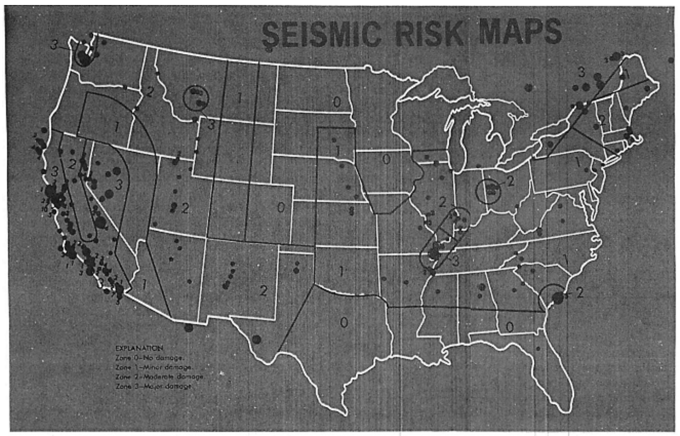
CHALLENGE: RISK COMMUNICATION

- What can I learn from these maps that will influence my behavior?
- What are these maps based on? (Underlying data, models, methods)
- What have we learned recently that influences the maps?
- What is the uncertainty in the maps?
- What products will help us communicate risk?

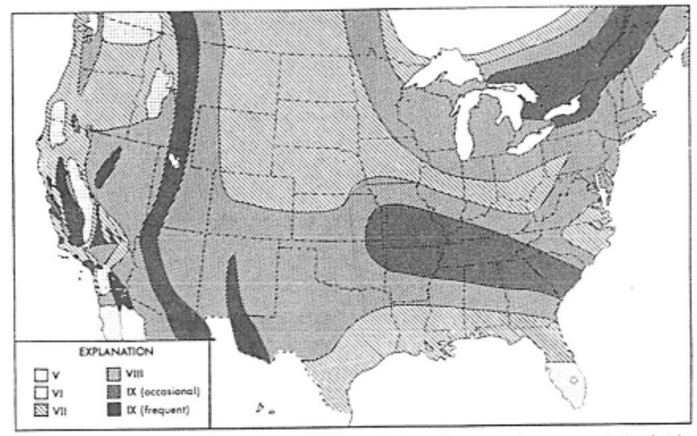
Pre-1996 maps

- Cascadia subduction zone not considered
- Only a few faults considered
- Mostly based on historic seismicity
- Later models considered tectonics
- Prior to 1976 based on 4 zones (0-3) or MMI, deterministic
- 1976 based on PGA with 1 Ground motion model, probabilistic

Early versions of U.S. hazard maps

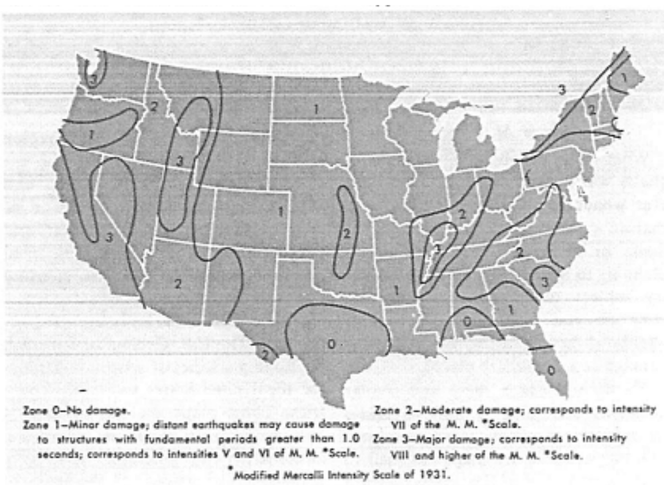


U.S. Coast and Geodetic Survey, 1948



Seismic risk map, developed in 1958 by Charles Richter, shows maximum expected seismic intensities (redrawn).

Richter, 1958



Seismic risk map of the United States, redrawn from map issued in 1969 by S. T. Algermissen of the U.S. Coast and Geodetic Survey (now with U.S. Geological Survey).

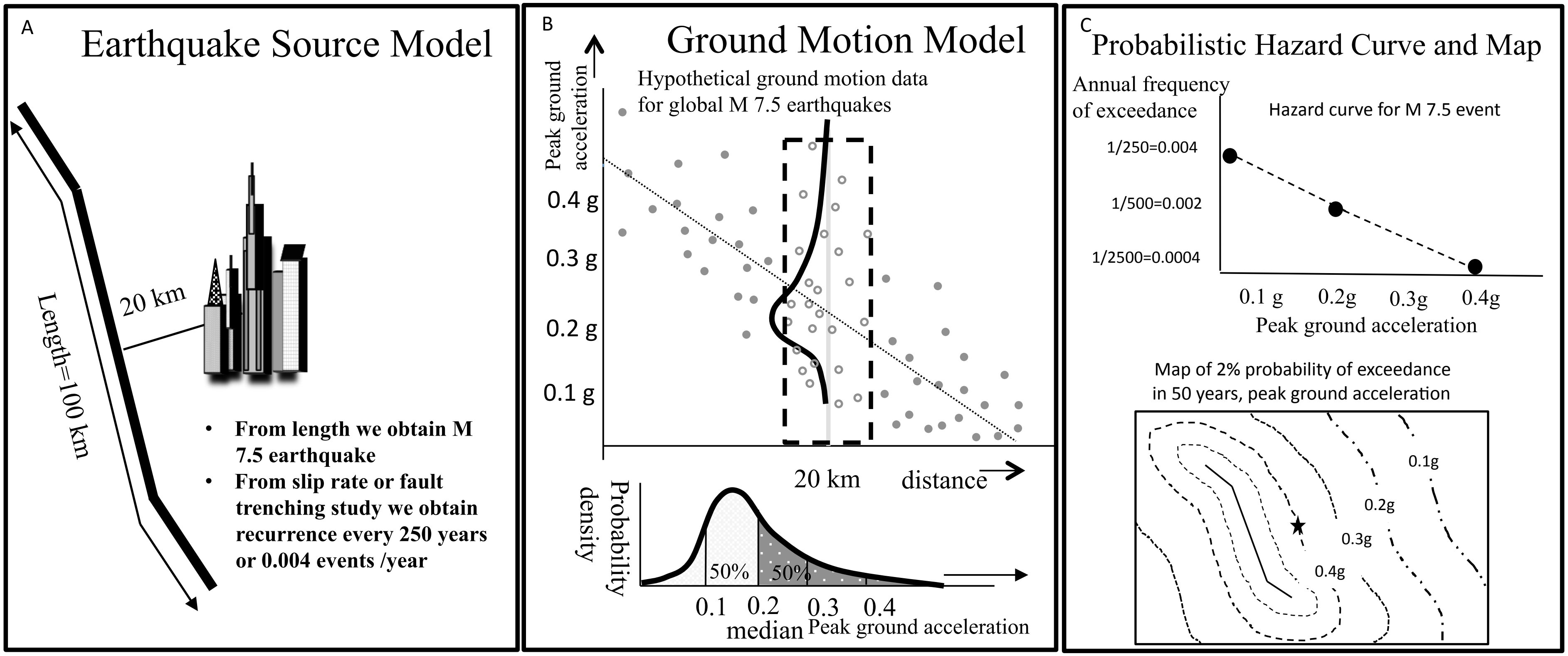
Algermissen, 1969

Algermissen and Perkins, 1976

Post 1996 maps

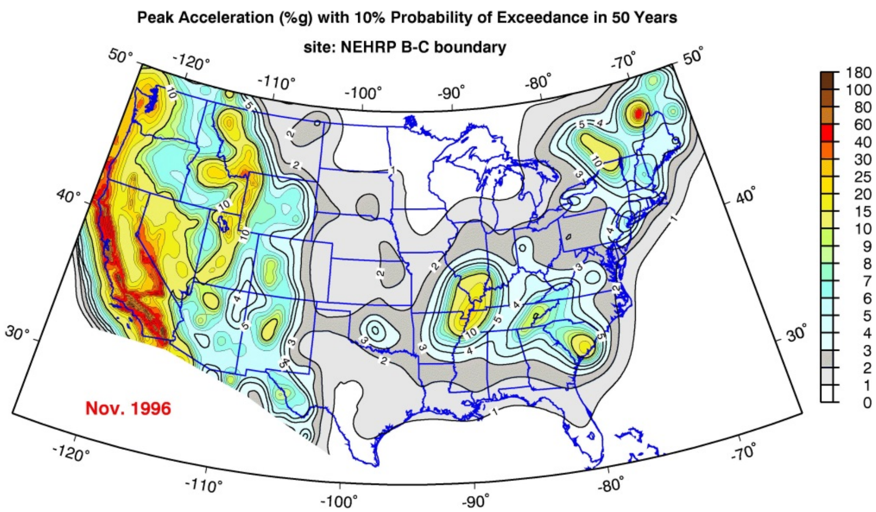
- Considered Cascadia Subduction Zone
- Several hundred faults
- Based on seismicity and fault data
- Based on working group data (CA, NGA, etc)
- Considered Basin and Range Summit input
- Considered WSSPC recommendations
- Considered many ground motion models: NGA, Subduction zone, CEUS

National Seismic Hazard Maps

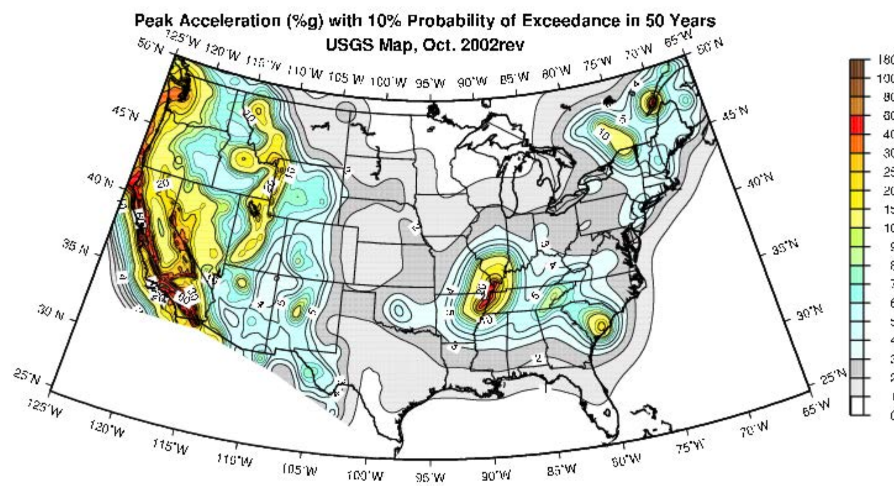


2% probability of exceedance in 50 years : spectral acceleration, Vs30=760m/s

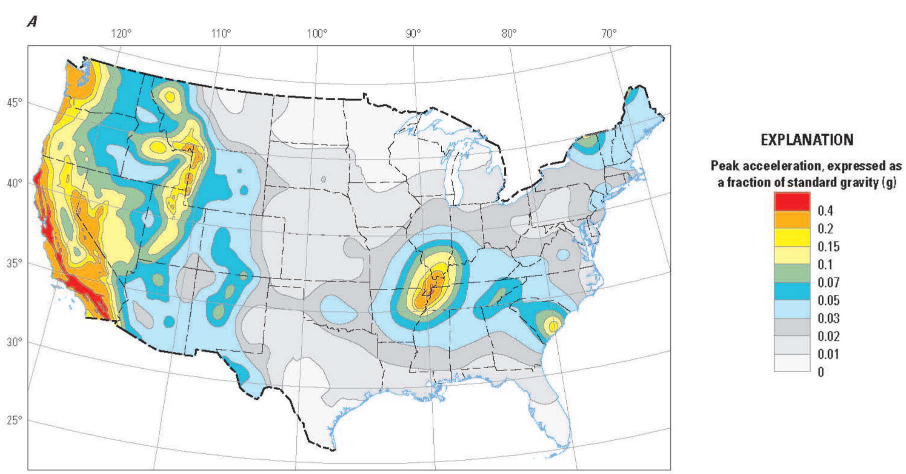
Later versions of the U.S. hazard maps



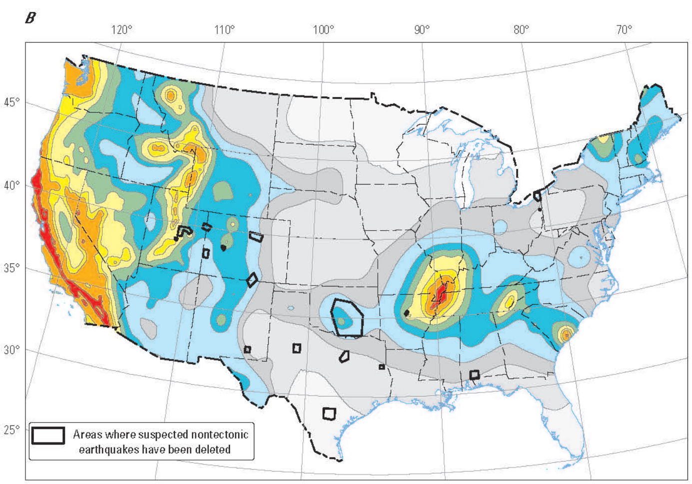
Frankel et al., 1996



Frankel et al., 2002



Petersen et al., 2008



Petersen et al., 2014

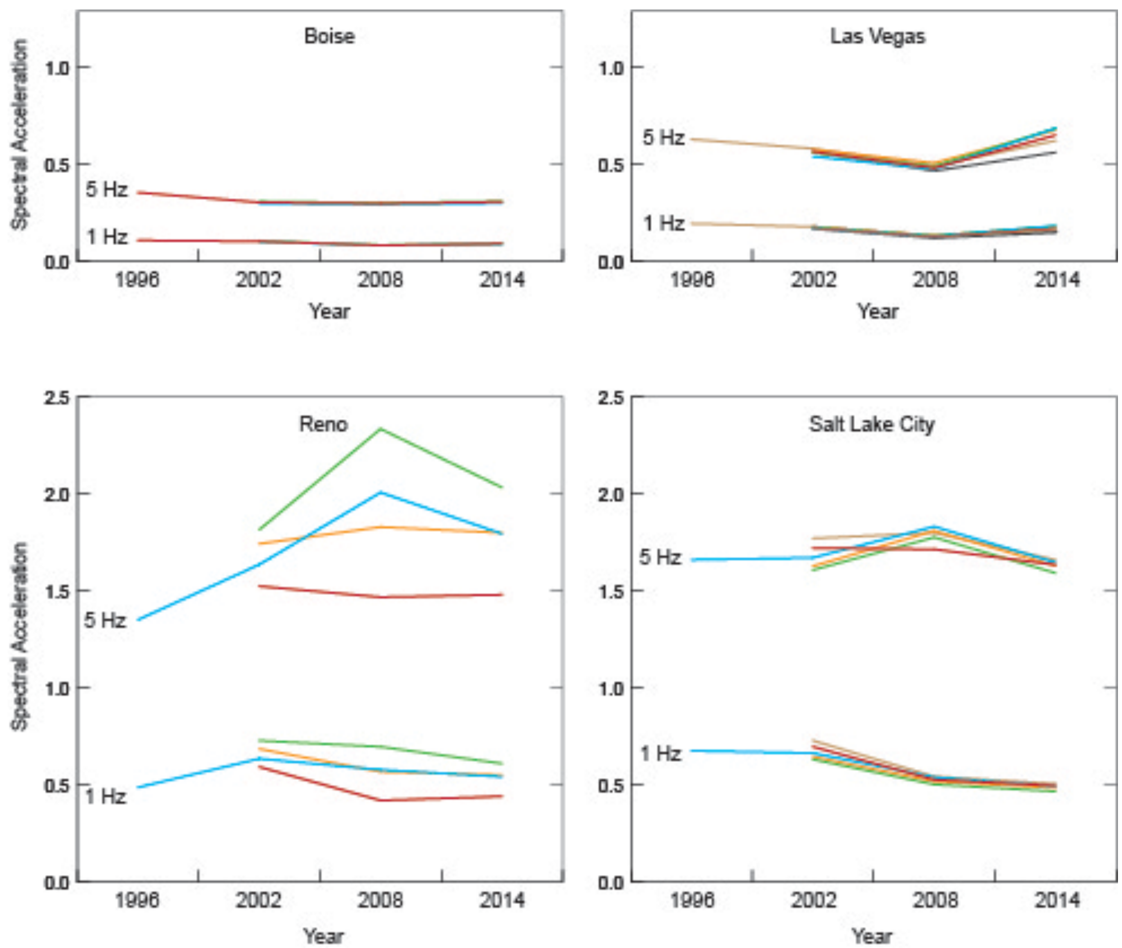
Best available science updates: Data

- Fault locations: geologic maps and cross sections, geophysical surveys, LiDAR (fault geometry)
- Geologic displacements, timing, slip rates (NEHRP grants; other)
- Geodetic based strain rates
- Geologic observations of landslides, liquefaction, precarious rocks, scarp degradation
- Seismicity magnitudes and locations (seismic networks, catalogs)
- Ground shaking observations (Wells, NV; Italy)

Best available science updates: Models

- Rupture models based on fault geometry and historic and prehistoric ruptures (Wasatch)
- Magnitude-scaling models (Magnitude-length/area)
- Magnitude-frequency distribution for earthquakes M 5 to 7+ based on historic seismicity rates
- Magnitude-frequency distribution on faults based on geologic (slip rates/geomorphology) information
- Magnitude-frequency distribution on faults based on combined geologic and geodetic information
- Ground motion models based on regressions of shaking data, magnitudes, distances, fault geometry

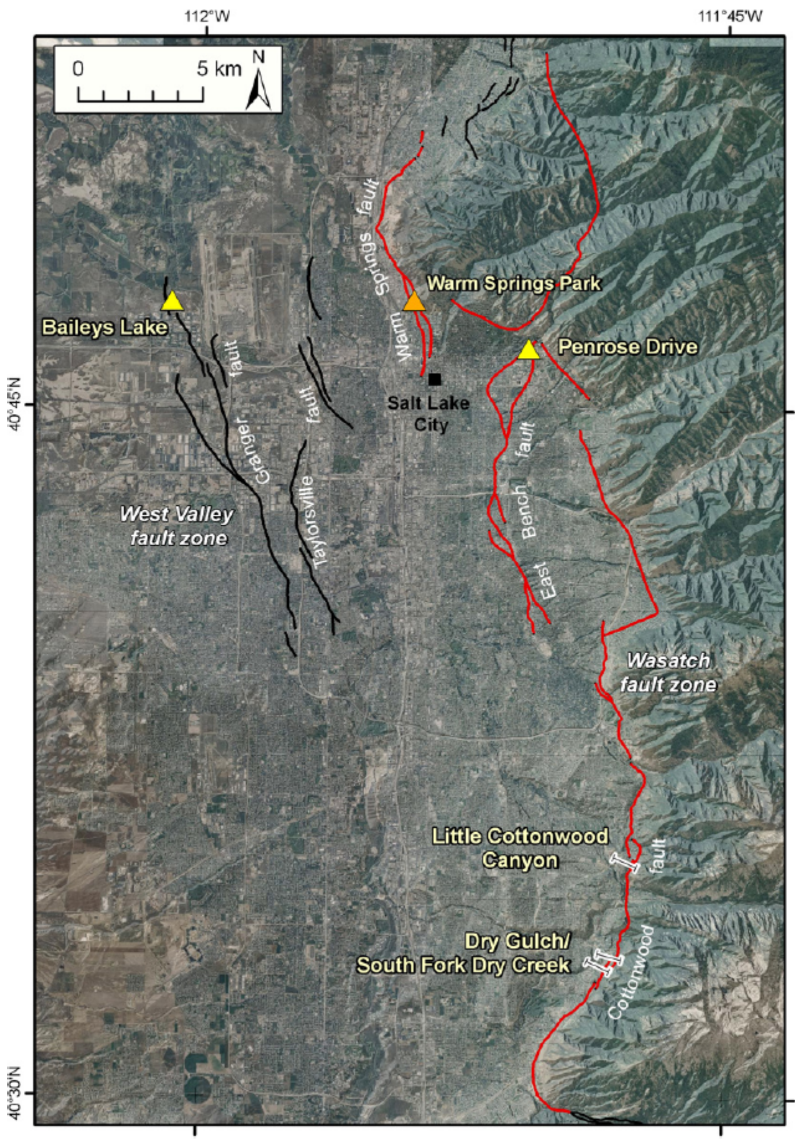
Changes in hazard since 1996

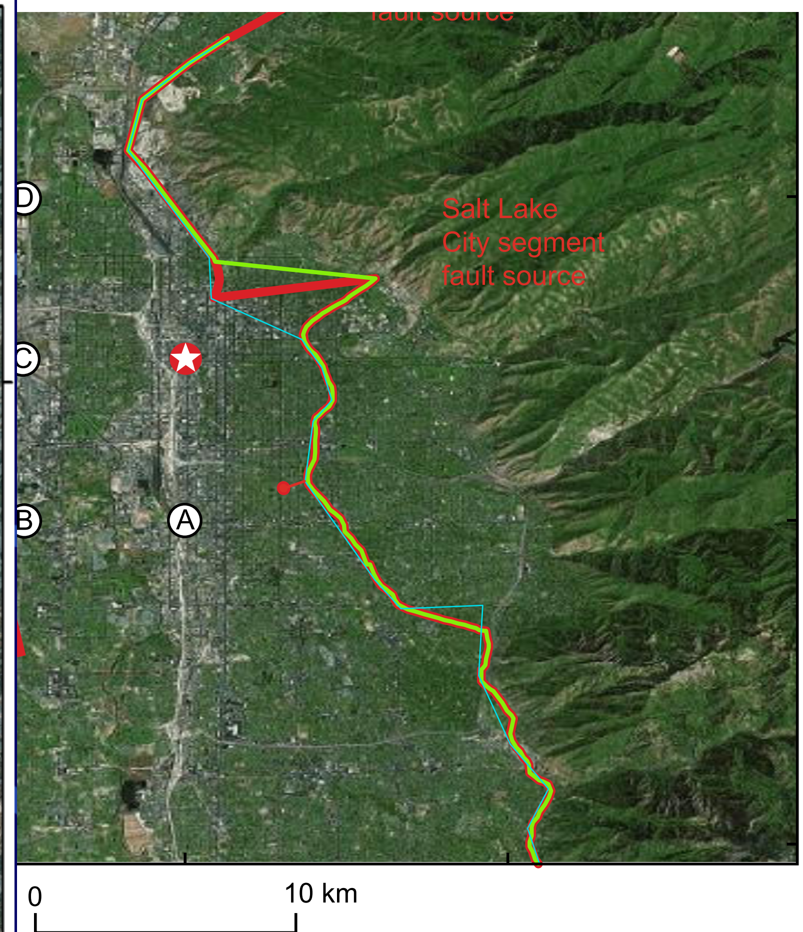


What has changed in 2014?

- Alternative fault rupture models
- Alternative rupture rates for faults
- Alternative gridded seismicity models
- Inclusion of geodetic data
- Modified maximum magnitude
- New ground motion models (NGA-West2)

Alternative fault rupture models

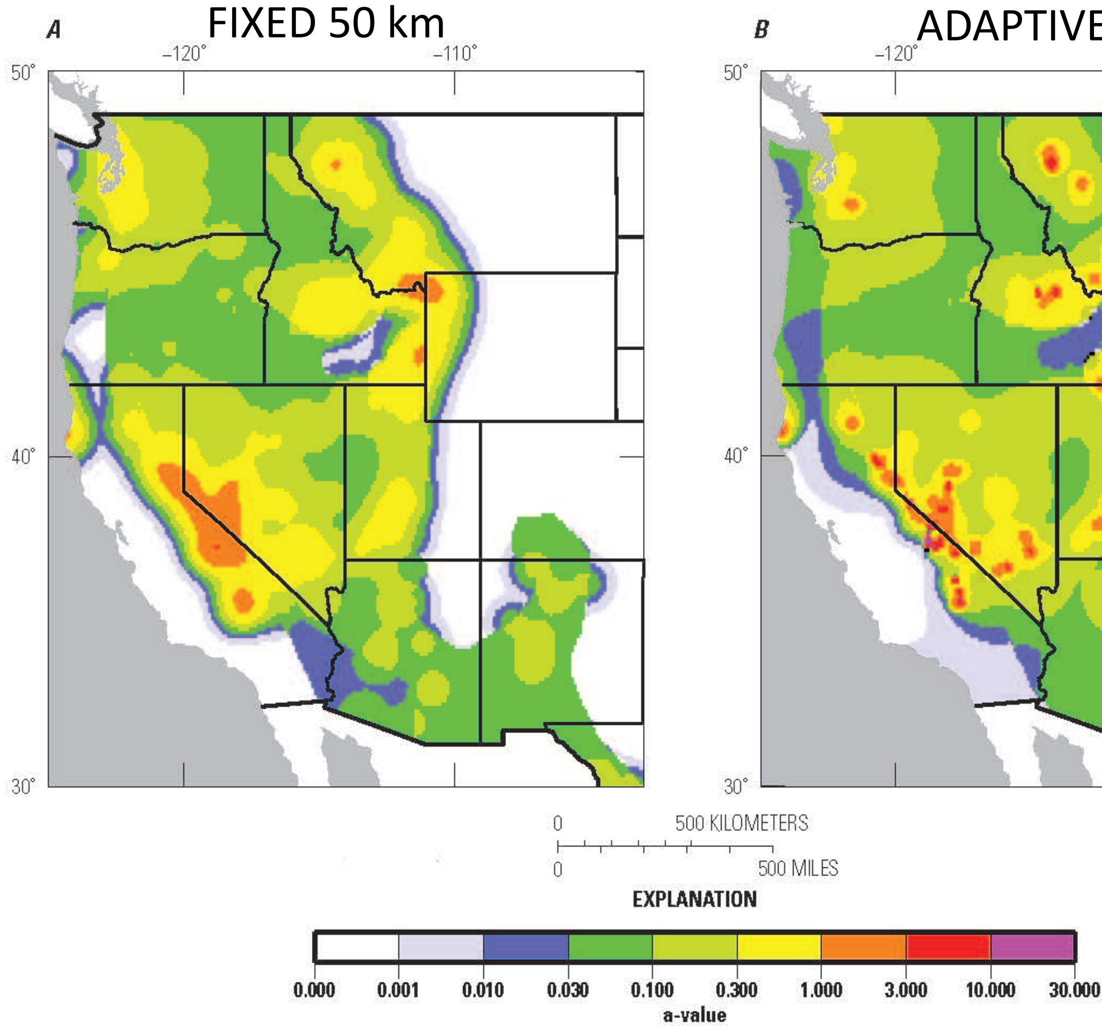




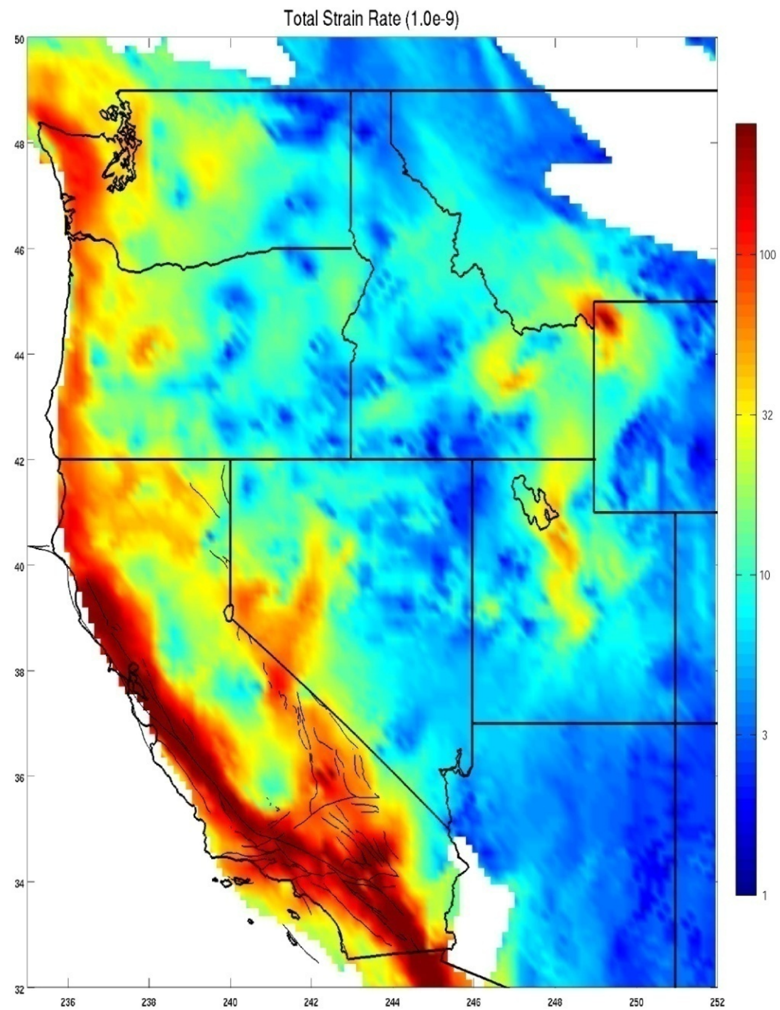
Alternative rupture rates

	Assigned M	2008	2014	5-Hz spectral acceleration
Eglington, NV	7.16	14 k.y.	2.2 k.y.	+ 0.3 g
Great Salt Lake, UT	7.00	0.78 mm/yr (1.3 k.y.)	4.2 k.y.	- 0.3–0.6 g
Centennial, ID	7.17	1.17 mm/yr (1.4 k.y.)	0.91 mm/yr (1.9 k.y.)	- 0.1 g

Alternative gridded seismicity models



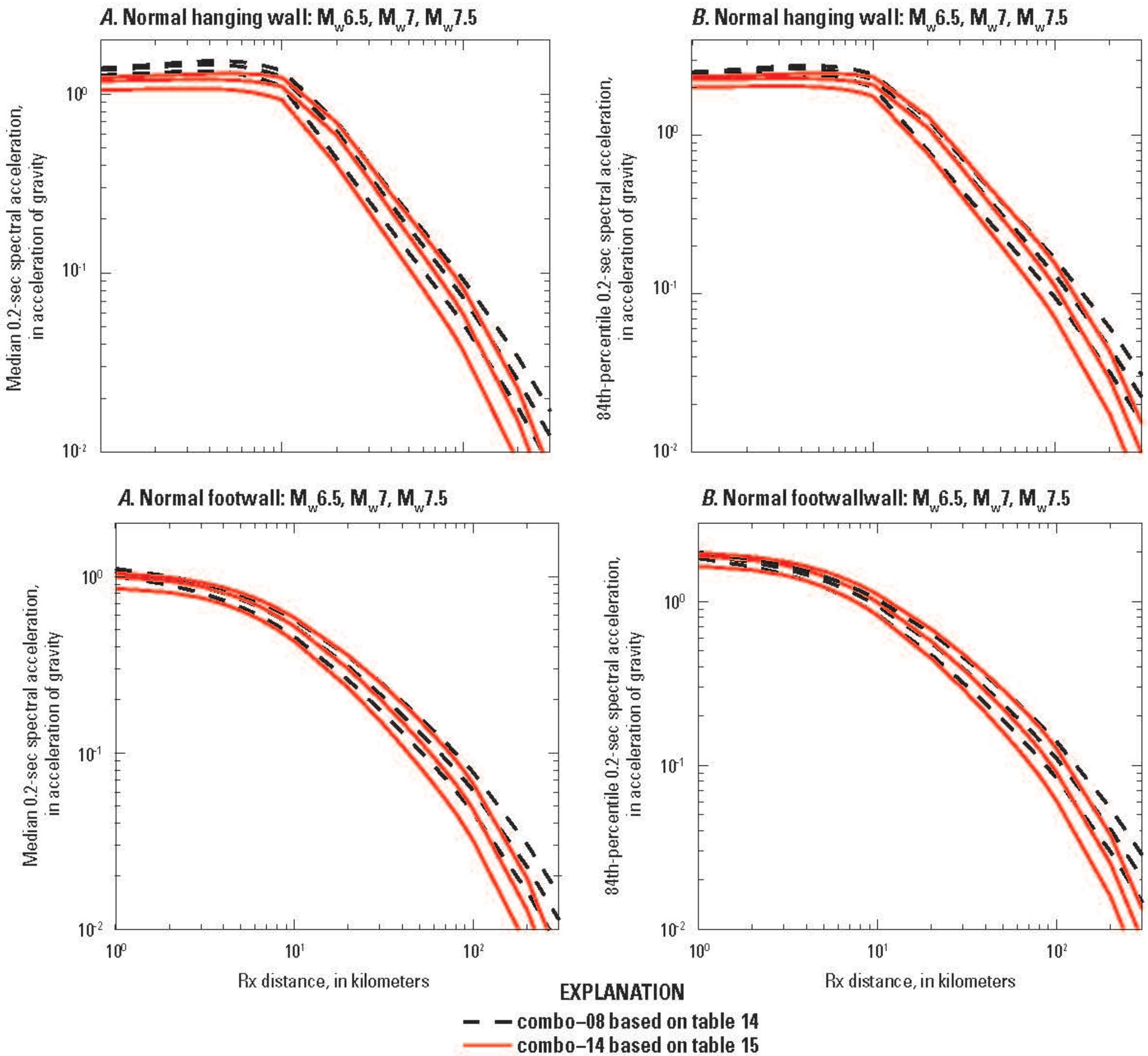
Inclusion of geodetic data



Maximum magnitude (WUS)

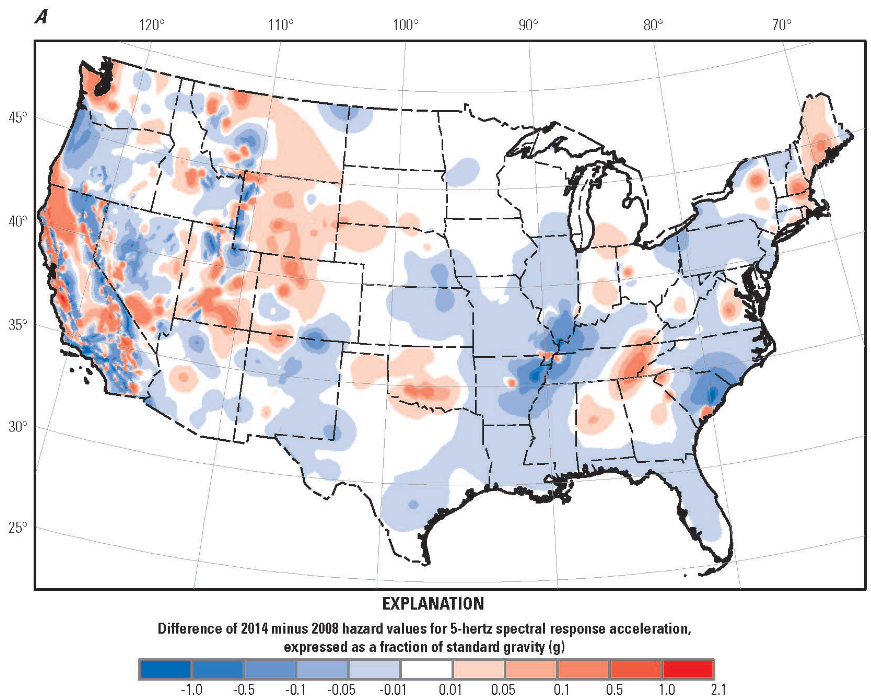
- 1996-2008 Typically about M 7.0 (with exceptions in zones)
- 2014 WUS M 7.45 (0.9), M 7.95 (0.1) WUS
- 2014 CA from M 7.25, 7.85

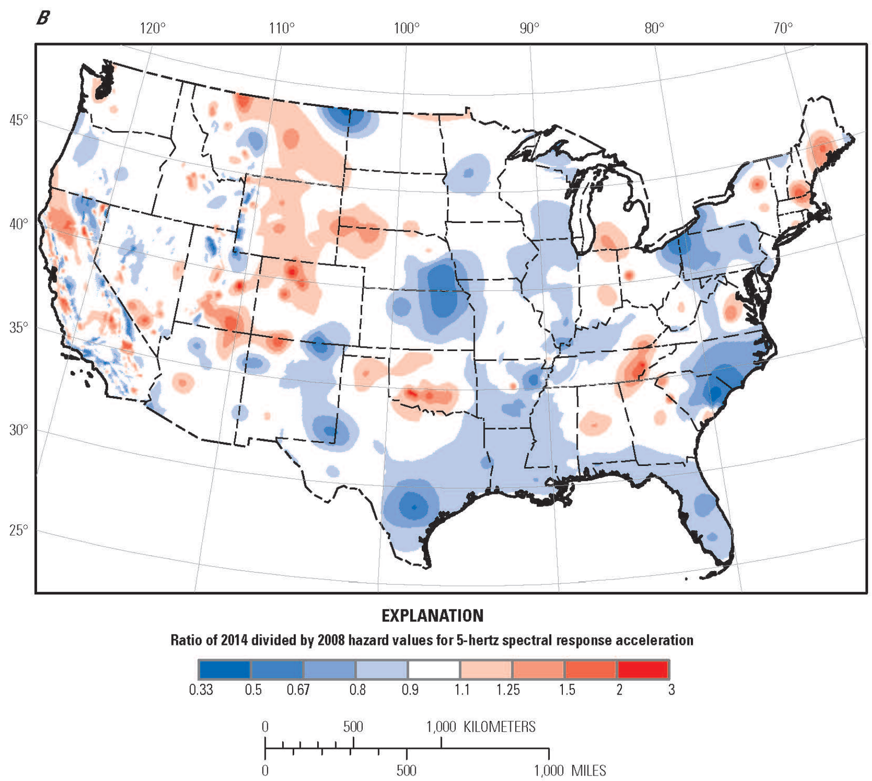
Ground motion models: Normal faults



1. Median lower or similar
2. Standard deviation higher

Comparison with 2008 model (5Hz-2% in 50)





CHALLENGES

- Uncertainty
- Hazard and risk communication

Uncertainties

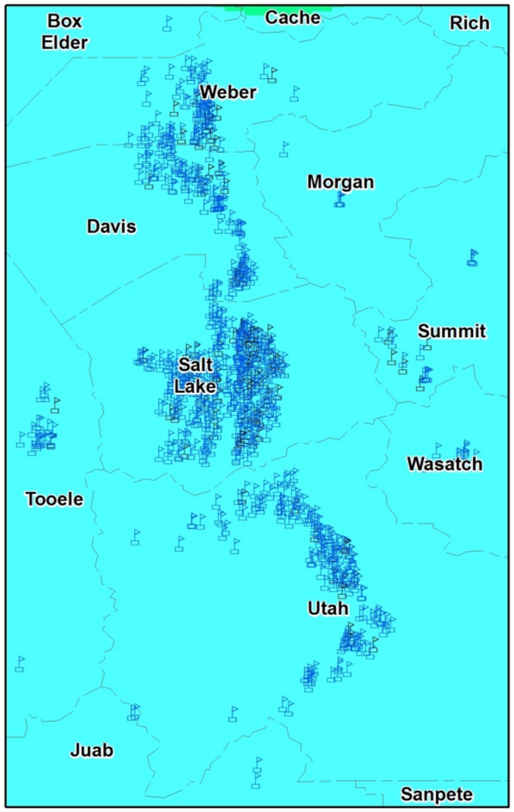
- Estimates of mean (GMM, M-scaling, recurrence, …) are quite variable, estimates of uncertainty about the mean are high- still rising
- Ground motion modelers studying how to better quantify the full range of uncertainty (M, distance, ground motion) including accounting for what we haven't seen
- Goal to better quantify uncertainties in NSHM

RISK COMMUNICATION

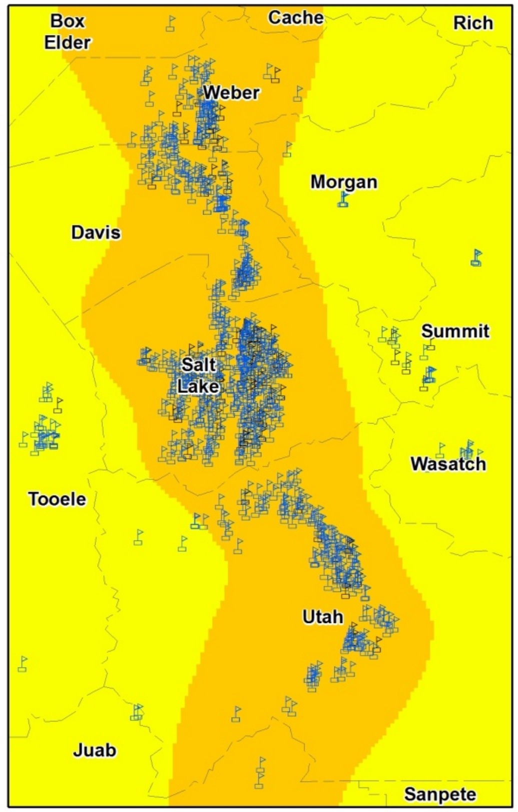
- What does hazard represent?
- What products can USGS develop to help people understand risk?
- What should people do to mitigate risk?

Salt Lake City

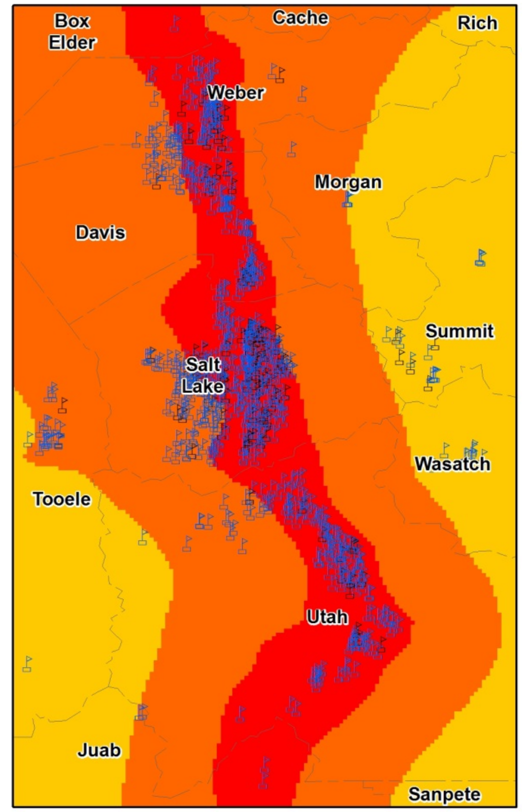
50% in 50 years



10% in 50 years

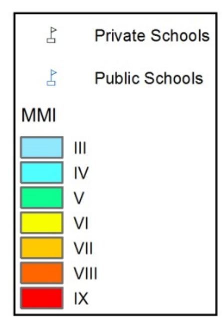


2% in 50 years

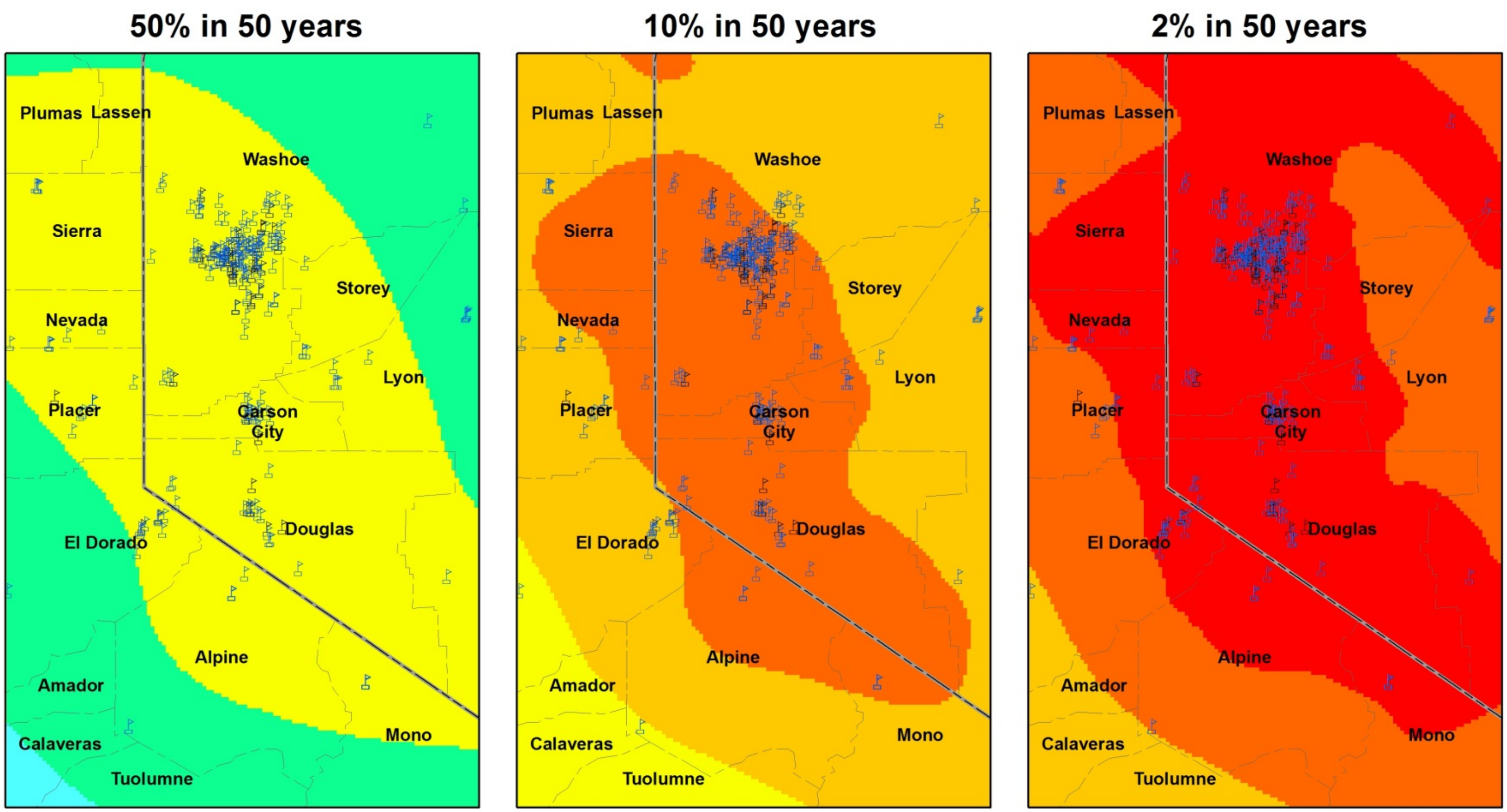


Number of schools in MMI zones

MMI	50% in 50 years	10% in 50 years	2% in 50 years
IV	841		
V			
VI		63	
VII		778	36
VIII			173
IX			632

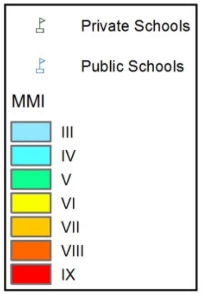


Reno



Number of schools in MMI zones

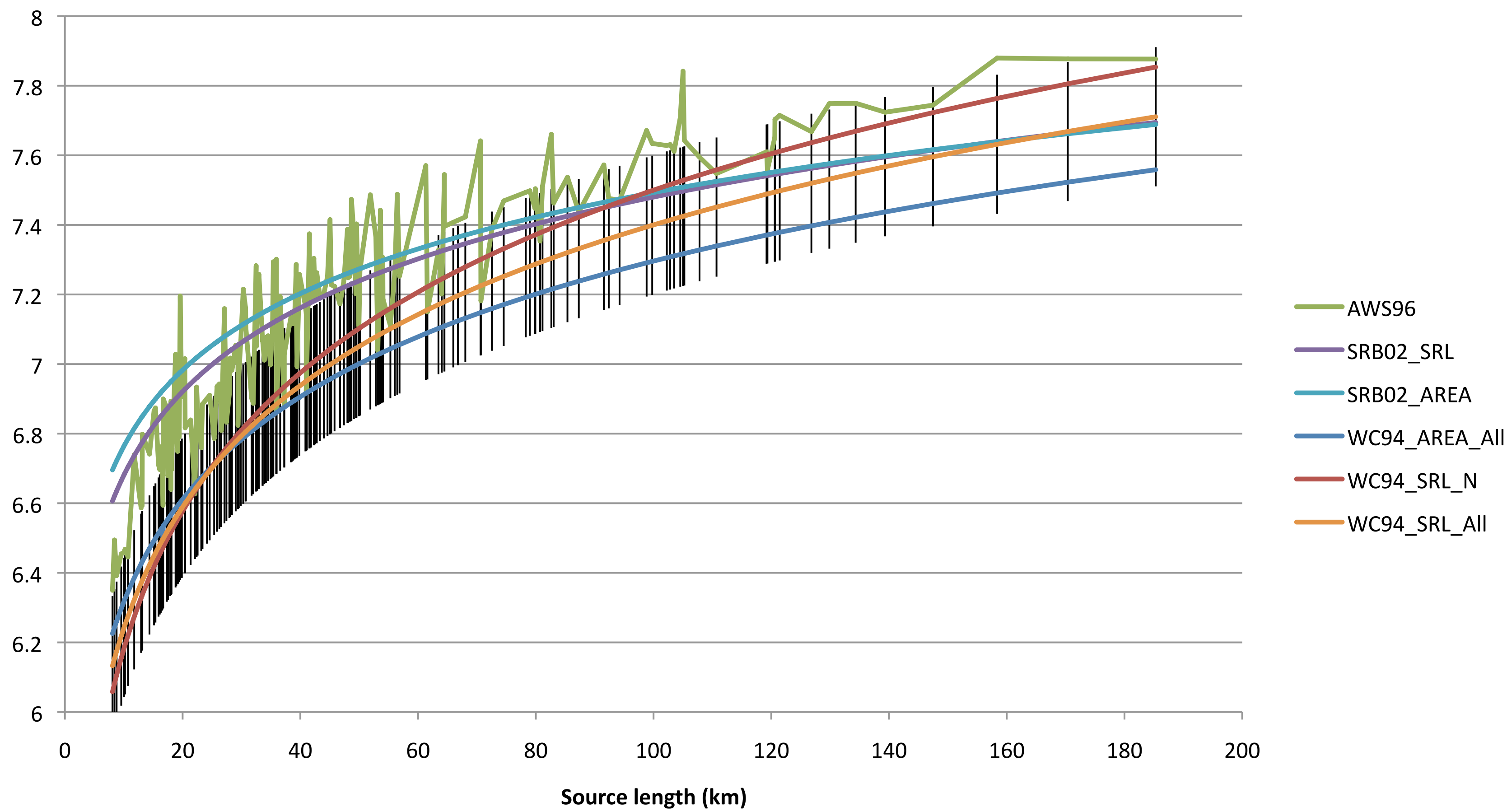
MMI	50% in 50 years	10% in 50 years	2% in 50 years
V	9		
VI	236	3	
VII		42	1
VIII		200	16
IX			228



Conclusions: Future research

- M-scaling relations
- New geologic/geodetic/seismic studies
- New assessments of seismicity (swarms)
- Paleoseismic vs slip rate based recurrence
- Induced seismicity?
- Uncertainty
- Risk/Communication

M scaling relations



DATA AND TOOLS FOR SEISMIC HAZARD INVESTIGATIONS

Steve Bowman, Geologic Hazards Program Manager
Utah Geological Survey, 1594 West North Temple, Suite 3110, P.O. Box 146100
Salt Lake City, Utah 84114-6100
stevebowman@utah.gov

The Utah Geological Survey (UGS) has collected and made available online (http://geology.utah.gov) a vast amount of geologic data relevant to seismic-hazard investigations in Utah. These data include maps, reports, aerial photography, LiDAR elevation data, photographs of various geologic hazards or events, and seamless scans of historical orthophotomaps and topographic maps. The 25 volume Paleoseismology of Utah publication series contains reports covering various paleoseismologic trench investigations and compilations of low-sun-angle aerial photography and other related work. An extensive collection of scanned geologic maps at a variety of scales and vintages is available from the UGS Interactive Geologic Maps of Utah. Over 88,000 scanned stereoscopic aerial photographs (vertical, low-sun-angle, and oblique) from 1935 to 2002, that include some of the best pre-development images of the Wasatch, West Valley, West Cache, East Cache, Washington, and Hurricane fault zones are available in the UGS Aerial Imagery Collection. The UGS GeoData Archive System contains over 12,700 items consisting of scans of much of our geologic-hazard related files, including consultant reports (geotechnical, geologic-hazard, and fault evaluation), unpublished information from UGS field reconnaissance and investigations (photographs, maps, notes, and videos), and photographs of various geologic hazards and events. The UGS has provided scans of all known 1936–1952 Soil Conservation Service orthophotomaps and 1900–1966 U.S. Geological Survey 15- and 30-minute topographic maps of Utah to the State Geographic Information Database (SGID, http://gis.utah.gov/data/), where the seamless data are available.

The UGS and local, state, and federal partners acquired over 8400 square kilometers of high-resolution, public domain LiDAR data in 2011 and 2013–2014 that covers the Wasatch, West Valley, and Hurricane (Utah portion only) fault zones, among other areas in Utah. The data include bare-earth (digital elevation model) and first return (digital surface model) data sets. The UGS is actively using this data to map fault traces of the Wasatch and West Valley fault zones at a scale of 1:10,000 to produce surface-fault-rupture hazard maps showing special study zones where surface-fault-rupture investigations are recommended prior to development.

The following is a PDF version of the author's PowerPoint presentation.

Data and Tools for Seismic Hazard Investigations

What information resources are available for your projects from the Utah Geological Survey

Steve D. Bowman
Geologic Hazards Program Manager

Utah Geological Survey (UGS)

The Utah Geological Survey, a division of the Utah Department of Natural Resources, provides timely scientific information about Utah's geologic environment, resources, and hazards. About 75 FTE staff and the State Geologist.

- Administration
- Geologic Hazards Program
- Geologic Mapping Program
- Groundwater and Paleontology Program
- Energy and Minerals Program
- Geologic Information and Outreach Program

Offices

- Salt Lake City
- Cedar City

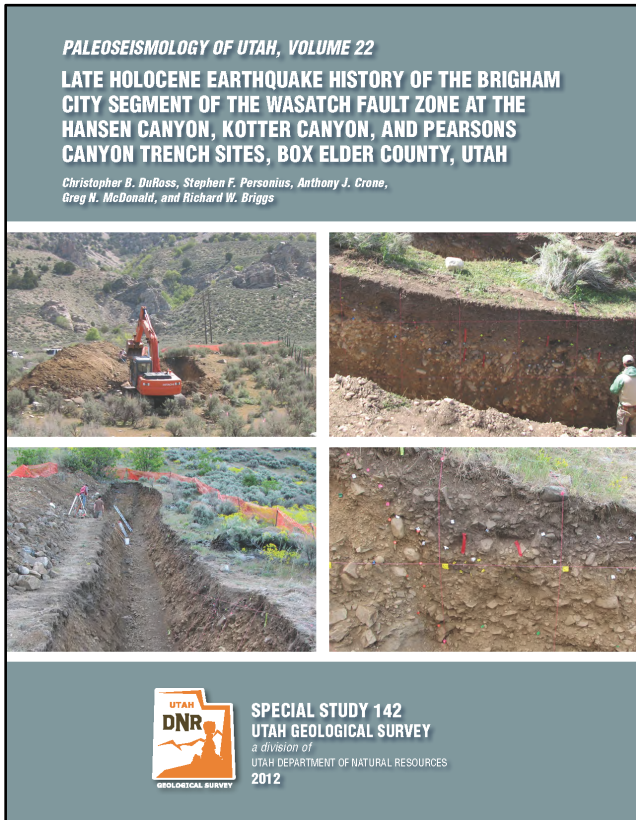
Utah Geological Survey Geologic Hazards Program

- Respond to geologic hazard emergencies by assisting the Utah Division of Emergency Management/state agencies and local governments (cities and counties).
- Create geologic hazard maps for land-use planning, management, development, and other uses.
- Provide geologic hazard outreach and information to Utah citizens, governments, and industry to increase awareness and reduce economic and life-safety impacts.

12-Mile Canyon Landslide

1999/2011+ Sherwood Hills Landslide

February 2010 Rockville Rock Fall


PALEOSEISMOLOGY OF UTAH, VOLUME 22
LATE HOLOCENE EARTHQUAKE HISTORY OF THE BRIGHAM CITY SEGMENT OF THE WASATCH FAULT ZONE AT THE HANSEN CANYON, KOTTER CANYON, AND PEARSONS CANYON TRENCH SITES, BOX ELDER COUNTY, UTAH
Christopher B. DuRoss, Stephen F. Personius, Anthony J. Crone, Greg N. McDonald, and Richard W. Briggs
UTAH DNR GEOLOGICAL SURVEY
SPECIAL STUDY 142
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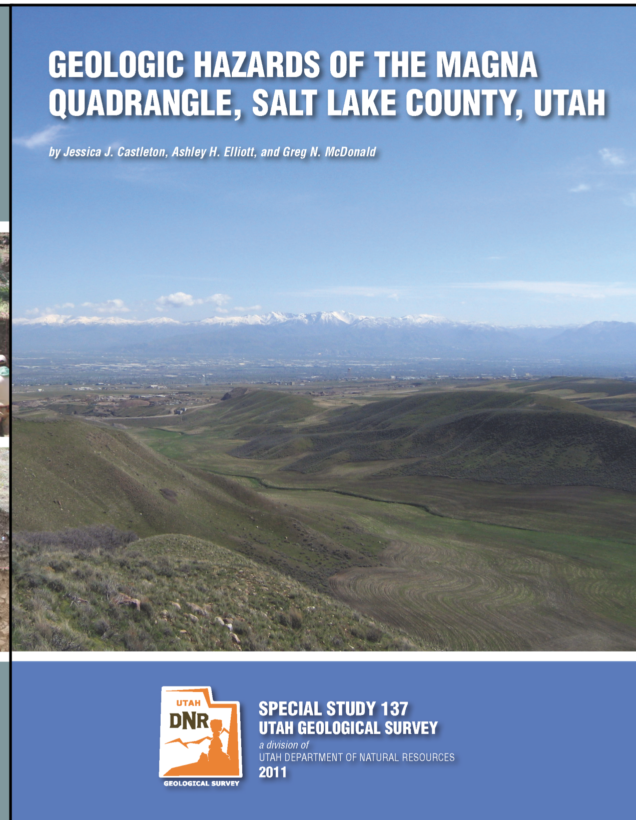
GEOLOGIC HAZARDS OF THE MAGNA QUADRANGLE, SALT LAKE COUNTY, UTAH
by Jessica J. Castleton, Ashley H. Elliott, and Greg N. McDonald
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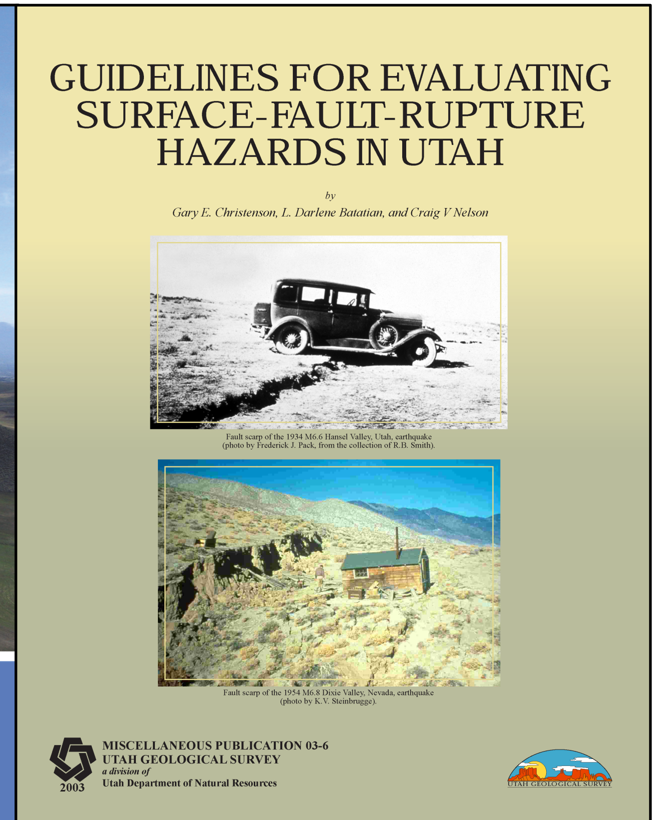
GUIDELINES FOR EVALUATING SURFACE-FAULT-RUPTURE HAZARDS IN UTAH
by
Gary E. Christenson, L. Darlene Batatian, and Craig V Nelson
Fault scarp of the 1934 M6.6 Hansel Valley, Utah, earthquake (photo by Frederick J. Pack, from the collection of R.B. Smith).
Fault scarp of the 1954 M6.8 Dixie Valley, Nevada, earthquake (photo by K.V. Steinbrugge).
MISCELLANEOUS PUBLICATION 03-6
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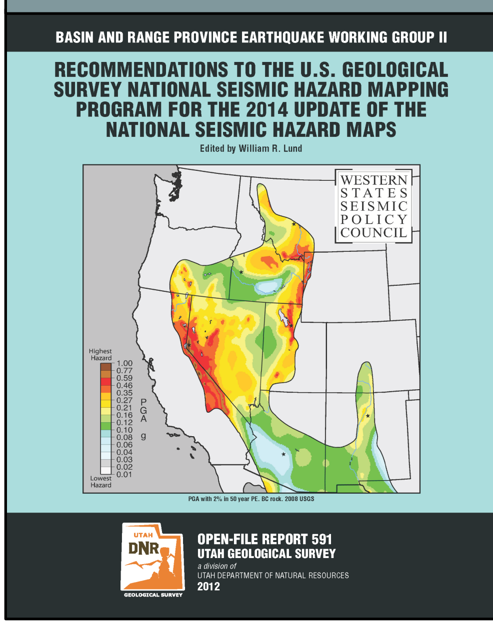
BASIN AND RANGE PROVINCE EARTHQUAKE WORKING GROUP II
RECOMMENDATIONS TO THE U.S. GEOLOGICAL SURVEY NATIONAL SEISMIC HAZARD MAPPING PROGRAM FOR THE 2014 UPDATE OF THE NATIONAL SEISMIC HAZARD MAPS
Edited by William R. Lund
WESTERN STATES SEISMIC POLICY COUNCIL
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Lowest Hazard
PGA g
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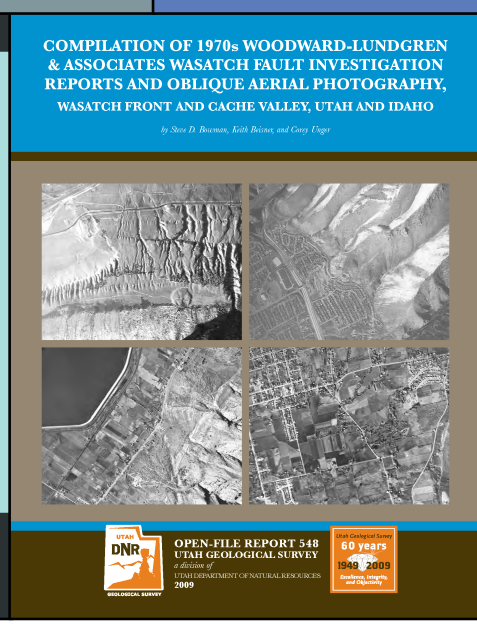
COMPILATION OF 1970s WOODWARD-LUNDGREN & ASSOCIATES WASATCH FAULT INVESTIGATION REPORTS AND OBLIQUE AERIAL PHOTOGRAPHY,
WASATCH FRONT AND CACHE VALLEY, UTAH AND IDAHO
by Steve D. Bowman, Keith Beisner, and Corey Unger
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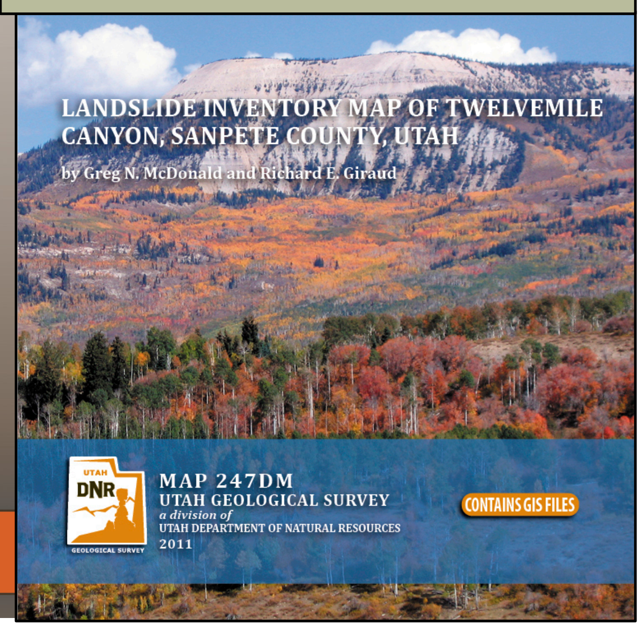
2009
60 years
1949 2009


LANDSLIDE INVENTORY MAP OF TWELVEMILE CANYON, SANPETE COUNTY, UTAH
by Greg N. McDonald and Richard E. Giraud
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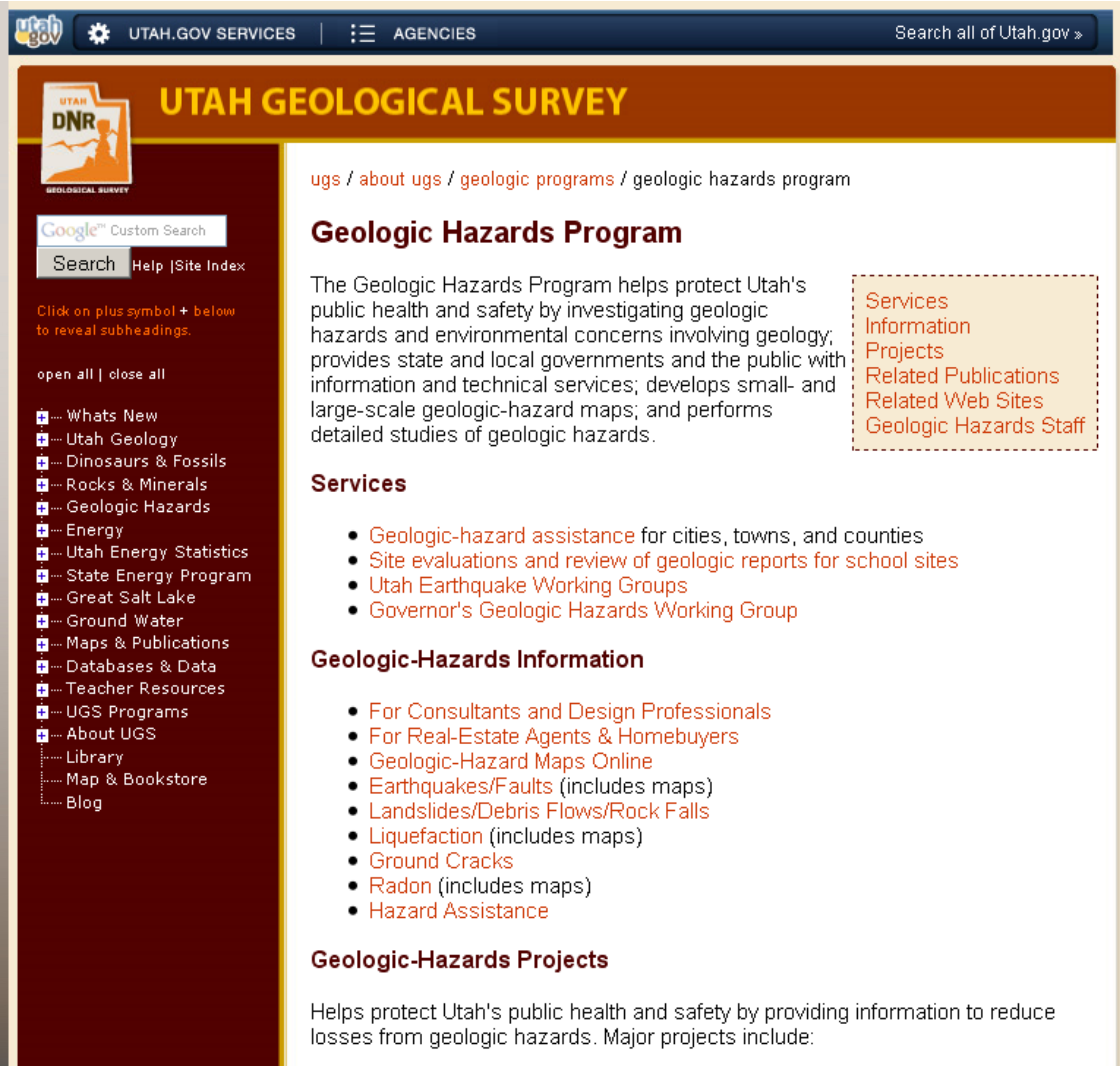
2011
CONTAINS GIS FILES

Geologic Hazards Program Webpage

http://geology.utah.gov/ghp



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Geologic Hazards Program

The Geologic Hazards Program helps protect Utah's public health and safety by investigating geologic hazards and environmental concerns involving geology; provides state and local governments and the public with information and technical services; develops small- and large-scale geologic-hazard maps; and performs detailed studies of geologic hazards.

Services
Information
Projects
Related Publications
Related Web Sites
Geologic Hazards Staff

Services

- Geologic-hazard assistance for cities, towns, and counties
- Site evaluations and review of geologic reports for school sites
- Utah Earthquake Working Groups
- Governor's Geologic Hazards Working Group

Geologic-Hazards Information

- For Consultants and Design Professionals
- For Real-Estate Agents & Homebuyers
- Geologic-Hazard Maps Online
- Earthquakes/Faults (includes maps)
- Landslides/Debris Flows/Rock Falls
- Liquefaction (includes maps)
- Ground Cracks
- Radon (includes maps)
- Hazard Assistance

Geologic-Hazards Projects

Helps protect Utah's public health and safety by providing information to reduce losses from geologic hazards. Major projects include:

Consultants Webpage

http://geology.utah.gov/ghp/consultants

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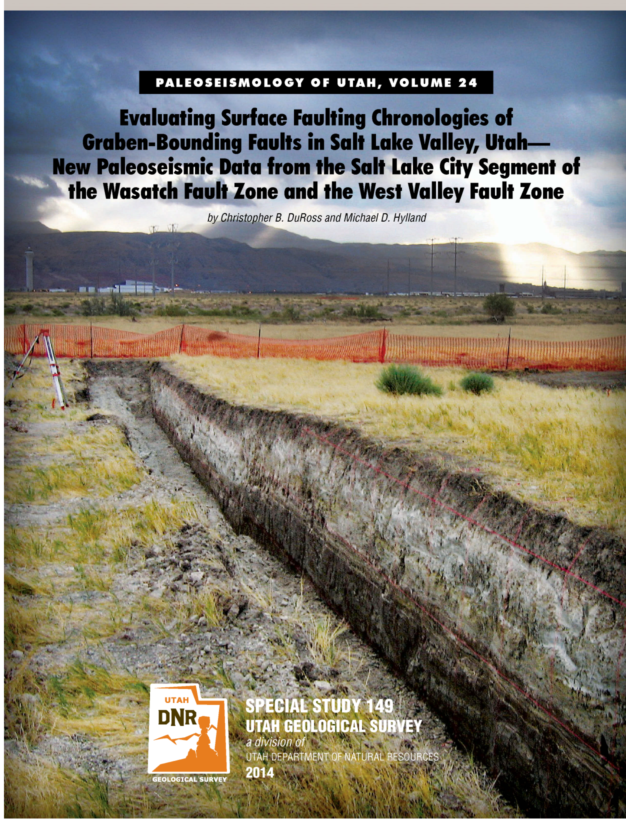
Geologic-Hazard Resources for Consultants and Design Professionals

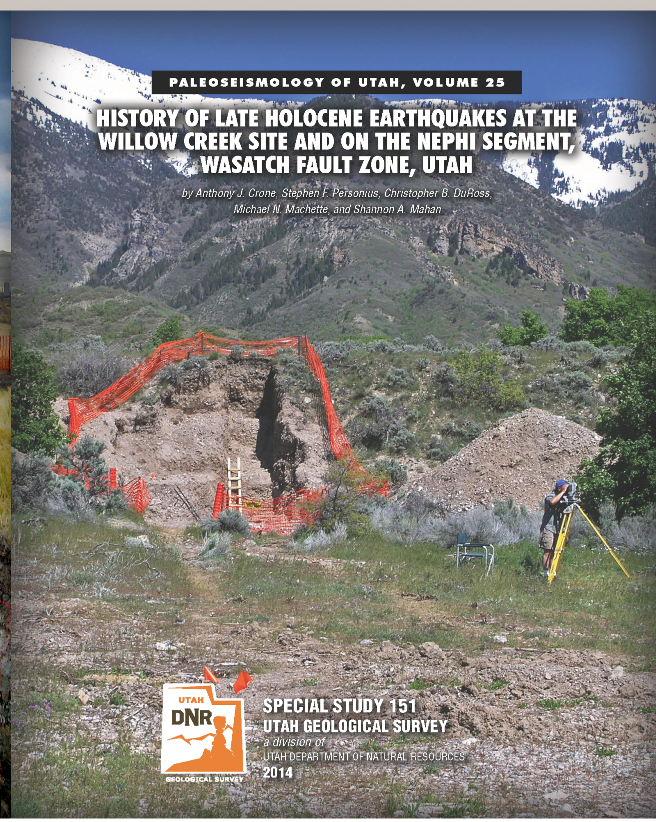
These resources are non-comprehensive and available to assist those involved with geotechnical, geologic-hazards, and other land-use investigations in Utah.

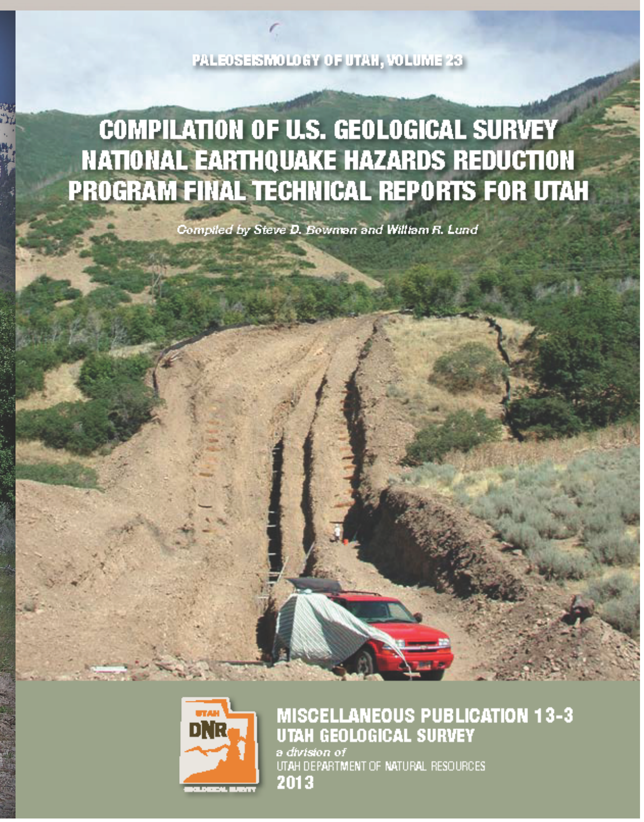
Recommended Report Guidelines
External Publications
Geologic Hazard Publications
Site-Specific Geologic-Hazards Studies
Geologic Hazard Maps
Geologic Maps
GIS Map Data
Ground-Water Monitoring Data
Ground-Water Publications
Paleoseismology of Utah Series
Historical Aerial Photography
Community Velocity Model (CVM) and Other Geophysical Data
Useful Websites
Natural Resources Library

UGS Paleoseismology of Utah Publication Series

- Total of 25 paleoseismology-related reports published about the Wasatch and other faults in Utah available online at http://geology.utah.gov/ghp/consultants/paleoseismic_series.htm.
- Includes paleoseismology trench investigations and compilations of prior reports and low-sun-angle aerial photography.

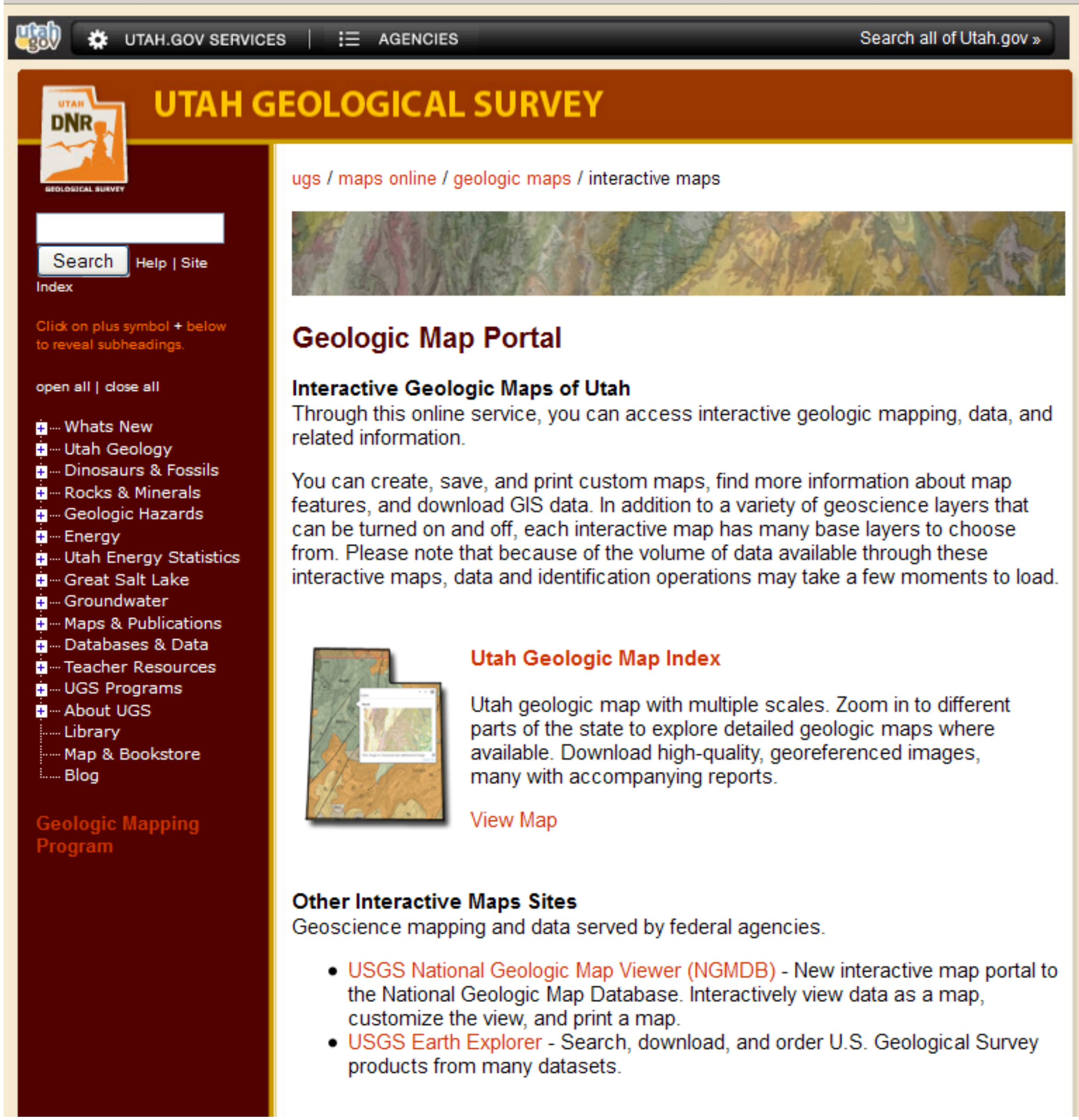






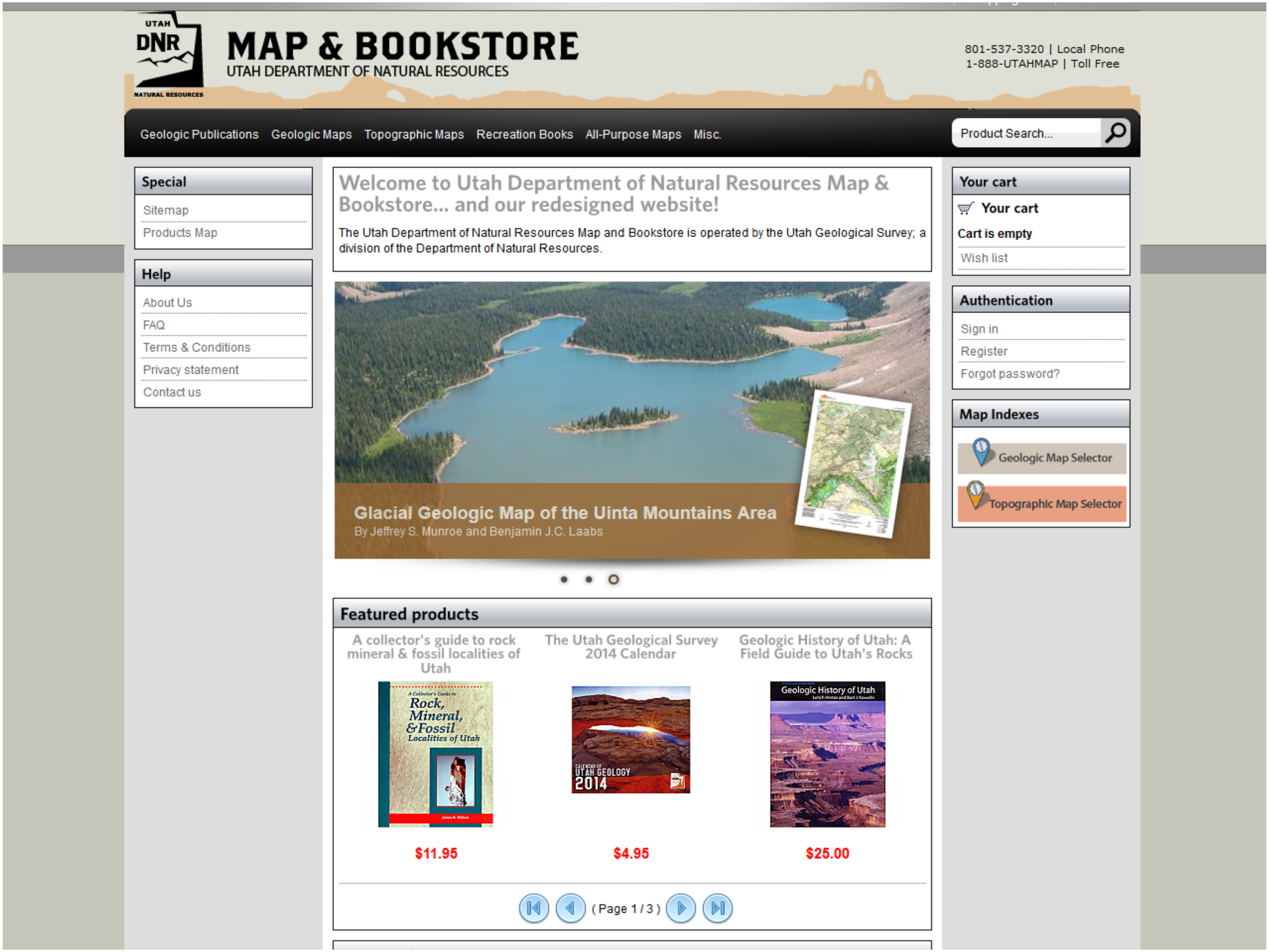
Geologic Maps

- UGS has a vast collection of geologic maps of Utah created by staff and others.
- Have scanned, touched up, and georeferenced 793 historical geologic maps.
- Will process another 225 maps in the coming year.
- Maps scanned at 400 dpi or greater (TIFF file).
- Map data available as:
  - Adobe PDF
  - Georeferenced JPEG (with world file) and GeoTIFF



Maps available at:

- UGS http://geology.utah.gov/maps/geomap/interactive/viewer/index.html
- AGRC http://gis.utah.gov/data/
- DNR Map and Bookstore http://www.mapstore.utah.gov/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The Utah Department of Natural Resources Map and Bookstore is operated by the Utah Geological Survey; a division of the Department of Natural Resources.
Glacial Geologic Map of the Uinta Mountains Area
By Jeffrey S. Munroe and Benjamin J.C. Laabs
Featured products
A collector's guide to rock mineral & fossil localities of Utah
A Collector's Guide to Rock, Mineral, & Fossil Localities of Utah
$11.95
The Utah Geological Survey 2014 Calendar
CALENDAR OF UTAH GEOLOGY 2014
$4.95
Geologic History of Utah: A Field Guide to Utah's Rocks
Geologic History of Utah
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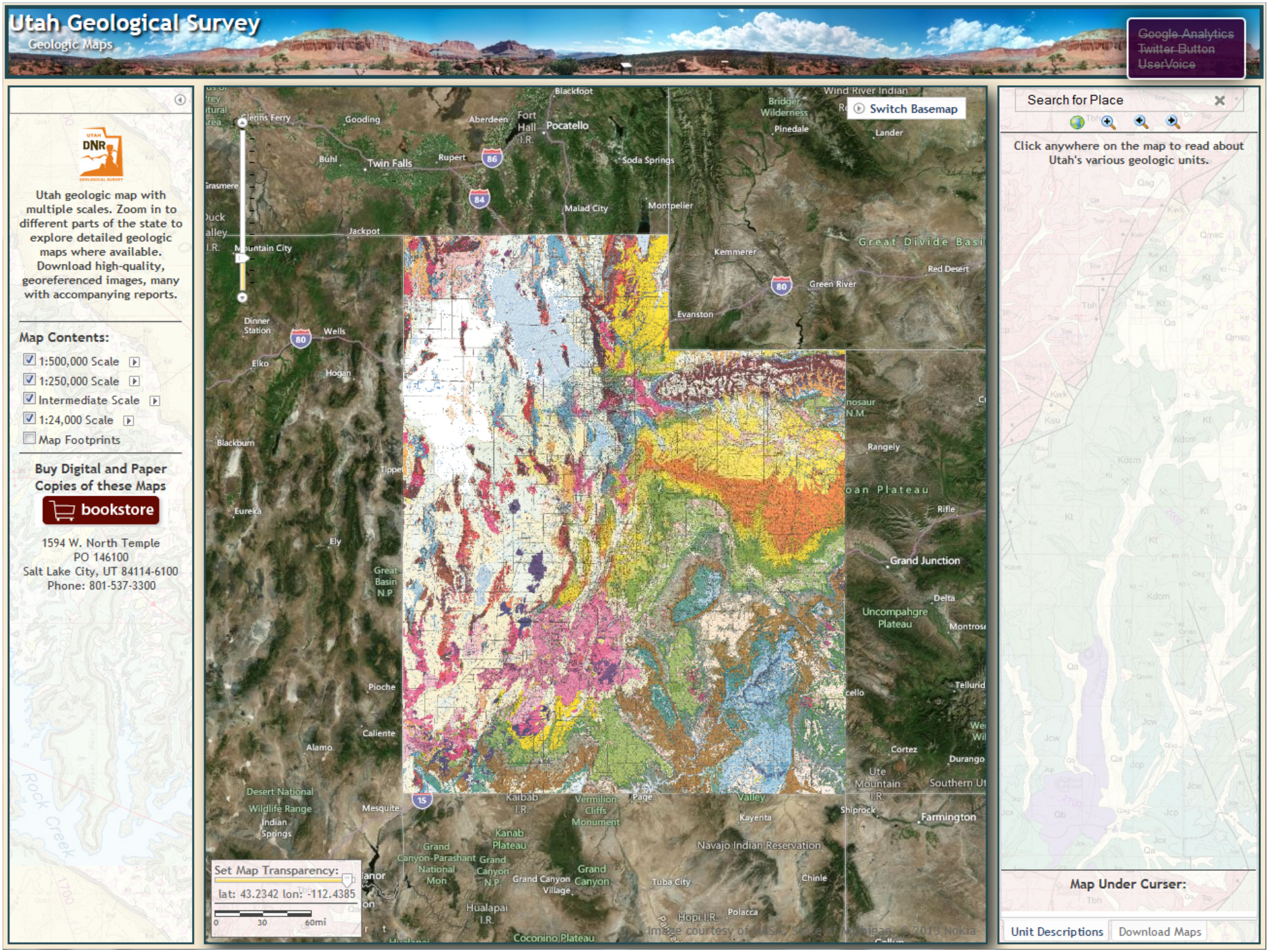
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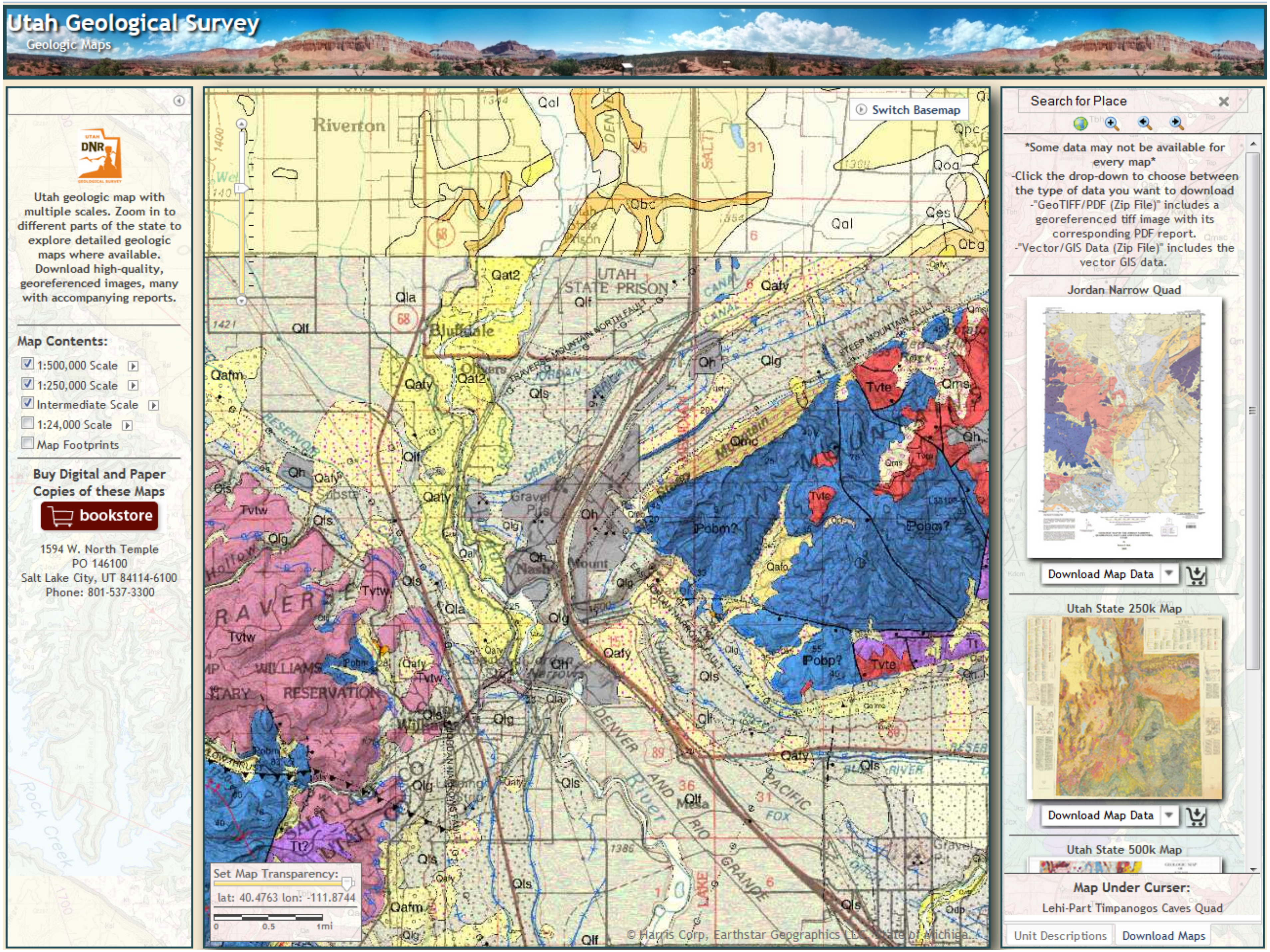
0 30 60mi
Search for Place
Click anywhere on the map to read about Utah's various geologic units.
Map Under Curser:
Unit Descriptions
Download Maps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Geologic Maps
Utah geologic map with multiple scales. Zoom in to different parts of the state to explore detailed geologic maps where available. Download high-quality, georeferenced images, many with accompanying reports.
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Set Map Transparency:
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-"Vector/GIS Data (Zip File)" includes the vector GIS data.
Jordan Narrow Quad
Download Map Data
Utah State 250k Map
Download Map Data
Utah State 500k Map
Map Under Curser:
Lehi-Part Timpanogos Caves Quad
Unit Descriptions
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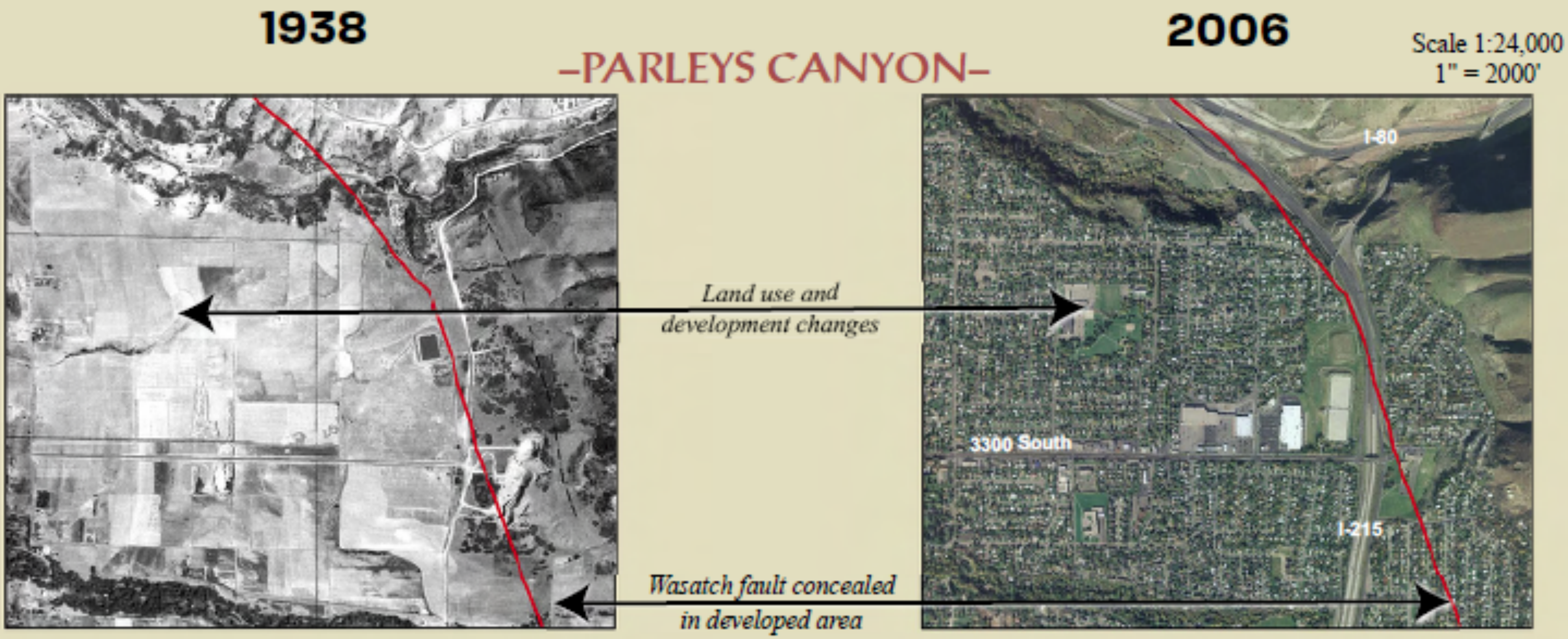
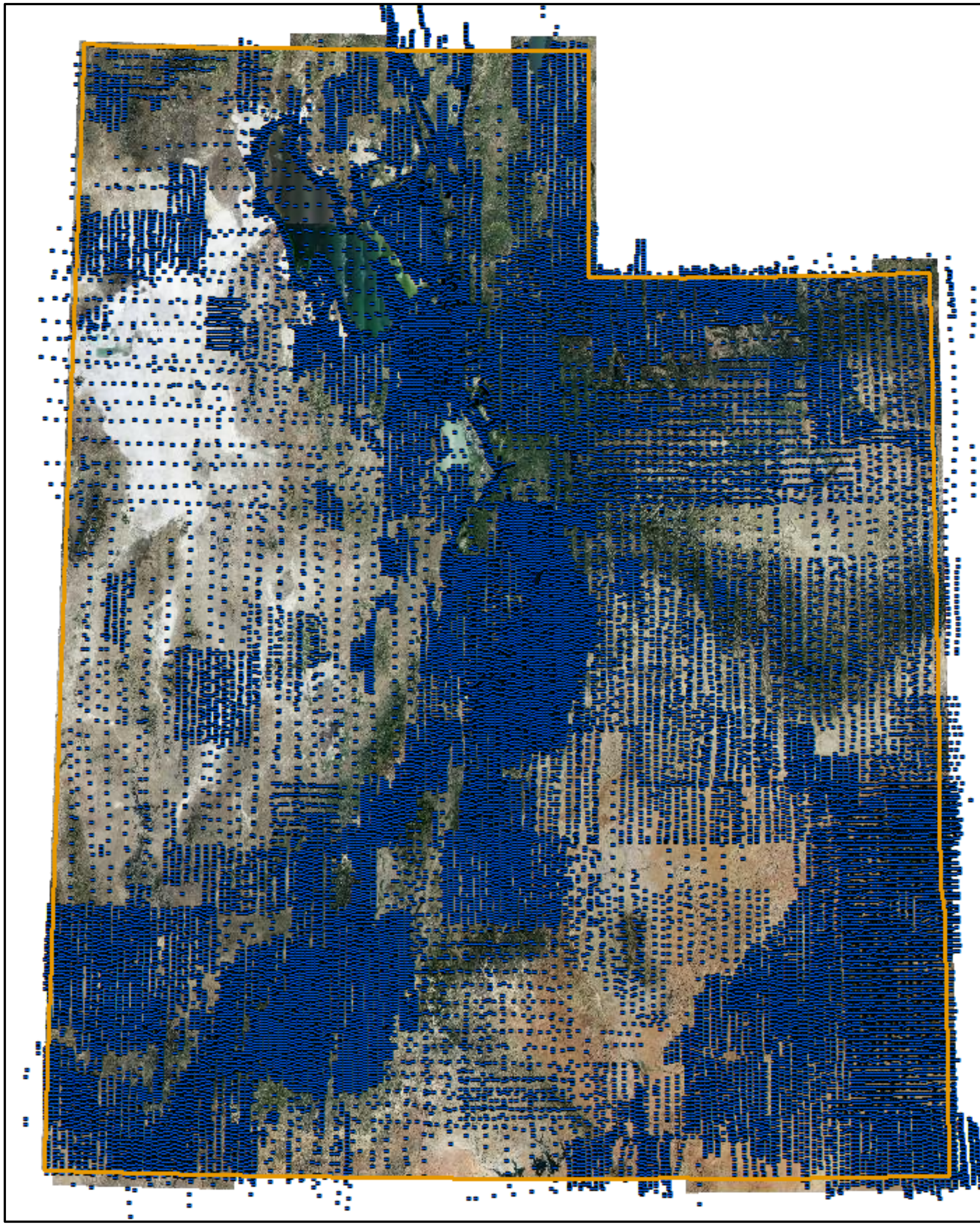
UGS Aerial Imagery Collection

- UGS collection of about 120,000 frames from 1935 to 2002.
  - 88,792 in database (as of January 1)
  - 275 individual aerial projects
- Digitally scanned
  - Paper prints scanned at 600 or 800 (starting 2010) dpi
  - Film scanned at 1200 dpi
  - TIFF (archive) format with lossless ZIP compression
- Available online at https://geodata.geology.utah.gov/imagery/.

AERIAL PHOTOGRAPHY COMPARISON



- Used in geologic, geotechnical, and environmental assessment and investigation projects; land-use planning; ASTM Phase I Environmental Site Assessments; projects documenting land-use, geomorphologic, geologic-hazard, and other changes that may have occurred in a particular area; and, as a historical archive.



88,792 frames currently entered into the UGS Aerial Imagery database

Notable Aerial Data Sets

1970 WF - Low-sun-angle data set along the Wasatch, West Valley, West Cache, and East Cache fault zones. Includes some of the best pre-development aerial photographs taken of these fault zones.

- Lower Bells Canyon Reservoir and the Salt Lake City segment of the Wasatch fault.

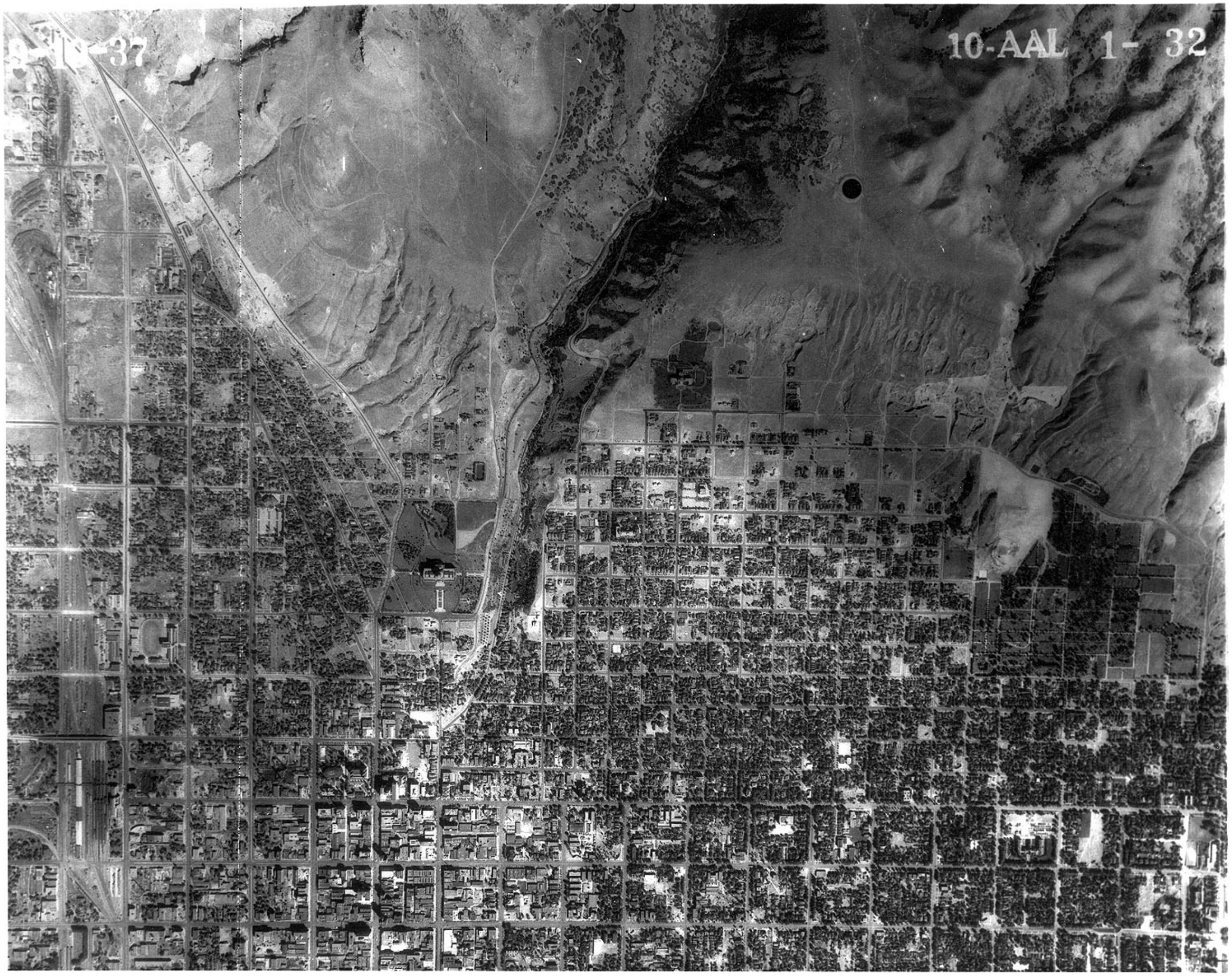
geology.utah.gov

1970s Woodward-Lundgren Low-Sun-Angle Aerial Photographs
Corner Canyon Area, Draper, Utah

Scan From Print (600 dpi)
UGS Open-File Report 548

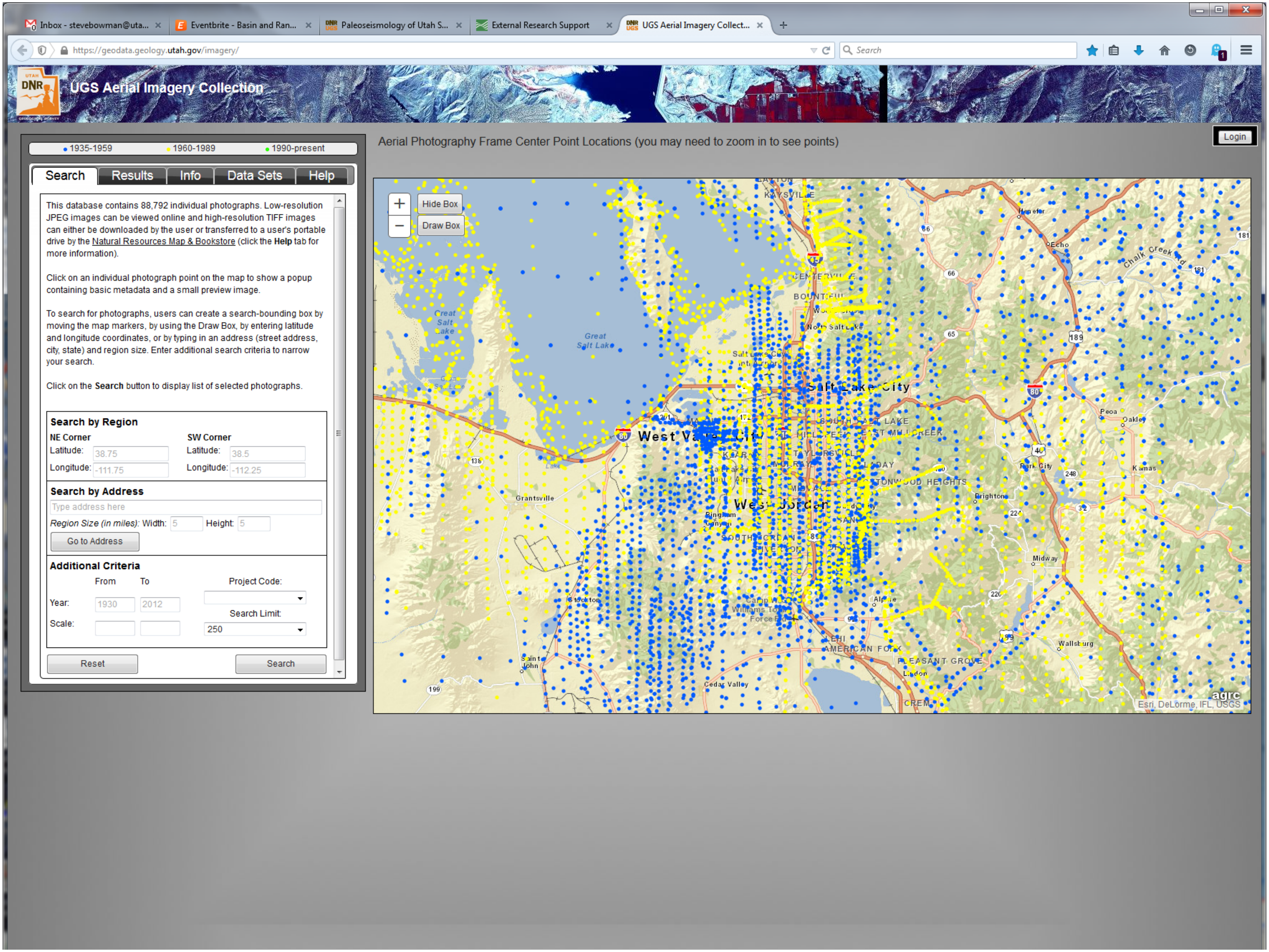
Scan From Original Film (1200 dpi)
Future UGS Publication

Notable Aerial Data Sets



1937 AAH, AAJ-AAK, and AAL - These 1:20,000-scale data sets are some of the earliest known aerial photographs along the Wasatch Front.

- Downtown SLC and Capitol.


Inbox - stevebowman@uta...
Eventbrite - Basin and Ran...
Paleoseismology of Utah S...
External Research Support
UGS Aerial Imagery Collect...
https://geodata.geology.utah.gov/imagery/
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Data Sets
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This database contains 88,792 individual photographs. Low-resolution JPEG images can be viewed online and high-resolution TIFF images can either be downloaded by the user or transferred to a user's portable drive by the Natural Resources Map & Bookstore (click the Help tab for more information).
Click on an individual photograph point on the map to show a popup containing basic metadata and a small preview image.
To search for photographs, users can create a search-bounding box by moving the map markers, by using the Draw Box, by entering latitude and longitude coordinates, or by typing in an address (street address, city, state) and region size. Enter additional search criteria to narrow your search.
Click on the Search button to display list of selected photographs.
Search by Region
NE Corner
Latitude: 38.75
Longitude: -111.75
SW Corner
Latitude: 38.5
Longitude: -112.25
Search by Address
Type address here
Region Size (in miles): Width: 5 Height: 5
Go to Address
Additional Criteria
From To
Project Code:
Year: 1930 2012
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Scale:
250
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Aerial Photography Frame Center Point Locations (you may need to zoom in to see points)
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Salt Lake City
West Valley City
West Jordan
Grantsville
Bountiful
Kaysville
Centerville
North Salt Lake
South Salt Lake
Millcreek
Holladay
Cottonwood Heights
Brighton
Park City
Kamas
Peoa
Oakley
Echo
Henefer
Chalk Creek Rd
Midway
Wallsburg
Alpine
Lehi
American Fork
Pleasant Grove
Lindon
Cedar Valley
Stockton
Saint John
Bingham Canyon
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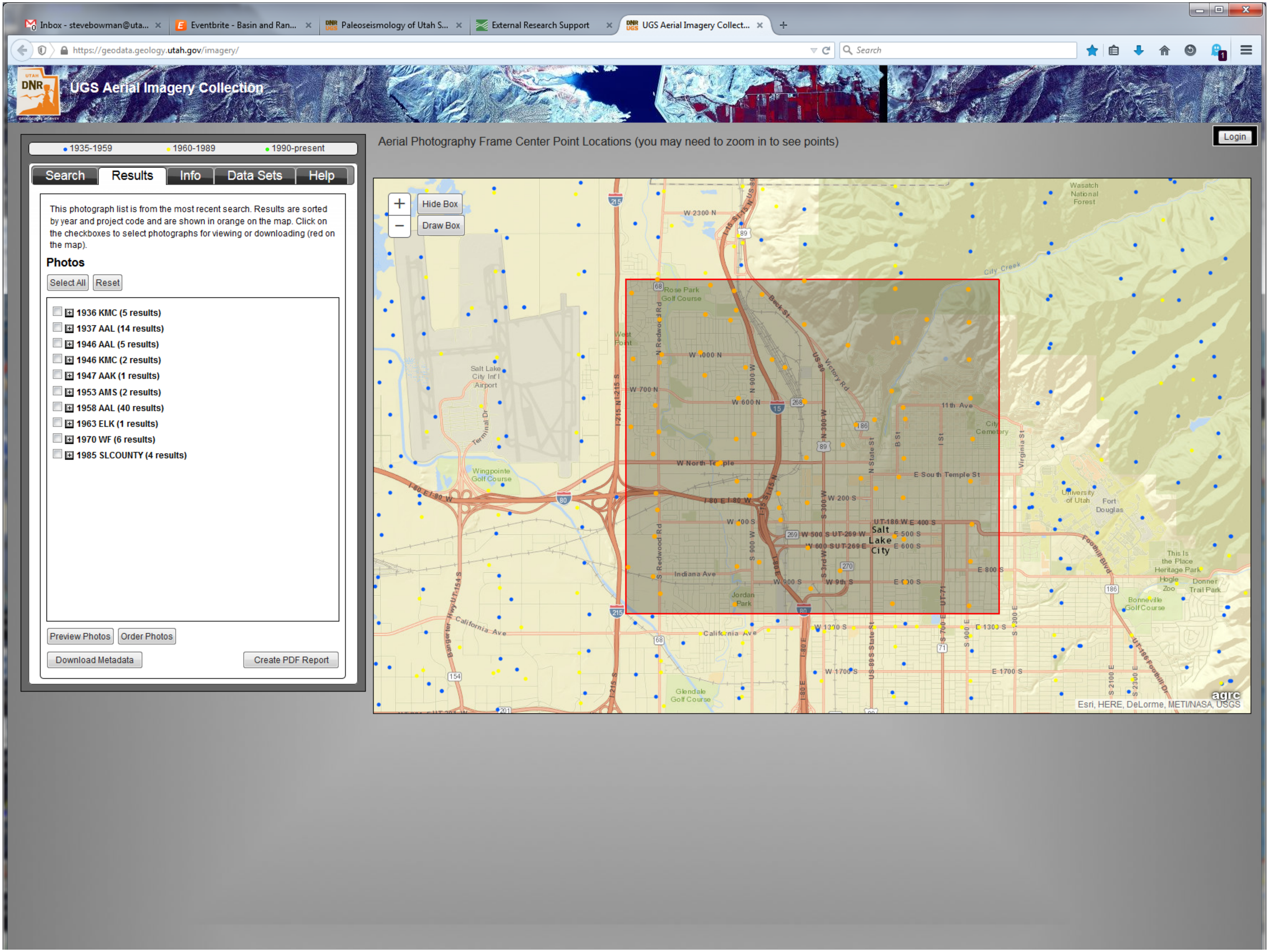
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External Research Support
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1990-present
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This photograph list is from the most recent search. Results are sorted by year and project code and are shown in orange on the map. Click on the checkboxes to select photographs for viewing or downloading (red on the map).
Photos
Select All
Reset
1936 KMC (5 results)
1937 AAL (14 results)
1946 AAL (5 results)
1946 KMC (2 results)
1947 AAK (1 results)
1953 AMS (2 results)
1958 AAL (40 results)
1963 ELK (1 results)
1970 WF (6 results)
1985 SLCOUNTY (4 results)
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Salt Lake City Int'l Airport
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Wingpointe Golf Course
Jordan Park
Glendale Golf Course
University of Utah
Fort Douglas
Wasatch National Forest
This Is the Place Heritage Park
Hogle Zoo
Donner Trail Park
Bonneville Golf Course
City Cemetery
W North Temple
E South Temple St
California Ave
Indiana Ave
Esri, HERE, DeLorme, METI/NASA, USGS

1937 AAL (23 frames) - Salt Lake County, Utah

Agency: USDA, Agricultural Stabilization and Conservation Service

Filename (tif or jpg)	Flight Line #	Roll #	Frame #	Other ID	Scale	Photo Date	Scan Resolution (dpi)	Latitude	Longitude
AAL_1-57		1	57		20000	Sep 19, 1937	600	40.69440	-111.91610
AAL_1-58		1	58		20000	Sep 19, 1937	600	40.68070	-111.91700
AAL_1-59		1	59		20000	Sep 19, 1937	600	40.66740	-111.91540
AAL_1-60		1	60		20000	Sep 19, 1937	600	40.65490	-111.91620
AAL_1-61		1	61		20000	Sep 19, 1937	600	40.64260	-111.91540
AAL_1-101		1	101		20000	Sep 19, 1937	600	40.63580	-111.94650
AAL_1-102		1	102		20000	Sep 19, 1937	600	40.64700	-111.94720
AAL_1-103		1	103		20000	Sep 19, 1937	600	40.65900	-111.94570
AAL_1-104		1	104		20000	Sep 19, 1937	600	40.67190	-111.94400
AAL_1-105		1	105		20000	Sep 19, 1937	600	40.68450	-111.94220
AAL_1-106		1	106		20000	Sep 19, 1937	600	40.69700	-111.94240
AAL_2-25		2	25		20000	Sep 19, 1937	600	40.70760	-111.97180
AAL_2-26		2	26		20000	Sep 19, 1937	600	40.69570	-111.97270
AAL_2-27		2	27		20000	Sep 19, 1937	600	40.68080	-111.97150
AAL_2-28		2	28		20000	Sep 19, 1937	600	40.66920	-111.97410
AAL_2-29		2	29		20000	Sep 19, 1937	600	40.65810	-111.97270
AAL_2-30		2	30		20000	Sep 19, 1937	600	40.64660	-111.97240
AAL_2-31		2	31		20000	Sep 19, 1937	600	40.63550	-111.97270
AAL_2-65		2	65		20000	Sep 19, 1937	600	40.64790	-112.00410
AAL_2-66		2	66		20000	Sep 19, 1937	600	40.66300	-112.00320
AAL_2-67		2	67		20000	Sep 19, 1937	600	40.67400	-112.00320
AAL_2-68		2	68		20000	Sep 19, 1937	600	40.68490	-112.00330
AAL_2-69		2	69		20000	Sep 19, 1937	600	40.69640	-112.00220

1953 AMS (3 frames) - Army Map Service

Agency: Army Map Service

Filename (tif or jpg)	Flight Line #	Roll #	Frame #	Other ID	Scale	Photo Date	Scan Resolution (dpi)	Latitude	Longitude
AMS_121-15-2744		15	2744	121	62400	Aug 06, 1953	800	40.63635	-111.91705
AMS_121-15-2745		15	2745	121	62400	Aug 06, 1953	800	40.65156	-111.98874
AMS_121-19-3407		19	3407	121	64000	Aug 12, 1953	800	40.64100	-111.96537

1958 AAL (51 frames) - Salt Lake County, Utah

Agency: USDA, Commodity Stabilization Service

Filename (tif or jpg)	Flight Line #	Roll #	Frame #	Other ID	Scale	Photo Date	Scan Resolution (dpi)	Latitude	Longitude
AAL_6V-38		6V	38		10000	May 27, 1958	600	40.70160	-111.99200
AAL_6V-39		6V	39		10000	May 27, 1958	600	40.69550	-111.99520
AAL_6V-40		6V	40		10000	May 27, 1958	600	40.68600	-111.99620
AAL_6V-41		6V	41		10000	May 27, 1958	600	40.67880	-111.99620
AAL_6V-42		6V	42		10000	May 27, 1958	600	40.67190	-111.99700
AAL_6V-43		6V	43		10000	May 27, 1958	600	40.66460	-111.99750
AAL_6V-44		6V	44		10000	May 27, 1958	600	40.65710	-111.99690
AAL_6V-45		6V	45		10000	May 27, 1958	600	40.65000	-111.99690
AAL_6V-46		6V	46		10000	May 27, 1958	600	40.64400	-111.99750
AAL_6V-47		6V	47		10000	May 27, 1958	600	40.63630	-111.99680
AAL_6V-90		6V	90		10000	May 27, 1958	600	40.63800	-111.97560
AAL_6V-91		6V	91		10000	May 27, 1958	600	40.64550	-111.97630
AAL_6V-92		6V	92		10000	May 27, 1958	600	40.65250	-111.97760
AAL_6V-93		6V	93		10000	May 27, 1958	600	40.66070	-111.97770
AAL_6V-94		6V	94		10000	May 27, 1958	600	40.66780	-111.97730
AAL_6V-95		6V	95		10000	May 27, 1958	600	40.67430	-111.97680
AAL_6V-96		6V	96		10000	May 27, 1958	600	40.68170	-111.97680
AAL_6V-97		6V	97		10000	May 27, 1958	600	40.68860	-111.97700
AAL_6V-98		6V	98		10000	May 27, 1958	600	40.69630	-111.97710
AAL_6V-99		6V	99		10000	May 27, 1958	600	40.70350	-111.97810
AAL_11V-59		11V	59		10000	May 27, 1958	600	40.70060	-111.95690
AAL_11V-60		11V	60		10000	May 27, 1958	600	40.69340	-111.95950
AAL_11V-61		11V	61		10000	May 27, 1958	600	40.68650	-111.95730
AAL_11V-62		11V	62		10000	May 27, 1958	600	40.67950	-111.95720
AAL_11V-63		11V	63		10000	May 27, 1958	600	40.67260	-111.95730
AAL_11V-64		11V	64		10000	May 27, 1958	600	40.66490	-111.95820
AAL_11V-65		11V	65		10000	May 27, 1958	600	40.65790	-111.95780

Page 1

PDF report of search results with basic metadata

GeoData Archive System

- Contains a collection of geologic hazard and geotechnical reports, data, and photographs on Utah (now 8790 items).
  - Consultant Reports
    - Geotechnical reports
    - Geologic-hazard reports
    - Fault evaluation reports
  - UGS Technical Reports
  - Unpublished Geologic-Hazard Information
    - Field Investigations
    - Documents
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Utah Geological Survey GeoData Archive System

The UGS GeoData Archive System, part of our Geologic Data Preservation Project, contains Utah geologic-related scanned documents, photographs (except aerial), and other digital materials (resources) from our files and those gathered from other agencies or organizations in one easy-to-use web-based system. Resources available to general users are all in the public domain and may contain reports submitted to state and local governments as part of permit reviews (and as a result are in the public domain). Metadata describing each resource is searchable, along with spatial searching for resources that are local or site-specific in nature (Geographic Search link in Simple Search pane). Resources representing counties, regional areas, or a larger area are not spatially searchable at this time and must be searched using text-based metadata (Simple or Advanced Search). Users are also encouraged to search the DNR Library for books and similar materials.

Authorized users may log in for more functionality and resource viewing. Not all resources may be available to all users due to copyright and/or distribution restrictions.

Upon searching for specific resources, they may be viewed directly, or downloaded to your local device. Documents are predominately in text-searchable PDF format. Adobe Reader 9 or greater, is needed to view the PDF files. Firefox 9 or greater is recommended for best web browser performance.

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Select Pan mode to zoom in/out and to move map in any direction. Select Bounding Box mode to create a bounding box by dragging cursor around search area. Once a bounding box is created, resources with geographic locations within the bounding box will be returned on a new page. Resources representing counties, regional areas, or a larger area are not spatially searchable at this time and must be searched using text-based metadata (Simple or Advanced Search).

Drag Mode: Bounding Box Pan

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Search using descriptions, keywords and resource numbers

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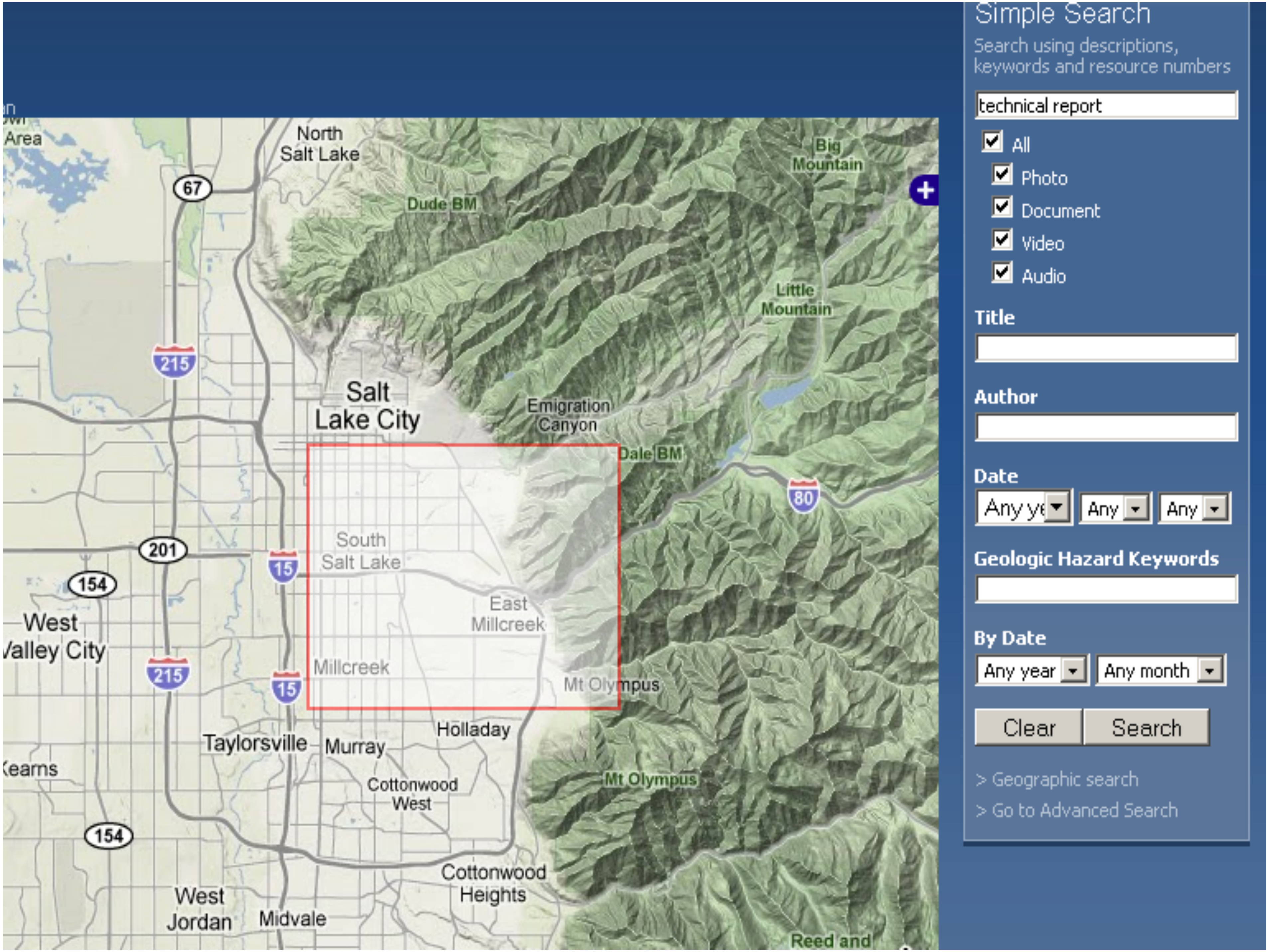
Simple Search
Search using descriptions, keywords and resource numbers
technical report
All
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Geologic Hazard Keywords
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Any year
Any month
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> Go to Advanced Search
North Salt Lake
Dude BM
Big Mountain
Little Mountain
Salt Lake City
Emigration Canyon
Dale BM
South Salt Lake
East Millcreek
Millcreek
Mt Olympus
West Valley City
Taylorsville
Murray
Holladay
Cottonwood West
Cottonwood Heights
West Jordan
Midvale
Reed and
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201
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Seismotectonic Study for Joes Valley, Scofield, and Huntington North Dams, Emery County and Scofield Projects, Utah
PDF
Foley, L.; Martin, R. Jr. and Sullivan, J.
U.S. Bureau of Reclamation
Seismotectonic Report No. 86-7
Public Domain
Report
slope stability, ground shaking, earthquake, debris flow, subsidence, liquefaction, surface fault rupture, seiche, paleoseismology, landslide
Surface Fault Rupture Hazard S
Proceedings Of Conference X...
Seismotectonic Report for Flami
Piety, Lucille A., and Ute R. Vet
National Earthquake Hazards...
National Earthquake Hazards...
Geologic Hazard Study; Propose
Edgar, R.
National Earthquake Hazards...
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Surface Fault Rupture Hazard S
Payton, C
Regional & Reservoir basin Geol
Everitt, Ben, and Dan Aubrey
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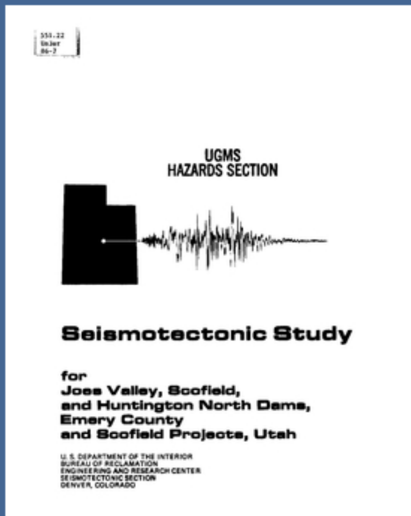
Seismotectonic Study for Joes Valley, Scofield, and Huntington North Dams, Emery County and Scofield Projects, Utah


UGMS HAZARDS SECTION

Seismotectonic Study

for Joes Valley, Scofield, and Huntington North Dams, Emery County and Scofield Projects, Utah

U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
ENGINEERING AND RESEARCH CENTER
SEISMOTECTONIC SECTION
DENVER, COLORADO

Resource Tools

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Resource Type
Document

Title
Seismotectonic Study for Joes Valley, Scofield, and Huntington North Dams, Emery County and Scofield Projects, Utah

Author
Foley, L.; Martin, R. Jr. and Sullivan, J.

Publisher
U.S. Bureau of Reclamation

Publication Identification/Reference
Seismotectonic Report No. 86-7

Availability
Public Domain

State
Utah

County
Emery, Utah, Sanpete, Emery

Source
UGS Files

Keywords
slope stability, ground shaking, earthquake, debris flow, subsidence, liquefaction, surface fault rupture, seiche, paleoseismology, landslide

Document Date
1986

Document Type
Report

Media Type
Bound Report

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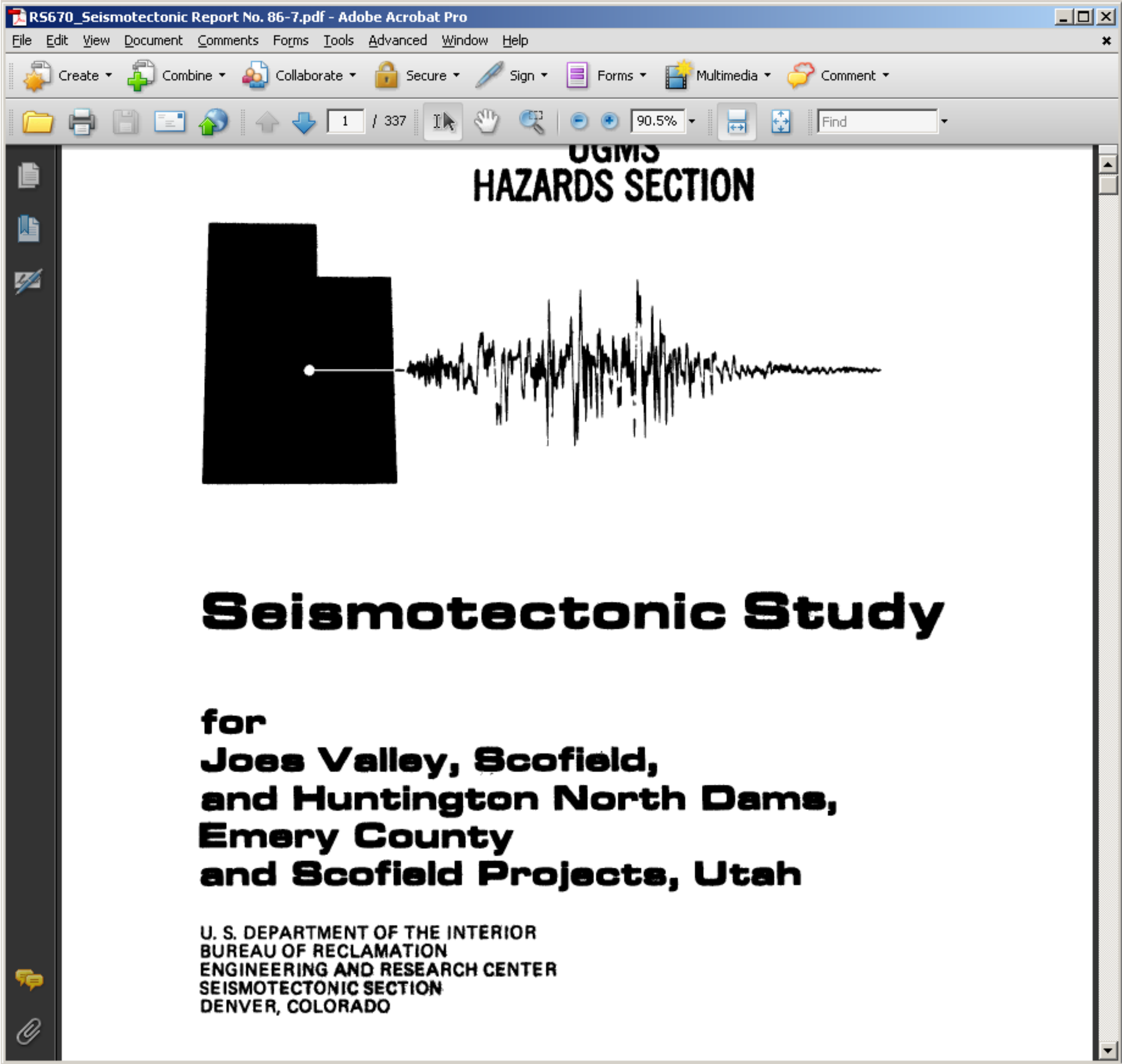

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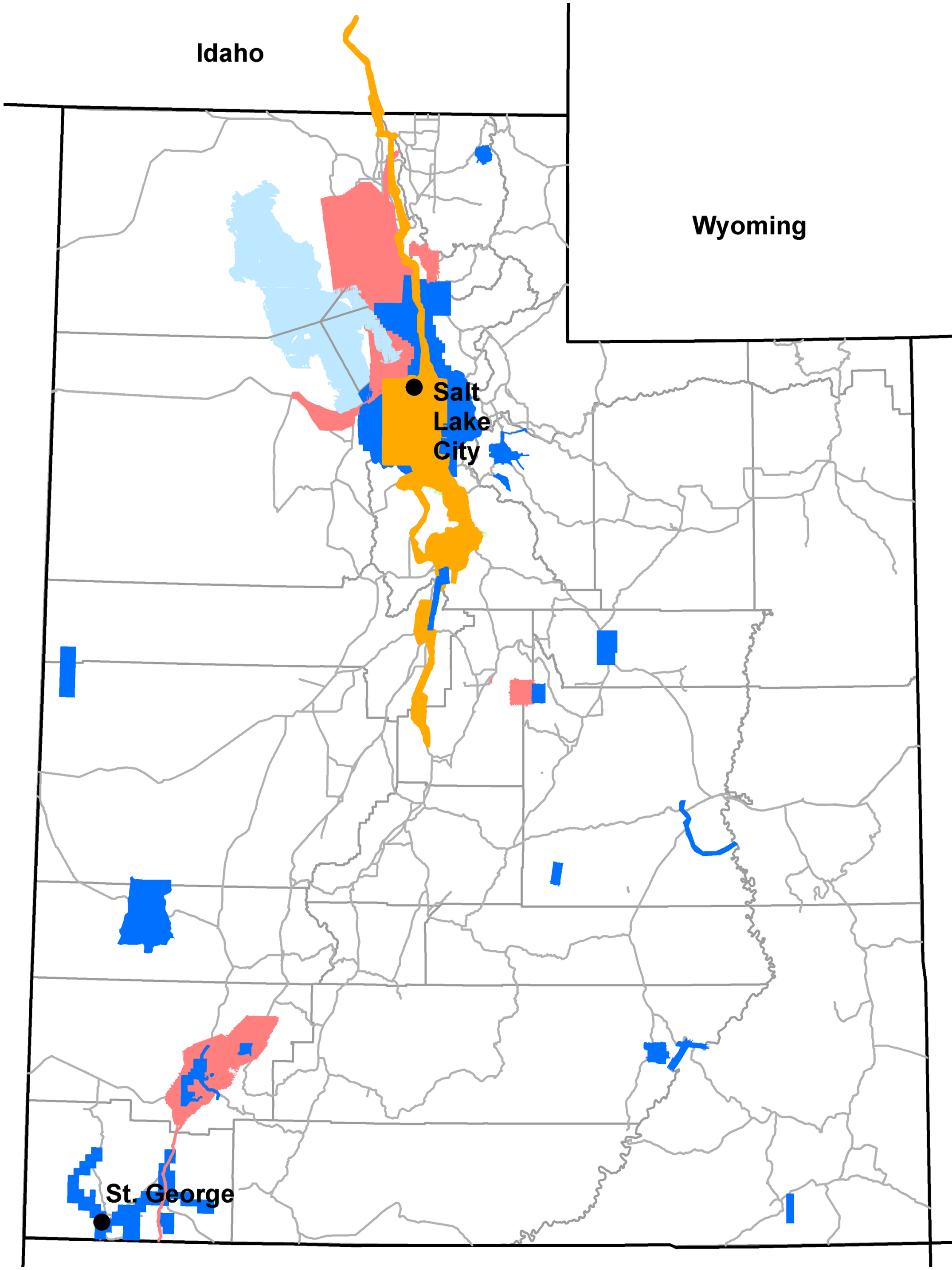


Available Utah LiDAR Data

- 0.5 meter (2013-2014, orange area)

Includes Wasatch fault zone, additional data acquisition planned for Cache Valley, Bear Lake, and Great Salt Lake in 2015.

- 1 meter (2011, red area)

Includes Hurricane fault zone

- 2 meter (2006 + other, blue areas)

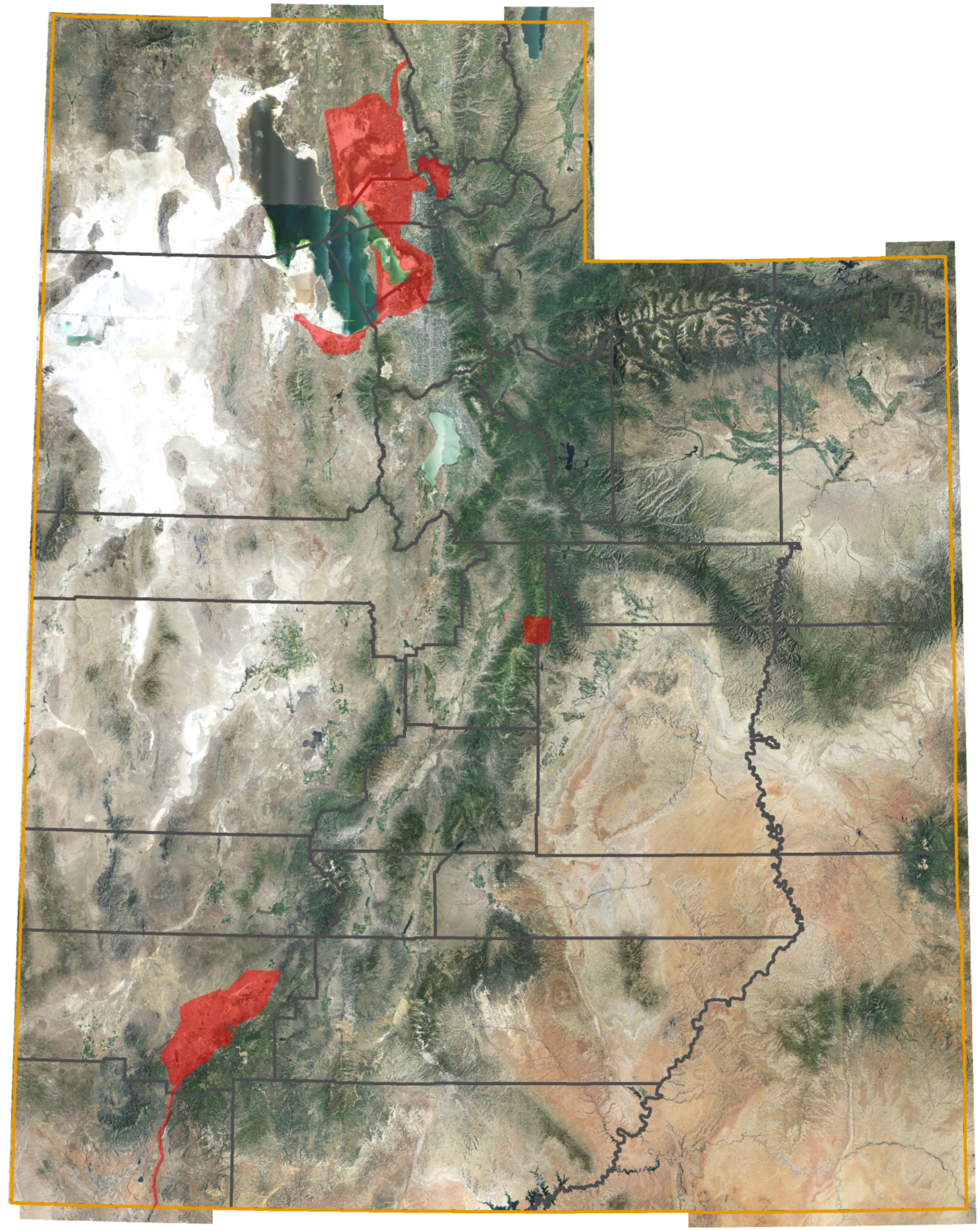
geology.utah.gov

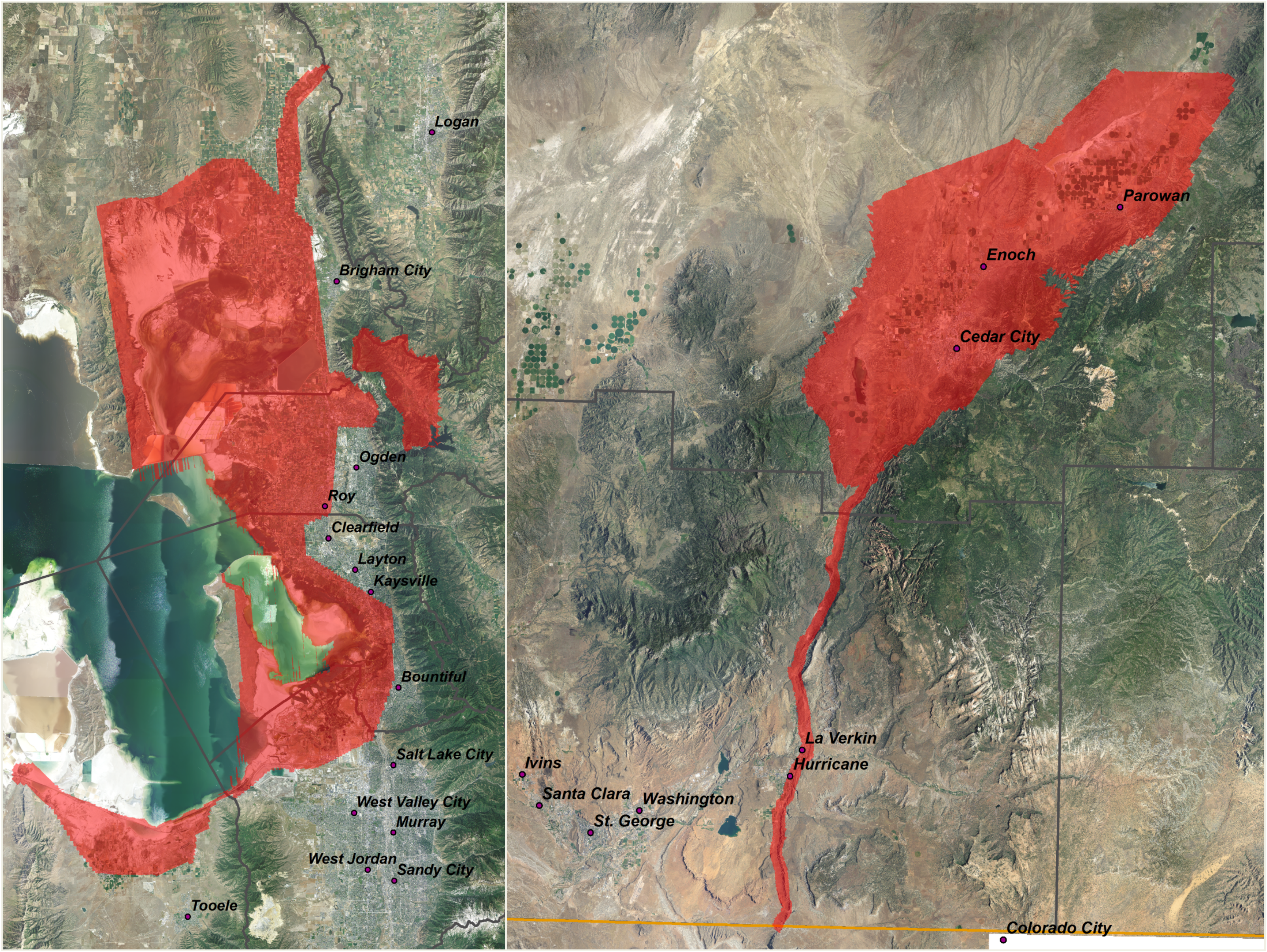
2011 UGS 1 m LiDAR Acquisition

- Hurricane Fault
- East Great Salt Lake
- West half of Ogden Valley
- Southern Great Salt Lake
- Cedar & Parowan Valleys
- North Odgen (FEMA/UDEM)
- Wasatch Plateau (Lowry Water area)

1867 square miles (4913 km^2)

Raw, DEM, and DSM data available.

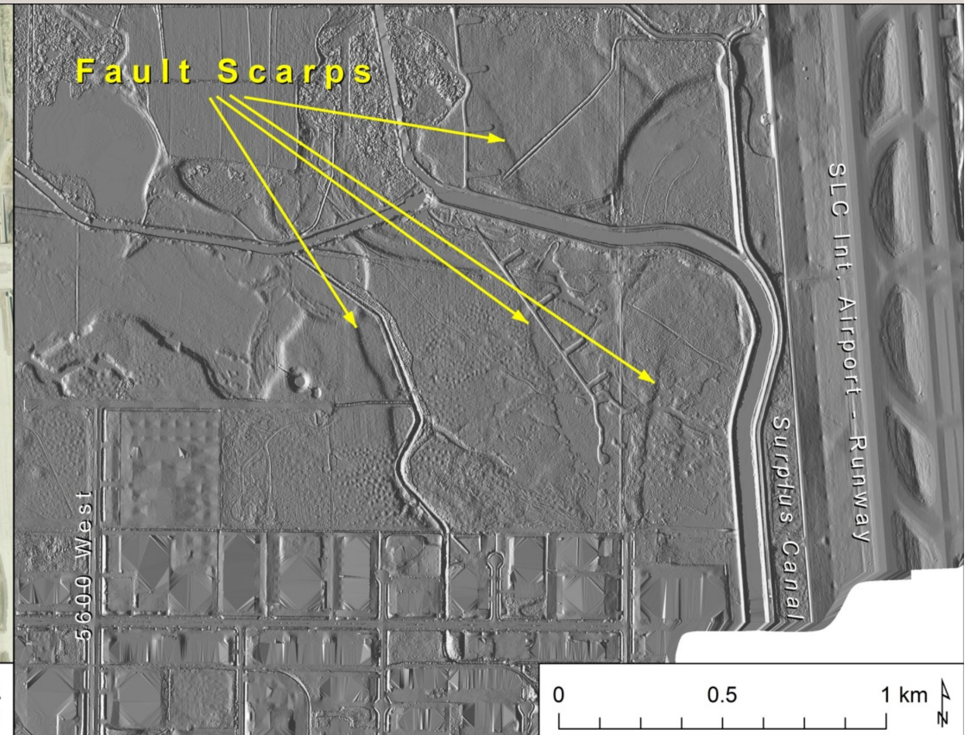



Logan
Brigham City
Ogden
Roy
Clearfield
Layton
Kaysville
Bountiful
Salt Lake City
West Valley City
Murray
West Jordan
Sandy City
Tooele
Parowan
Enoch
Cedar City
La Verkin
Hurricane
Ivins
Santa Clara
Washington
St. George
Colorado City

More Faults Than Previously Mapped on the Grainger Fault, West Valley Fault Zone

2006 NAIP

2011 1-Meter LiDAR



Mapping for the Baileys Lake and Salt Lake City North 7-1/2 min. quadrangles.

2013 UGS High-Resolution 0.5 m LiDAR Acquisition

- Salt Lake Valley
- Utah Valley
- Wasatch Fault Zone

1352 square miles (3502 km^2)

Raw, DEM, and DSM data will be available to all late spring 2014.

In partnership with the Utah Division of Emergency Management, Salt Lake County, U.S. Geological Survey, Federal Emergency Management Agency, and the Utah Automated Geographic Reference Center.

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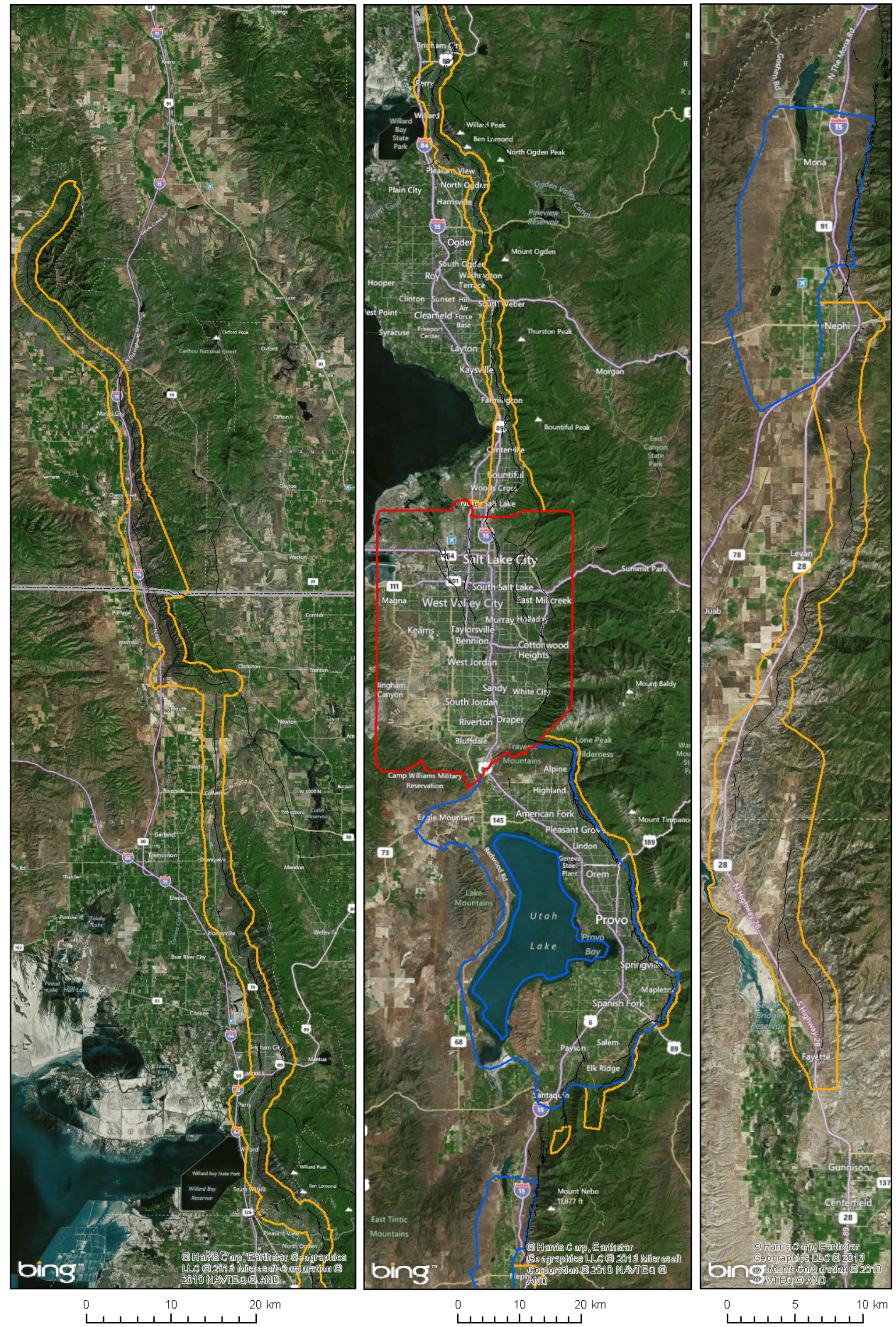


LiDAR Data Availability

- UGS
  - LiDAR Data Web Page (includes extent/tile indexes and metadata)
    - http://geology.utah.gov/databases/lidar/lidar.htm
- AGRC
  - DEM and Metadata
    - 2011 - http://gis.utah.gov/data/elevation-terrain-data/2011-lidar
    - 2013-2014 - http://gis.utah.gov/data/elevation-terrain-data/2013-2014-lidar
- OpenTopography
  - All Data
    - Utah Geological Survey LiDAR Data Page http://opentopography.org/

All data is in the public domain and can be freely distributed with credit to the UGS and its partners.

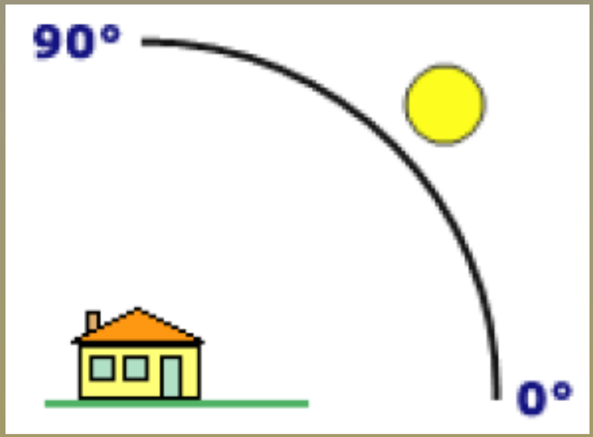
Hill Shade

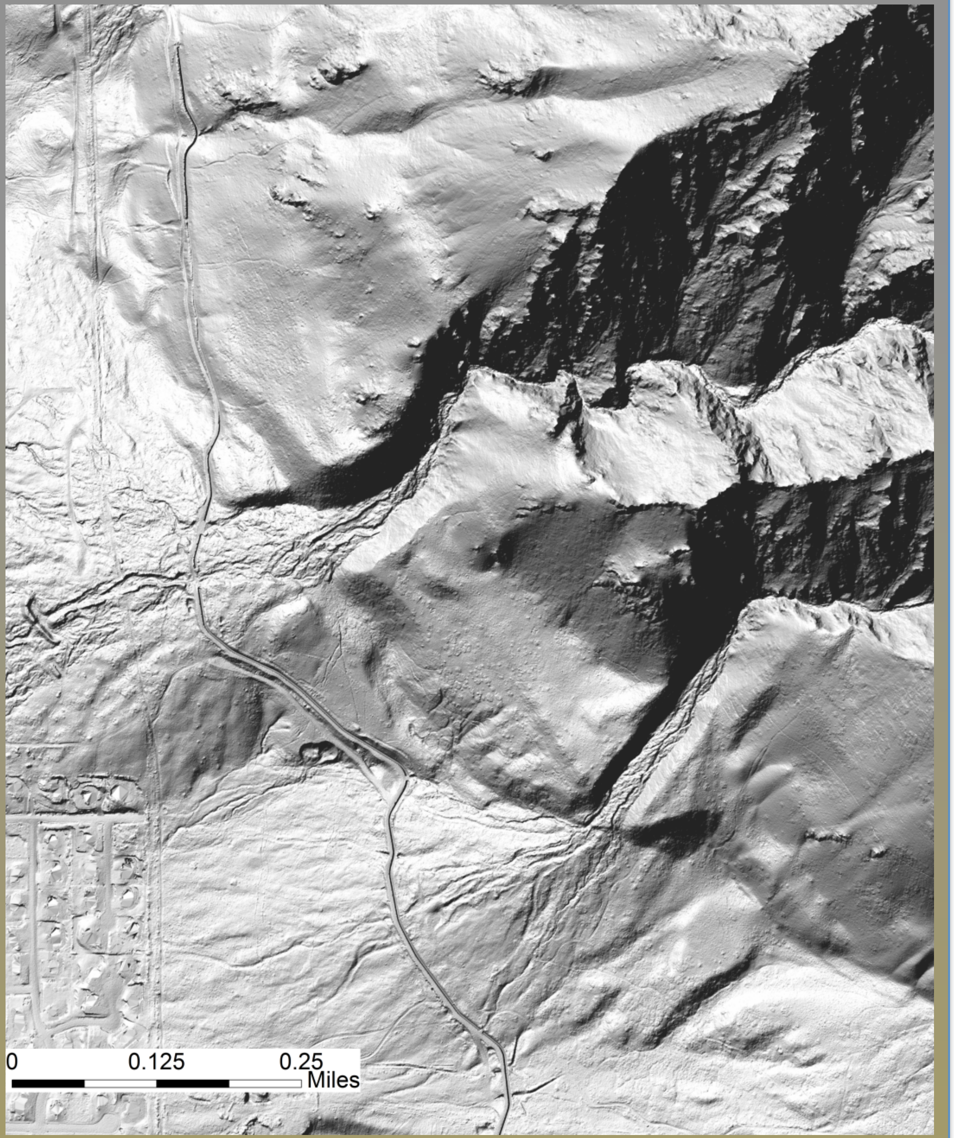
Adam McKean's Urban Area Geologic Mapping

0.5 m LiDAR, 2013
45-315 hill shade

Azimuth = 315°

Altitude = 45°





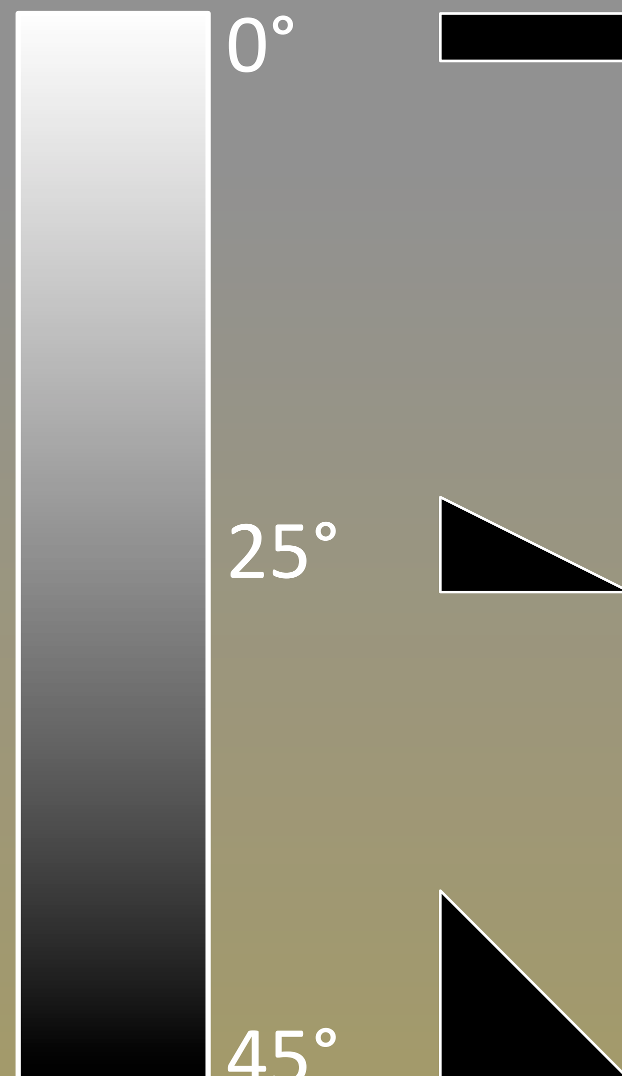
Figures from http://help.arcgis.com

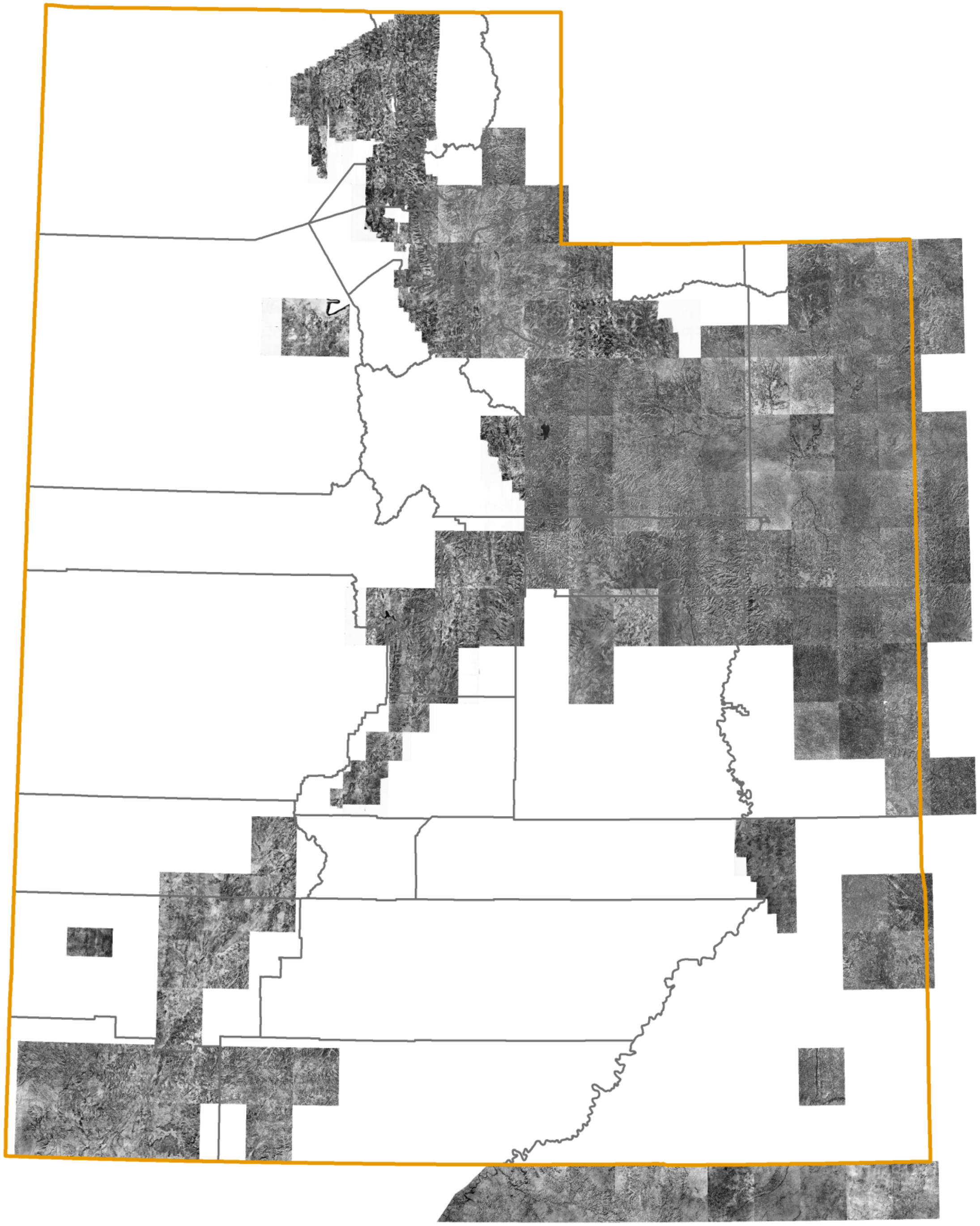
Slope shade

Adam McKean's Urban Area Geologic Mapping

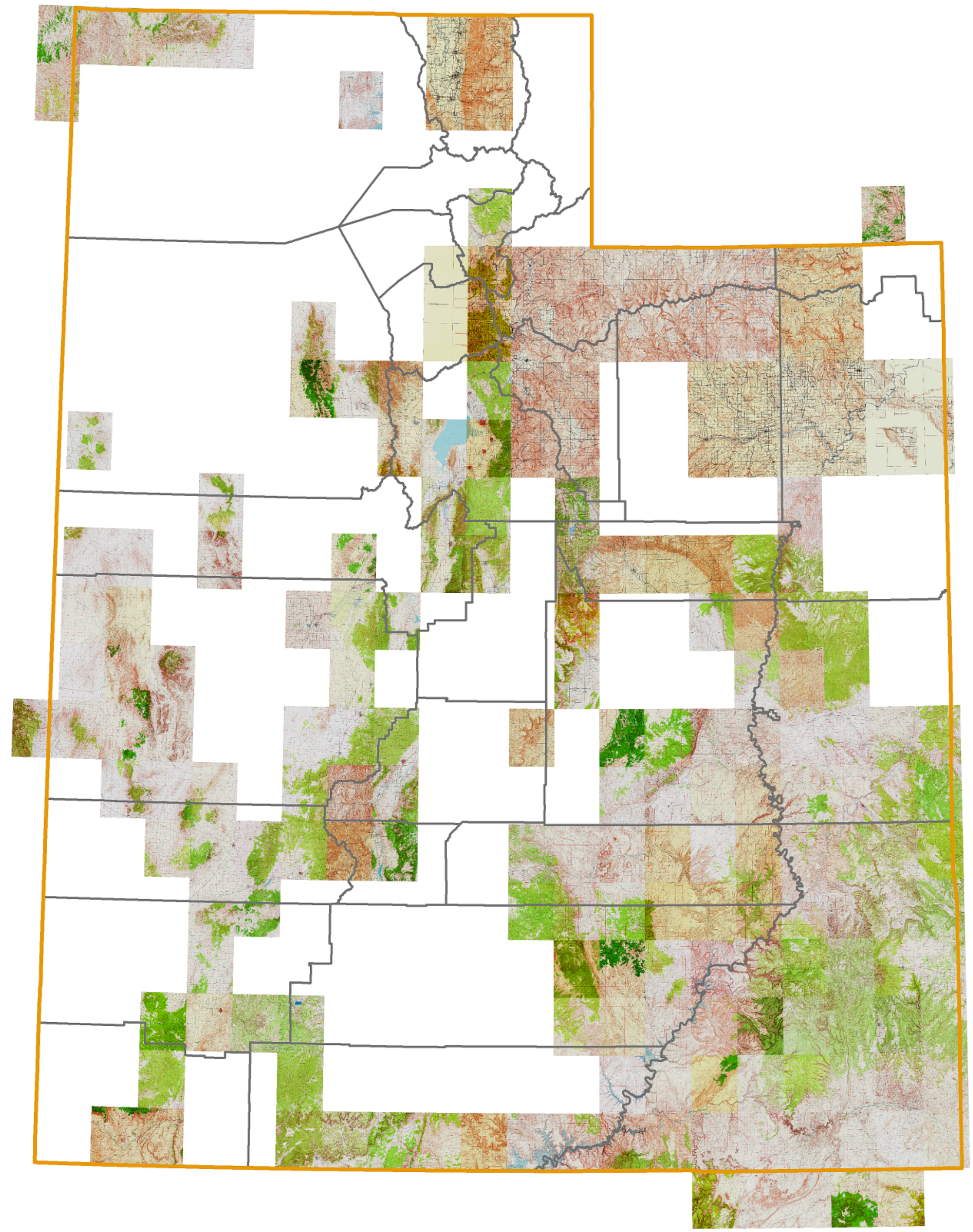
0.5 m LiDAR, 2013
0-45 slope shade

Slope Angle





Coverage of historical (1936-1952) Soil Conservation Service (SCS) semi-controlled orthophotomaps scanned and georeferenced by the UGS and available from AGRC (http://gis.utah.gov/data/utah-sgid-image-server/).



Coverage of historical (1900-1966) USGS 15- and 30-minute topographic maps available from AGRC (http://gis.utah.gov/data/utah-sgid-image-server/).

Available Utah Geologic Hazard Information

- UGS Geologic Hazards Program
  http://geology.utah.gov/ghp/index.htm
  - Consultants/Design Professionals: http://geology.utah.gov/ghp/consultants/
  - Geologic Hazard Maps: http://geology.utah.gov/maps/geohazmap/index.htm
  - Geologic Hazard Reports: http://geology.utah.gov/ghp/consultants/pubs/index.htm
  - Report Guidelines: http://geology.utah.gov/ghp/consultants/rpt_guidelines.htm

- UGS GeoData Archive System (Generally unpublished geologic hazard reports/data)
  http://geodata.geology.utah.gov

- UGS Geologic Maps
  http://geology.utah.gov/maps/geomap/interactive/viewer/index.html

- UGS LiDAR Elevation Data
  http://geology.utah.gov/databases/lidar/lidar.htm

- UGS Historical Aerial Photography (1935-2004)
  http://geology.utah.gov/online/aerial_photos/index.htm

The Utah Geological Survey, a division of the Utah Department of Natural Resources, provides timely scientific information about Utah's geologic environment, resources, and hazards.

2012 Seeley Fire Debris Flows

Questions and Discussion

Society can prepare for and deal with geologic hazards.

UTAH DNR GEOLOGICAL SURVEY

UTAH GEOLOGICAL SURVEY

12-Mile Landslide, Sanpete County

Technical Session 2 – M_{max} Issues in the Basin and Range Province

Moderator: Ivan Wong, URS Corporation

Issues and Approaches for Estimating M_{max} for Earthquake Sources in the Basin and Range Province: *Donald Wells, AMEC Foster Wheeler* .

Analysis and Selection of Magnitude Relations for the Working Group on Utah Earthquake Probabilities: *Christopher DuRoss, U.S. Geological Survey; Susan Olig, Olig Seismic Geology, Inc.; and David Schwartz, U.S. Geological Survey*

Estimating Surface Lengths for Prehistoric Ruptures in the Basin and Range Province: *Craig dePolo, Nevada Bureau of Mines and Geology*

Fault Linkage, Complexity, and Earthquake Displacement: *Glenn Biasi and Steve Wesnousky, University of Nevada, Reno*

Slip at a Point Variability—Implications for Earthquake-Magnitude Distributions Near M_{max}: *Suzanne Hecker, U.S. Geological Survey; Norm Abrahamson and Kathryn Wooddell, Pacific Gas and Electric Company* [abstract only]

Estimating Magnitudes of Large Earthquakes from Geological Observations of Faults with Low Slip Rates: *John Anderson, Steve Wesnousky, and Glenn Biasi, University of Nevada, Reno*

Lessons Learned from Six Historic Earthquakes in the Intermountain West Regarding Maximum Magnitude: *Kathy Haller and Mark Petersen, U.S. Geological Survey*

ISSUES AND APPROACHES FOR ESTIMATING M_{MAX} FOR EARTHQUAKE SOURCES IN THE BASIN AND RANGE PROVINCE

Donald L. Wells
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Estimation of the maximum expected magnitude (M_{max}) for an earthquake source is a key component of seismic-hazard analysis. For any fault source, the M_{max} may be assessed from the magnitude of the largest historical earthquake occurring on the fault or from the observed characteristics of the fault. Historical earthquakes of magnitude 7 and larger in the Basin and Range Province that may represent the M_{max} event for the causative fault include the 1872 Owens Valley, 1887 Pitaycachi, 1915 Pleasant Valley, 1954 Dixie Valley, and 1959 Hebgen Lake earthquakes. However, the faults that generated these M_{max} events represent only a small percentage of the total number of fault sources in the Basin and Range Province. Therefore, use of the largest historical earthquake on a fault to represent M_{max} is not a viable approach for the vast majority of Basin and Range Province faults.

Fault rupture characteristics such as surface rupture length, maximum and average surface displacement, and rupture area are related to magnitude, and relationships among these source parameters are typically assessed through regression analysis of data for historical earthquakes. In the Basin and Range Province, fault characteristics for expected surface rupture length or observed maximum displacement for paleoearthquakes often are used to assess the expected M_{max} from relationships between moment magnitude (M_W) and surface rupture length, M_W and maximum displacement, and M_W and rupture area. For well-characterized faults, e.g., the Wasatch fault zone, sufficient paleoseismic data are available to estimate the average displacement from paleoearthquakes for use in estimating M_{max}.

We prepared new regression analyses to assess empirical relationships for earthquake source parameters of M_W, rupture area, rupture length, and displacement. The analyses are based on an update of the data base for the 1994 Wells and Coppersmith (WC94) relationships to incorporate data and source parameters for recent earthquakes (post-1993) and new information for earthquakes assessed in WC94. In addition to developing an expanded earthquake database, we also quantified the epistemic uncertainty and assigned a quality ranking (A, B, C, or D) to the source parameters.

We performed ordinary least squares (OLS) regression analyses with data sets that are about 30% larger than the WC94 data sets. New all-slip-type regressions for the larger data sets of M_W and surface rupture length, M_W and displacement, and M_W and rupture area all show the same trends and statistical results as the WC94 OLS all-slip-type regressions. Specifically, the regressions results do not appear to be different at a 95% confidence level, with the exception of average displacement versus M_W, where the new regression predicts higher M_W (0.1 to 0.2 magnitude units) for average displacement values greater than 1.0 m.

Regressions for smaller data sets where the source parameters are judged to be better constrained (i.e., “A” quality) show generally improved statistical relationships (higher correlation coefficient) compared to the larger data sets with “A” and “B” quality data, and for rupture area versus M_W and maximum displacement versus M_W, the regressions appear to be statistically different at the 95% confidence level compared to those for the larger data sets. Specifically, the observed change-in-slope of the “A” quality regressions appears to result from exclusion of events with small rupture area or small maximum displacements.

Comparison of data for historical Basin and Range Province earthquakes to the global data reveals no systematic difference or bias among source parameters. Therefore, the global all-slip-type relations are appropriate for use in evaluating source parameters for Basin and Range Province faults.

Another preliminary observation from the analyses is that the more limited data sets such as for different slip types or higher quality data may not represent the aleatory variability of earthquake rupture processes as well as the larger data sets. In particular for many earthquakes, it is difficult to assess whether the observed variability for source parameters is due to measurement errors (epistemic uncertainty) or natural (aleatory) variability in earthquake processes. In addition, as noted for the WC94 regressions, updated OLS regressions for rupture area versus M_W and maximum and average displacement versus M_W under-predict the dependent variable (M_W) at the largest values for the independent variable. This under-prediction is more apparent with the addition of new data, including several recent M_W 7.5+ earthquakes, that provides better characterization of aleatory variability for the largest events. We are performing additional refinement of the data sets and fitting of alternative regressions to model errors in both dependent and independent variables, and final regression models are expected to result in improved fits to the data compared to the OLS models.

In current practice, several alternative approaches and regression models have been developed to address the under-prediction of dependent variables in the WC94 OLS regressions. Stirling and others (2002) prepared "censored" regressions that model data for earthquakes with rupture length greater than ~10 km and M_W greater than ~6.4. Hanks and Bakun (2002, 2008) developed a bi-linear OLS regression for rupture area versus M_W, where the slope of the regression changes at M_W 6.7. Shaw (2009, 2013) developed regressions for rupture area versus M_W based on a constant stress drop model. All of these models provide improved fit of regressions to data to mitigate under-prediction of dependent variables at large values of the independent variable, and are useful for estimating M_W from rupture parameters.

For the Basin and Range Province, Carpenter and others (2012) note a separate issue in estimating M_{max} from displacement and surface rupture length estimates. They observe that for the Wasatch fault zone and other well-characterized Basin and Range Province faults, M_{max} estimates from maximum displacement typically exceed estimates from surface rupture length. They suggest this difference results from the practice of characterizing surface rupture length as equal to single fault segment lengths, while in past Basin and Range Province ruptures, the observed surface rupture length typically extends beyond the extent of a single fault segment. Therefore, use of single fault segment lengths appears to underestimate surface rupture length for earthquakes in the Basin and Range Province, and results in underestimates of M_{max} for the earthquakes. They propose the use of a modified rupture length regression based on the length of single fault segments, and provide a preliminary relationship that shows better agreement with M_{max} estimates from maximum displacement. However, because the database used to develop the regression is very small, the confidence interval for the mean is broad, and this relationship should not be considered as reliable as other relationships that are developed from a larger data base of earthquake source parameters.

In summary, new OLS regressions for expanded data sets for rupture area, surface rupture length, and maximum and average displacement versus M_W, for all-slip-type regressions, show nearly the same trends and statistical results as the comparable WC94 OLS regressions. Additional refinement of the data sets and fitting of alternate regression models will be performed to develop new regressions to represent errors in the source parameters and to improve the reliability of the predictive relationships. As recommended in WC94, the all-slip-type relationships are appropriate for most applications, and these relationships are appropriate for the Basin and Range Province as well as more active tectonic regions. A specific issue for the WC94 relationships is the under-prediction of magnitude for large values of rupture area and maximum and average displacement. An additional issue is the apparent under-prediction of magnitude for single-segment fault rupture lengths compared to displacement estimates for faults in the Basin and Range Province. Several alternative regression models have been published that appear to better predict M_W and are suitable for use in many applications. For faults in the Basin and Range Province, use of multiple source parameters and regressions is advisable to reduce the potential for under-estimation of M_{max}. It also may be appropriate to consider multi-segment ruptures in addition to single-segment ruptures, even where the dating of past earthquakes appears to indicate that adjoining fault segments do not rupture in a single earthquake.

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Shaw, B.E., 2009, Constant stress drop from small to great earthquakes in magnitude-area scaling: Bulletin of the Seismological Society of America, v. 99, no. 2, p. 871-875, doi: 10.1785/0120080006.

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Stirling, M., Rhoades, D., and K. Berryman, 2002, Comparison of earthquake scaling relations derived from data of the instrumental and preinstrumental era: Bulletin of the Seismological Society of America, v. 92, no. 2, p. 812–830.

Wells, D.L., and K.J. Coppersmith, 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: Bulletin of the Seismological Society of America, v. 84, no. 4, p. 974-1002.

The following is a PDF version of the author's PowerPoint presentation.

BASIN AND RANGE PROVINCE SEISMIC HAZARDS SUMMIT III
January 12 – 17, 2015
Salt Lake City, Utah

Issues and Approaches for Estimating M_{max} for Earthquake Sources in the Basin and Range

Donald Wells, AMEC, Oakland, CA

Approaches and Issues in Estimating Maximum Magnitudes for Fault Sources in Seismic Hazard Analyses

Donald Wells
Geomatrix Consultants
Oakland, CA

Basin and Range Seismic Hazards Summit II
Western States Seismic Policy Council
Reno-Sparks, Nevada, 2004

GEOMATRIX

Outline

1. Approaches to Estimating M_{max}
2. Tools to evaluate M_{max} (aka, empirical relationships)
   - Update to Wells & Coppersmith (1994) [WC94]
   - Other issues and relationships regarding M_{max}

Approaches to Estimate M_{max}

Based on occurrence of large magnitude historical earthquake

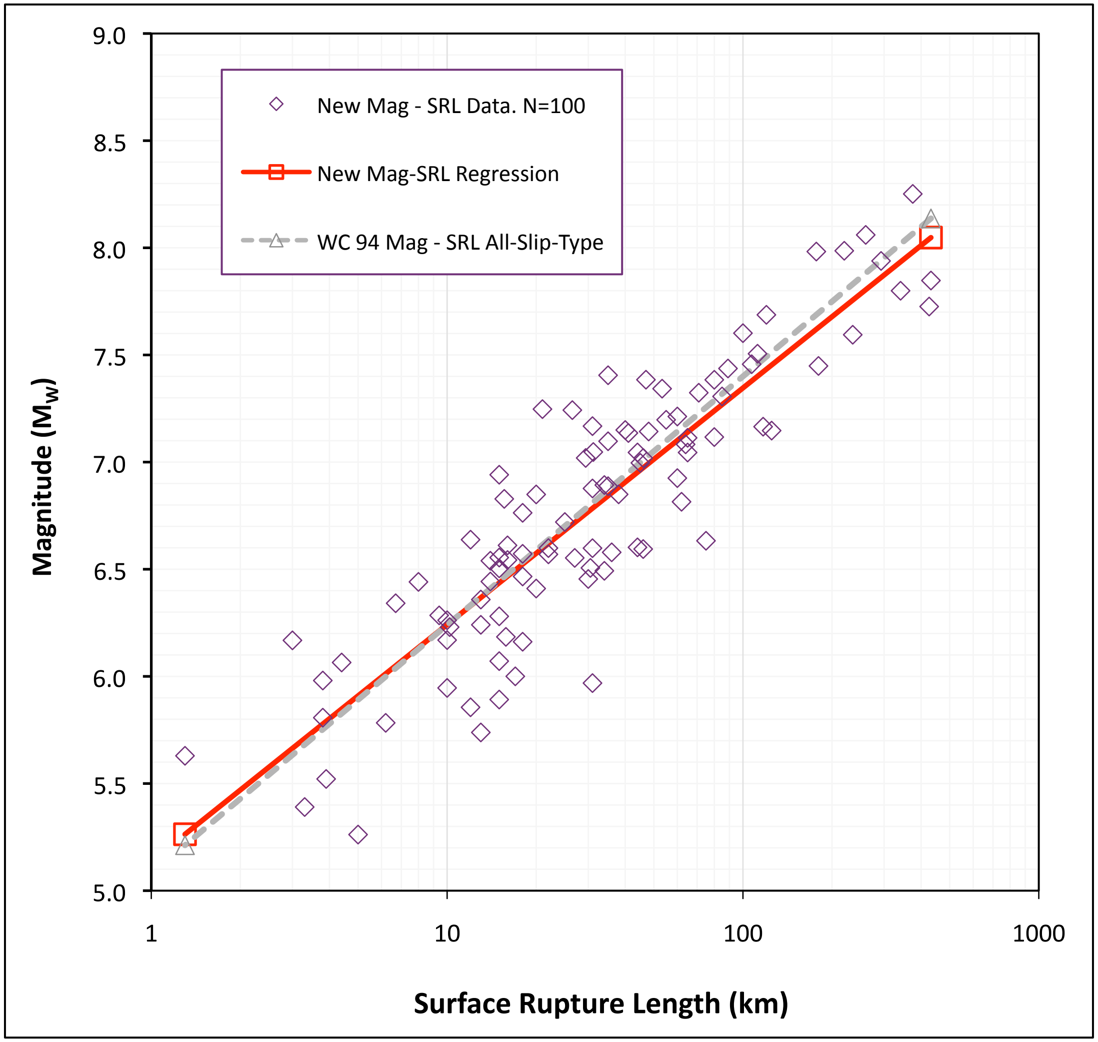
- 1915 Pleasant Valley
- 1954 Dixie Valley
- 1959 Hebgen Lake
- Arguably about 6 additional earthquakes may represent M_{max} for the causative fault
- Represents small percentage of total fault sources in Basin and Range

Based on empirical relationships between earthquake source parameters and magnitude

- EQ Source parameters represented by expected fault rupture parameters
- Surface Rupture Length
- Maximum Surface Displacement
- Average Surface Displacement
- Rupture Area

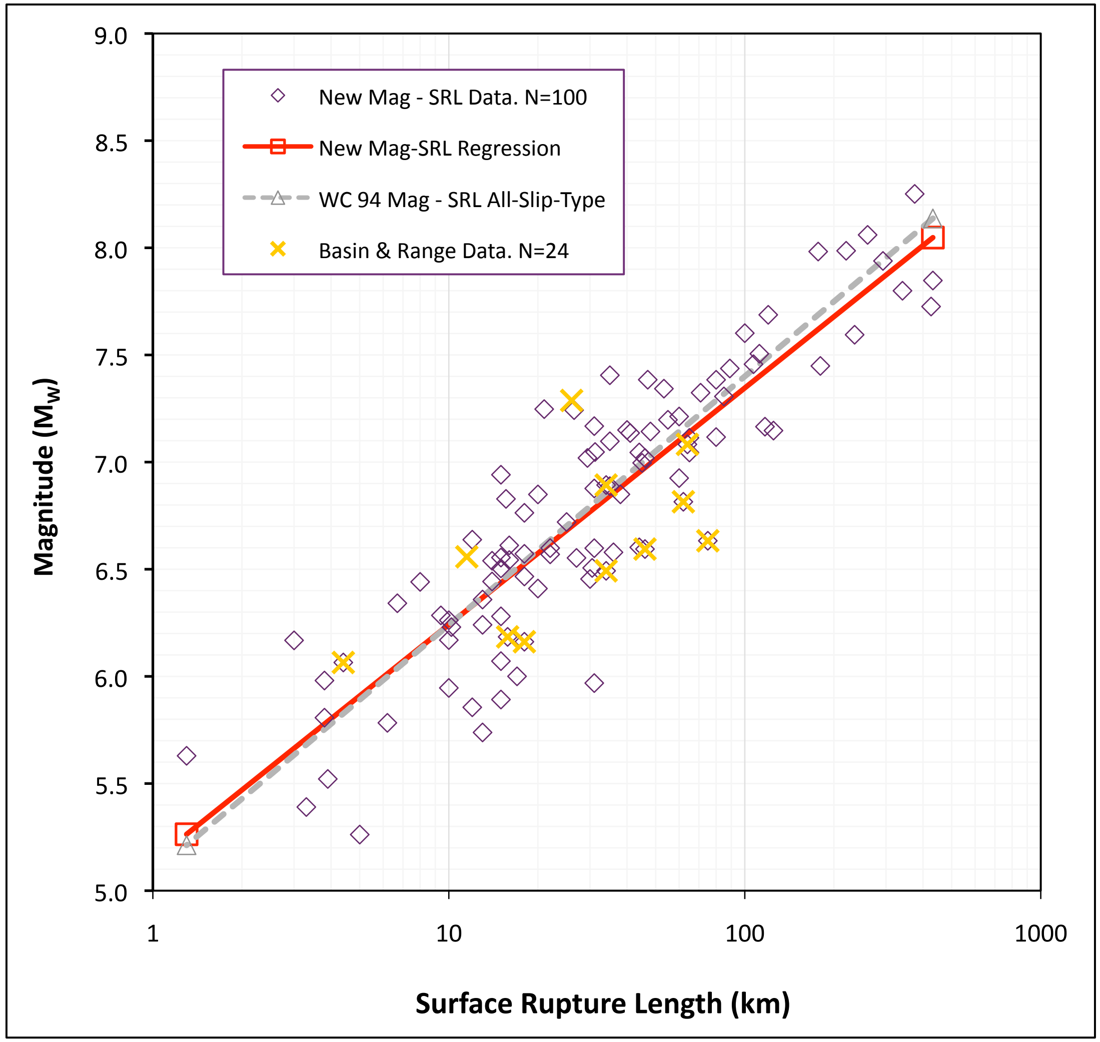
Surface Rupture Length

- New magnitude – surface rupture length data and regression.
- Unchanged from WC94



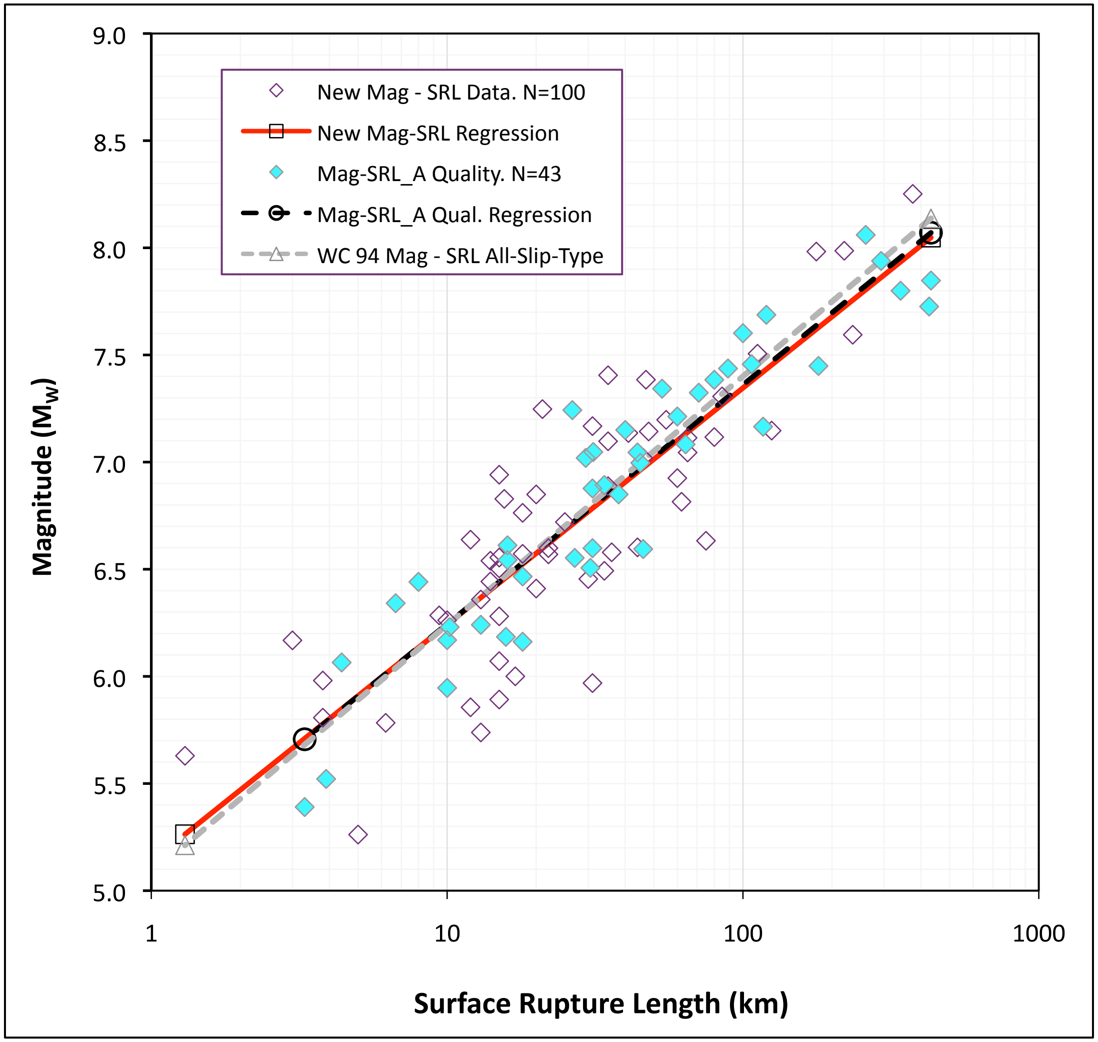
Surface Rupture Length

- Basin and Range Data



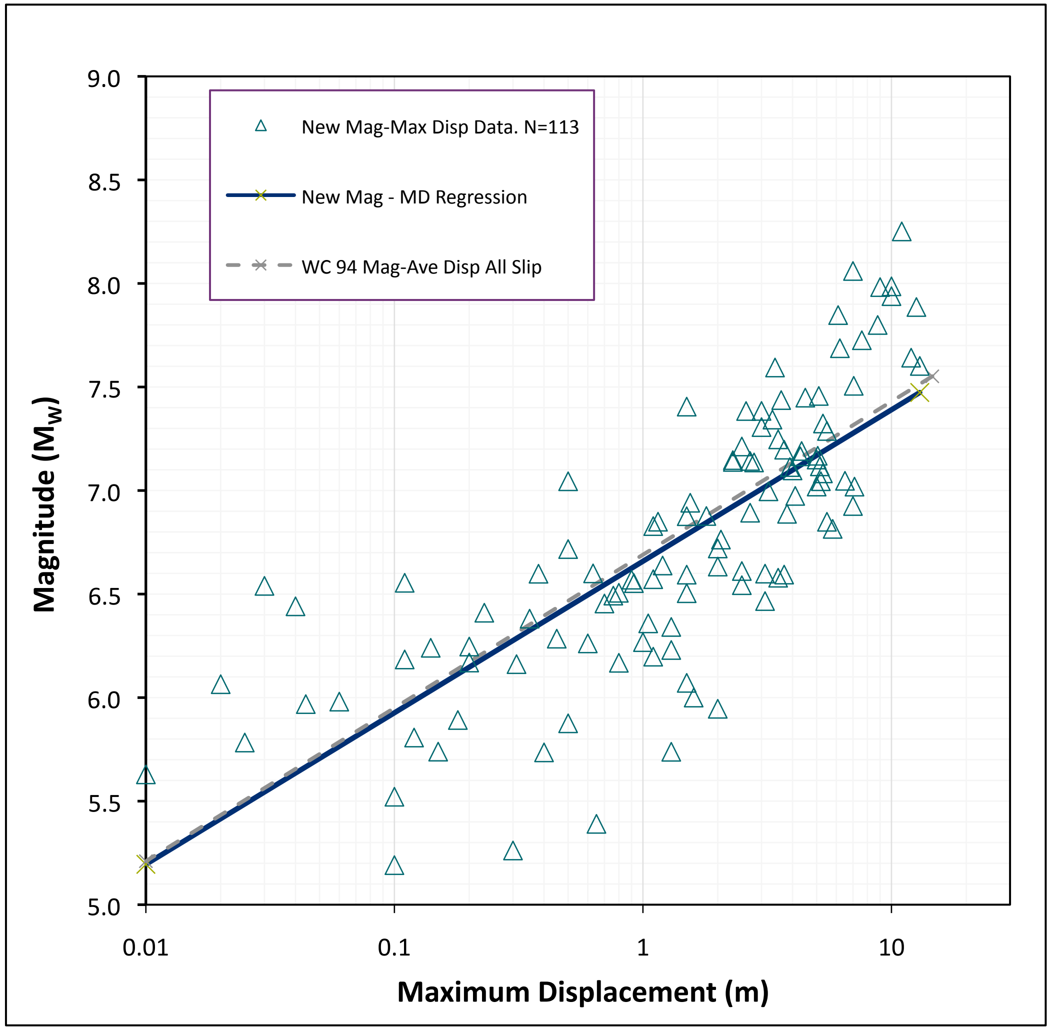
Surface Rupture Length

- "A" Quality Data and regression.
- Less "scatter" and slightly improved statistics
- Regression is essentially unchanged
- Good fit to data



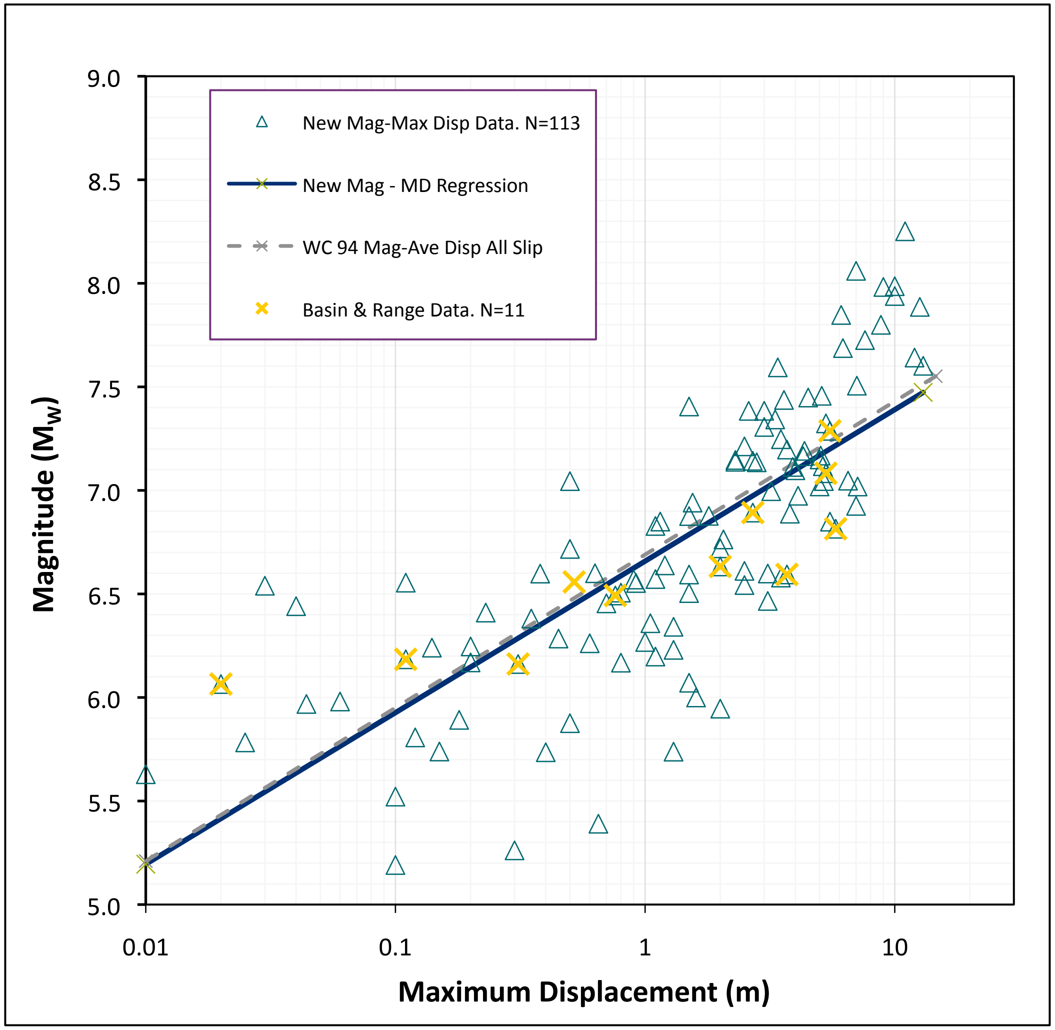
Maximum Displacement

- New Maximum Displacement Data and Regression
- Unchanged from WC94.



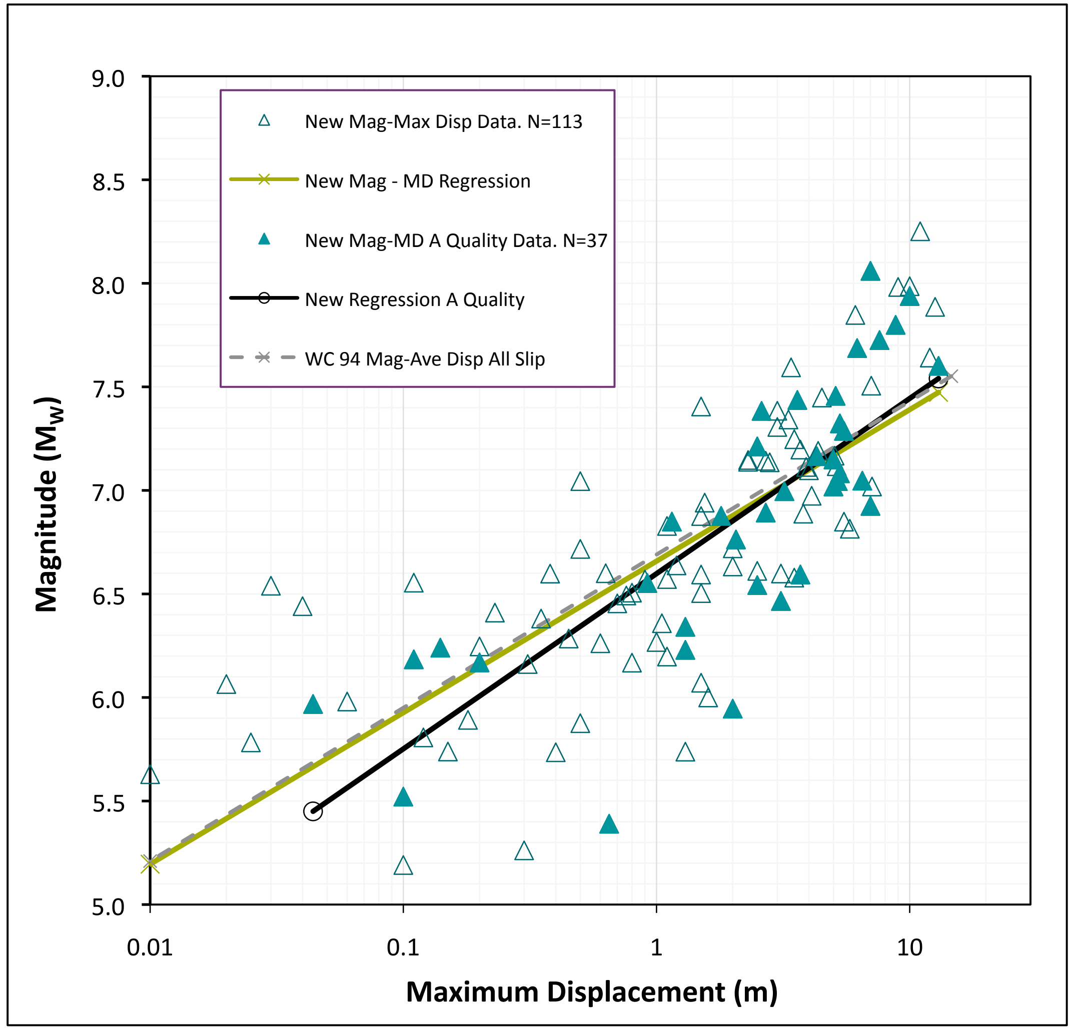
Maximum Displacement

- ▶ Basin and Range Data



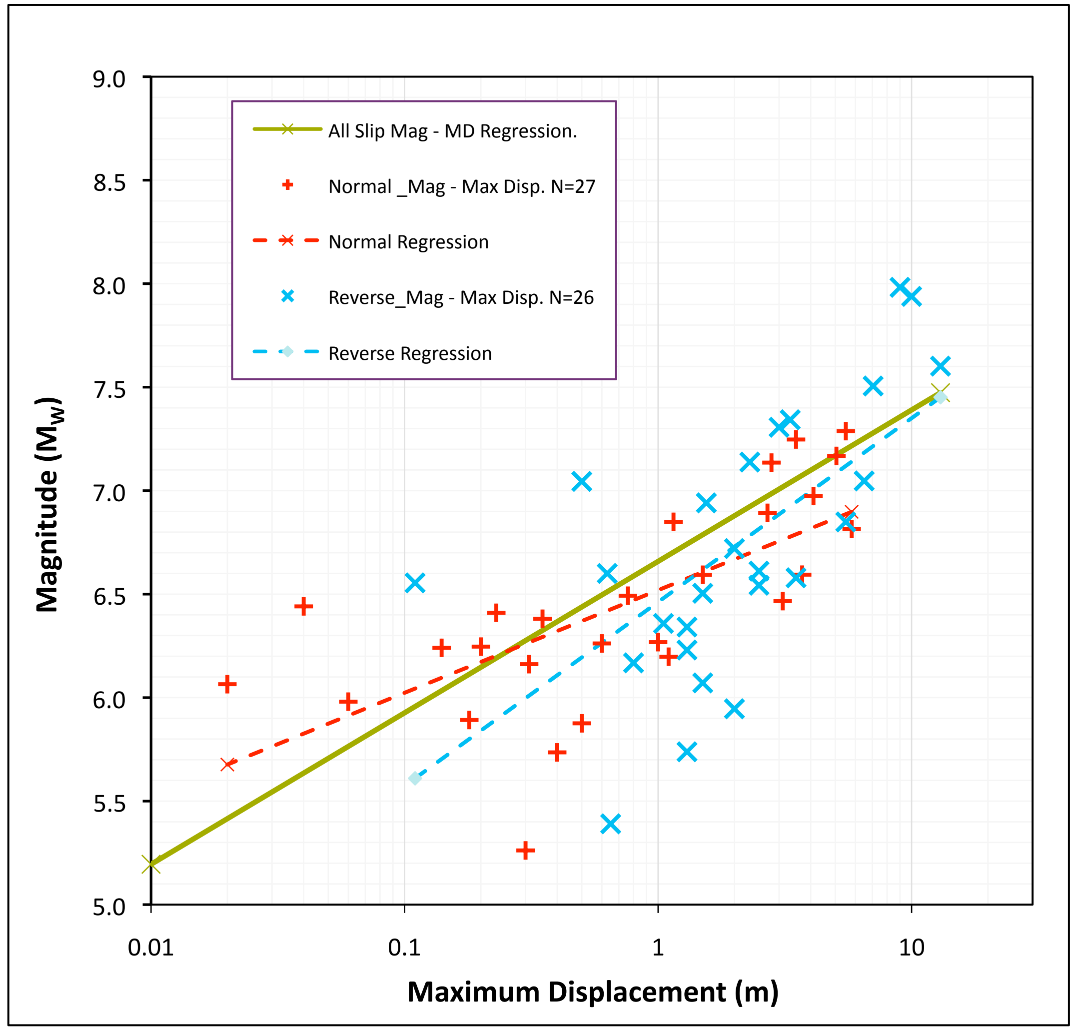
Maximum Displacement

- "A" Quality Data and regression
- Improved correlation
- Appears to under-predict magnitude for large displacements



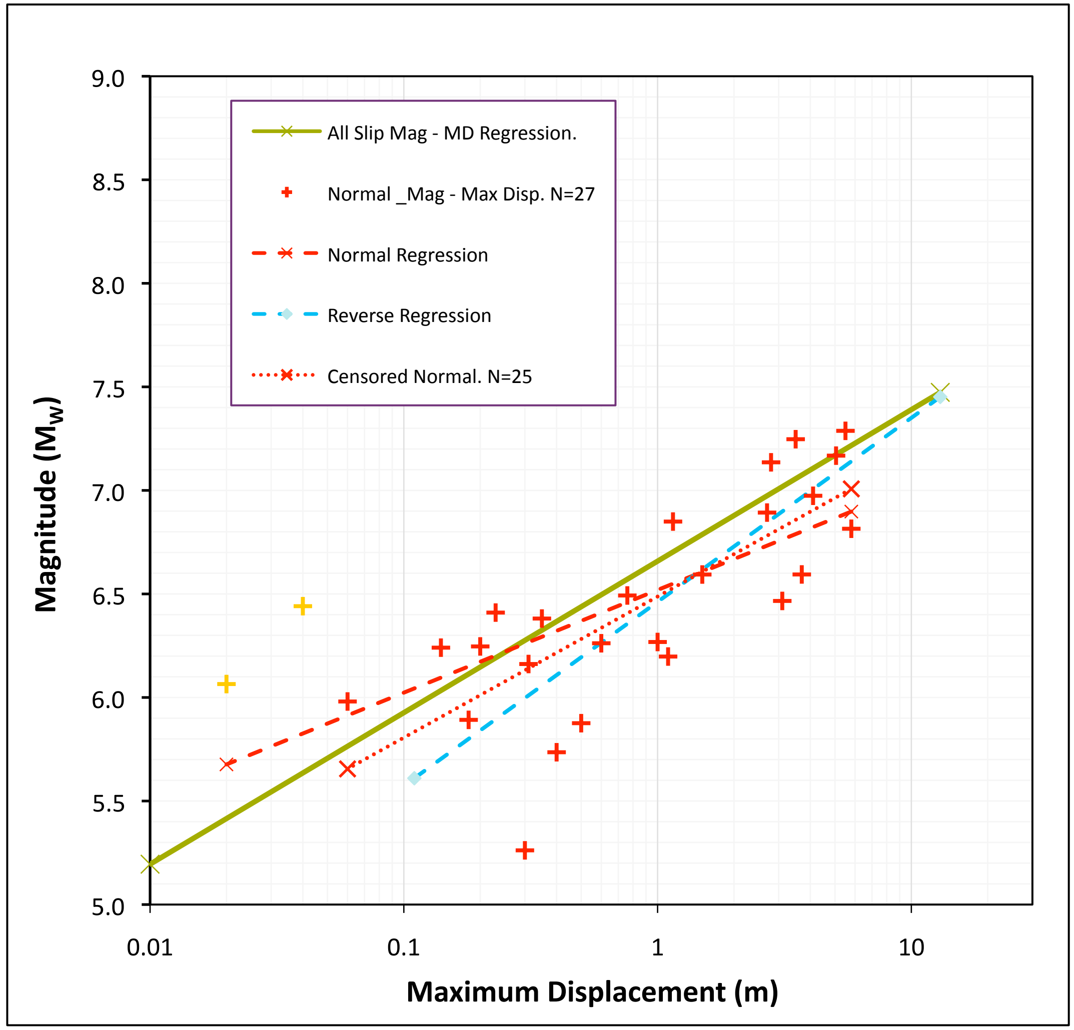
Maximum Displacement

- Comparison of Reverse and Normal Slip Regressions
- Some difference to All-Slip-Regression, but is sensitive to scatter of data
- Scatter due in part to difficulty in measuring net offset for dip-slip ruptures



Maximum Displacement

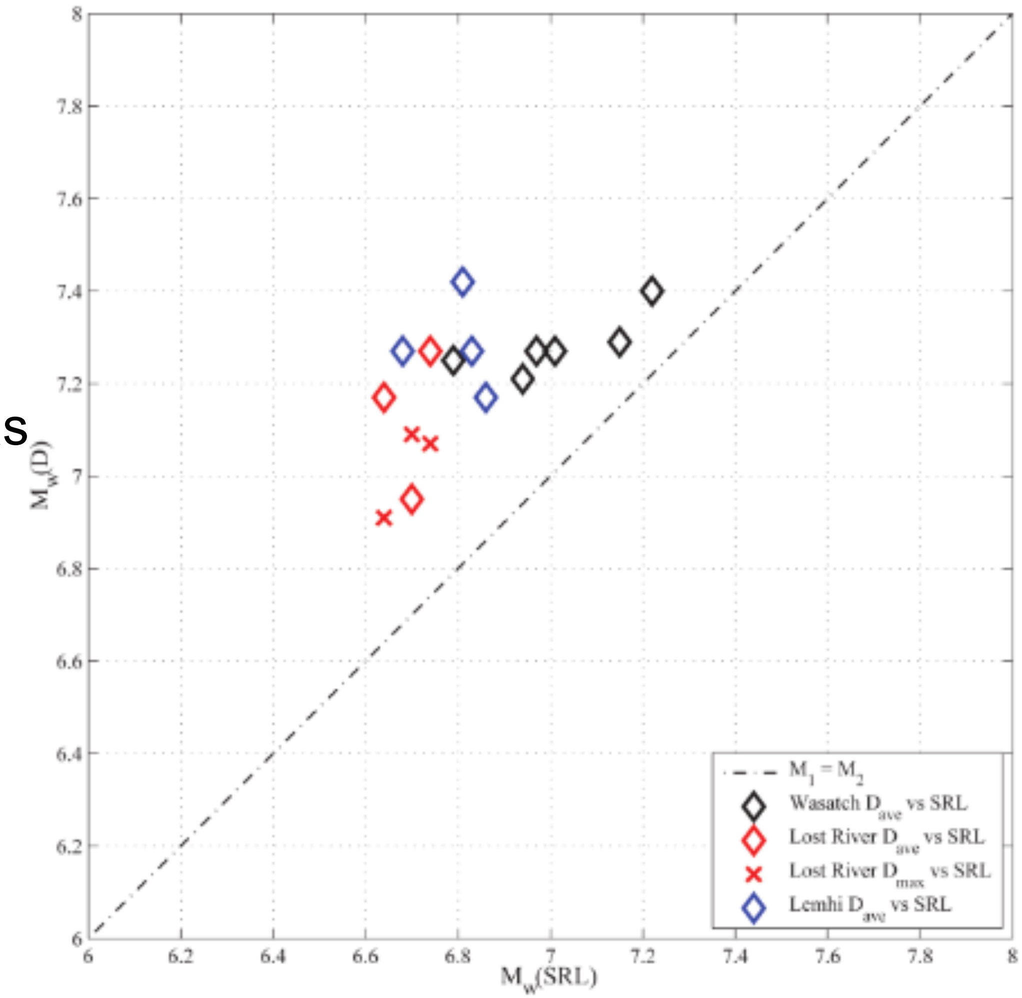
- Sensitivity Test for Reverse Regression
- Remove two low slip events.
- Strong effect on regression



Inconsistency of Magnitude from Surface Rupture Length and Maximum Displacement

Carpenter et al (2012) note that magnitudes predicted from displacement exceed magnitudes estimated from rupture length

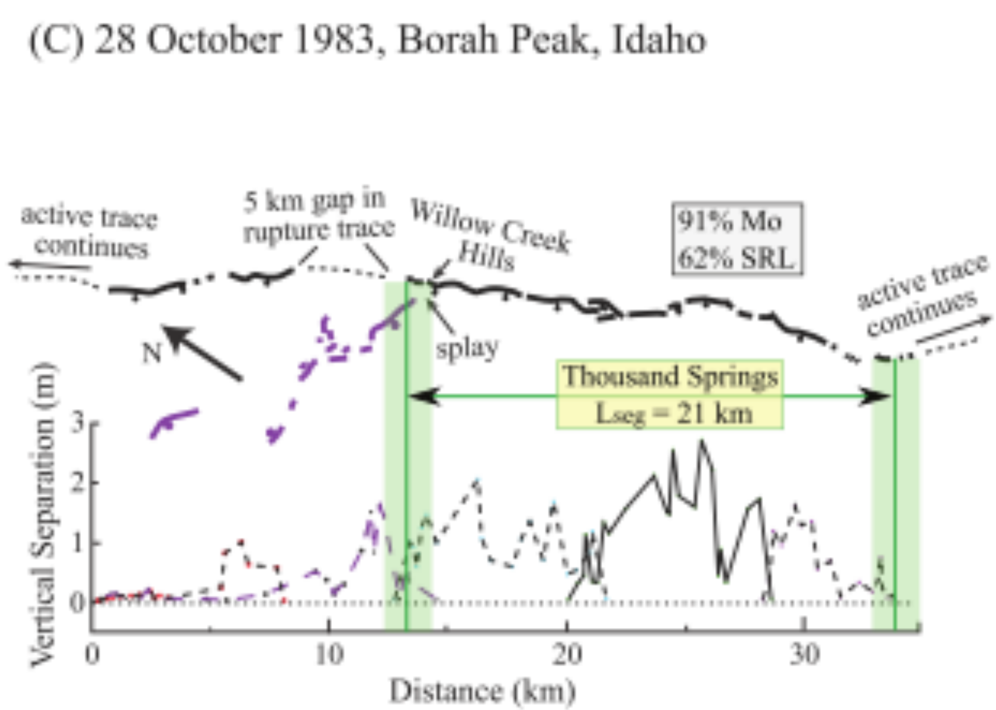
- ► Rupture length taken as segment length



Inconsistency for Surface Rupture Length and Maximum Displacement

Carpenter et al. note that

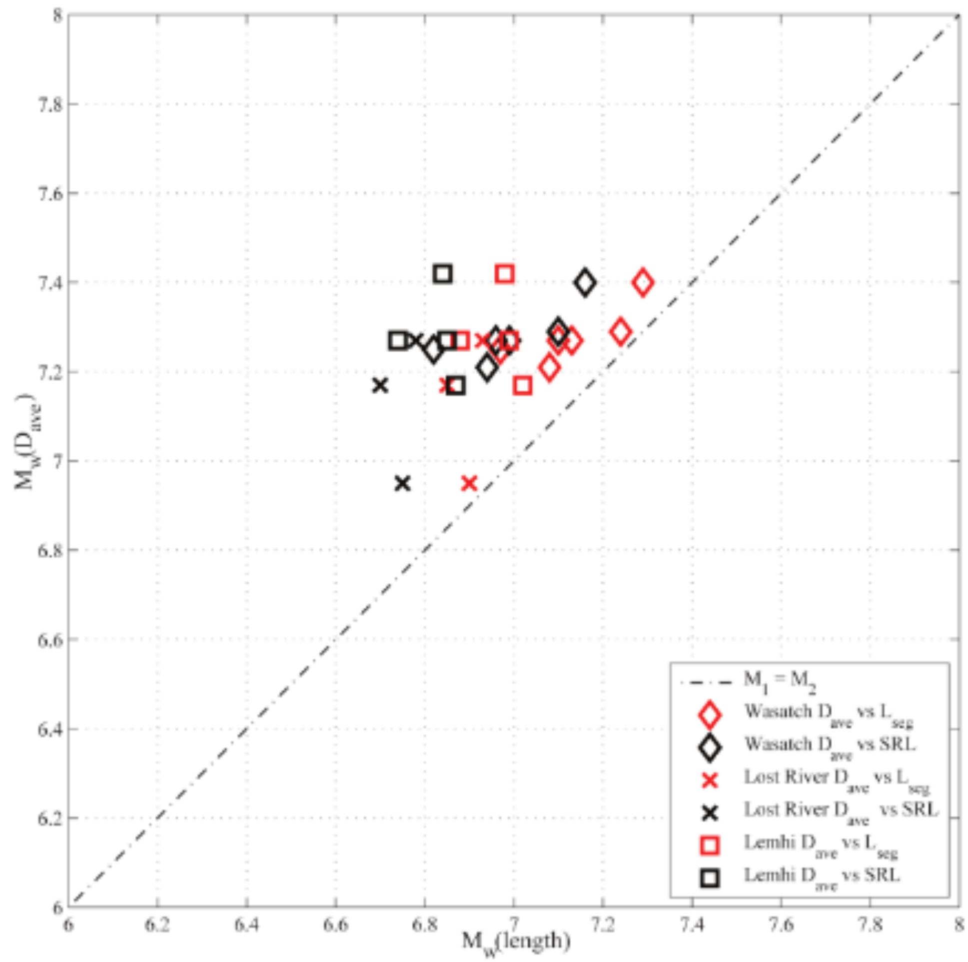
- ► Actual ruptures tend to spill over segments
- ► Most moment and largest displacement on primary rupture segment
- ► Provide preliminary regressions based on ruptured segments rather than actual surface rupture length
- ► Potentially useful for segmented faults such as Wasatch



Inconsistency for Surface Rupture Length and Maximum Displacement

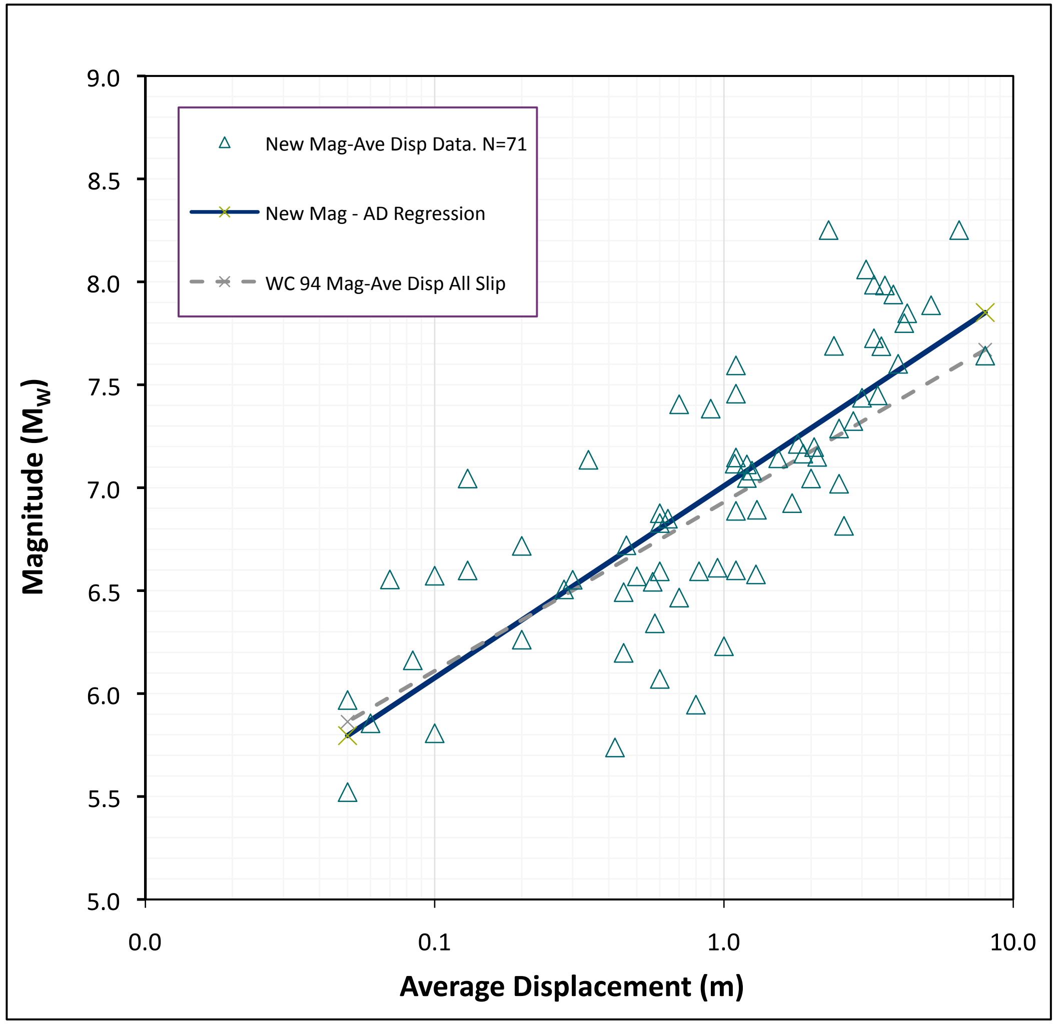
Carpenter et al. show improved agreement for magnitude from segment length and from displacement.

- But need more data to define regression (only 7 events used).
- Inconsistency is less of an issue when considering multi-segment ruptures



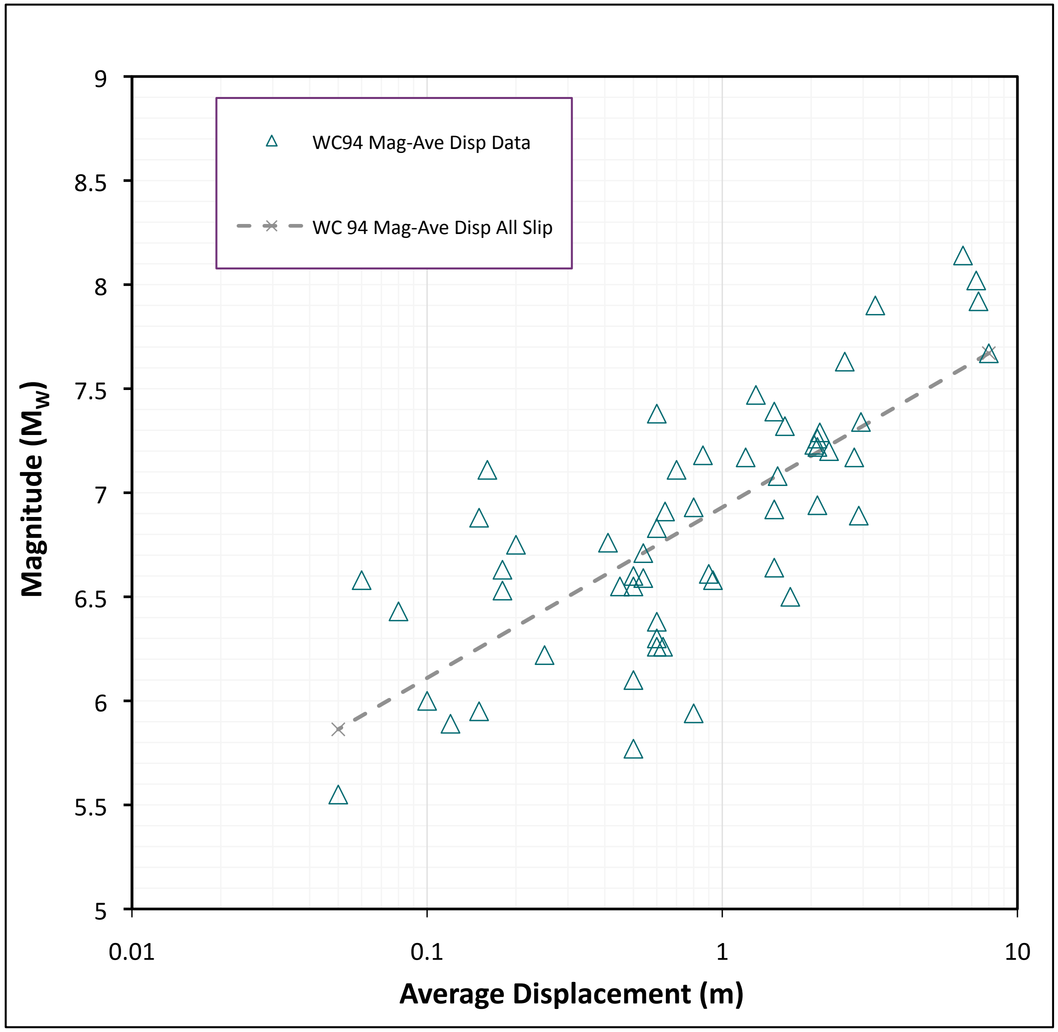
Average Displacement

- New magnitude and average displacement data and regression
- Improved correlation



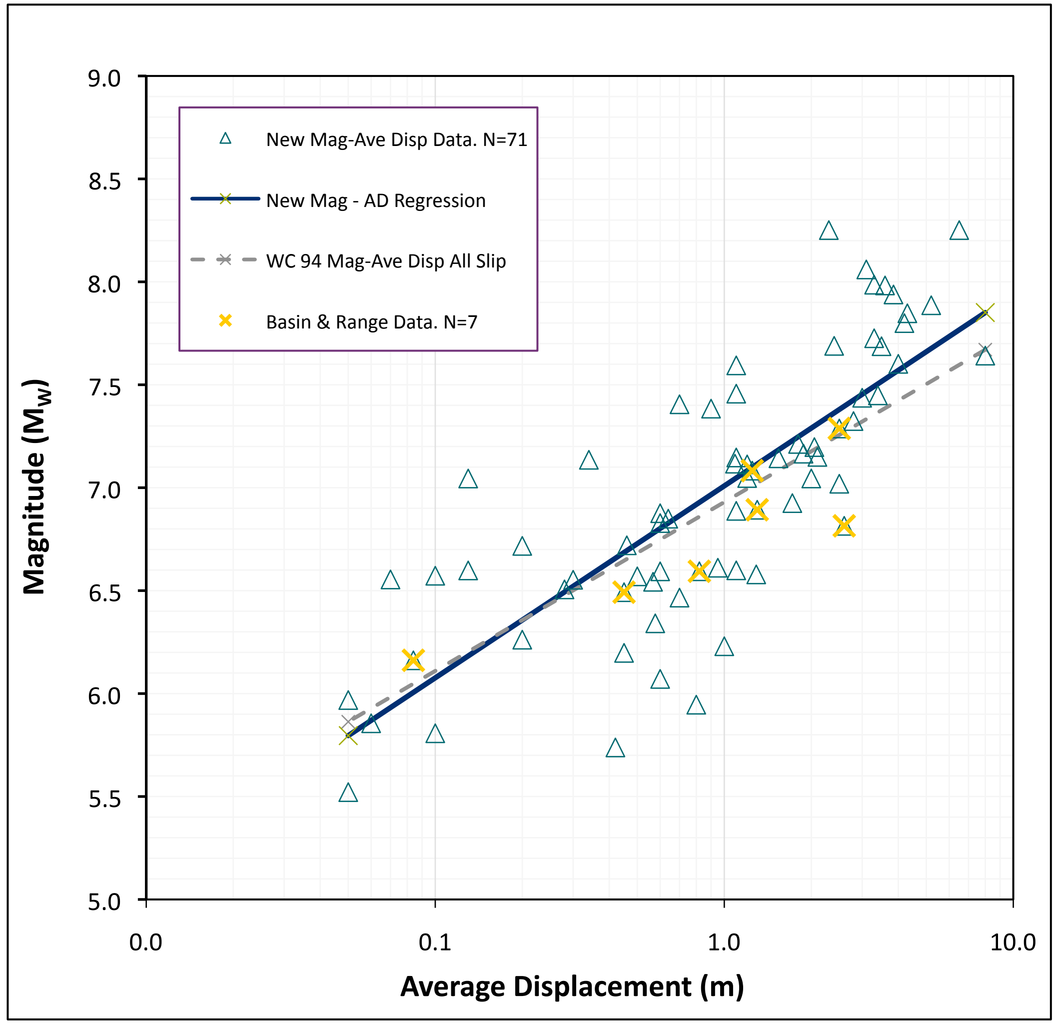
Average Displacement

- WC94 data and regression



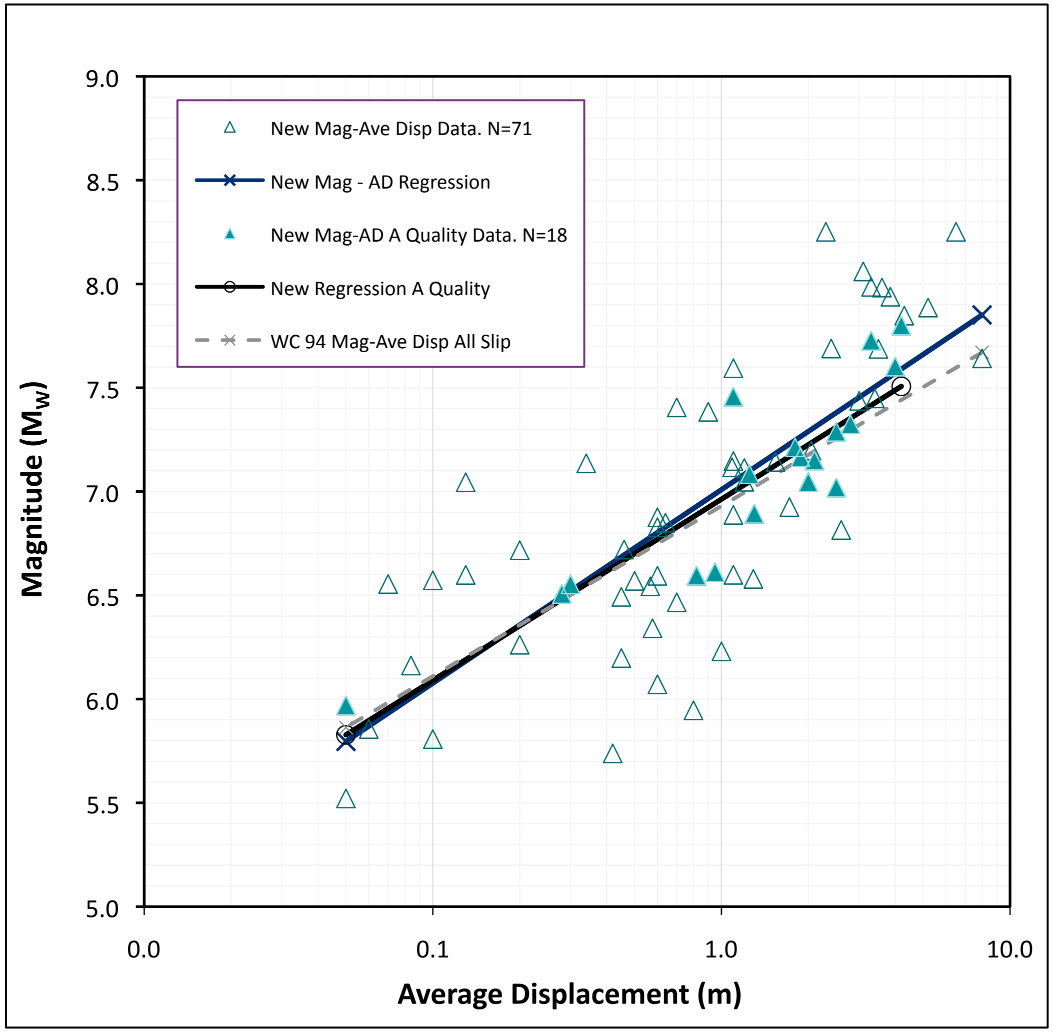
Average Displacement

- ▶ Basin and Range data



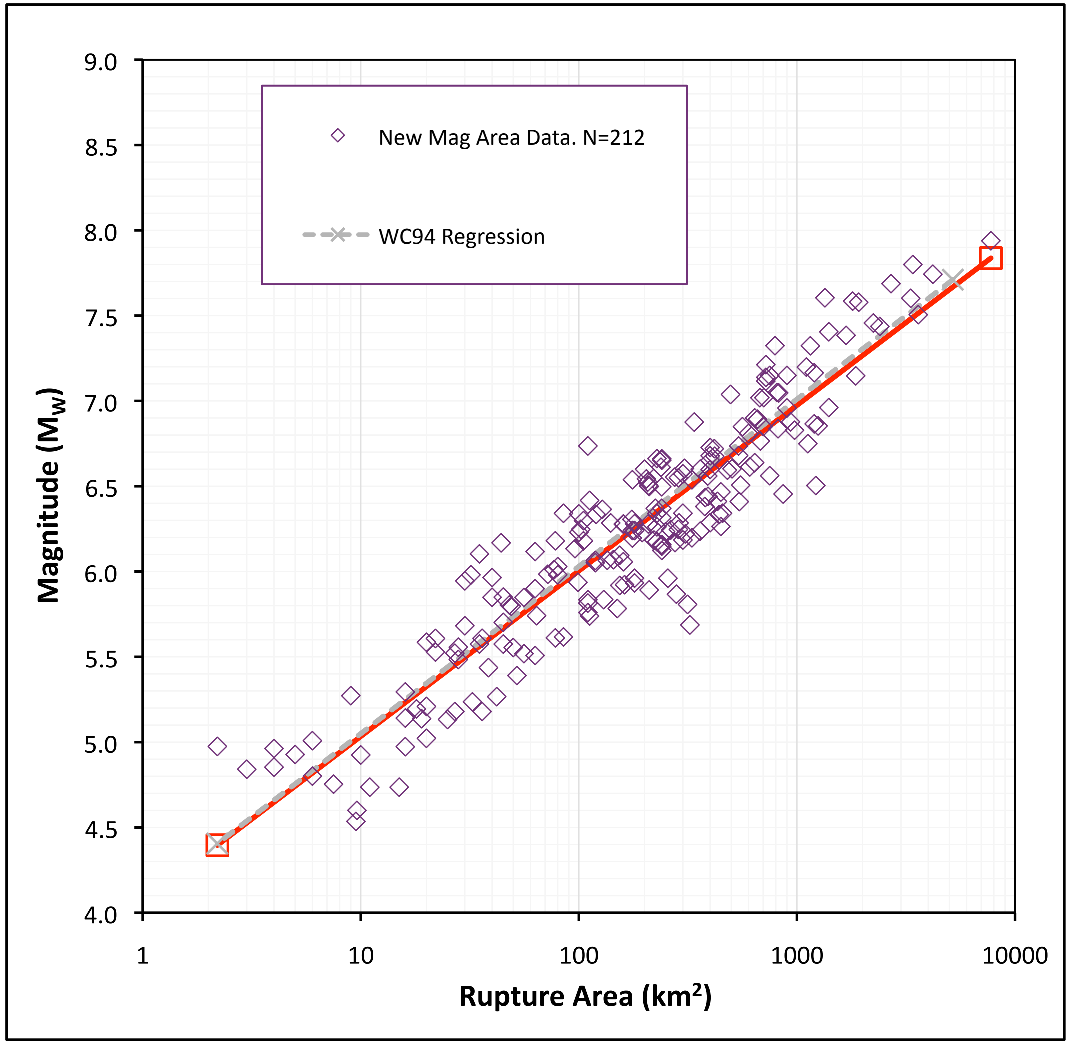
Average Displacement

- "A" Quality Data and regression.
- Improved correlation
- Appears to under-predict magnitude for large displacements



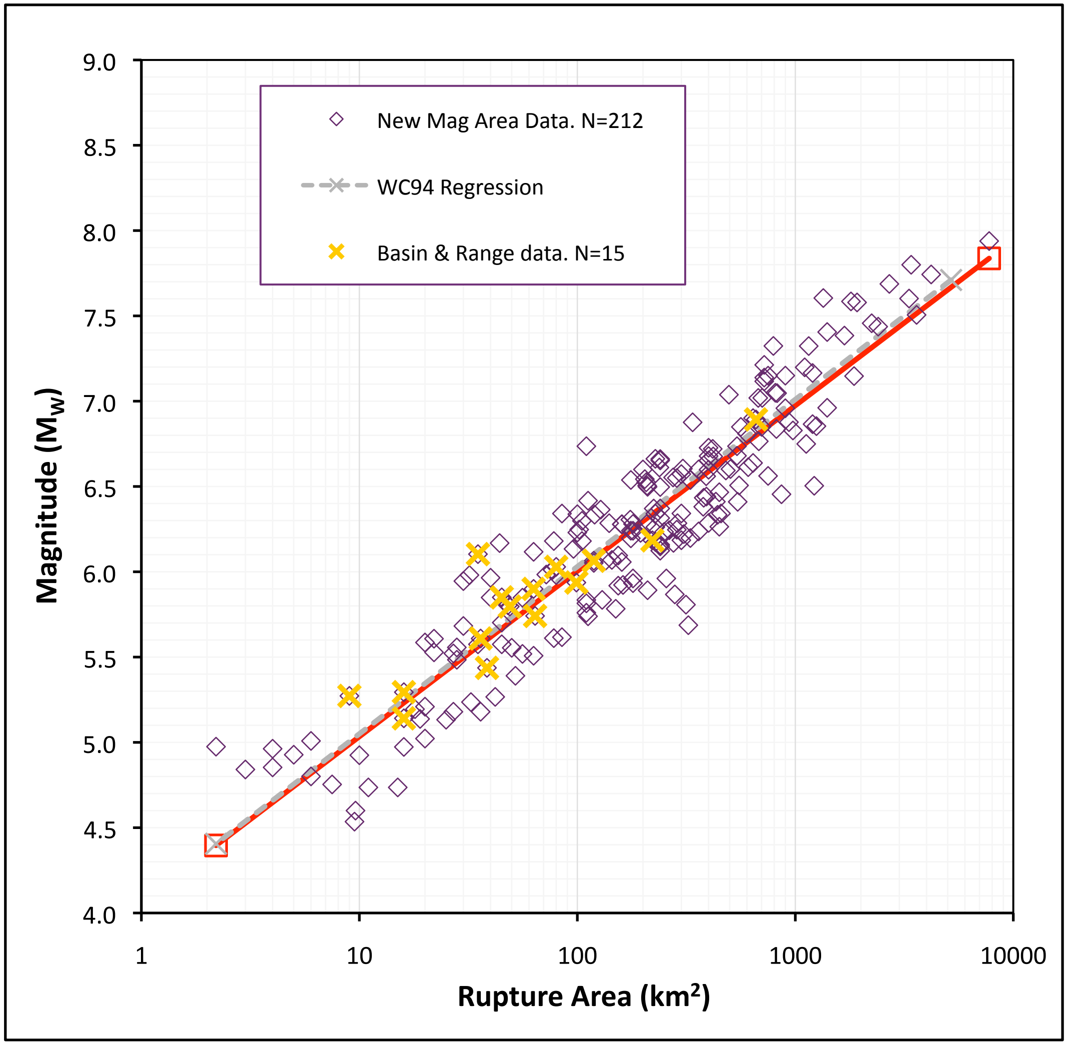
Rupture Area

- ▶ New magnitude area data and regression
- ▶ Unchanged from WC94



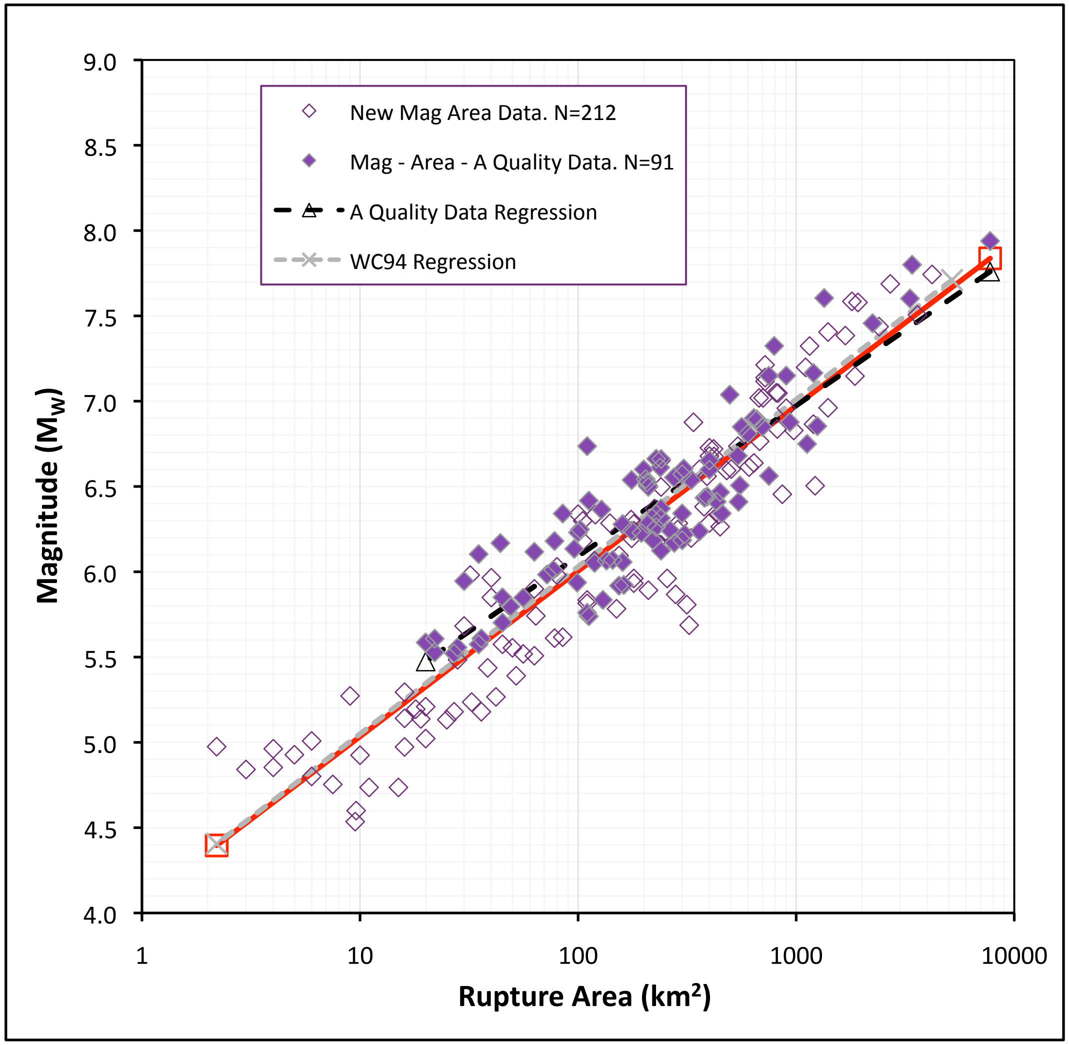
Rupture Area

- ▶ Basin & Range Data

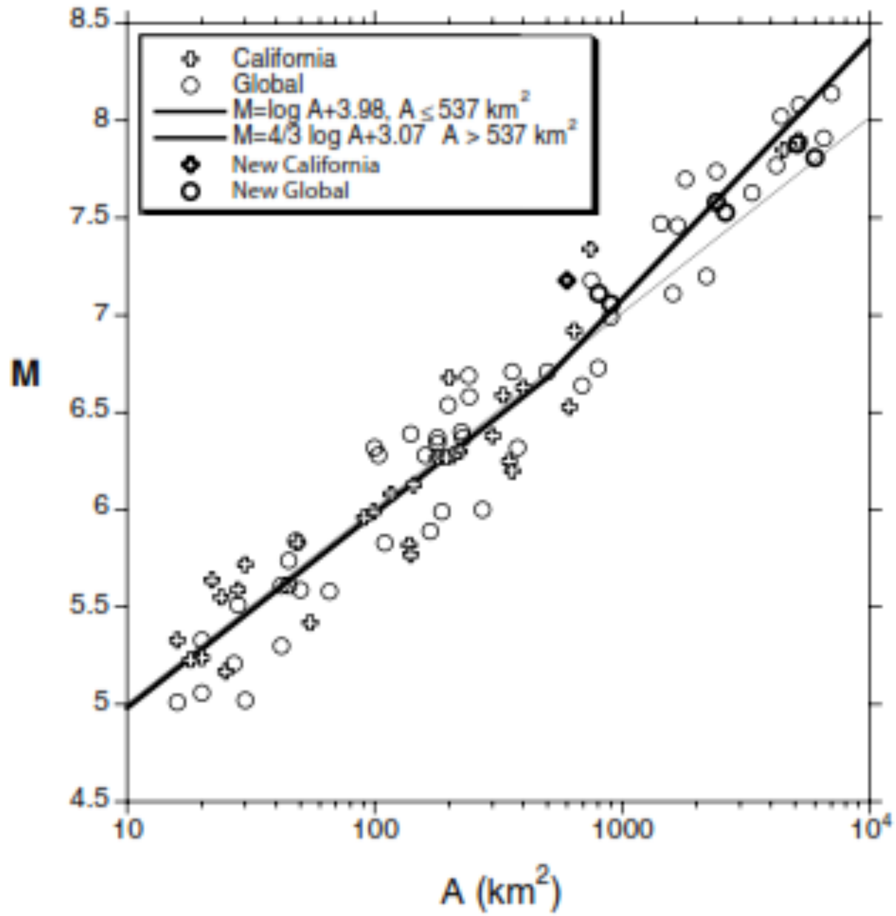


Rupture Area

- "A" Quality Data and regression
- Under-prediction of magnitude for larger rupture area still present
- Improved fit by multi-linear (or other) regression model

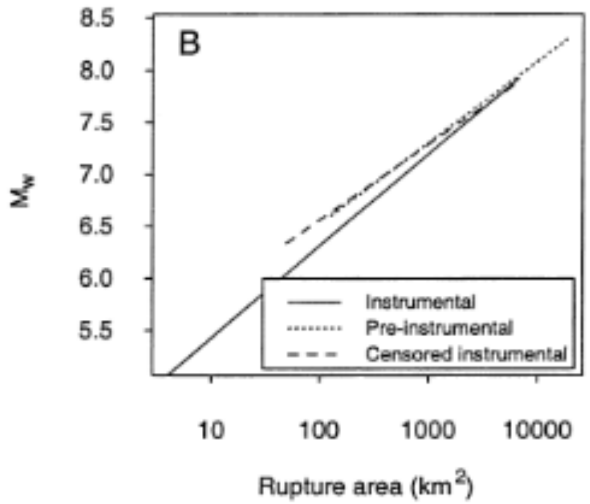


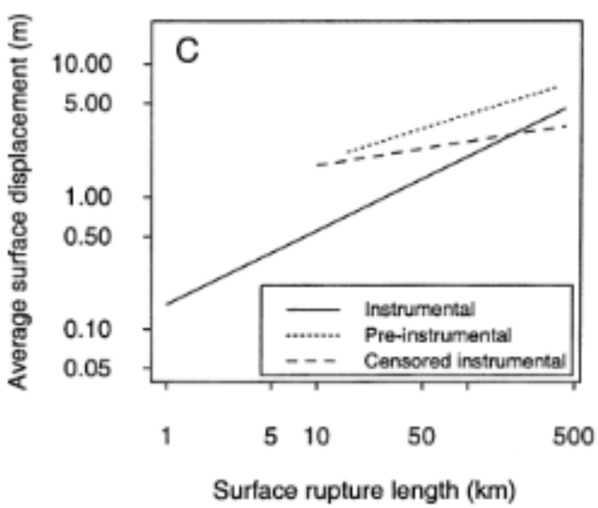
Rupture Area



Hanks and Bakun (2002, 2008) Bi-linear regression still reasonable "solution" for under-prediction by OLS regressions

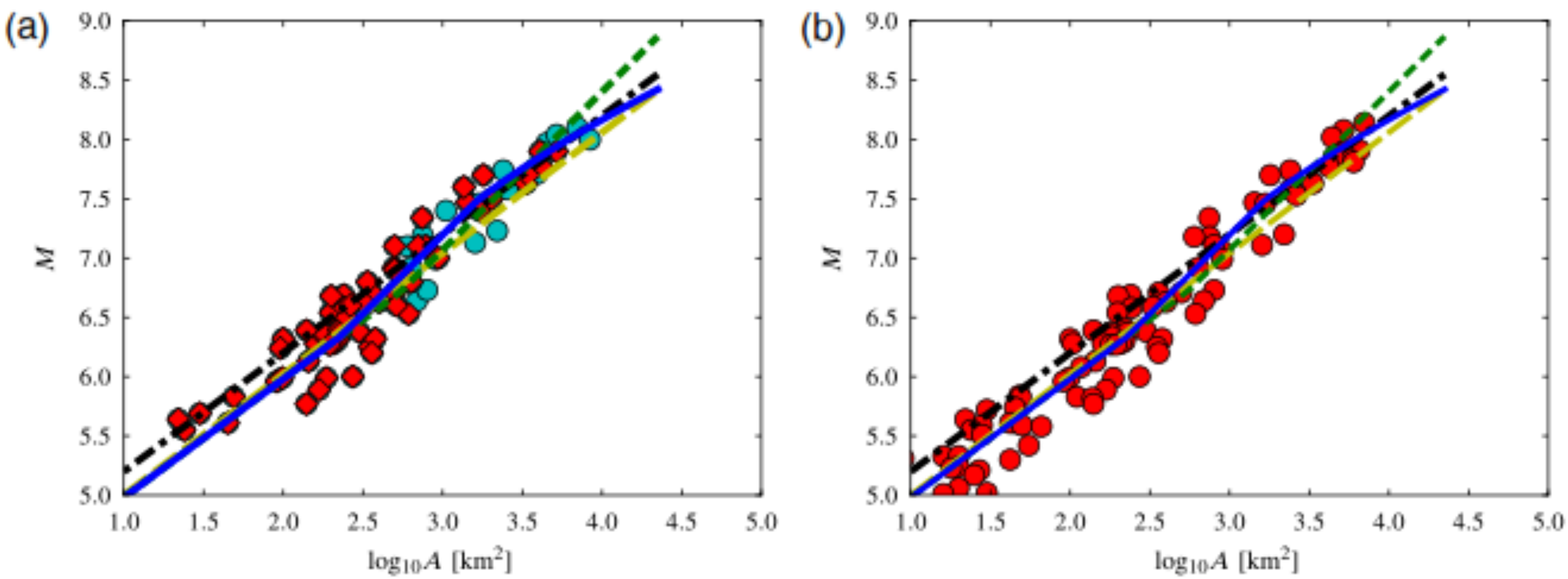
Rupture Area





Stirling et al. (2002) approach for "Censored" regression also is a reasonable "solution" for under-prediction by OLS regressions

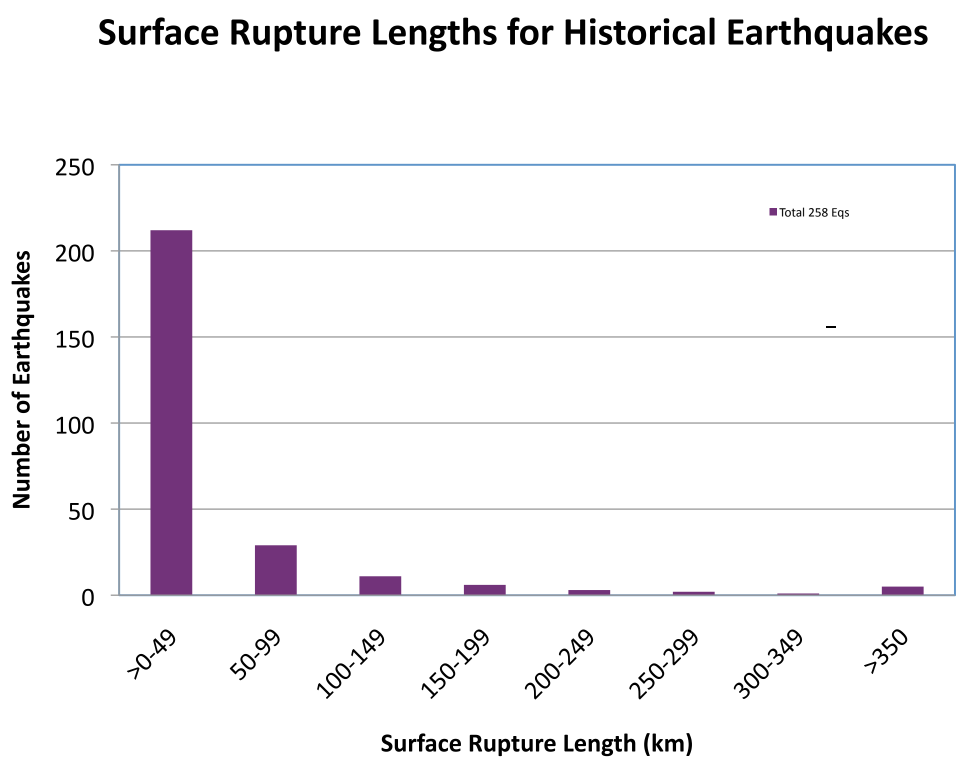
Rupture Area



Shaw (2009, 2013) notes constant stress drop in modelling rupture area (and fault slip) data

- Possibly the consistent physical model for relating rupture parameters

Frequency of Multi-Segment (Fault) Rupture



Pseudo-proxy for frequency of multi-segment or multi-fault ruptures.

Conclusions

- All-slip-type regressions appear to reasonably represent all crustal fault types
- “A” Quality data shows improved correlations, but not statistically different than all “A” and “B” data
- Confirm that Basin and Range earthquakes look like other global earthquakes

Next Update --- Pasadena!

- Considered limits on regressions - e.g., drop the lower magnitude/displacement data
- Compute regressions considering epistemic uncertainty
- Develop alternate regression models to address under-prediction in displacement and area regressions

ANALYSIS AND SELECTION OF MAGNITUDE RELATIONS FOR THE WORKING GROUP ON UTAH EARTHQUAKE PROBABILITIES

Christopher B. DuRoss [1], Susan S. Olig [2], and David P. Schwartz [3]
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[2]Olig Seismic Geology, Martinez, California (formerly AECOM, Oakland, California)
[3]U.S. Geological Survey, Menlo Park, California
Senior author's email address: cduross@usgs.gov

Prior to calculating time-independent and -dependent earthquake probabilities for faults in the Wasatch Front region, the Working Group on Utah Earthquake Probabilities (WGUEP) updated a seismic-source model for the region (Wong and others, 2014) and evaluated 19 historical regressions on earthquake magnitude (**M**). These regressions relate **M** to fault parameters for historical surface-faulting earthquakes, including linear fault length (e.g., surface-rupture length [SRL] or segment length), average displacement, maximum displacement, rupture area, seismic moment (M_o), and slip rate. These regressions show that significant epistemic uncertainties complicate the determination of characteristic magnitude for fault sources in the Basin and Range Province (BRP). For example, we found that **M** estimates (as a function of SRL) span about 0.3–0.4 units (figure 1) owing to differences in the fault parameter used; age, quality, and size of historical earthquake databases; and fault type and region considered.

Uncertainty in characterizing characteristic magnitude for BRP faults also results in a displacement- versus length-based discrepancy in **M**, where **M** based on average displacement or Mo exceeds that based on SRL or rupture area. The central segments of the Wasatch fault zone (WFZ) exemplify this discrepancy, where, for single-segment ruptures, **M** based on M_o is on average 0.2 units larger than that based on SRL or rupture area (figure 2). Possible explanations for the **M** discrepancy include (1) consistently larger vertical displacements (and thus M_o release) per segment rupture length than expected from the empirical regressions (possibly due to higher stress drop earthquakes); (2) rupture lengths extending beyond the mapped fault ends or segment boundaries (e.g., Hemphill Haley and Weldon, 1999; Carpenter and others, 2012), and/or (3) regressions biased by datasets dominated by small earthquakes (Stirling and others, 2002), or those in strike-slip, reverse, and/or megathrust plate-boundary environments (e.g., Wells and Coppersmith, 1994; Leonard, 2011). Regressions addressing this **M** discrepancy include the displacement regressions of Hemphill-Haley and Weldon (1999), censored-instrumental regression on SRL (herein, SRL-censored) of Stirling and others (2002), and the segment-length regressions of Carpenter and others (2012). Of these, we prefer the SRL-censored regression, which is based on a more statistically robust earthquake dataset, yields **M** estimates for central WFZ segments that are very similar to those based on Mo (average difference of 0.04 **M** units; figure 2), avoids potential issues in calculating fault-parallel average displacement, and can be applied to faults in the Wasatch Front region that have limited (if any) paleoseismic displacement data.

To address epistemic uncertainties in **M**, including the displacement-length **M** discrepancy, we selected and weighted regressions that yield (1) relatively large **M** per length––the SRL-censored regression of Stirling and others (2002) and the M_o relation of Hanks and Kanamori (1979)––and (2) relatively small **M** per length––the Wells and Coppersmith (1994) and Wesnousky (2008) SRL-**M** regressions. These **M** regressions characterize the upper and lower bounds of the **M** uncertainty (figure 1), are widely accepted and commonly used for BRP faults, include the most up-to-date and well-vetted earthquake datasets, and yield relatively large magnitudes consistent with the central WFZ paleoseismic data. We have less confidence in regressions that are based on limited earthquake datasets (e.g., normal-fault specific or segment-length regressions), use estimates of displacement or slip rate, which are not well resolved for most BRP faults, or include earthquake slip types (e.g., megathrust events) that are not applicable to the BRP. One exception is for antithetic faults (e.g., the West Valley fault zone) that are truncated at depth by a master fault; for these we used the rupture-area regressions of Wells and Coppersmith (1994) and Stirling and others (2002) to better account for the smaller size of the fault rupture planes.

We weight our preferred **M** regressions according to fault type: *A*, *B*, and *C* (table 1). For *A* faults, which include segmented faults that have sufficient displacement data for calculating M_o (e.g., the central WFZ), we heavily weighted the M_o and SRL-censored regressions as they yield moment-balanced recurrence intervals for central WFZ segments that are most consistent with estimates based on paleoseismic data. We applied similar weights to the regressions for type *B* faults, which are long, segmented faults that have limited average displacement data, but possibly a similar displacement-length scaling to that of the central WFZ. To determine average displacement (and thus, M_o) for *B* faults, we used an average-displacement–length linear regression calculated for the central WFZ (AD = 0.044 L) based on segment length and the mean vertical displacement for each of the central five segments. Type *C* faults consist of relatively short, unsegmented faults that generally lack paleoseismic displacement information. As a result, we are less confident that their rupture behavior (e.g., M_o release and **M** per SRL) is similar to that for *A* faults, and chose not to estimate average displacement using our central WFZ average-displacement–length relation. For *C* faults, we excluded the M_o regression and weighted the remaining regressions (Stirling and others, 2002; Wells and Coppersmith, 1994; Wesnousky, 2008) equally because of uncertainty in whether regressions yielding larger or smaller **M** are more applicable to *C* faults, and to adequately bracket larger epistemic uncertainties in estimating **M** for these less well understood faults. For antithetic faults, we equally weighted the two rupture area regressions.

Our evaluation, selection, and weighting of **M** regressions for faults in the Wasatch Front region have helped to address epistemic uncertainties in estimating characteristic magnitude, including those related to a displacement- versus length-based **M** discrepancy. Ultimately, new self-consistent relations that address these inconsistencies, which are known to exist for other areas of the BRP (e.g., Mason, 1996; Olig and others, 1997), need to be developed. For now, our preference is for the most statistically robust regressions stemming from global, all-fault-type earthquake data (table 1), which can be applied in other regional earthquake-hazard assessments in the BRP.

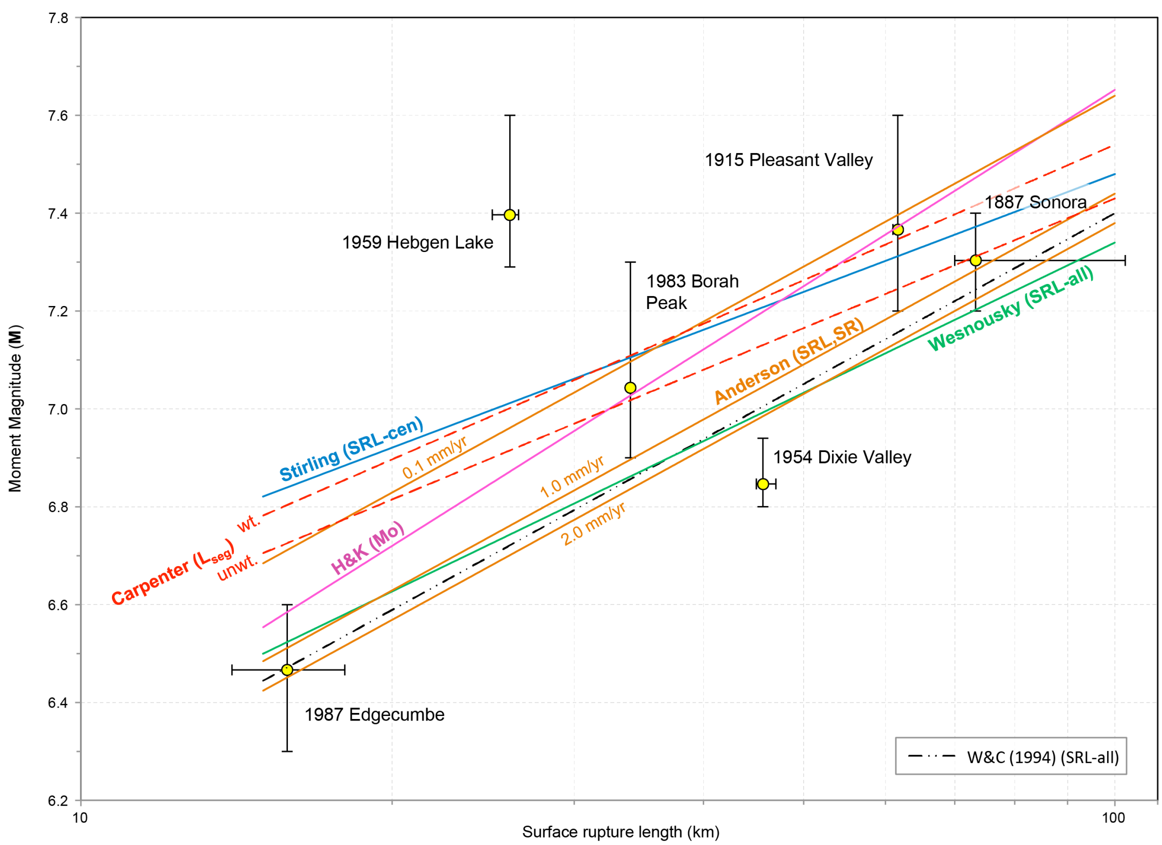

Figure 1. *Comparison of several historical regressions on **M** with six historical large-magnitude normal-faulting earthquakes. The M_o-**M** curve of Hanks and Kanamori (1979) uses the L_{seg}-AD scaling relation developed for the central WFZ by the WGUEP. The **M** regressions based on both SRL and SR of Anderson and others (1996) assumes SR values of 0.1, 1.0, and 2.0 mm/yr. For the L_{seg}-**M** regressions (Carpenter and others, 2012), both weighted (W) and unweighted (UW) curves of are shown. SRLs and **M**s for the historical earthquakes are based on values reported in Wells and Coppersmith (1994), Stirling and others (2002), and Wesnousky (2008). For the 1887 Sonora, Mexico earthquake, the maximum SRL is 102 km (Suter, 2006).*

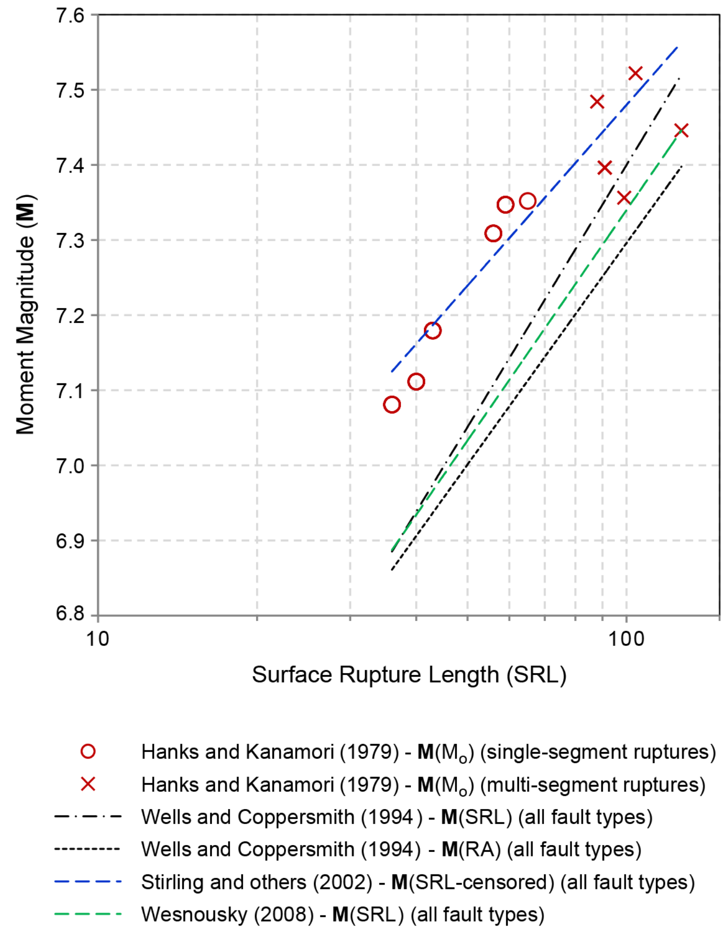

***Figure 2. M** for single- and multi-segment ruptures on the central WFZ based on estimates of M_o (using regression of Hanks and Kanamori, 1979), which compares well with the censored-instrumental SRL-**M** regression of Stirling and others (2002). For single-segment ruptures, these **M** estimates are on average about 0.2 units greater than those based on SRL-**M** and RA-**M** regressions developed by Wells and Coppersmith (1994) and Wesnousky (2008).*

***Table 1.** Moment-magnitude regressions and weights selected by the WGUEP for Wasatch Front faults.*

Magnitude regression[1]			Regression parameters[2]			Wasatch Front fault category[3]			
			N	R^2	σ	A	B	C	AF
Hanks and Kanamori (1979)	M_o, all	$2/3\log(M_o)-10.7$	NR	NA	NA	0.45	0.4	0	-
Stirling and others (2002) (censored instrumental)	SRL, all	5.88+0.80log(SRL)	50	NR	0.3	0.45	0.4	0.34	-
Wesnousky (2008)	SRL, all	5.30+1.02log(SRL)	27	0.81	0.28	0.05	0.1	0.33	-
Wells and Coppersmith (1994)	SRL, all	5.08+1.16log(SRL)	77	0.89	0.28	0.05	0.1	0.33	-
Stirling and others (2002) (censored instrumental)	RA, all	5.09+0.73log(RA)	47	NR	0.26	-	-	-	0.5
Wells and Coppersmith (1994)	RA, all	4.07+0.98log(RA)	148	0.95	0.24	-	-	-	0.5

[1] M_o – seismic moment, RA – rupture area, SRL – linear surface rupture length. All – implies regressions based on strike-slip, normal, and reverse faulting earthquakes.

[2] N is number of earthquakes; R^2 is regression coefficient; σ is standard deviation in magnitude. NA - not applicable. NR - not reported.

[3] Wasatch Front fault categories: *A* – segmented with good displacement data, *B* – segmented with limited displacement data, *C* – unsegmented with limited displacement data, AF – antithetic fault pairs where the down-dip width of the secondary fault is truncated by the primary (master) fault at a relatively shallow seismogenic depth.

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The following is a PDF version of the authors' PowerPoint presentation.

Analysis and Selection of Magnitude Relations for the Working Group on Utah Earthquake Probabilities

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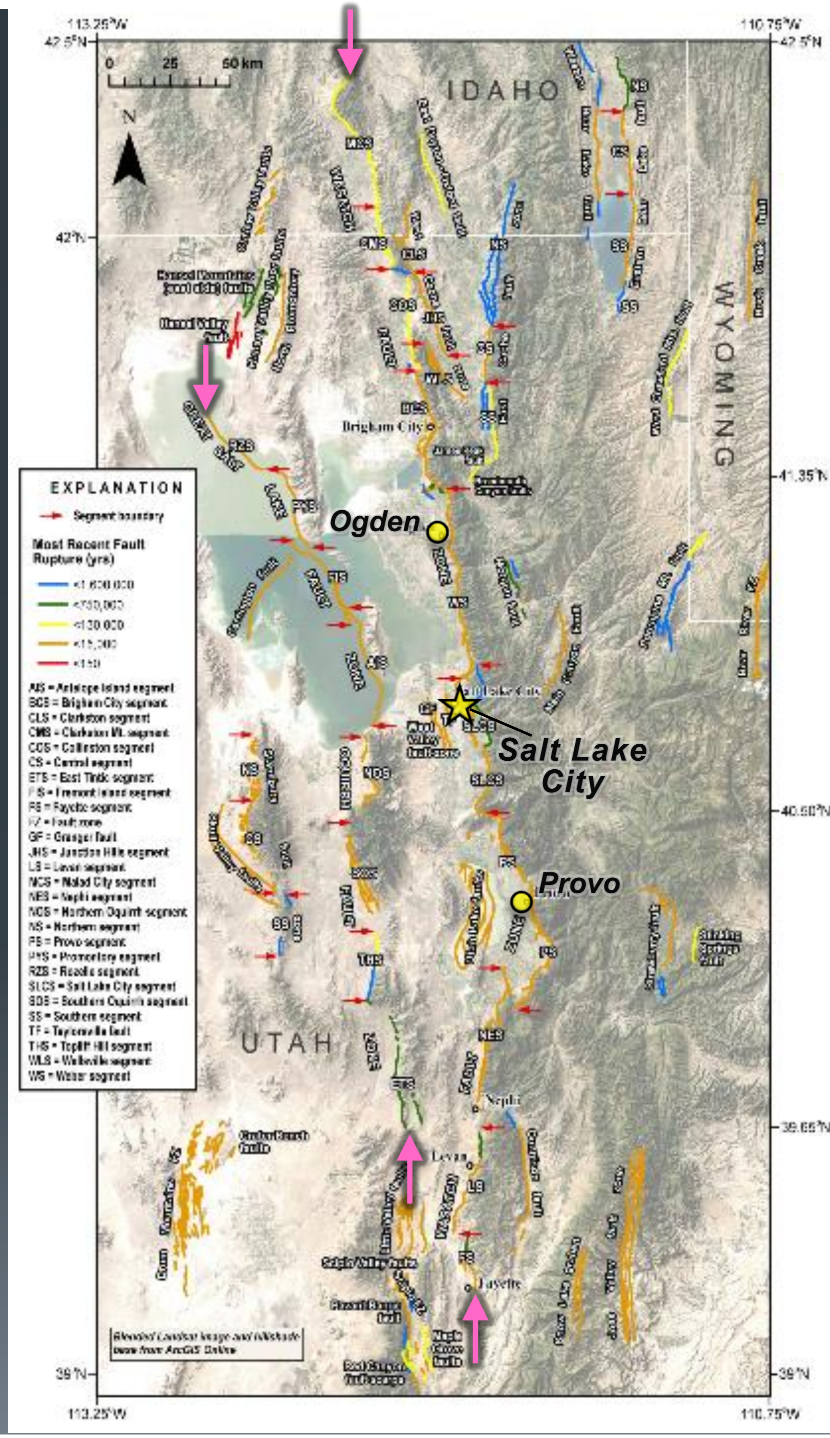
Basin and Range Province Seismic Hazards Summit III – January 9, 2015

Introduction

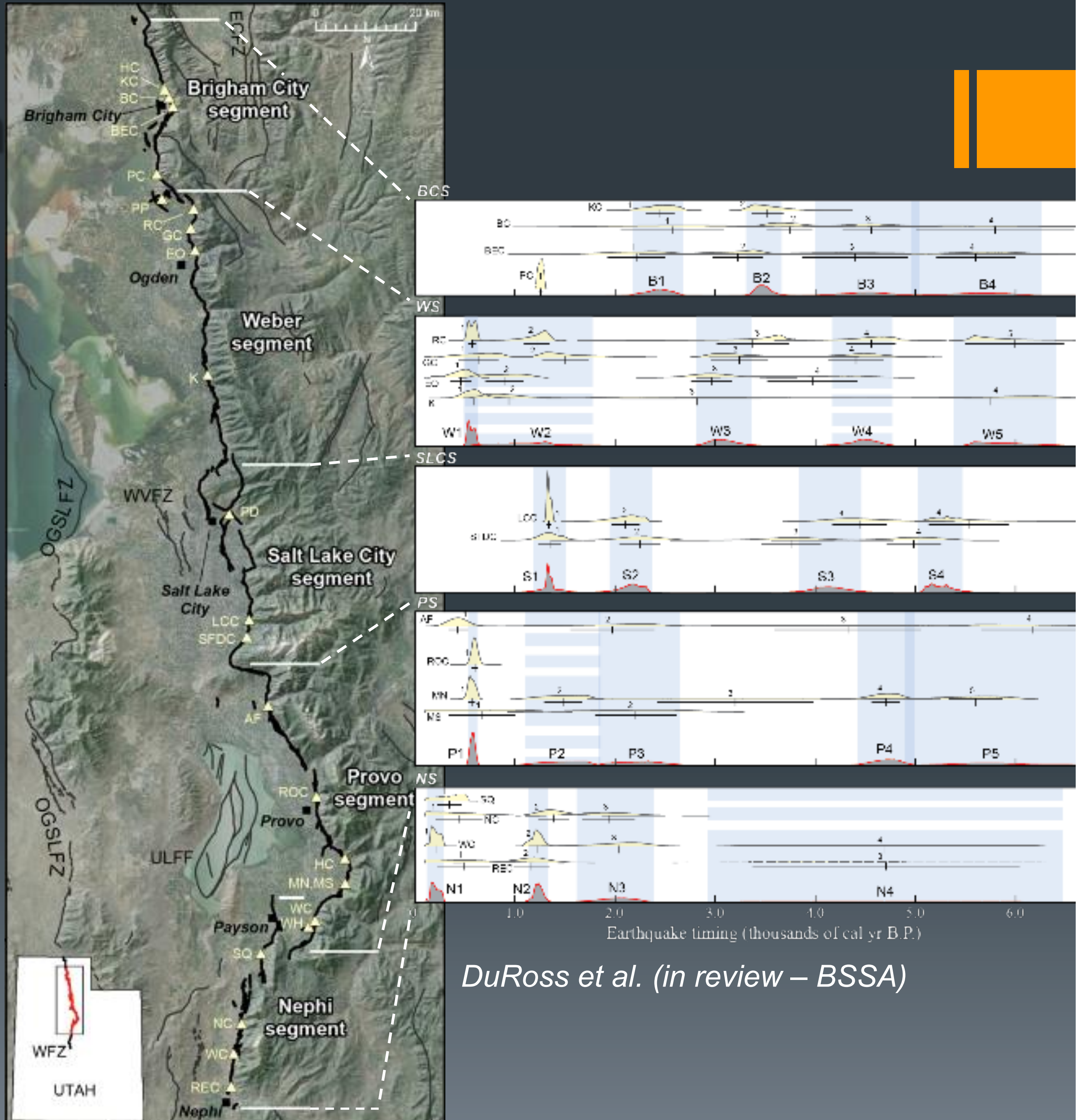
- ➢ *Working Group on Utah Earthquake Probabilities*
  - Calculate time-independent and –dependent earthquake probabilities (**M** ≥6 and ≥6.75) for the Wasatch Front region
  - Source model: 47 faults, including the longest and most hazardous faults, the Wasatch and Oquirrh-Great Salt Lake fault zones

Wong et al. (in prep) – Earthquake Probabilities for the Wasatch Front region: Utah, Idaho, and Wyoming



Introduction

- *Wasatch fault zone*
  - Five central segments
  - Paleoseismic data in support of ≥22 surface-faulting earthquakes since ~6 ka



DuRoss et al. (in review – BSSA)

Introduction

Issues at hand:

1. Which fault parameters & regressions should be used for estimating moment magnitude (**M**)?

2. How should these regressions be applied to faults with varying amounts/ qualities of paleoseismic data?

3. What is the nature of the discrepancy between **M** based on fault length and **M** based on displacement or seismic moment? How should it be handled in the WGUEP study?

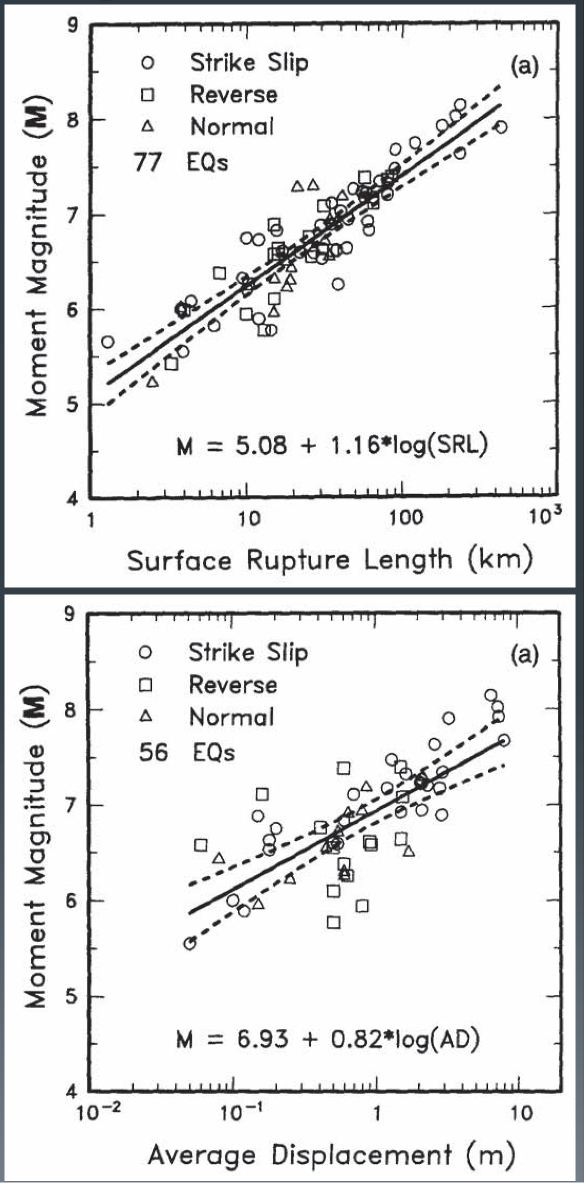
Acronym Overload:

- SRL – Surface rupture length
- L_{sub} – Subsurface rupture length
- L_{seg} – Segment length
- AD – Average displacement
- MD – Maximum displacement
- W – Down-dip rupture width
- RA – Rupture Area
- M_o – Seismic Moment
- **M** – Moment magnitude

Background: Seismic Moment (M_o) & **M**

- ***M_o** = m*RA*AD* (Aki, 1966)
  - RA = L_{sub}*W (or SRL*W)
  - *AD* = Average slip on fault *(average dislocation over area of fault surface)*
  - *m* = crustal rigidity (3 x 10^{11} dyne-cm)
  - **M** = (2/3)log M_o–10.7 (Hanks & Kanamori, 1979)

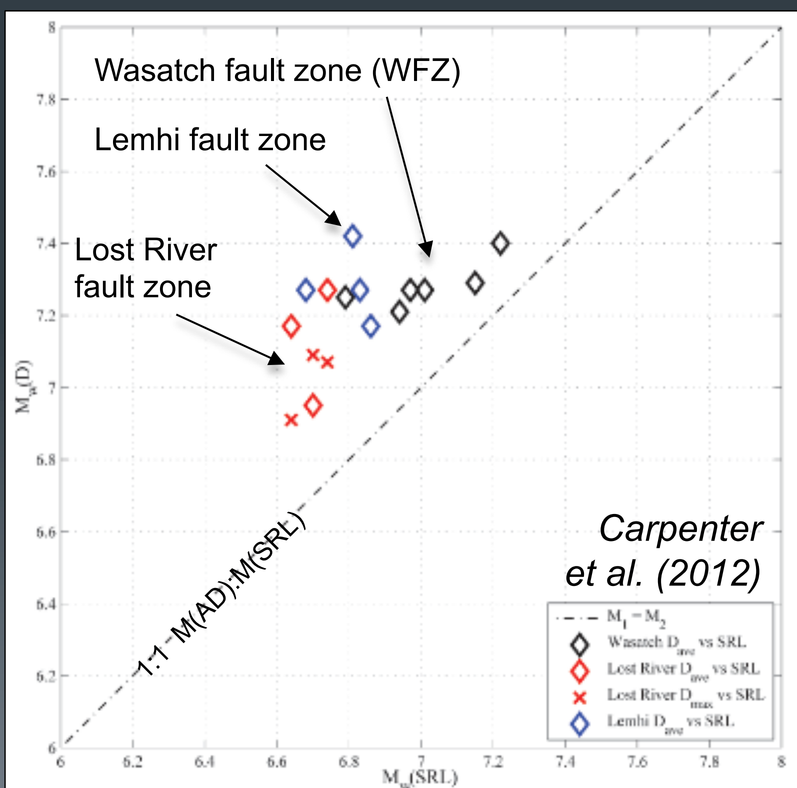
- Empirical linear regressions (Wells & Coppersmith, 1994 – WC94)
  - **M** regressions on SRL, RA, AD, MD, for strike-slip, reverse, normal, and all-slip types
  - WC94 recommended all-slip-type regressions (statistically more robust)
    - All-slip types: n = 56-148
    - Normal-type: n = 12-22

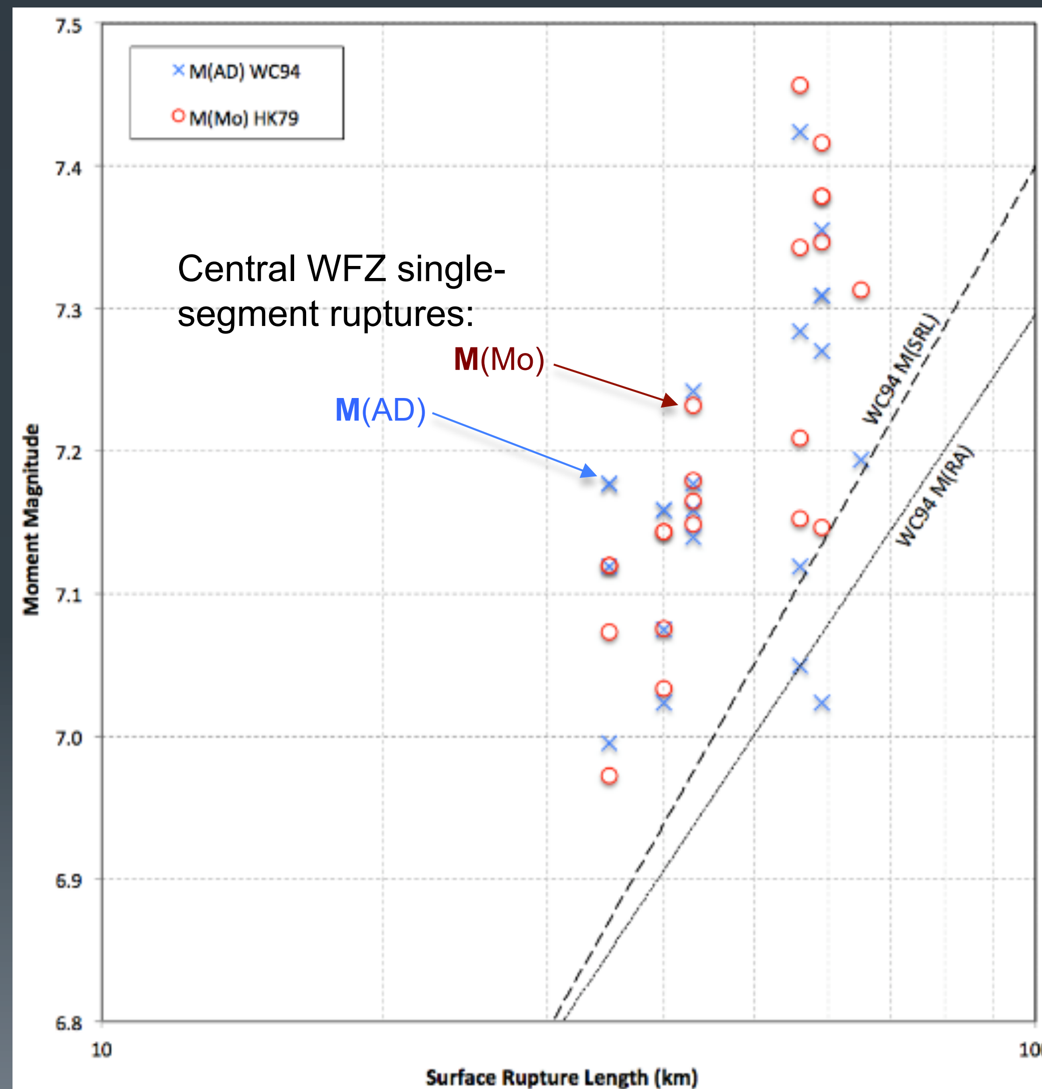


SRL and AD regressions of Wells & Coppersmith (1994)

SRL vs. AD/M_o Discrepancy in **M**

- ***M****(AD) and* ***M****(Mo) greater than M(SRL) or M(RA)*
  - For WFZ, average difference in **M** of ~0.2





Potential Sources of the **M** Discrepancy

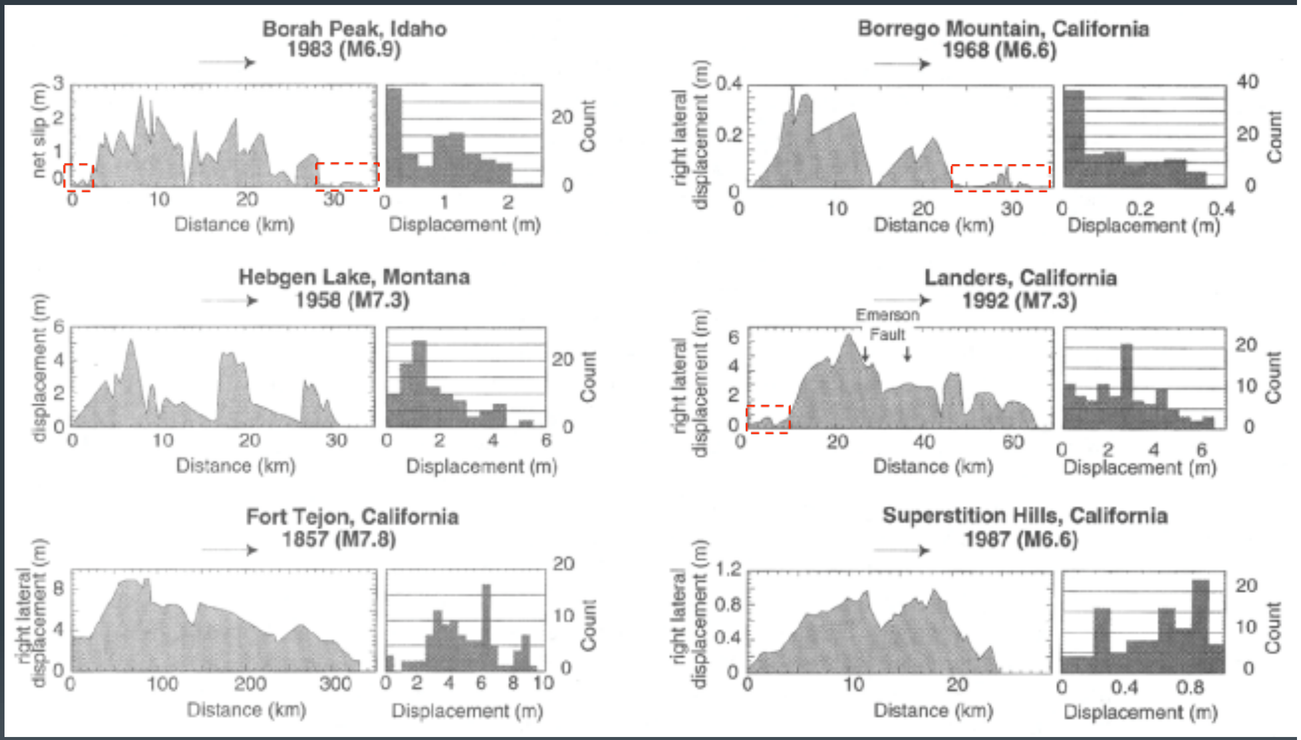
- *Issues with the inputs?*
  - Underestimated SRL
  - Overestimated AD. *Do paleoseismic displacement observations reasonably approximate subsurface slip?*
  - Fault dip & seismogenic depth

- *Issues with regressions?*
  - Inconsistencies in defining/using AD or SRL
  - Scaling issues?

- *Other: large stress drop earthquakes?*

Potential Input Issues: SRL

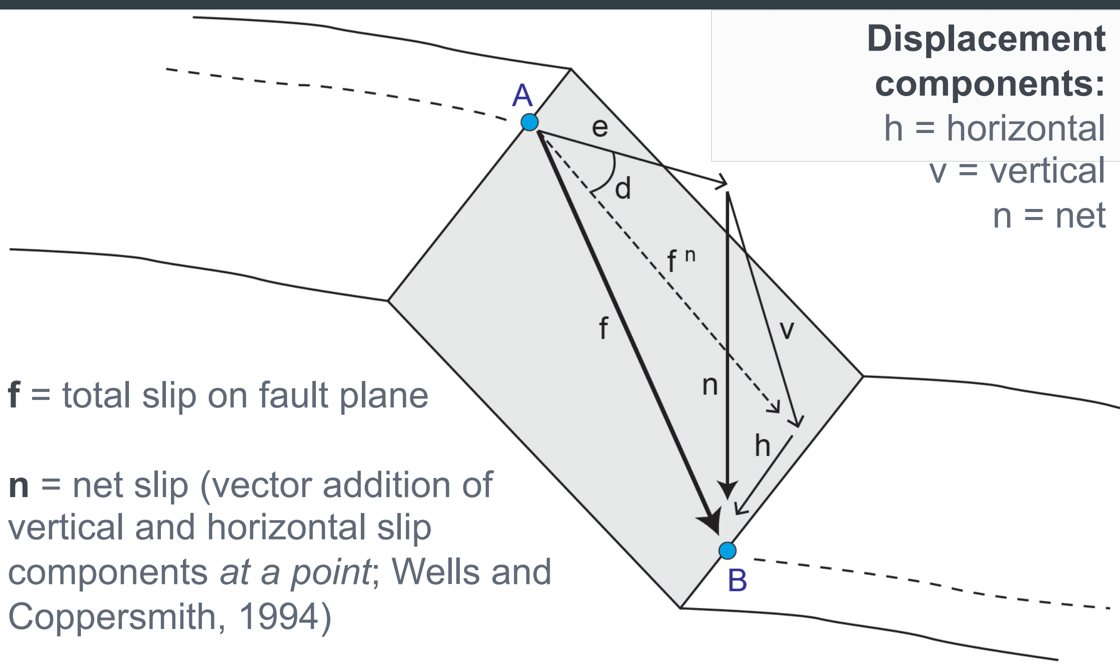
- *SRL – how likely that full rupture length observed?*
  - Erosion or burial of small scarps at rupture ends
  - Multi-segment ruptures
- *For long, segmented faults*
  - Is segment length (L_{seg}) a reasonable estimate of SRL?



Historical earthquake displacement profiles; Hemphill-Haley & Weldon (1999)

Potential Input Issues: Displacement

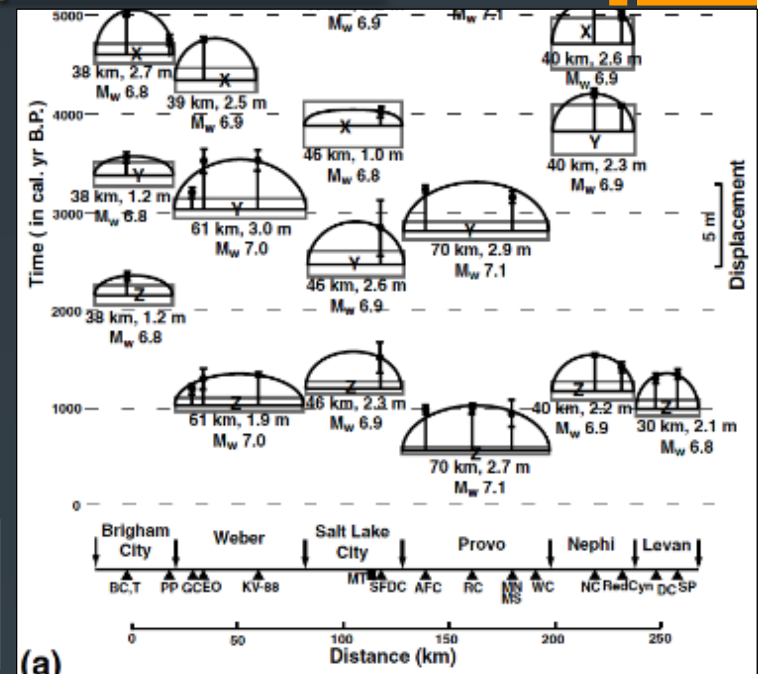
- *Net vs. fault displacement*
  - M_o relation uses fault slip (if d<90°);
  - **M** regressions use net slip (v, h, or v+h)
- *From point displacements to AD*
  - *# observations?*
  - *Segmentation model?*



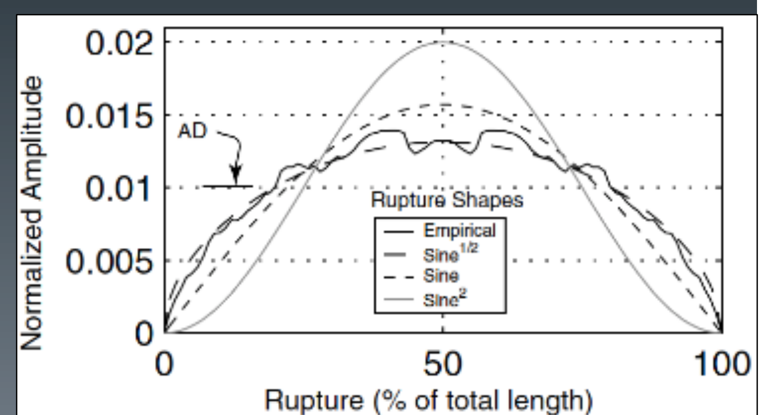
Displacement components:
h = horizontal
v = vertical
n = net

f = total slip on fault plane

n = net slip (vector addition of vertical and horizontal slip components *at a point*; Wells and Coppersmith, 1994)



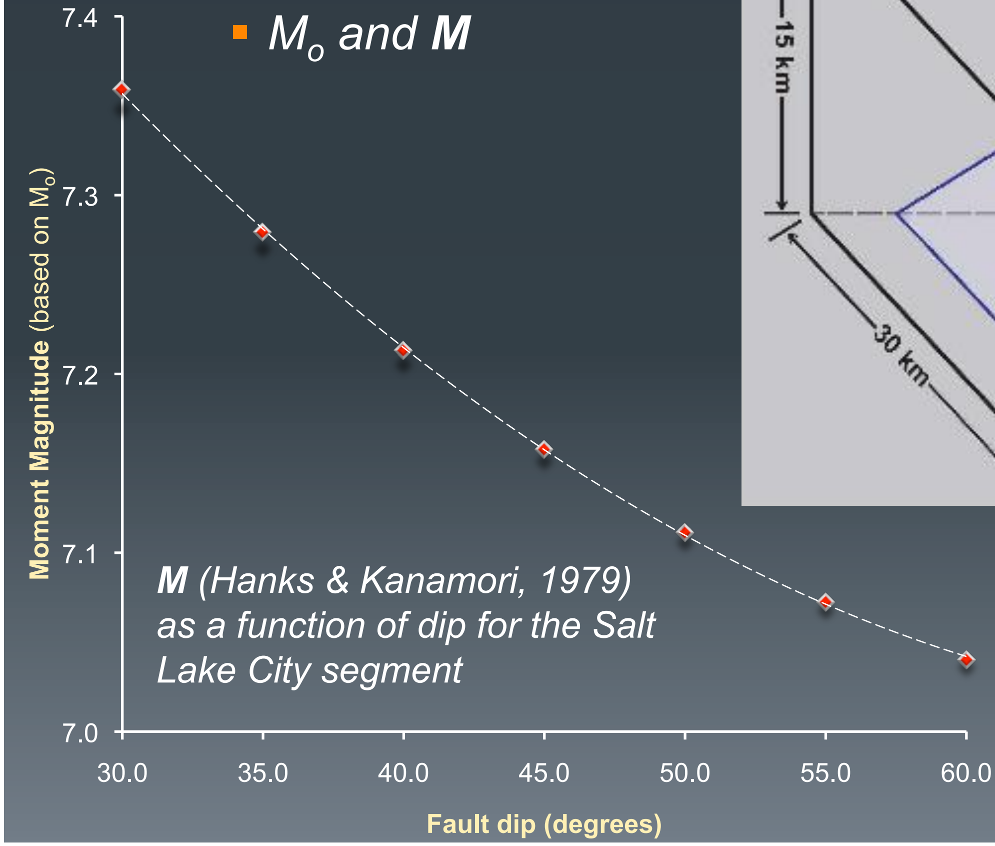
Chang & Smith (2002)



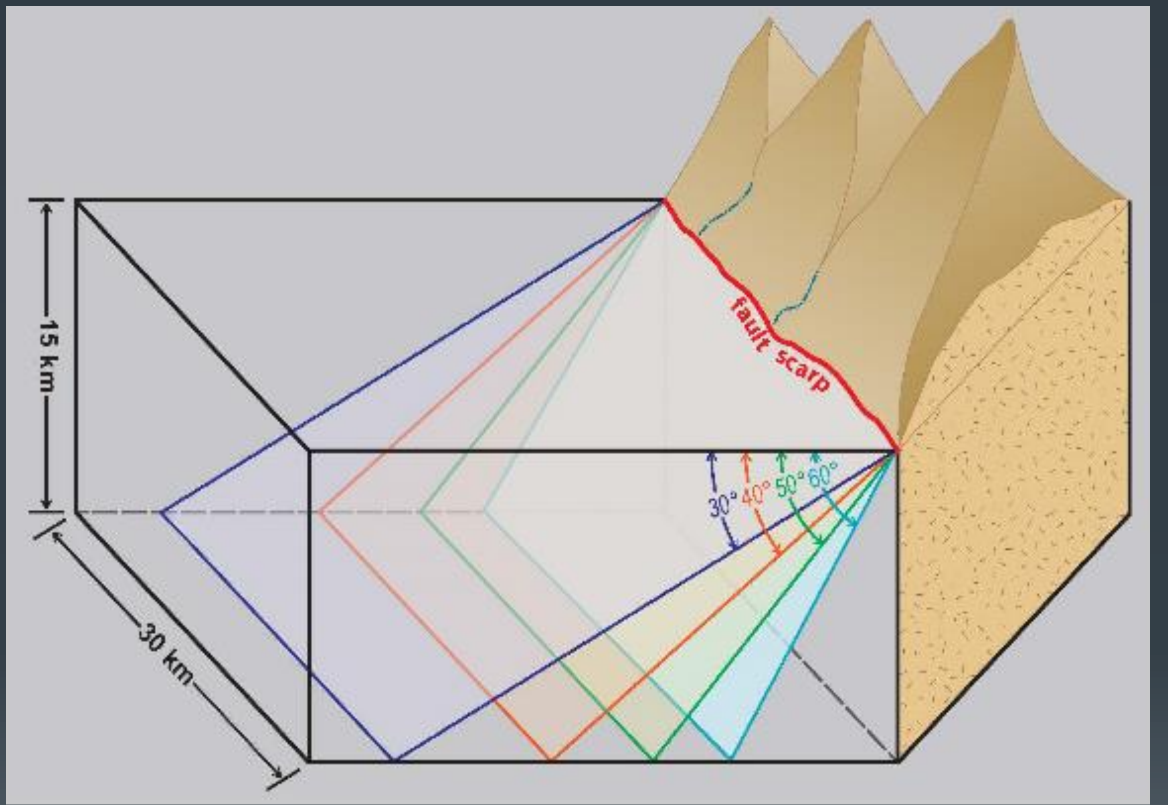
Biasi & Weldon (2009)

Potential Input Issues: Fault Geometry

- *Fault dip affects:*
  - *Rupture area*
  - *Fault-parallel displacement*
  - *M_o and **M***



M *(Hanks & Kanamori, 1979) as a function of dip for the Salt Lake City segment*

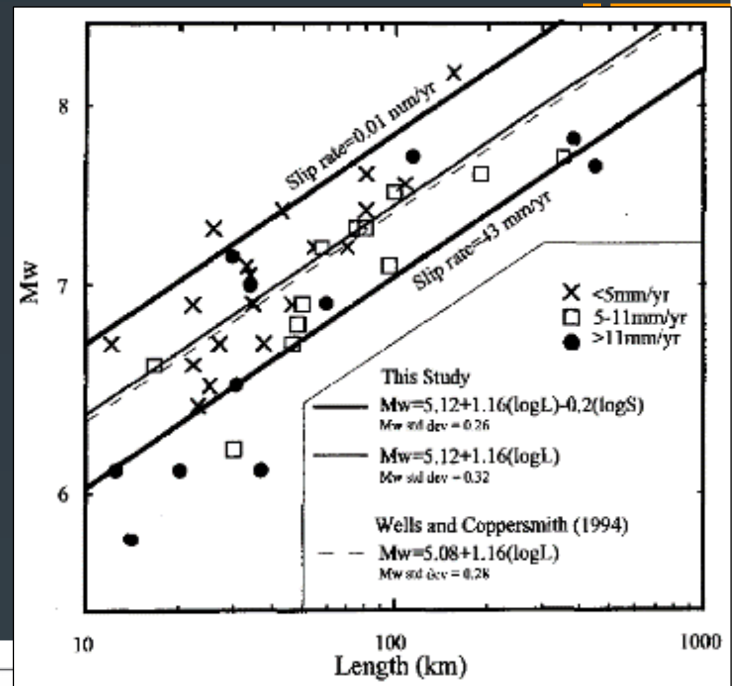


Wong et al. (in prep)

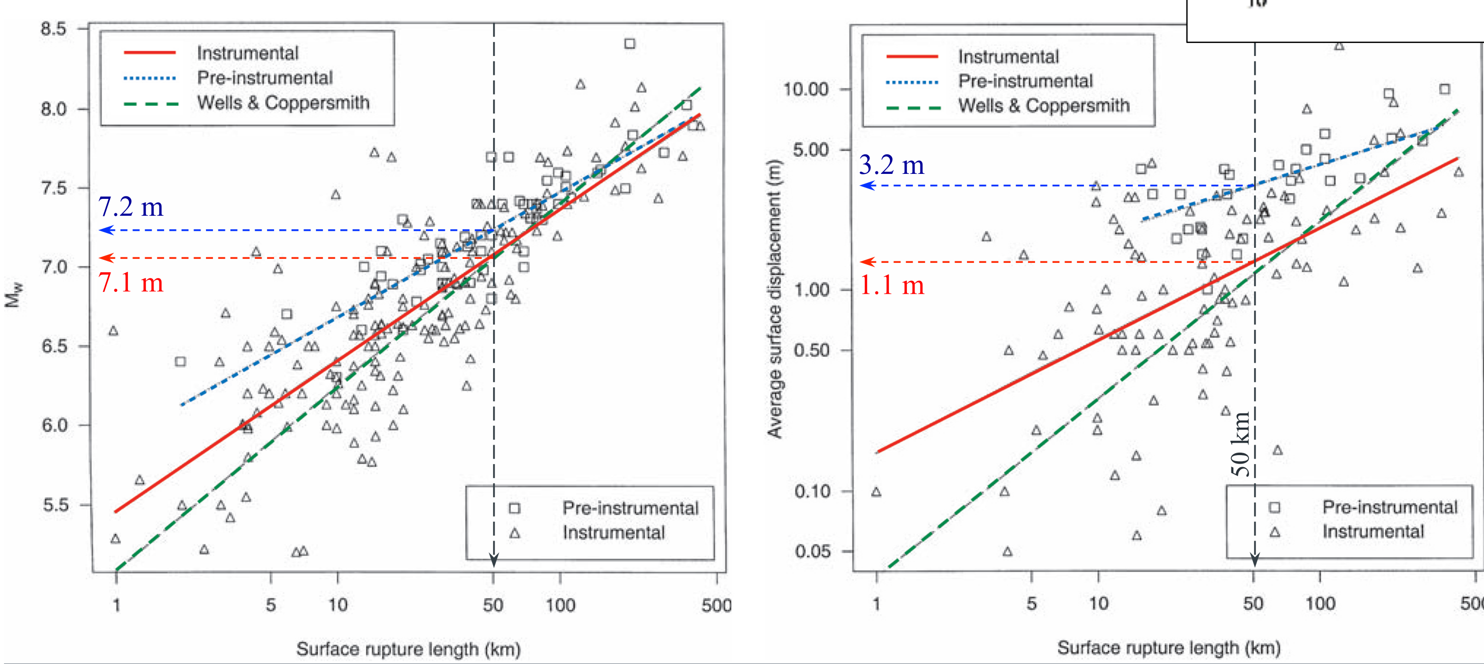
Assumptions:
SRL: 40 km
Seismogenic depth: 15 km

Potential Scaling Issues

- *Different scaling relations for:*
  - Slip type (WC94)
  - Slip rate/tectonic environment (Anderson et al., 1996)
  - Instrumental vs. pre-instrumental (including prehistoric) (Stirling et al., 2002)



Anderson et al. (1996)



Modified from Stirling et al. (2002)

Addressing the **M** Discrepancy

- *1. Use a corrected AD or MD*
  (Hemphill-Haley & Weldon, 1999)

- *Pros*
  - Avoids issue of rupture preservation
  - Correction based on # samples and % of rupture sampled

- *Cons*
  - Large uncertainties if sample # <5
  - % of rupture studied?
  - Introduces error in measuring AD/MD
  - WC94 AD and MD regressions are not as statistically robust as SRL/RA regressions

Statistical Parameters for Use with Varying Sample Analyses

Number of Samples	Percent Fault Sampled	Upper Value (UVCDS)	Mode Value (MVCDS)	Lower Value (LVCDS)
	10	0.08	0.99	2.35
	25	0.14	0.86	2.25
2	50	0.29	0.74	2.17
	75	0.29	0.88	2.03
	100	0.12	1.07	1.94
	10	0.09	0.89	2.31
	25	0.19	0.84	2.15
3	50	0.4	0.74	1.98
	75	0.43	0.81	1.88
	100	0.27	0.96	1.77
	10	0.09	0.99	2.32
	25	0.23	0.68	2.11
4	50	0.45	0.67	1.92
	75	0.5	0.88	1.76
	100	0.36	1.05	1.69
	10	0.09	0.97	2.31
	25	0.21	0.78	2.17
5	50	0.42	0.74	1.95
	75	0.45	0.81	1.86
	100	0.3	0.97	1.73

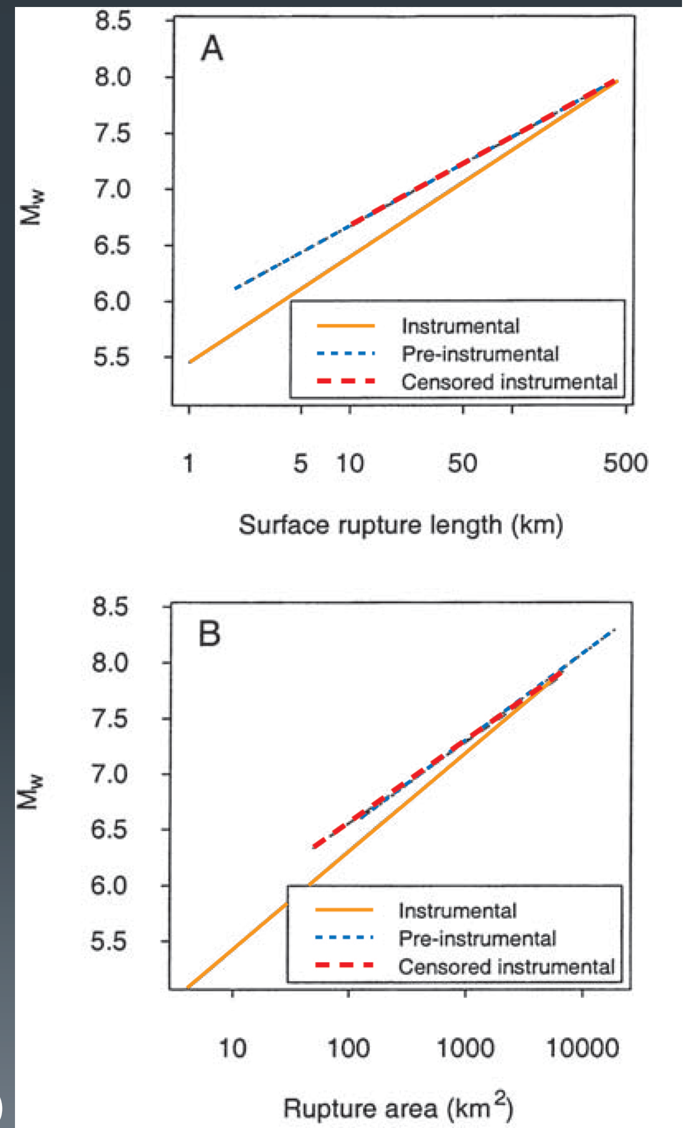
M *= 6.93 + 0.82 * log (AD * MVCDS);*
Hemphill-Haley & Weldon (1999)

Addressing the **M** Discrepancy

- *2. Use a censored-instrumental earthquake database* (Stirling et al., 2002)

- *Pros*
  - Instrumental regressions that correspond well with preinstrumental/prehistoric data
  - Based on earthquake data updated from Wells & Coppersmith (1994), but filtered for earthquake/rupture size
  - Can be applied to faults with little/no displacement data

- *Cons*
  - Limited EQ database (filtered for SRL <10 km, RA <200 km^2, AD <2 m, **M** <6.5)
  - Applicable to regional investigations?



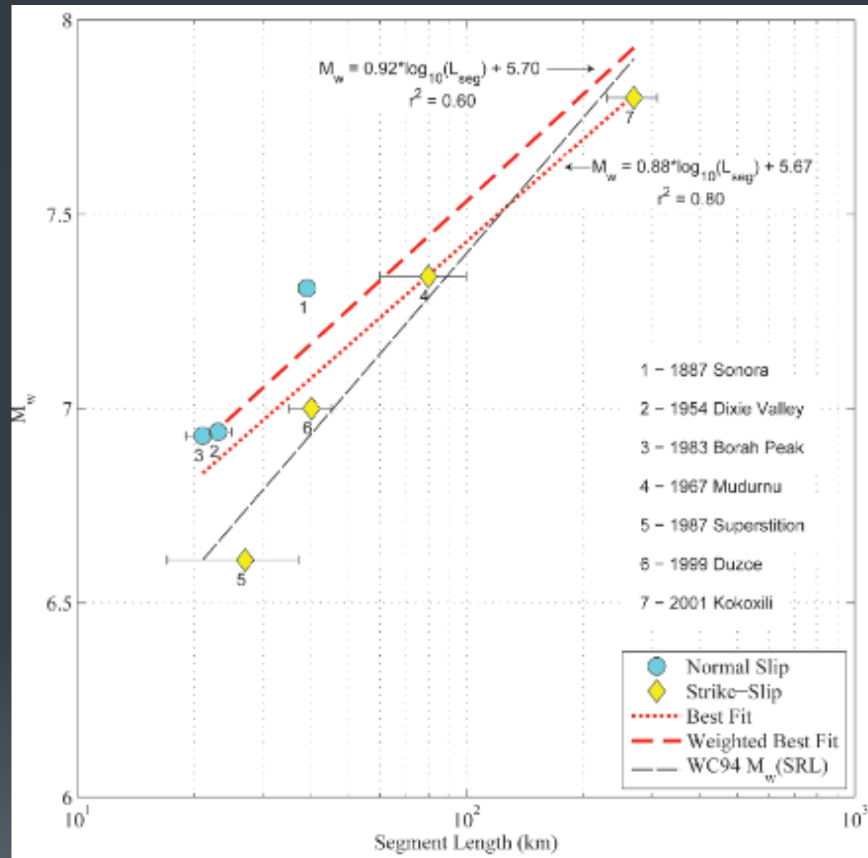
Stirling et al. (2002)

Addressing the **M** Discrepancy

- *3. For segment faults, calculate **M** as a function of segment length (L_{seg}) rather than SRL* (Carpenter et al., 2012)

- *Pros*
  - Segment length is generally known

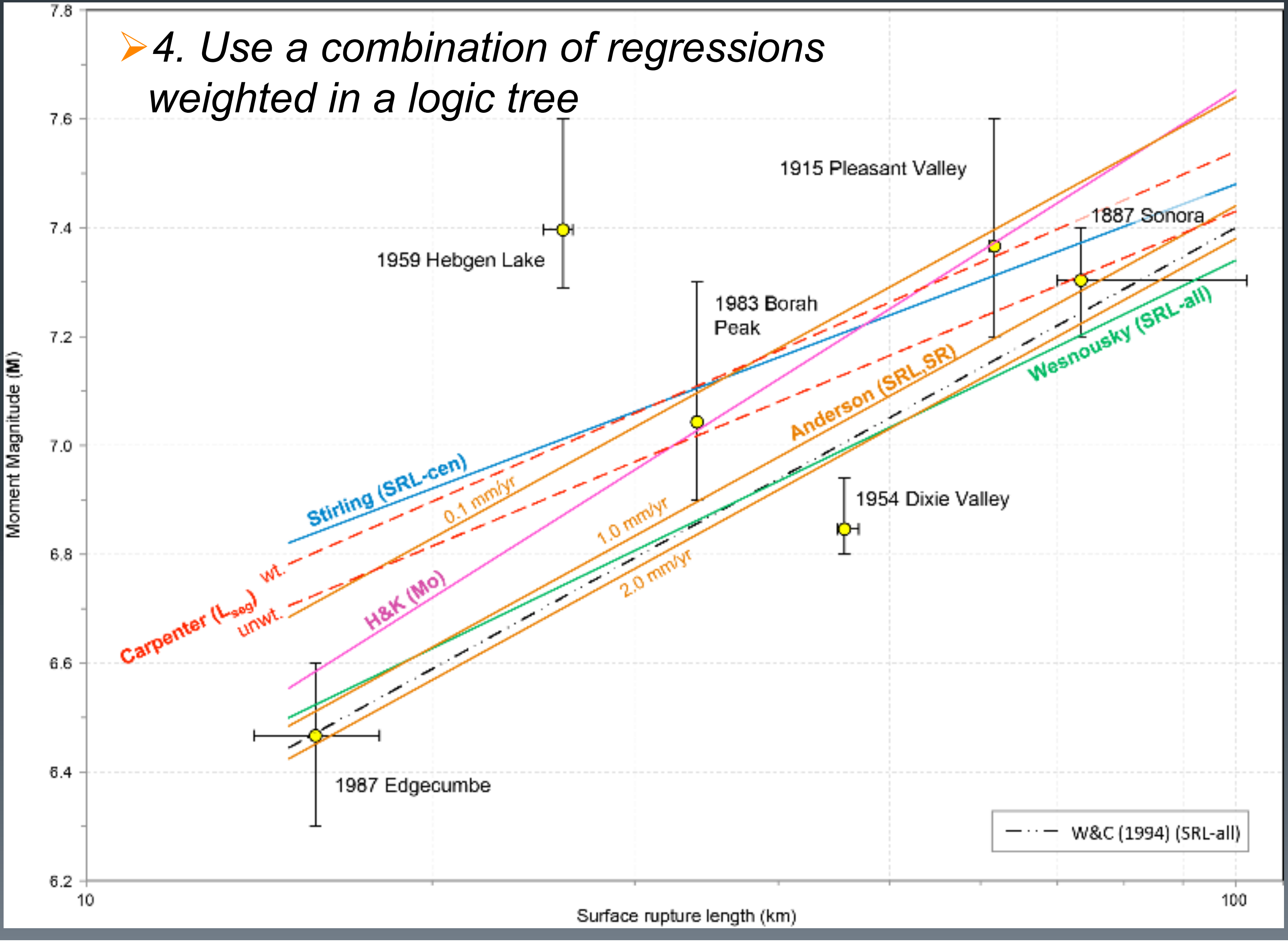
- *Cons*
  - Regression based on very limited data
  - Measurement of segment length is complicated by other geometric complexities along the fault



L_{seg} regressions of Carpenter et al. (2012)

Addressing the M Discrepancy

- *4. Use a combination of regressions weighted in a logic tree*



Approach of the WGUEP

- *We evaluated 19 M regressions, and preferred those that*
  1. Characterize the upper and lower bounds of the M uncertainty
  2. Are widely accepted and used in the BRP
  3. Include the most up-to-date and well-vetted earthquake datasets

- *We have less confidence in regressions that*
  1. Are based on limited earthquake datasets (e.g., normal-fault specific or L_{seg} regressions)
  2. Use estimates of displacement or slip rate, which are not well resolved for most BRP faults
  3. Include earthquake slip types (*e.g.*, megathrust events; e.g., Leonard, 2010) that are not applicable to the BRP

Approach of the WGUEP

➢ *Assumptions*

1. Rupture length
   - SRL is a reasonable approximation of L_{sub}, but…
   - For long, segmented faults, we know L_{seg}, but not L_{sub} or SRL
   - Uncertainties in rupture length are accounted for by rupture models and defined segment boundary uncertainties

2. Displacement
   - WFZ vertical displacements are a reasonable approximation of subsurface fault slip
   - Long, segmented faults in the study region have similar AD-L and **M**-L scaling as the central Wasatch fault

3. Subsurface fault geometry
   - Seismogenic depth: ~15 km, based on historical earthquake catalog
   - Fault dip: ~50° ± 15°, based on historical BRP earthquakes

Approach of the WGUEP

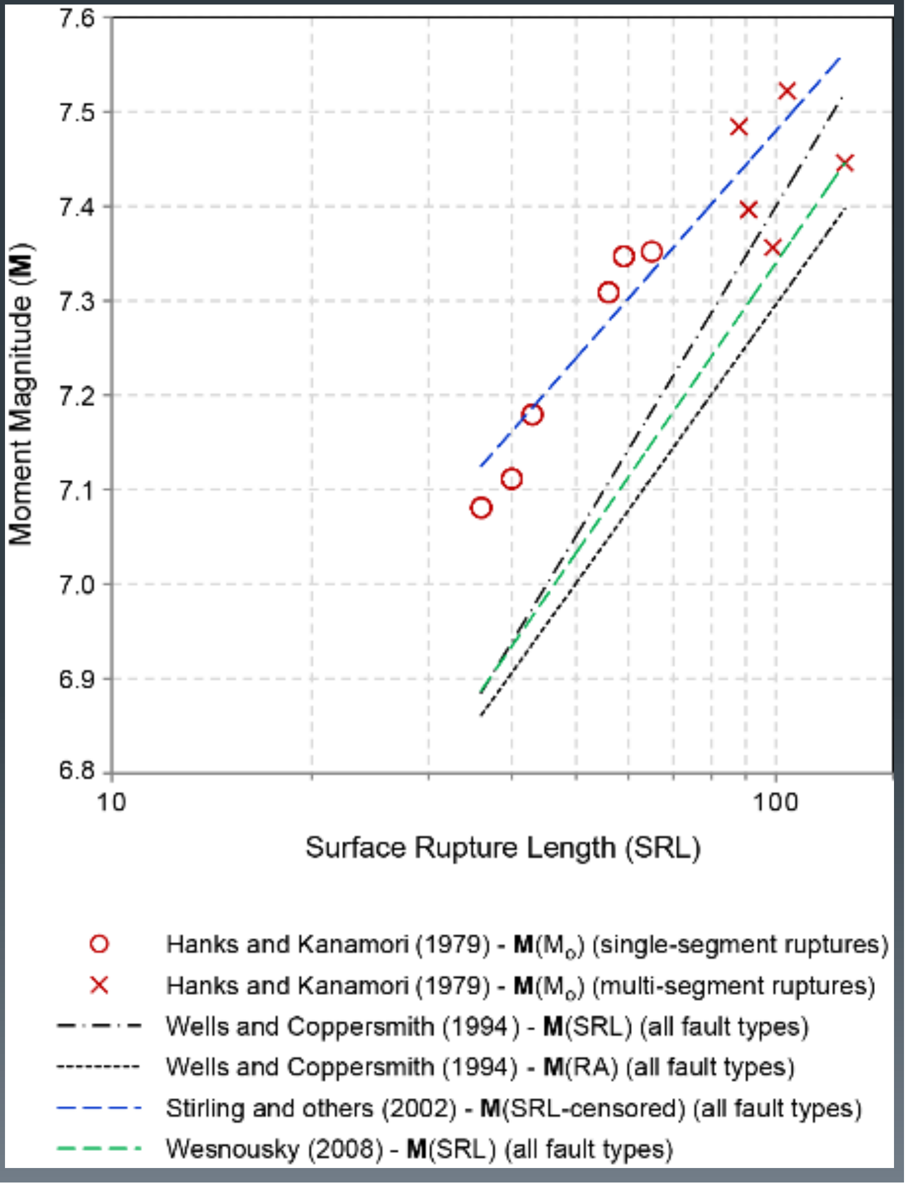
Selection of Regressions:

➢ *Regressions yielding larger **M** per SRL:*

- M_o – Hanks & Kanamori (1979)
- SRL – censored-instrumental; Stirling et al. (2002)

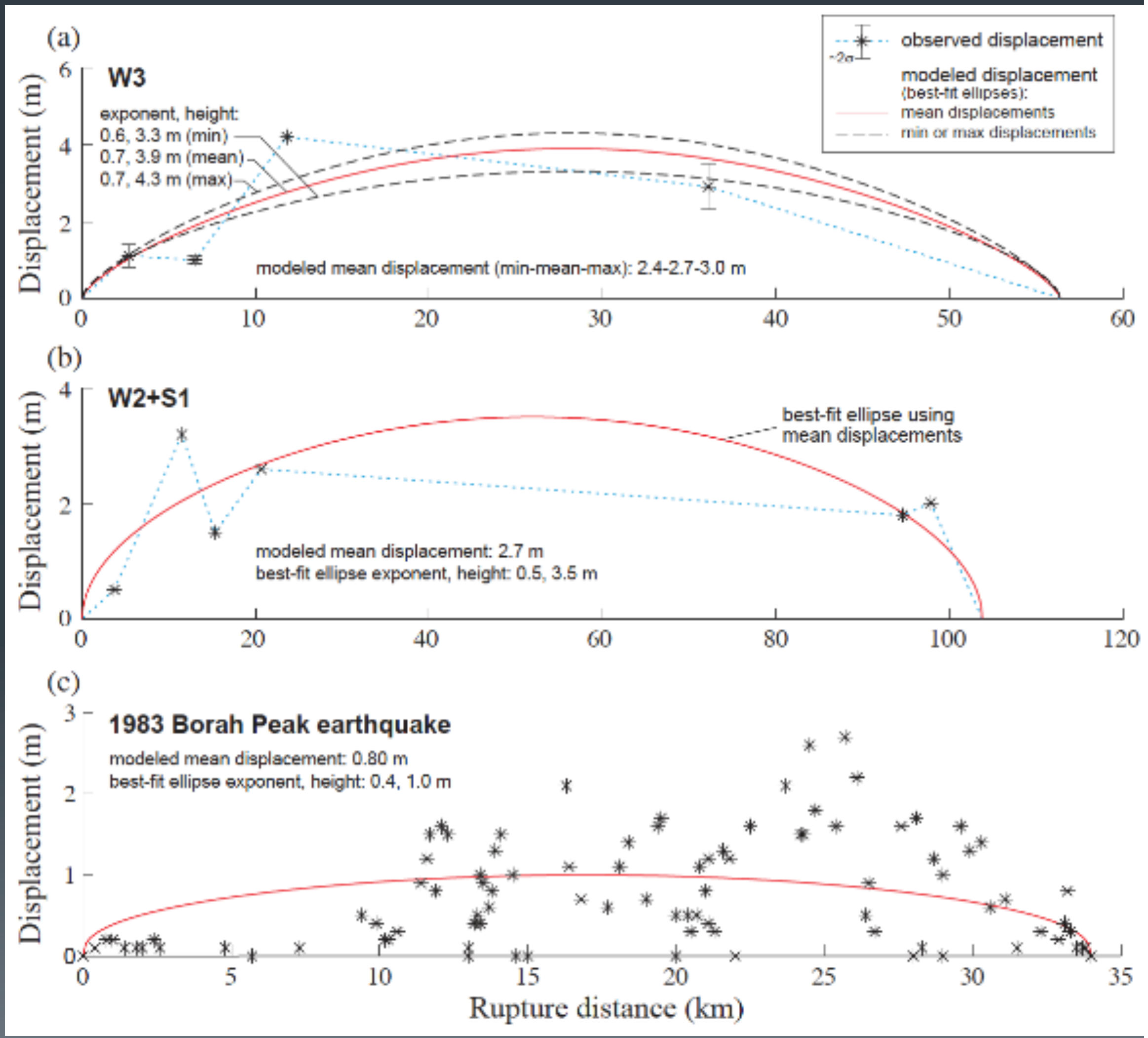
➢ *Regressions yielding smaller **M** per SRL:*

- SRL – Wells & Coppersmith (1994) (all slip types)
- SRL – Wesnousky (2008) (all slip types)



Approach of the WGUEP

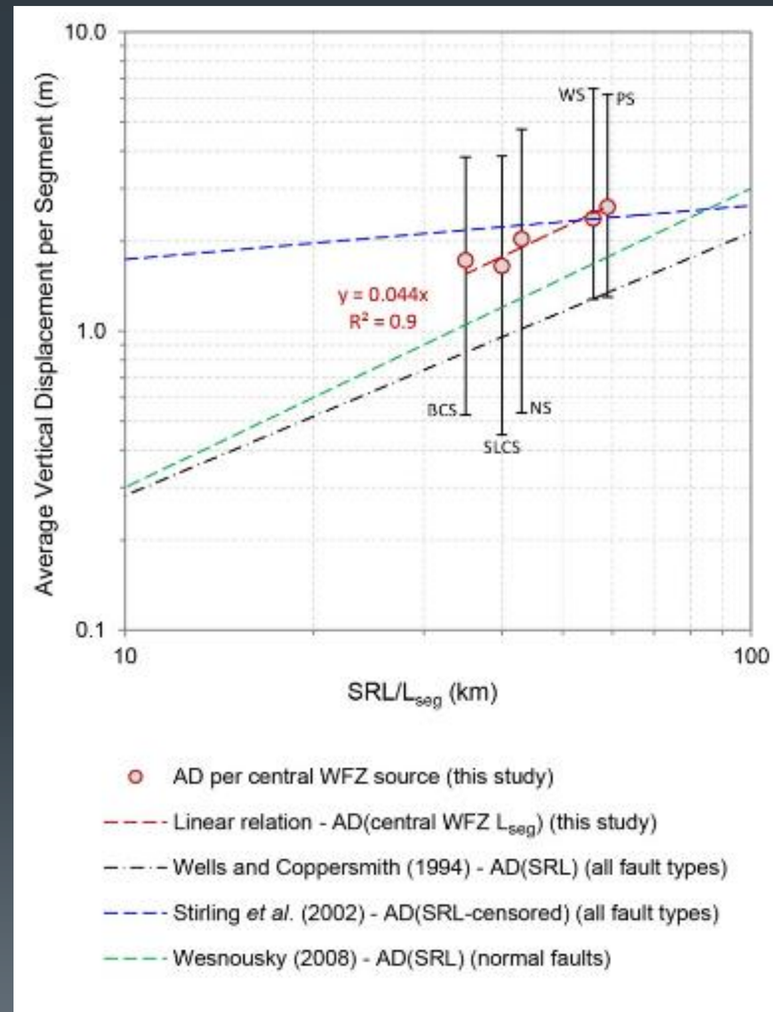
- *Calculation of AD (for M_o)*
  - Best-fit analytical displacement curve (sin(L)^n), after Chang and Smith (2002) and Biasi and Weldon (2009)
  - Both curve height and shape (n) allowed to vary



DuRoss et al. (in review)

Approach of the WGUEP

- *Complication: Should **M**(M_o) be calculated for faults lacking paleoseismic data?*
  - Shorter, unsegmented faults? (no)
  - Long, segmented faults? (yes). We apply a AD-SRL scaling relation based on central WFZ data



M Regressions & Weighting

- *Type A faults* – Wasatch and Oquirrh Great Salt Lake faults
  - Hanks & Kanamori (1979) (M_o) 0.45
  - Stirling et al. (2002) (SRL-censored) 0.45
  - Wesnousky (2008) (SRL) 0.05
  - Wells & Coppersmith (1994) (SRL) 0.05

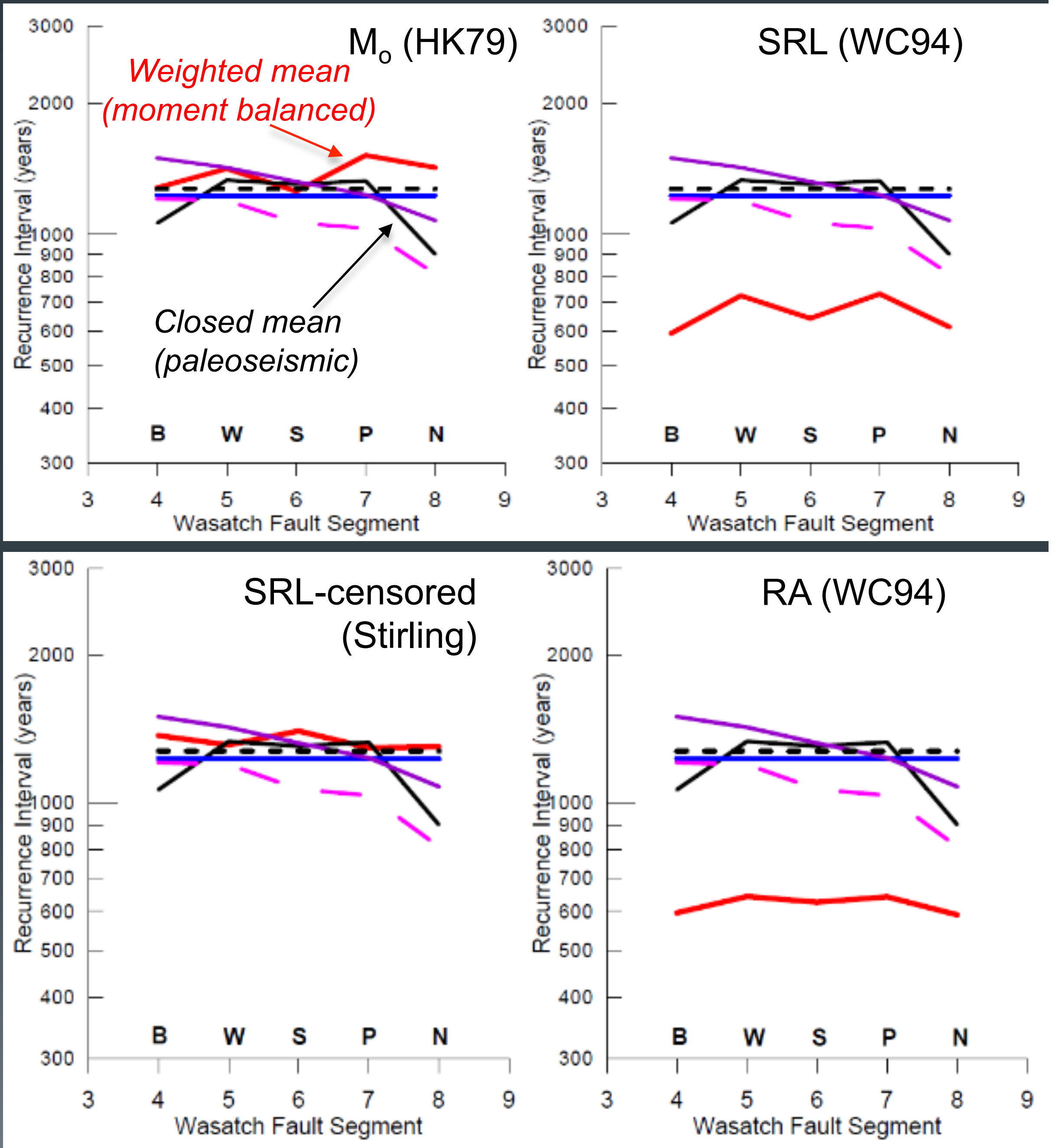
Table 1. Moment-magnitude regressions and weights selected by the WGUEP for Wasatch Front faults

Magnitude regression[1]			Regression parameters[2]			Wasatch Front fault category[3]			
			N	R^2	σ	A	B	C	AF
Hanks and Kanamori (1979)	M_o, all	$2/3\log(M_o)–10.7$	NR	NA	NA	0.45	0.4	0	-
Stirling and others (2002) (censored instrumental)	SRL, all	5.88+0.80log(SRL)	50	NR	0.3	0.45	0.4	0.34	-
Wesnousky (2008)	SRL, all	5.30+1.02log(SRL)	27	0.81	0.28	0.05	0.1	0.33	-
Wells and Coppersmith (1994)	SRL, all	5.08+1.16log(SRL)	77	0.89	0.28	0.05	0.1	0.33	-

Wong et al. (in prep)

Justification

- *Sensitivity studies support larger-**M** regressions*
  - M_o and SRL-censored regressions yield moment-balanced recurrence intervals ≈ paleoseismic recurrence intervals
  - SRL regressions yield moment-balanced recurrence intervals < paleoseismic intervals



WGUEP, unpublished

M Regressions & Weighting

- *Type B faults* – Other long, segmented faults
  - Hanks & Kanamori (1979) (M_o) 0.4
  - Stirling et al. (2002) (SRL-censored) 0.4
  - Wesnousky (2008) (SRL) 0.1
  - Wells & Coppersmith (1994) (SRL) 0.1

Table 1. Moment-magnitude regressions and weights selected by the WGUEP for Wasatch Front faults

Magnitude regression[1]			Regression parameters[2]			Wasatch Front fault category[3]			
			N	R^2	σ	A	B	C	AF
Hanks and Kanamori (1979)	M_o, all	$2/3\log(M_o)-10.7$	NR	NA	NA	0.45	0.4	0	-
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Wells and Coppersmith (1994)	SRL, all	5.08+1.16log(SRL)	77	0.89	0.28	0.05	0.1	0.33	-

Wong et al. (in prep)

M Regressions & Weighting

- *Type C faults* – Everything else (short, unsegmented faults)
  - Hanks & Kanamori (1979) (M_o) 0
  - Stirling et al. (2002) (SRL-censored) 0.34
  - Wesnousky (2008) (SRL) 0.33
  - Wells & Coppersmith (1994) (SRL) 0.33

Table 1. Moment-magnitude regressions and weights selected by the WGUEP for Wasatch Front faults

Magnitude regression[1]			Regression parameters[2]			Wasatch Front fault category[3]			
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Wells and Coppersmith (1994)	SRL, all	5.08+1.16log(SRL)	77	0.89	0.28	0.05	0.1	0.33	-

Wong et al. (in prep)

M Regressions & Weighting

- *Antithetic faults* – E.g., West Valley fault zone
  - Stirling et al. (2002) (RA) 0.5
  - Wells & Coppersmith (1994) (RA) 0.5

Table 1. Moment-magnitude regressions and weights selected by the WGUEP for Wasatch Front faults

Magnitude regression[1]			**Regression parameters[2]**			**Wasatch Front fault category[3]**			
			N	**R^2**	**σ**	**A**	**B**	**C**	**AF**
Hanks and Kanamori (1979)	M_o, all	$2/3\log(M_o)–10.7$	NR	NA	NA	0.45	0.4	0	-
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Wells and Coppersmith (1994)	SRL, all	5.08+1.16log(SRL)	77	0.89	0.28	0.05	0.1	0.33	-
Stirling and others (2002) (censored instrumental)	RA, all	5.09+0.73log(RA)	47	NR	0.26	-	-	-	0.5
Wells and Coppersmith (1994)	RA, all	4.07+0.98log(RA)	148	0.95	0.24	-	-	-	0.5

Wong et al. (in prep)

Conclusions

- Our evaluation, selection, and weighting of **M** regressions for Wasatch Front faults helps to address uncertainties in calculating **M**, including those related to a **M** discrepancy.

- New self-consistent relations that address these inconsistencies (which exist for other areas of the BRP) need to be developed.

- For now, our preference is for the most statistically robust regressions stemming from global, all-fault-type earthquake data, which can be applied in other regional earthquake-hazard assessments in the BRP.

ESTIMATING SURFACE LENGTHS FOR PREHISTORIC RUPTURES IN THE BASIN AND RANGE PROVINCE

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In the Basin and Range Province, estimating surface-rupture lengths of prehistoric earthquakes is commonly challenging because of limited paleoseismic information, complex earthquake rupture patterns (including short-term re-rupturing of faults), overlap of adjacent ruptures, and complex structural patterns of late Quaternary faults.

Historical Basin and Range Province surface-faulting earthquakes exhibit a variety of surface-rupture patterns ranging from single-trace ruptures to small, discontinuous, scattered multiple-fault ruptures. There also has been a remarkable amount of variability in surface expression along individual historical breaks. Prehistoric ruptures in the province had similar variability, and where multiple faults were involved, it takes more work to reconstruct the event. Many larger earthquakes in the province ruptured entire fault zones, which is a target of consideration for paleorupture reconstruction. However, when faults get large (>60 km long), they tend to exhibit segmented earthquake behavior. Another potential complication for paleoseismic interpretation is the documented historical re-rupturing of faults with different sized earthquakes within hours to about 50 years (e.g., Rainbow Mountain fault zone had surface rupture twice—on July 6th in places and again on August 23rd in places (Caskey and others, 2004); Wonder fault had surface rupture in 1903 and 1954 (Slemmons and others, 1959). Trench exposures of prehistoric re-ruptured surface breaks have the potential to appear as one event, and smaller offsets can be overprinted by larger ones. Some sections of historical ruptures have been along overlapping segments, or sections of a fault zone that are ruptured during earthquakes on either side of them; an example is the northern part of the 1954 Dixie Valley, Nevada earthquake rupture, which overlaps with a paleoearthquake rupture to the north (cf., Caskey and others, 1996). Overlap segments are part of both adjacent earthquake paleoruptures, and need to be identified and included in rupture length estimations.

The complexity of surface-fault rupture is also affected by fault maturity. There is a spectrum of fault maturity in the province, ranging from faults that have been active for a long time to structurally emergent, potentially growing, and linking faults. The 1932 M7.1 Cedar Mountain earthquake may be an example of a group of faults that are linking together, but still have a discontinuous, scattered surface rupture pattern; alternatively, this could have been a relatively unique cascading rupture of smaller faults that gives the impression of a larger zone.

Geomorphic expression of paleoearthquake ruptures (big scarps) is one of the easiest identified indicators of the higher displacement parts of a paleorupture, but this works best with younger surface breaks. Unfortunately, part, most, or all of the geomorphic expression of surface ruptures may be indecipherable because of poor initial expression (e.g., surface warping versus discrete faulting or small ground displacement rupture), severe erosion (e.g., ruptures formed in easily eroded materials, monsoonal rain activity, pluvial shoreline erosion and deposition), and/or burial by sediments. In some of these cases, there might be vestiges of surface ruptures still visible, such as alignments of discontinuous scarps, closed depressions or ponds, or captured or deflected young stream channels. Additional paleorupture indicators include relatively fresh bedrock exposures above a fault trace, or the lack of otherwise dominant lichen from a fault facet, but these require fairly detailed field investigations to discover and interpret.

Another common way to study paleoruptures is with trenching investigations, such as the studies conducted along the Wasatch fault zone (Wasatch fault zone studies actually included both trenching and geomorphic investigations). Successful trenching investigations are commonly evolutionary scientific endeavors, requiring skill in locating sites with distinct paleoseismic signals and age control, developing those sites and data, and weaving multiple sites into a paleoseismic interpretation using a number of techniques. The most confident cases can be made when adjacent earthquake segments of a fault zone have differences in the timing of paleoruptures and in rupture behavior (e.g., multiple events within a timeframe along one segment versus a single event on an adjacent segment). When adjacent paleoseismic ruptures are close in age, the precision of dating techniques becomes a limiting factor. A single or a couple of paleoseismic ruptures along a fault might be able to be determined with a year or so effort, but developing the paleoseismic history and extent of ruptures on a fault or fault segment based on trenching investigations can take years to decades to unfold, critically reason through, and document.

Paleoearthquake ruptures may have been complex, only partly preserved at any one site, and may have had some non-characteristic ruptures; so in general, a large effort must be undertaken in paleorupture reconstruction and length estimation, and in the unraveling of multiple paleoearthquake ruptures along a fault zone. Persistent research of many sites using multiple approaches and techniques is commonly required, and can take years to decades to achieve. This level of effort needs to be conducted on many faults within the Basin and Range Province to gain a better understanding of the earthquake behavior of faults through time, and to gain better understanding of the threat from the highest risk faults for probabilistic and deterministic seismic-hazard analyses.

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Caskey, S.J., Bell, J.W., Ramelli, A.R., and Wesnousky, S.G., 2004, Historical surface faulting and paleoseismology in the area of the 1954 Rainbow Mountain-Stillwater earthquake sequence, central Nevada: Bulletin of the Seismological Society of America, v. 94, p. 1255-1274.

Caskey, S.J., Wesnousky, S.G., Zang, P., and Slemmons, D.B., 1996, Surface faulting of the 1954 Fairview Peak (M_s 7.2) and Dixie Valley (M_s 6.8) earthquakes, central Nevada: Bulletin of the Seismological Society of America, v. 86, p. 761-787.

Slemmons, D.B., Steinbrugge, K.V., Tocher, D., and Oakeshott, G.B., 1959, Wonder, Nevada, earthquake of 1903: Bulletin of the Seismological Society of America, v. 49, p. 251-265.

The following is a PDF version of the author's PowerPoint presentation.

Estimating Surface Lengths for Prehistoric Ruptures in the Basin and Range Province

Craig M. dePolo

Nevada Bureau of Mines and Geology

Prehistoric Earthquake Ruptures

- Inform us on how contemporary deformation is accommodated on a fault.
- Key information for the earthquake segmentation of faults.

- **Prehistoric Earthquake Ruptures**
- **Historic Earthquake Ruptures**
- **Future Earthquake Ruptures** (the next earthquake)

Historic Earthquake Ruptures

- Consistent stuff
- Complexity

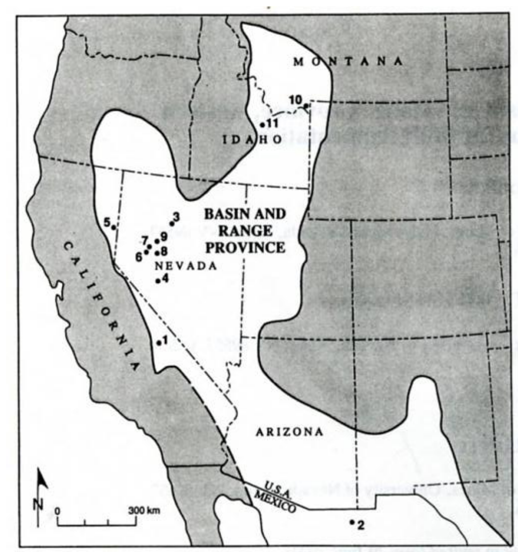
Historic Ruptures – Consistent Stuff

- **Rupture length and displacement generally scale with earthquake moment and magnitude.**
- **Commonly a core segment.**
- **Larger events are commonly multiple structural segments.**
- **Natural scale of rupture for larger events.**

Historical BRP Earthquakes
dePolo, Clark, Slemmons, Ramelli (1991)

Longer (>15-20 km) BRP ruptures were complex, involved multiple geometric and structural segments, and/or multiple faults.

About 1/2 of rupture end-points distinct fault zone discontinuities.



Number of Structural or Geometric Segments vs Total Rupture Length for BRP Earthquakes

one fault segment common

< 15-20 km <

two fault segments common

< 30-50 km <

three segments common

< 60-110 km <

four segments common

mod. from dePolo and others (1991)

Fault Segments

- Primary or core fault segment(s)

- Adjacent segments *with benefits*
  - **Rupture overlap segments**

- Indicators of multi-segment behavior
  - **paleoseismic evidence**
  - **single-event displacements**
  - **weak discontinuity**

I

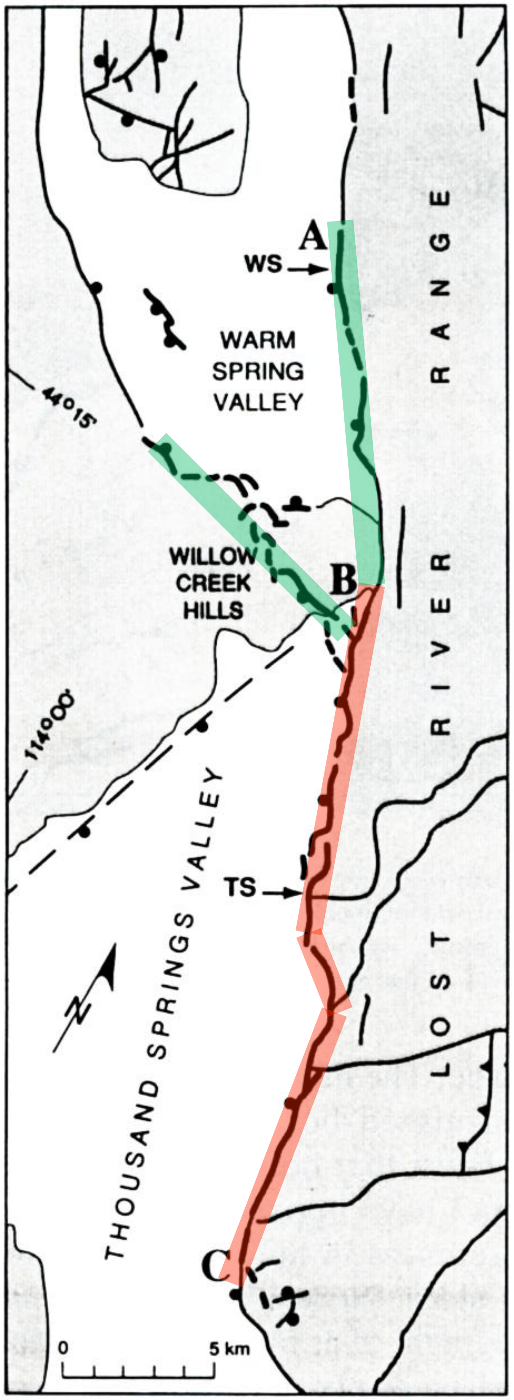
Fault Segmentation

In many cases there is a core or primary segment within a BRP earthquake rupture

- Several BRP ruptures have one or two primary or core segments (with adjacent secondary ruptures)

- Strategies (e.g., Carpenter and others, 2012)

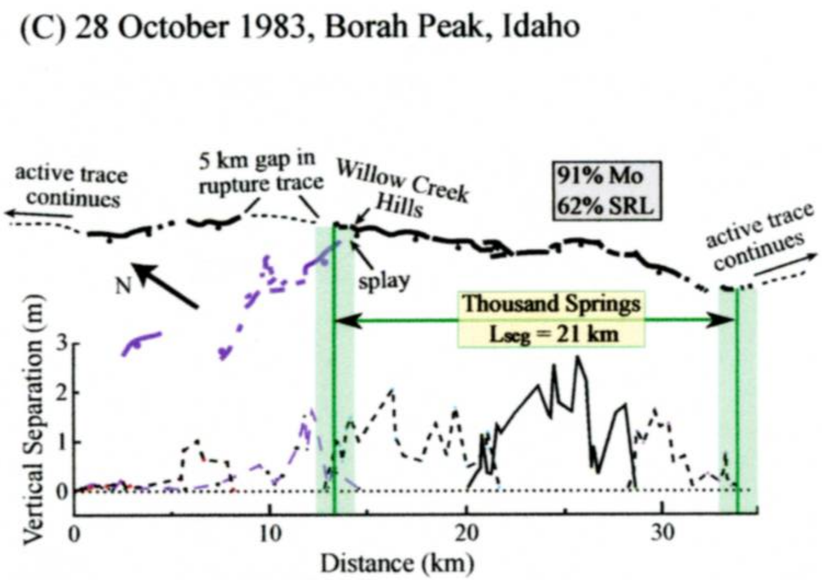
- core segment - **minimum maximum earthquake?**

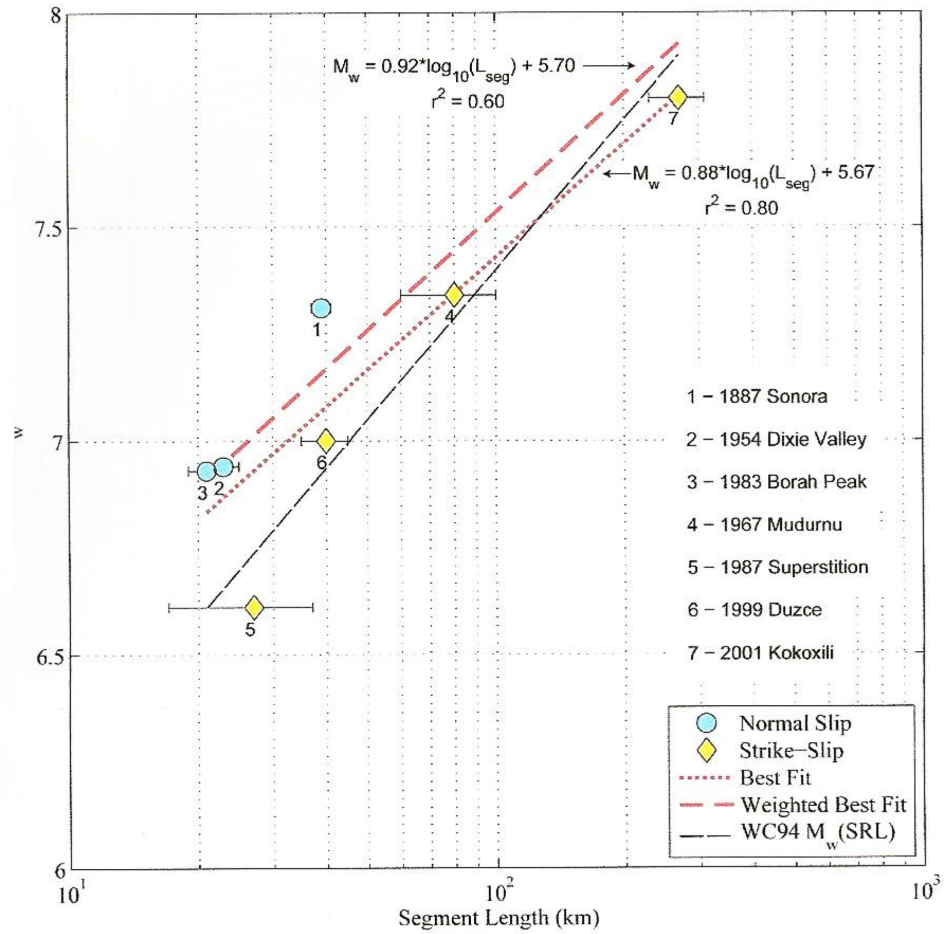


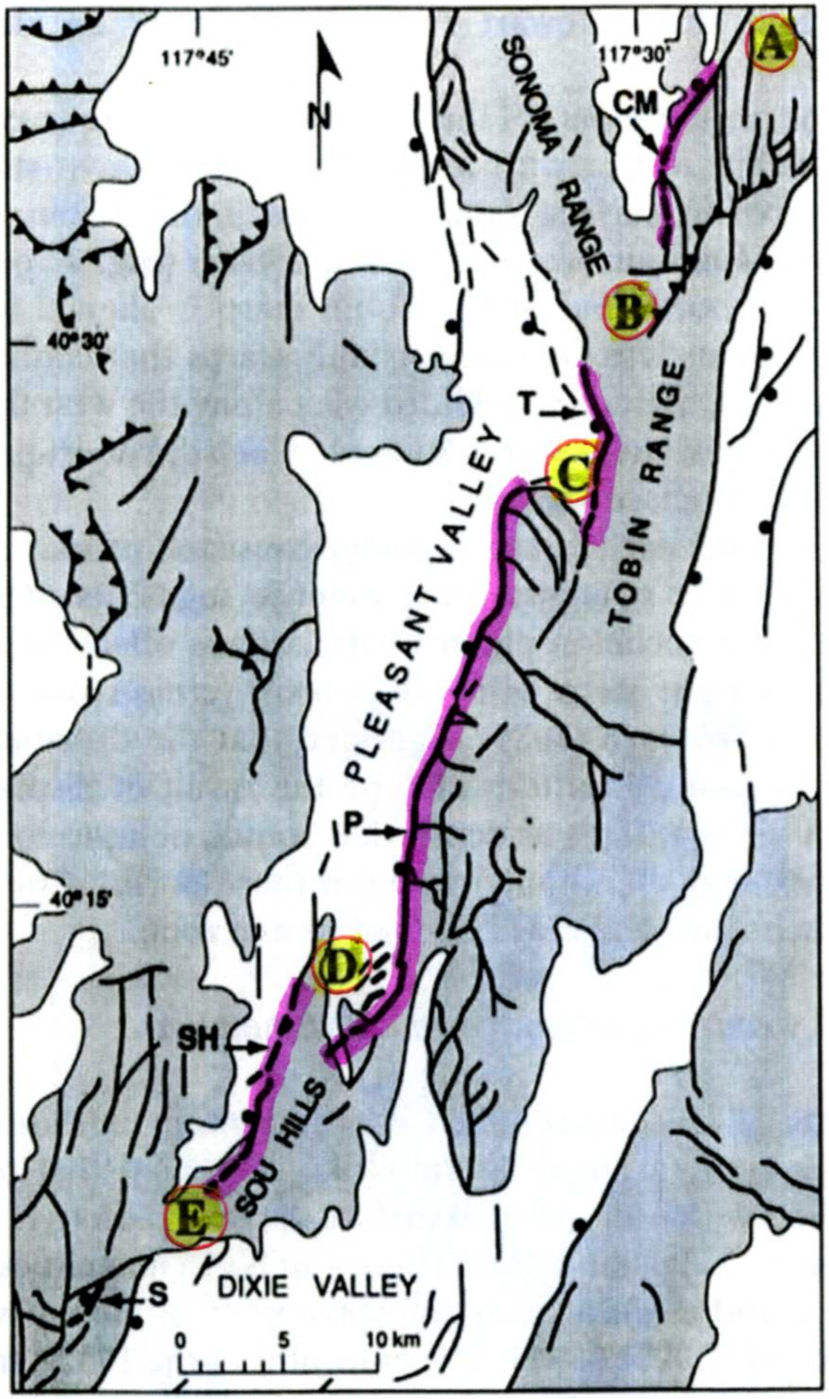
1983 Borah Peak, Idaho Earthquake

core segment:
salient "C" to transverse Ridge "B"

Carpenter and others (2012)

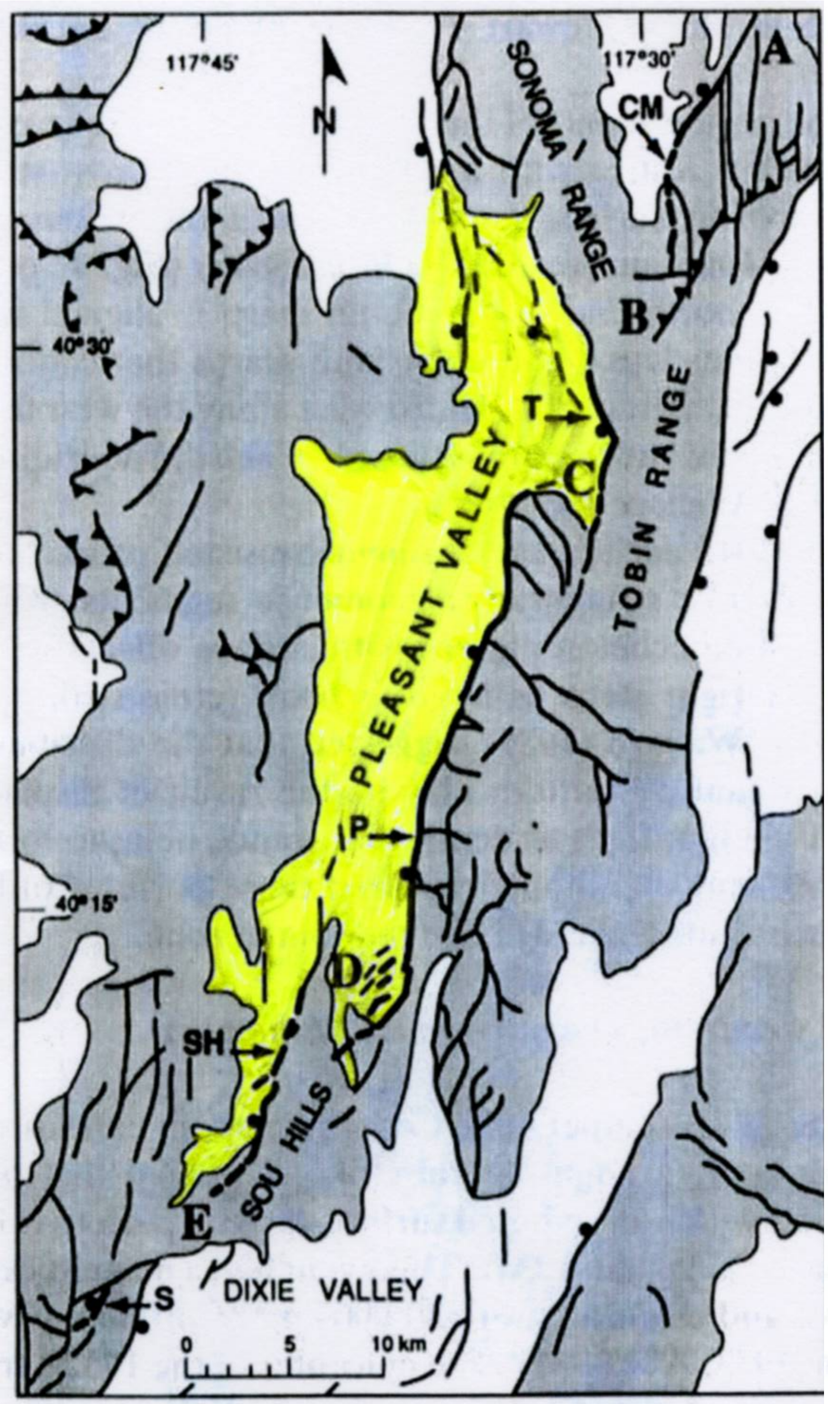






1915 Pleasant Valley, Nevada Earthquake $M_w 7.3$

Centennial Anniversary!


117°45'
117°30'
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CM
B
40°30'
T
C
TOBIN RANGE
PLEASANT VALLEY
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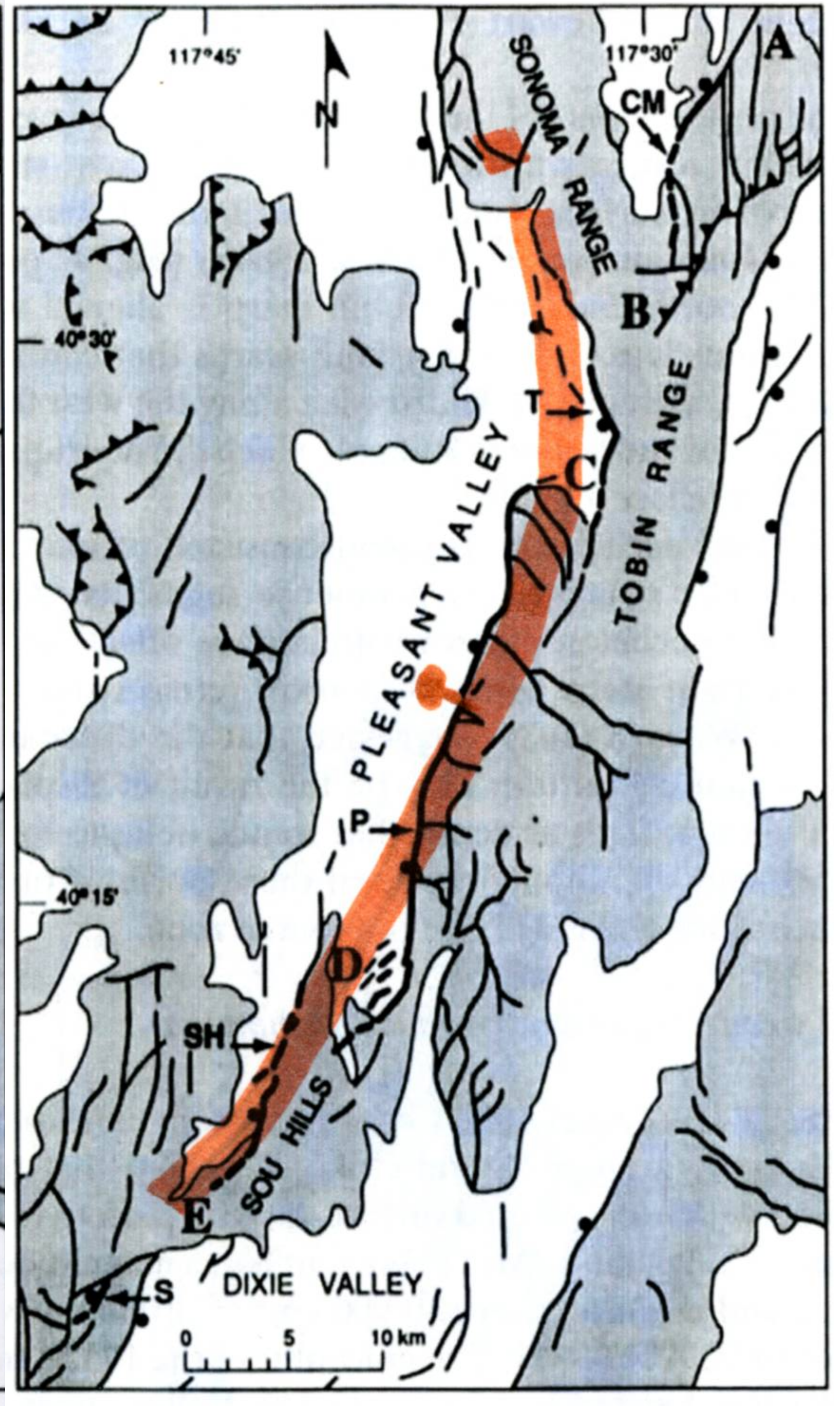
40°15'
D
SH
SOU HILLS
E
S
DIXIE VALLEY
0
5
10 km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DIXIE VALLEY
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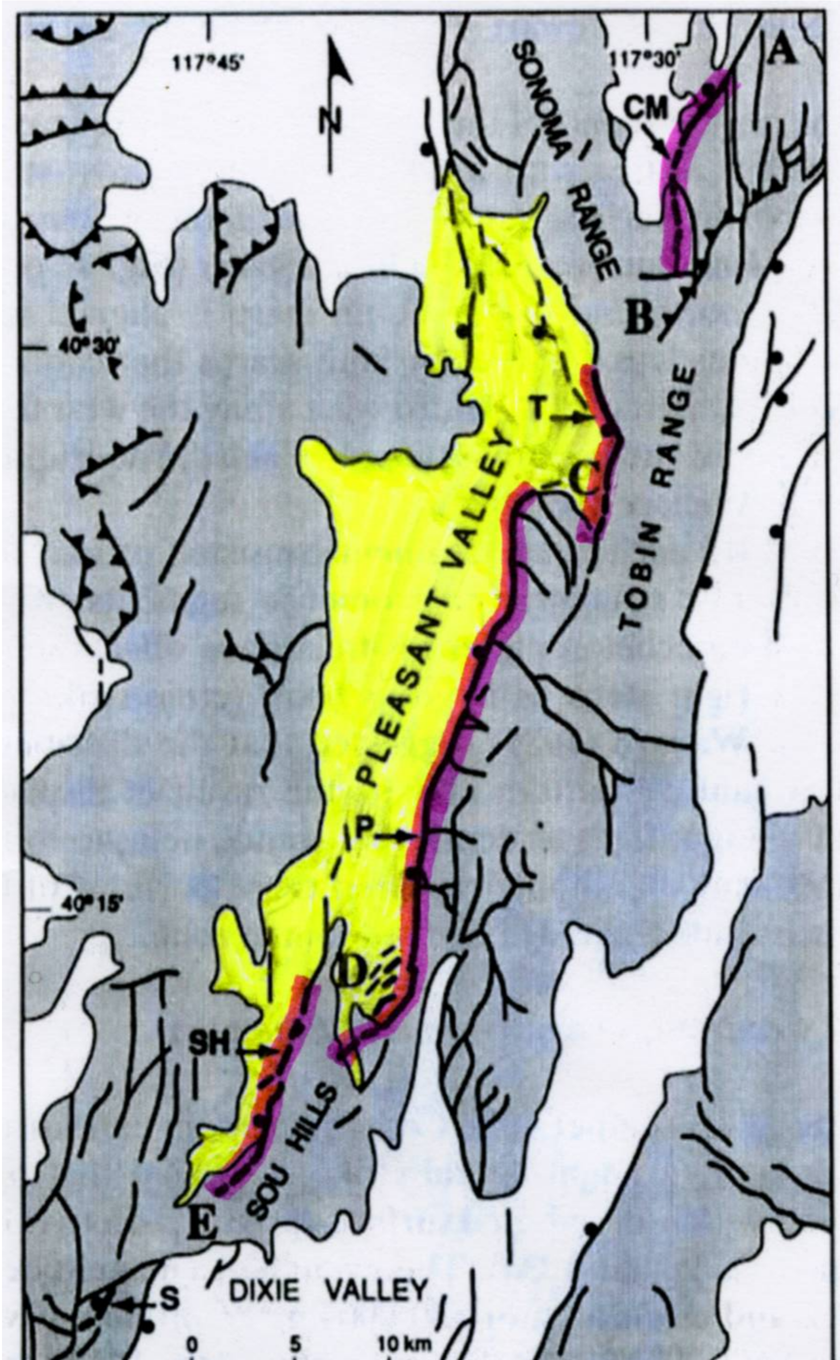
10 km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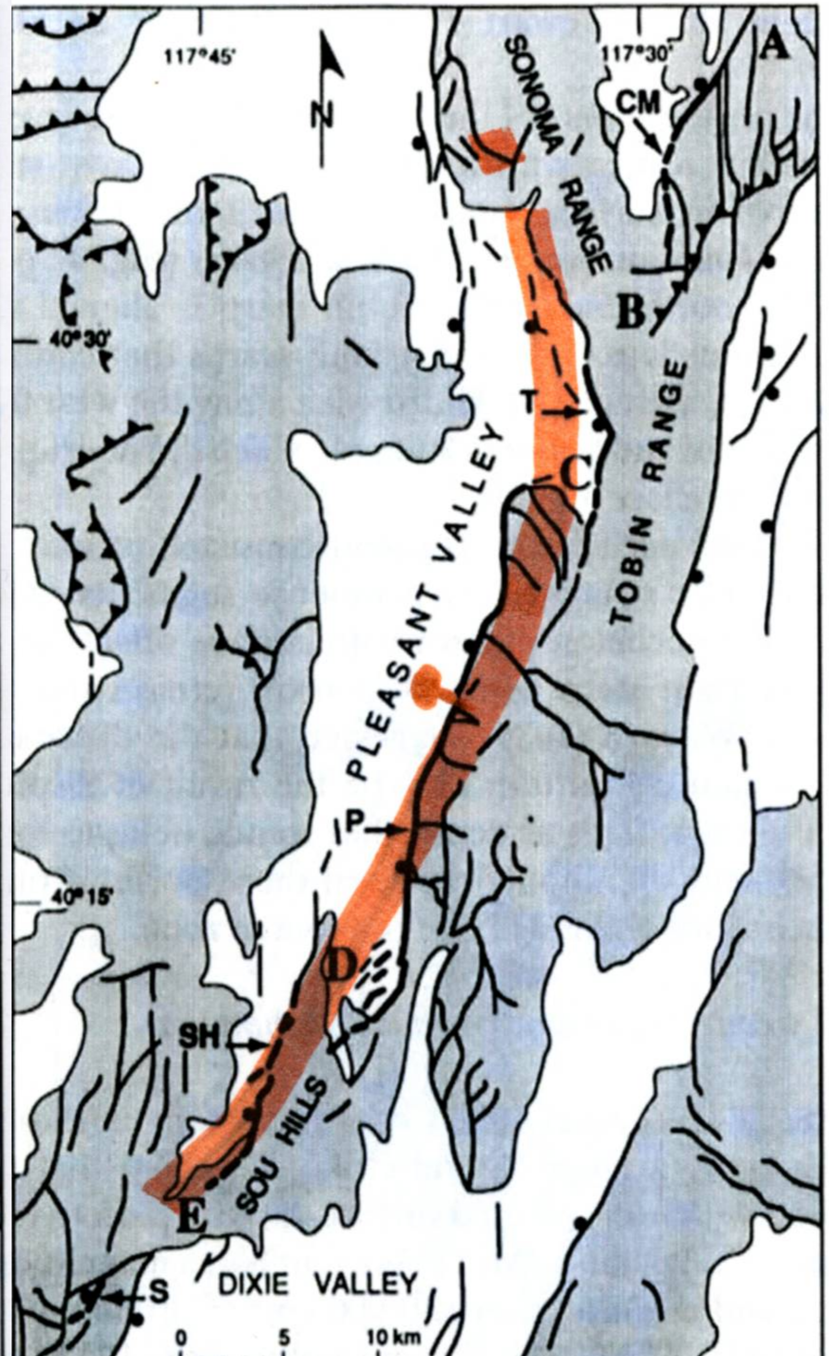
0 5 10 km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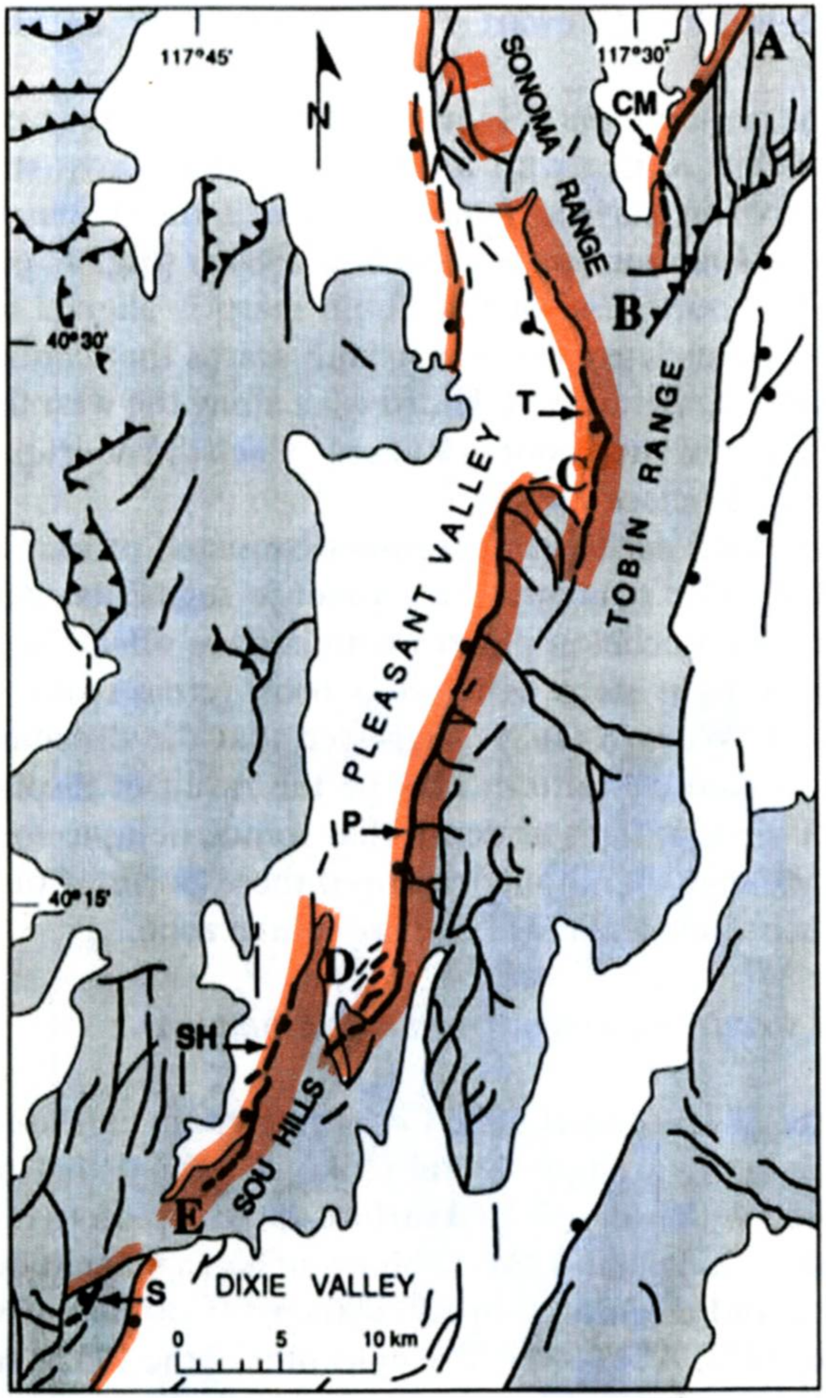
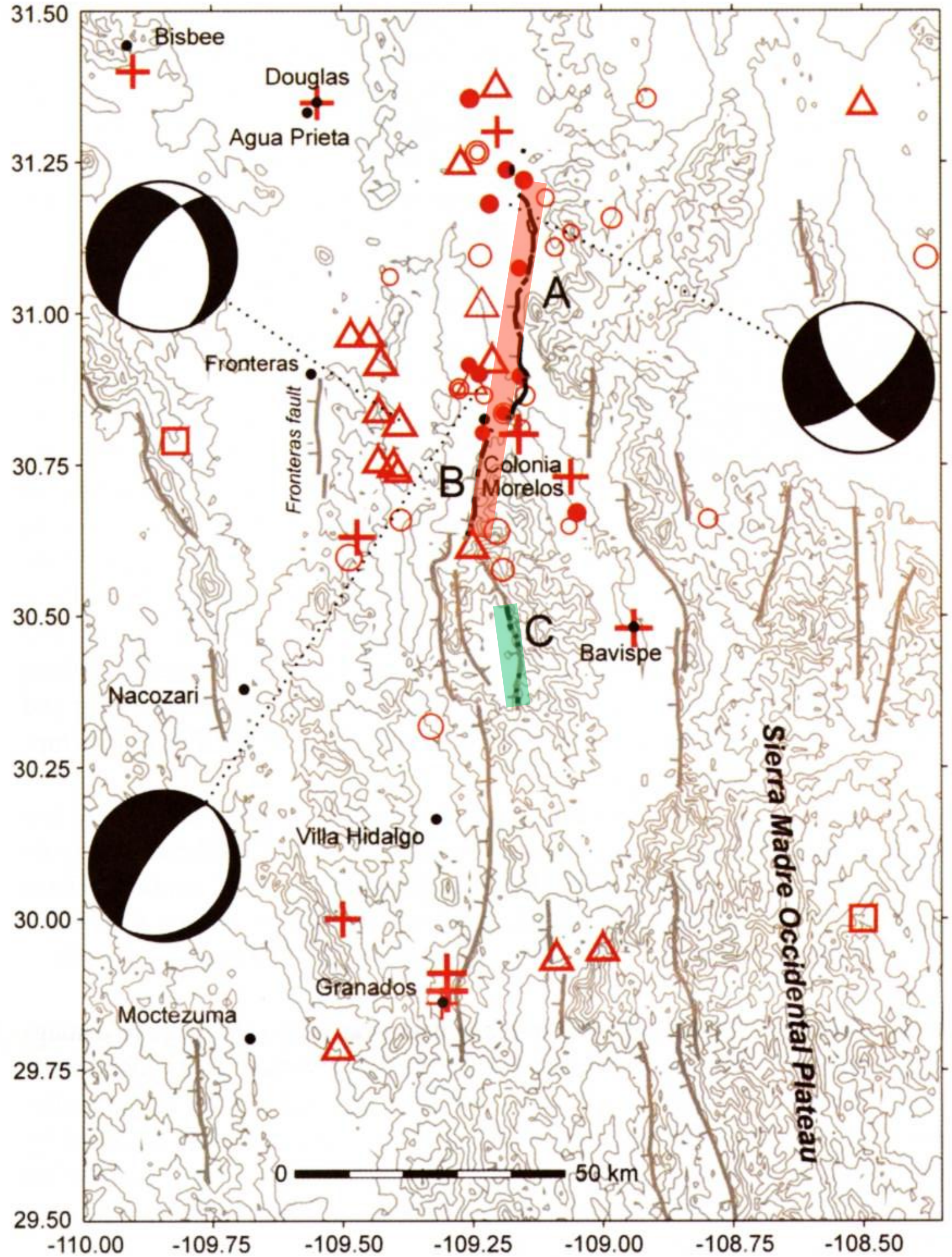
0 5 10 km



Earthquake Rupture Scenarios

Pleasant Valley fault zone

30-km core segment gives a M7 ¼ish; ½ way between 1983 and 1887 core lengths.



1887 Sonora, Mexico Earthquake M7.5

Suter and Contreras (2002)

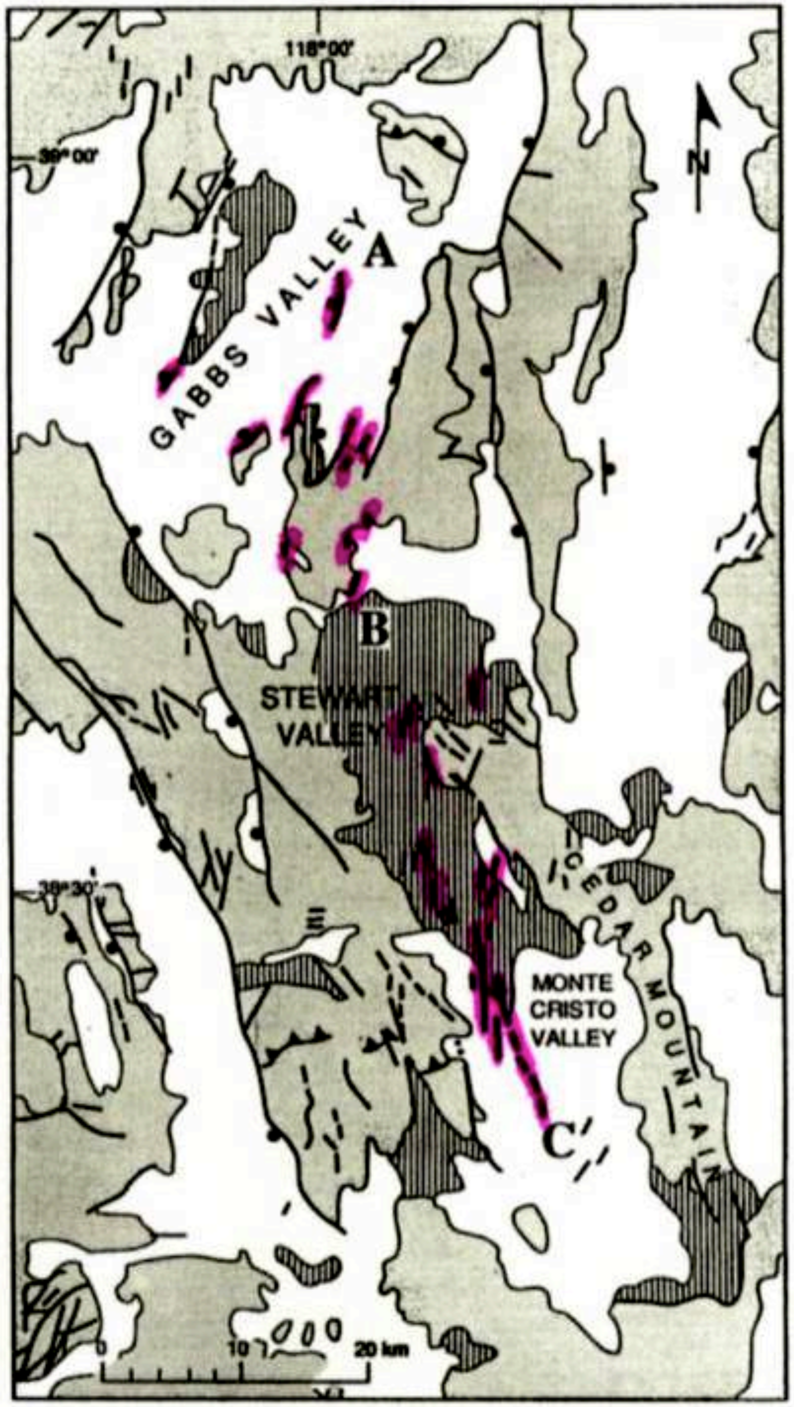
BRP Earthquakes Revisited

Eq.	Endpt. 1	Endpt. 2	Nature of Rupture
1872	fe	fe/be	entire Owens V fz
1887	fe	os	½ flt sys
1915	b	fe/od	~entire fz
1932	sr	cf	multiple-flt; unpredict.
1950	fi	fi	total flt. rupture
1954d	fe	fe	total rupture 1-2 fzs
1954e	os	fe	range-front seg (core)
1959	fe	df?	2 ll range-front segs
1983	fi/tr	sal	range-front seg (core)

Historic Ruptures – Complexity

These Historic Earthquake Ruptures have not been Angels

- **Cascading failure of faults**
- **Complicated rupture ends**
- **Overlapping rupture segments**
- **Re-rupture within months or decades**
- **Parallel fault ruptures**
- **Small rupture preservation or overprint**

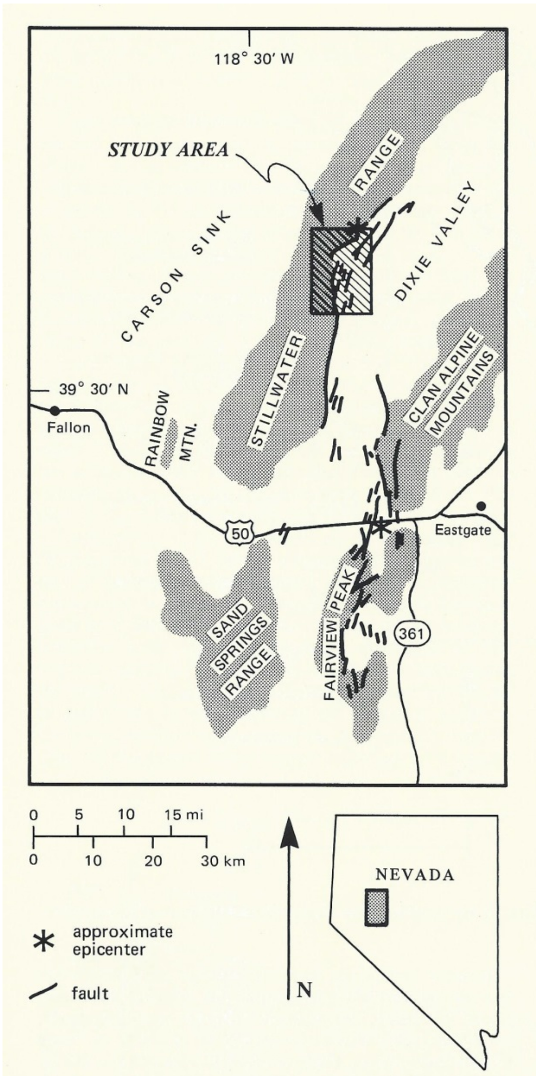


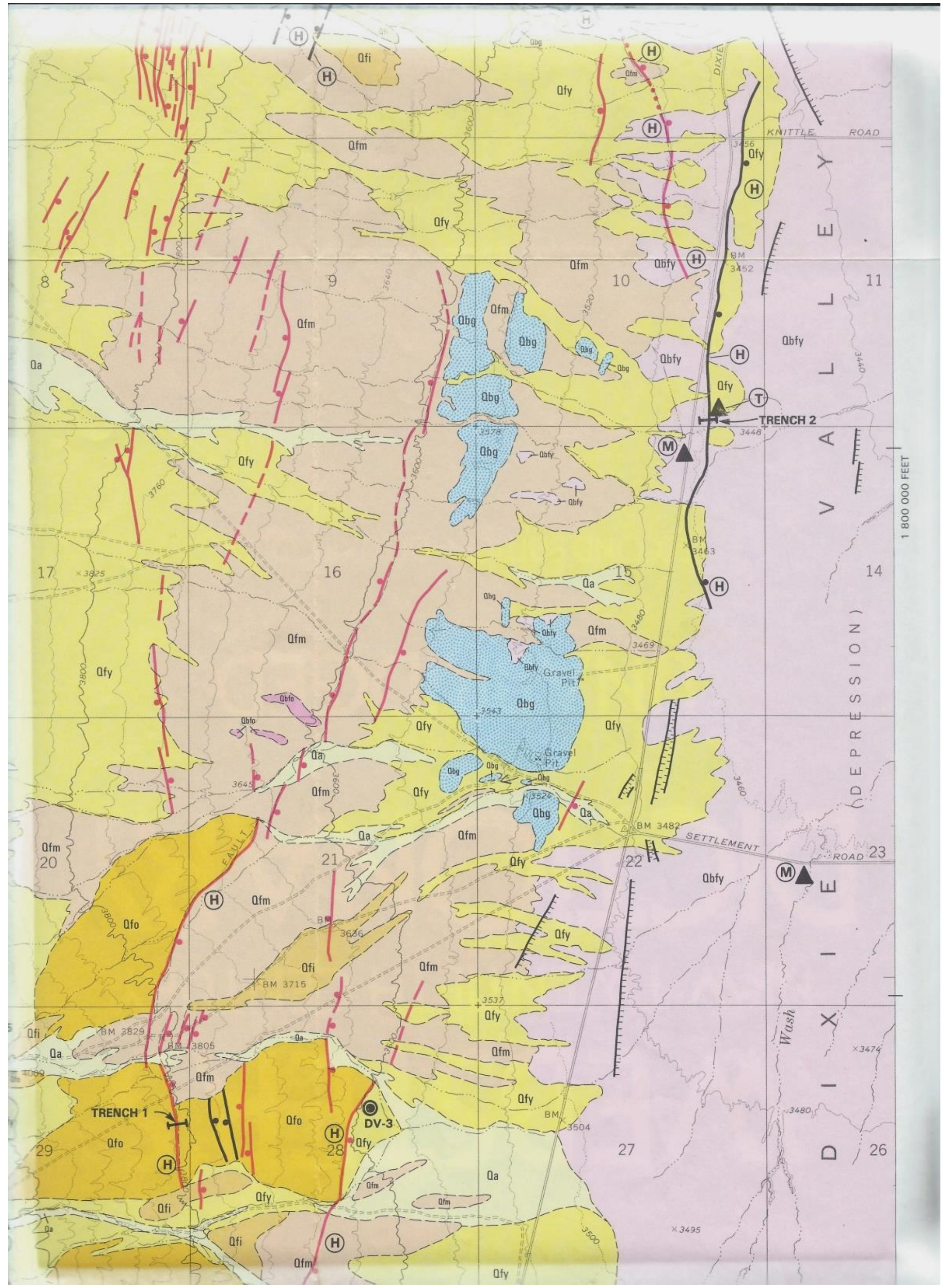
Cascading Failure of Faults

1932 Cedar Mountain, Nevada Earthquake

M_w 7.1

Overlapping Rupture Segments





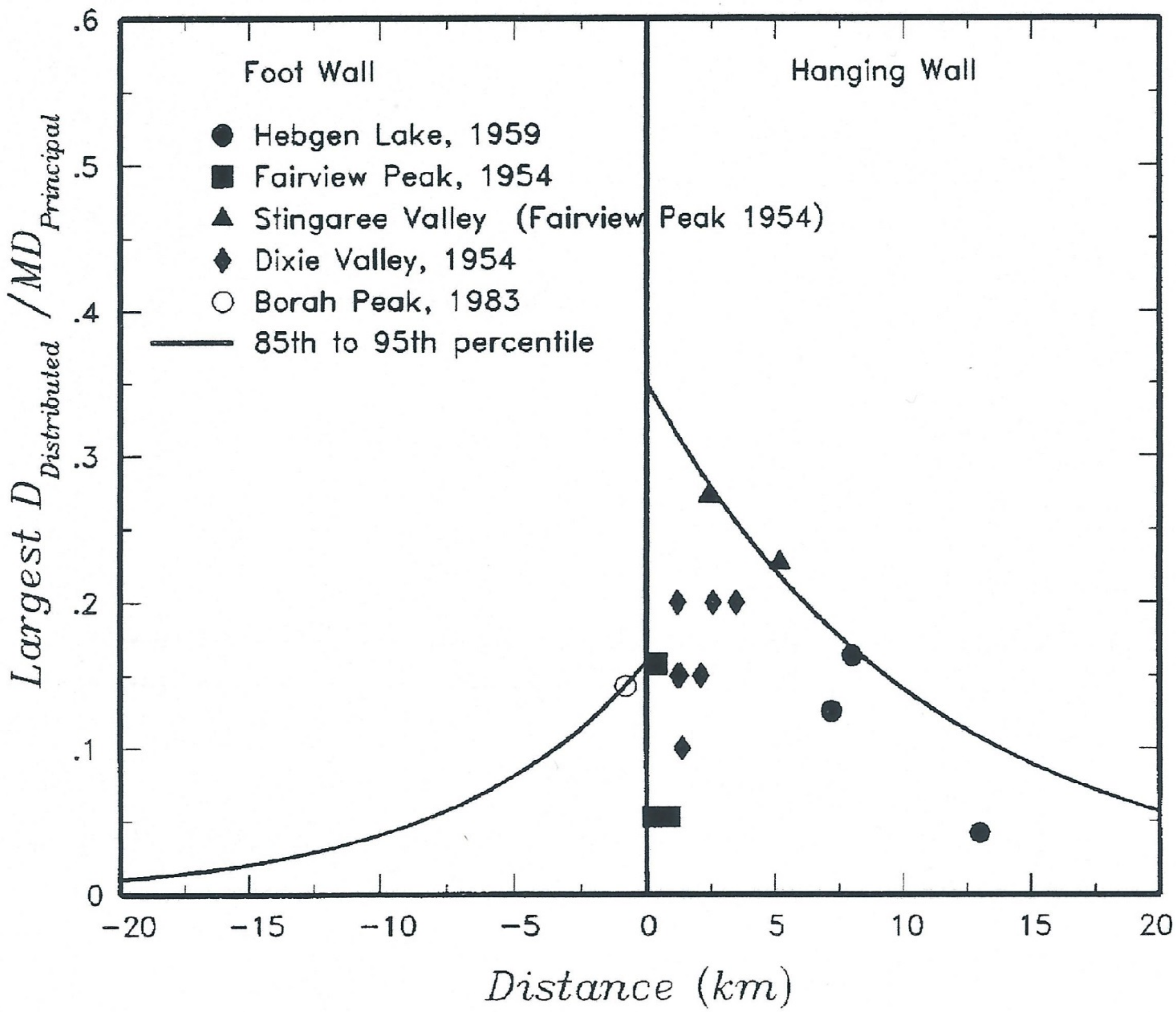
J. Bell & T. Katzer (1987)
Dixie Valley fault study

Re-rupture of faults over short time periods

1903 Wonder, Nevada Earthquake surface rupture (fault) re-ruptured in 1954 (Slemmons et al., 1959; Caskey et al., 1996)

1954 Rainbow Mtn., Nevada Eq. - parts re-ruptured 49 days later (Tocher, 1956; Caskey et al., 2004)

Subparallel Fault Ruptures



Data compiled by C. dePolo; reported in Youngs et al. (2003)

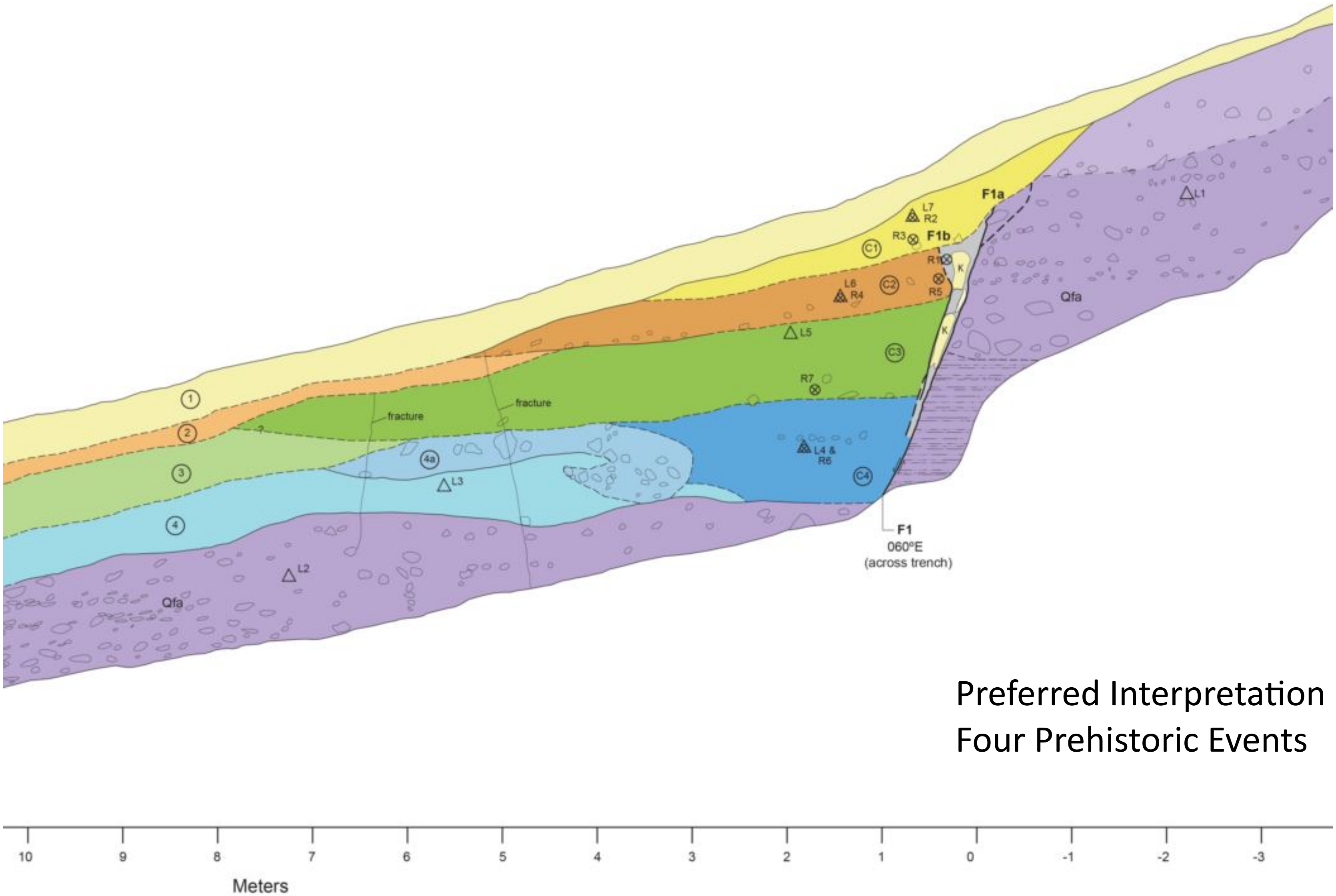
Geomorphic Expression of Ruptures

- **First study of a fault (least expensive)**
- **Great technologies (LiDAR)**
- **Characterization of bedrock environments**
- **Can be strong evidence of prehistoric rupture**
- **Features can be compound, or enhanced or reduced in size, or distributed (uncertainty)**

Fault Trenching Investigations

- **Location, location, location.**
- **Rapidly increasing ability to get fairly precise, good dates.**
- **Commonly multiple trench investigations required to reconstruct a prehistoric surface rupture.**

Kings Canyon fault zone
Carson City, Nevada



Preferred Interpretation
Four Prehistoric Events

Prehistoric Earthquake Investigations

You know you are serious when you start constructing

Prehistoric Space-Time Diagrams for multiple ruptures.

Within a region – fault to fault or along a single, long fault zone

John Bell et al. (2004)

Central Nevada Seismic Belt

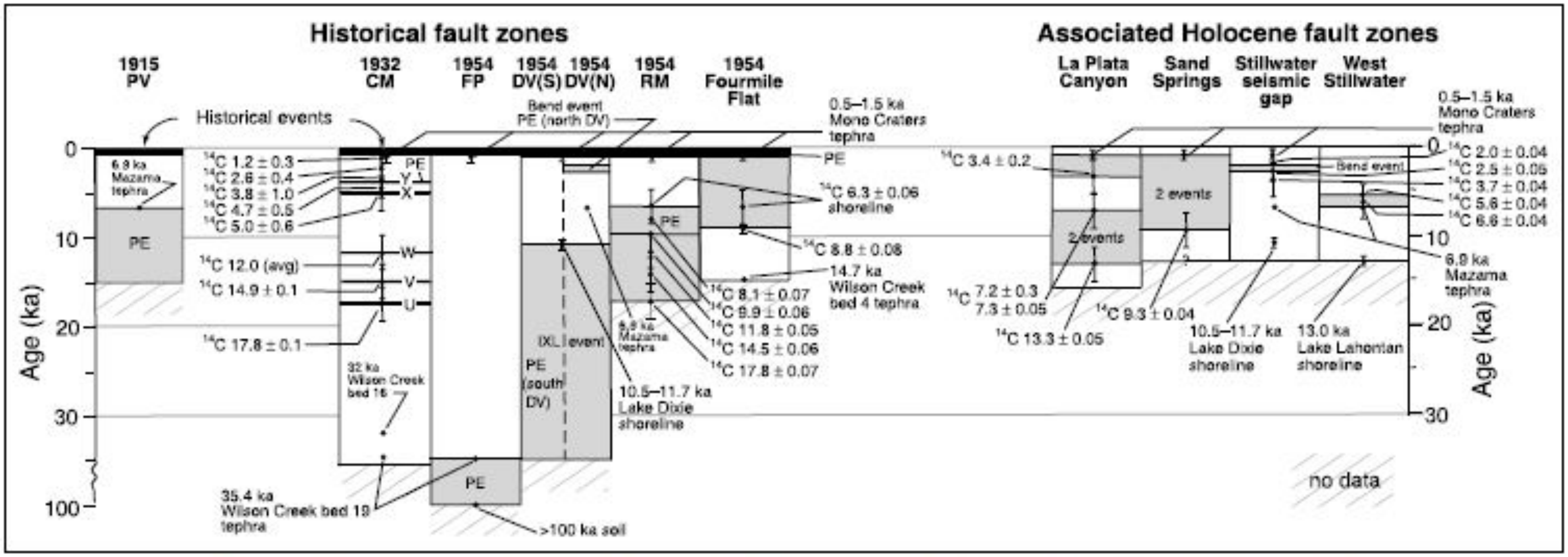
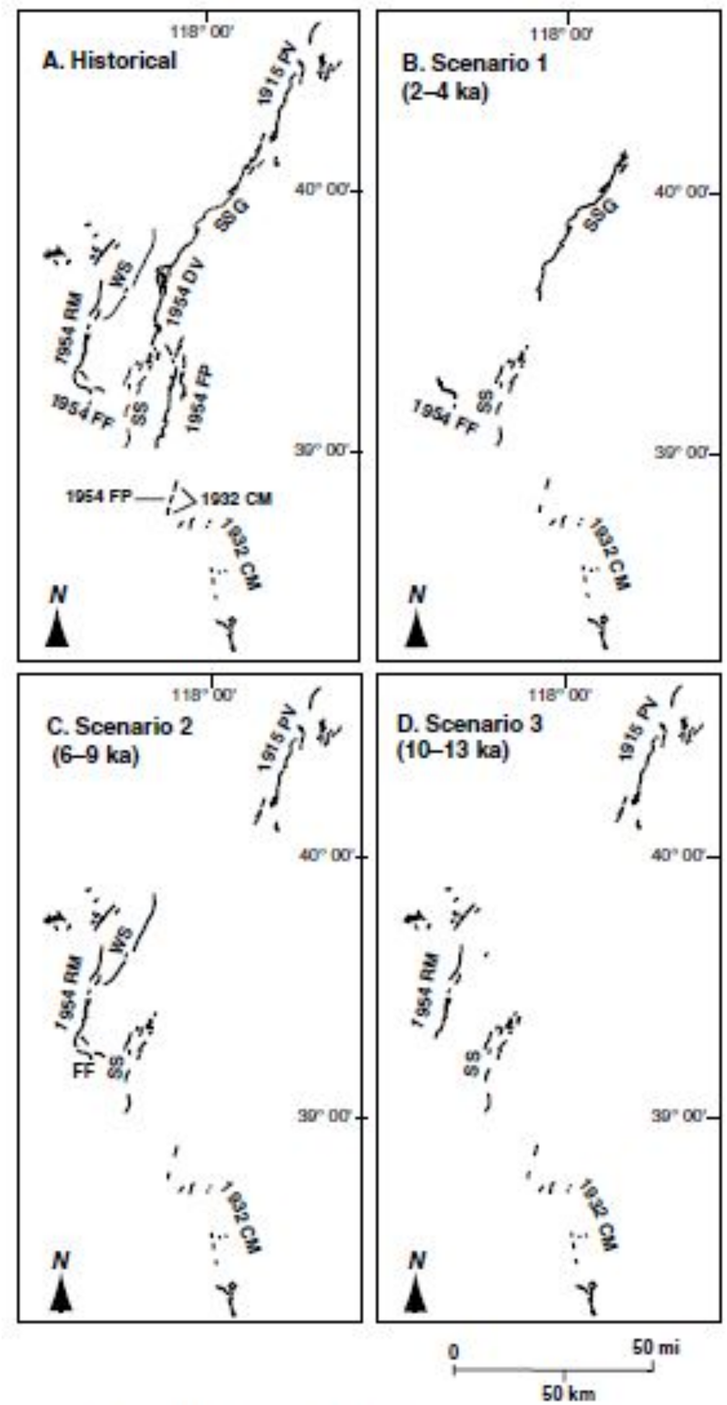


Figure 8. Space-time diagram showing age constraints for events on historical and associated Holocene faults in the CNSB. Ages are in radiocarbon years (^{14}C yr B.P.). Calibrated ages are listed in the Appendix. For radiocarbon samples on buried soils (MRT ages), possible ±2-ka error bars are shown. Data from previous studies were obtained from the following: 1915 Pleasant Valley (Anderson and Machette, 2003), 1932 Cedar Mountain (Bell *et al.*, 1999), and 1954 Dixie Valley (Bell and Katzer, 1990). The 1954 Rainbow Mountain–Stillwater and Fourmile Flat age relations are discussed in Caskey *et al.* (2004).

John Bell et al. (2004)

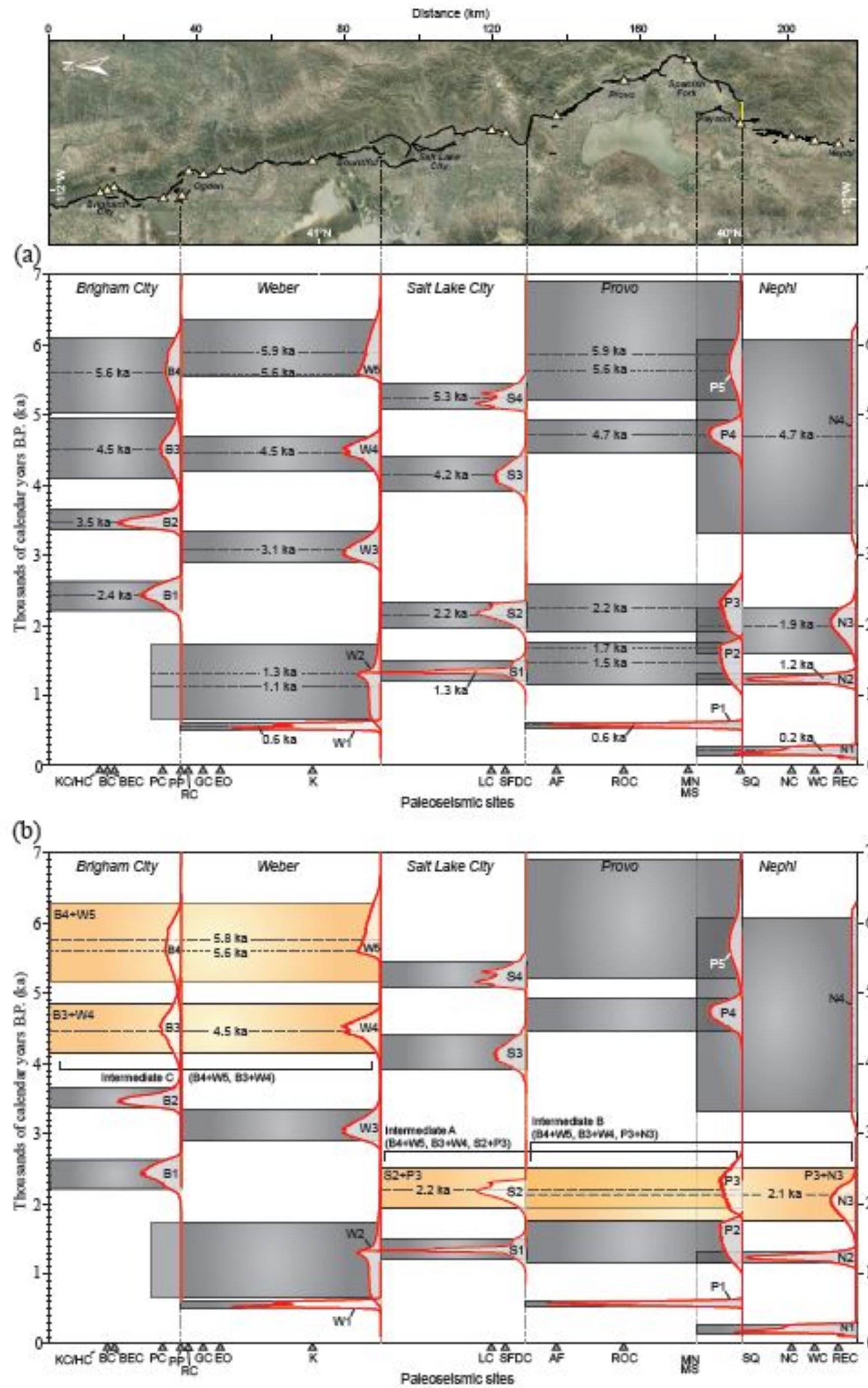
Central Nevada Seismic Belt

Prehistoric CNSBs?



DuRoss et al. (in review)

Wasatch fault zone



Decades in the making

Prehistoric Rupture Length Conclusions

- Get your segments together
- Core segment – potentially useful concept
- Multiple segment ruptures happen
- Cascading failures happen
- Surface geomorphology
- Multiple trench investigations
- Prehistoric space-time diagrams – enlightenment

FAULT LINKAGE, COMPLEXITY, AND EARTHQUAKE DISPLACEMENT

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Senior author's email address: glenn@unr.edu

Fault-to-fault ruptures and complex rupture geometries are increasingly becoming standard elements of seismic-hazard assessments. The Uniform California Earthquake Rupture Forecast 3 (Field and others, 2014) for example, made extensive use of fault-to-fault ruptures to improve rupture model realism, and to recognize potential connectivity of faults in California. Empirical data from actual ground-rupturing earthquakes provide an important baseline and reference for potential rupture complexity.

Wesnousky (2008) synthesized rupture mapping and coseismic displacement in a standardized format for 37 earthquakes. These data provided important metrics for the viability of fault-to-fault ruptures, including the rough upper limit of 5 km for steps crossed in strike-slip ruptures and probabilities of about 50% that steps greater than 1 km will arrest rupture. We have added ruptures to approximately double the strike-slip set and increased the normal and reverse mechanism sets enough for preliminary mechanism-specific relations for both. The additional events have come from two main sources. First are events that occurred since the closing of the Wesnousky (2008) set. The second are events for which new studies and/or documentation have become available. We have also begun compiling gaps in surface ruptures.

The recent right-oblique El Major Cucapah earthquake included a gap variously measured at 7 or 15 km, and raised interest in gaps in general. Approximately half of ruptures in the new event set include gaps in the main rupture trace of 1 km or greater. In the larger data set, we find that 65% of strike-slip ruptures include a step in the surface trace of 1 km or larger. A geometric model of steps within strike-slip ruptures indicates steps of 1 km or larger are crossed about 59% (50–69) of the time. Steps may be similarly or slightly more effective in stopping normal and reverse ruptures, at 62 (45–78)% and 41 (20–61)%, respectively. In additional to these quantitative measures, a rich set of complex rupture behaviors are observed. We review cases that could have application in Basin and Range Province seismic hazard, and conclude with a potentially uniting view from the perspective of the regional stress field.

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Wesnousky, S.G. (2008). Displacement and geometrical characteristics of earthquake surface ruptures—Issues and implications for seismic-hazard analysis and the process of earthquake rupture: Bulletin of the Seismological Society of America, v. 98, p. 1609-1632.

The following is a PDF version of the authors' PowerPoint presentation.

Fault Linkage, Complexity, and Earthquake Displacement

Glenn Biasi and Steve Wesnousky

University of Nevada Reno

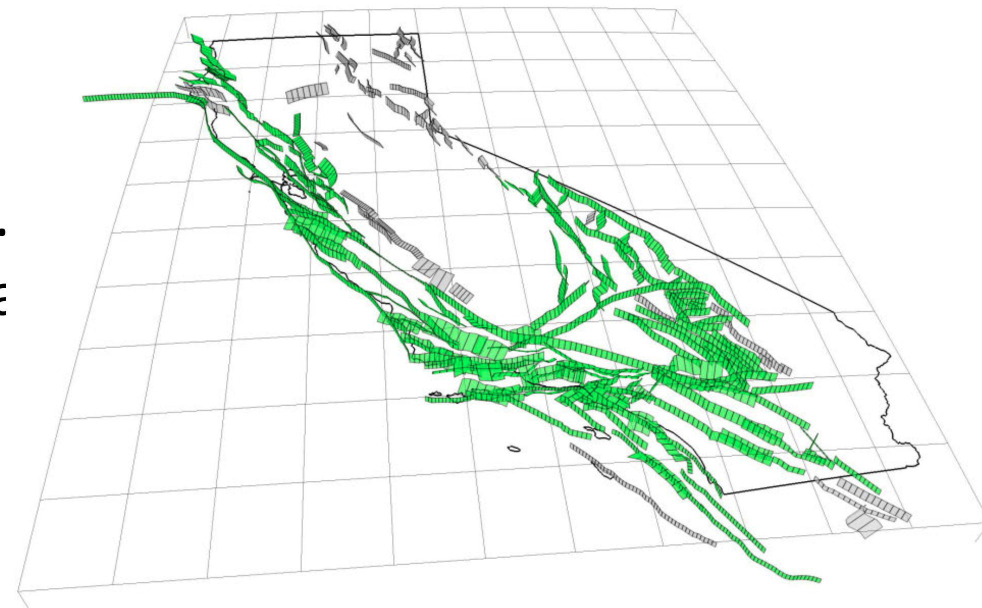
Seismological Laboratory

Reno, NV 89557

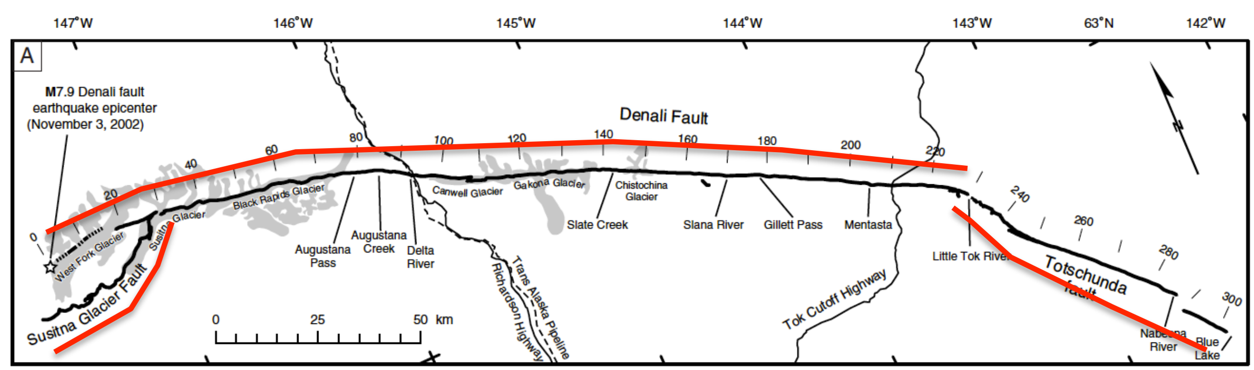
"It's amazing what you can see by looking." Yogi Berra

Motivation

- Fault-to-fault connections in ground ruptures are a reality.
- Fault-to-fault ruptures open a Pandora's box of issues
  - Which faults can connect?
  - How often?
  - How large can they grow?
- Probability of ruptures crossing steps and gaps is one part of assigning probabilities to scenario ruptures



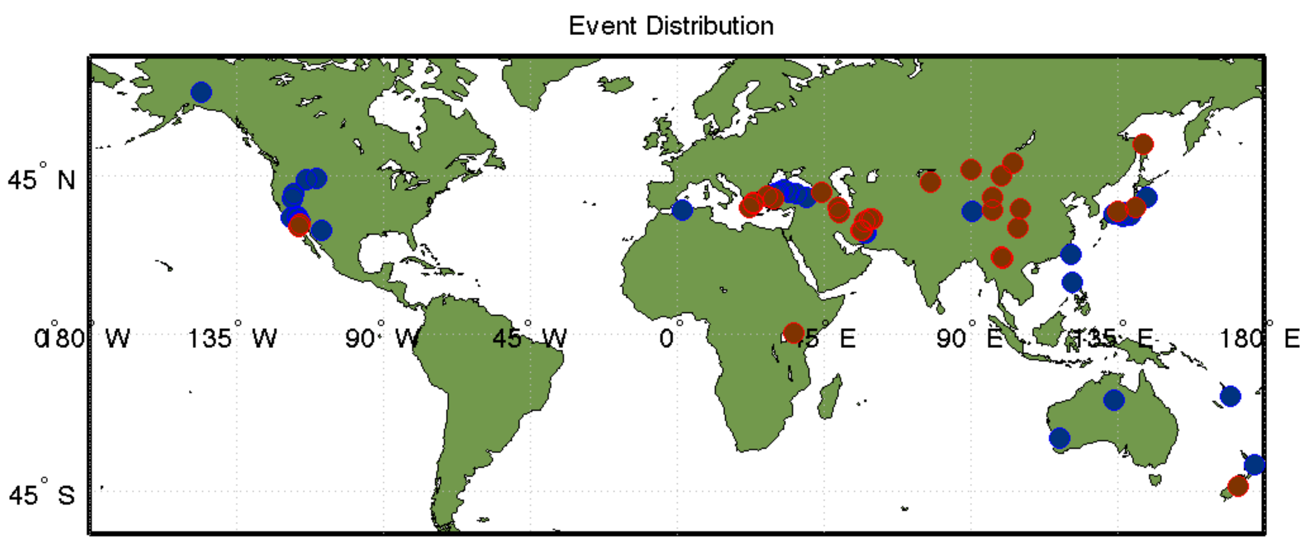
All faults in green connect with a step <5 km (UCERF3, Fault Model 3.1)



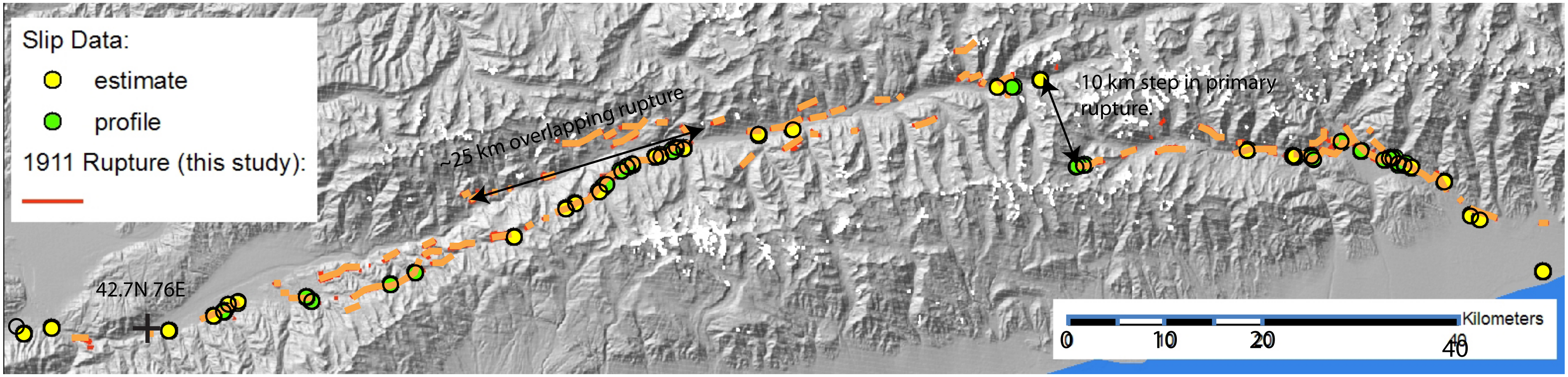
3 faults in 2002 Denali rupture

Data for Fault Steps and Gaps

- 37 events analyzed in Wesnousky (2008).
- 35 new analyses:
  - Surface-rupturing earthquakes in Wells and Coppersmith (1994).
  - Events postdating or not covered in Wesnousky (2008).
  - 22 strike-slip, 7 normal, 6 reverse.



1911 rupture. Treat as field confirmation of 1911 rupture map

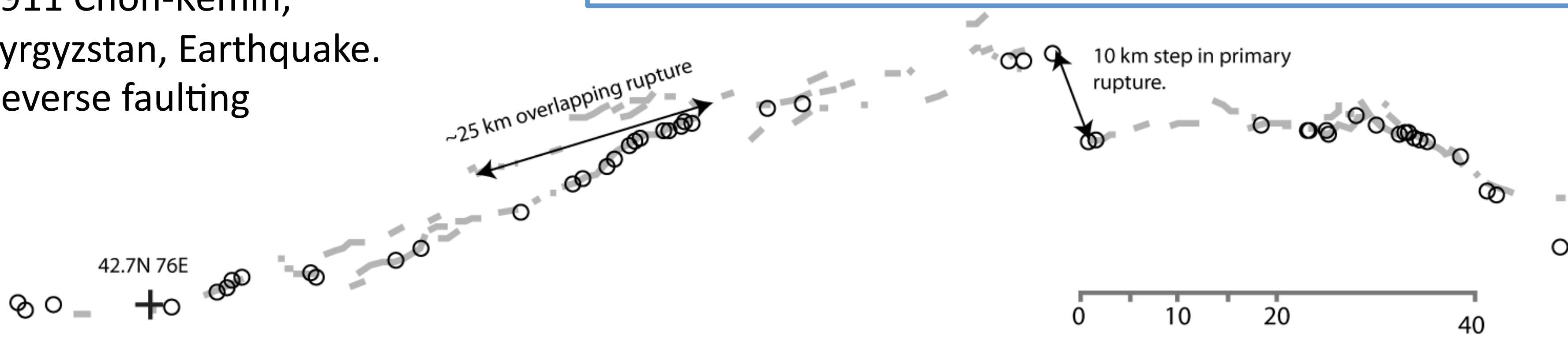


3 January 1911
Chon-Kemin Earthquake

Process:
Find, scan best available surface rupture map.
Trace surface rupture, active and nearby faults, and contextual features
Measure steps, gaps inside the rupture trace
Where possible, measure distances to unruptured features at ends of rupture.
Result below: distilled essence of rupture.

Circles: locations of slip estimates by Arrowsmith et al on 1911 rupture. Treat as field confirmation of 1911 rupture map

1911 Chon-Kemin, Kyrgyzstan, Earthquake. Reverse faulting

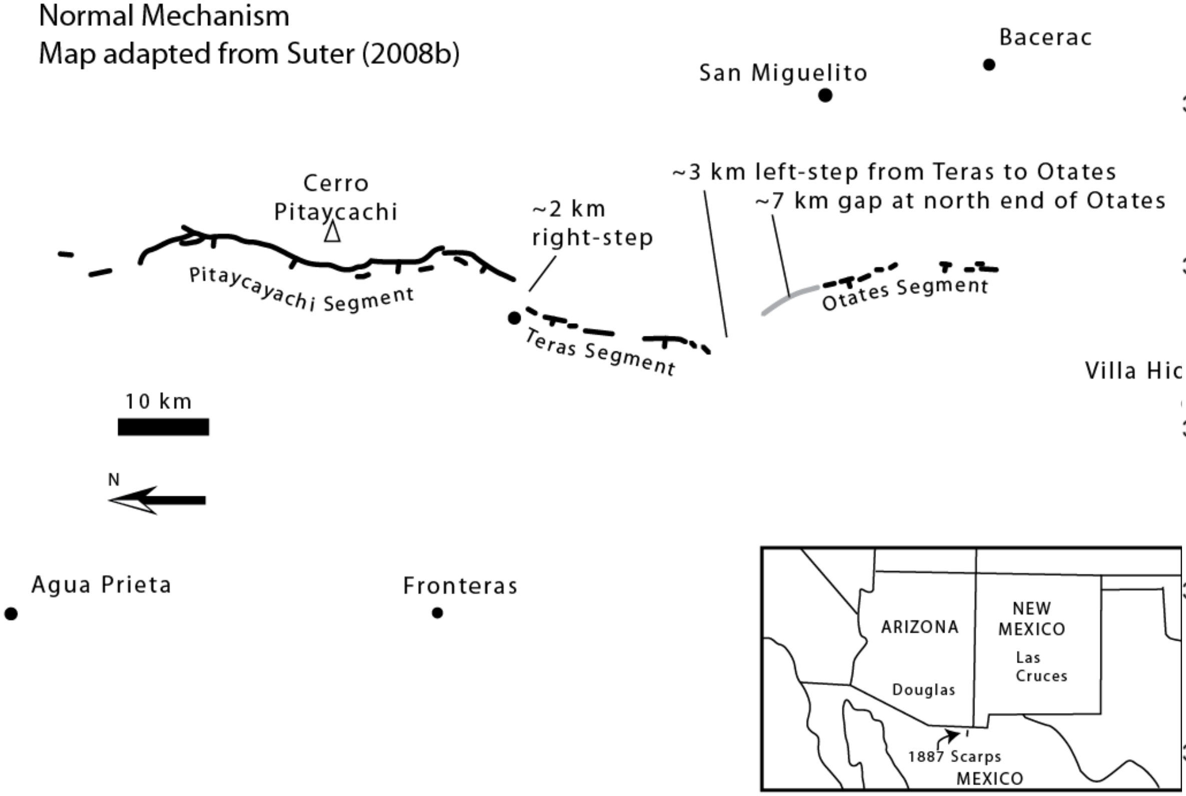


Fault continues west; observed in displacement of Holocene sediments.

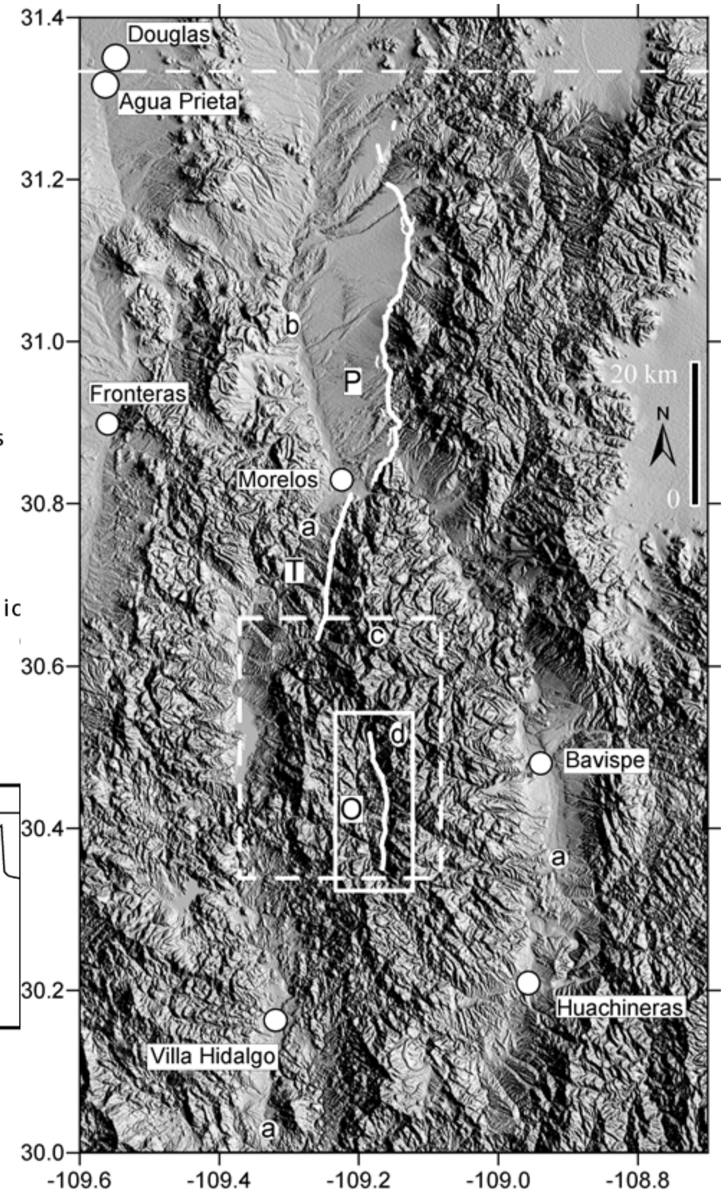
Discontinuous rupture reported in Bogodovich et al. 1914; not included in gap tabulation because of potential detection and preservation problems in alpine reach. Fault system continuity recognized in Delvaux et al 2001.

1887 Pitacayachi (Sonora) Earthquake

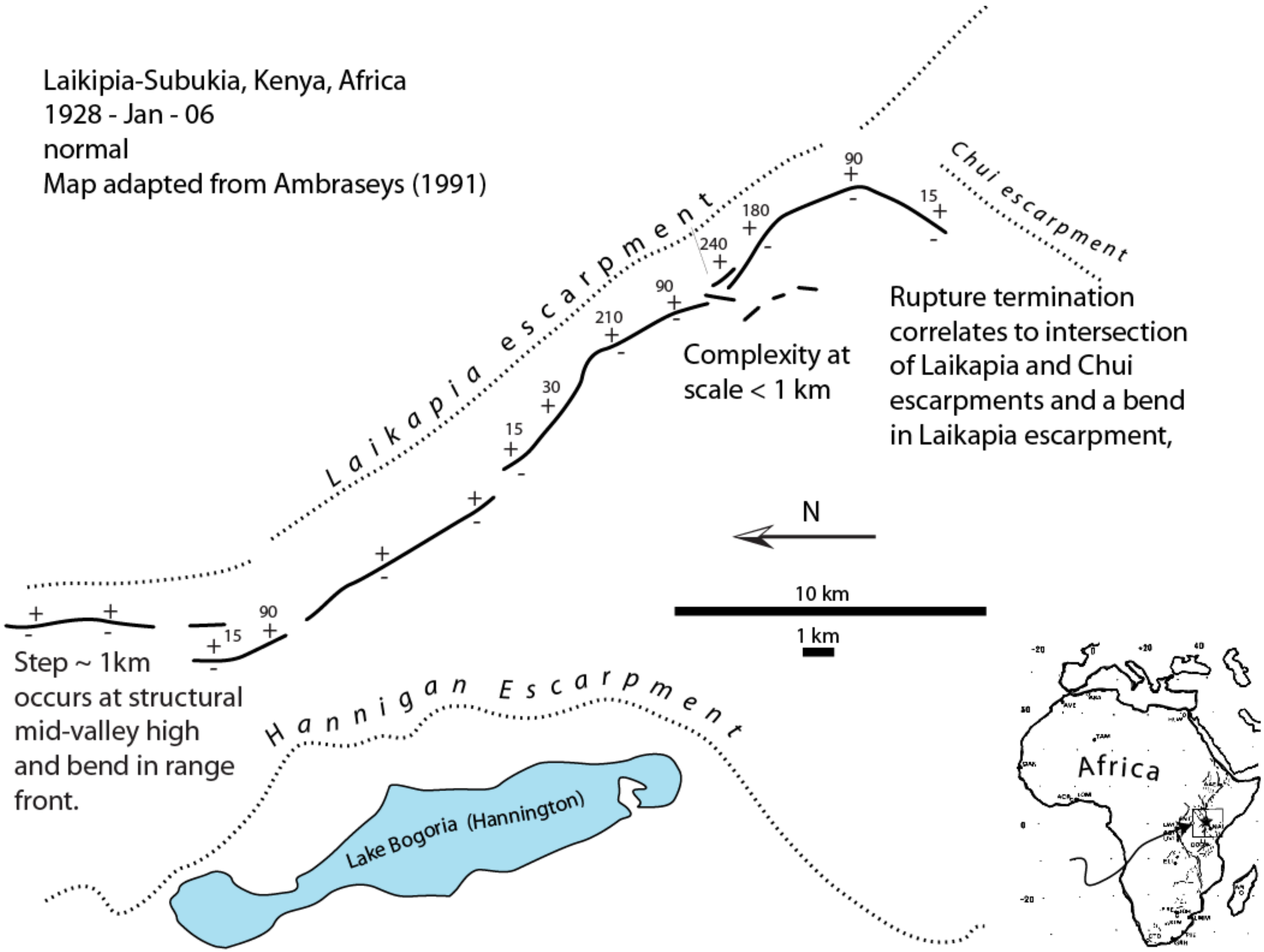
Sonoran (Pitacayachi) Earthquake, Mexico
1887 - May - 03
Normal Mechanism
Map adapted from Suter (2008b)



Map from Suter, 2008, BSSA

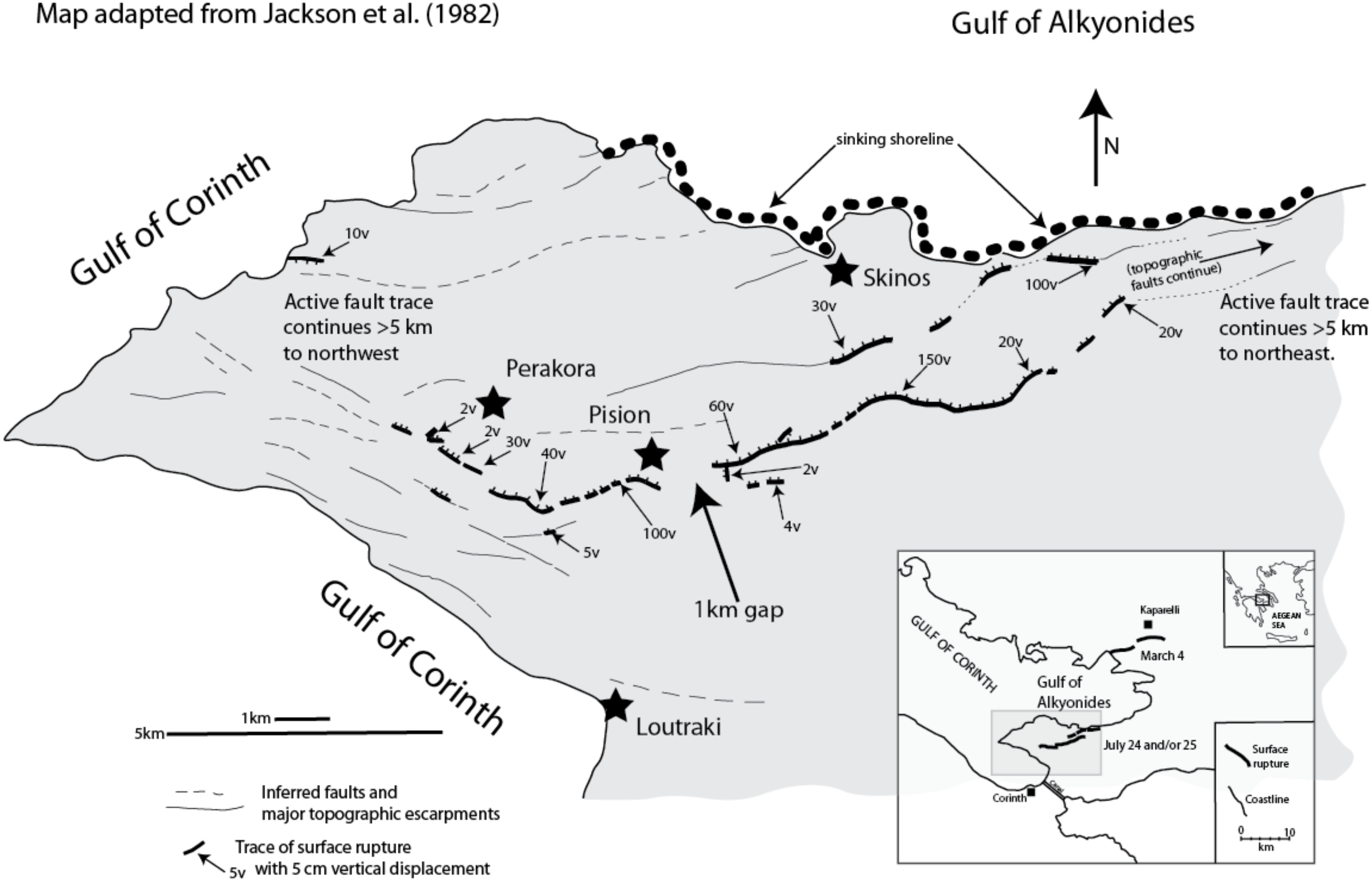


Normal-faulting event with large step.

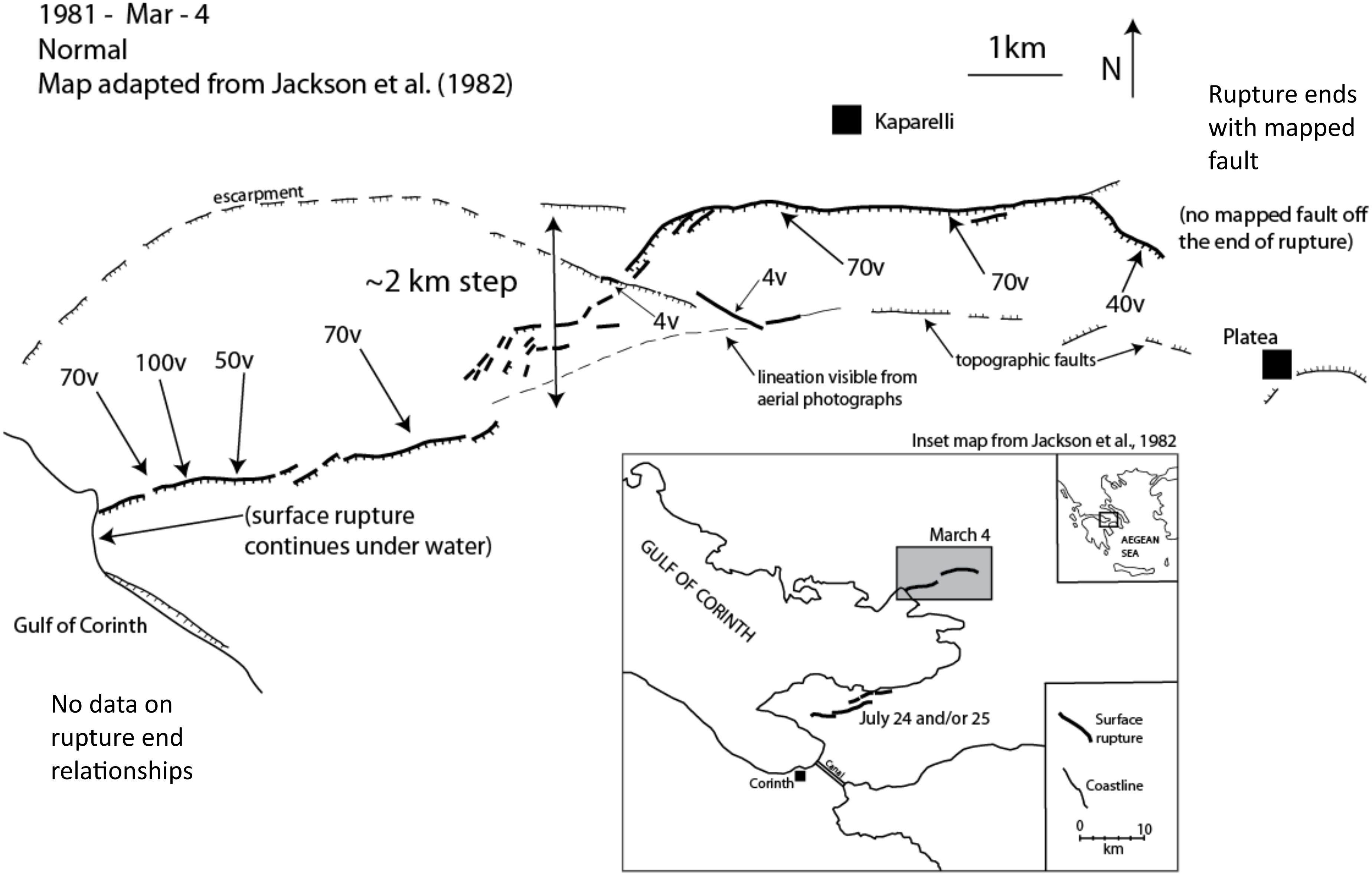


Laikipia-Subukia, Kenya, Africa
1928 - Jan - 06
normal
Map adapted from Ambraseys (1991)
Laikapia escarpment
Chui escarpment
90
180
15
240
90
210
30
15
90
15
Complexity at scale < 1 km
Rupture termination correlates to intersection of Laikapia and Chui escarpments and a bend in Laikapia escarpment,
N
10 km
1 km
Step ~ 1km occurs at structural mid-valley high and bend in range front.
Hannigan Escarpment
Lake Bogoria (Hannington)
Africa

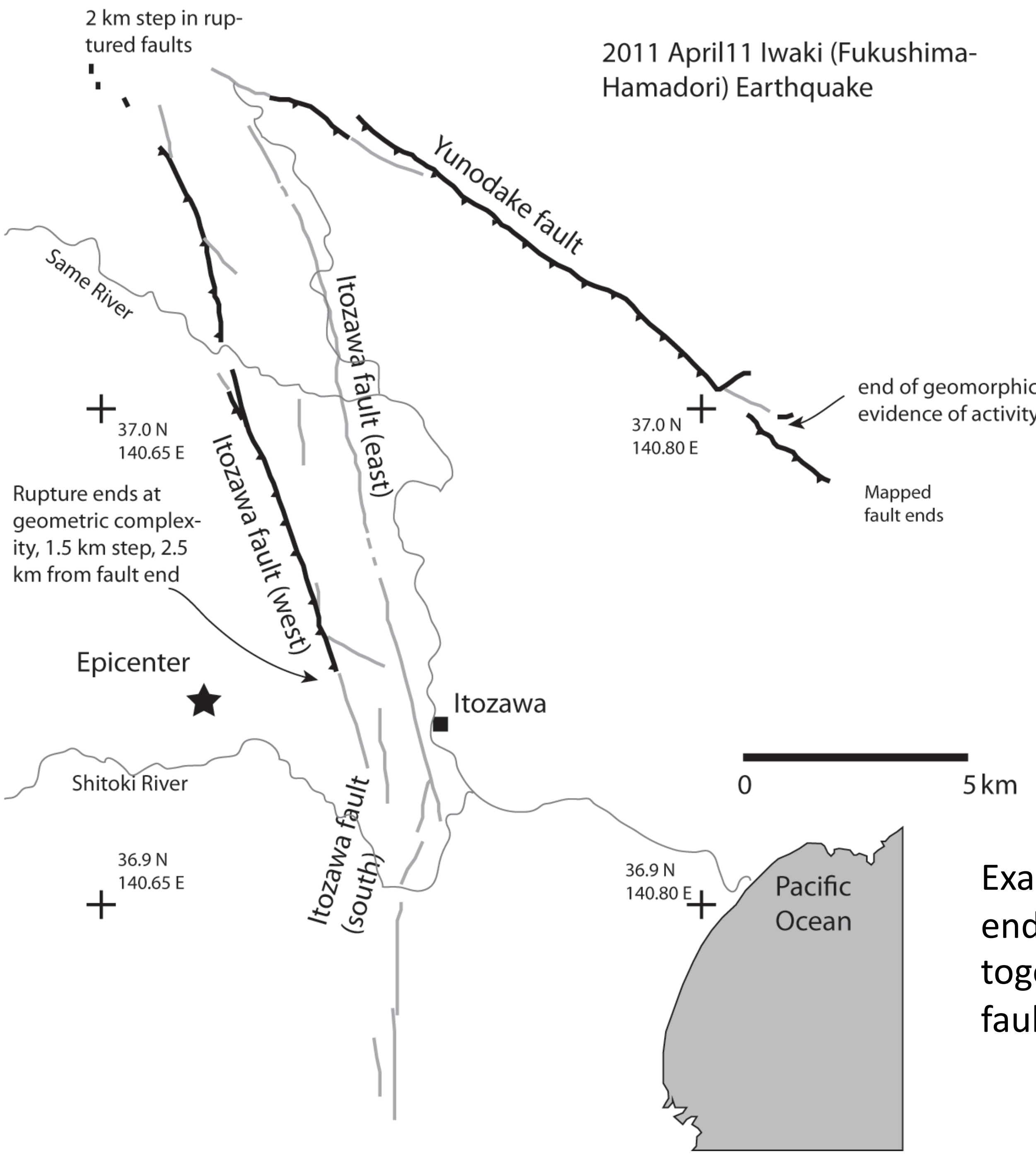
Corinth, Greece
1981 - Feb - 24/25
Normal
Map adapted from Jackson et al. (1982)



Corinth, Greece
1981 - Mar - 4
Normal
Map adapted from Jackson et al. (1982)



No data on rupture end relationships



11 April 2011

Triggered by unloading after the 11 March 2011 Tohoku M9.0.

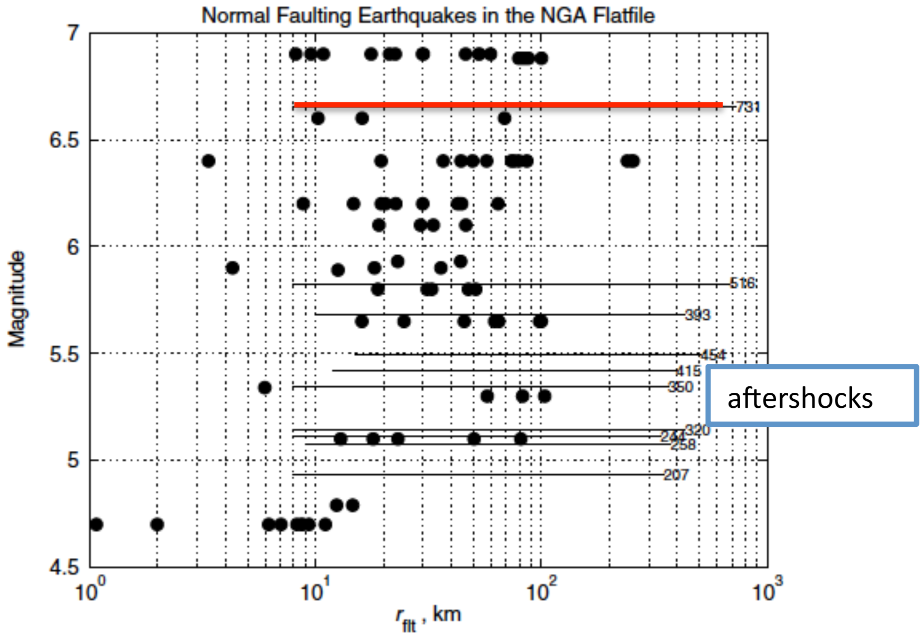
Normal faulting rupture on the Itozawa and Yunodake faults (14 km, 15 km, resp.)

Exceptional topology of rupture.

Best recorded large normal fault ever.

Example of a rupture with four ends (?!). Two faults ruptured together. Three rupture ends at fault ends.

More station data in main shock than entire NGA database for normal faulting earthquakes.



Unpaid advertisement for Anderson et al. 2013

By far the best recorded normal rupture ever.
Site-response adjusted PGA up to 3.7x 2008 GMPE medians.
Adjusted PGV ~1.5x median.

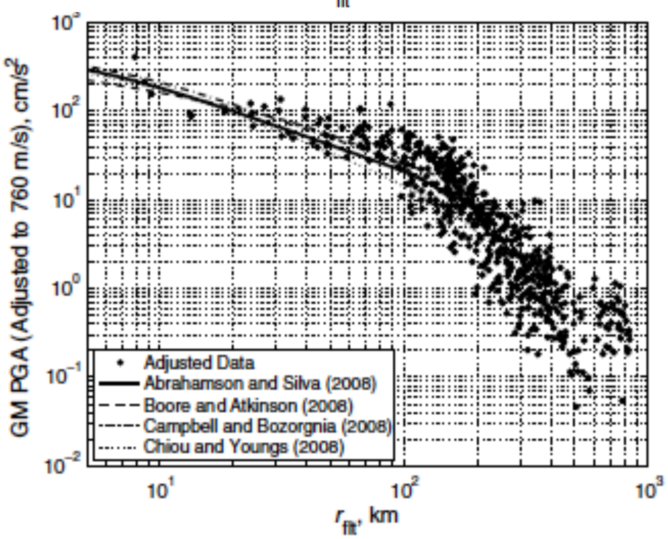


Figure 11. PGA, adjusted to $V_{S30} = 760$ m/s, using the adjustment factors from Kawase and Matsuo (2004a,b). The NGA model predictions in this figure also use $V_{S30} = 760$ m/s.

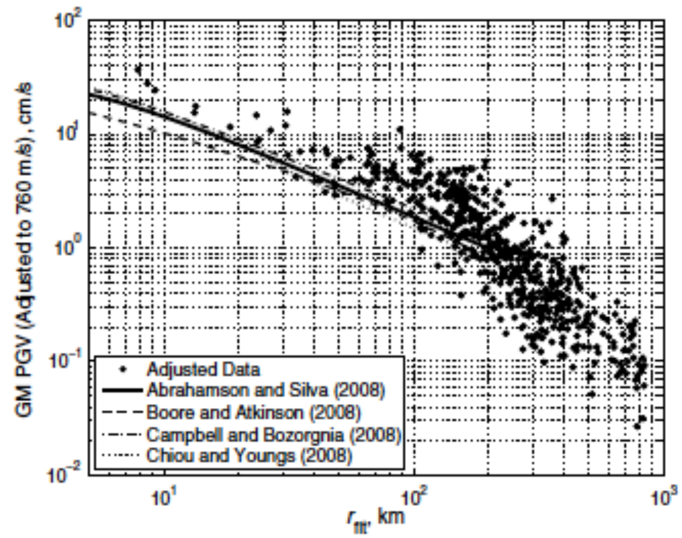


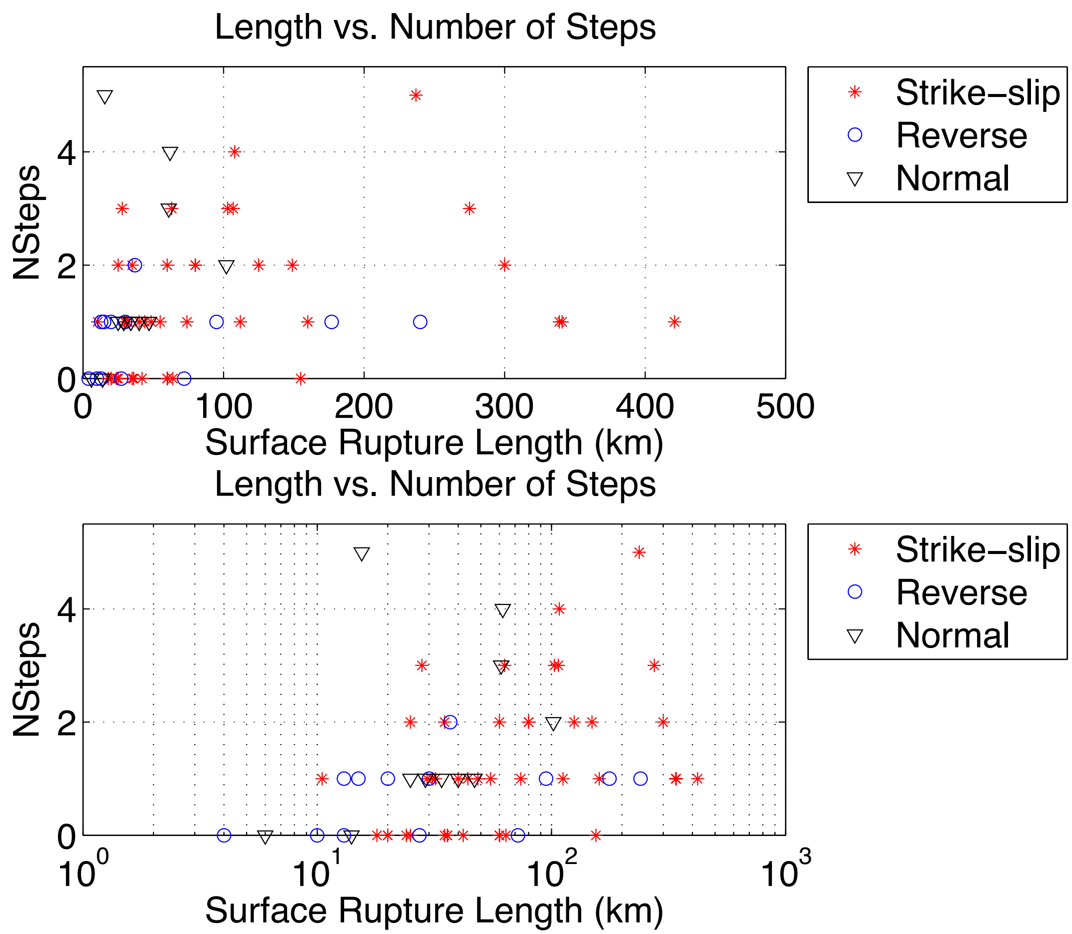
Figure 12. PGV, adjusted to $V_{S30} = 760$ m/s, using the adjustment factors from Kawase and Matsuo (2004a,b). The NGA model predictions in this figure also use $V_{S30} = 760$ m/s.

Table 1a New Events

Count steps, gaps, and how ruptures end.

Date	Earthquake	lat	lon	Mechanism	Length (km)	Magnitude	# of gaps	# of internal steps	entry >0: rupture end step size, 0=fault ends; -1=no data; -2 flt continues	entry >0: rupture end step size, 0=fault ends; -1=no data; -2 flt continues
1892-02-02	Laguna-Salada, Baja, CA	32.40	-115.60	S	42	7.2	0	0	-1	-1
1/3/1911	Chon-Kemin (Kebin), Kyrgyzstan	43.50	77.50	R	177	7.7	nd	1	-1	-1
12/16/1920	Haiyuan, China	36.60	105.32	S	237	8.3	0	5	-2	-2
3/7/1927	Tango, Japan	35.80	134.92	S	35	7	0	1	0	-1
1/6/1928	Laikipia - Subukia Kenya	0.16	35.75	N	40	6.9	0	1	0	-2
8/10/1931	Fuyun, China	46.57	89.97	S	160	7.9	2	1	-1	-1
12/25/1932	Changma, China	39.77	96.69	S	149	7.6	4	2	0	10
3/18/1953	Yenice-Gonen, Turkey	40.12	27.62	S	60	7.2	0	2	0	-2
2/9/1956	San Miguel, Mexico	31.67	-116.10	S	20	6.7	0	0	3.5	-1
12/4/1957	Gobi-Altai, Mongolia	45.15	99.21	S	245	8	1	9	-1	-1
9/1/1962	Buyin Zara (Ipak fault), Iran	35.56	49.81	S	103	6.9	2	3	-1	-1
1/5/1967	Mogod, Mongolia	48.20	102.93	S	48.5	7.1	1	1	-1	-1
8/31/1968	Dasht-e-bayaz, Iran	34.05	58.96	S	74	7.1	0	1	2	-2
3/28/1970	Gediz, Turkey	39.17	29.55	N	40	0	0	1	-1	-1
12/19/1977	Bob-Tangol, Iran	30.92	56.41	S	20	5.9	0	0	1.5	-2
9/16/1978	Tabas, Iran	33.27	57.39	R	95	7.3	3	1	-1	0
11/27/1979	Khuli-Buniabad, Iran	34.06	59.76	S	55	7	1	1	-2	0
1981 - 02 - 2	Gulf of Corinth, Greece	38.10	23.17	N	14	6.6	1	0	-2	-2
3/4/1981	Gulf of Corinth, Greece	38.20	23.30	N	13	0	0	1	0	-1
9/13/1986	Kalamata, Greece	37.08	22.18	N	6	5.8	0	0	0	-2
11/6/1988	Lancang, Yunnan, China	22.81	99.61	S	35	7	0	2	-1	-1
11/6/1988	Gengma, Yunnan, China	23.23	99.44	S	24	6.9	0	0	-1	-1
12/7/1988	Spitak, Armenia	40.93	44.11	R	20	6.7	1	1	-1	-1
6/20/1990	Rudbar, Iran	37.00	49.19	S	80	7.4	1	2	-1	-1
5/27/1995	Neftegorsk (Sakhalin), Russia	52.60	142.83	S	36	7	0	0	4.5	3
5/10/1997	Zirkuh, Iran	33.83	59.80	S	125	7.2	0	2	0	-2
2/22/2005	Dahuiyeh (Zarand), Iran	30.80	56.65	R	13	6.4	1	1	0	0
5/12/2008	Wenchuan, China	31.50	104.50	R	240	8	1	1	-2	-1
4/4/2010	Sierra Mayor - Cucapah, Mexico	32.40	-115.50	S	108	7.2	1	4	-1	-2
4/14/2010	Yushu, China-1	36.20	96.60	S	32	6.9	0	1	6	-2
4/14/2010	Yushu, China-2	0.00	0.00	S	18	6.1	0	0	6	-2
9/4/2010	Christchurch, New Zealand	-43.56	172.12	S	29.5	7	0	1	-1	-1
4/11/2011	Iwaki, (Fukushima-ken Hamadori), Japan	36.95	140.69	N	29	6.7	0	1	0	-2

Number of Steps vs. Surface Rupture Length

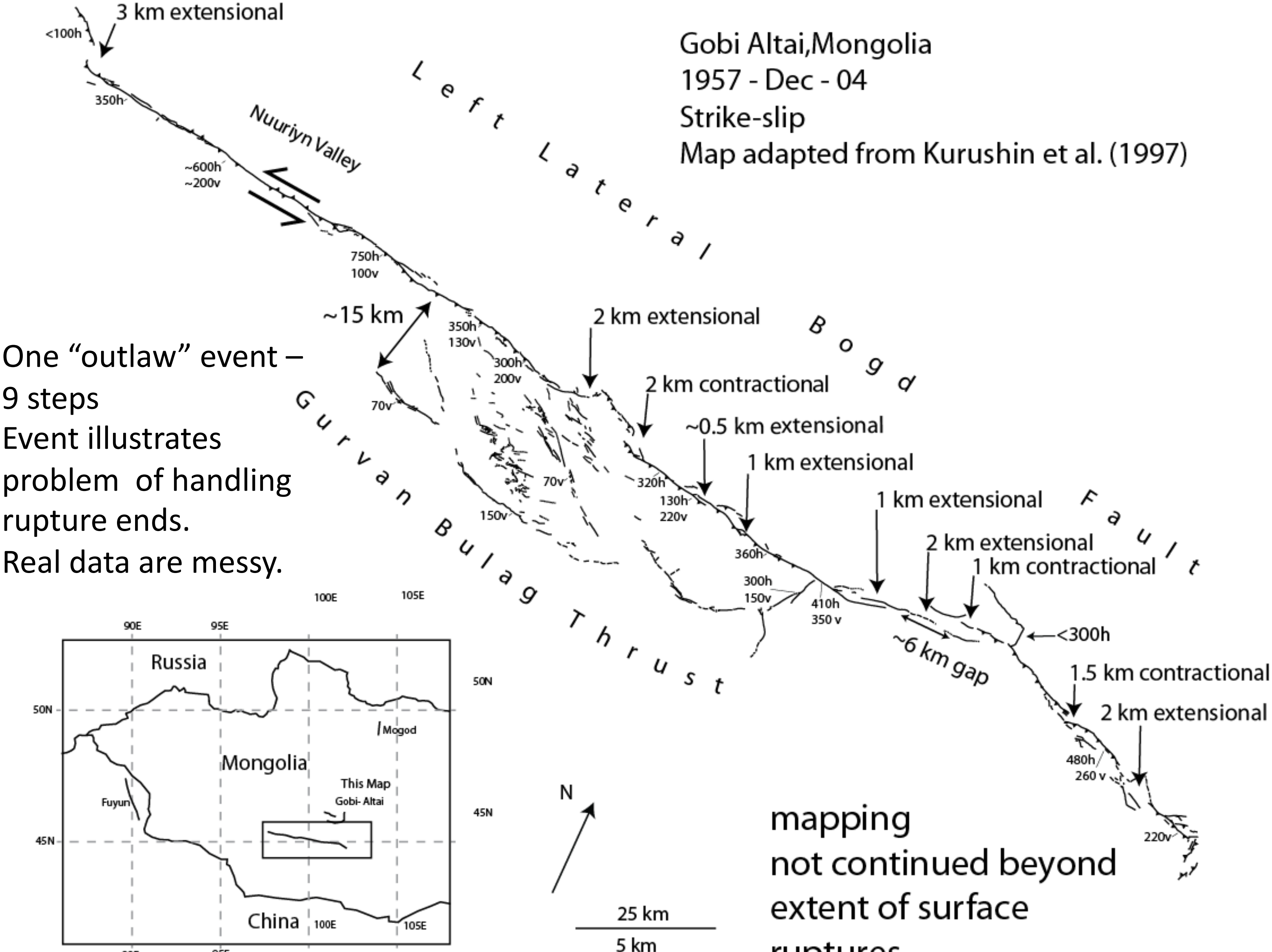


No clear relationship between numbers of steps and rupture length.

Long ruptures are not growing by linking segments bounded by steps.

Possible explanation: most large ruptures are on relatively smooth faults

Gobi Altai,Mongolia
1957 - Dec - 04
Strike-slip
Map adapted from Kurushin et al. (1997)

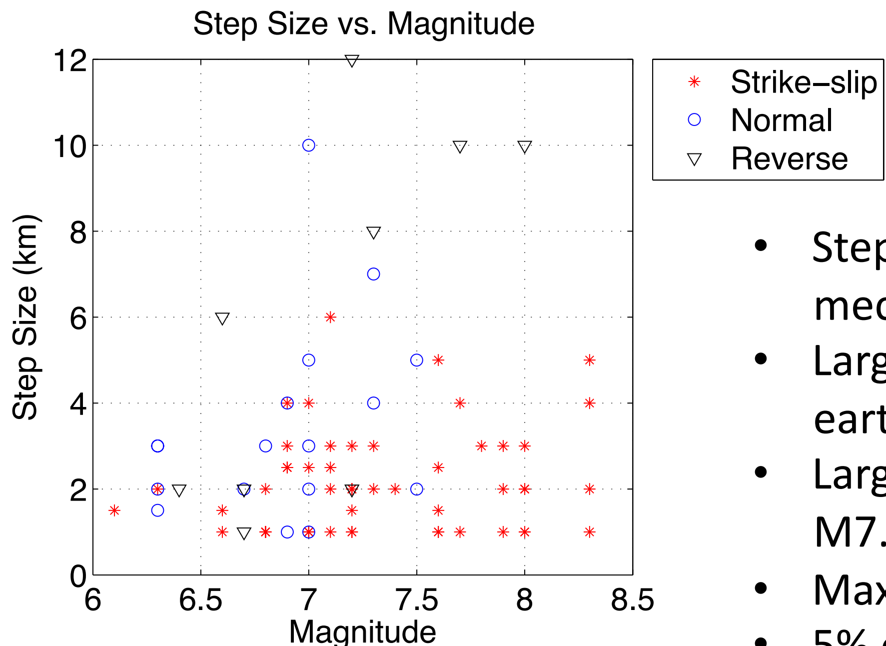


Inset map from Bayasgalan and Jackson, 1999

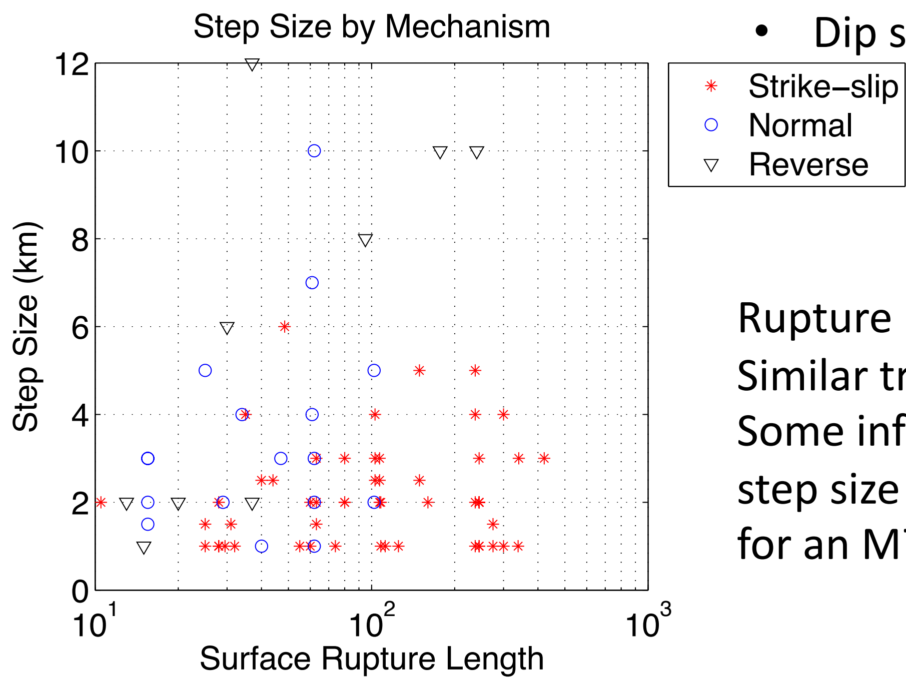
One “outlaw” event –
9 steps
Event illustrates problem of handling rupture ends.
Real data are messy.

mapping
not continued beyond
extent of surface
ruptures

Step Size vs. Magnitude and Rupture Length

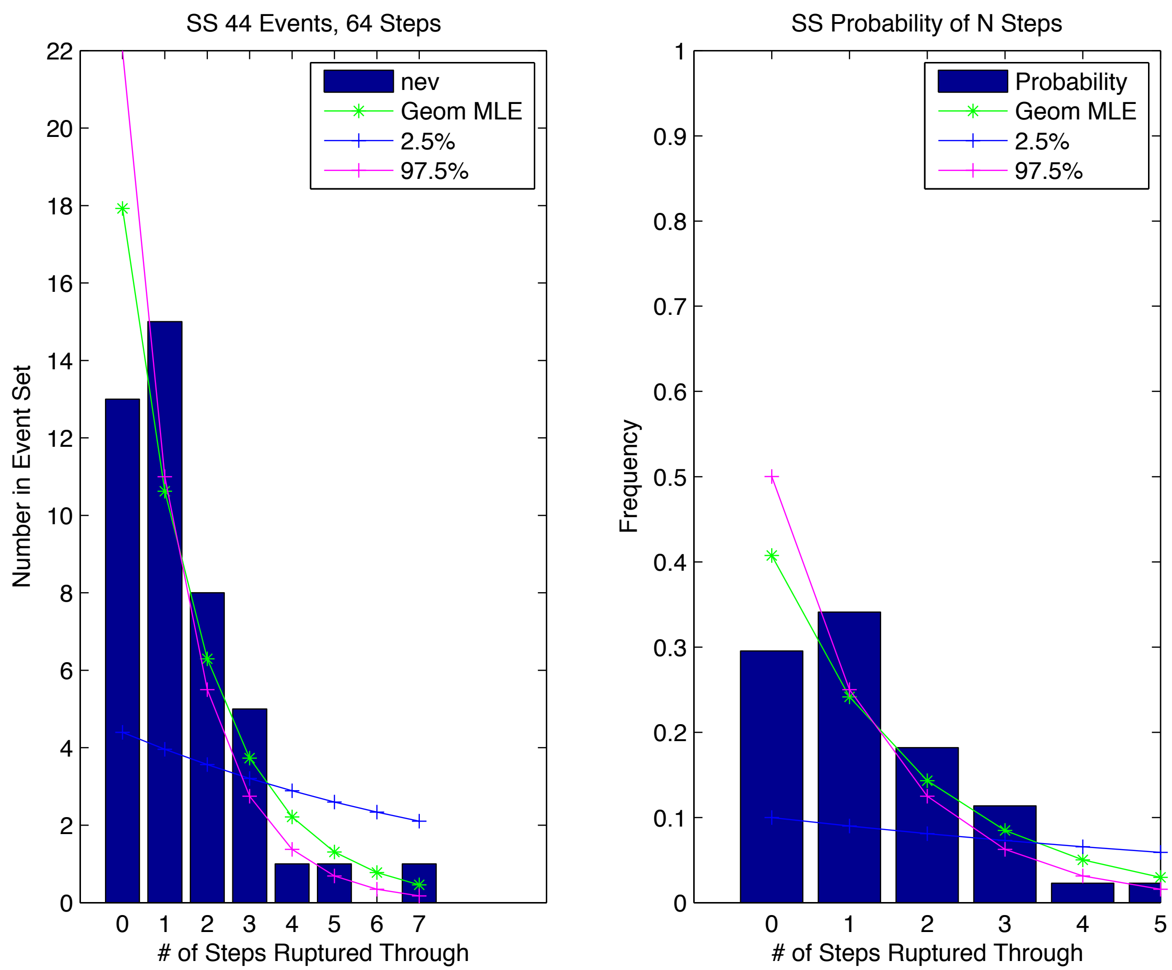


- Step size versus magnitude separates by rupture mechanism
- Largest step sizes crossed for dip slip earthquakes at about M7.0
- Largest steps crossed for strike-slip events at M7.1 to ~7.4
- Max SS step crossed: 6 km
- 5% of SS steps are greater than 4 km
- Dip slip ruptures jump farther.



Rupture length vs. step size
Similar trends to step size vs. magnitude
Some information might be gained comparing step size and magnitude (largest SS step is short for an M7.1 – high stress drop?)

Geometric Model for Passing Steps



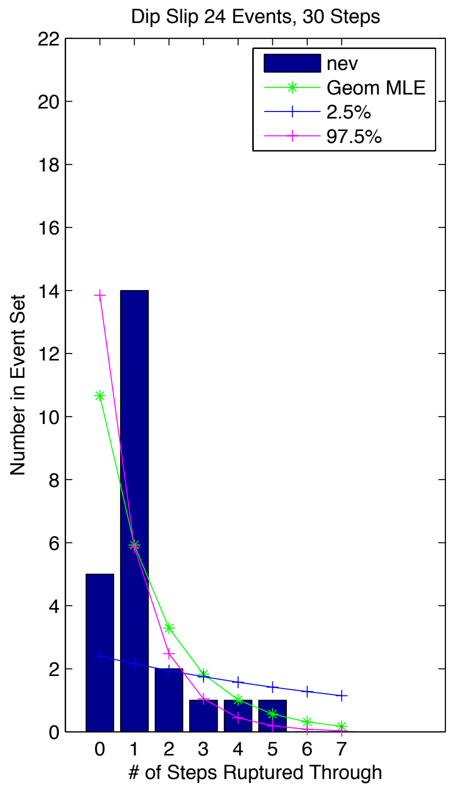
Seek the probability that steps arrest rupture
Each step of 1 km or larger is modeled as "challenges" to rupture
Analogy: flip a coin, stop at the first "tail".

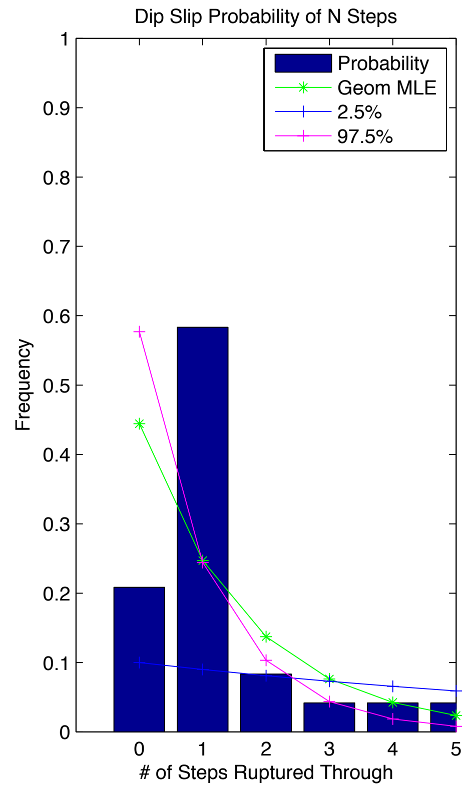
44 strike-slip events, 64 interior steps.

Probability of step stopping rupture: 41% (31-50%)

Method as applied in Wesnousky and Biasi, 2011, BSSA

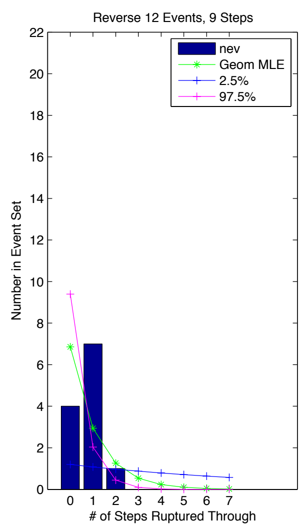
Dip Slip Mechanisms

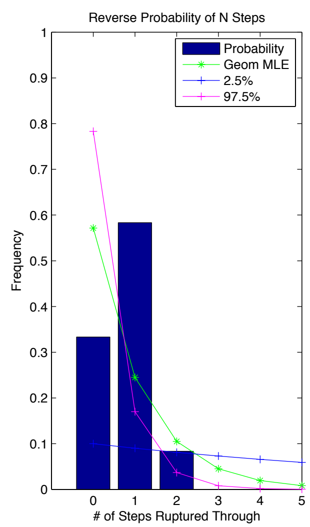




Normal and reverse mechanisms considered together.
24 events, 30 steps
Suppose mechanics are similar – rupture solves a dilational or compressional space problem at depth.

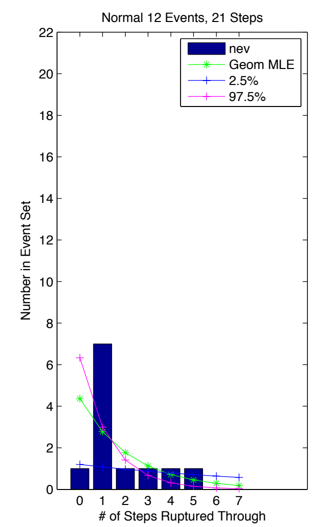
Step stops rupture: 46% (33-59%)

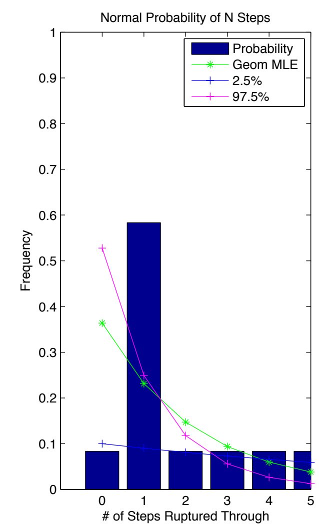




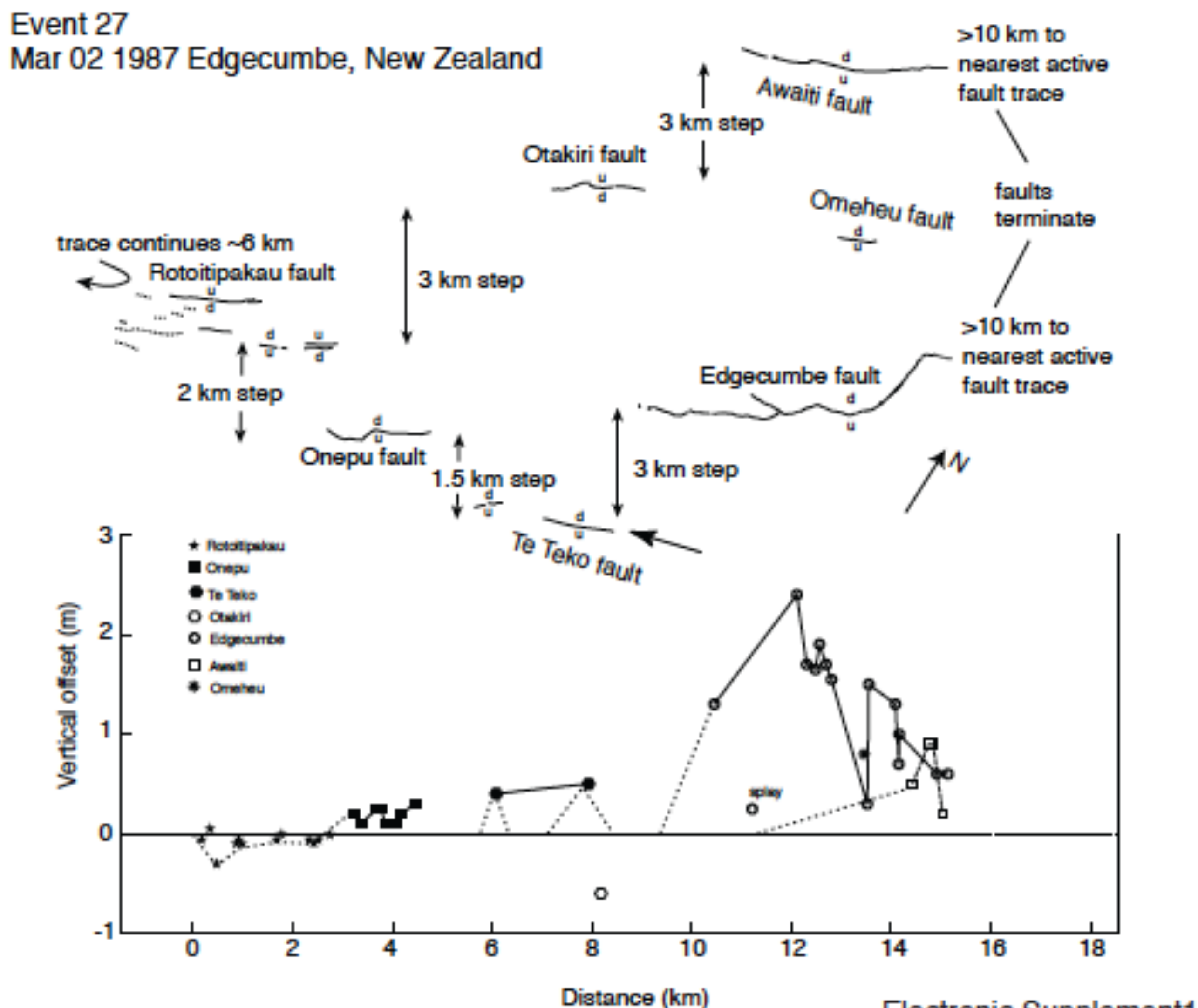
Reverse: 12 events, 9 steps. Reverse mechanism events tend to be more compact?

Normal: 12 events, 21 steps.





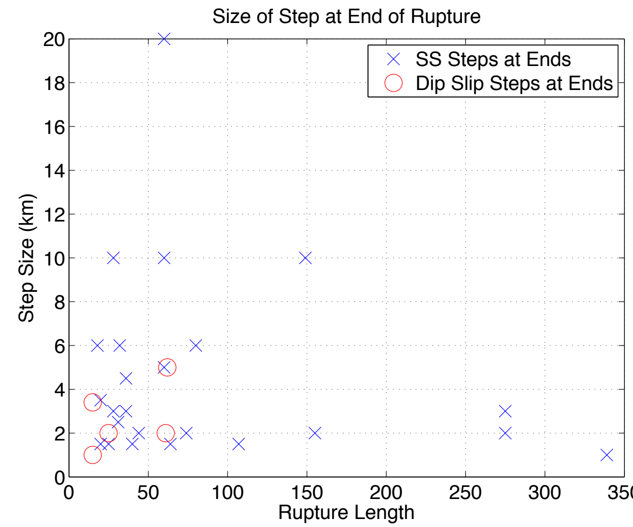
Extreme Normal Fault Example: 1987 Edgecumbe, New Zealand

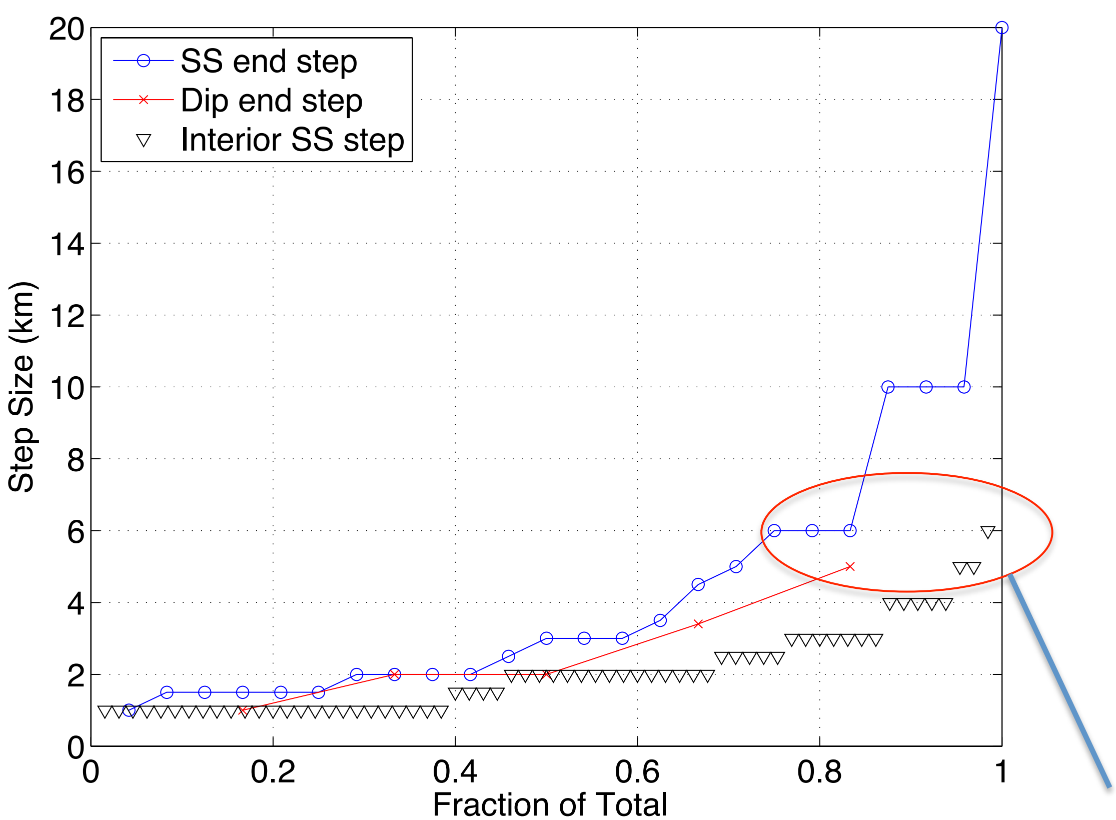


Electronic Supplement1

From Wesnousky, 2008

Is there something different about steps that end ruptures?





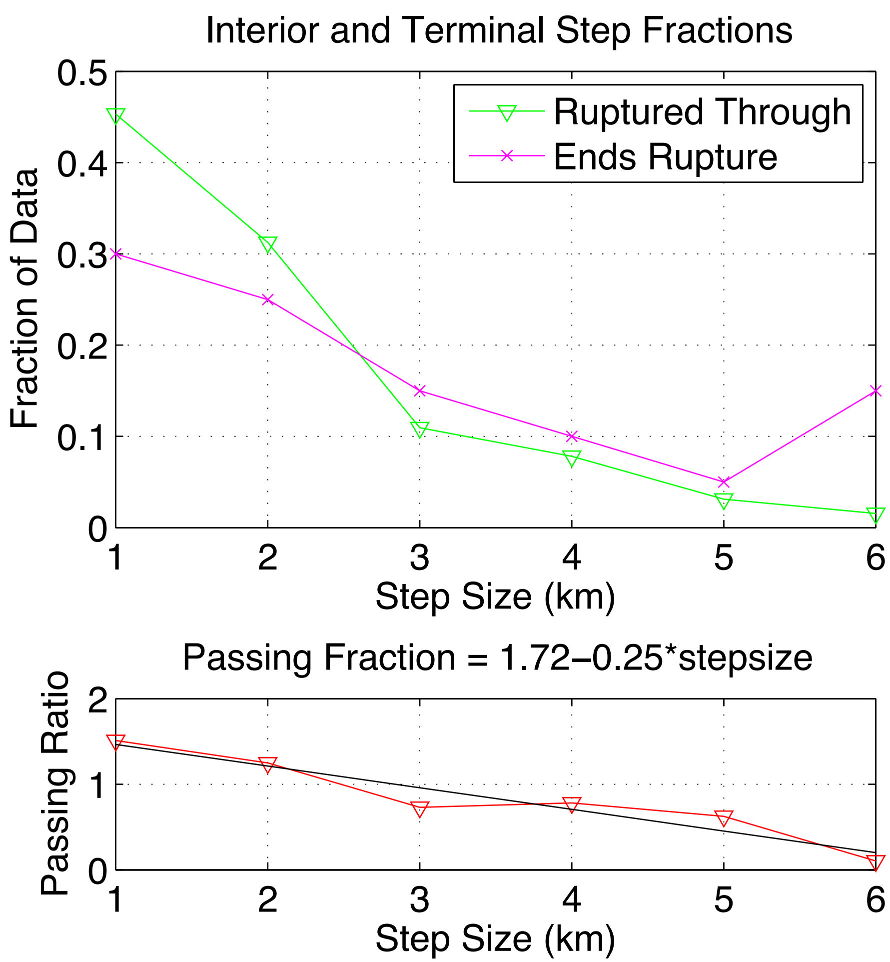
All steps inside ruptures are broken; all at ends resisted rupture.

Step size for statistics (≥1 km) was chosen because it is typically visible on rupture maps, and not for physical reasons.

Can observational data help?

No strike-slip >6 km broken. Compare steps ≤ 6 km next.

Step Effectiveness vs. Step Size (Strike-Slip)



Steps of 1 km are ruptured through more often than they arrest rupture.

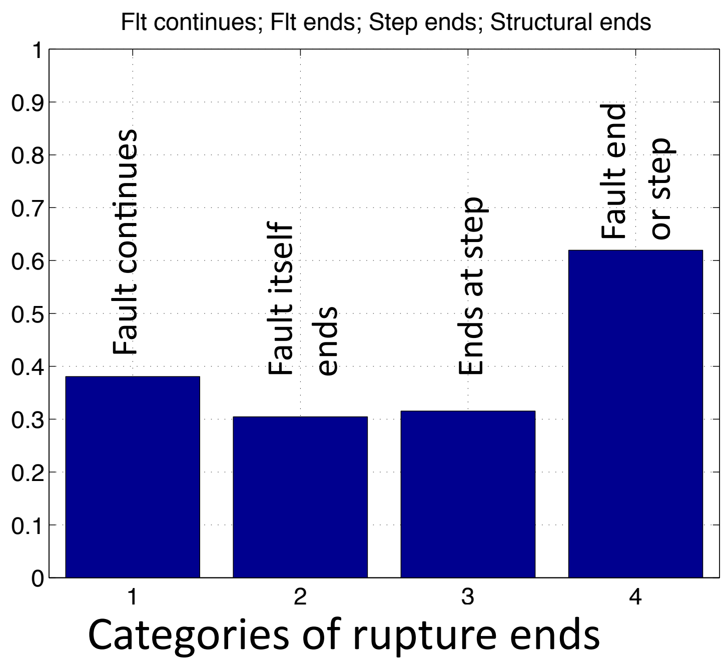
This ratio reverses for large step size.

The 50% point occurs near 3 km.

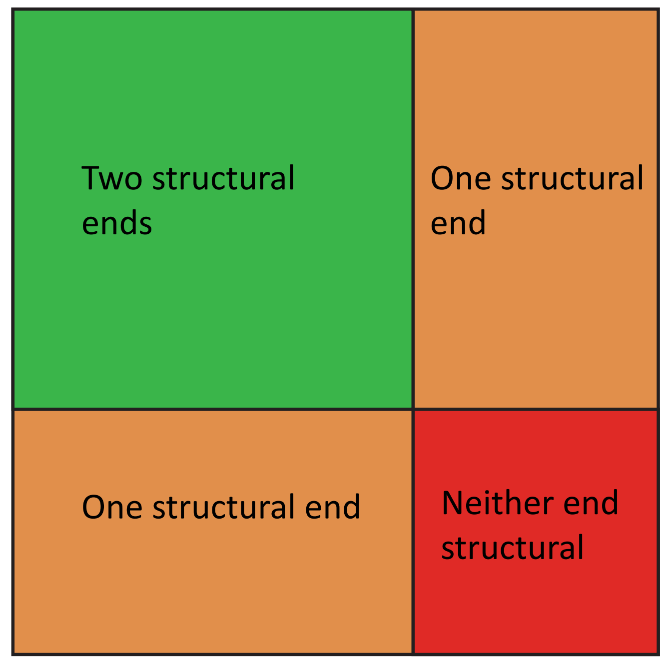
A trend fitting the step success/failure ratio may have uses in scenario development.

Dynamic modelers have been looking for data on step effectiveness versus step size.

How helpful is fault structure for rupture scenarios?



“Structure” here also includes the fraction of ruptures that end at the end of the mapped trace.
Most ruptures have one or both ends at a step or fault end.

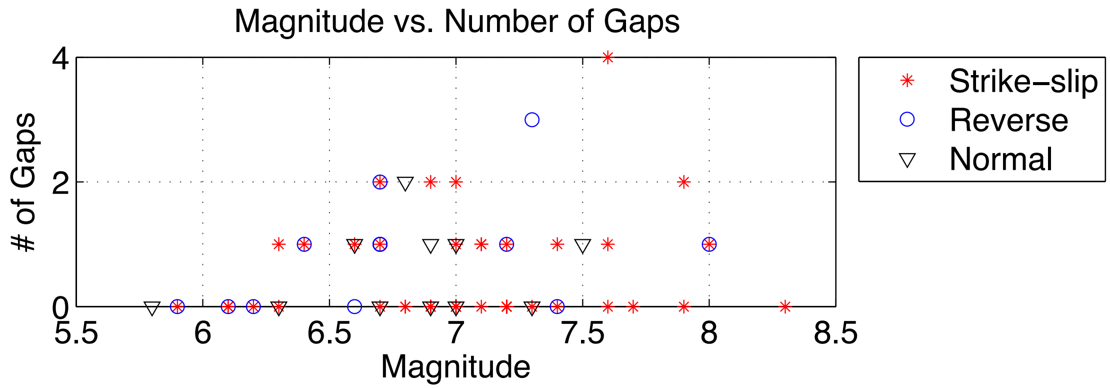


Only 14% of ruptures can be expected to truly float.

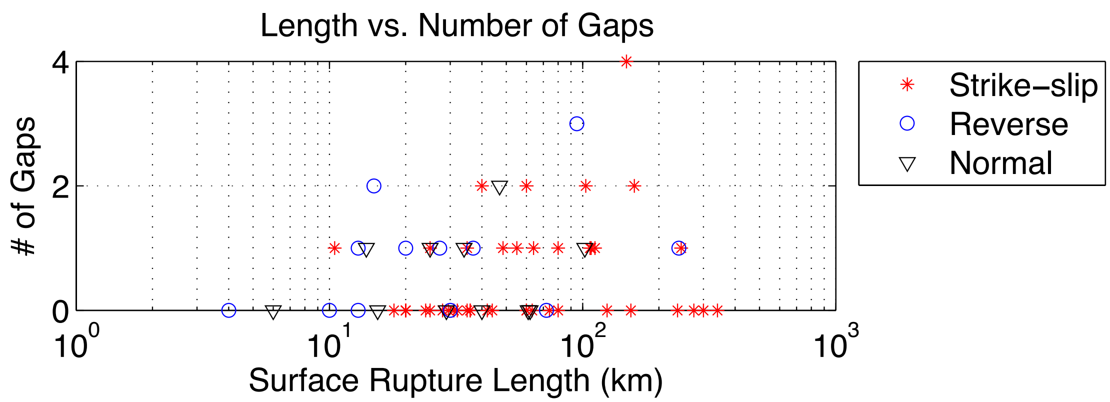
86% end with one or both ends at structural features – steps or physical fault ends.

Some float, most don’t.

Data, Interior Gaps in Rupture Traces



No clear pattern relating number of gaps to earthquake magnitude.



Normal and reverse mechanism events include gaps in shorter length ruptures.

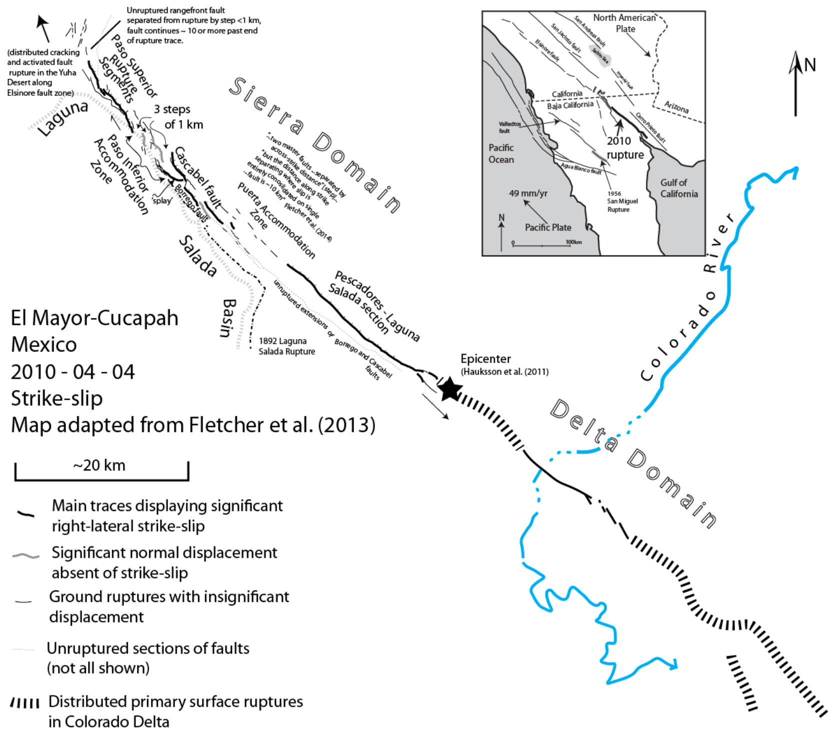
Gaps of 1 km or more are observed in ~40% of surface ruptures.
Future estimates may be smaller with better observation of distributed shear.
What they mean is, for now, unclear.

Fraction of ruptures with gaps:

Strike slip:	16/42 = 38%
Normal:	5/13 = 38%
Reverse:	7/12 = 58%

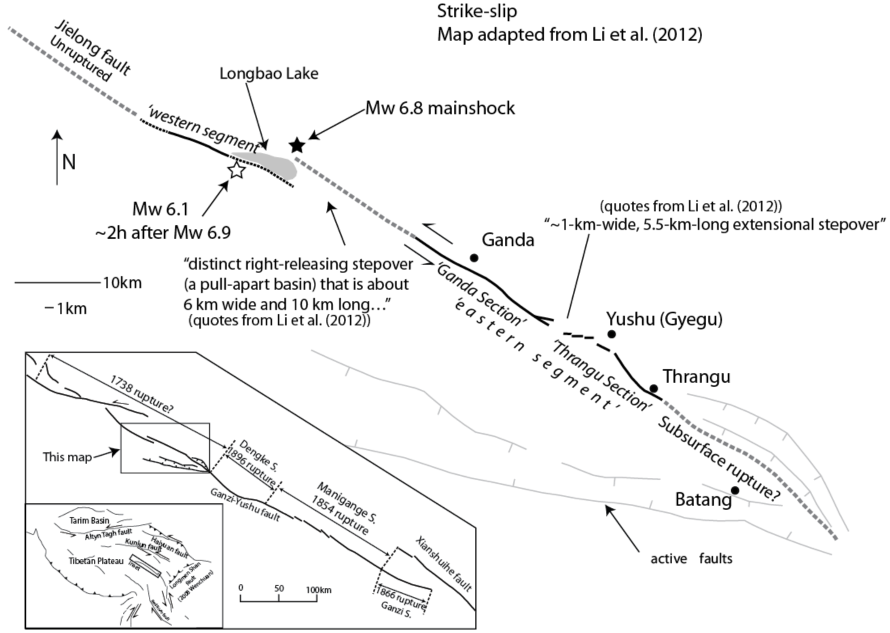
Rupture Gaps to Ponder

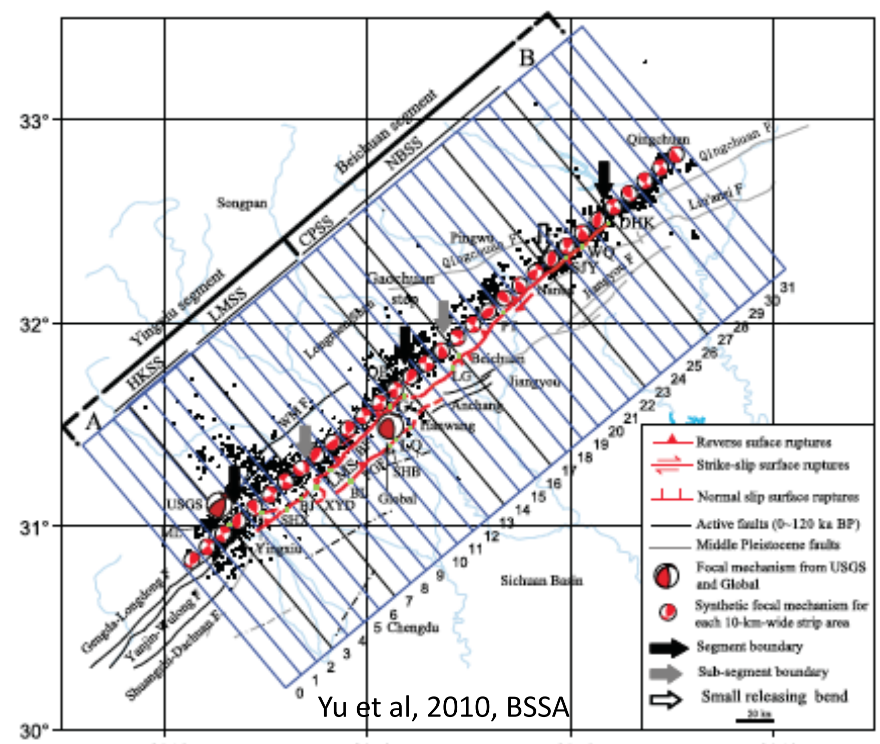
-- El Mayor-Cucapah: 7-12 km interior gap.
-- Yushu, China: ~15 km "gap" from epicenter to nearest surface rupture.
-- Wenchuan, China: NE 90 km of coseismic strike-slip, no surface rupture.



El Mayor-Cucapah
Mexico
2010 - 04 - 04
Strike-slip
Map adapted from Fletcher et al. (2013)

Yushu, China
2010 - 04 - 14
Strike-slip
Map adapted from Li et al. (2012)

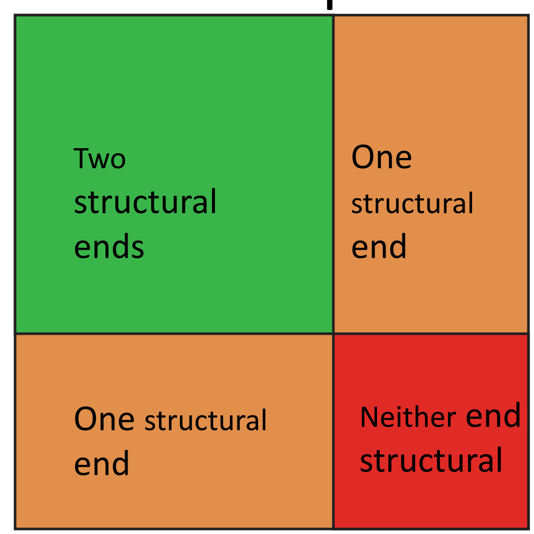




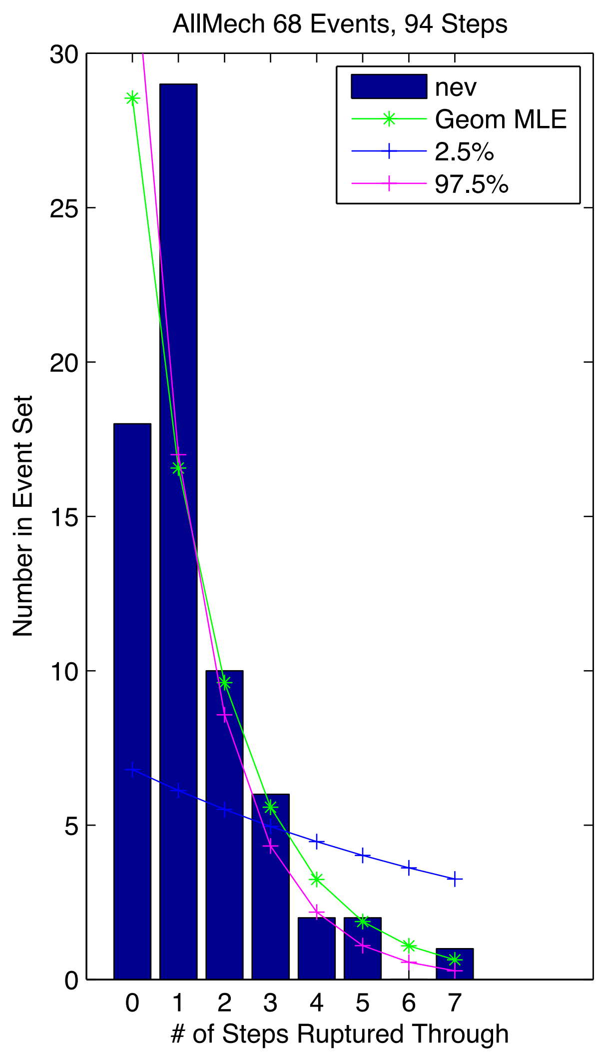
Yu et al, 2010, BSSA

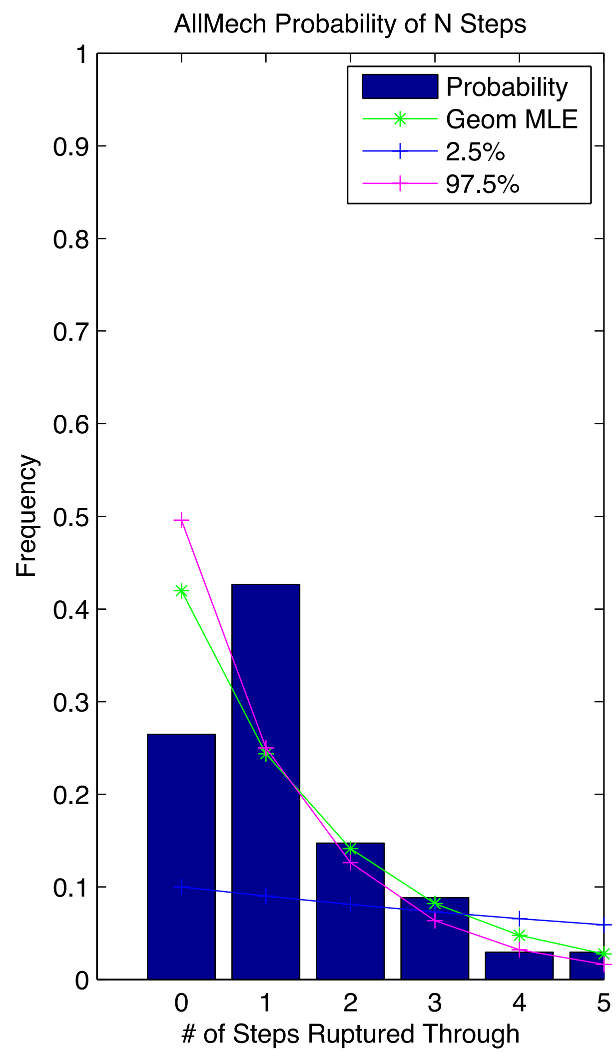
Conclusions

- A statistical basis for the impact of fault steps is observed.
  - Ensemble basis: steps of >=1 km stop ruptures about 45% of the time.
  - Steps are slightly more effective for strike-slip ruptures than for dip-slip ruptures.
- Largest steps in strike-slip events are 5-6 km. Only ~5% are larger than 4 km.
- Dip-slip ruptures jump larger steps – up to 10-12 km.
- Effectiveness of step depends on step size, with 3 km steps having about a 50% chance.



All Mechanisms, Geometric Fit





SLIP AT A POINT VARIABILITY—IMPLICATIONS FOR EARTHQUAKE-MAGNITUDE DISTRIBUTIONS NEAR M_{max}

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The now-routine use of surface-rupturing displacements to infer paleoearthquake magnitudes and, moreover, the magnitude-frequency behavior of faults was pioneered in the Basin and Range Province (Schwartz and Coppersmith, 1984). The vertically stacked, rupture-generated deposits (primarily colluvial wedges) that develop on active normal faults facilitate recognition of events and comparison of the displacement size of successive events at a common location. The number of events that can be sampled at a site; however, on both strike-slip and dip-slip faults, is generally small, too small for statistically robust analysis of event-to-event variability.

To overcome this sample-size limitation, we compiled and analyzed a composite dataset of slip-at-a-point variability derived from many crustal faults worldwide (171 sites in Hecker and others, 2013; 292 sites in Hecker and others, 2014; figure 1). This approach, which involves normalizing the slip values by the mean slip at each site, presumes that the long-term behavior of an individual fault can be represented by the grouped behavior of all similar faults. We used the observed variability in slip at a point (as represented by the coefficient of variation, CV, given by the ratio of the standard deviation to the mean) to formally test the two principal competing models of earthquake-size distribution on faults: the truncated-exponential (aka Gutenberg-Richter, GR) model and the characteristic-earthquake (CEQ) model (as originally reported in Hecker and others, 2013). These models describe distinctly different distributions near the maximum magnitude (M_{max}), with the CEQ model having relatively more events in a narrow range of magnitudes near the maximum, at the expense of smaller, moderate-magnitude events, than would be predicted from an exponential distribution of earthquakes. Thus, the two models can lead to widely differing estimates of the frequency of damaging earthquakes at a site and permit differing estimates of the upper-bound magnitude on a fault. Because the paleoseismic record samples the upper (surface-rupturing) portion of the magnitude-frequency spectrum of a fault, it provides evidence that bears directly on the models' differences.

We used a forward modeling approach to simulate, for each magnitude-frequency distribution, the distribution of surface displacements expected to be observed at a point and then compared the CV of the predicted displacements with the CV of the global dataset (Hecker and others, 2013). We did this for a range of M_{max} values (or, for the CEQ model, values at the upper end of the characteristic magnitude). The forward model incorporates several parameters that could affect displacement variability at a site, including the magnitude threshold of surface rupture, the variability of (average) displacement for a given magnitude, and the variability in rupture pattern for a given magnitude. We also modeled the effect of displacements that are too small to be resolved as separate events in the geologic record and evaluated the possible bias introduced by the small number of observations per site. To account for sub-resolution displacements, we developed a probabilistic threshold-of-detection model that considers site conditions and study methods (as in figure 2) and an event's position in a sequence and that conserves cumulative displacement. The forward model does not include a representation of measurement error; however, and so the modeled CV should be less than the empirical value.

The global dataset of normalized displacements has a computed CV value of about 0.5 (~0.53 for all data and ~0.48 for a subset of sites judged to be more reliable, as reported by Hecker and others, 2013; results in Hecker and others, 2014 are comparable). The CV is not significantly different for dip-slip faults and strike-slip faults (0.53 +/- 0.4 versus 0.50 +/- 0.06, respectively), but is significantly larger for small-displacement sites, those with mean displacements less than 1 m, than larger-displacement sites (0.63 +/- 0.08 versus 0.48 +/- 0.03, respectively). The subset of sites with small mean displacements represents 23% of sites in the dataset.

The results of our forward modeling (table 1; Hecker and others, 2013, their table 2) indicate that the GR distribution of earthquakes produces CV values larger than observed, with the possible exception of the small maximum-magnitude (M_{max} 7.05) model. In contrast, the CEQ model (as formalized by Youngs and Coppersmith, 1985) produces CV values within or below the range of observations for cases where the variability of slip at a point for a given earthquake magnitude (a combination of the variability of average displacement and variability in rupture pattern) is small (table 1). This requirement implies stability in surface slip distributions and nearly constant scaling of site-specific displacement with magnitude, which conceptually is consistent with the CEQ model, but inconsistent with the stochastic process of earthquake generation implied by the GR model. If we compare the small maximum-magnitude GR model with the subset of small-displacement sites, modeled CVs are smaller than observed (CV~0.63) for cases that assume some magnitude-specific variability in slip at a point (table 1). Although this result allows for a significant difference in the magnitude distribution of smaller surface-rupturing earthquakes, the larger CV of the data may instead reflect larger measurement errors or greater variability in the displacement pattern of smaller ruptures or the tails of larger ruptures.

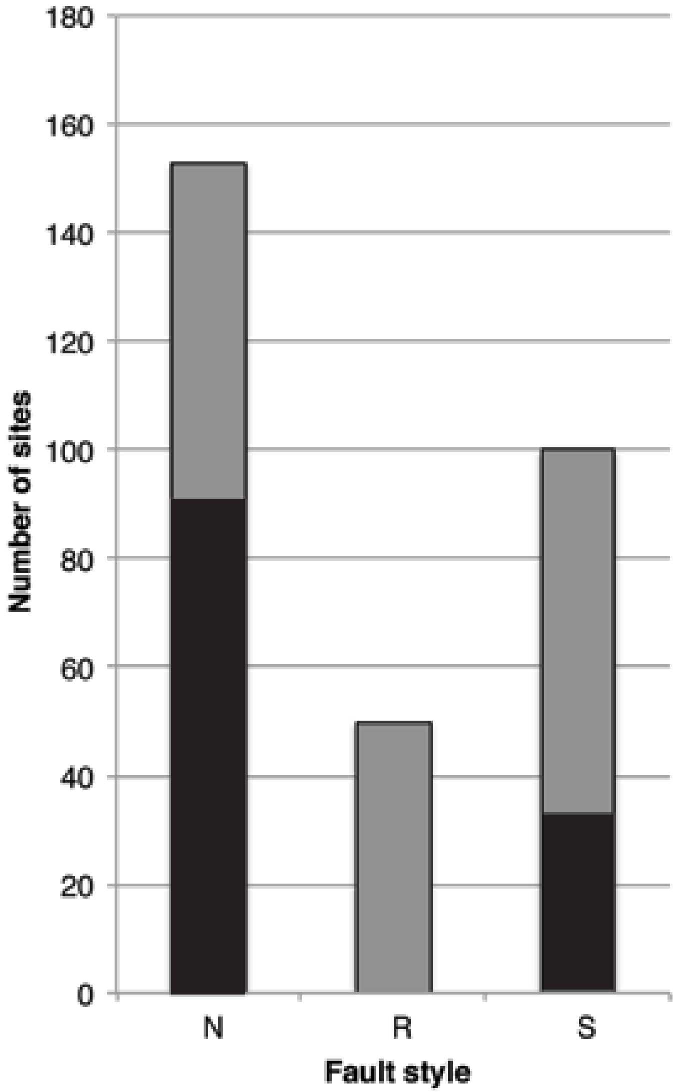

Figure 1. Distribution of sites by fault style (adapted from figure 2 of Hecker and others, 2014). Eleven sites on oblique-slip faults having subequal components of horizontal and vertical slip are double-counted. N=normal slip; R=reverse slip; S=strike slip. Many sites (38%) in this global dataset are from the greater Basin and Range region, represented by black bars.

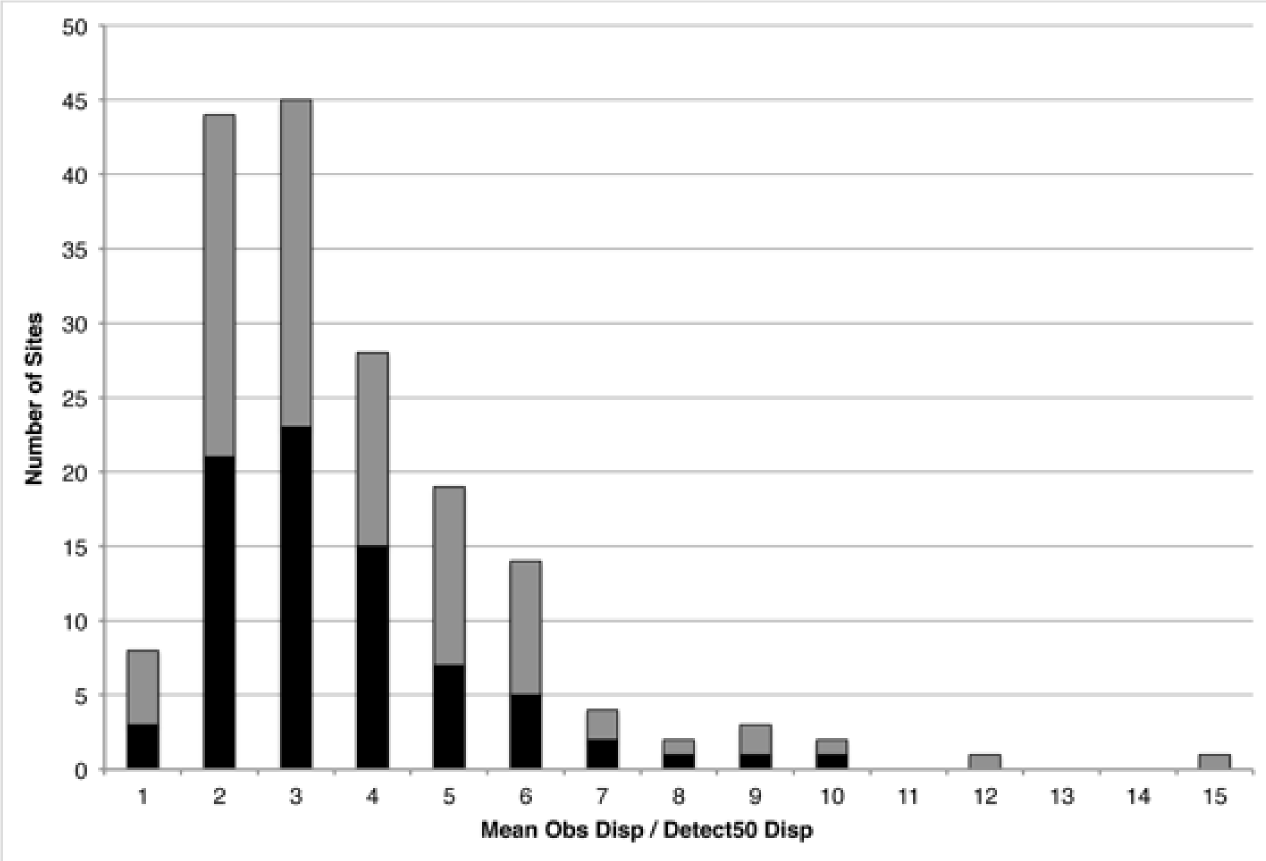

Figure 2. *Distribution of sites by the ratio of the mean displacement observed at a site to the modeled threshold-of-detection displacement (Detect50, with 50% chance of being detected as a discrete event). Values of Detect50 range from 0.1 to 2 m, with approximately two-thirds of sites in the Basin and Range region (represented by black bars) assigned Detect50 values of 0.5 m. The chance of detecting an event depends on the ratio of the actual displacement to the detection threshold, and using actual rather than the observed displacements at a site would result in smaller ratios. For ratios less than 2, there is a significant chance (>25%) that the event will not be detected. By this measure, the distribution shows that at least a third of the sites in the database have a significant chance of including undetected events (adapted from figure 12 of Hecker, and others, 2013). Note that the dataset is an earlier, smaller version of the dataset shown in figure 1.*

Table 1. *Comparison of CV values for the alternative magnitude-distribution models, implemented using the displacement scaling relations of WC94 (Wells and Coppersmith, 1994) and Wes08 (Wesnousky, 2008), and several values for the variability of displacement for a given magnitude (comprised of variability of average displacement, $\sigma_{AD(log10)}$, and variability in the pattern of displacement distribution). The top row of CV values uses empirically constrained values of average-displacement variability from global models and the full along-strike displacement variability of individual ruptures (from Wesnousky, 2008). In all cases presented, the forward modeling incorporates the same sample-size and detection-category distributions as the data set.*

Variability of displacement for a given magnitude		**Y&C Characteristic (M_{char}=6.8)**		**Y&C Characteristic (M_{char}=7.5)**		**Truncated Exponential (M_{max}=7.05)**		**Truncated Exponential (M_{max}=7.75)**		**Truncated Exponential (M_{max}=8.25)**	
σAD (log10)	CV Along Strike	**WC94**	**Wes08**	**WC94**	**Wes08**	**WC94**	**Wes08**	**WC94**	**Wes08**	**WC94**	**Wes08**
0.36 (WC94) 0.33 (Wes08)	0.6	0.71 ± 0.03	0.72 ± 0.03	0.83 ± 0.03	0.79 ± 0.03	0.72 ± 0.03	0.71 ± 0.03	0.86 ± 0.04	0.78 ± 0.03	0.96 ± 0.04	0.83 ± 0.04
0.1	0.6	0.51 ± 0.02	0.51 ± 0.02	0.61 ± 0.03	0.57 ± 0.02	0.59 ± 0.02	0.55 ± 0.02	0.75 ± 0.03	0.63 ± 0.02	0.86 ± 0.03	0.70 ± 0.03
0.1	0.3	0.46 ± 0.02	0.45 ± 0.02	0.52 ± 0.03	0.49 ± 0.02	0.56 ± 0.02	0.52 ± 0.02	0.71 ± 0.03	0.60 ± 0.02	0.83 ± 0.03	0.66 ± 0.02
0.0	0.0	0.41 ± 0.02	0.38 ± 0.02	0.44 ± 0.02	0.42 ± 0.02	0.53 ± 0.02	0.49 ± 0.02	0.69 ± 0.02	0.56 ± 0.02	0.81 ± 0.02	0.63 ± 0.02

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ESTIMATING MAGNITUDES OF LARGE EARTHQUAKES FROM GEOLOGICAL OBSERVATIONS OF FAULTS WITH LOW SLIP RATES

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Nevada Seismological Laboratory, University of Nevada, Reno, Nevada 89557
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Anderson and others (1996) examined whether the slip rate of an active fault could help to improve estimates of the magnitude for a given rupture length. Based on 43 earthquakes culled from the database of Wells and Coppersmith (1994), they suggested the following relationship: M_W=5.12+1.16 log L-0.20 log S , where L is the rupture length in units of km, and S is the slip rate in units of mm/yr. With funding from the U.S. Geological Survey, we have initiated a project to re-evaluate this relationship in the light of additional data. Our expanded database has 89 events, approximately double the size of the initial study. A contribution from the slip rate does seem to be present in our preliminary analysis of the new database, but it also appears that a considerable amount of scatter remains to be explained. We are looking at subsets of the data to assess optimal relationships for faults with low slip rates and normal faulting mechanisms. A strong slip-rate dependency could affect the rates and magnitudes estimated for faults in the Walker Lane and the Basin and Range Province. Results will be presented at the meeting.

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Anderson, J.G., Wesnousky, S. G., and Stirling, M., 1996, Earthquake size as a function of fault slip rate: Bulletin of the Seismological Society of America, v. 86, p. 683-690.

Wells, D.L., and Coppersmith, K.J., 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: Bulletin of the Seismological Society of America, v. 84, p. 974-1002.

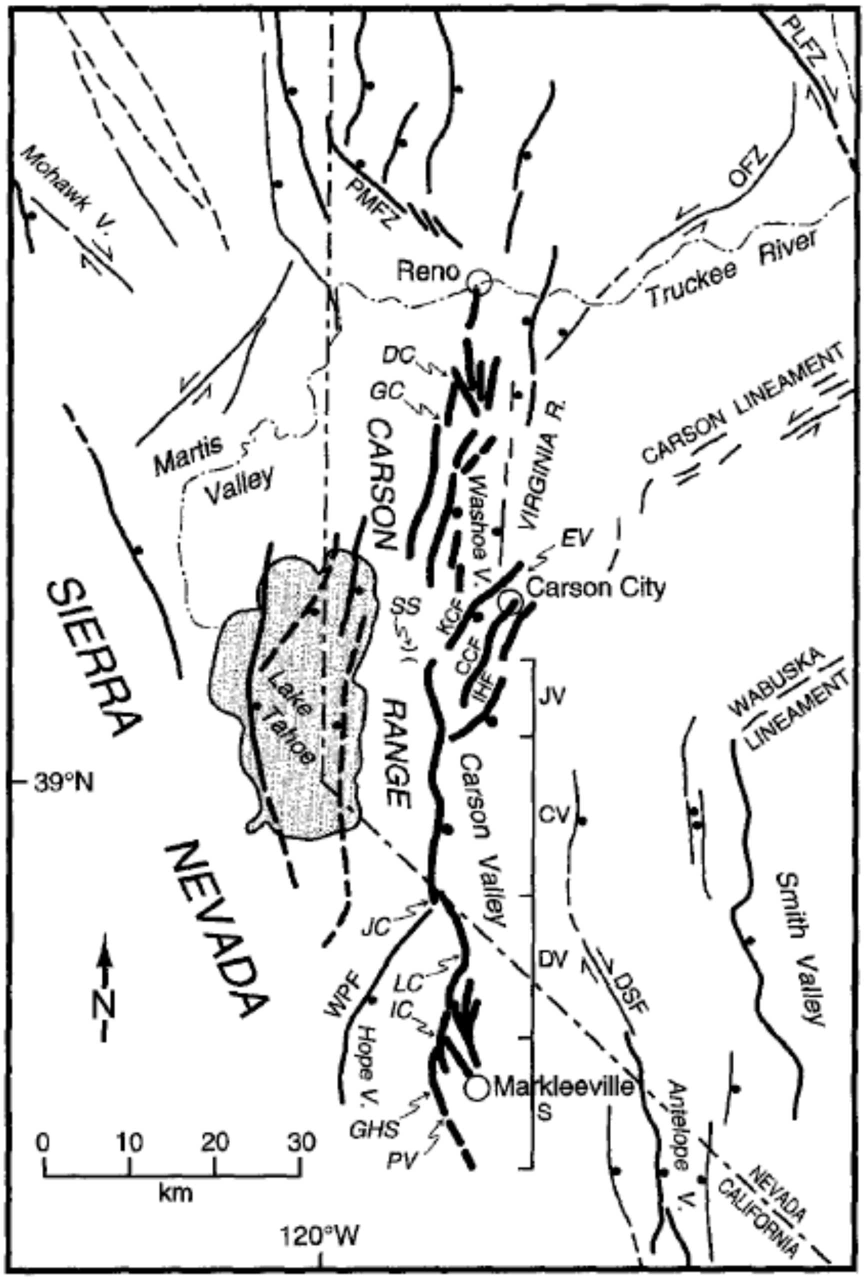
The following is a PDF version of the authors' PowerPoint presentation.

Estimating Magnitudes of Large Earthquakes from Geological Observations of Faults with Low Slip Rates

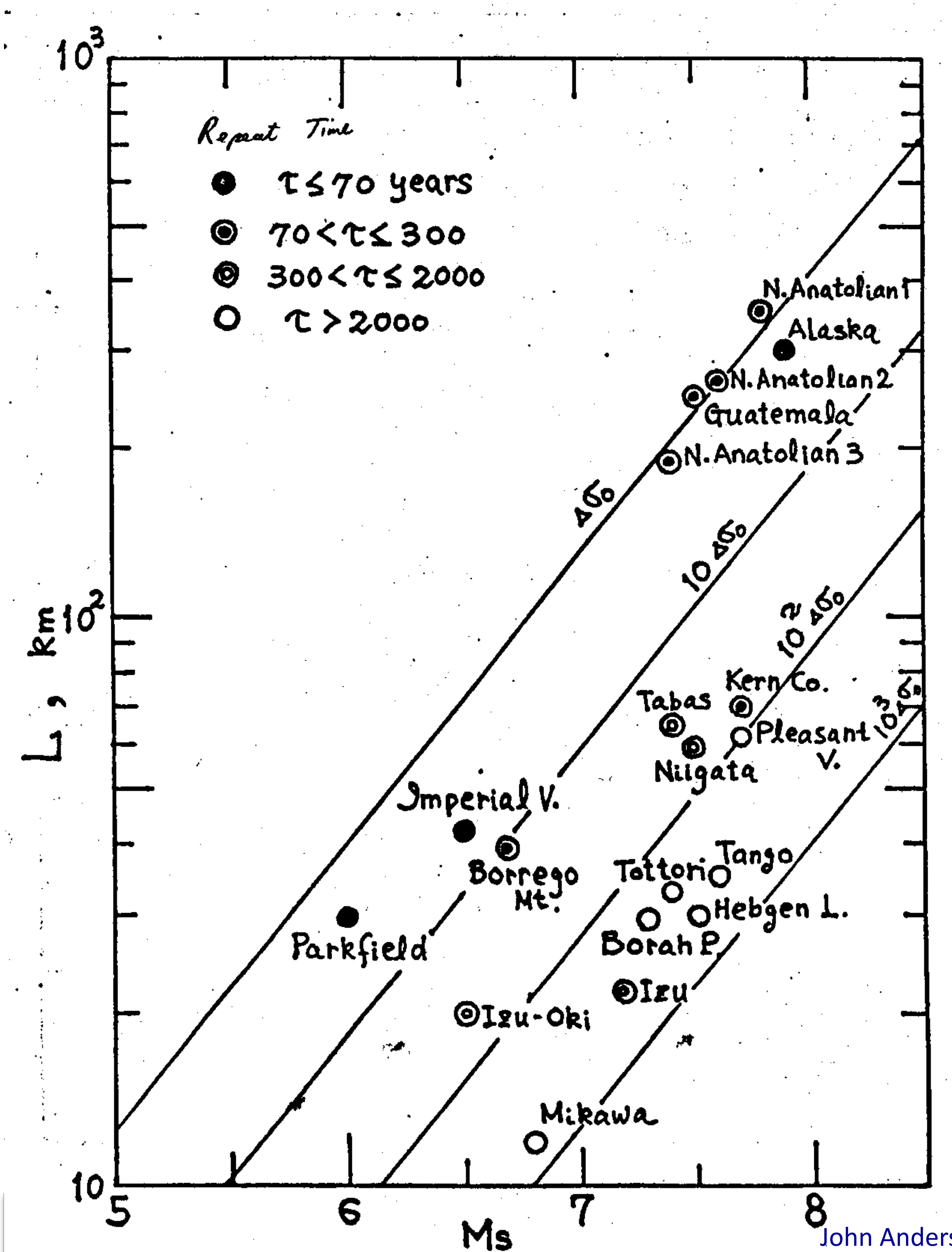
John G. Anderson, Glenn Biasi,

Steve Wesnousky

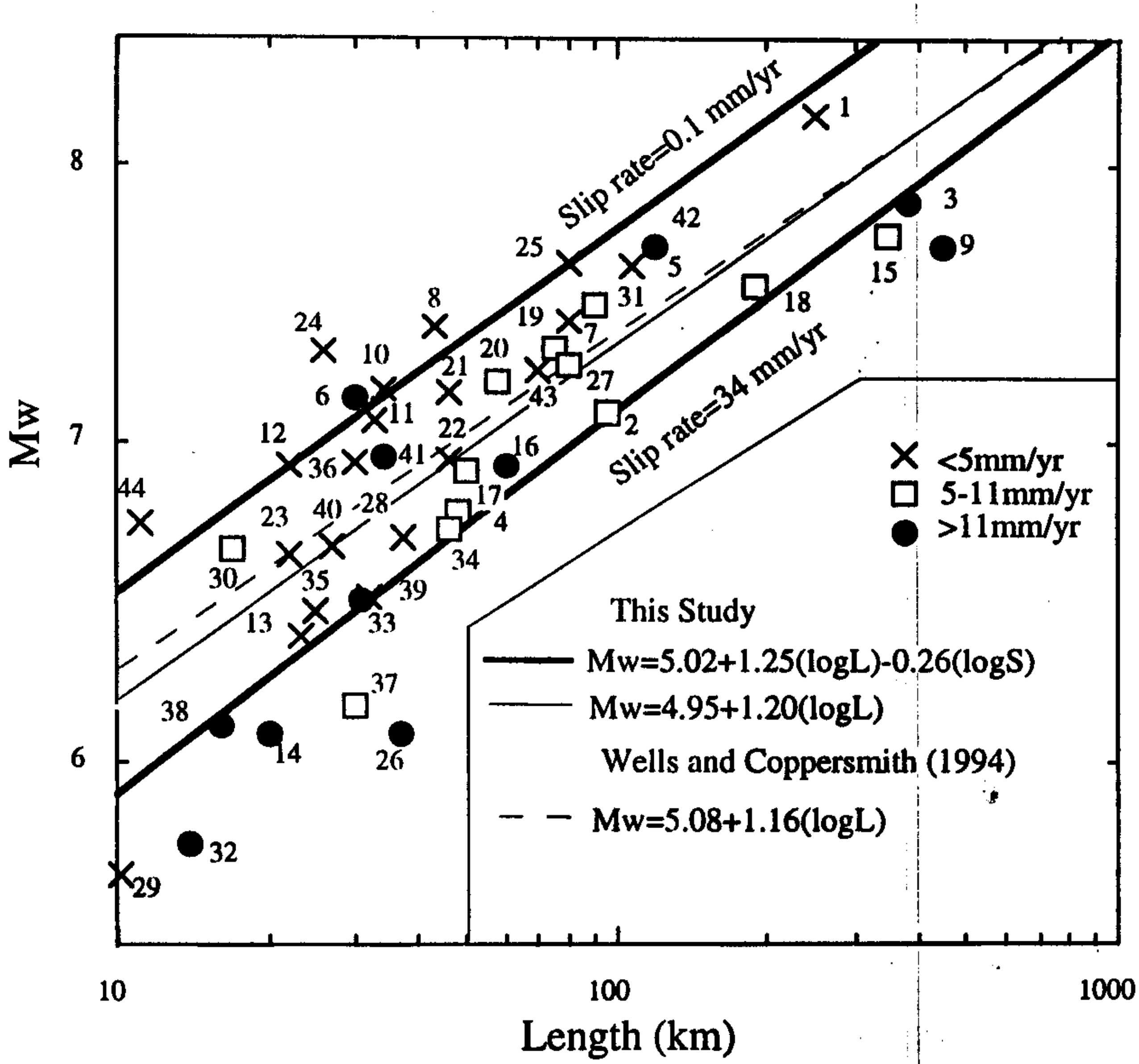
Genoa fault system



Ramelli et al., 1999



Kanamori and Allen (1982) suggested that faults with longer repeat times generally have more slip, when normalized to a common rupture length.



Noting the inverse relationship between repeat time and slip rate, Anderson et al (1998) proposed a relationship between rupture length, slip rate, and moment magnitude.

We use an expanded data set to test this hypothesis.

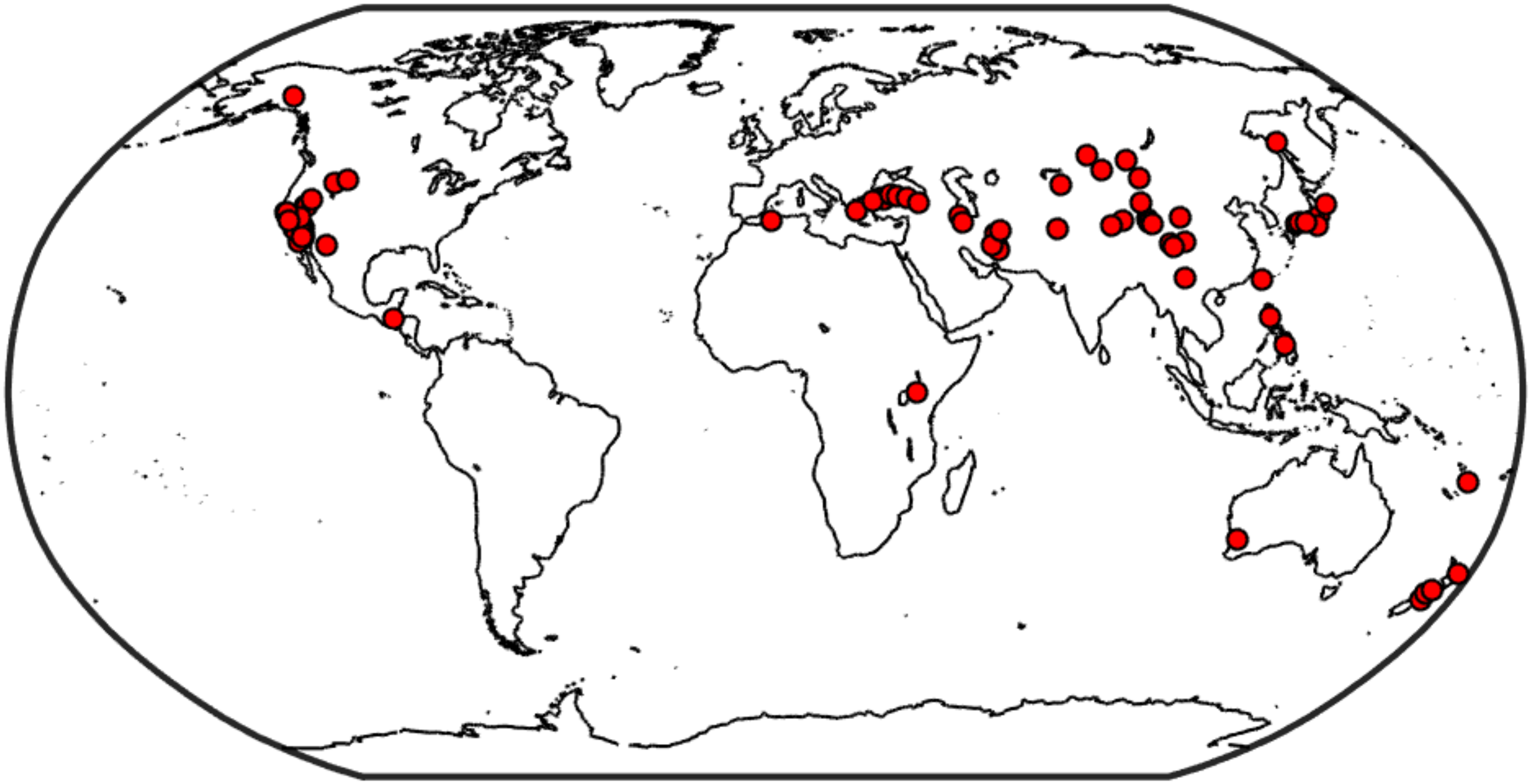
Data

- ALL RESULTS ARE PRELIMINARY
- ALL RESULTS ARE PRELIMINARY
- 85 Earthquakes
  - 58 Strike Slip
  - 15 Reverse
  - 12 Normal

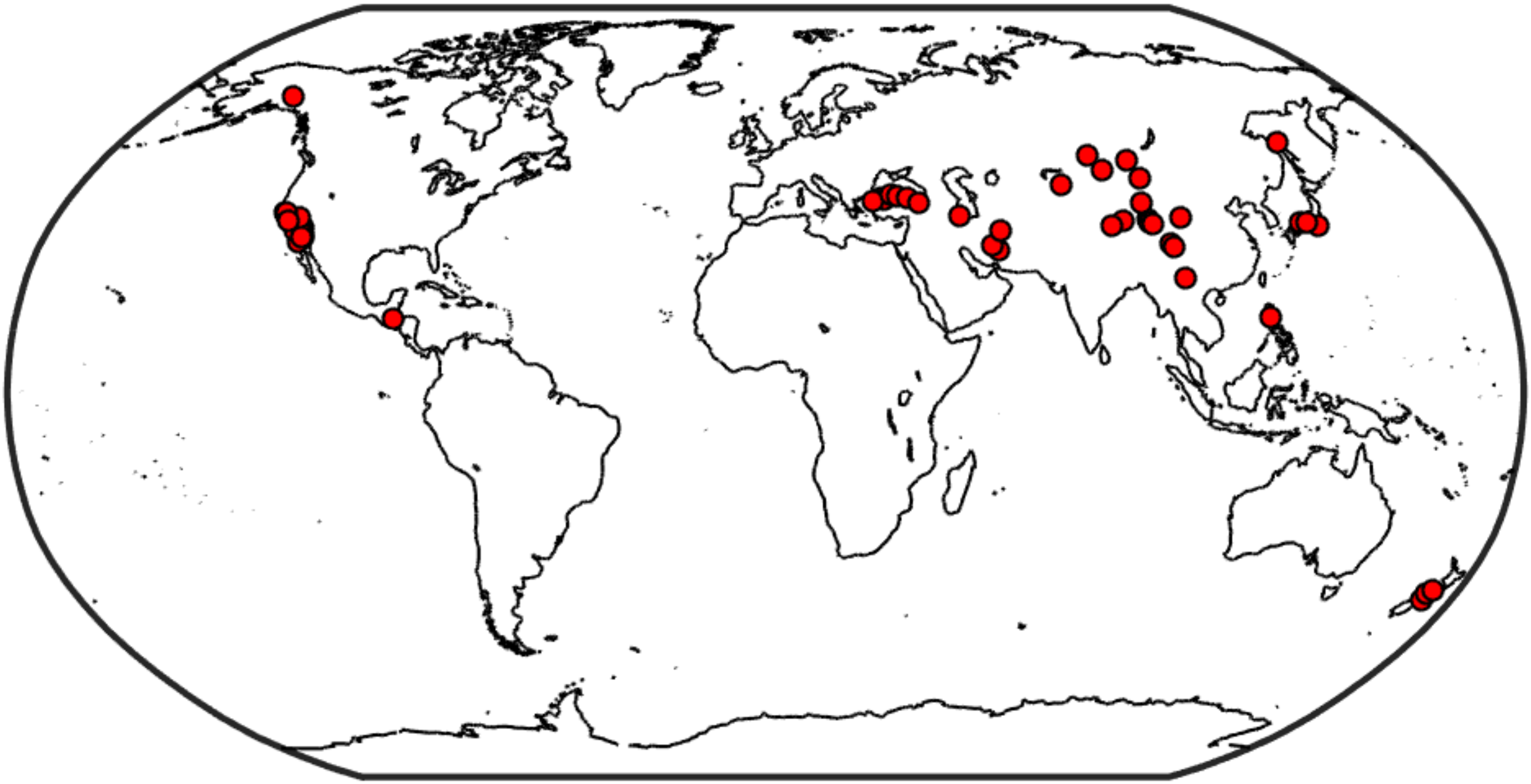
Outline

- Characteristics of the data
- Analysis equivalent to Wells & Coppersmith (1994)
- Bi-linear model motivated to by a constant stress drop model.
- Bi-linear model seeking constant stress drop for all magnitudes.

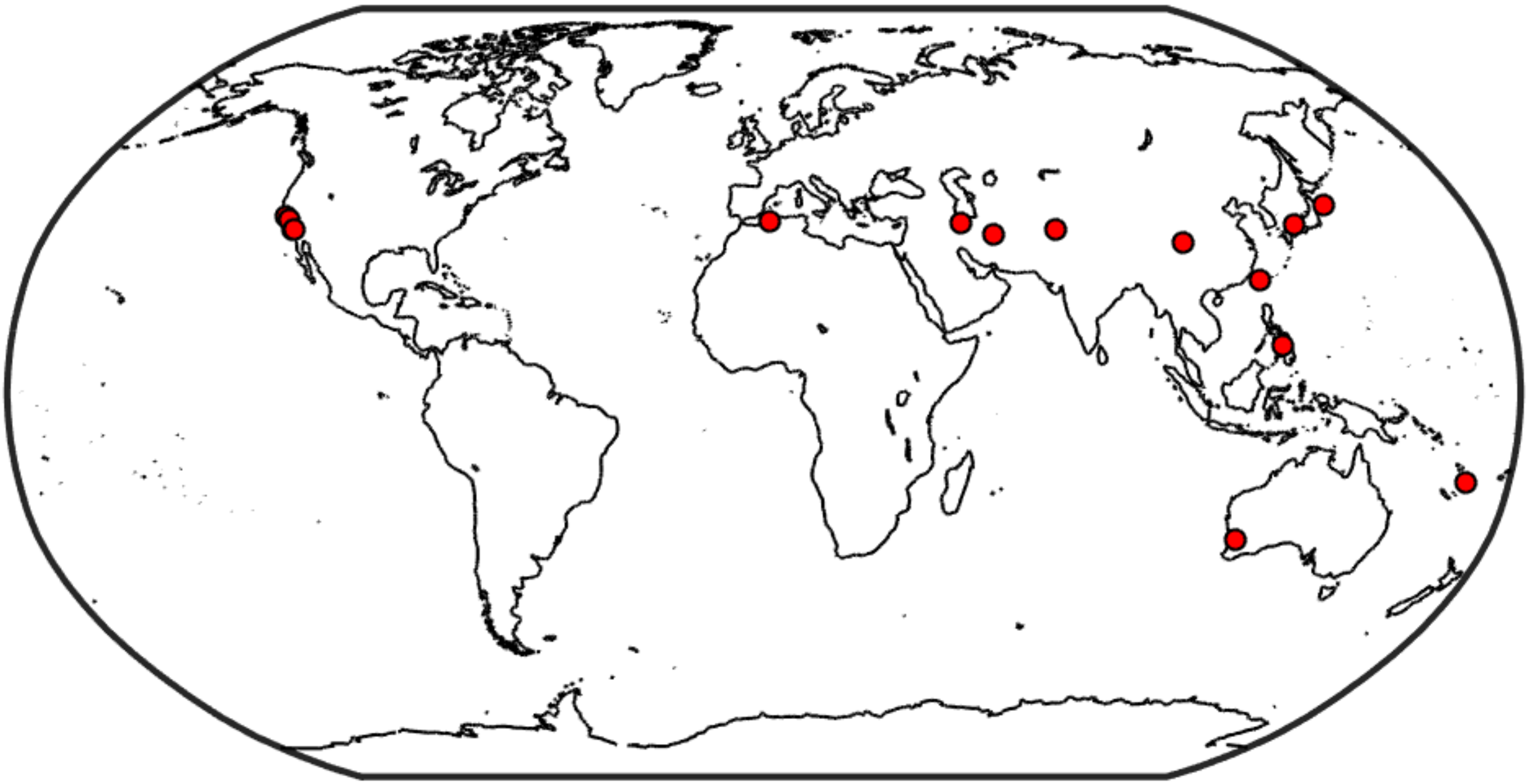
Surface Rupture Events



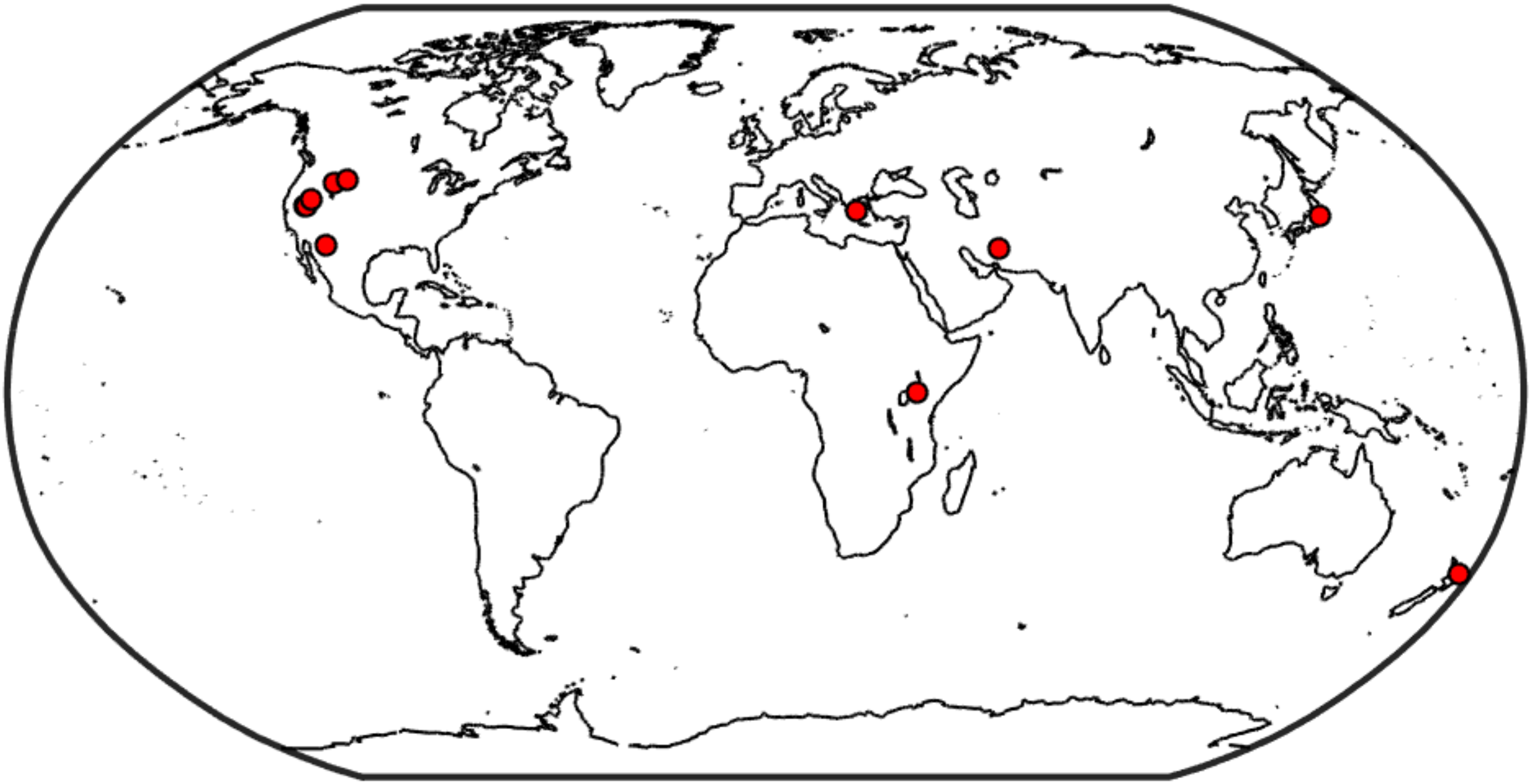
Strike Slip

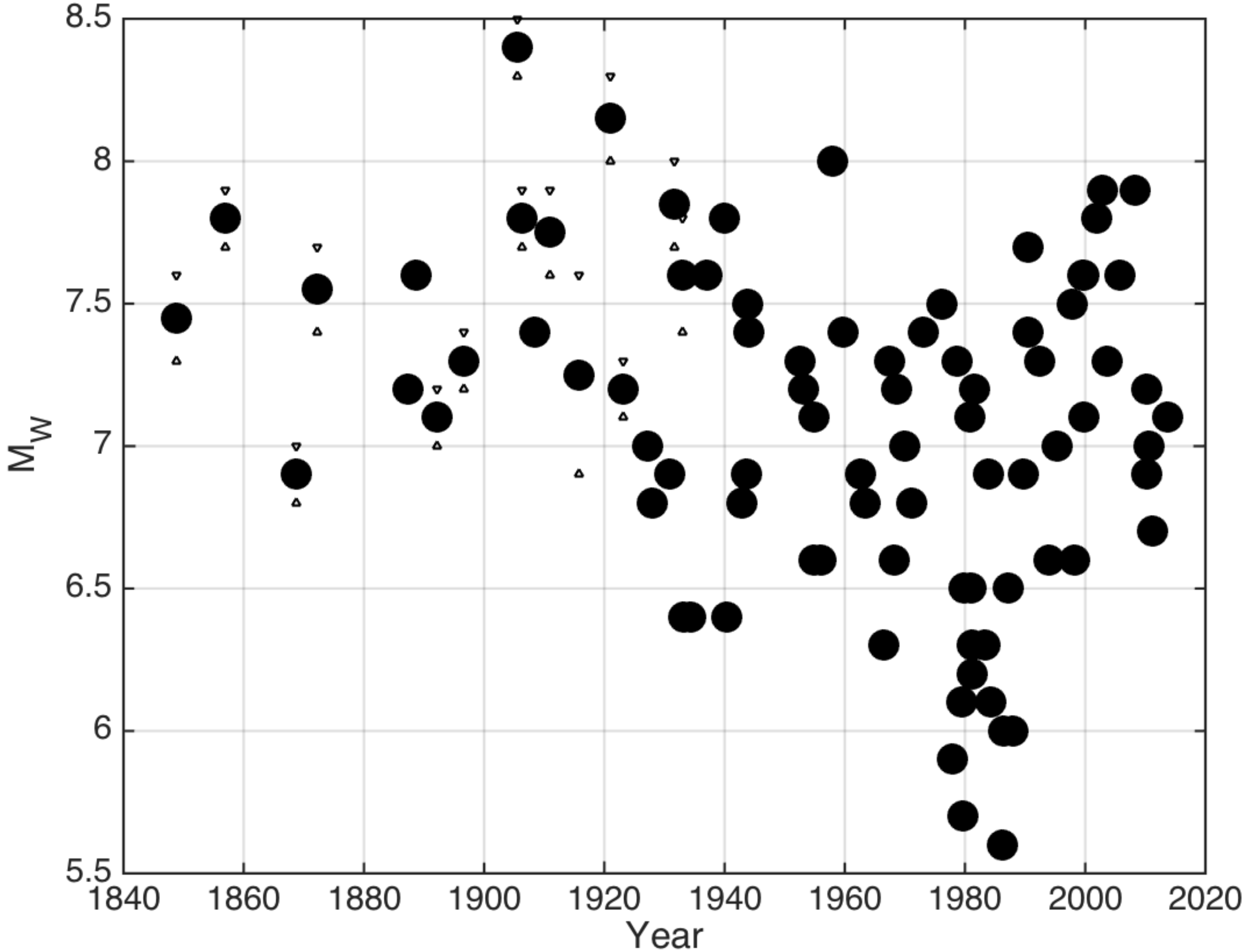


Reverse



Normal





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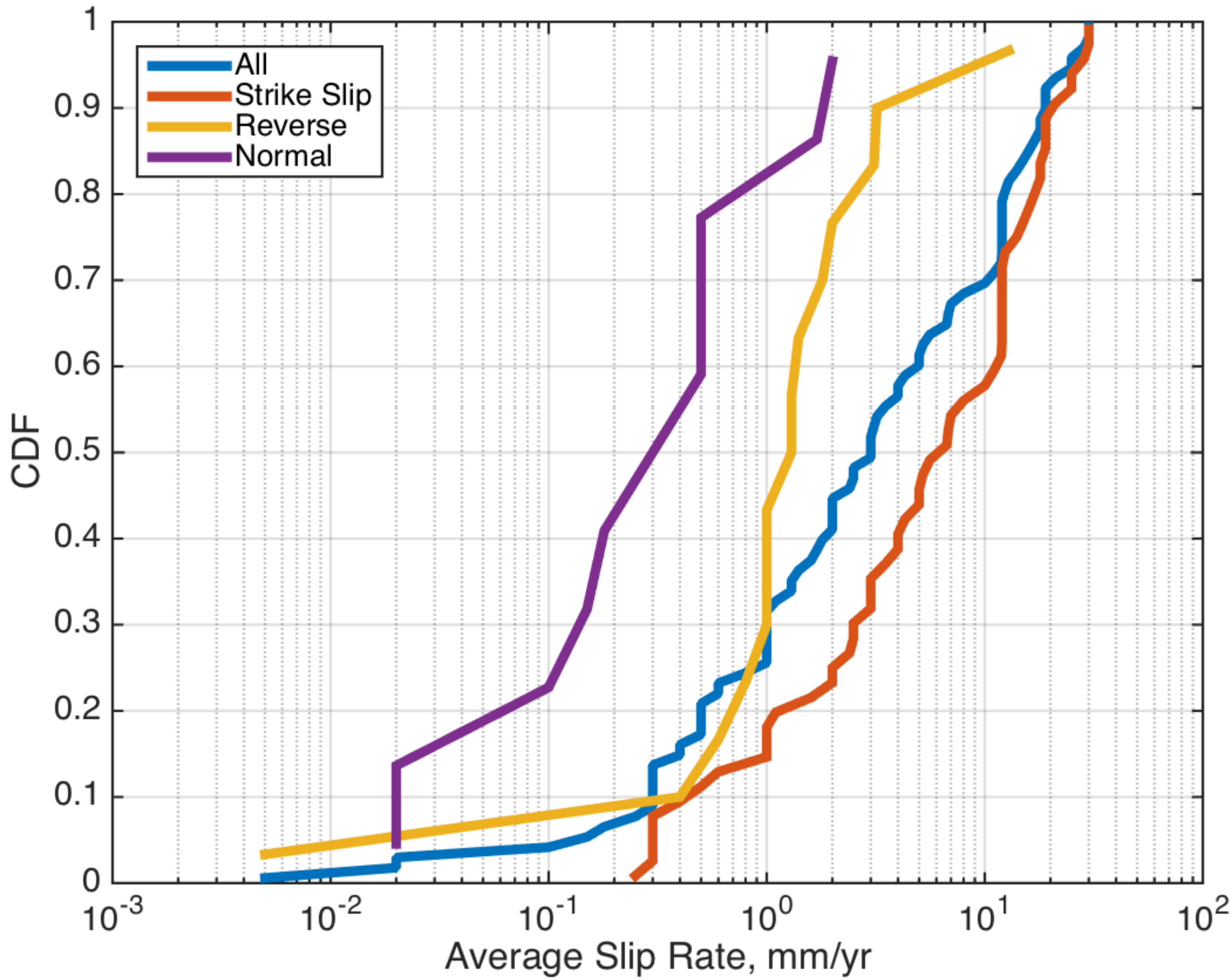

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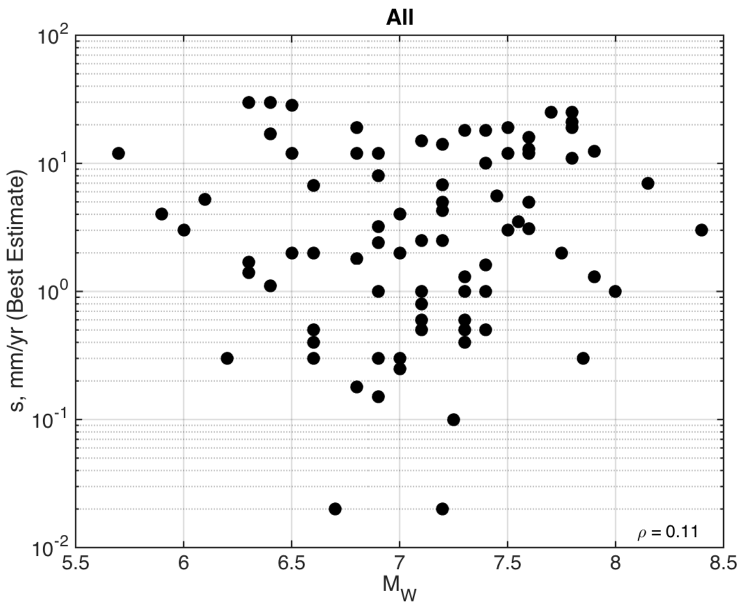

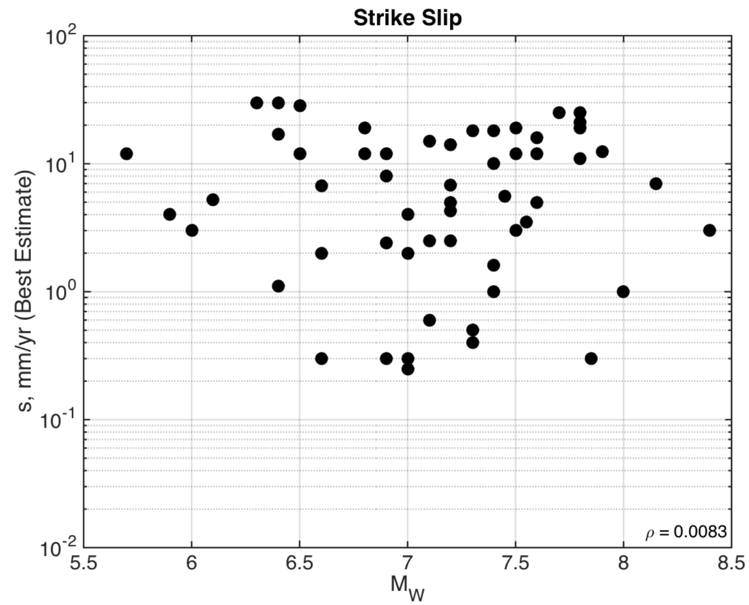

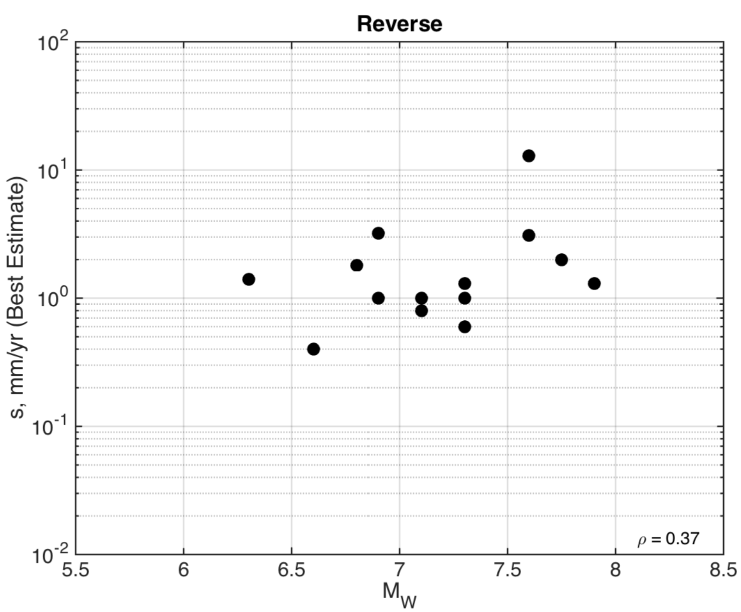

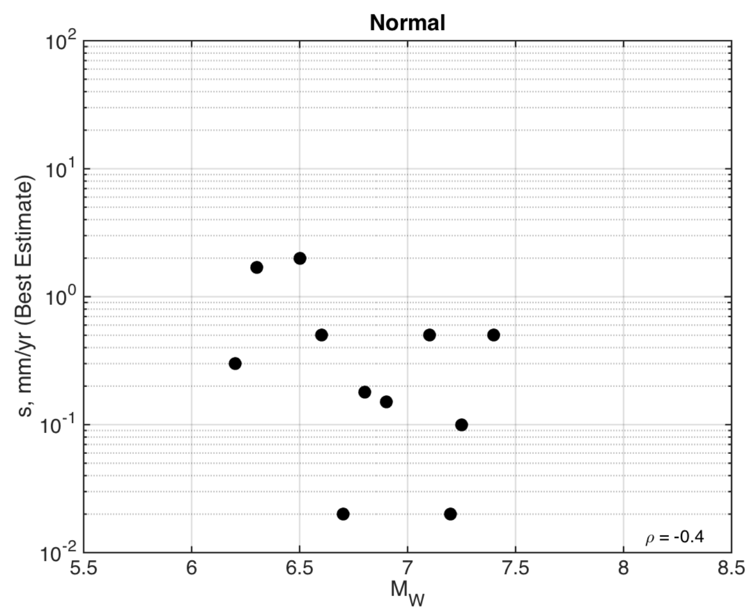

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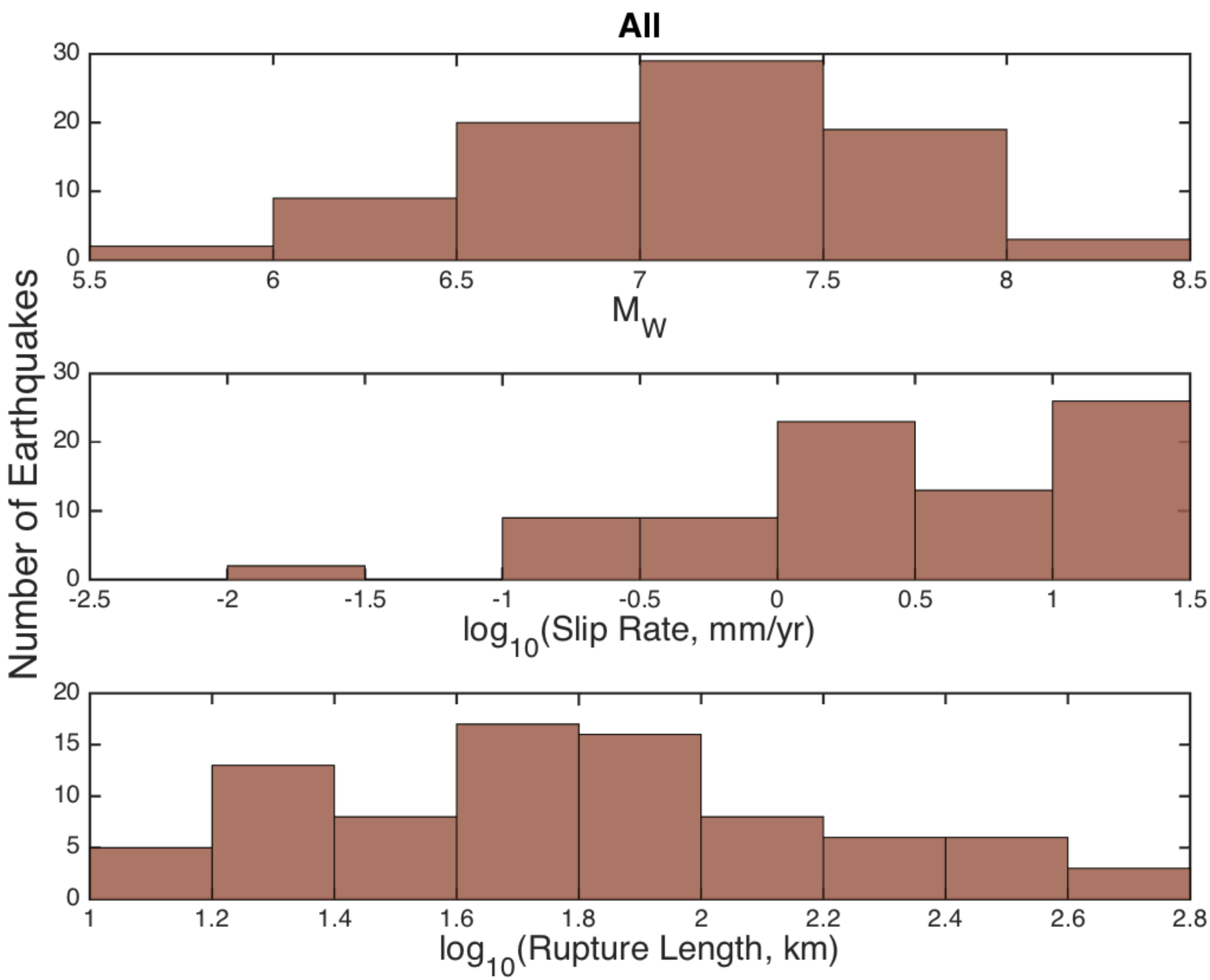

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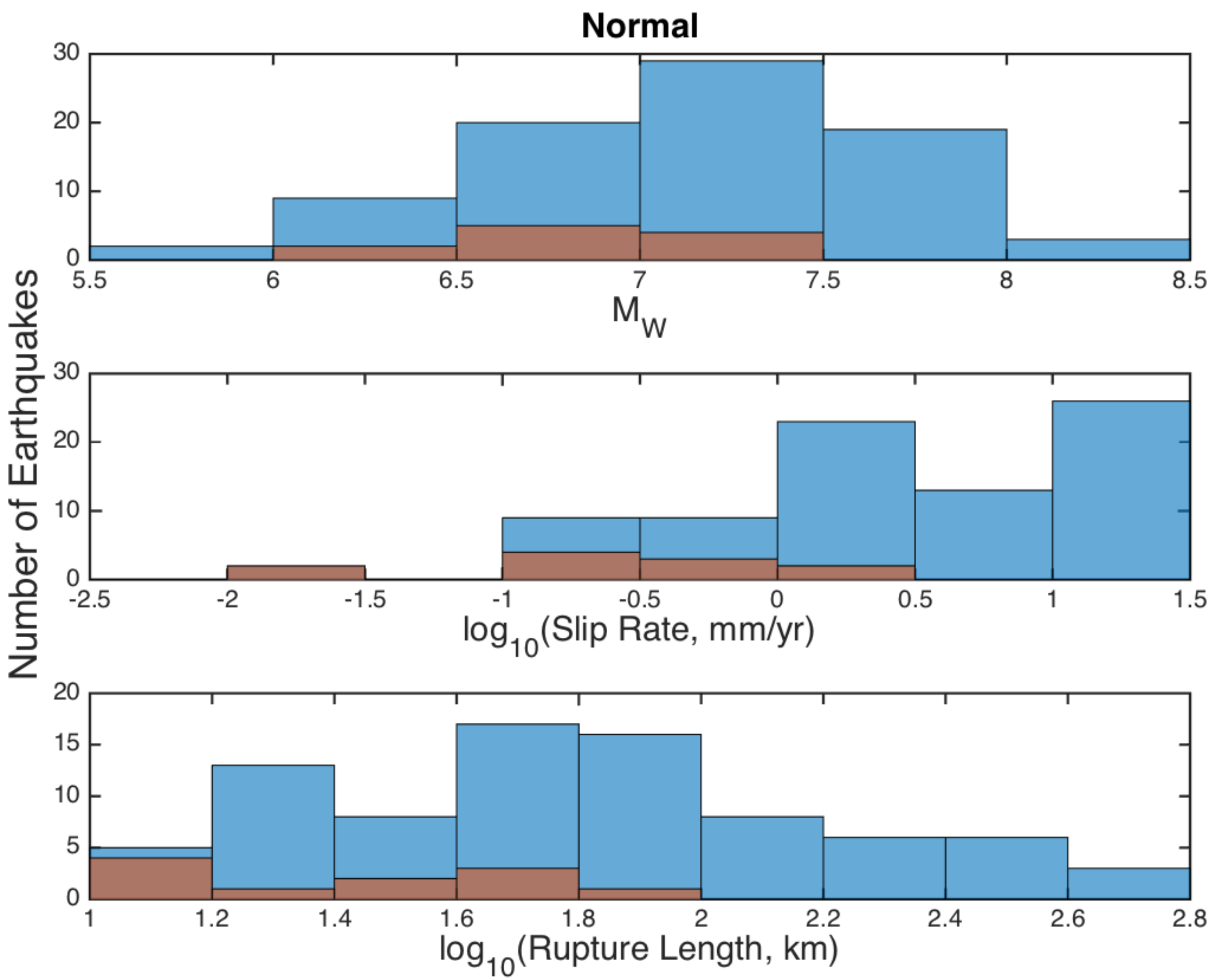

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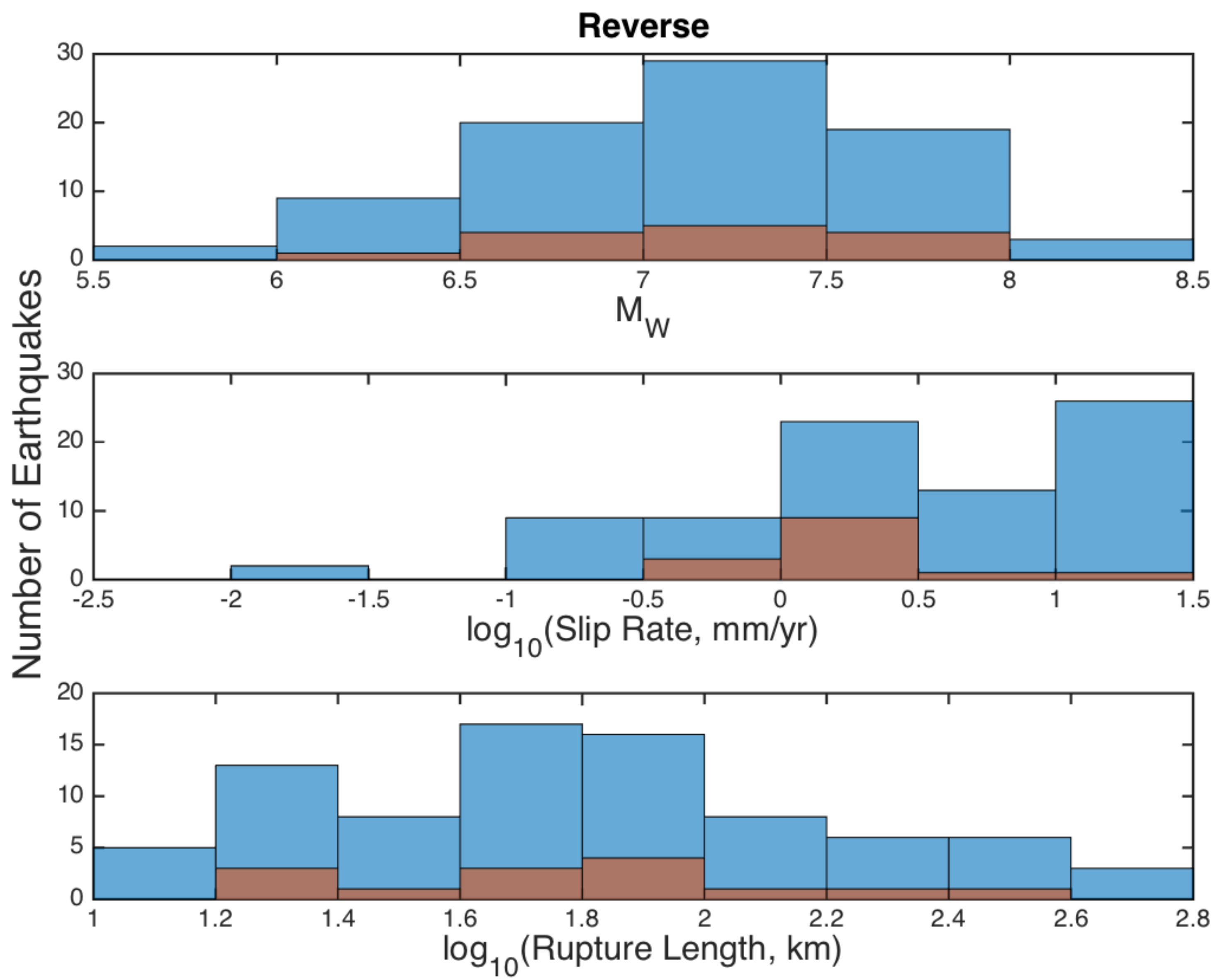

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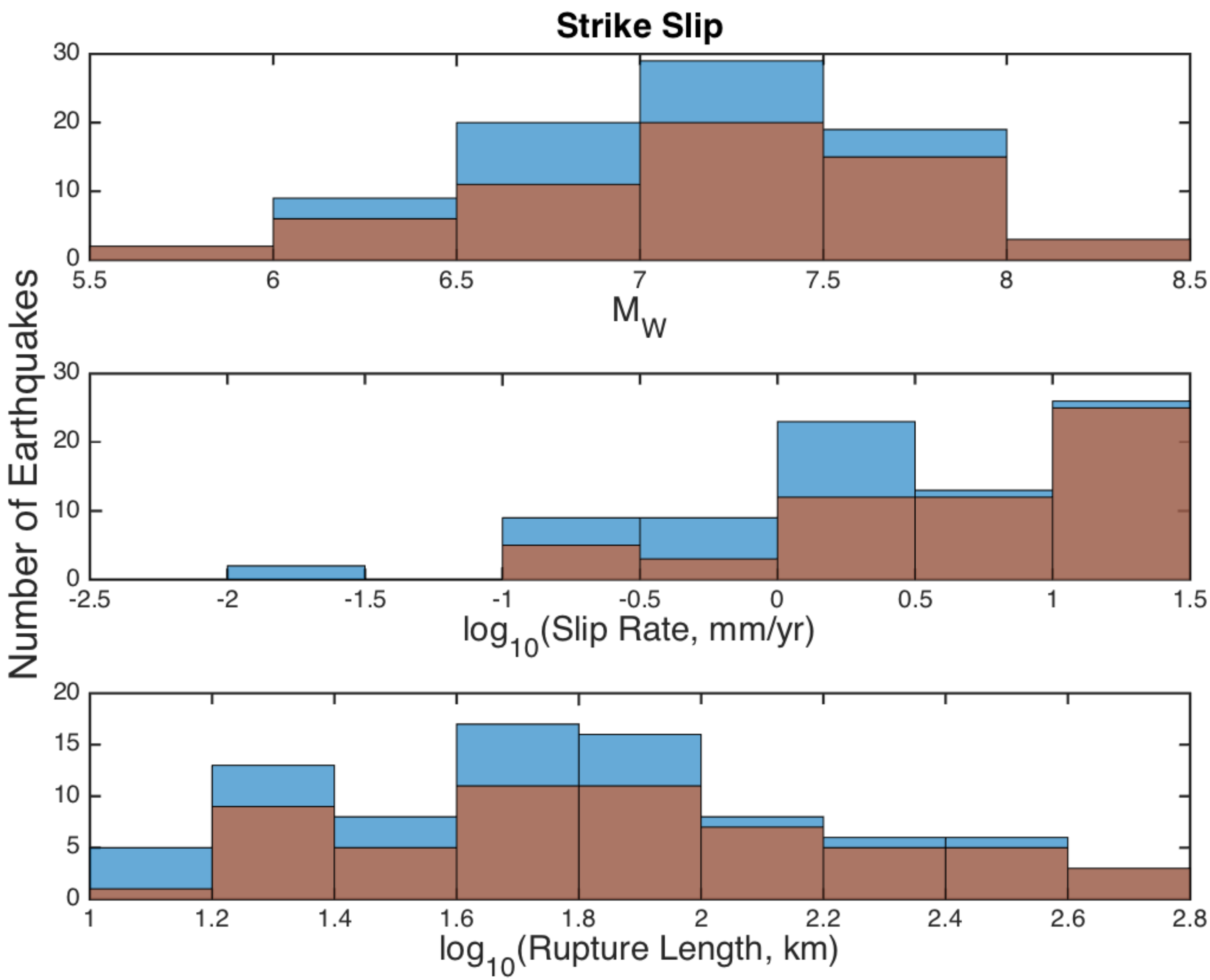

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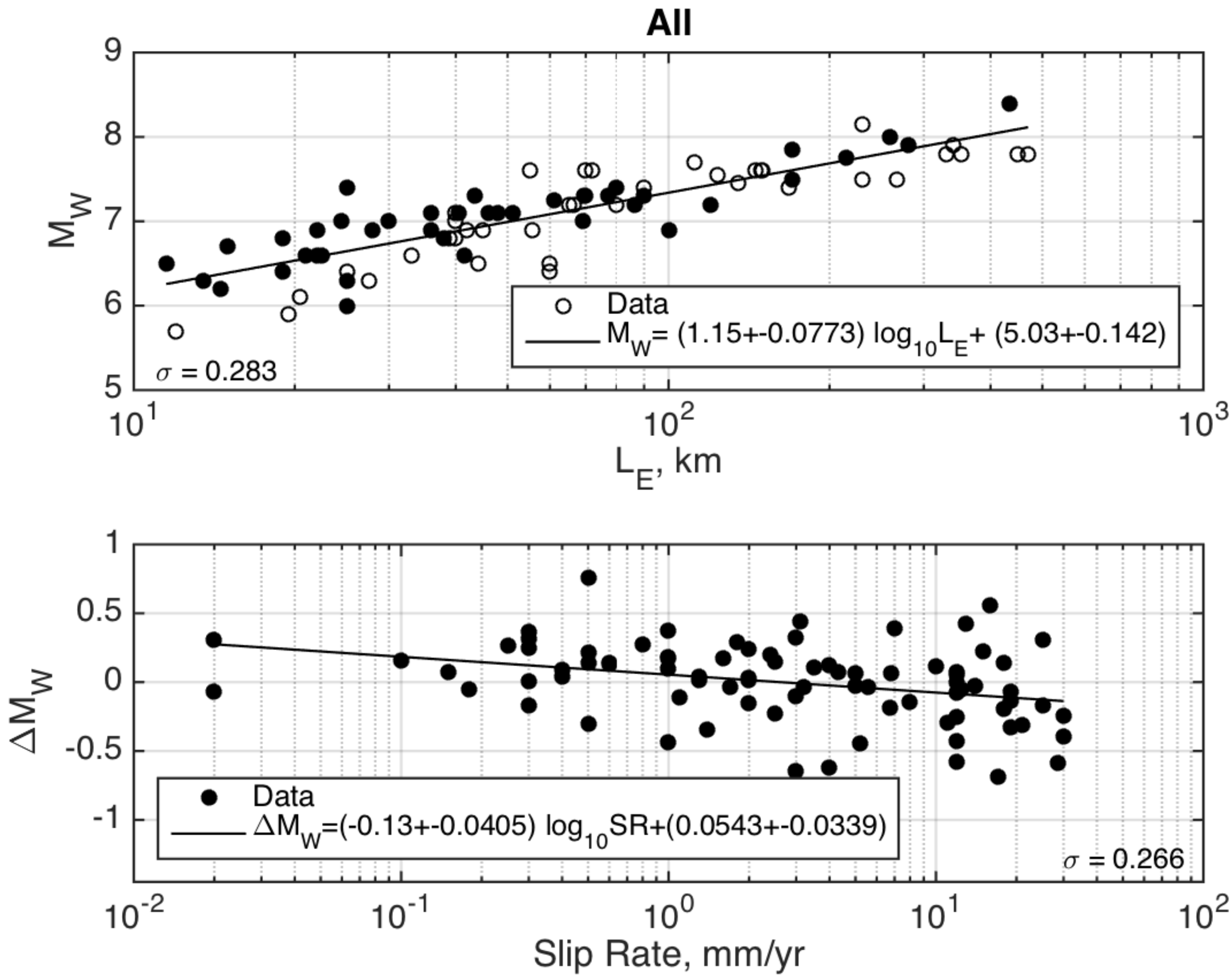
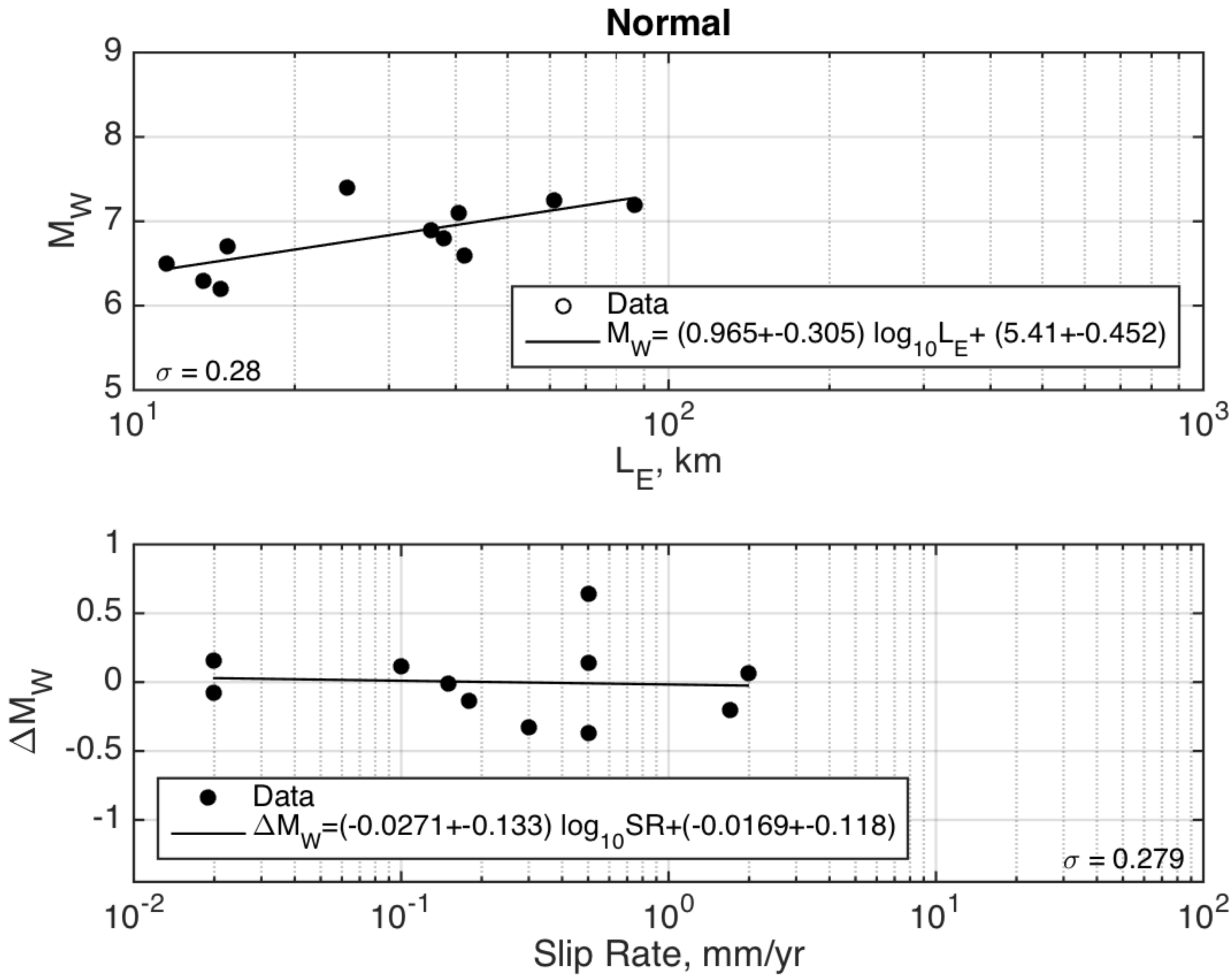


Full Data Set: Linear



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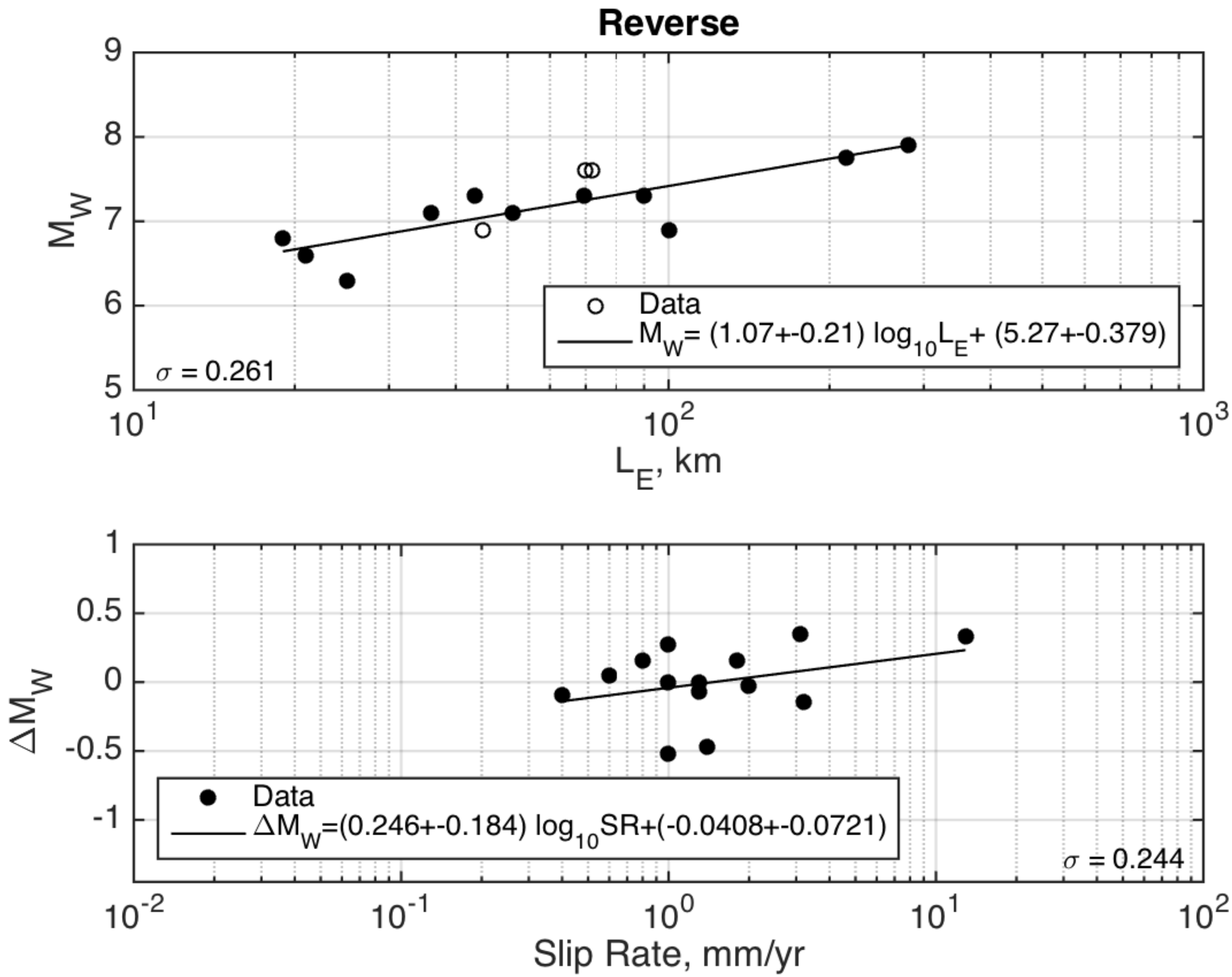

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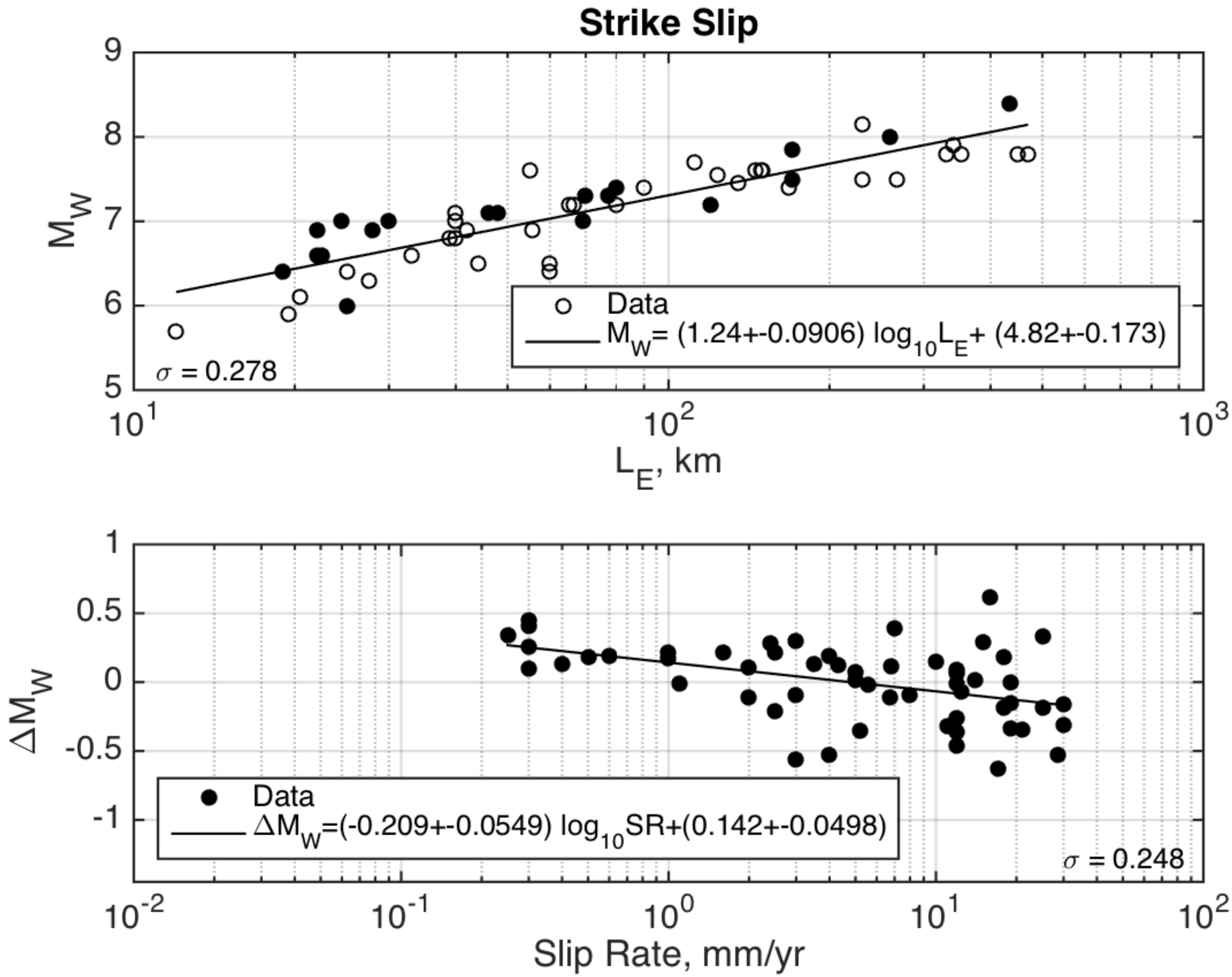

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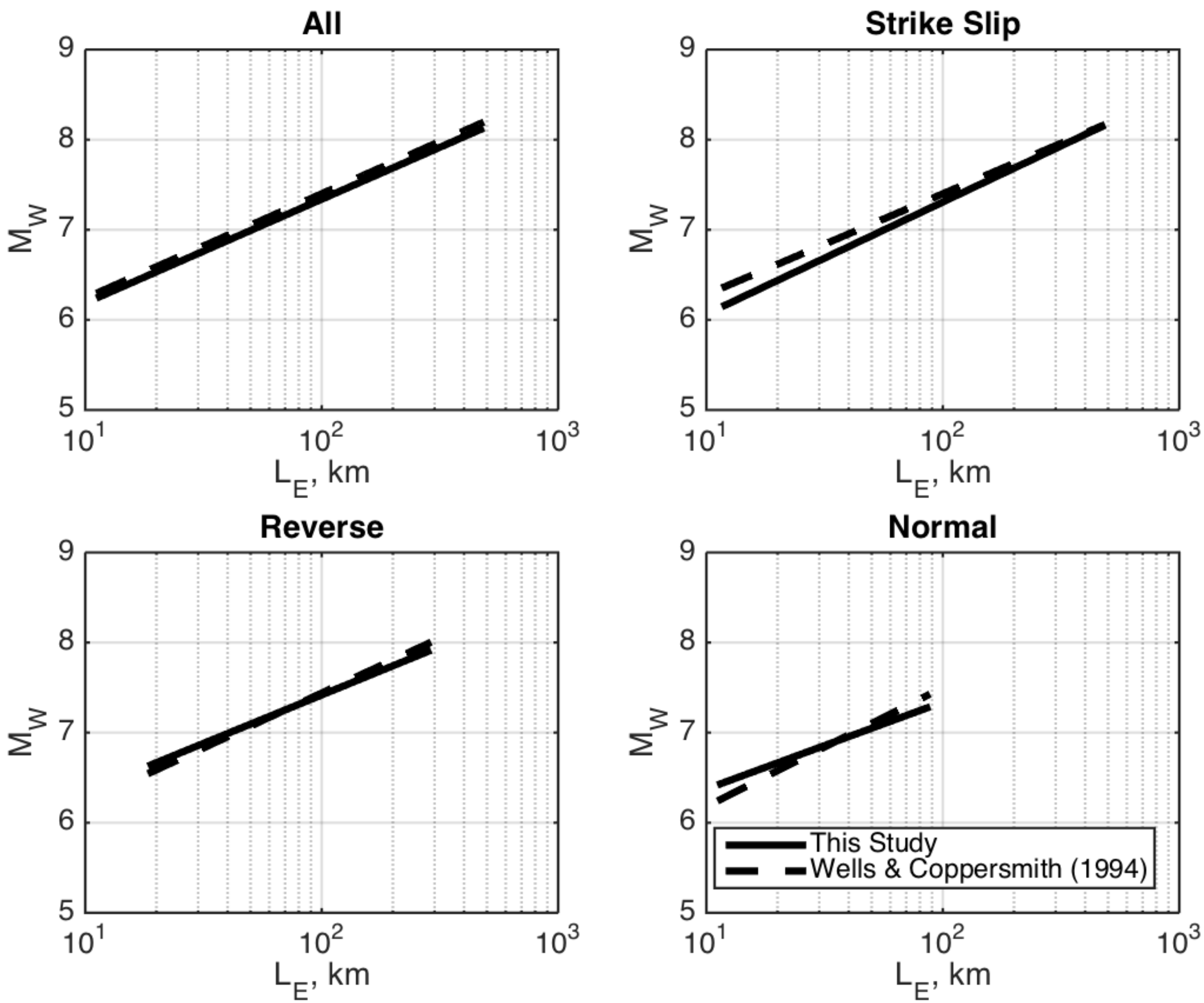

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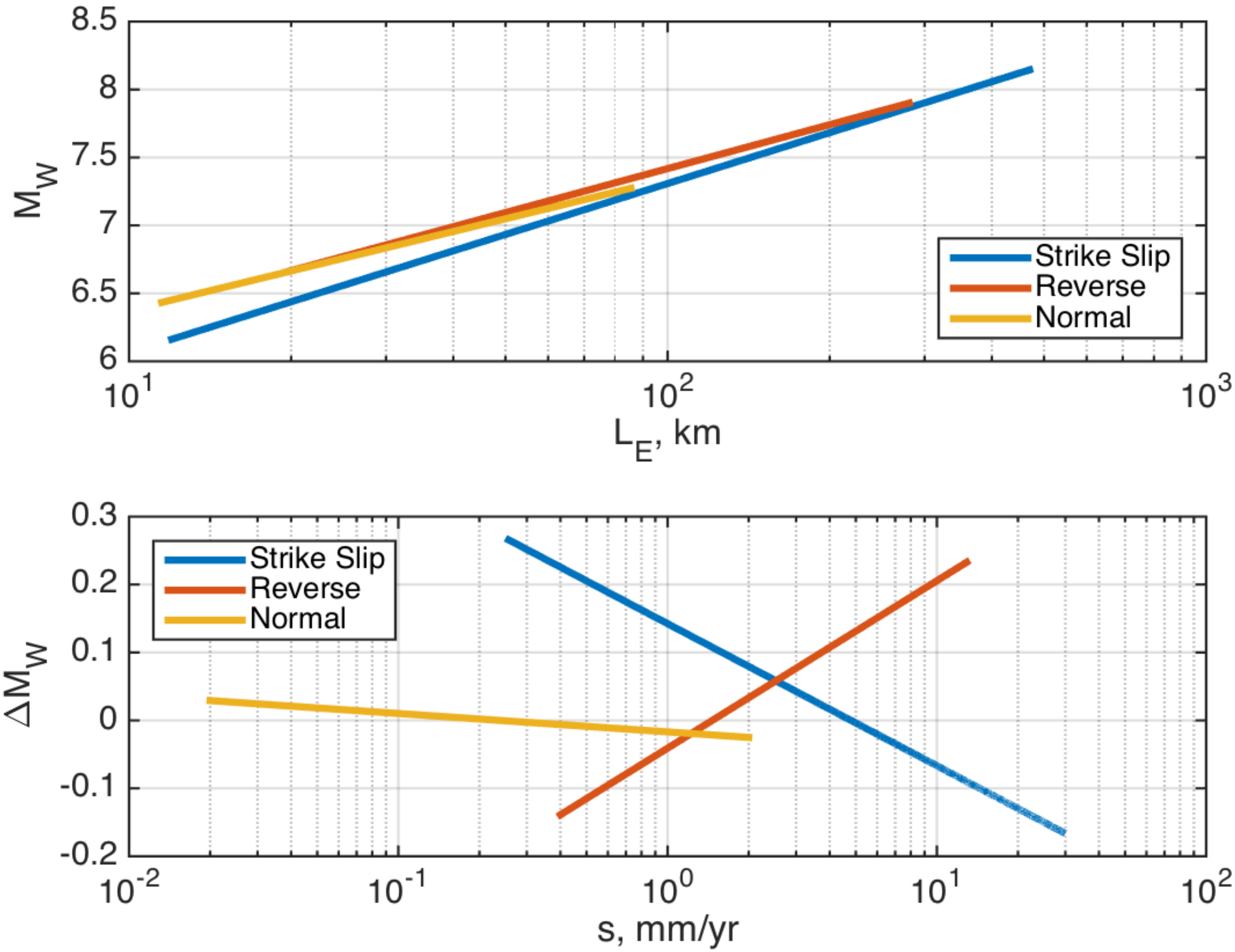


Full Data Set: Linear

Kanamori & Anderson (1975)

- For a circular fault:

$$\Delta\tau_s = \frac{7\pi}{16}\mu\frac{\overline{D}_E}{r_E}$$

- For a strike-slip fault:

$$\Delta\tau_s = \frac{2}{\pi}\mu\frac{\overline{D}_E}{W_E}$$

- For a normal or thrust fault:

$$\Delta\tau_s = \frac{4\left(\lambda_e + \mu\right)}{\pi\left(\lambda_e + 2\mu\right)}\mu\frac{\overline{D}_E}{W_E}$$

Kanamori & Anderson (scaling relations)

- For a circular fault with radius r_E:

$$M_0 = \frac{16}{7} \Delta\tau_S r_E^3$$

- For a strike-slip fault:

$$M_0 = \frac{\pi}{2} \Delta\tau_S W_E^2 L_E$$

- For a normal or thrust fault:

$$M_0 = \frac{\pi\left(\lambda_e + 2\mu\right)}{4\left(\lambda_e + \mu\right)} \Delta\tau_S W_E^2 L_E$$

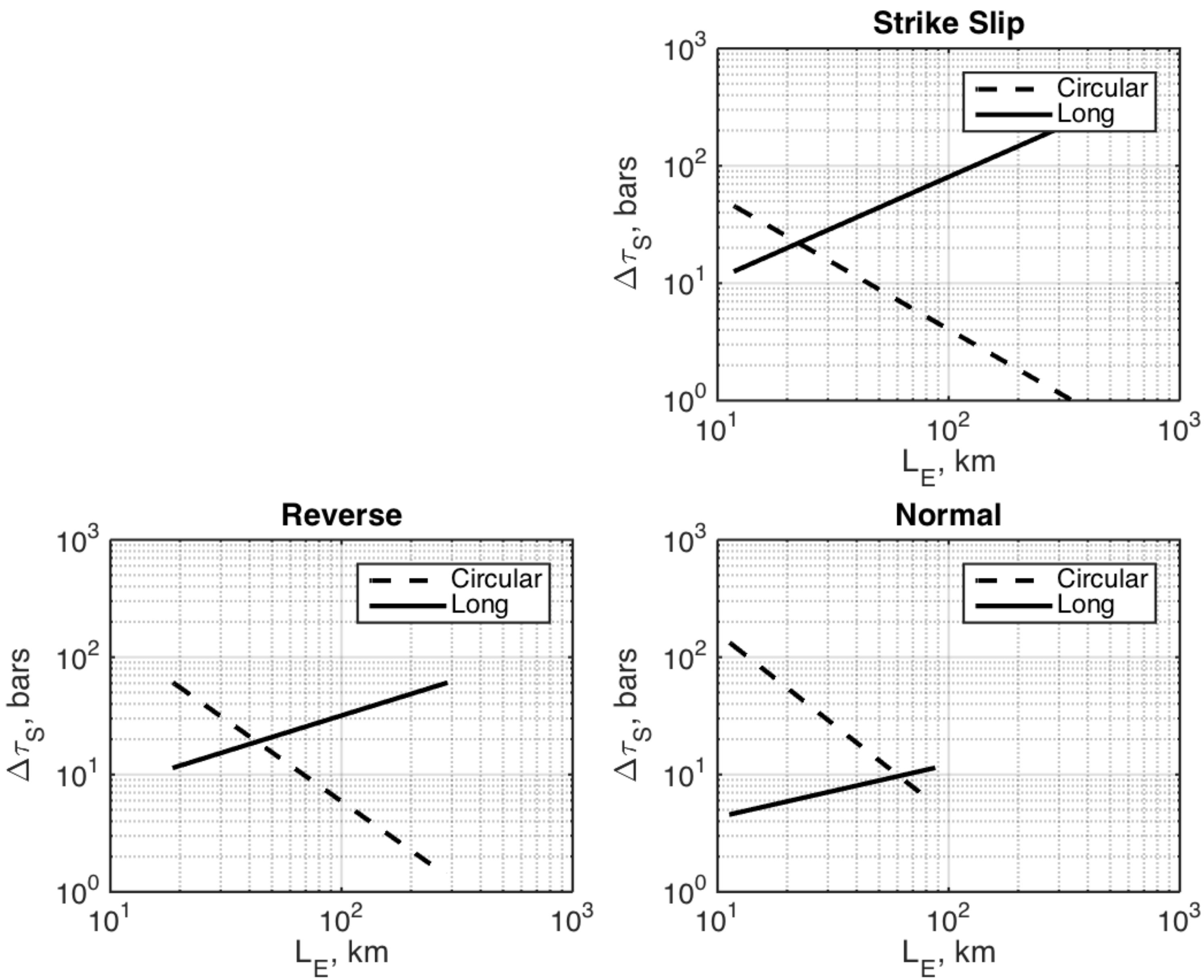
Kanamori & Anderson (scaling relations)

Table 1: Relationships of fault size, stress drop

Case	All lengths in km, stress drop in bars
1. Buried, circular	$M_W = 2\log d_E + \frac{2}{3}\log\Delta\tau_S + 2.9040$
2. Strike-slip, L=W	$M_W = 2\log L_E + \frac{2}{3}\log\Delta\tau_S + 3.1359$
3. Strike-slip, long	$M_W = \frac{2}{3}\log L_E + \frac{4}{3}\log W_E + \frac{2}{3}\log\Delta\tau_S + 3.1359$
4. Dip-slip, long	$M_W = \frac{2}{3}\log L_E + \frac{4}{3}\log W_E + \frac{2}{3}\log\Delta\tau_S + 3.3141$

These relations are obtained by substituting the seismic moment relations from the previous slide into the definition of moment magnitude:

$$M_W = \frac{2}{3}\left(\log M_0 - 16.1\right)$$



Full Data Set: Linear

Kanamori & Anderson (scaling relations)

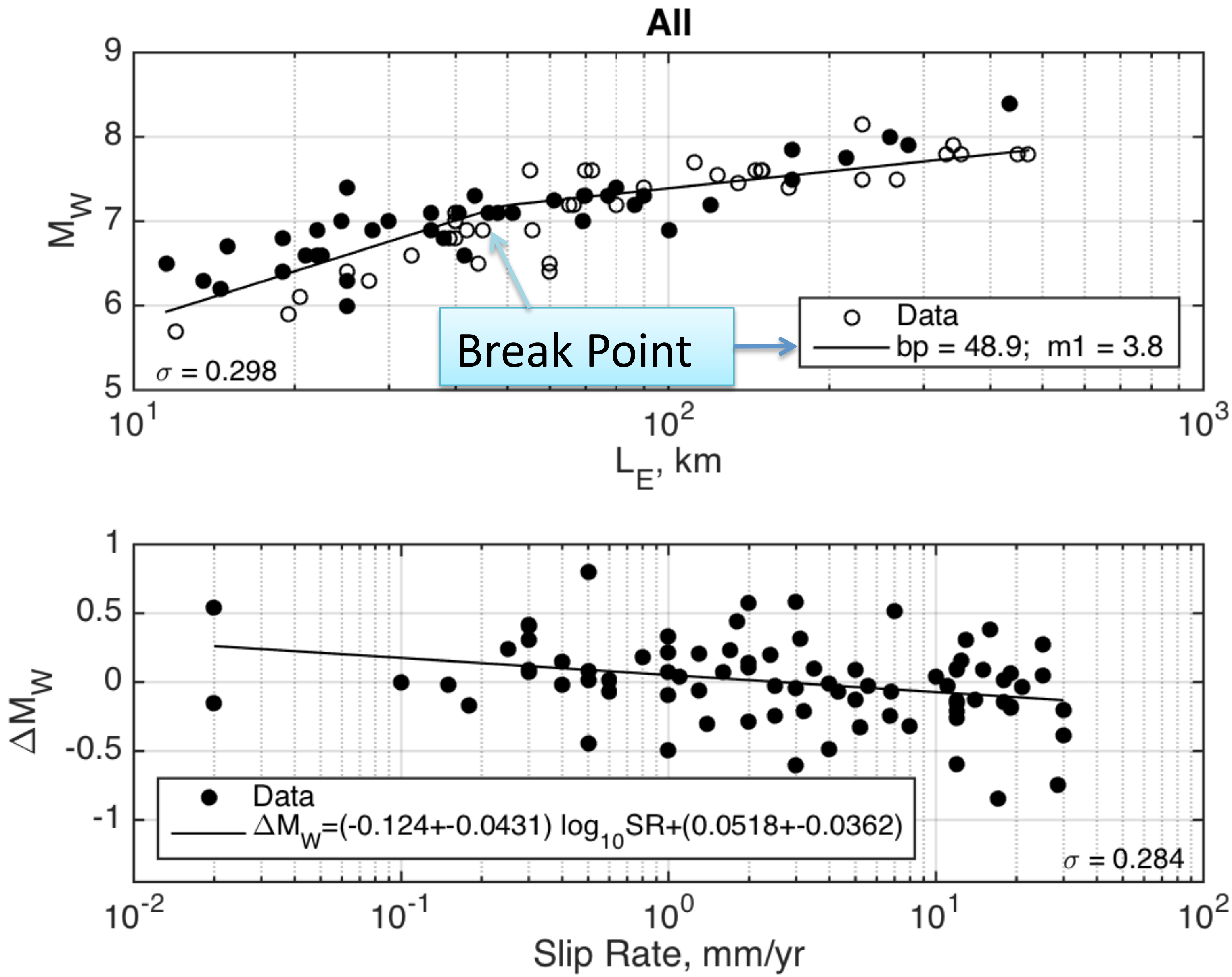
Table 1: Relationships of fault size, stress drop

Case	All lengths in km, stress drop in bars
1. Buried, circular	$M_W = 2\log d_E + \frac{2}{3}\log\Delta\tau_S + 2.9040$
2. Strike-slip, L=W	$M_W = 2\log L_E + \frac{2}{3}\log\Delta\tau_S + 3.1359$
3. Strike-slip, long	$M_W = \frac{2}{3}\log L_E + \frac{4}{3}\log W_E + \frac{2}{3}\log\Delta\tau_S + 3.1359$
4. Dip-slip, long	$M_W = \frac{2}{3}\log L_E + \frac{4}{3}\log W_E + \frac{2}{3}\log\Delta\tau_S + 3.3141$

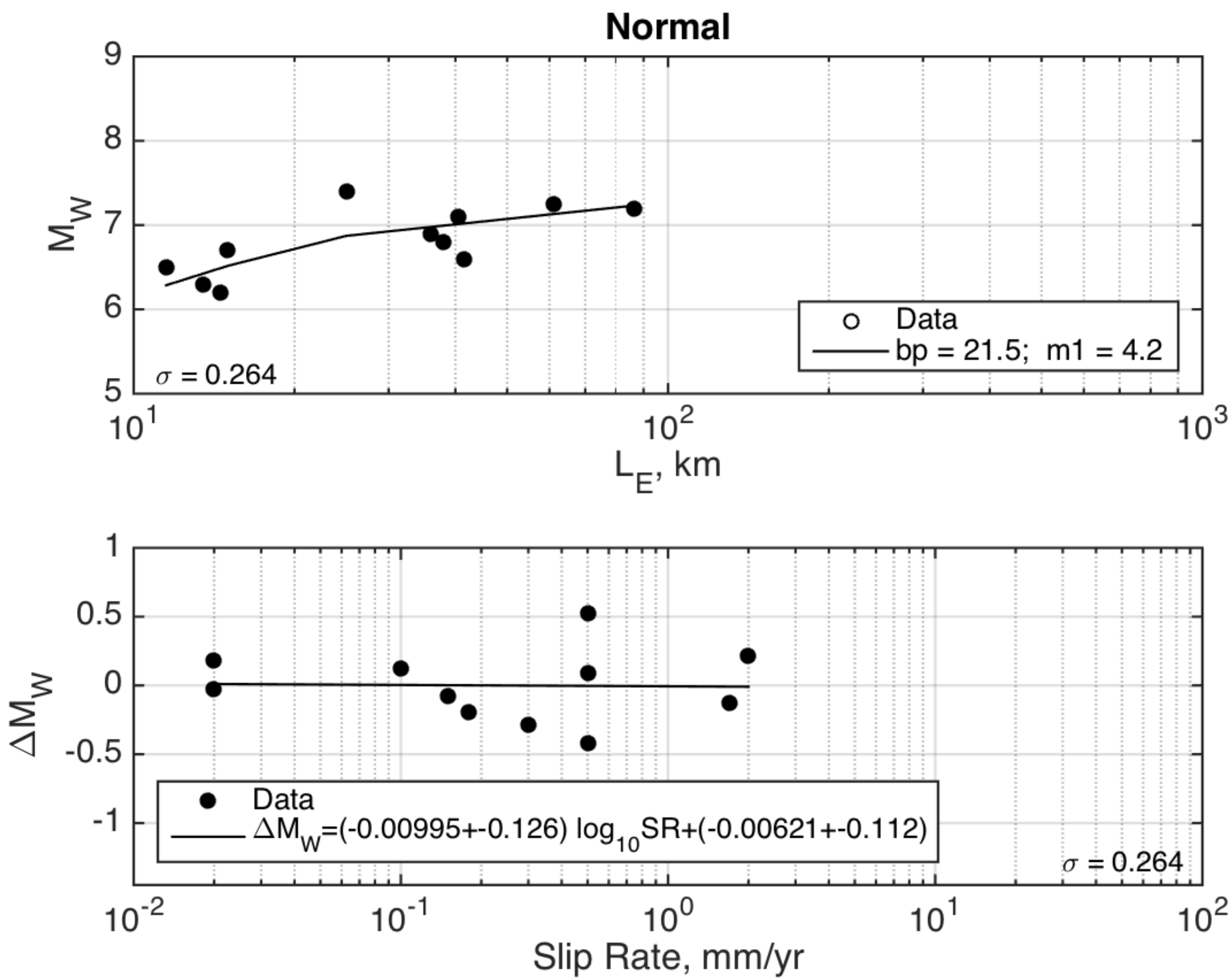
To obtain a constant stress drop using this model requires a bi-linear relationship with slopes:

s1 = 2 for small rupture sizes

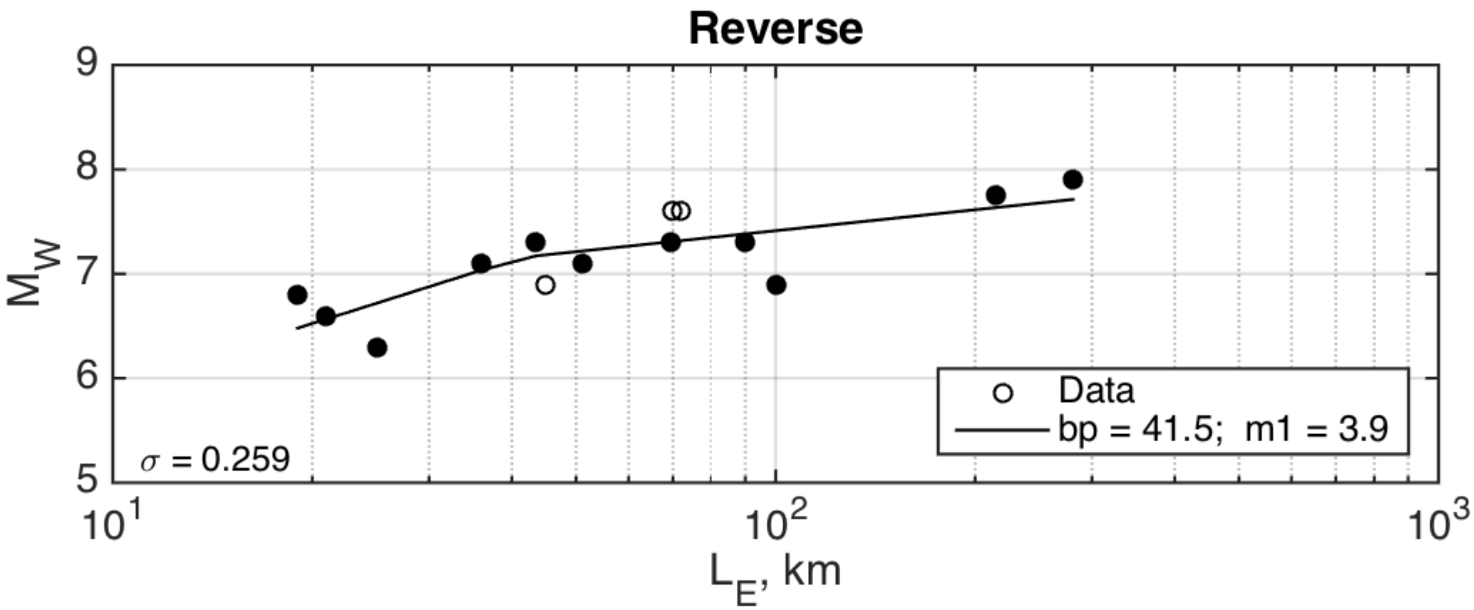
s2 = 2/3 for long ruptures

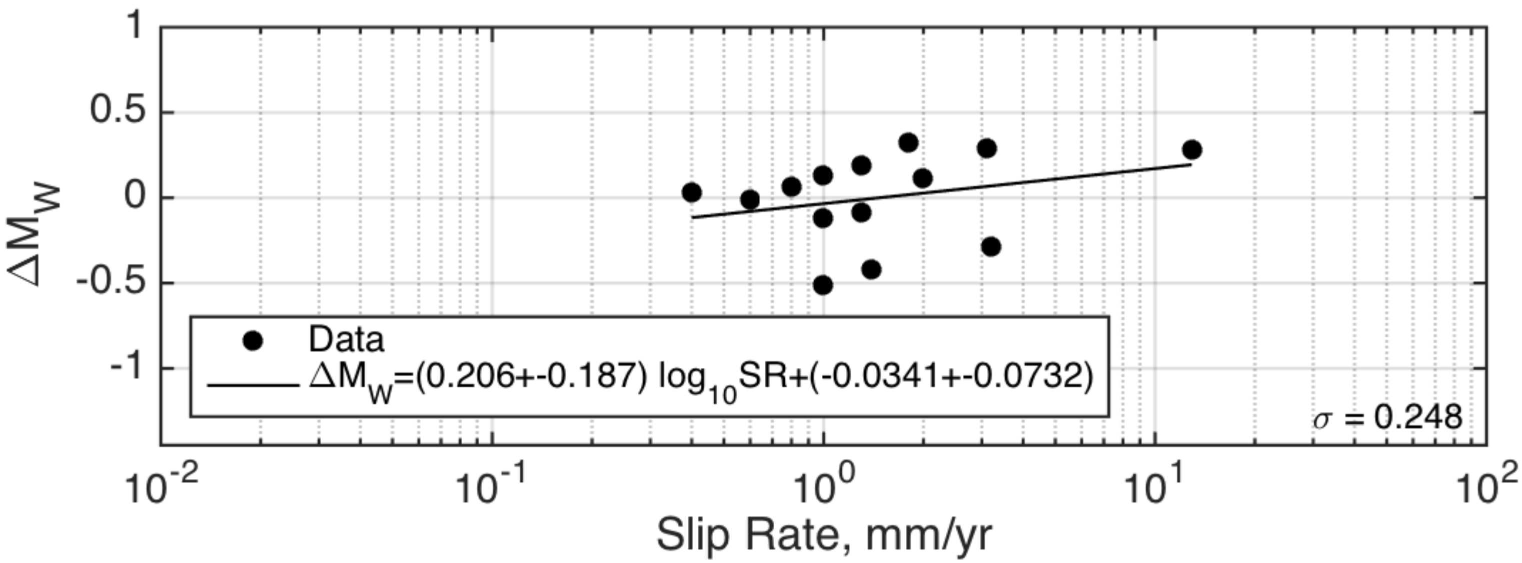


Full Data Set: Bilinear, slopes 2, 2/3

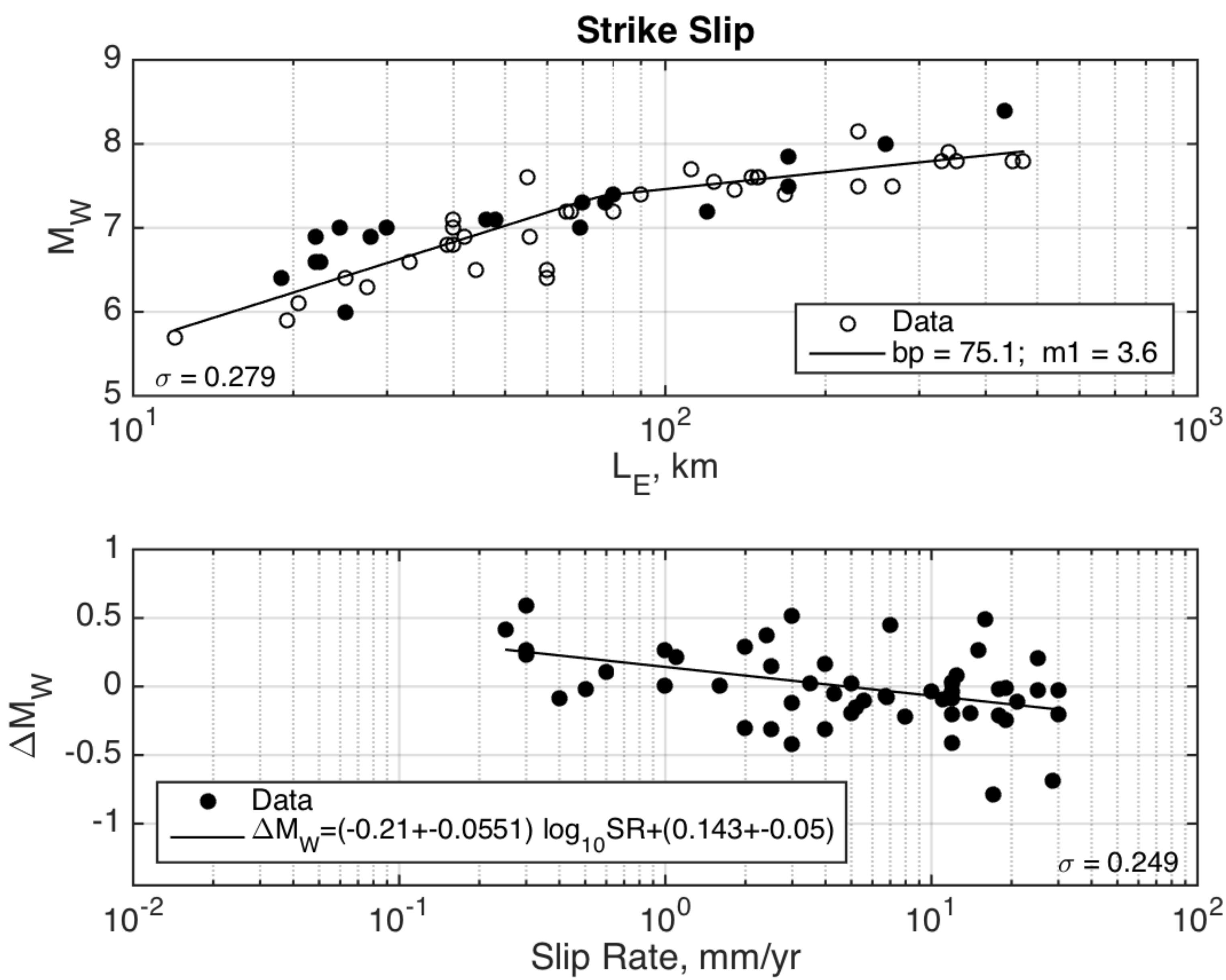


Full Data Set: Bilinear, slopes 2, 2/3

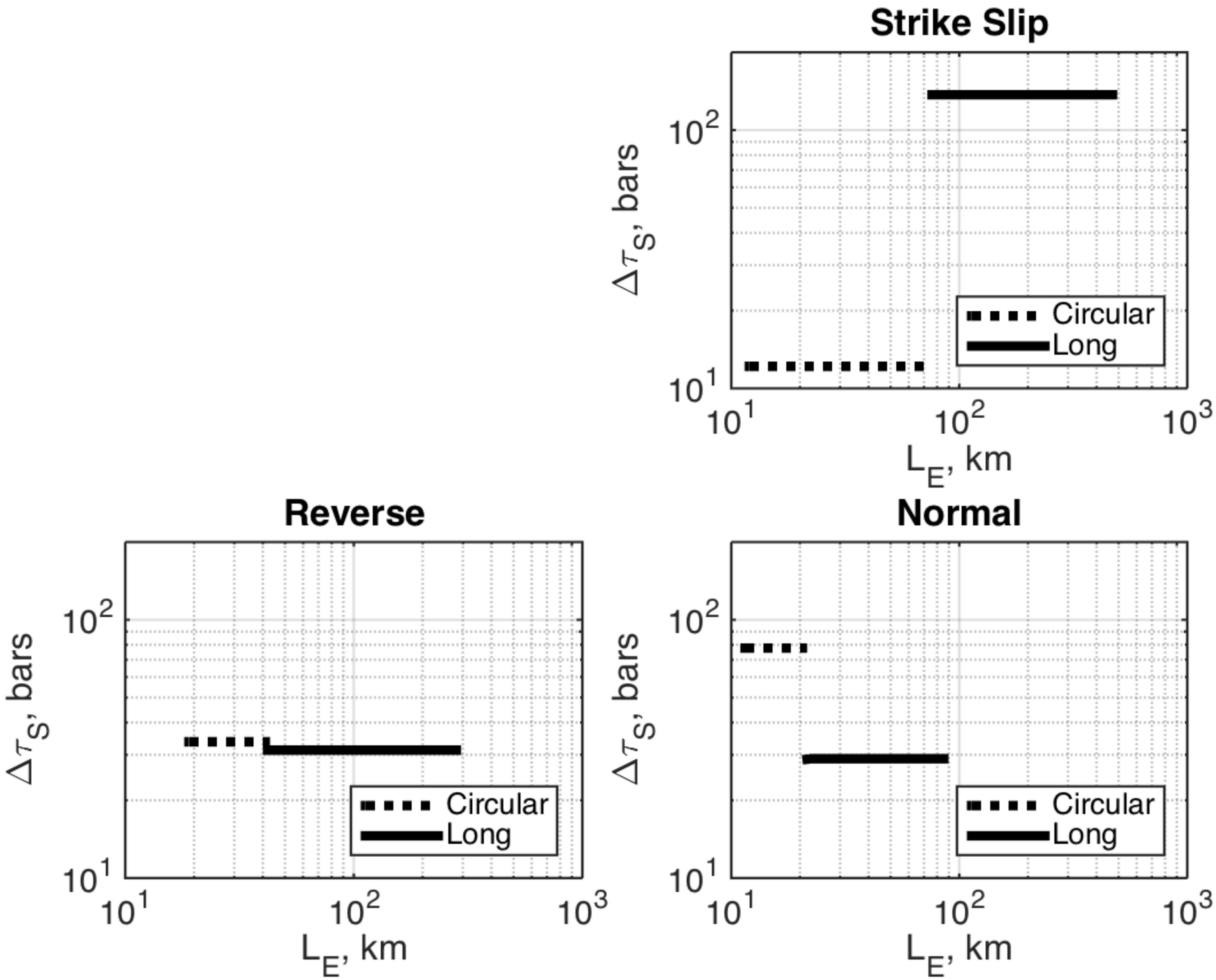




Full Data Set: Bilinear, slopes 2, 2/3



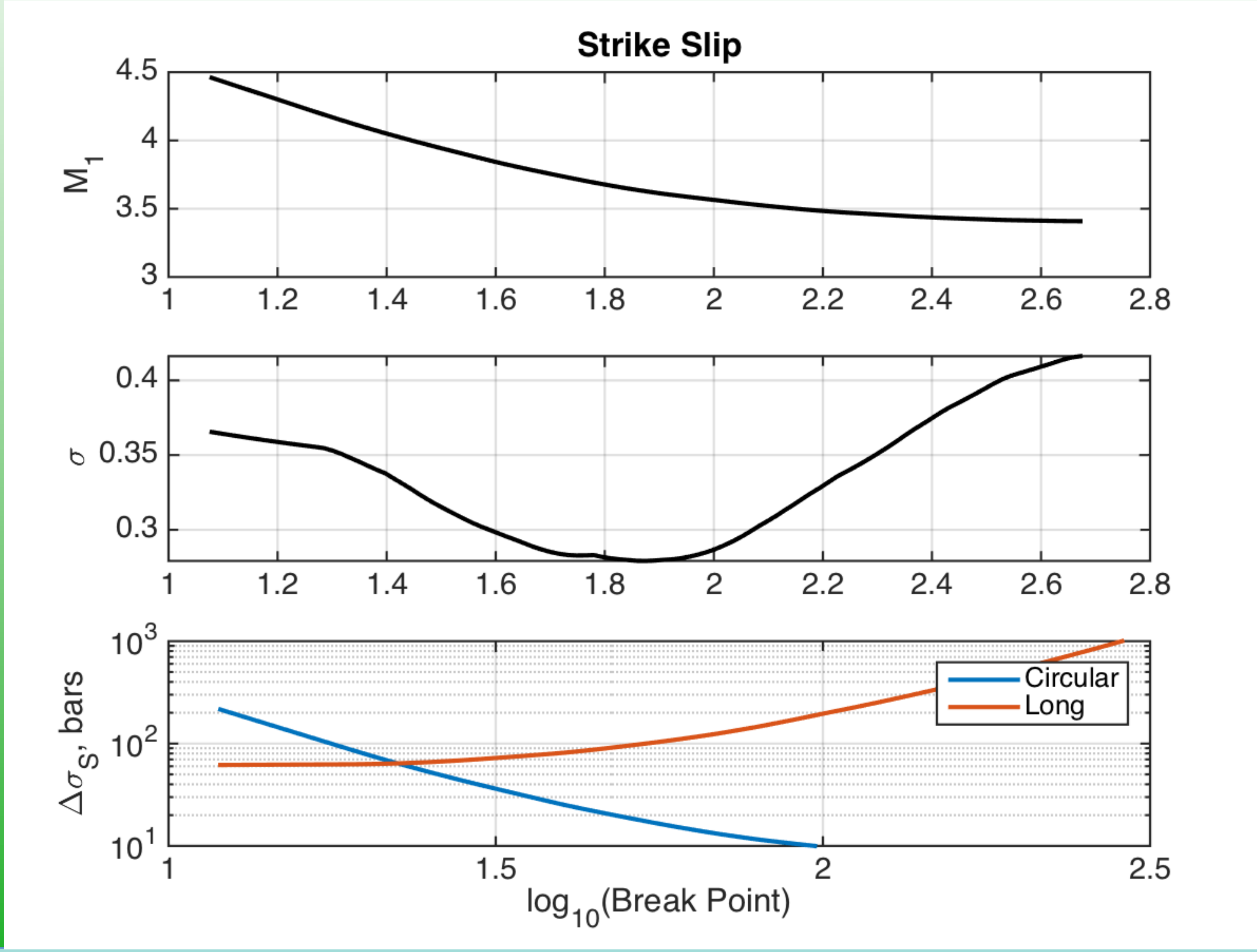
Full Data Set: Bilinear, slopes 2, 2/3

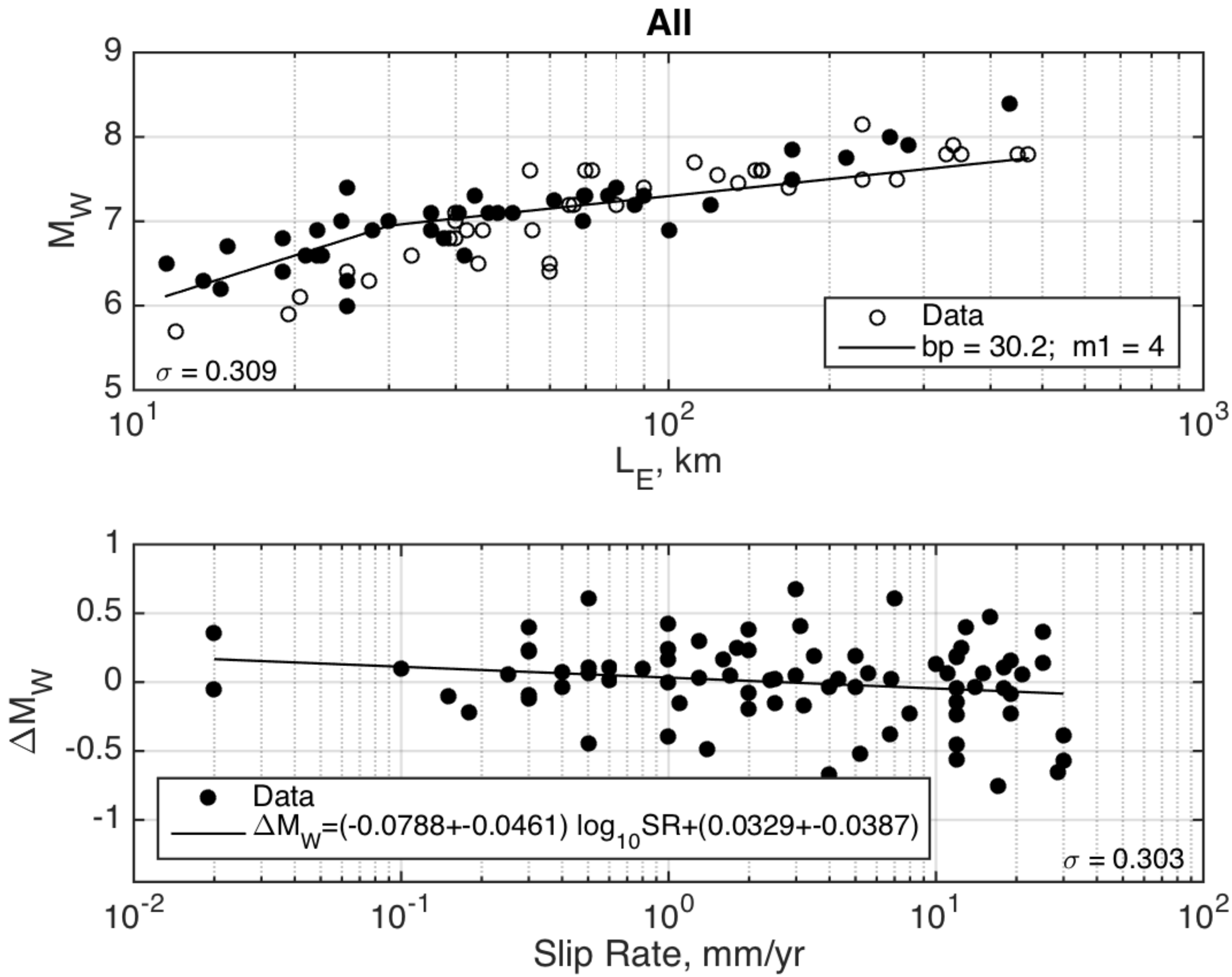


Full Data Set: Bilinear, slopes 2, 2/3

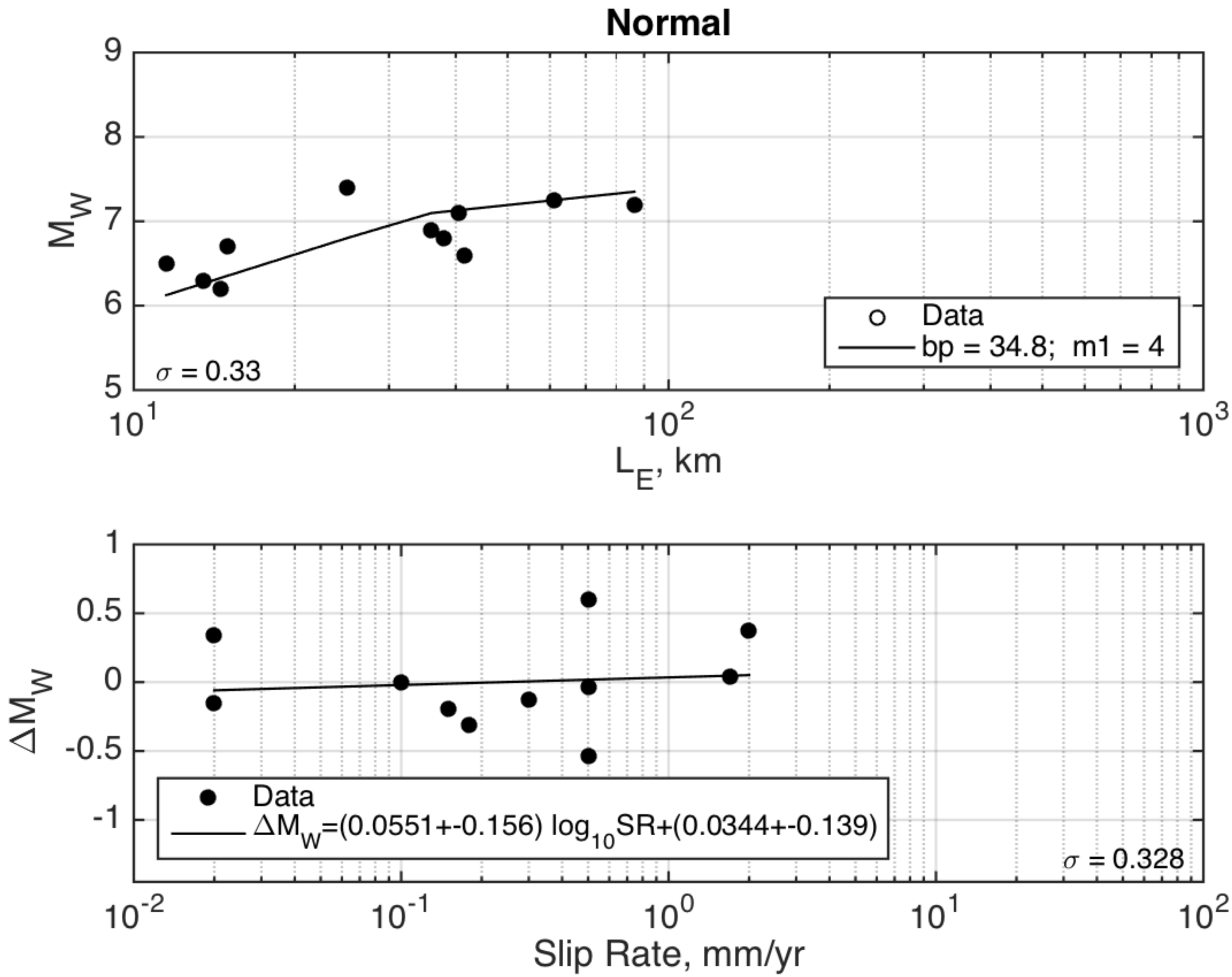
Bilinear breakpoint selection:

1. Minimize sigma
2. Equalize stress drop.

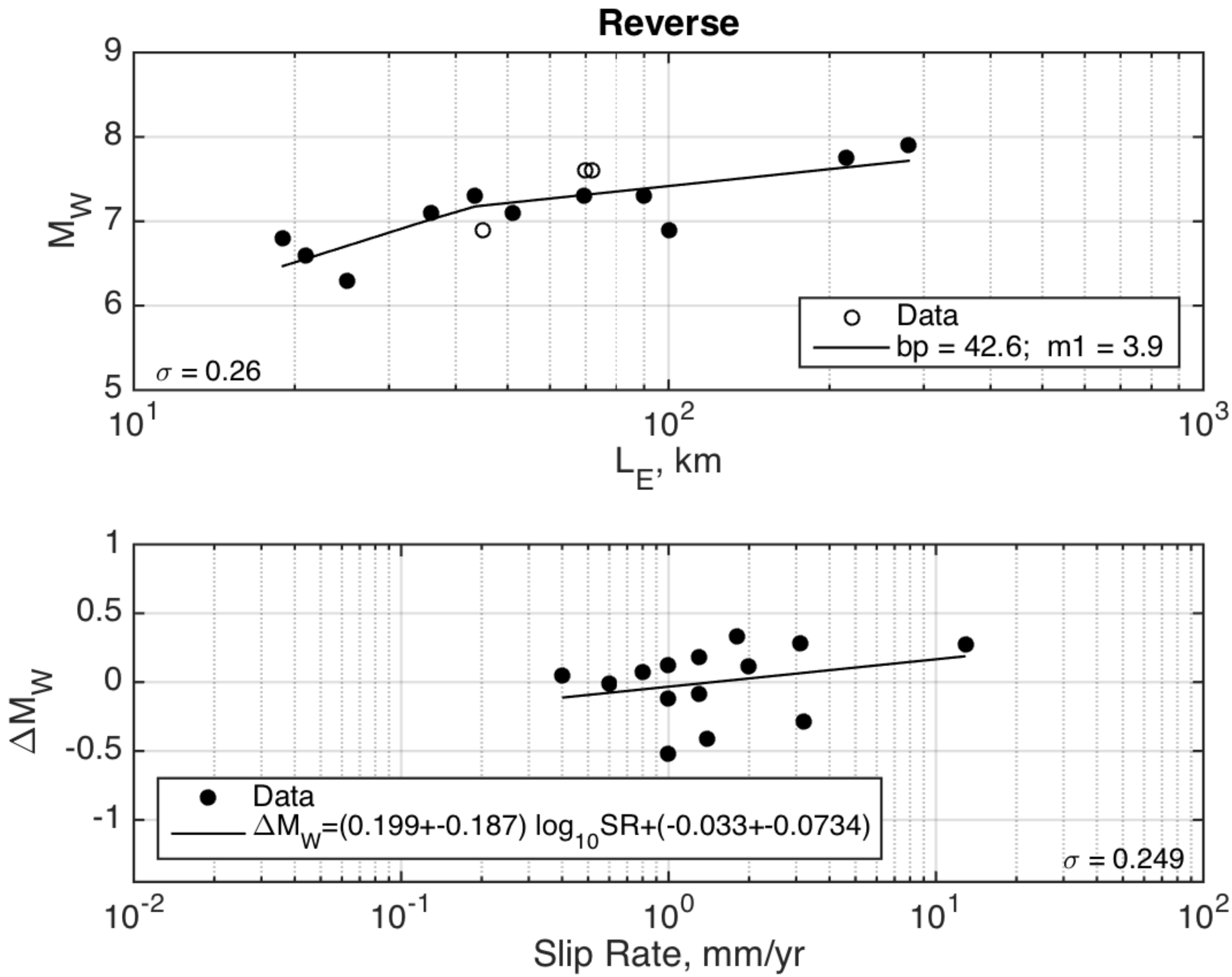




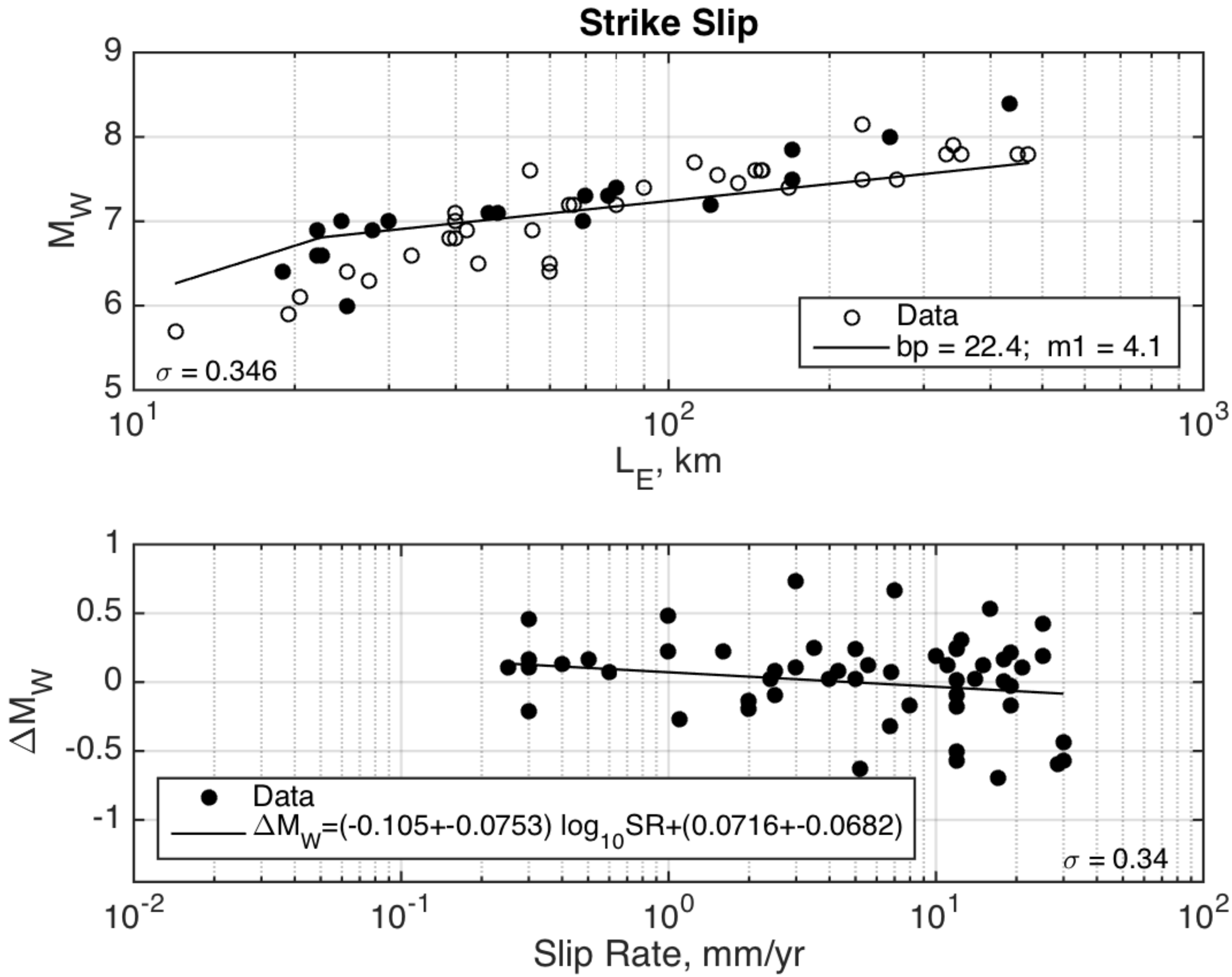
Full Data Set: Bilinear, stress drop equalized



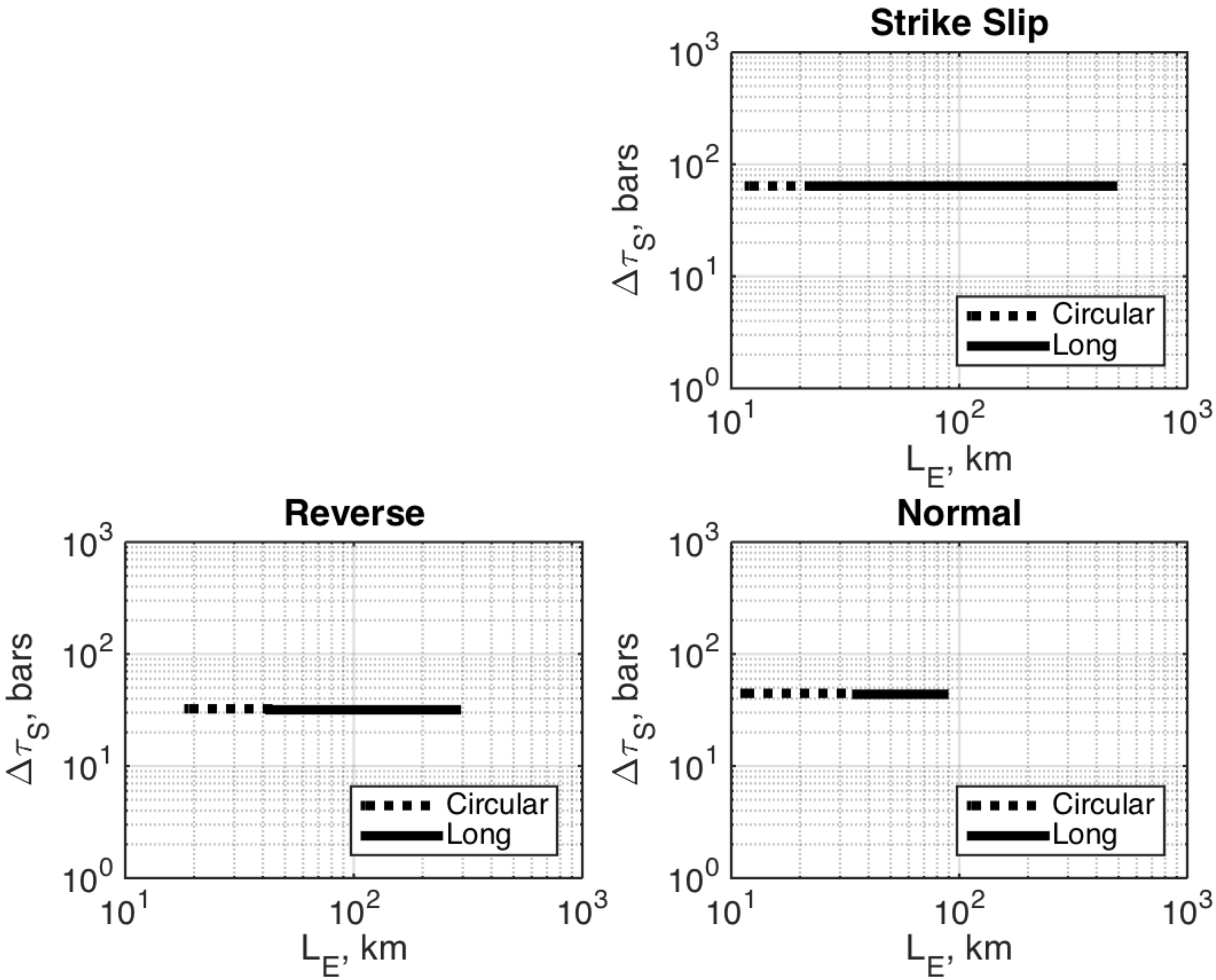
Full Data Set: Bilinear, stress drop equalized



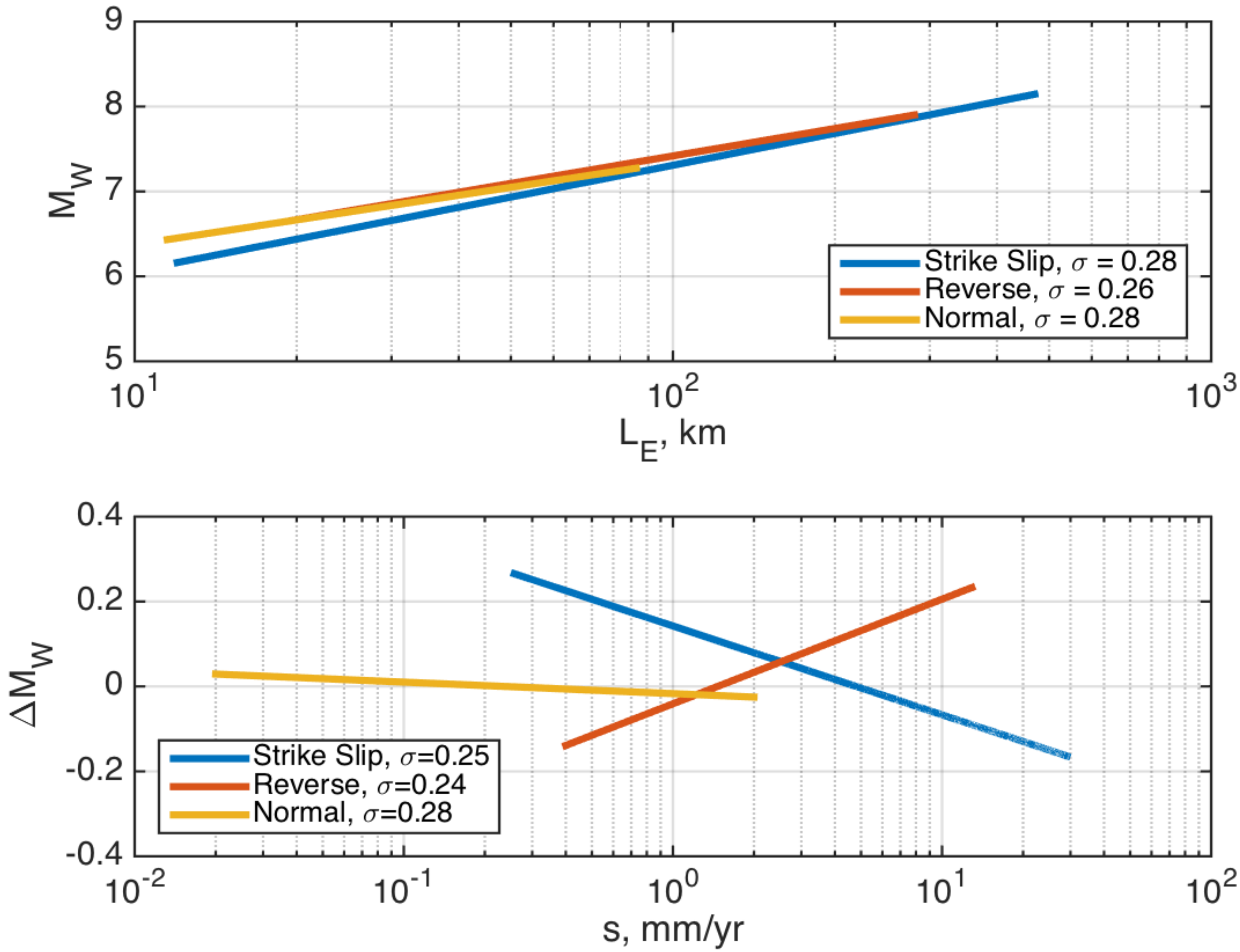
Full Data Set: Bilinear, stress drop equalized



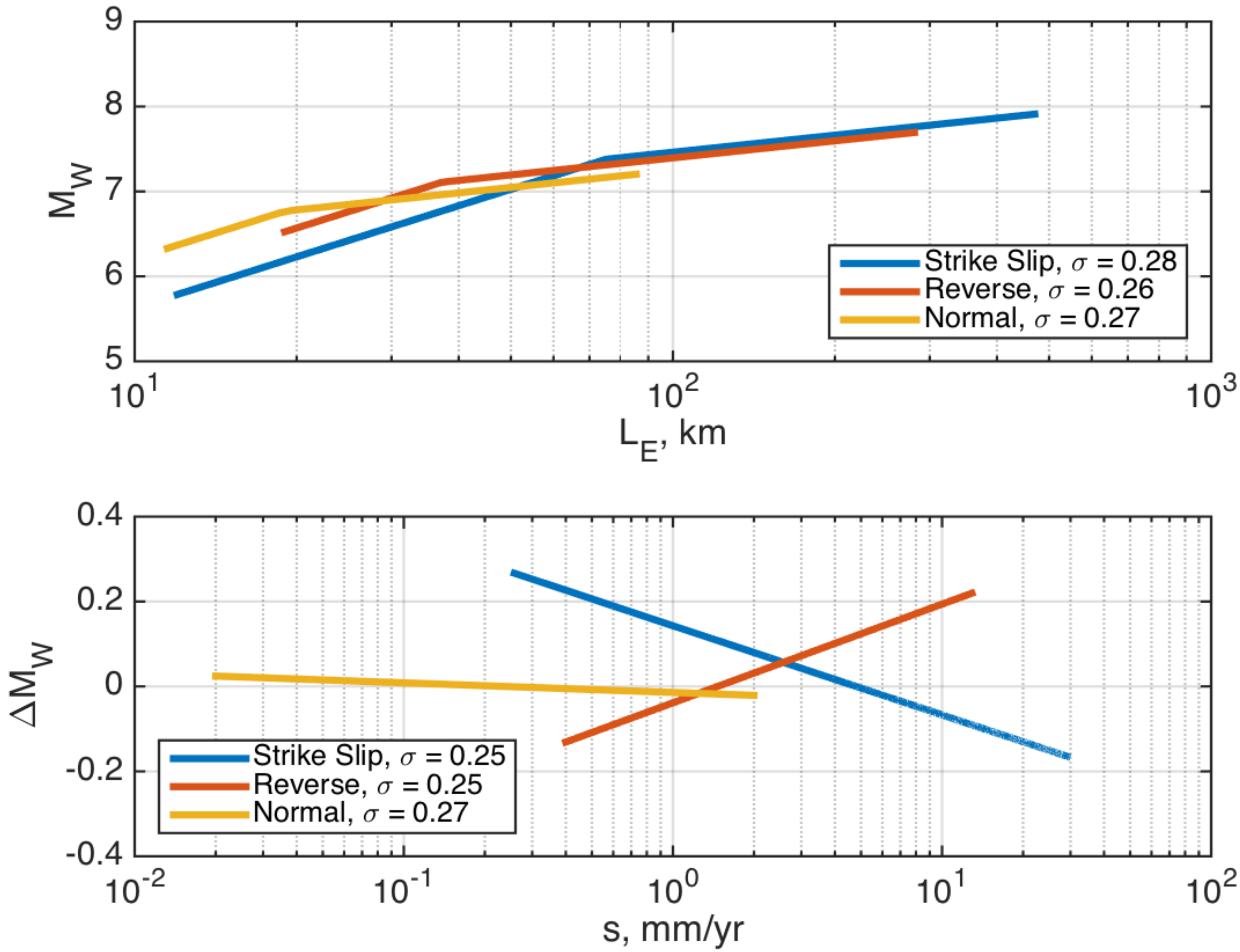
Full Data Set: Bilinear, stress drop equalized



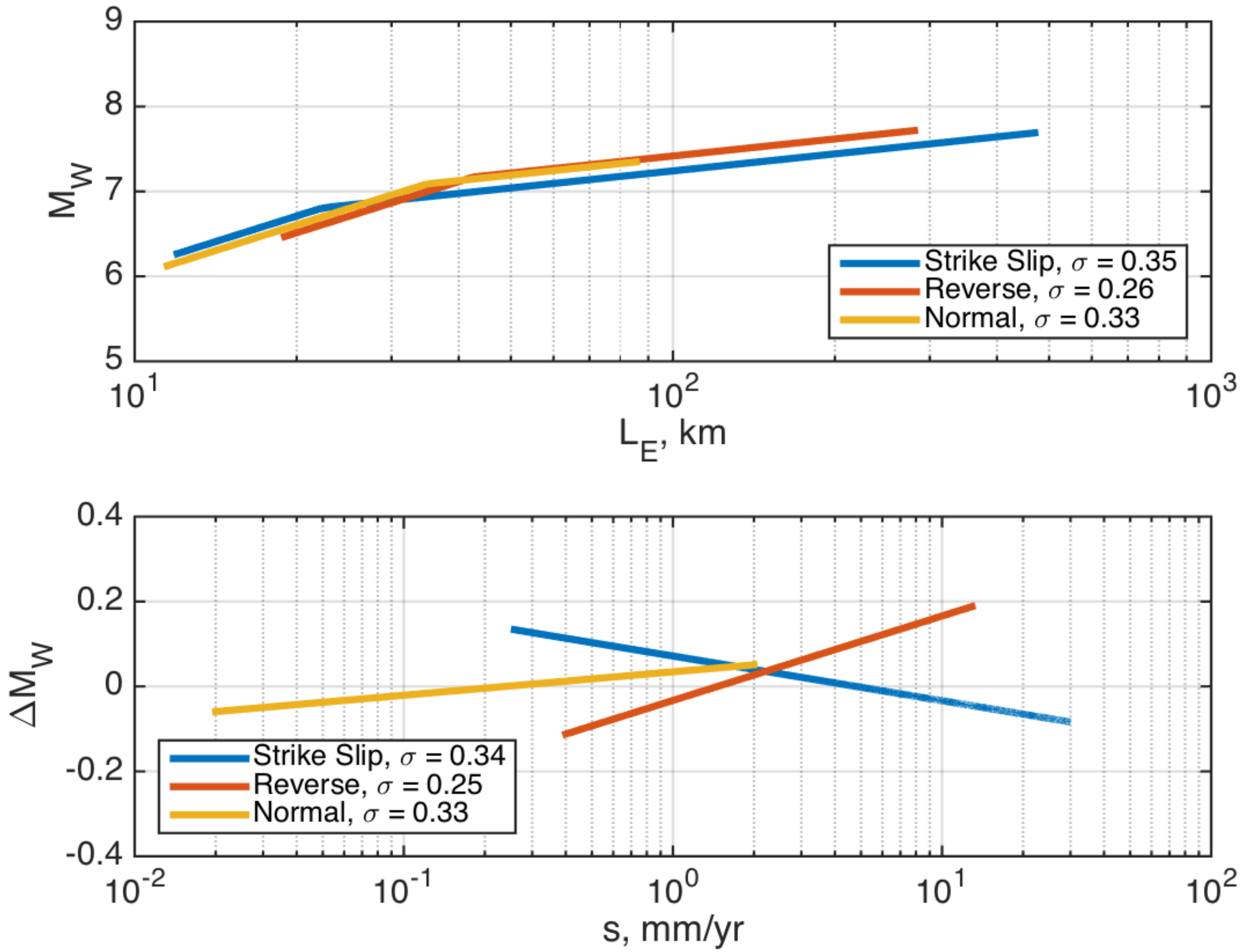
Full Data Set: Bilinear, stress drop equalized



Full Data Set



Full Data Set: Bilinear, slopes 2, 2/3



Full Data Set: Bilinear, stress drop equalized

Preliminary Summary

- ALL RESULTS ARE PRELIMINARY
- Data as a whole suggest a slip-rate dependence in prediction of MW from L.
- Data is dominated by strike-slip events, which do show the effect.
- For strike-slip events, the dependence on s is similar to the dependence found by Anderson et al (1994).

Preliminary Summary

- ALL RESULTS ARE PRELIMINARY
- Reverse and normal events are on faults with lower slip rates. Estimated magnitudes generally larger than for the strike-slip case (with higher slip rates).
- No additional dependence on s found for normal events in this data set.
- Slip rate dependence is present for reverse faulting events, but uncertainties are too large to consider it statistically significant.

Preliminary Conclusions (cont.)

- If we a create a reference model based on the assumptions of constant stress drop and constant fault width, we pay a penalty in misfit.
- The increase in sigma is tolerable for reverse and normal faults. For strike-slip events, the fit to the data is visibly degraded by this model.

LESSONS LEARNED FROM SIX HISTORIC EARTHQUAKES IN THE INTERMOUNTAIN WEST REGARDING MAXIMUM MAGNITUDE

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The largest possible earthquake in the Intermountain West, the broad region of high topography from the western side of the Rocky Mountains to the eastern side of the Sierra Nevada, is poorly understood. For the 2014 U.S. Geological Survey (USGS) seismic-hazard model (Petersen and others, 2014), several lines of evidence support increasing the M_w 7 regional maximum magnitude, the M_w 7.5 maximum magnitude for the Central Nevada seismic zone, and the M_w 7.6 maximum magnitude for shear zones identified by geodetic data (Petersen and others, 2008). For this update, we increased the maximum magnitude to M_w 7.45 with 90% weight and M_w 7.95 with 10% weight. The scientific community generally supports increasing the maximum magnitude in the conterminous United States and the Intermountain West, specifically, because (1) the large, recent Tohoku, Japan, and Denali, Alaska, earthquakes ruptured multiple faults or multiple fault segments, (2) there is potential for large stress-drop earthquakes in the region similar to the Hebgen Lake, Montana, earthquake, and (3) historical earthquakes in the region have formed long, discontinuous multi-fault or multi-segment ruptures in earthquakes larger than M_w 7.

Linking of ruptures across multiple faults or fault segments in the region is documented for the 1857 Sonoran, Mexico; 1915 Pleasant Valley, 1954 Fairview Peak and Dixie Valley, Nevada; 1959 Hebgen Lake, Montana; and the 1983 Borah Peak, Idaho, earthquakes. The magnitudes of these historical earthquakes are not all well constrained. However, by considering scaling relations with respect to maximum and average displacement data in addition to surface-rupture length, all may have exceeded M_w 7; the Sonoran, Pleasant Valley, Fairview Peak, and Hebgen Lake earthquakes probably fall within the range of M_w 7–7.5.

The current model relaxes segmentation, but no consideration is given to the possibility of linkage of future ruptures across multiple faults or fault segments as implemented in the Uniform California Earthquake Rupture Forecast version 3 (UCERF3) model. The large regional maximum magnitude compensates for this and the incomplete inventory of fault sources in the current model. Known faults in the region are not included due to the lack of critical data to constrain the frequency of future earthquakes. Progress on that front is slow; we only added four new fault sources in the 2014 update (0.2 percent of the known Quaternary fault inventory). Only 317 of the 1645 recognized Quaternary faults and fault sections in the region (as defined in the USGS Quaternary Fault and Fold Database) are included in the hazard model. Fewer than 40 percent of the known Quaternary faults or fault sections less than 30 km in length (equivalent to M_w6.8), 50 percent of faults about 40 km long (equivalent to M_w 7), and 70–80 percent of 75 km or longer faults (equivalent to M_w 7.3 and larger) are modeled. In general, the faults in the region have low slip rates and long recurrence intervals, which makes correlating multi-fault ruptures difficult. Recurrence intervals for large earthquakes on the faults that ruptured in the Sonoran, Pleasant Valley, and Fairview Peak earthquakes are exceptionally long, measured in many tens to possibly 100 kyr.

Additional geologic conditions may contribute to the existence of unknown faults or unrecognized prehistoric earthquakes. Globally, approximately 15 percent of M_w 7 do not rupture the Earth's surface, and about the same percentage of M_w 7–7.4 earthquakes similarly do not result in surface rupture (Wells and Coppersmith, 1993); slightly smaller percentages are suggested for the Intermountain West region, with about 95 percent of M_w 7 earthquakes potentially resulting in surface rupture (Pezzopane and Dawson, 1996). If these relations are accurate, paleoseismic histories on known faults may be incomplete. Even though some smaller earthquakes have resulted in surface rupture in the Intermountain West, the sample size is too small to constrain a regional threshold magnitude. For these reasons, we cannot be certain that all M_w 7 and larger earthquakes are recognizable in the geologic record. In addition, glacial lakes covered large parts of the Basin and Range Province and possibly buried evidence of paleoearthquakes, particularly those on faults characterized by long recurrence intervals.

The six largest historical earthquakes in the Intermountain West in the past 150 years produced complex, discontinuous surface ruptures. All ruptured through hypothesized segment boundaries or across step overs up to 15 km wide in map view. At this time, we do not know if these patterns repeat past ruptures, nor has this behavior been recognized elsewhere in the region. The prior maximum magnitude for the region of M_w 7 is inconsistent with the historical record, and a conservative assessment of regional maximum magnitude is prudent given the incomplete inventory of potential fault sources. At a minimum, the regional maximum magnitude should be at least as large as the largest historical earthquake (M_w7–7.5), with due consideration to the uncertainty in magnitudes assigned to poorly recorded earthquakes. Future models should address possible fault linkage, especially in cases where magnitudes inferred from displacement data greatly exceed magnitudes based on surface rupture length.

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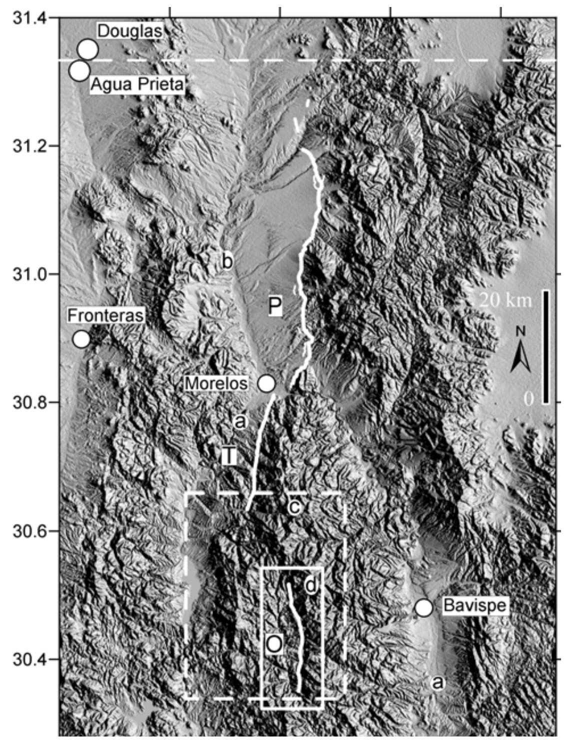
The following is a PDF version of the authors' PowerPoint presentation.

Lessons learned from 6 historic IMW earthquakes regarding maximum magnitude

Kathy Haller and Mark Petersen
USGS

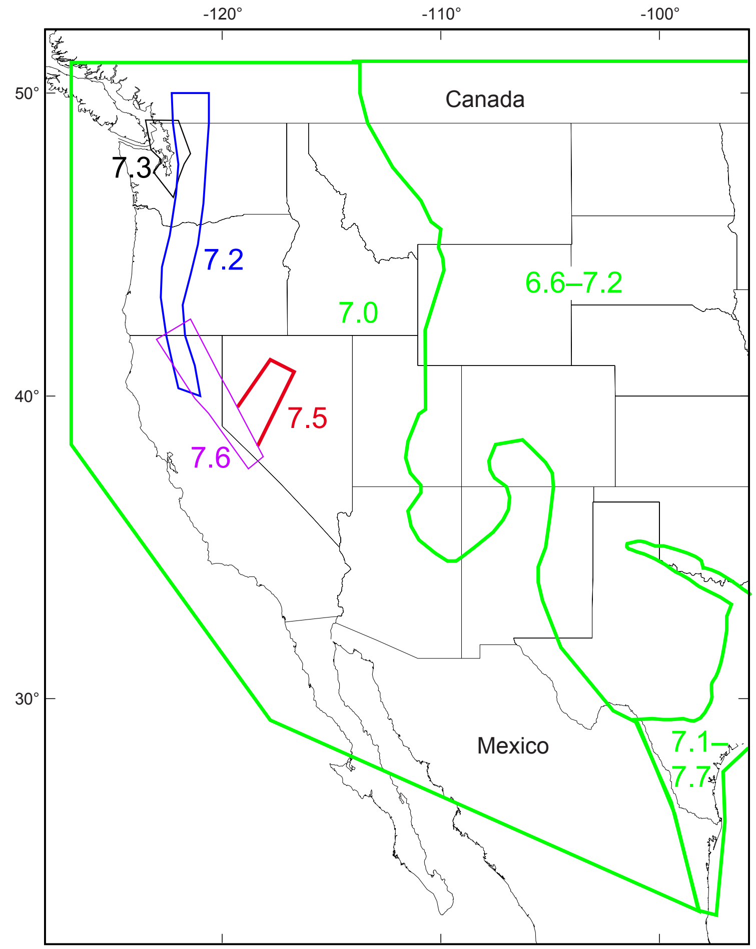
Sonora Mexico earthquake
May 03 1887



Points

- Regional maximum magnitude was increased because historical earthquakes were larger than M7
- Historical earthquakes ruptured more than one segment or multiple faults and the current model does not consider linking of rupture on more than one fault
- The present inventory of fault sources is incomplete; therefore, possible earthquakes are unaccounted for in the model

2008 maximum-magnitude zones

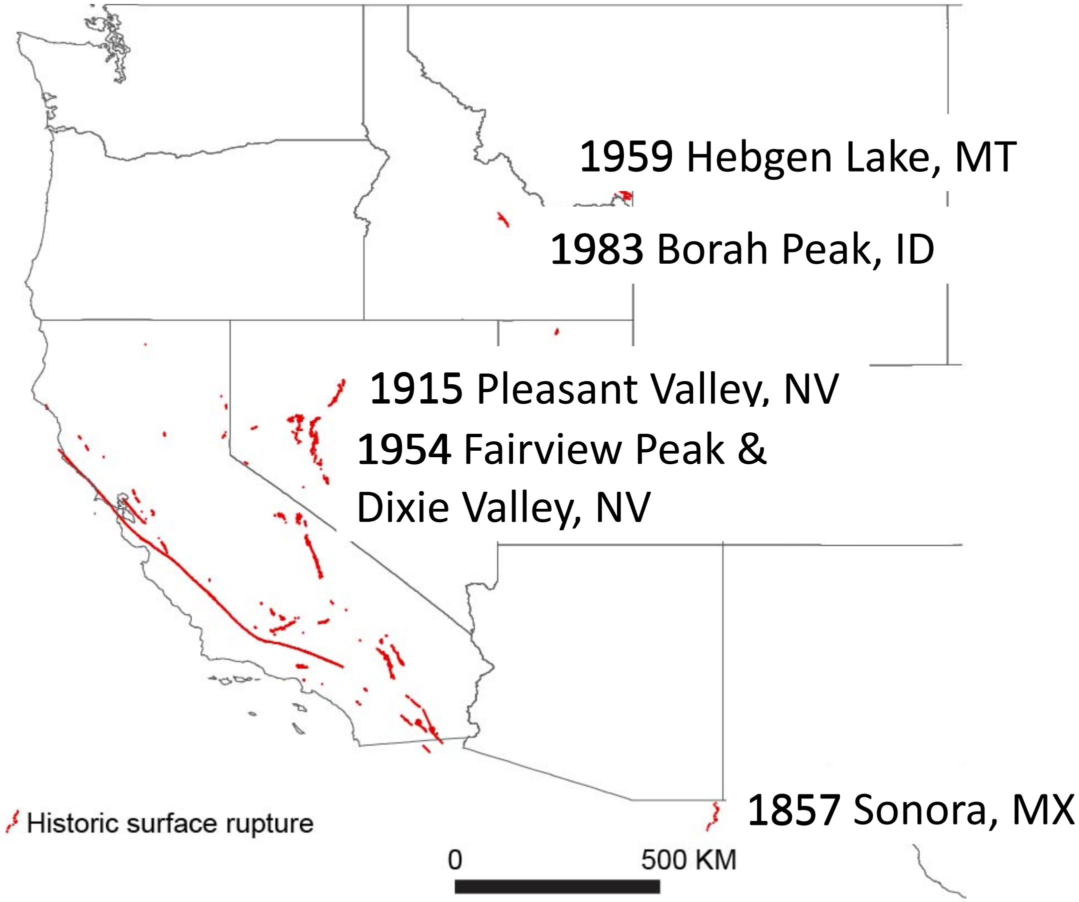


Maximum magnitude

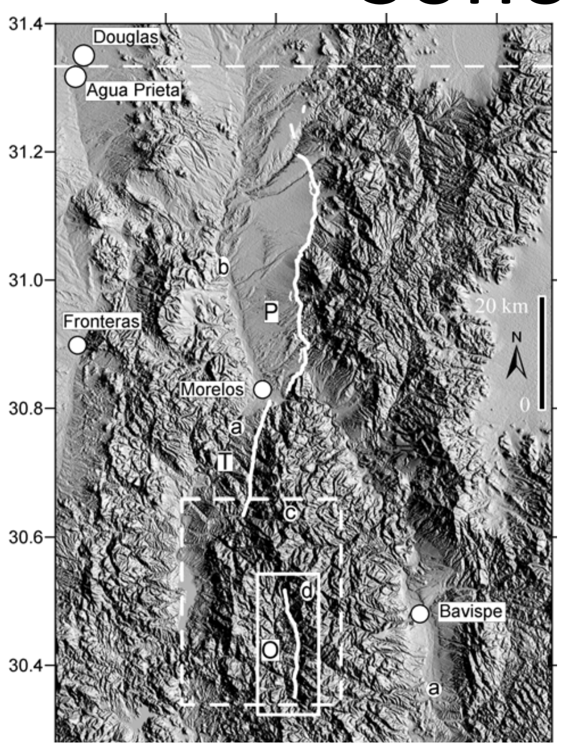
- 1996-2008 WUS: Typically about M 7.0 (with exceptions in zones and over faults)
- 2014 CA: from M 7.3(0.1), 7.6 (0.8), 7.9 (0.1) (average 7.6)
- 2014 WUS: (non CA) M 7.45 (0.9), M 7.95 (0.1) (average 7.5)
- 2014 Craton: M 6.5-7.95 (average ~M 7.1)
- 2014 Extended Margin: M 6.8-7.95

  (average ~M 7.1)

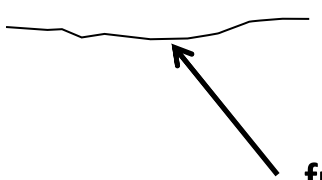
Historical earthquakes

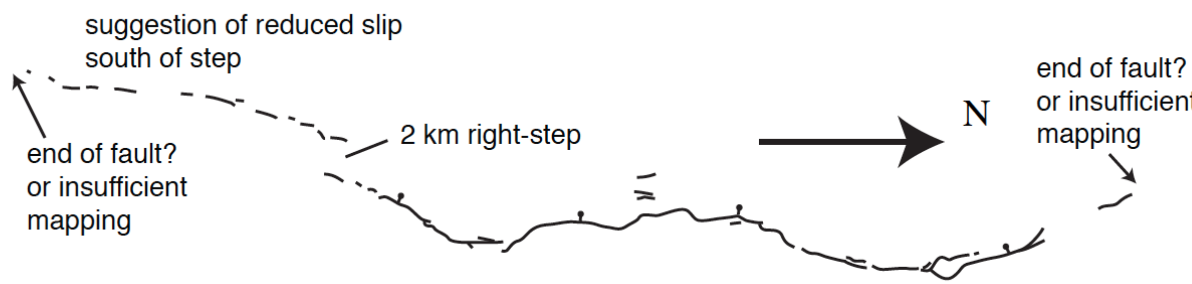


Sonora Mexico earthquake May 03 1887



- Mw7.4*
- 102-km-long rupture (Suter 2008)
- Multi-fault rupture
  Three discontinuous en echelon ruptures
- 15-km-wide gap in surface rupture between the southern two faults
- Previous surface faulting in late Quaternary (possibly 200 k.y. ago)



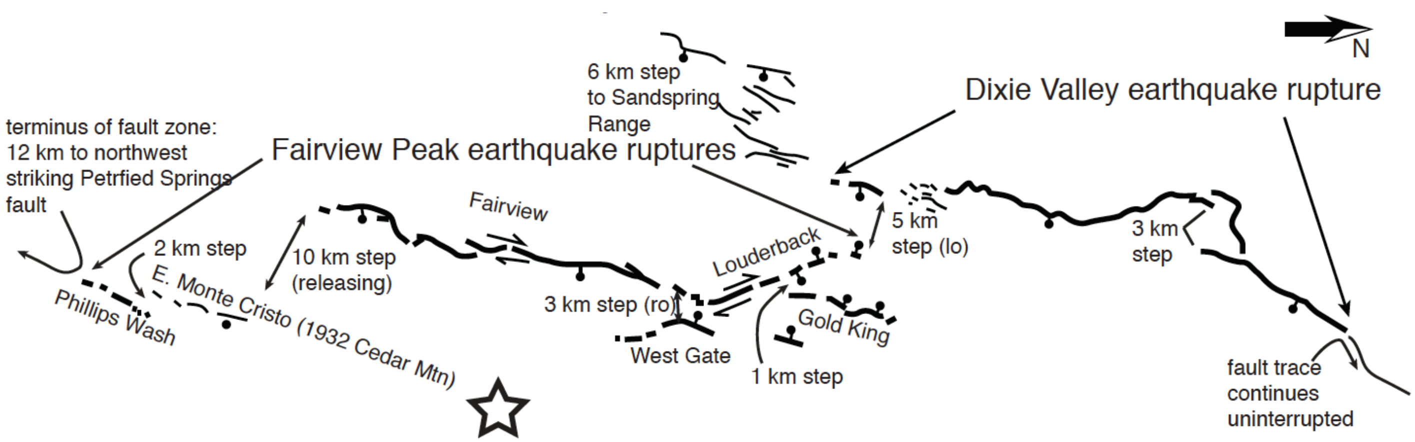


from Suter 2008

***from Wesnousky 2008 (Electronic Supplement)**

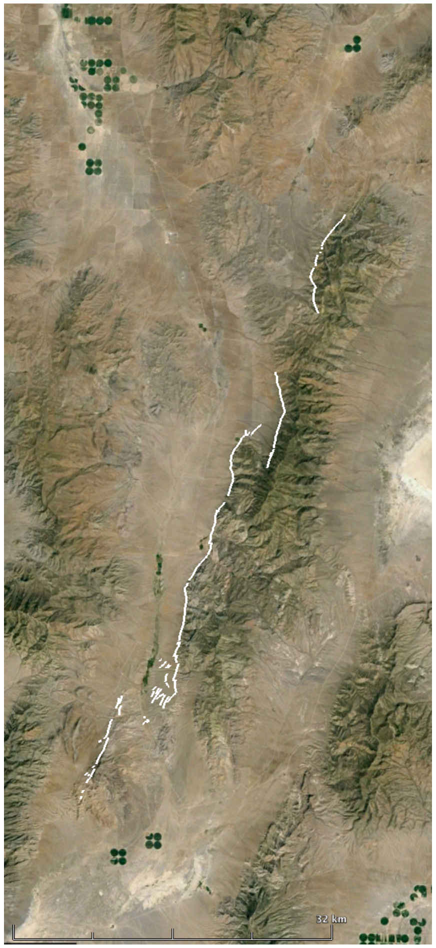
Fairview Peak & Dixie Valley earthquakes December 16 1954

- Mw7.1* and Mw6.8* (4 minutes apart)
- 62- and 47-km-long surface ruptures
- Multi-fault rupture
  Five subparallel faults
- 1- to 5-km-wide gaps in surface rupture
- Mean recurrence interval probably tens of thousands of years

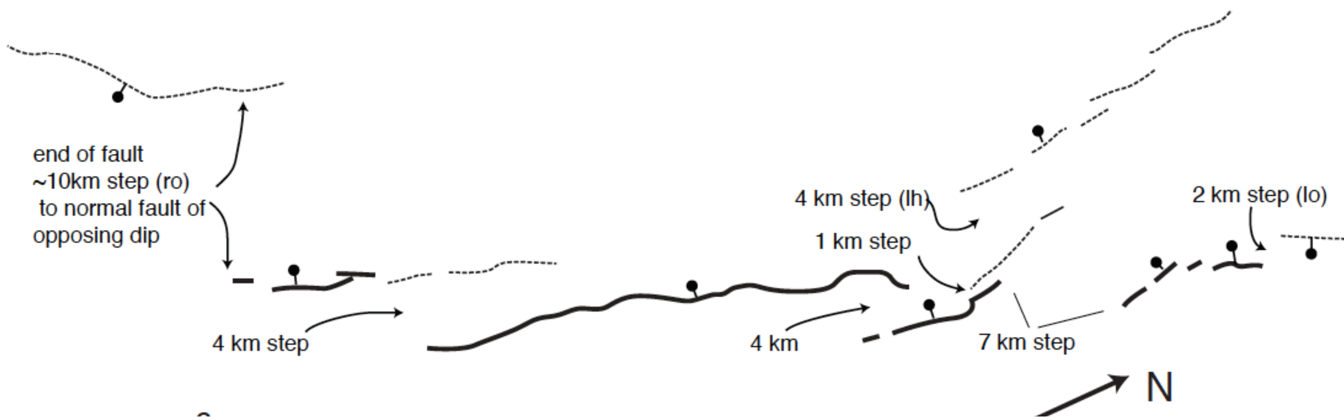


***from Wesnousky 2008 (Electronic Supplement)**

Pleasant Valley earthquake October 02 1912



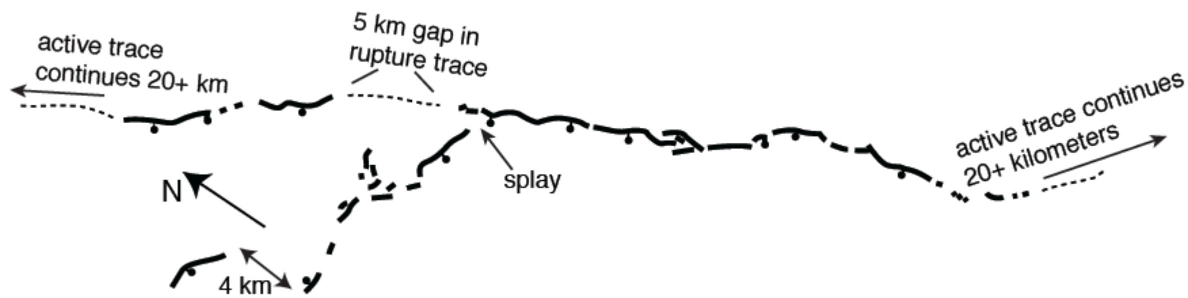
- Mw7.3*
- 61-km-long rupture
- Four discontinuous en echelon ruptures
- 4- to 7-km-wide gaps in surface rupture
- Unconstrained recurrence interval (possibly a few to 20 k.y.)



***from Wesnousky 2008 (Electronic Supplement)**

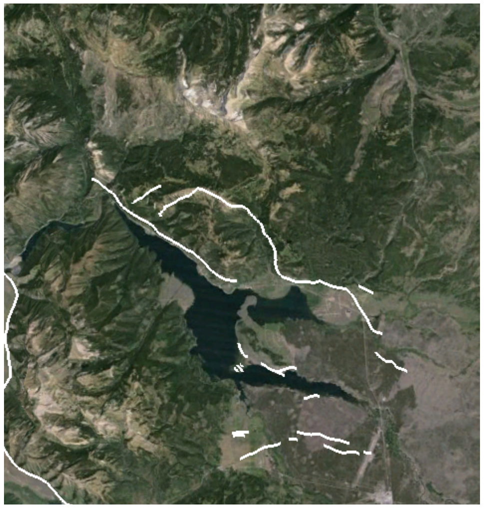
Borah Peak earthquake October 28 1983

- Mw7.0*
- 34-km-long rupture
- Multi-segment and multi-fault rupture
  Complex rupture pattern of central part of longer active fault
- 4- and 5-km-wide gaps in surface rupture
- Prior Holocene surface faulting

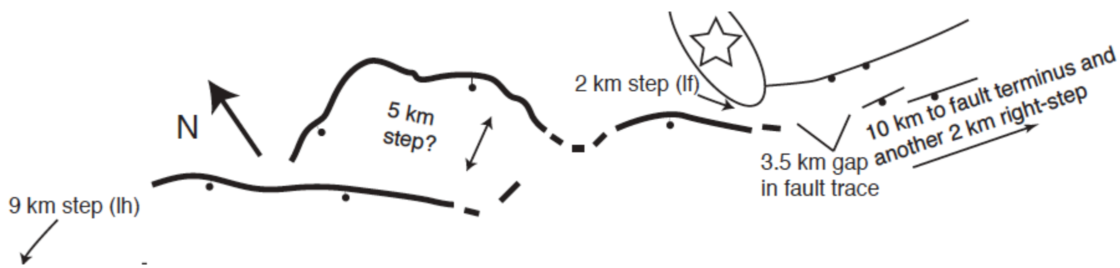


***from Wesnousky 2008 (Electronic Supplement)**

Hebgen Lake earthquake August 18 1959



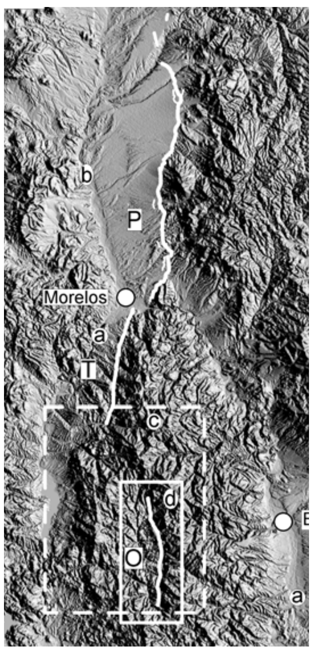
- Mw7.1*
- 25-km-long rupture
- Multi-fault rupture
  Five to eight subparallel faults
- 15-km-wide gap in surface rupture between the southern two faults
- 3.5- to 9-km-wide gaps in surface rupture
- Prior Holocene surface faulting

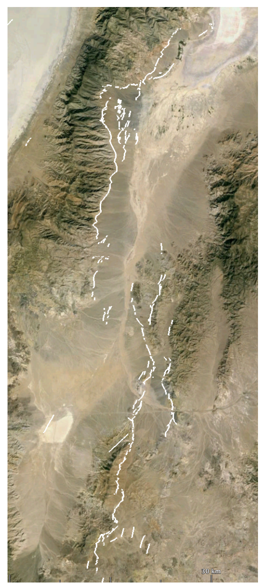


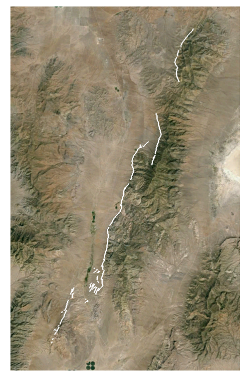
***from Wesnousky 2008 (Electronic Supplement)**

Summary of historical earthquakes

	Sonora, MX	Fairview Peak, NV	Dixie Valley, NV	Pleasant Valley, NV	Borah Peak, ID	Hebgen Lake, MT
Mw	7.4	7.1	6.8	7.3	7.0	7.1
Length (km)	102*	62	47	61	34	25
Displacement						
Maximum (m)	3.6	4.5	3	5.8	2.8	4.1
Average (m)	1.9	1.0	0.8	1.8	0.9	1.9





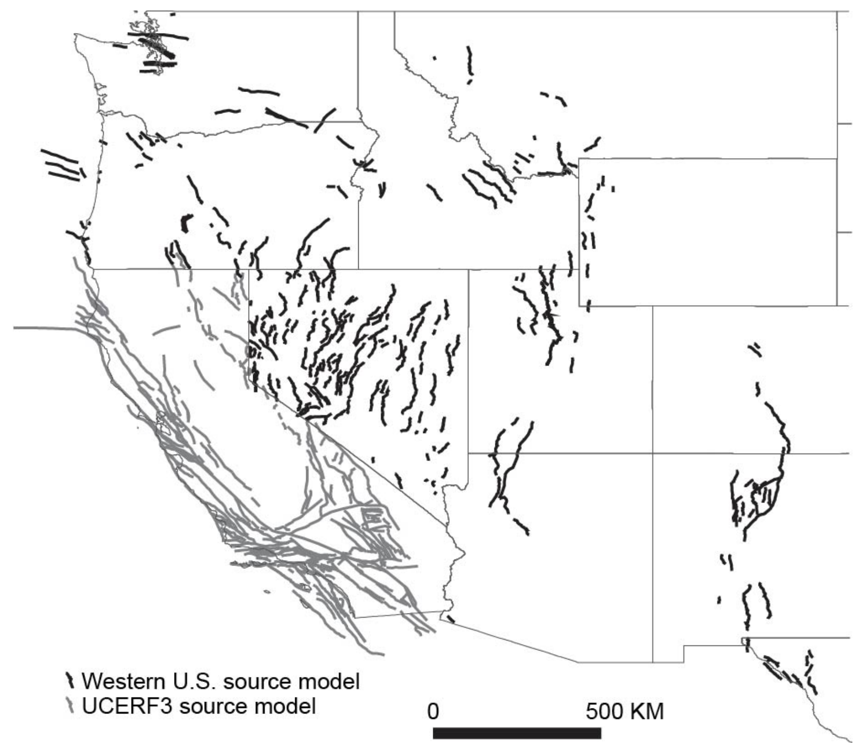


20 km

Data from Wesnousky 2008 (Electronic Supplement)
*** from Suter 2008**

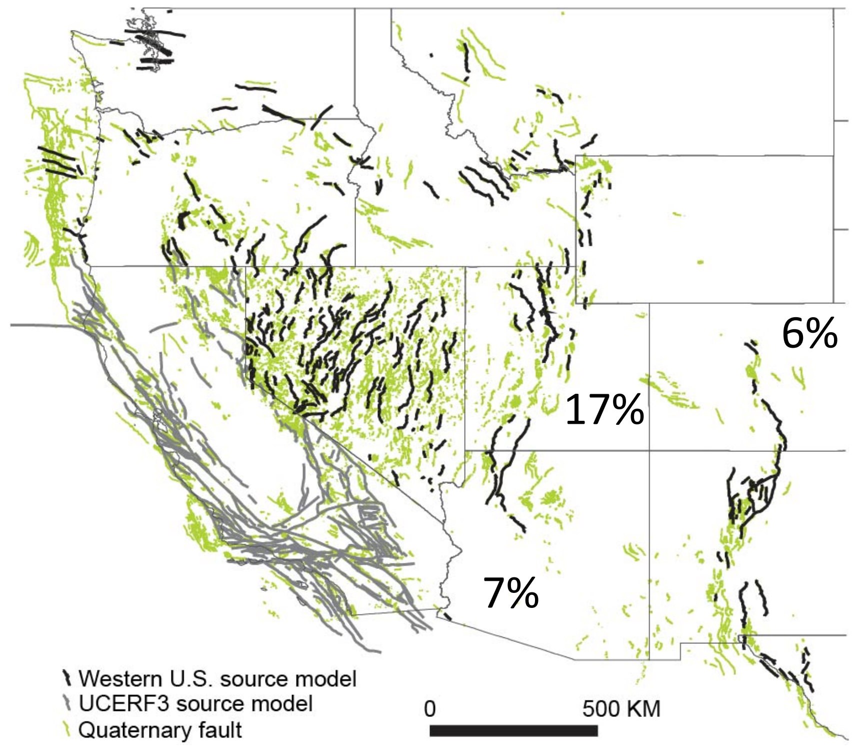
Fault sources in 2014 model

- Fault Sources
  - Inclusion is based on published paleoseismologic, geologic, and geodetic data and interpretations of that data

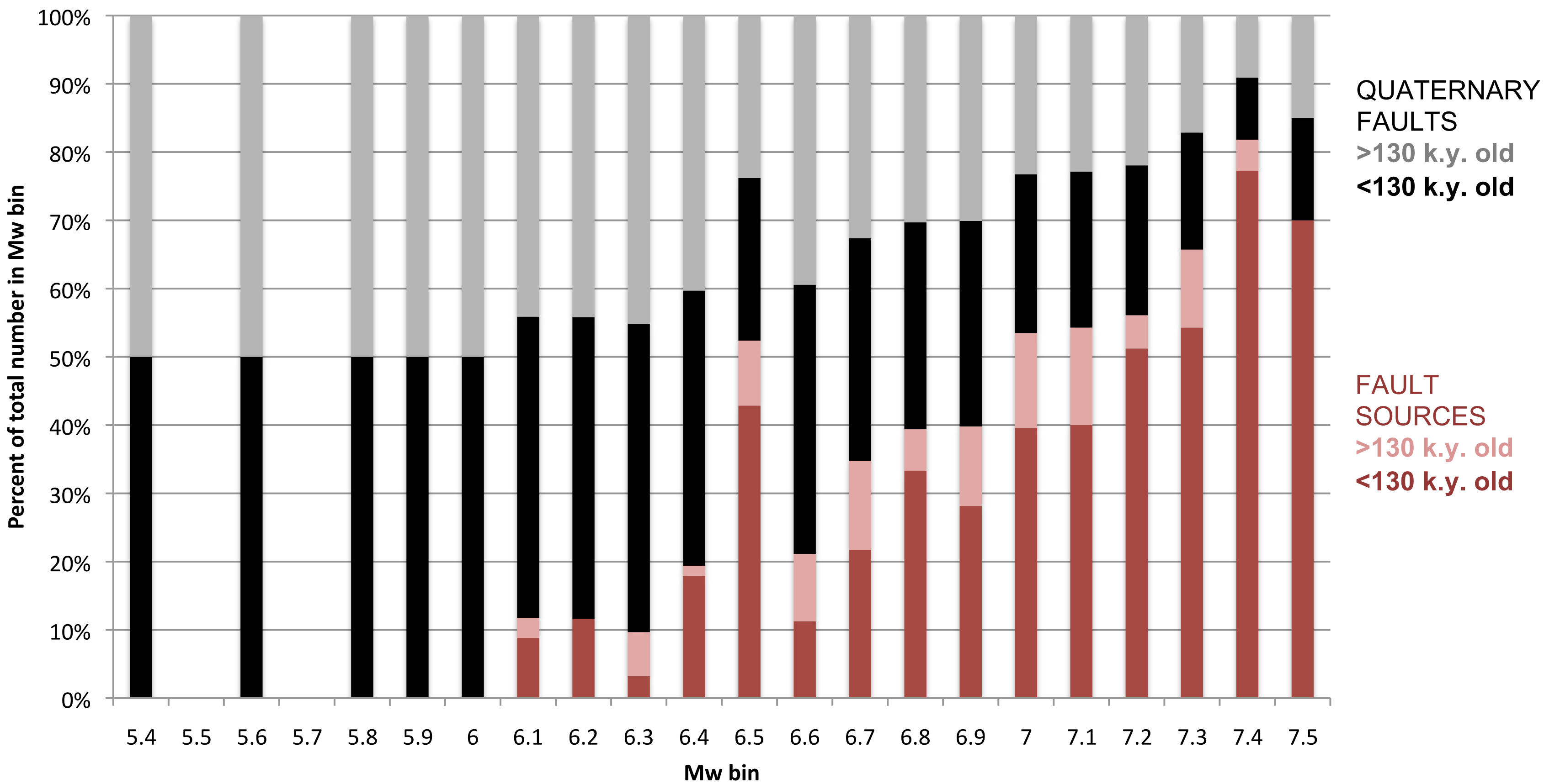


Inventory of Quaternary faults

- 2,000 known Quaternary faults
- Regionally, 25% are included as fault sources
- Colorado, Arizona, and Utah contain the lowest percent of Quaternary faults considered in the model



Percentage of Quaternary and late Quaternary faults and fault sources

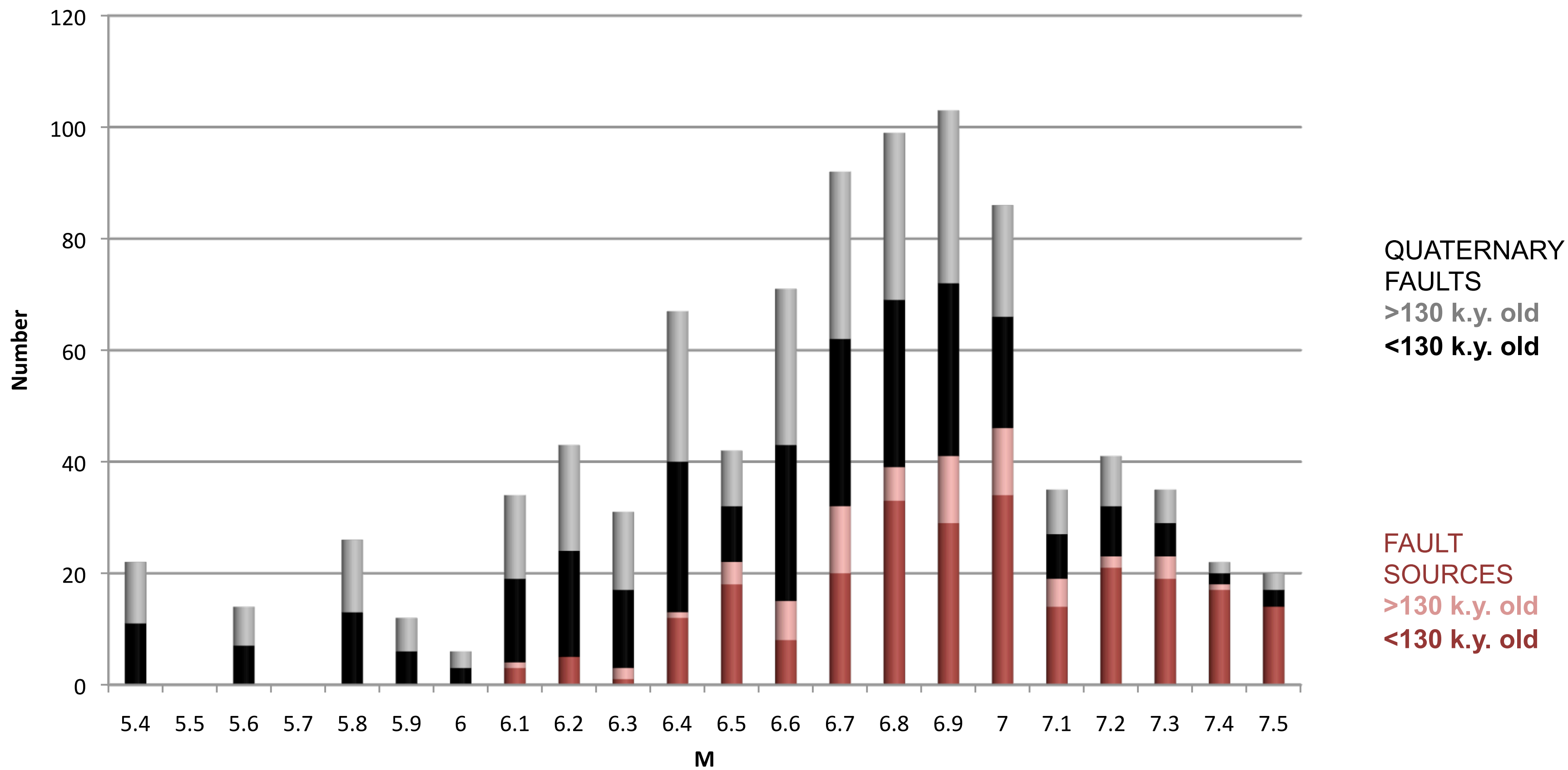


Conclusions

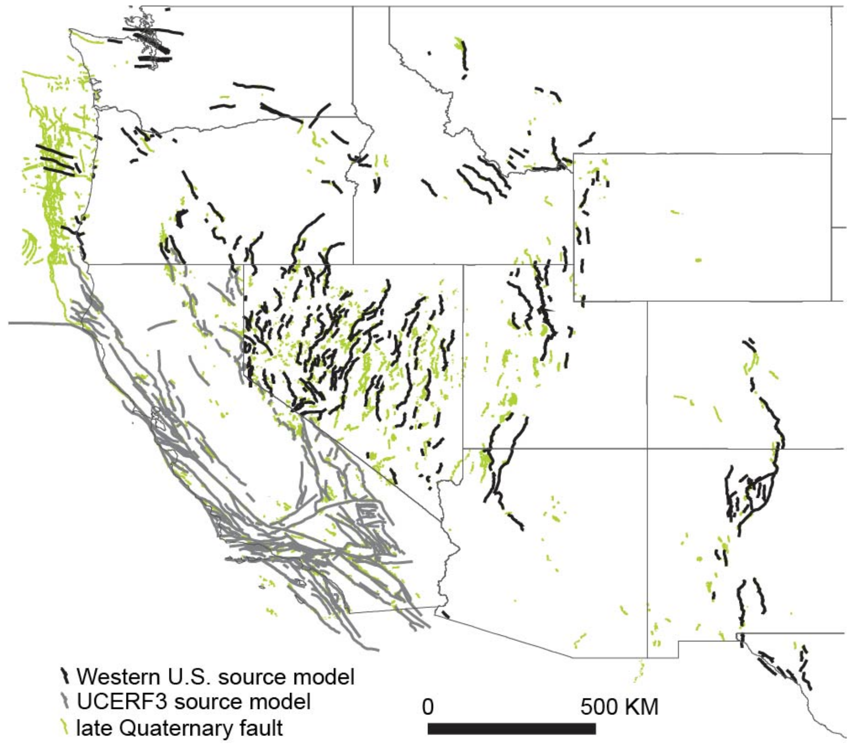
- 2014 National Seismic Hazard Models included an maximum magnitude to level consistent with observed seismicity (~M7.5)
- To account for larger ruptures, earthquakes up to M 7.95 were also considered with a truncated exponential distribution that decays very quickly after M 7.5. This model is consistent with more complex multi-segment ruptures and is similar to earthquakes considered in other areas of the U.S.

Extras

Population of Quaternary and late Quaternary faults and fault sources

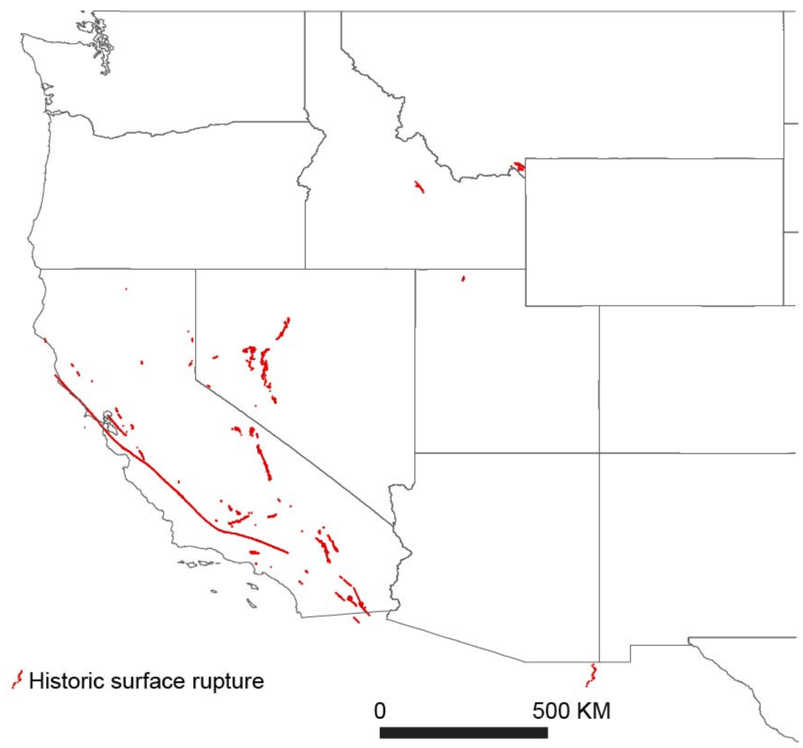


Inventory of late Quaternary faults



Historical earthquakes

- 1857 Sonora, MX
- 1915 Pleasant Valley, NV
- 1954 Fairview Peak & Dixie Valley, NV
- 1959 Hebgen Lake, MT
- 1983 Borah Peak, ID



M of IMW historical earthquakes