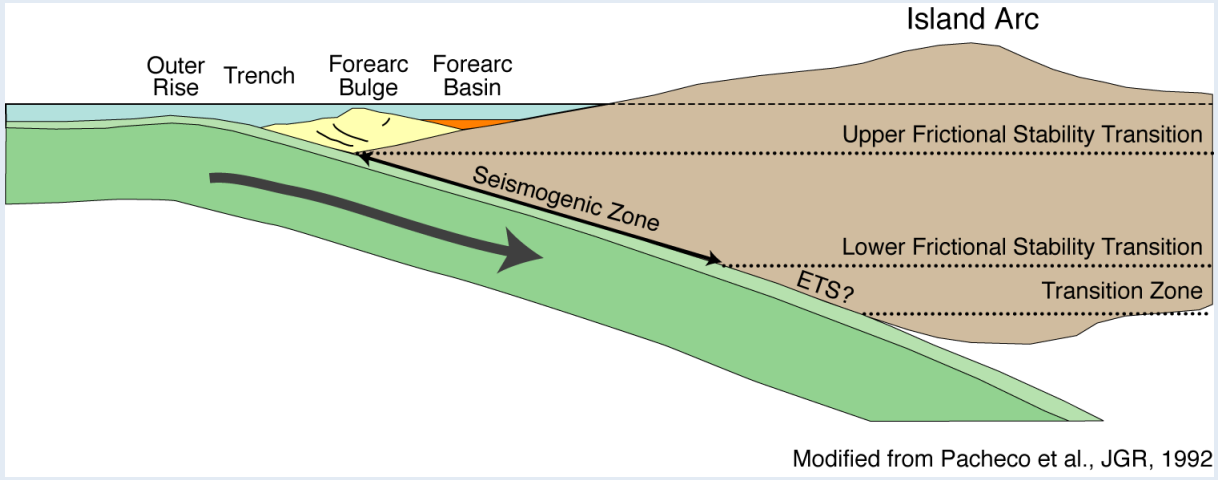
Controls on the Size, Frequency and Slip Behavior of Subduction Plate Boundaries



Thorne Lay

UC Santa Cruz

SCD Implementation Workshop
January 5-7, 2011

Topic 4.1 from GeoPRISMS Draft Science Plan 2010:

What governs the size, location and frequency of great subduction zone earthquakes and how is this related to the spatial and temporal variation of slip behaviors observed along subduction faults?

- What controls the magnitude and recurrence interval of earthquakes?
- What mechanical properties and/or fault zone conditions control the wide spectrum of slip rates observed on subduction megathrusts?

Factors Influencing Megathrust Earthquake Size – All mentioned already in Draft Plan

Width of Seismogenic Zone – Continental versus Island Arc

Convergence Rate – Poor correlation overall

Lithospheric Age – Poor correlation overall

Back-Arc Spreading/Trench Roll-back – Reduced coupling Tonga/Mariana

Segmentation – Changes in slab dip, upper plate 'blocks'

Sediments – Homogenization? Influence on shallow megathrust?

Sea-floor Topography – Seamounts, Horst and Graben structures

Upper plate – Forearc basins, gravity lows (cause/effect?)

Seismic coupling relationship to mechanical coupling?

Mechanical Properties Influencing Slip Rates - All mentioned already in Draft Plan

Temperature structure, yes, but how?

Fluid pressure

Sediments, clay mineralogy, pressure solution hardening

Role of serpentinization

Trench roll-back

Transitional Frictional States, SSEs, ETS, VLFEs

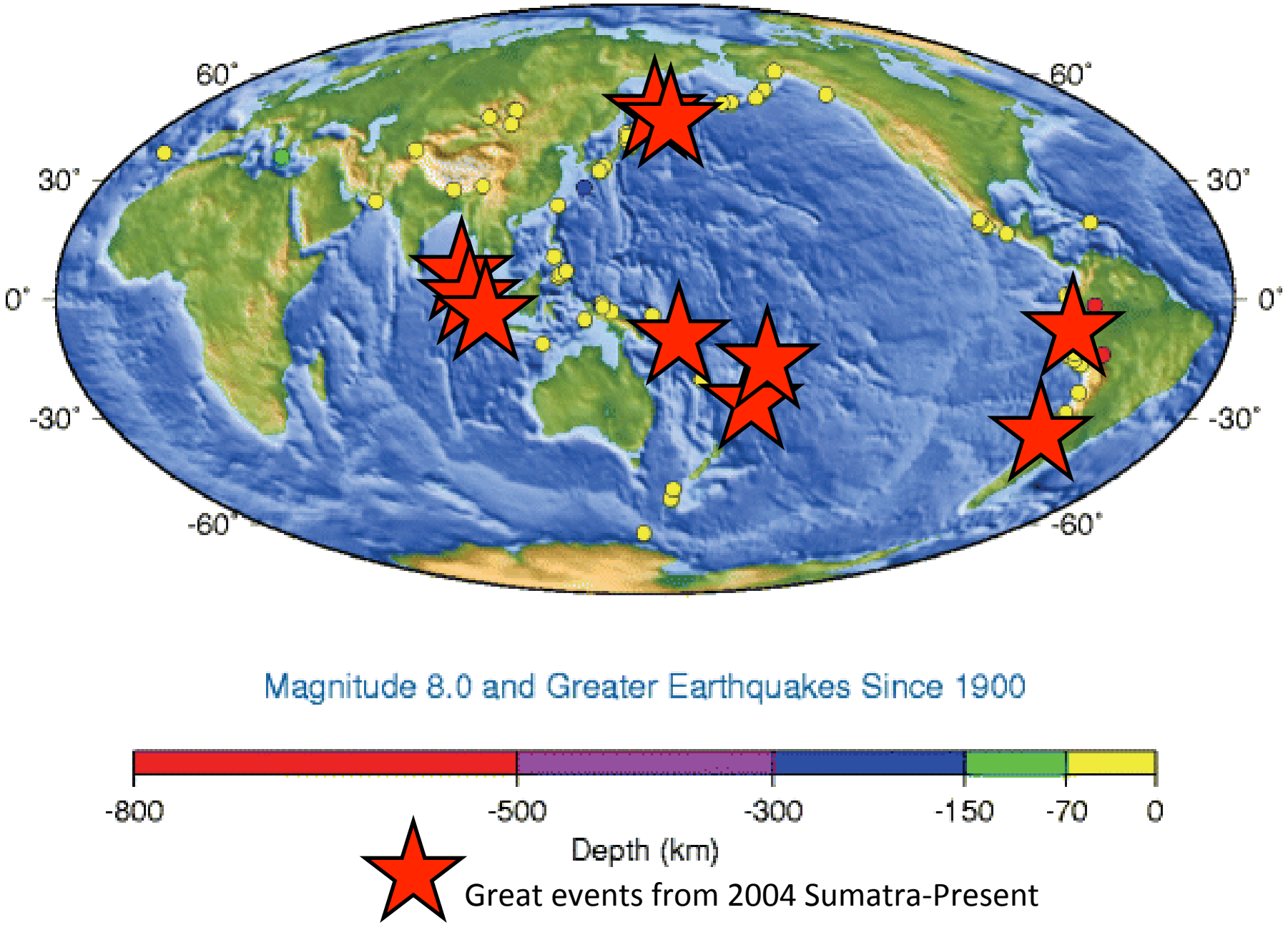
So, what are the New Opportunities for making progress on these long-standing questions? My choice for top 3:

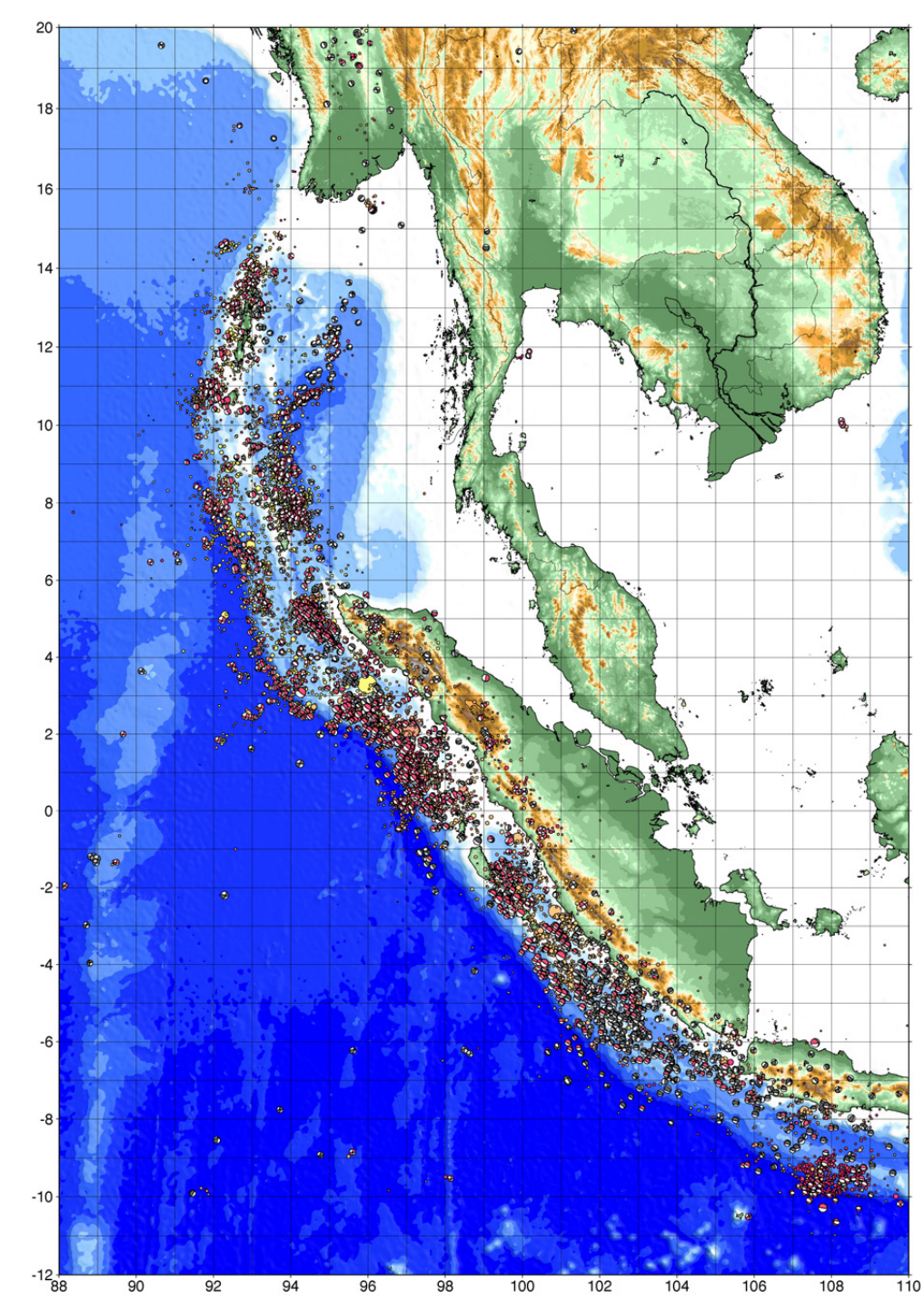
1) Numerous Great Earthquakes have finally been well-recorded seismically and geodetically; I think that we MUST exploit this new information fully for pre-seismic, co-seismic, and post-seismic behavior and lateral effects

2) Geodetic tools for locating 'not-slipping' regions of megathrust have matured (not fully, in my opinion); again, it seems imperative to exploit this fully in as many regions as possible; warrants 3D heterogeneous media modeling, but need to get off-shore constraints with ocean geodesy

3) Wide spectrum of slip-velocity processes have been detected, adding nuance to notions of frictional processes. Still observationally driven/challenged. Need expanded seismic/geodetic/hydrologic characterization of many regions

For the past 6 years, great earthquake rate has been 1.7/yr; over last century 0.7/yr





Sumatra-Sunda has been struck by a 'cluster' of great/large earthquakes since 2004.

Dec. 26, 2004 – 'unexpected' northward extension to Andaman Islands. 9.2

Mar. 2005 – adjacent 'aftershock'. 8.6

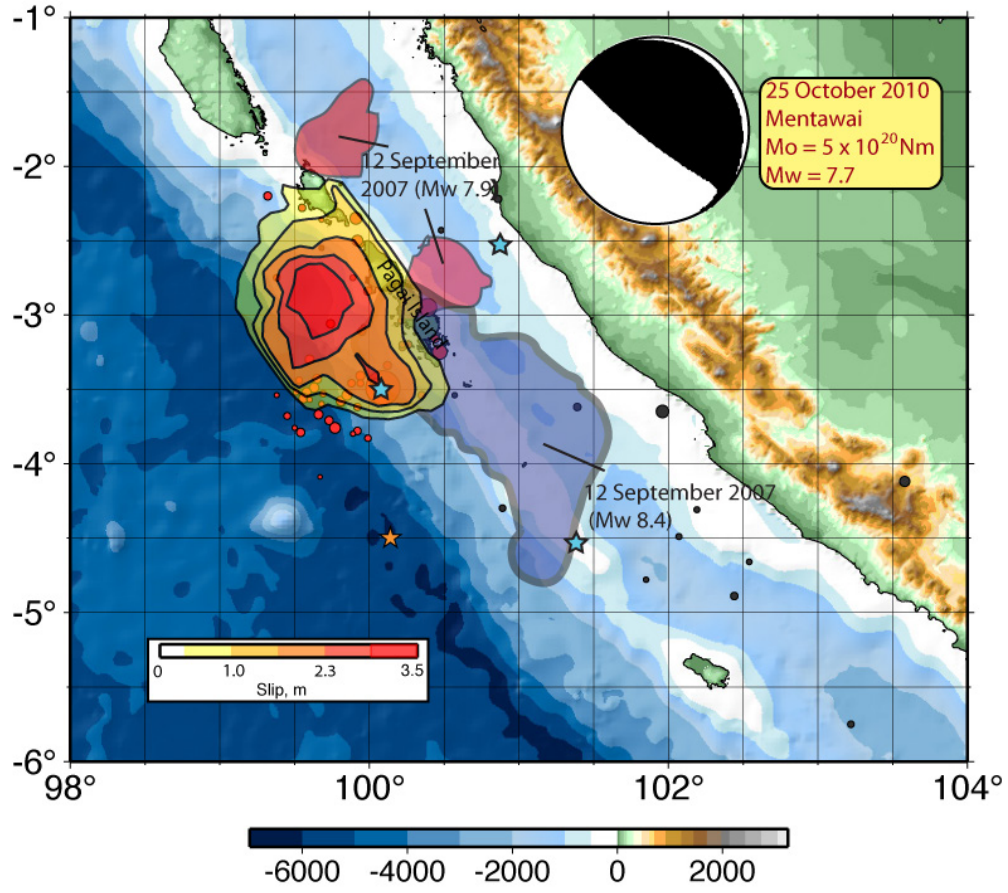
July 2006 – Java tsunami earthquake. 7.8

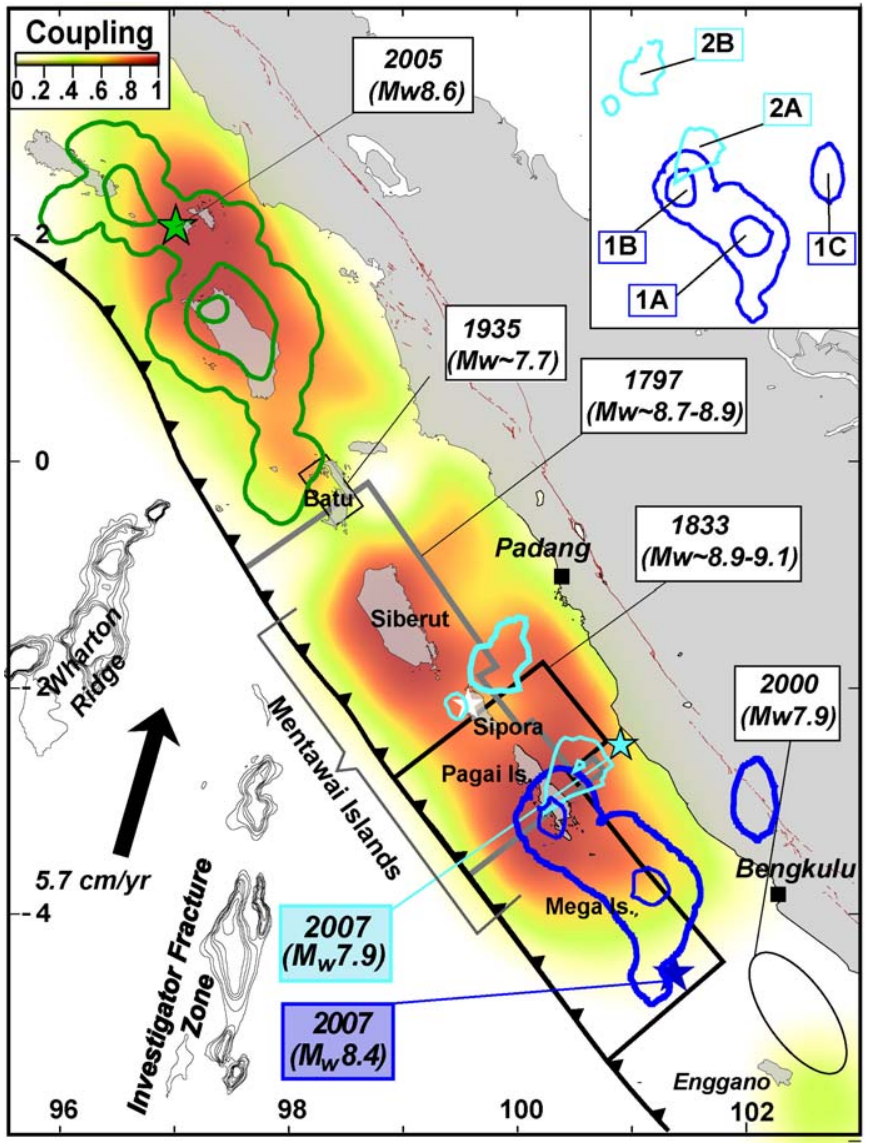
Sept. 2007 – Kepulauan pair. 8.5, 7.9

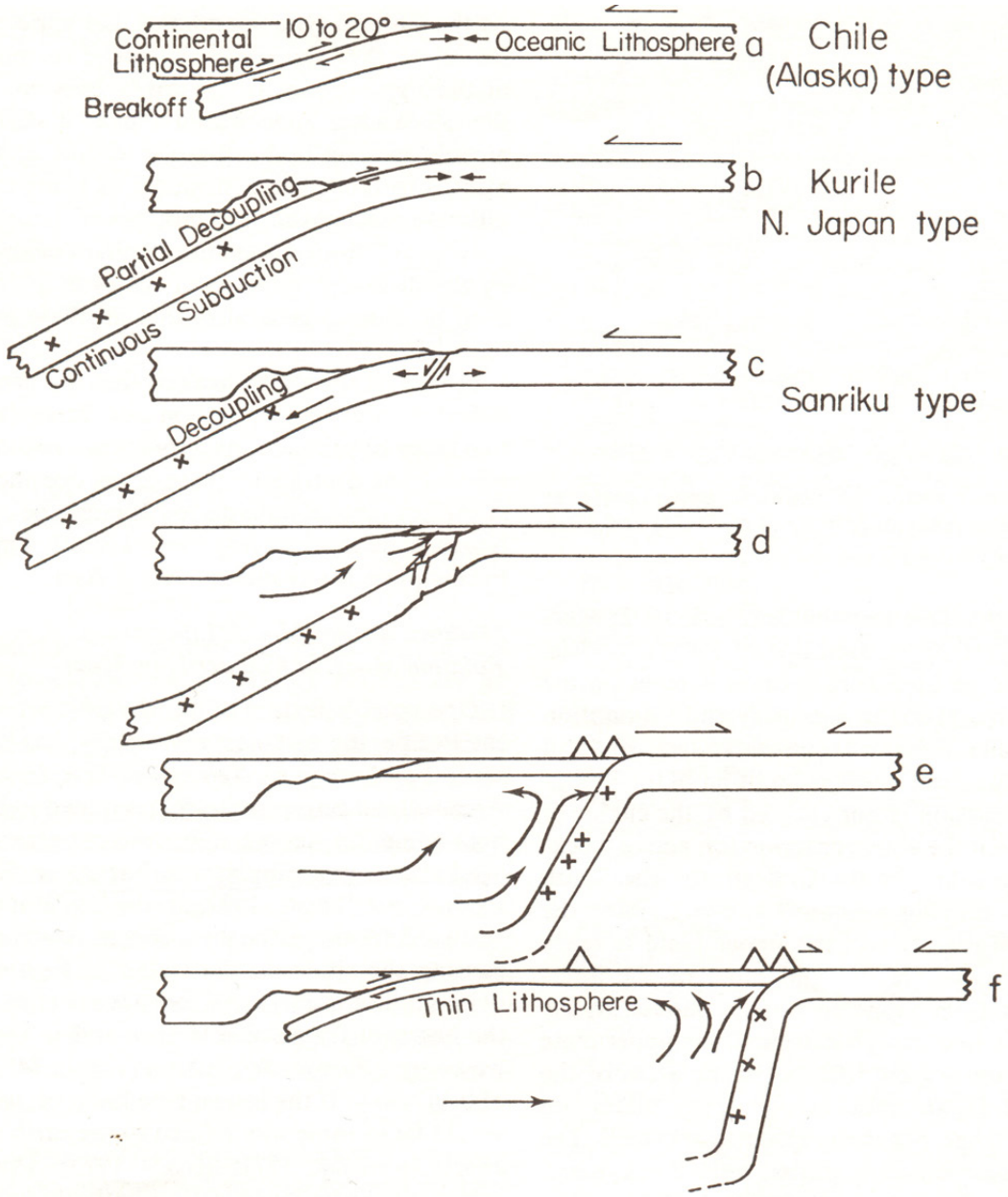
Oct. 2010 – Mentawai tsunami earthquake. 7.8

Akin to Alaska-Aleutians 1946, 1957, 1964, 1965

Where is next one? Sumba trigger potential? 1797 'gap'? Sumatran Fault?


25 October 2010
Mentawai
Mo = 5 x 10^20 Nm
Mw = 7.7
12 September
2007 (Mw 7.9)
Pagai Island
12 September 2007
(Mw 8.4)
0 1.0 2.3 3.5
Slip, m
-1°
-2°
-3°
-4°
-5°
-6°
98°
100°
102°
104°
-6000 -4000 -2000 0 2000


Coupling
0 .2 .4 .6 .8 1
2005
(Mw8.6)
2B
2A
1B
1C
1A
1935
(Mw~7.7)
1797
(Mw~8.7-8.9)
1833
(Mw~8.9-9.1)
2000
(Mw7.9)
Batu
Padang
Siberut
Sipora
Pagai Is.
Mega Is.
Bengkulu
Enggano
Wharton
Ridge
Mentawai Islands
5.7 cm/yr
Investigator Fracture
Zone
2007
(Mw7.9)
2007
(Mw8.4)
2
0
-4
96
98
100
102

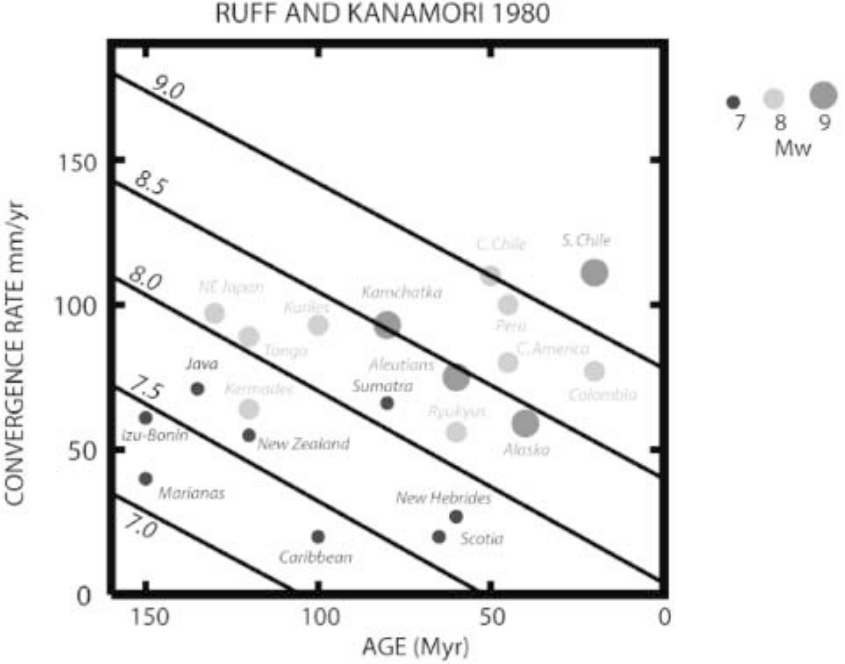


Uyeda and Kanamori, 1979

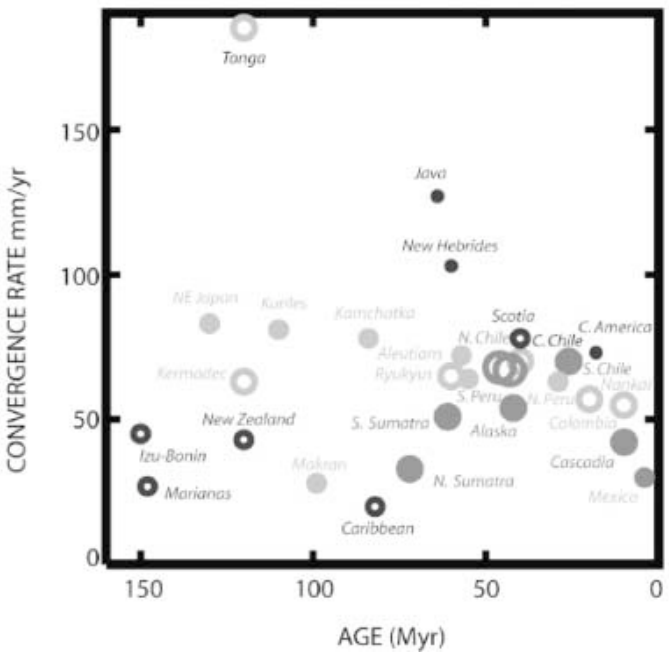
Subduction zone spectrum of 'stages' of evolution

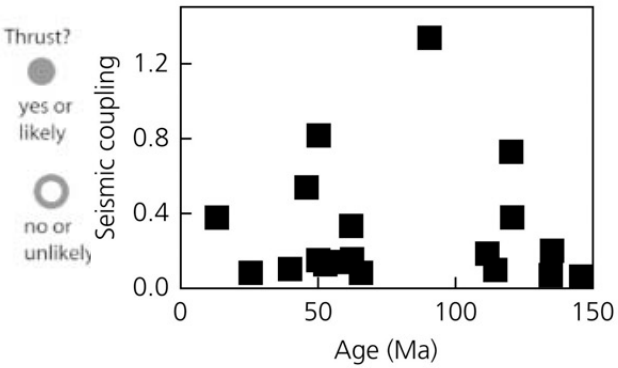
Degree of mechanical Coupling on megathrust Reflects earthquake Size to first order.

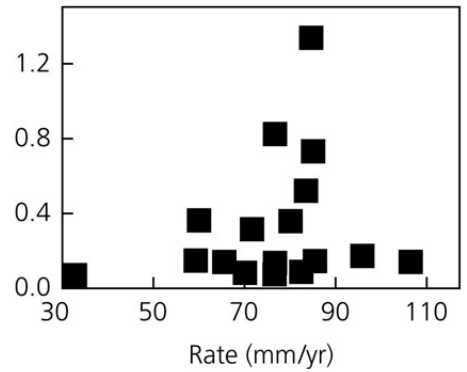
This motivated efforts in 'Comparative Subductology'



‘Comparative Subductology’, once quite promising, now appears to be too limited for defining kinematic and structural controls on maximum earthquake size in different regions.



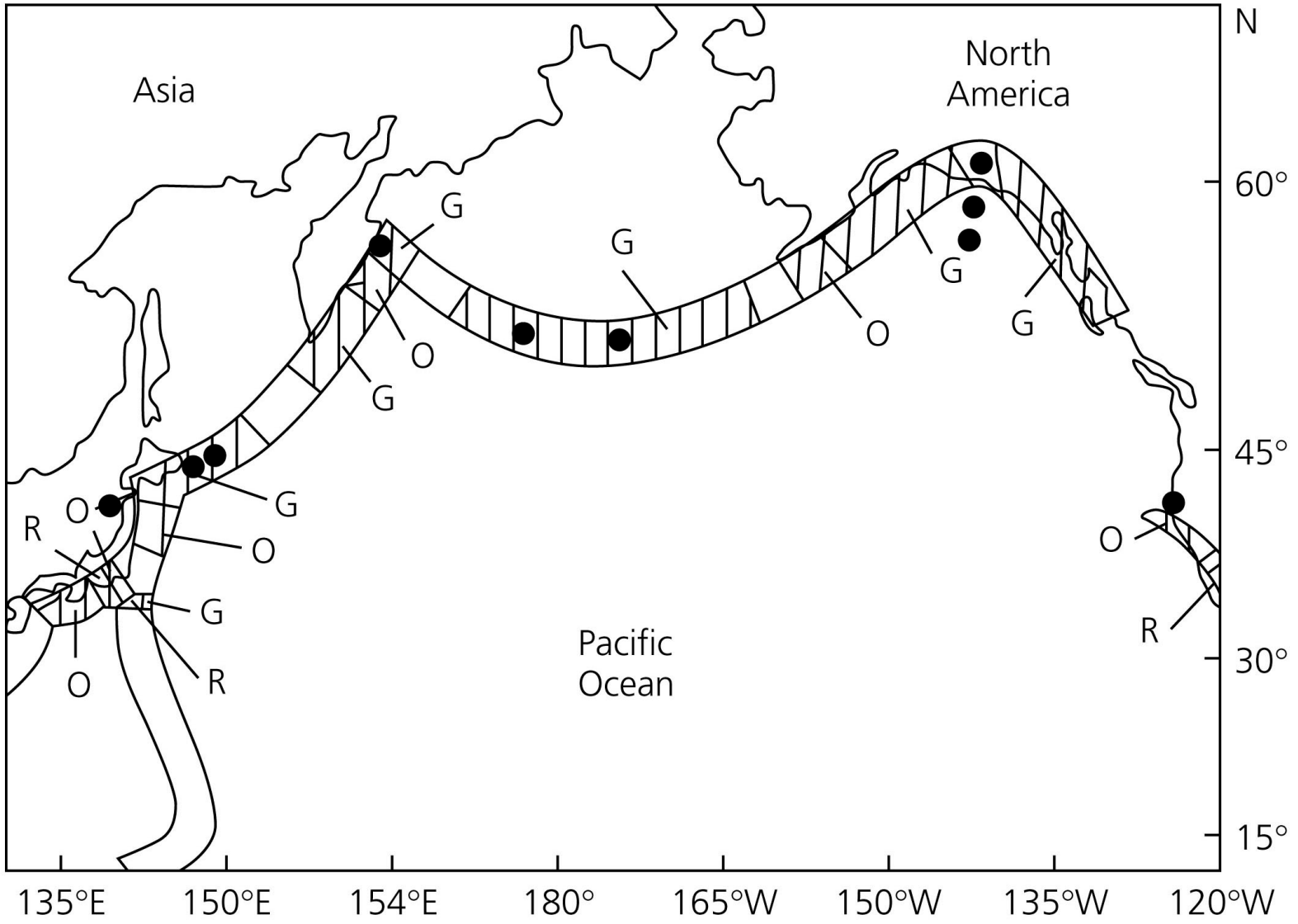




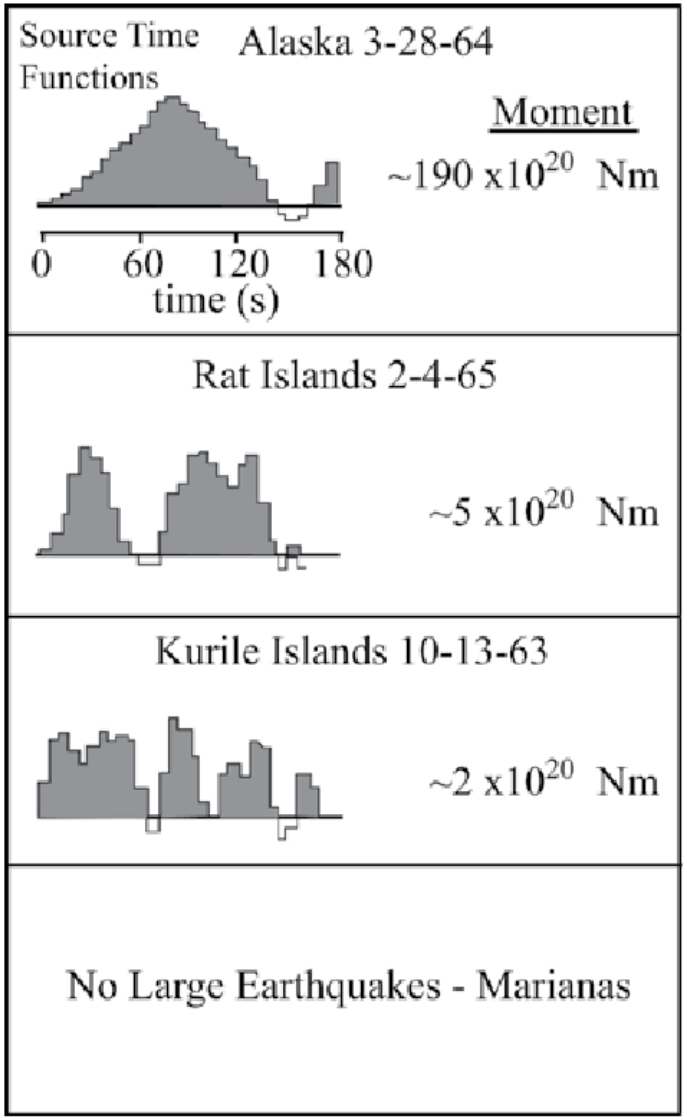
Pacheco et al., 1993

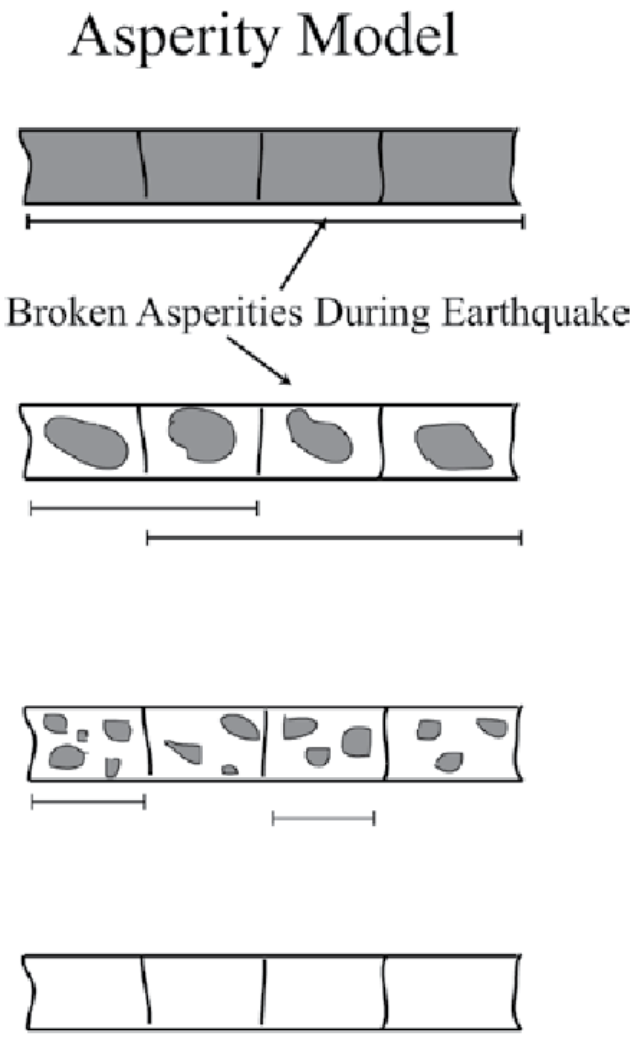
Stein and Okal, 2007

Simple ‘seismic gap’ ideas have been criticized;
perhaps more nuanced notions called for



Earthquake Rupture characteristics can define regional 'behavior', or tendencies





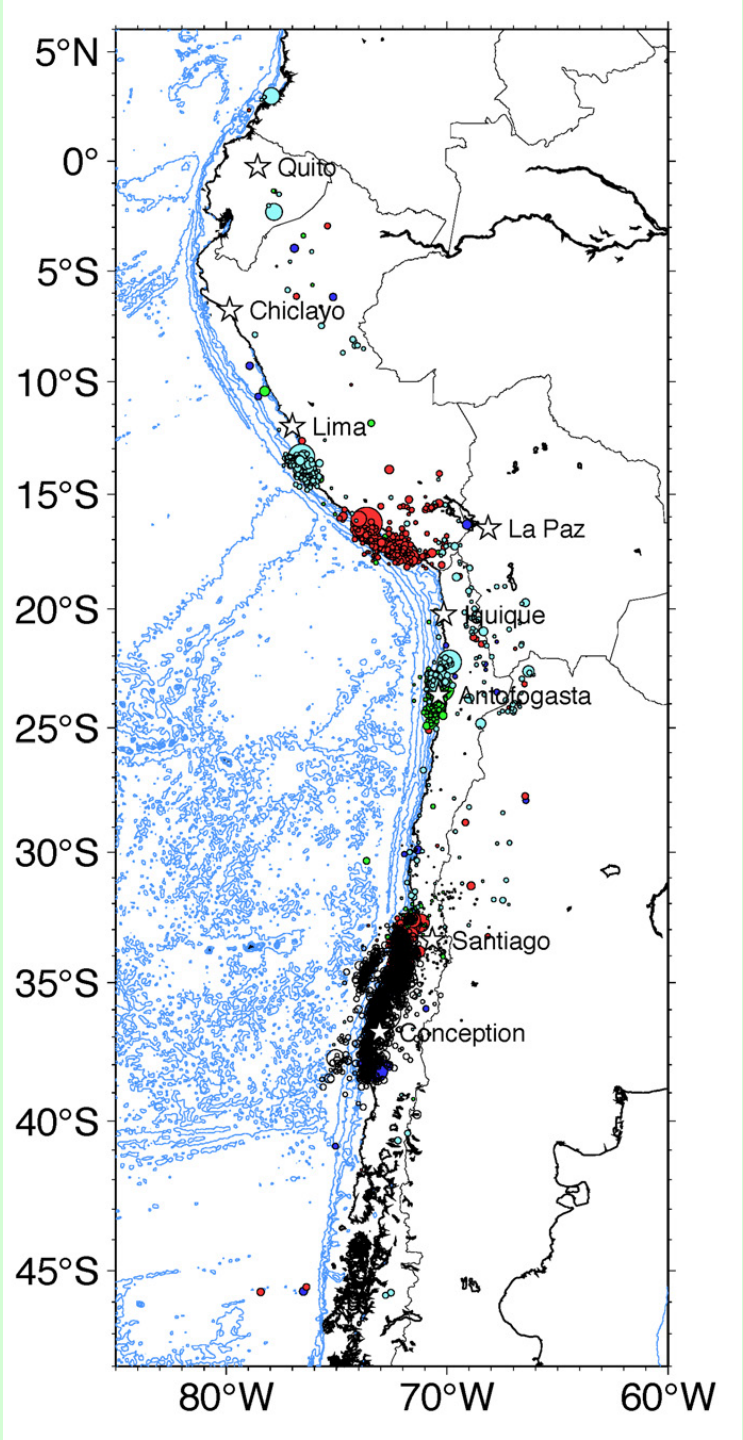
Ruff and Kanamori, 1983

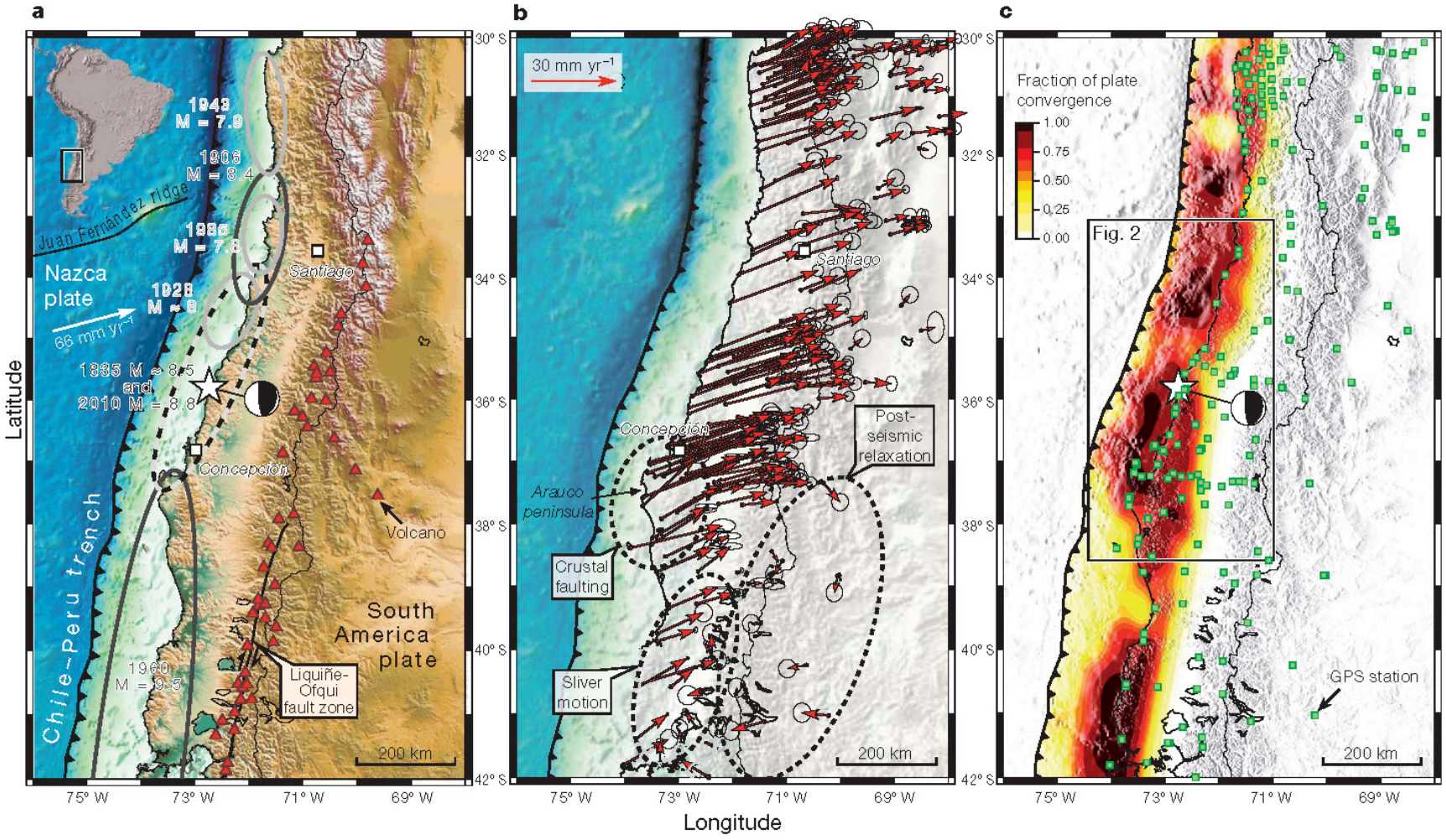
Lay and Kanamori, 1981

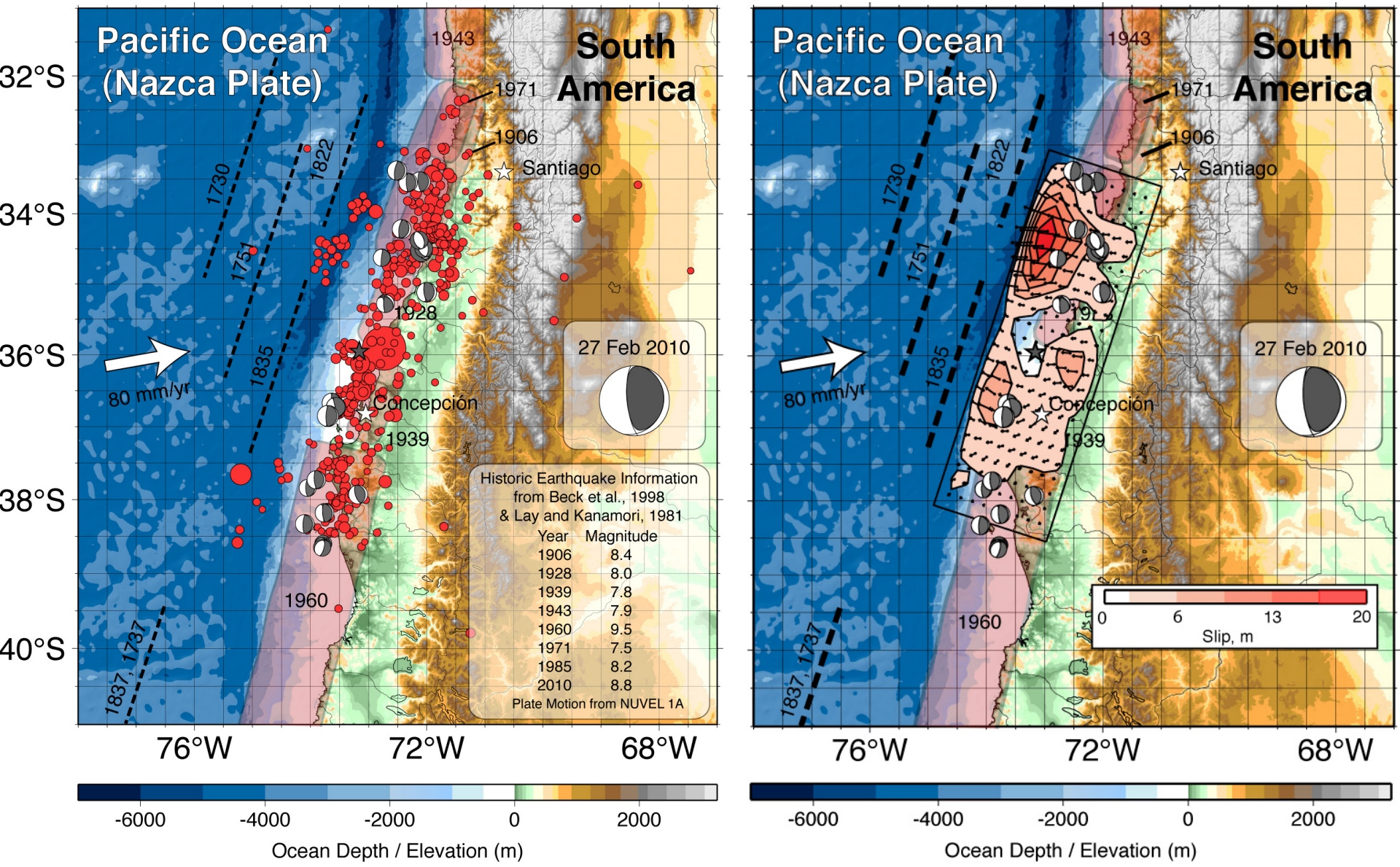
S. America, recently struck by the
2001 Peru 8.4
2007 Antofagasta 7.7
2007 Peru 8.0
2010 Chile 8.8

What is next?

Is this going to be like Sumatra?




a
b
c
1943
M = 7.9
1906
M = 8.4
1985
M = 7.8
1928
M ~ 8
1835 M ~ 8.5
and
2010 M = 8.8
1960
M = 9.5
Juan Fernández ridge
Nazca
plate
66 mm yr⁻¹
Chile–Peru trench
South
America
plate
Santiago
Concepción
Volcano
Liquiñe-
Ofqui
fault zone
200 km
Latitude
30° S
32° S
34° S
36° S
38° S
40° S
42° S
75° W
73° W
71° W
69° W
30 mm yr⁻¹
Arauco
peninsula
Crustal
faulting
Sliver
motion
Post-
seismic
relaxation
Longitude
Fraction of plate
convergence
1.00
0.75
0.50
0.25
0.00
Fig. 2
GPS station

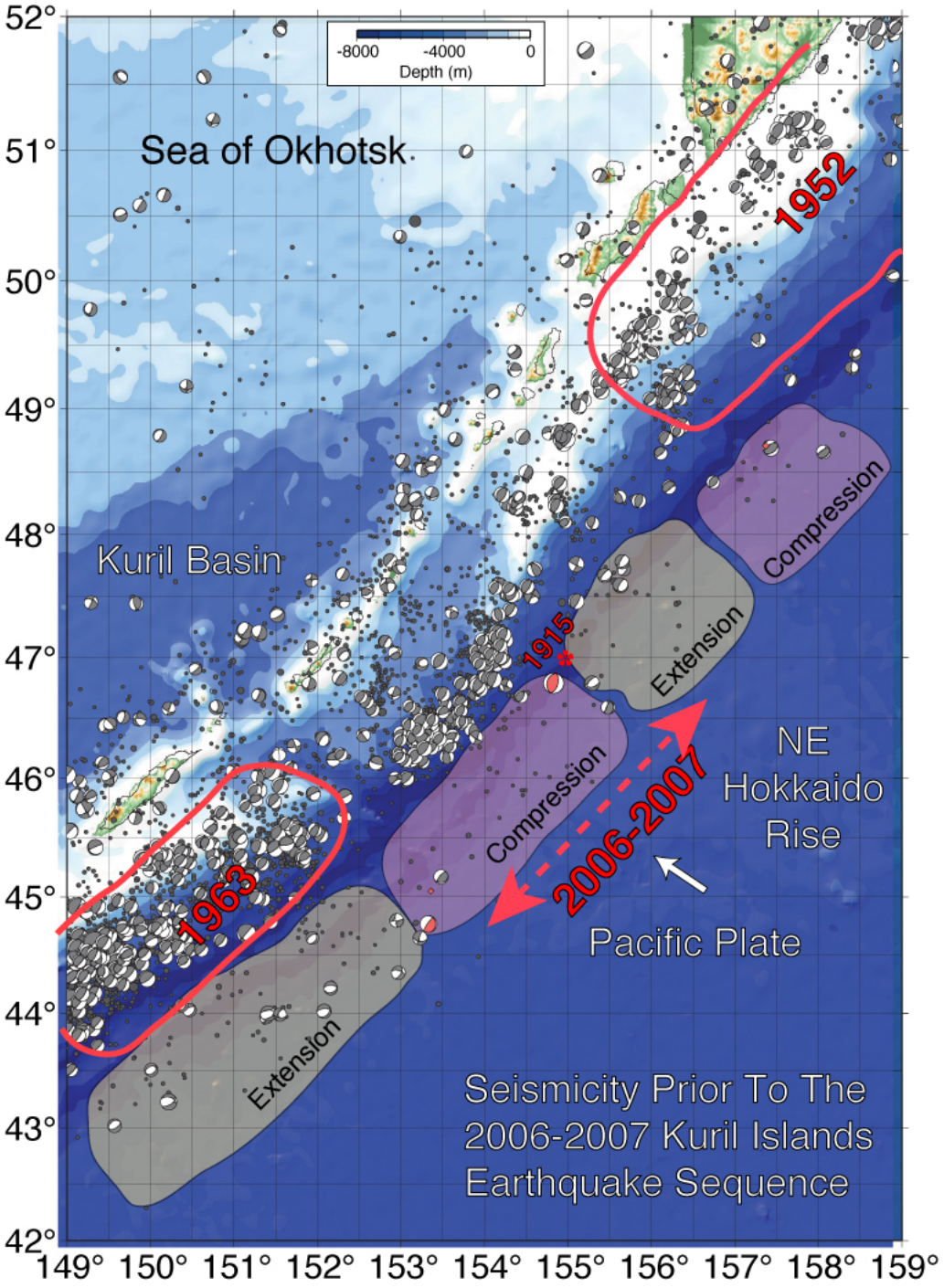

Pacific Ocean
(Nazca Plate)
South
America
1943
1971
1906
Santiago
1730
1822
1751
1928
1835
80 mm/yr
Concepción
1939
1960
1837, 1787
27 Feb 2010
Historic Earthquake Information
from Beck et al., 1998
& Lay and Kanamori, 1981
Year Magnitude
1906 8.4
1928 8.0
1939 7.8
1943 7.9
1960 9.5
1971 7.5
1985 8.2
2010 8.8
Plate Motion from NUVEL 1A
32°S
34°S
36°S
38°S
40°S
76°W
72°W
68°W
-6000
-4000
-2000
0
2000
Ocean Depth / Elevation (m)
Pacific Ocean
(Nazca Plate)
South
America
1943
1971
1906
Santiago
1730
1822
1751
1835
80 mm/yr
Concepción
1939
1960
1837, 1787
27 Feb 2010
0
6
13
20
Slip, m
76°W
72°W
68°W
-6000
-4000
-2000
0
2000
Ocean Depth / Elevation (m)

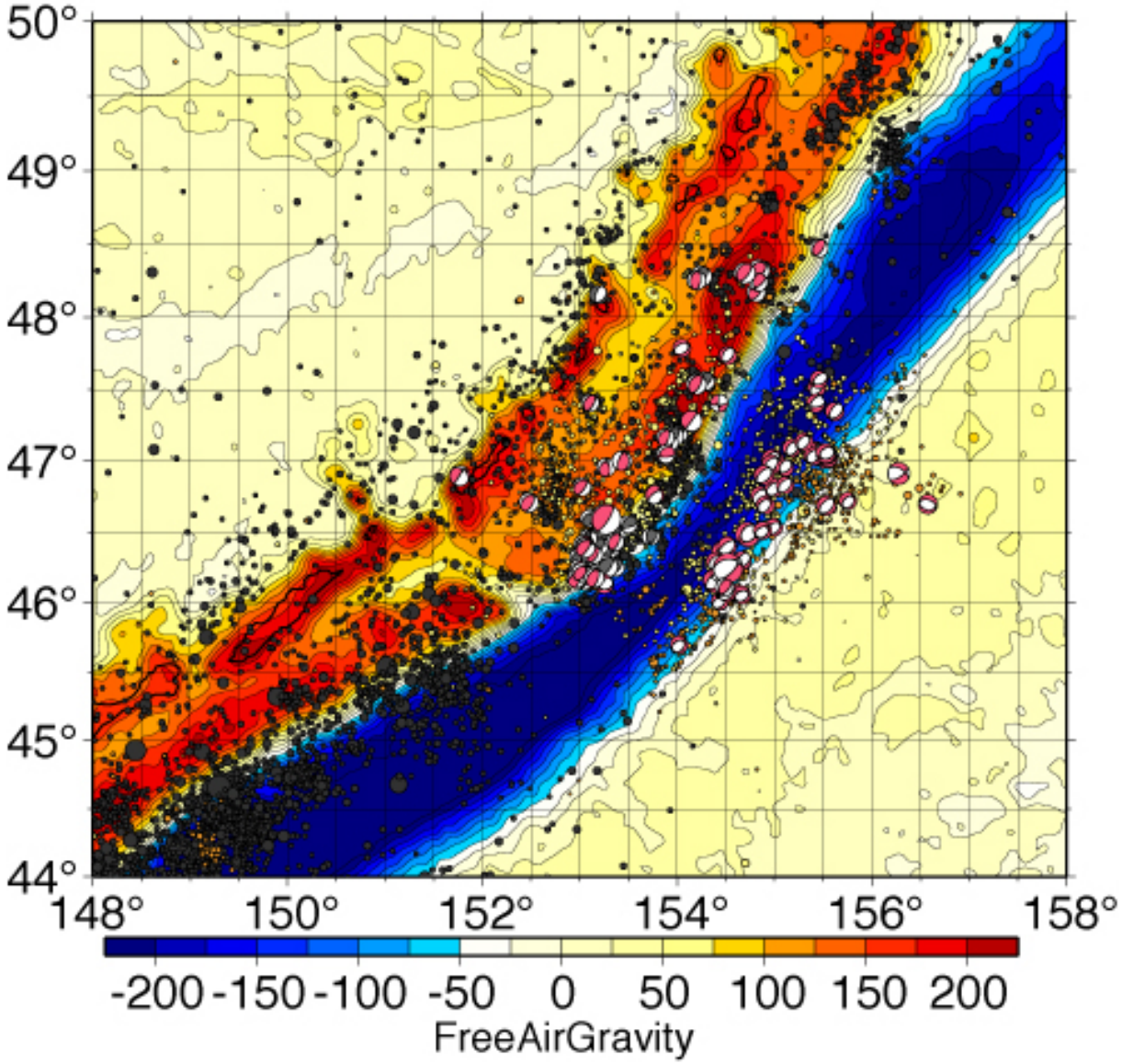
The doublet occurred
in the Central Kuril
Islands Seismic Gap
between the 1952 and 1963 events

Prior Gap activity:
1915 (outer rise?)

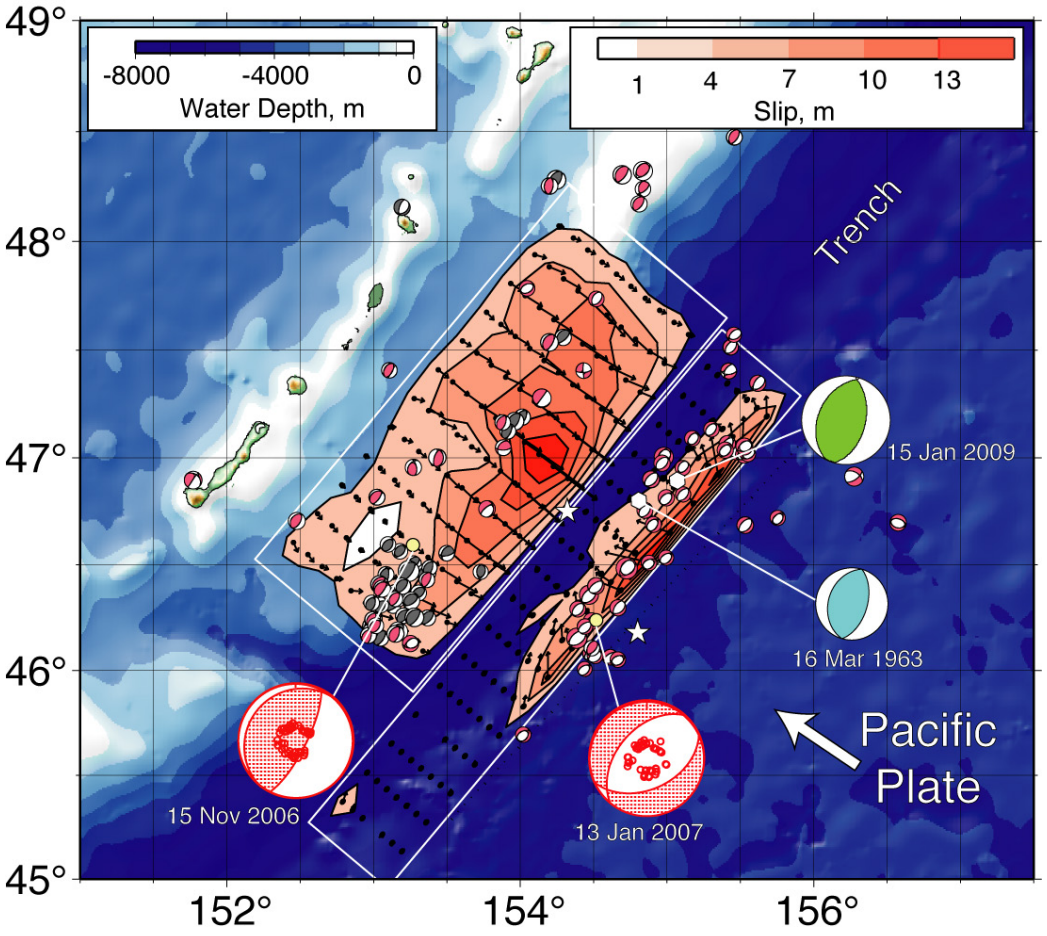
1780 event may have
ruptured southern part of gap

1963 Large outer rise compression
event

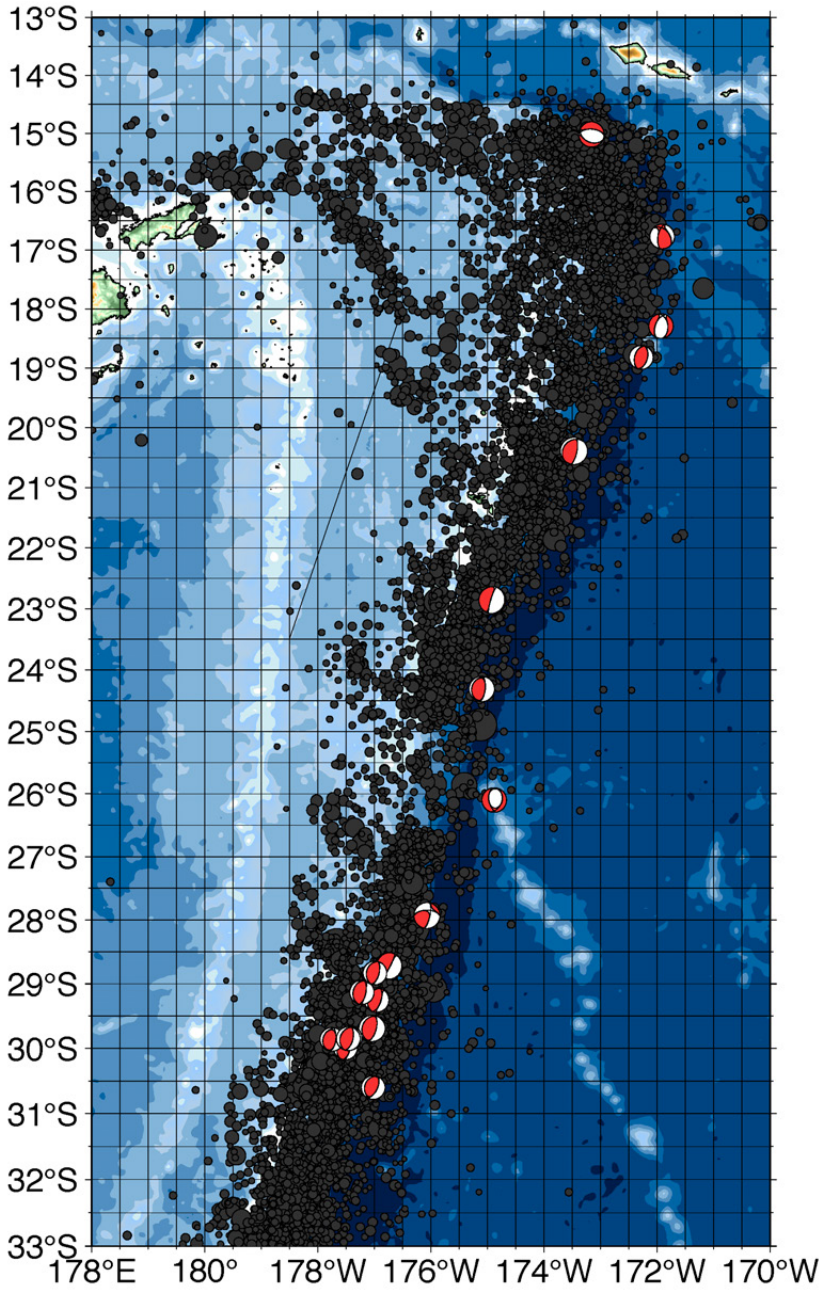



50°
49°
48°
47°
46°
45°
44°
148°
150°
152°
154°
156°
158°
-200 -150 -100 -50 0 50 100 150 200
FreeAirGravity

2007 Kuril event occurred after a large thrust. Outer rise stress cycled from compressional to extensional to compressional



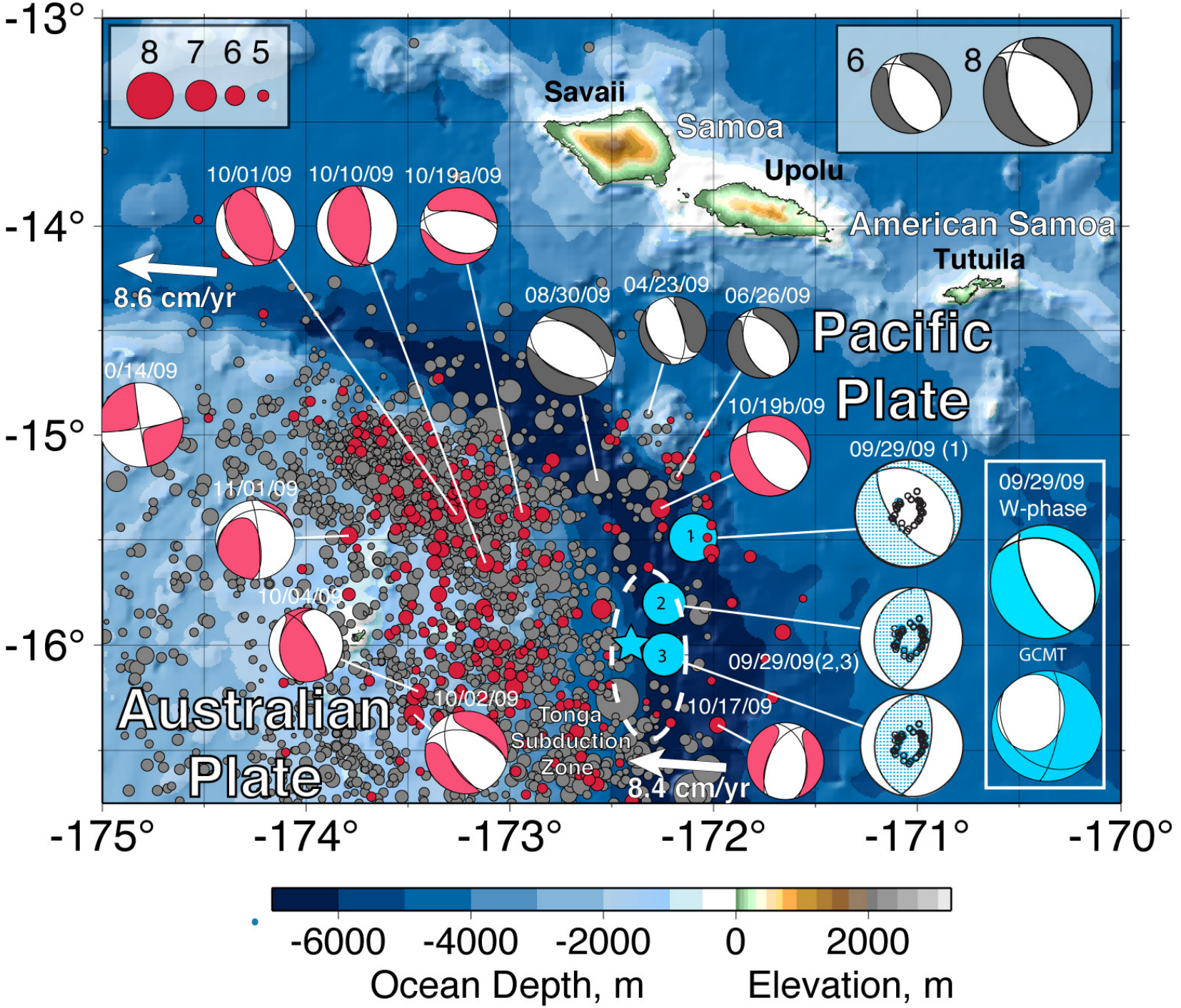
Lay et al., JGR (2009)

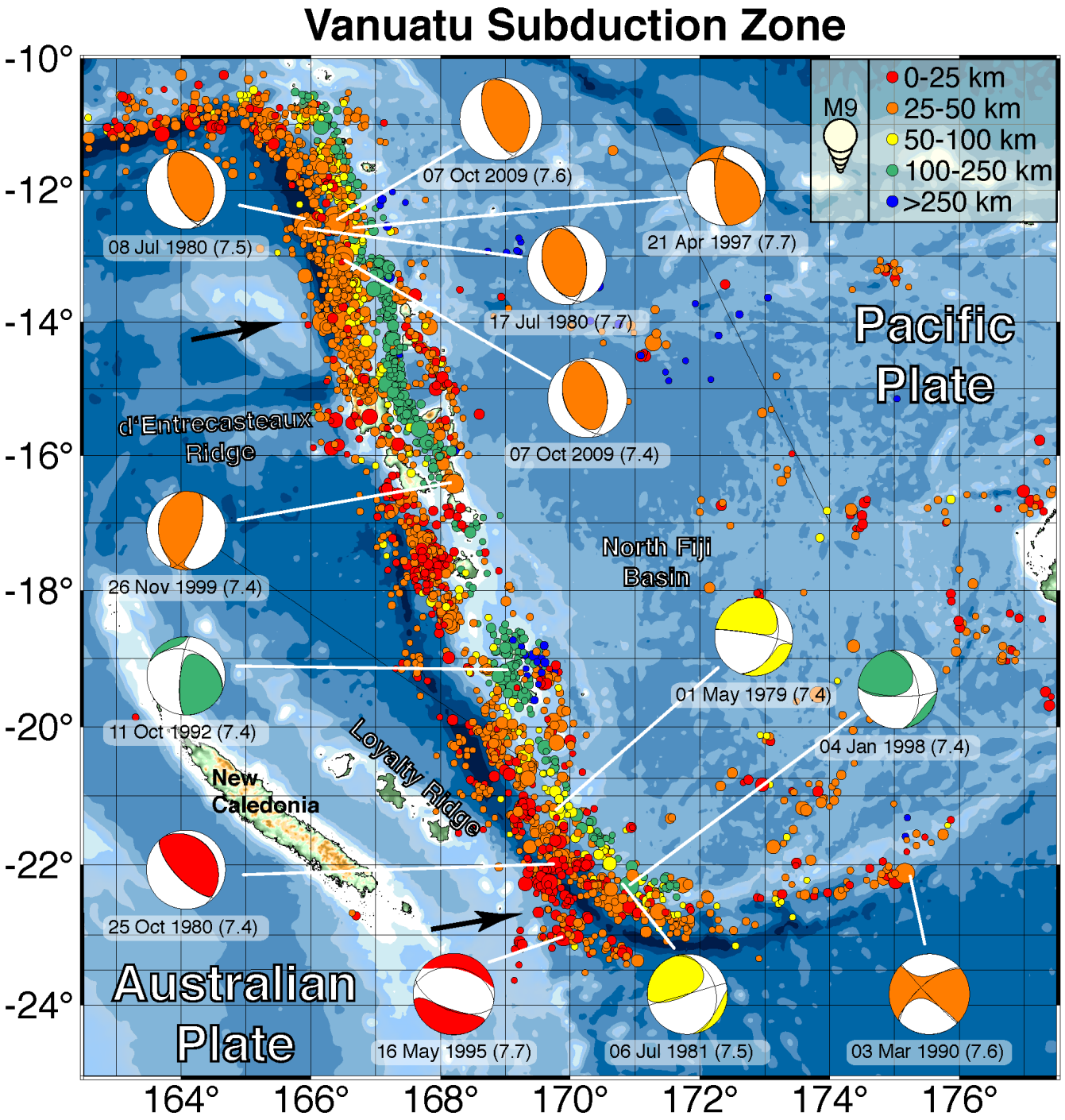


What controls earthquake size in regions with low seismic coupling? Tonga region has very high seismicity rates, but very few large underthrusting events. Kermadec has more thrusting events, but not great ruptures.

N. Island New Zealand has frequent slow slip events.

Tonga has the highest convergence rate in the world; how is is accomodated; SSEs?, ETS? Stable sliding?

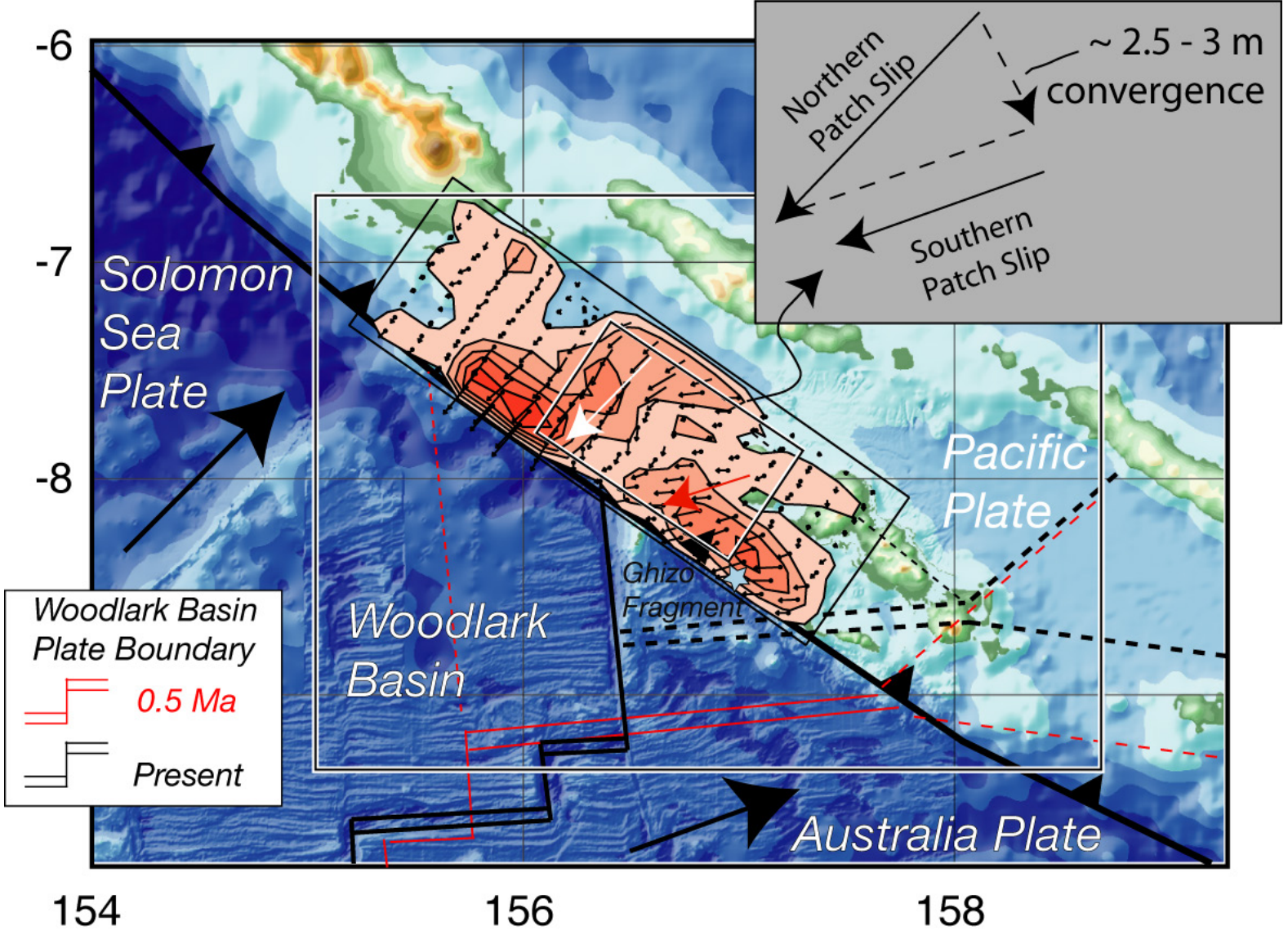

8 7 6 5
6
8
Savaii
Samoa
Upolu
American Samoa
Tutuila
10/01/09
10/10/09
10/19a/09
8.6 cm/yr
08/30/09
04/23/09
06/26/09
Pacific Plate
0/14/09
10/19b/09
09/29/09 (1)
09/29/09 W-phase
11/01/09
1
2
3
10/04/09
09/29/09(2,3)
GCMT
10/02/09
10/17/09
Tonga Subduction Zone
Australian Plate
8.4 cm/yr
-13°
-14°
-15°
-16°
-175°
-174°
-173°
-172°
-171°
-170°
-6000
-4000
-2000
0
2000
Ocean Depth, m
Elevation, m



Can Island arc systems support great events? Andaman-Nicobar rupture in 2004 suggests regions can be 'driven' to fail together.

What causes clusters of events like those in Vanuatu and Solomon Islands?

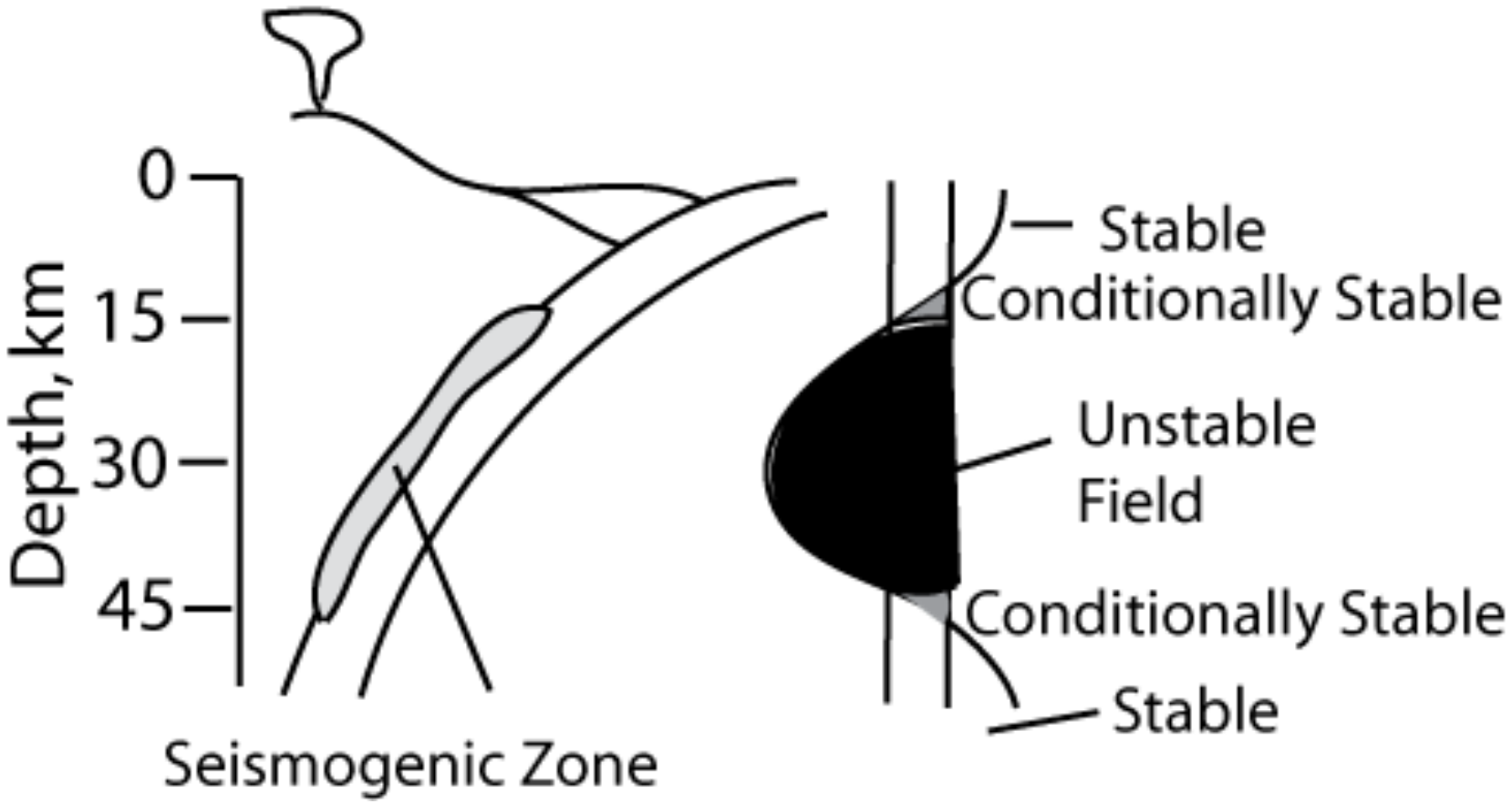
Cleveland et al., 2009

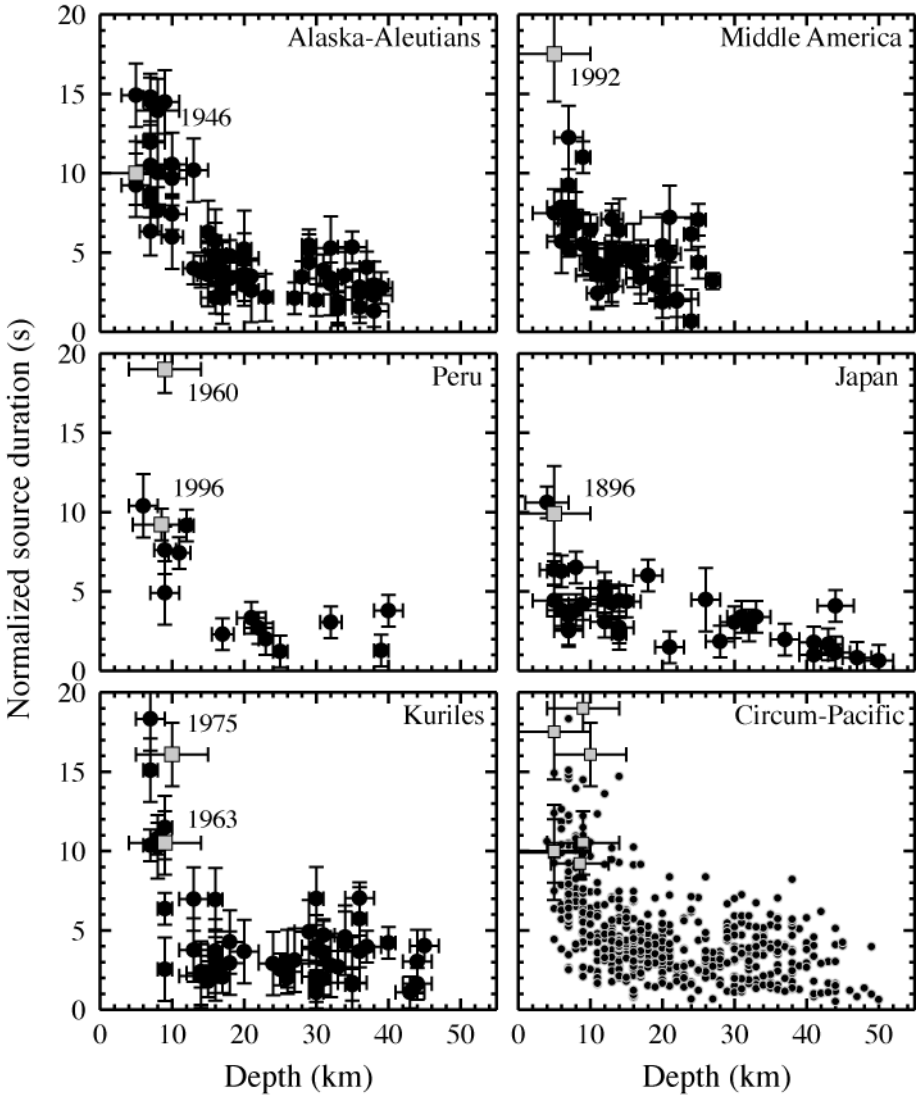


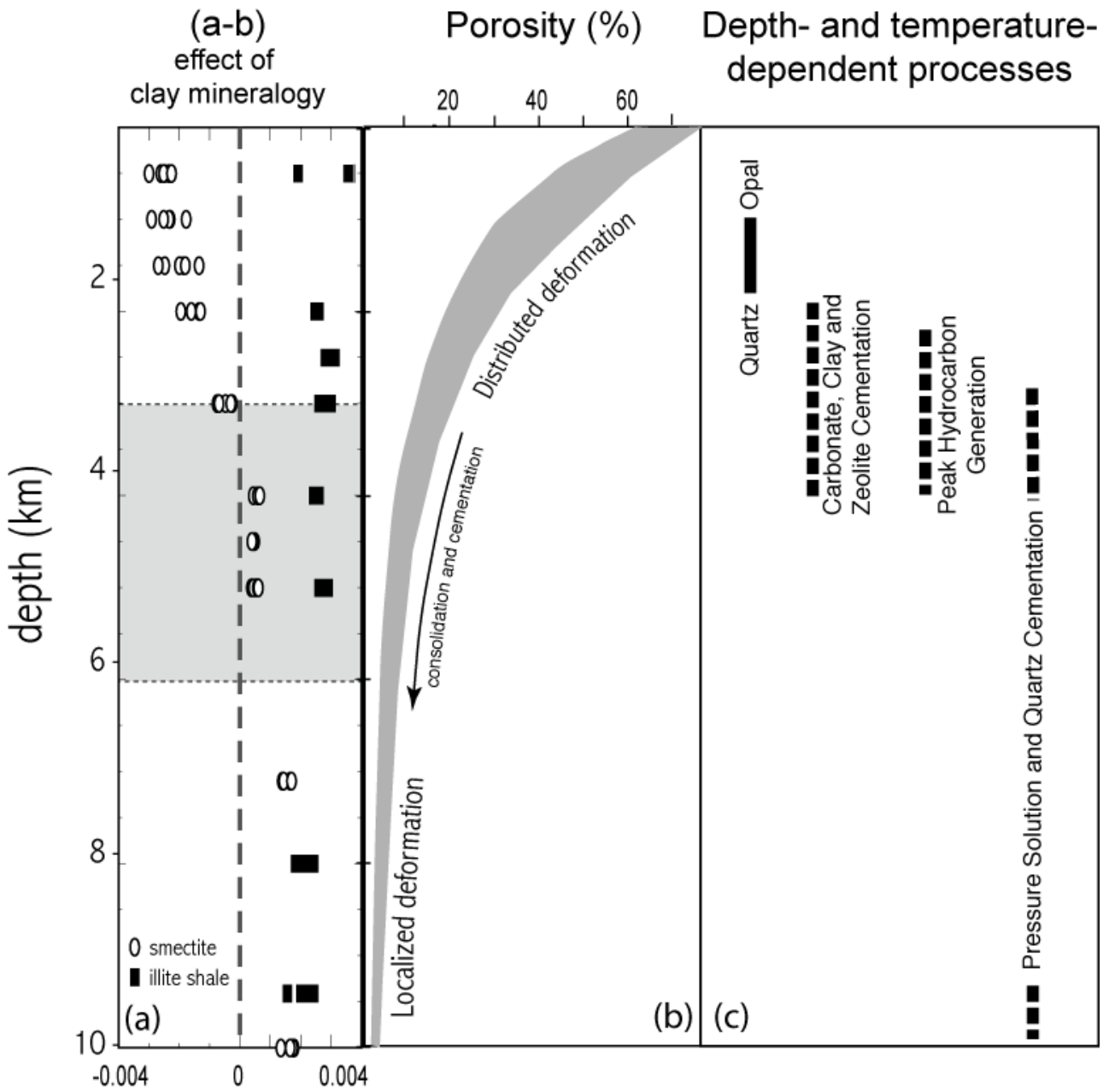
Furlong, Lay, Ammon, Science, 2009

April 1, 2007 Solomon Islands Earthquake Mw=8.1
Rupture of a Triple Junction

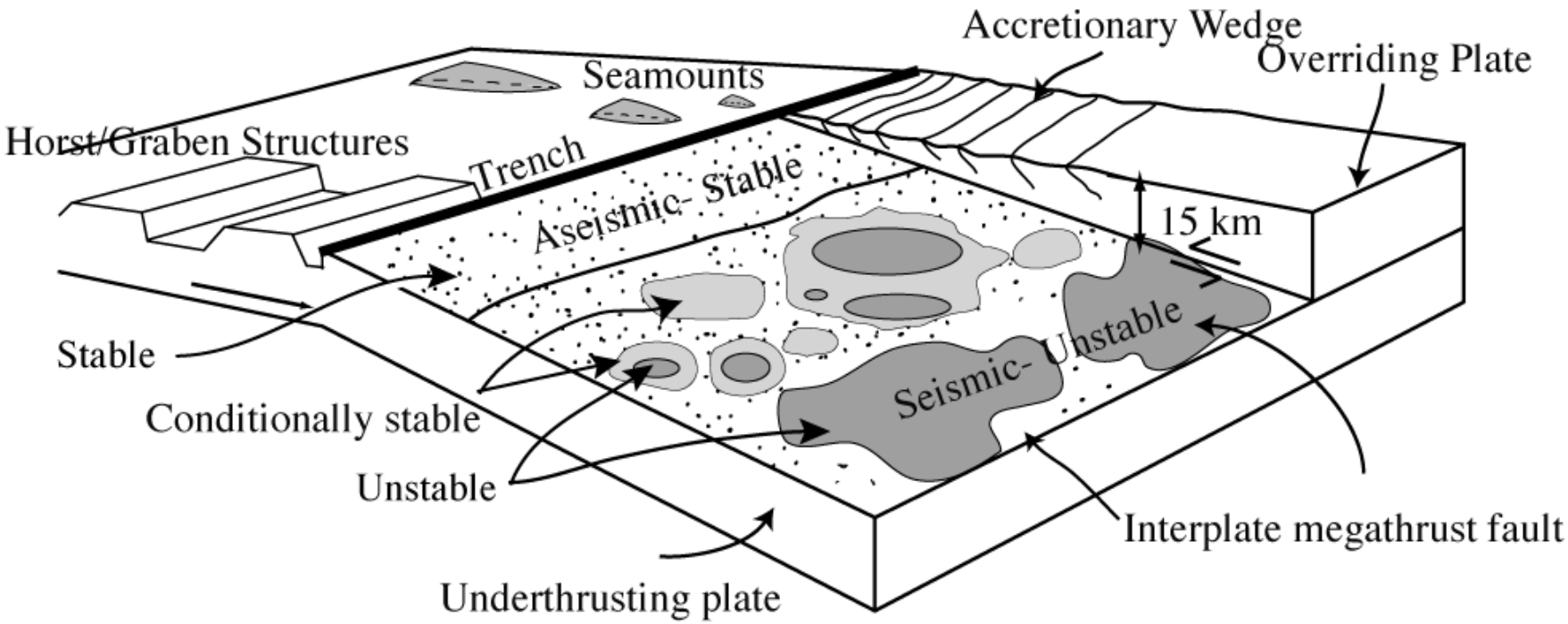
One-Dimensional Model




Alaska-Aleutians
1946
Middle America
1992
Peru
1960
1996
Japan
1896
Kuriles
1975
1963
Circum-Pacific
Normalized source duration (s)
Depth (km)
Depth (km)
0
5
10
15
20
0
10
20
30
40
50

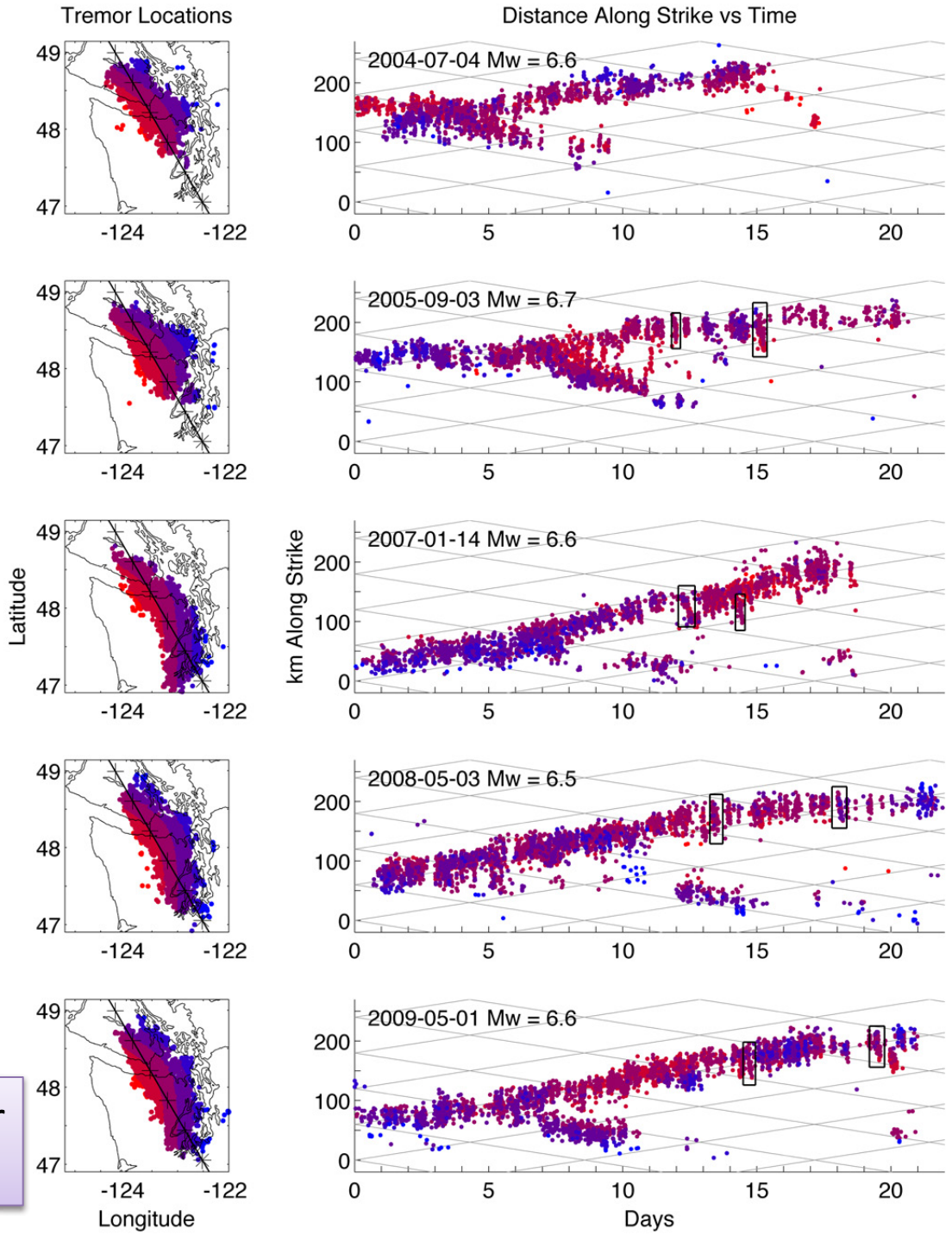

(a-b)
effect of
clay mineralogy
Porosity (%)
20
40
60
Depth- and temperature-
dependent processes
depth (km)
2
4
6
8
10
-0.004
0
0.004
smectite
illite shale
(a)
Distributed deformation
consolidation and cementation
Localized deformation
(b)
(c)
Quartz
Opal
Carbonate, Clay and
Zeolite Cementation
Peak Hydrocarbon
Generation
Pressure Solution and Quartz Cementation

Two-Dimensional Notion Seems More Reasonable



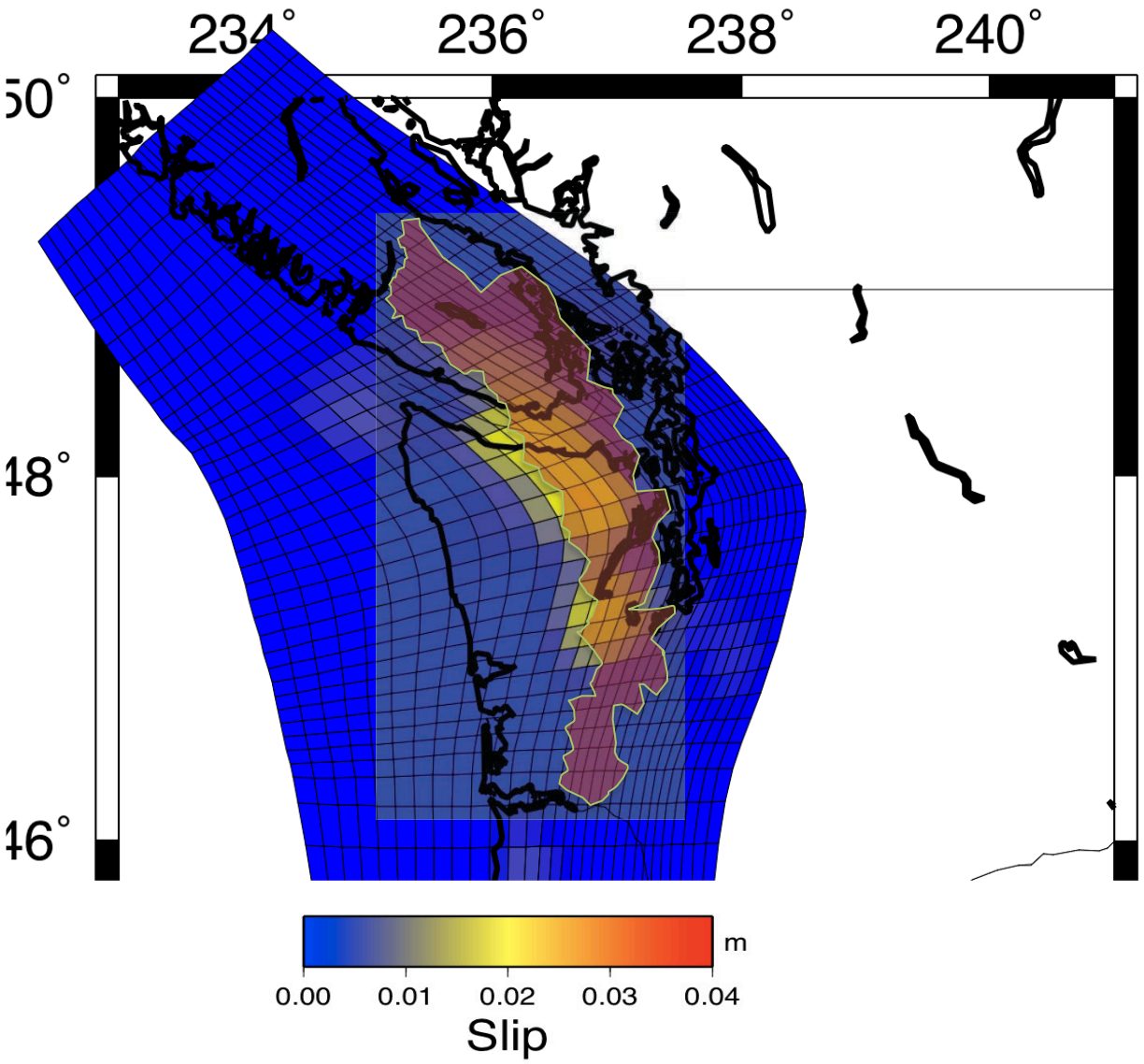
Time vs Distance along strike

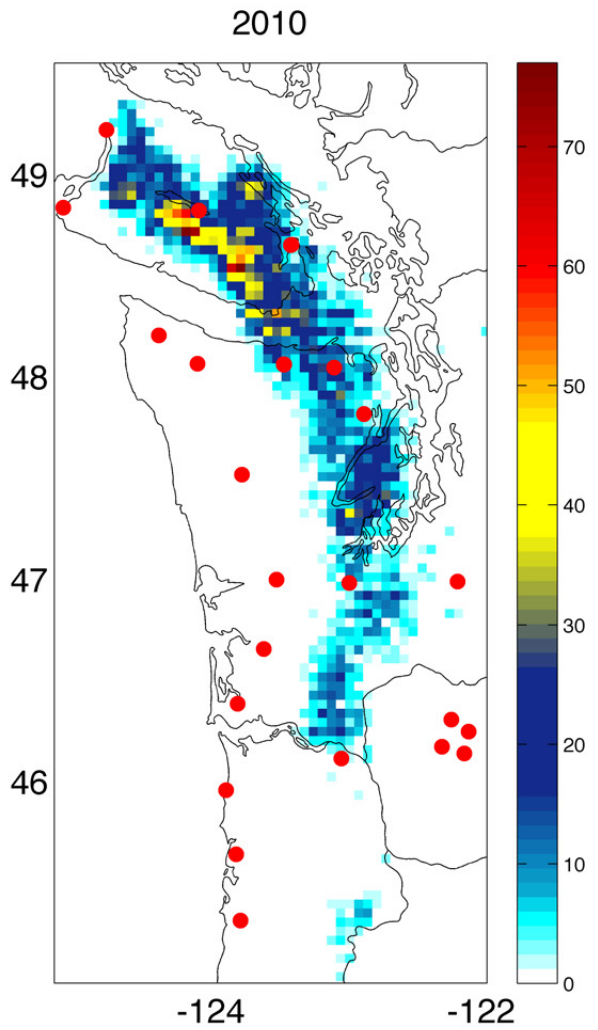
- Along-strike propagation velocity varies
  - 7 to 12 km/day
- General tendency to move updip
  - Wech and Creager
- Originate in 3 places



Houston, Delbridge, Wech, Creager
Nature Geoscience, in revision

Slip extends updip from Tremor?





Melbourne

Similar results from Schmidt and Krogstad

Conclusions – Extensions to Draft Science Plan

Great Earthquake Size/Occurrence also influenced by:

a) Dynamic triggering effects – expand rupture dimensions, trigger conditionally stable regions, rupture beyond seismic 'gaps' (2004 Sumatra, 2007 Solomon Islands, 2009 Samoa, 2009 Vanuatu, 2010 Chile)

b) Short observational history – underestimate seismic potential based on short record (1700 Cascadia, 2004 Sumatra, 2006 Kuril)

c) Characterization of 'asperity' regions useful for short-term hazard assessment, particularly combined with geodetic 'not-slipping' characterization (2010 Mentawai; 2010 Chile)

Recommendations:

a) Study the end-members (aseismic convergence in Marianas/Tonga/Sumba/N. Island, NZ – what processes; S. Peru-Antofagasta locking?; up-dip regions of C. Chile 1985, 2010)

b) Exploit the opportunities provided by recent great events that are well recorded; Sumatra example indicates adjacent regions likely to fail; 1797 Sumatra region, S. Sumatra-Sumba region