Anomalous E_s/M_o Earthquakes: Trends and Exceptions to the Trends

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U.S. Geological Survey

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- What criteria can be used to characterize an earthquake as anomalously energetic (strong) or anomalously enervated (weak).
- Where do anomalously strong or anomalously weak earthquakes occur.
- If they occur non-randomly, what do they tell us about fault characteristics and stress conditions at subduction zones.
- Can patterns of energetic and enervated earthquakes provide guidance on tsunami potential.

Measures of Earthquake Size

Moment is sensitive to displacement:

$$M_o = 4\pi\,(\rho_o \rho_o c_s)^{1/2} c_o^{5/2} \frac{R}{F}\,\bar{u}$$

$$M_W = 2/3 \log M_0 - 6.0$$

Energy is sensitive to velocity:

$$\varepsilon^*_{gP} = \int_0^\infty \dot{u}(t)^2\,dt = \frac{1}{\pi}\int_o^\infty \omega^2 |u|^2\,d\omega$$

$$M_e = 2/3 \log E_S - 2.9$$

Radiated Energy Relative to Earthquake Size

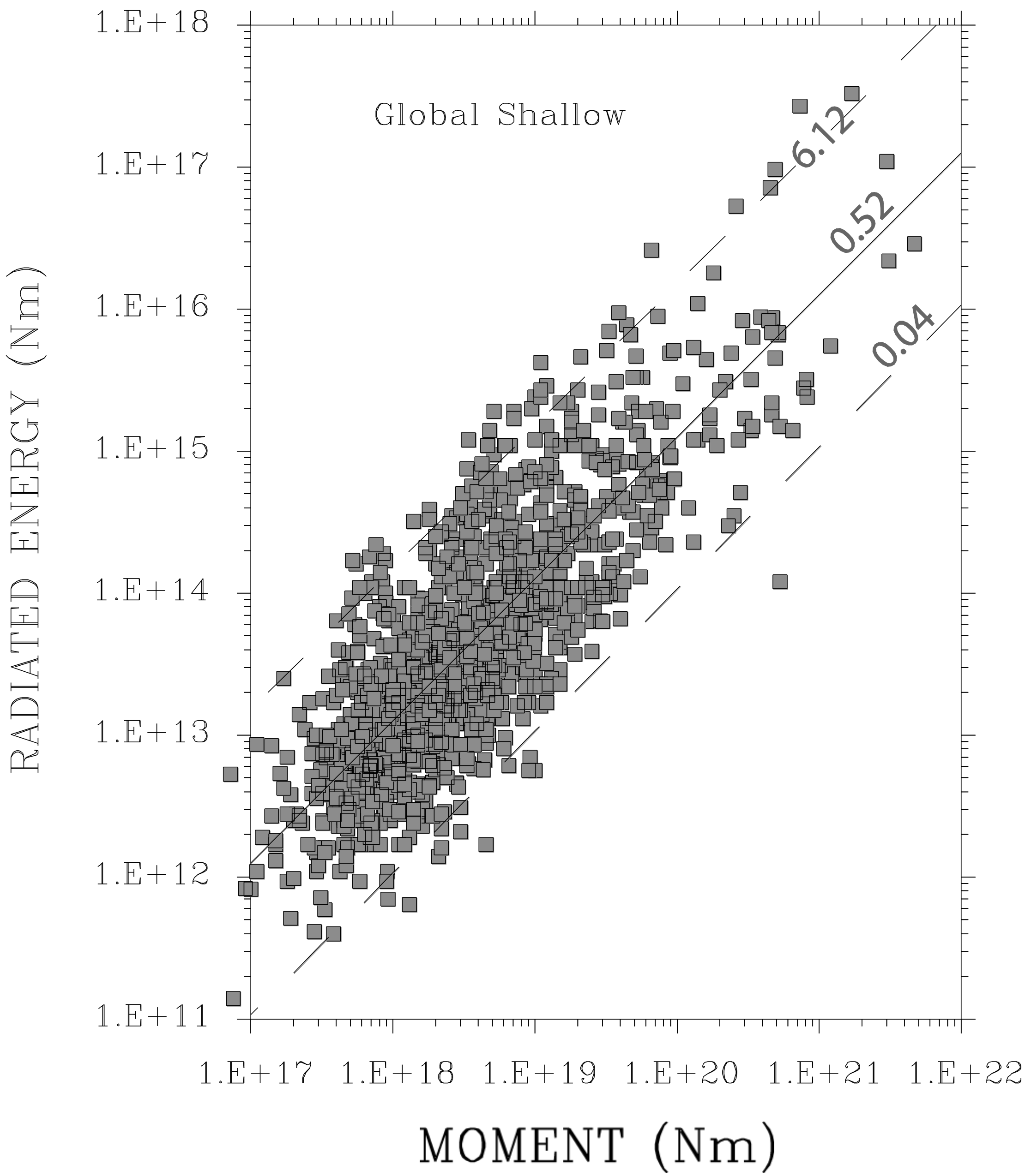
- Apparent stress, $\tau_a = \mu E_S / M_0$
- Scaled energy, E_S / M_0
- Slowness parameter, $\theta = \log(E_S / M_0)$

(Newman & Okal, 1998)

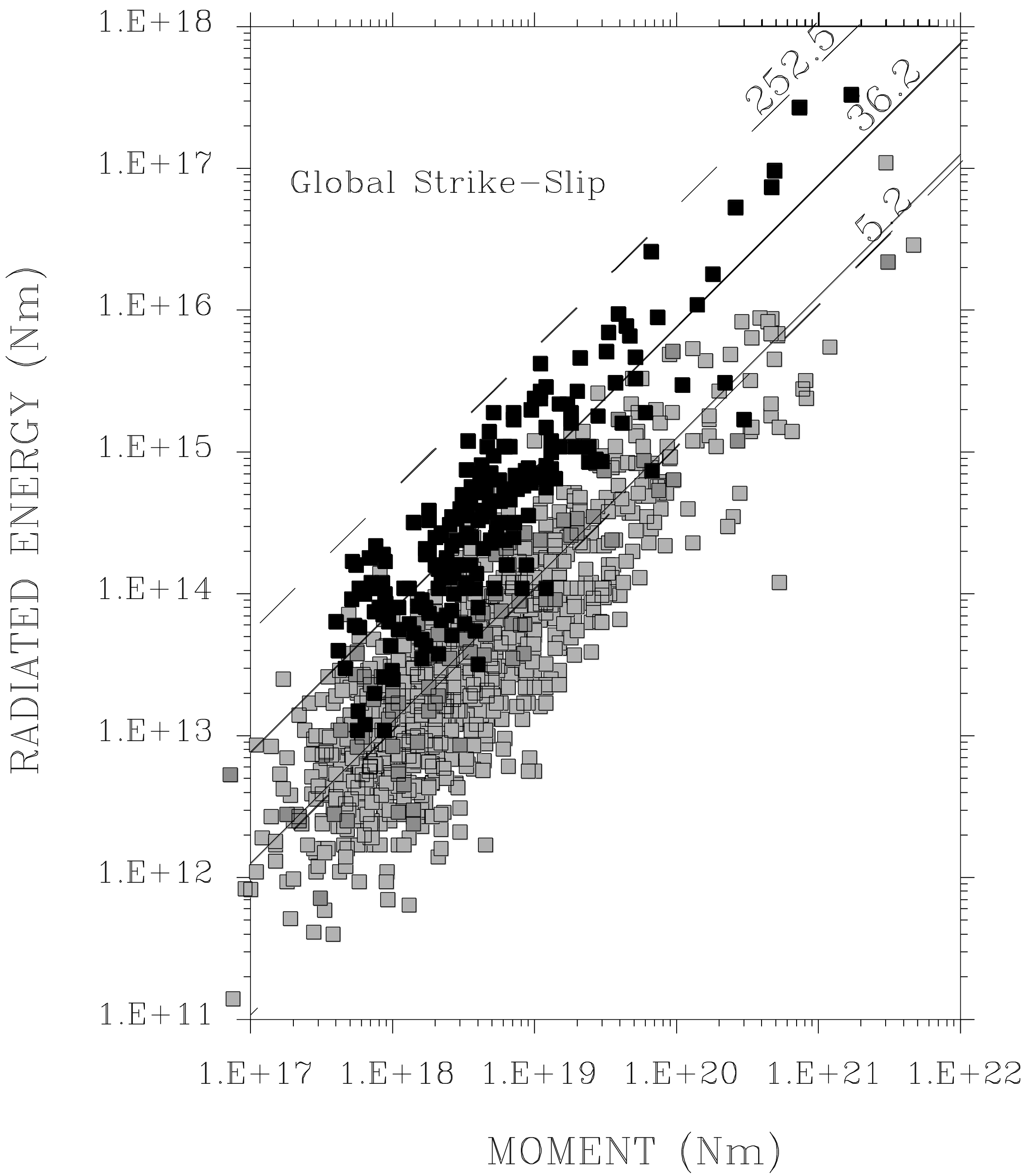
- Differential Magnitude, $\Delta M = M_W - M_e$

(Choy & Kirby, 2004)

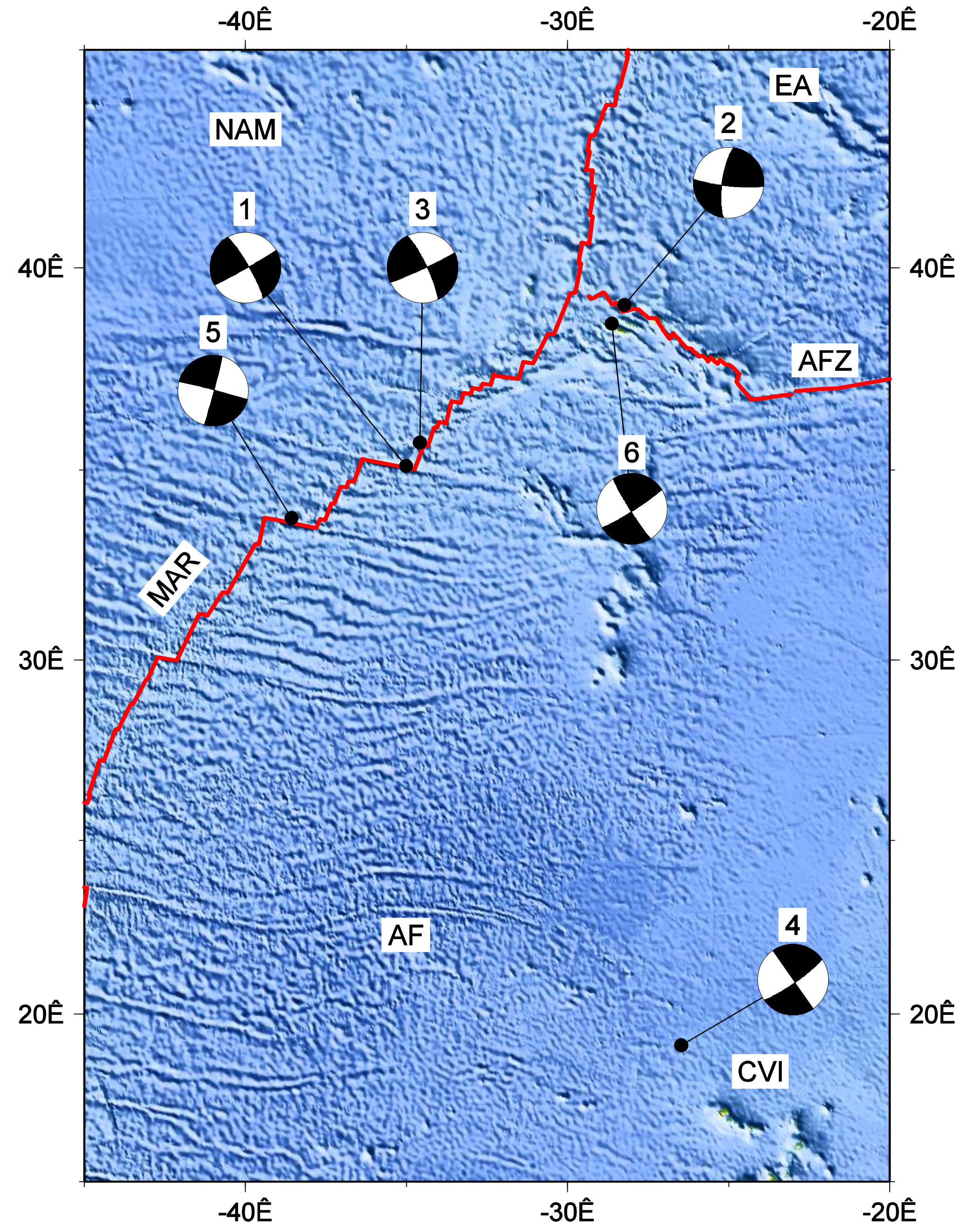
(Note: $\theta < -5.5$, an indicator of tsunami earthquakes equivalent to $\Delta M > 0.5$)



Global Shallow
6.12
0.52
0.04
RADIATED ENERGY (Nm)
1.E+18
1.E+17
1.E+16
1.E+15
1.E+14
1.E+13
1.E+12
1.E+11
1.E+17
1.E+18
1.E+19
1.E+20
1.E+21
1.E+22
MOMENT (Nm)

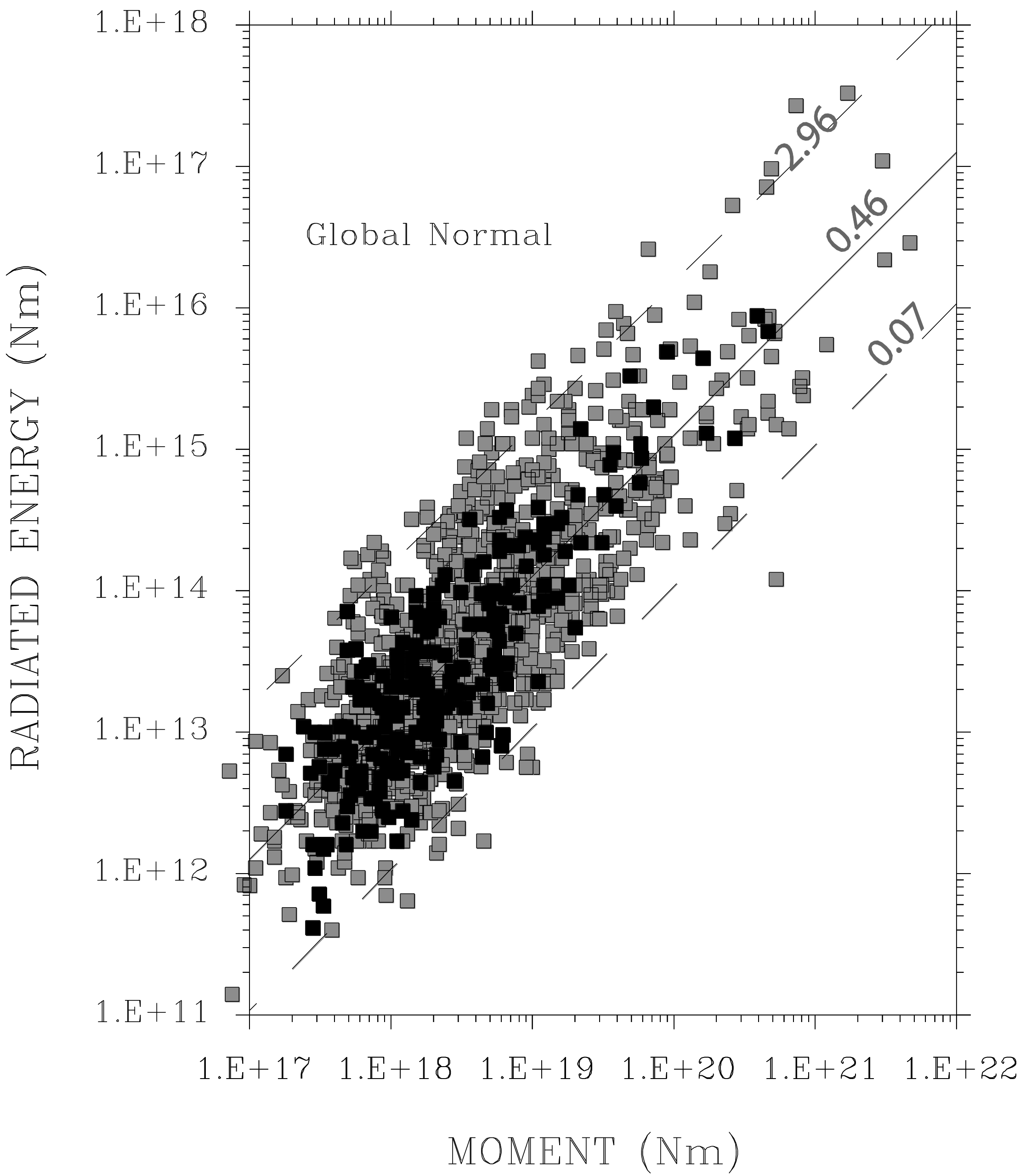


Global Strike-Slip
252.5
36.2
5.2
RADIATED ENERGY (Nm)
1.E+18
1.E+17
1.E+16
1.E+15
1.E+14
1.E+13
1.E+12
1.E+11
1.E+17
1.E+18
1.E+19
1.E+20
1.E+21
1.E+22
MOMENT (Nm)



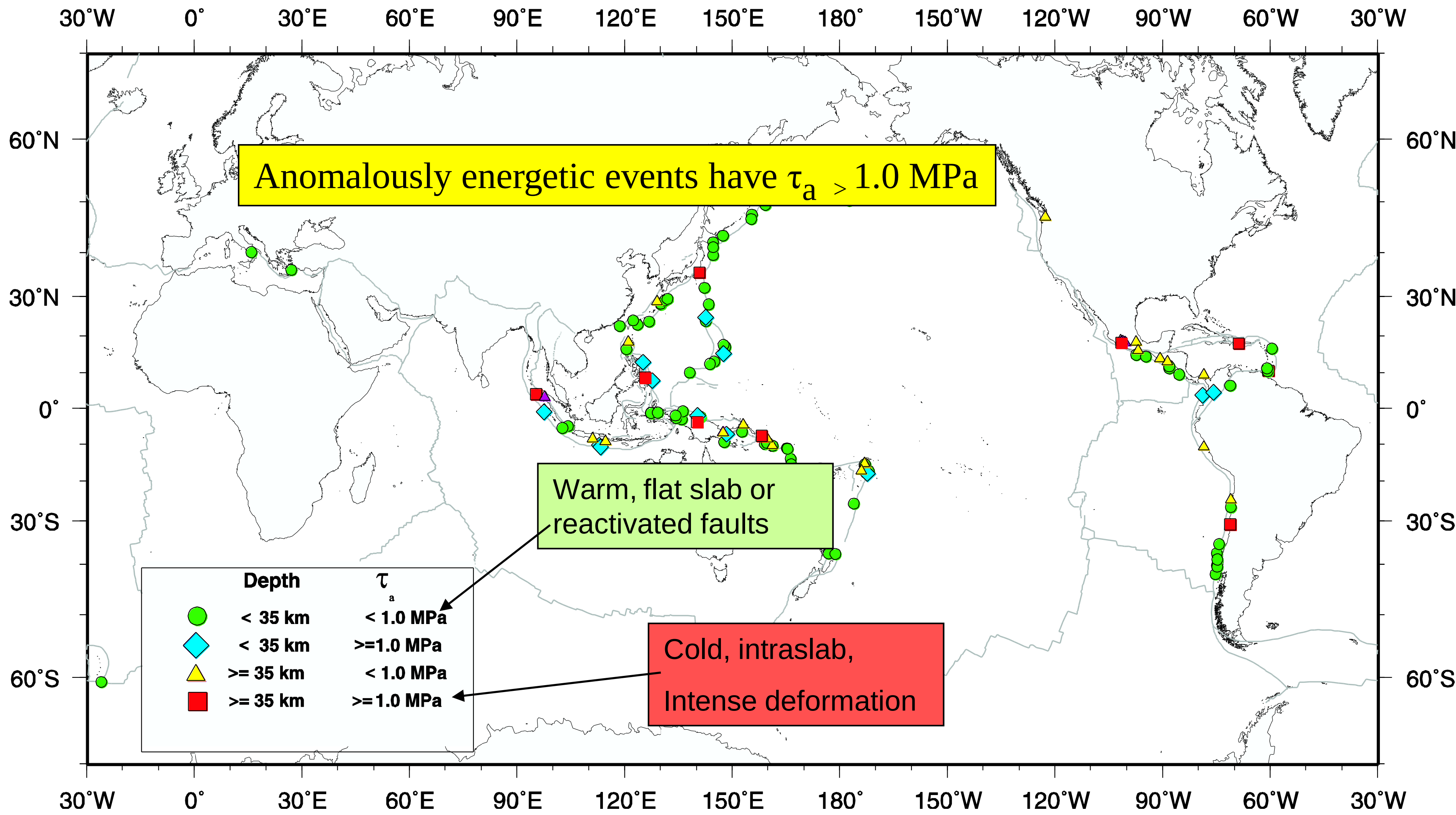
North Atlantic Ocean and Azores Region

Choy and McGarr, 2002



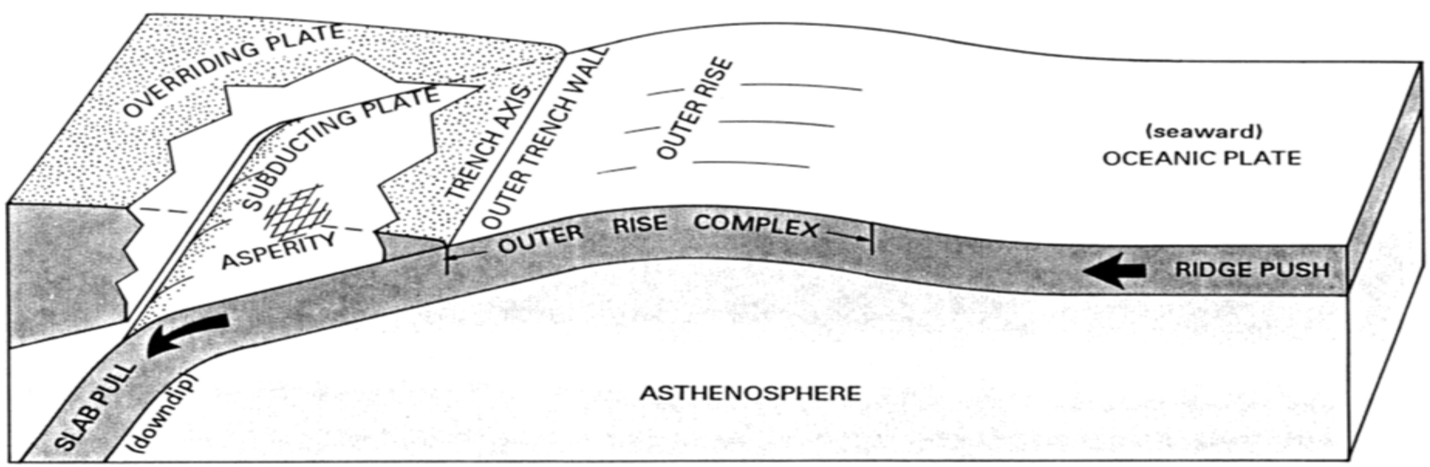
Global Normal
2.96
0.46
0.07
RADIATED ENERGY (Nm)
1.E+18
1.E+17
1.E+16
1.E+15
1.E+14
1.E+13
1.E+12
1.E+11
1.E+17
1.E+18
1.E+19
1.E+20
1.E+21
1.E+22
MOMENT (Nm)

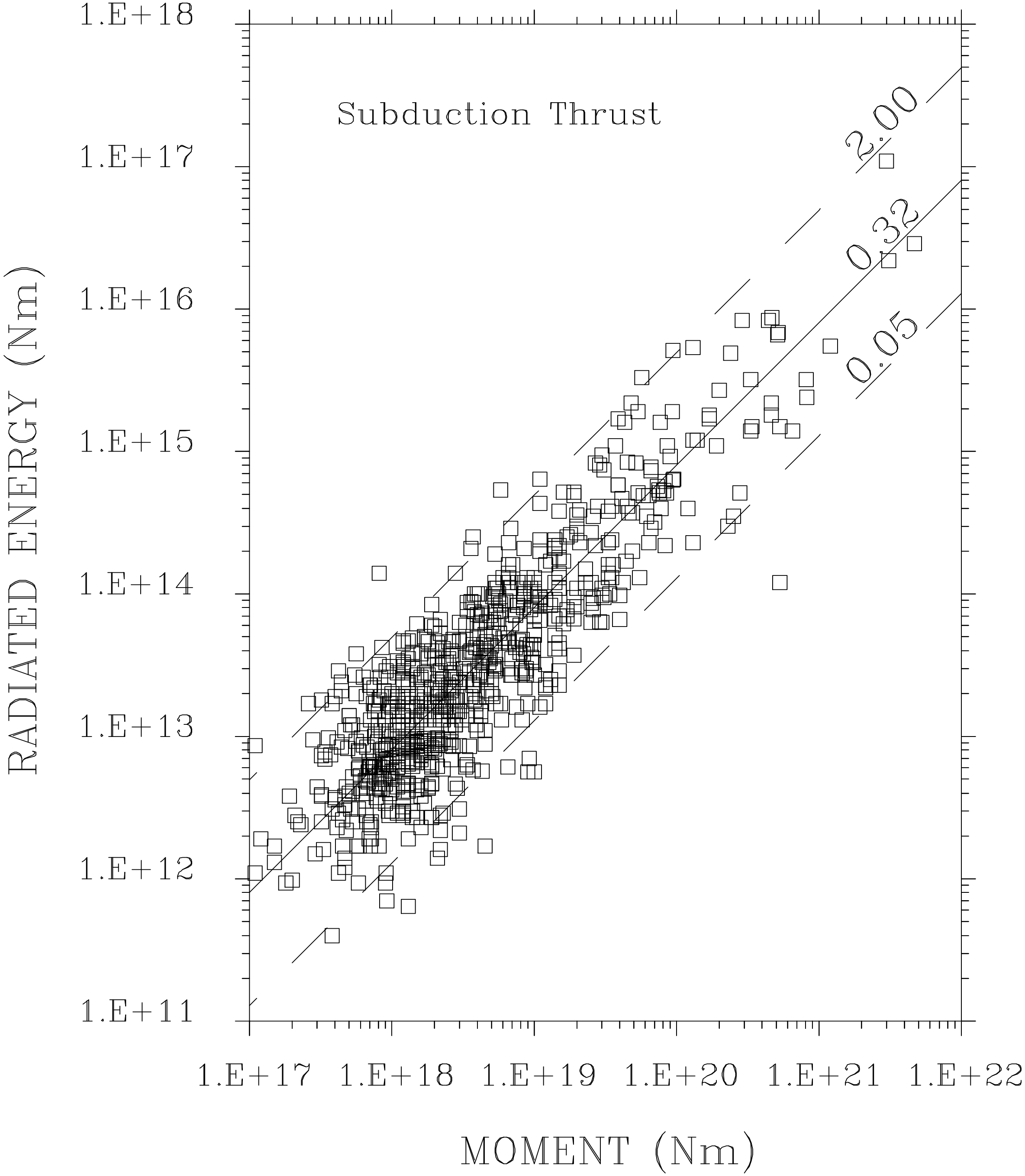
Subduction Normal Fault Earthquakes



Choy & Kirby, 2004

$<\tau_a>$ MPa	Low → High 0.3	0.6	1.7	2.3	9.1
Subduction zone environment	Interplate	Outer-rise/Near-trench reactivated mid-ocean fabric	Outer-rise/Near trench cross-cutting mid-ocean fabric	Intraslab High deformation (slab bends and dueling slabs)	Intraoceanic
Mechanism	Thrust	Normal	Normal	Normal	Strike-slip
Fault Maturity	High ← Low				

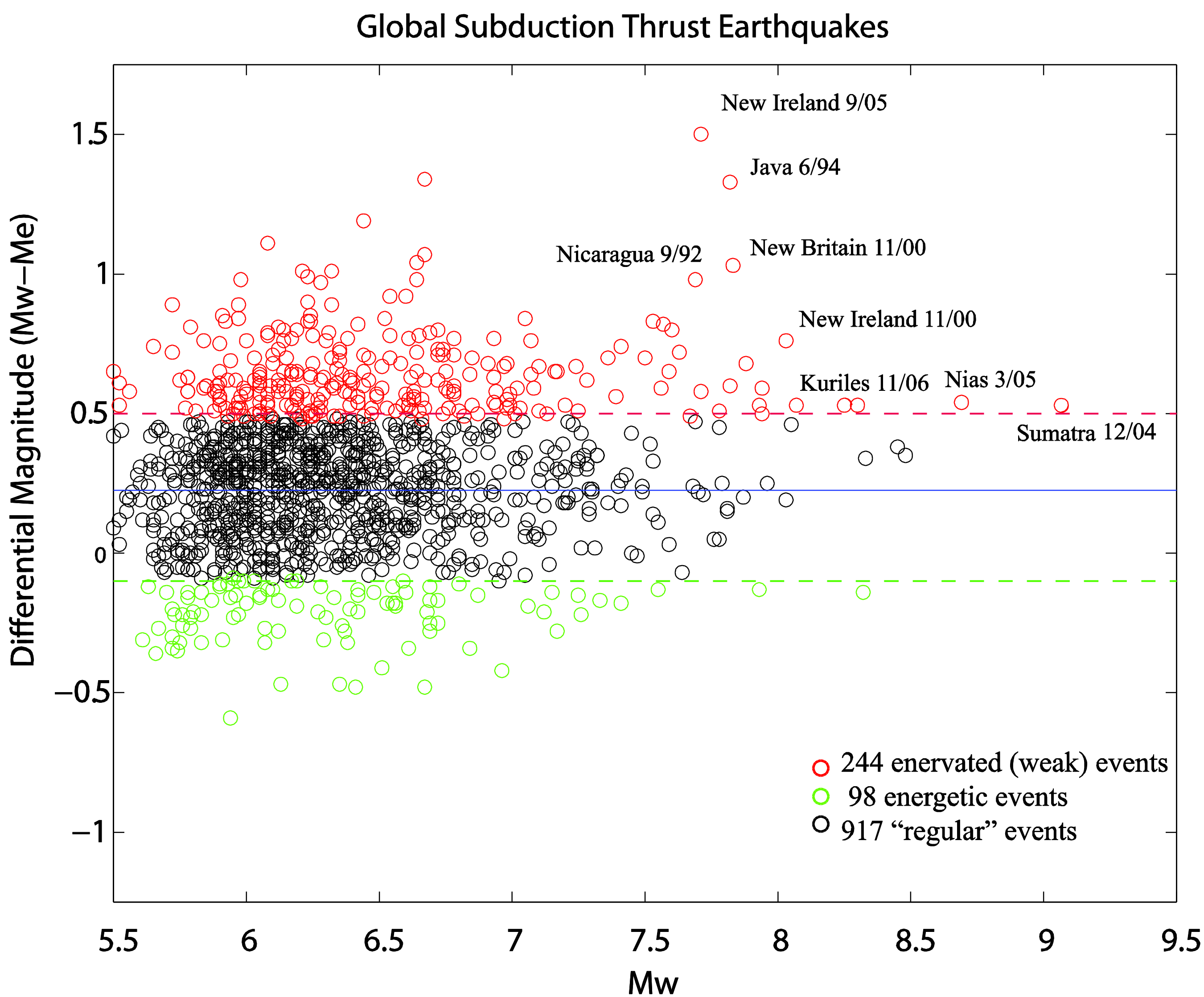



Subduction Thrust
2.00
0.32
0.05
RADIATED ENERGY (Nm)
1.E+18
1.E+17
1.E+16
1.E+15
1.E+14
1.E+13
1.E+12
1.E+11
1.E+17
1.E+18
1.E+19
1.E+20
1.E+21
1.E+22
MOMENT (Nm)

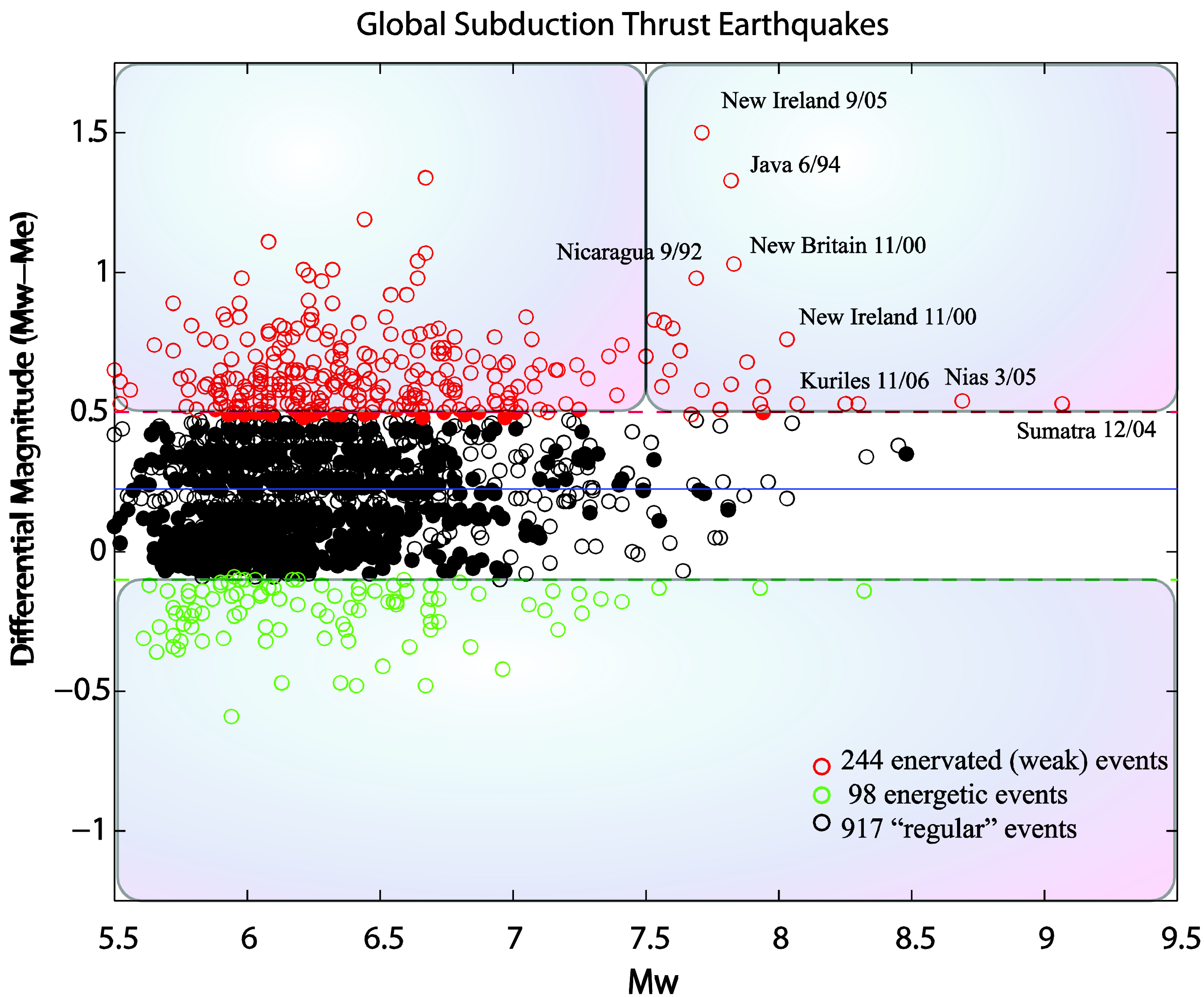
Identifying Thrust Earthquakes with Anomalously Weak or Strong E_S

$\tau_a > 1$ MPa are regarded as ***energetic*** (Choy & Kirby, 2004)

$\Delta M > 0.5$ are regarded as ***enervated;*** equivalent to $\Theta > -5.5$, an indicator of tsunami earthquakes (Newman & Okal, 1998)



Global Subduction Thrust Earthquakes
Differential Magnitude (Mw−Me)
Mw
1.5
1
0.5
0
−0.5
−1
5.5
6
6.5
7
7.5
8
8.5
9
9.5
New Ireland 9/05
Java 6/94
Nicaragua 9/92
New Britain 11/00
New Ireland 11/00
Kuriles 11/06
Nias 3/05
Sumatra 12/04
244 enervated (weak) events
98 energetic events
917 "regular" events



Global Subduction Thrust Earthquakes
Differential Magnitude (Mw–Me)
Mw
1.5
1
0.5
0
−0.5
−1
5.5
6
6.5
7
7.5
8
8.5
9
9.5
New Ireland 9/05
Java 6/94
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244 enervated (weak) events
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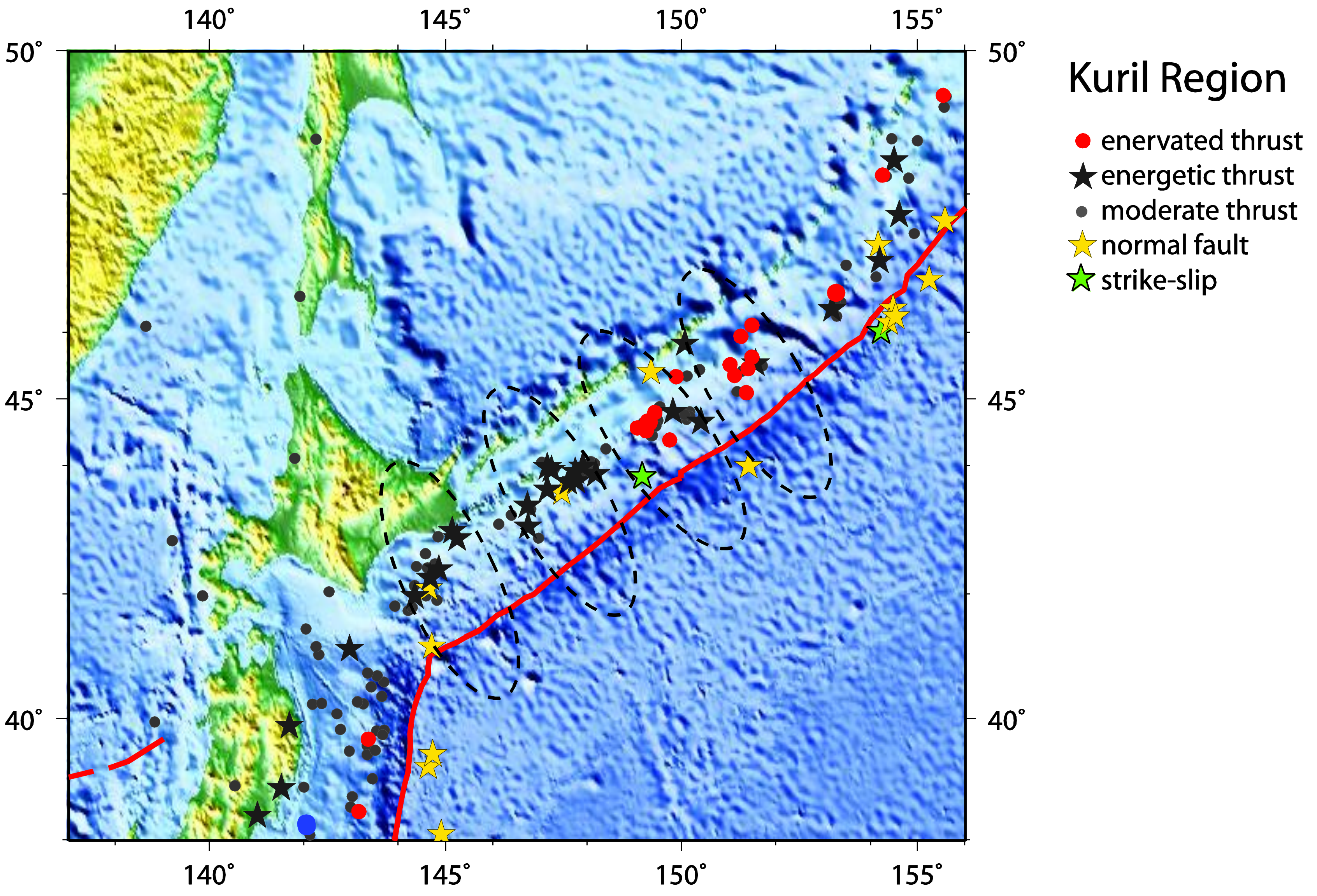
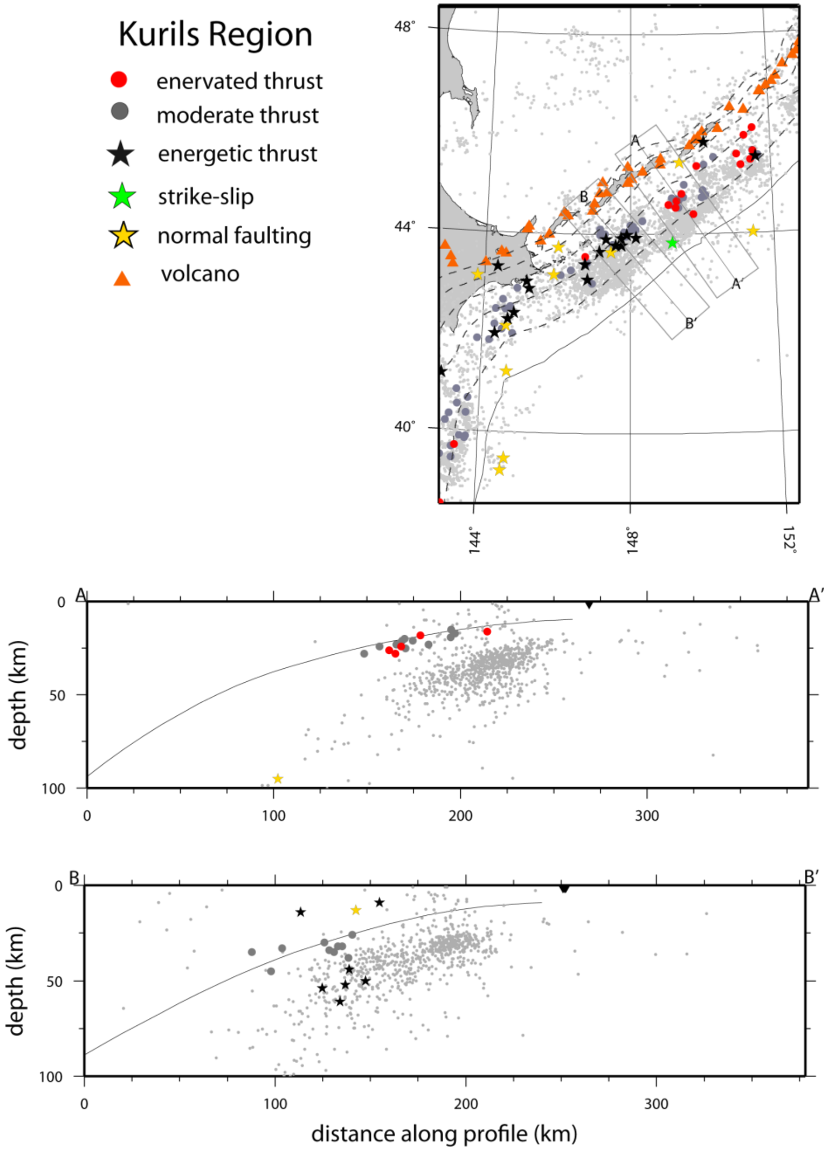
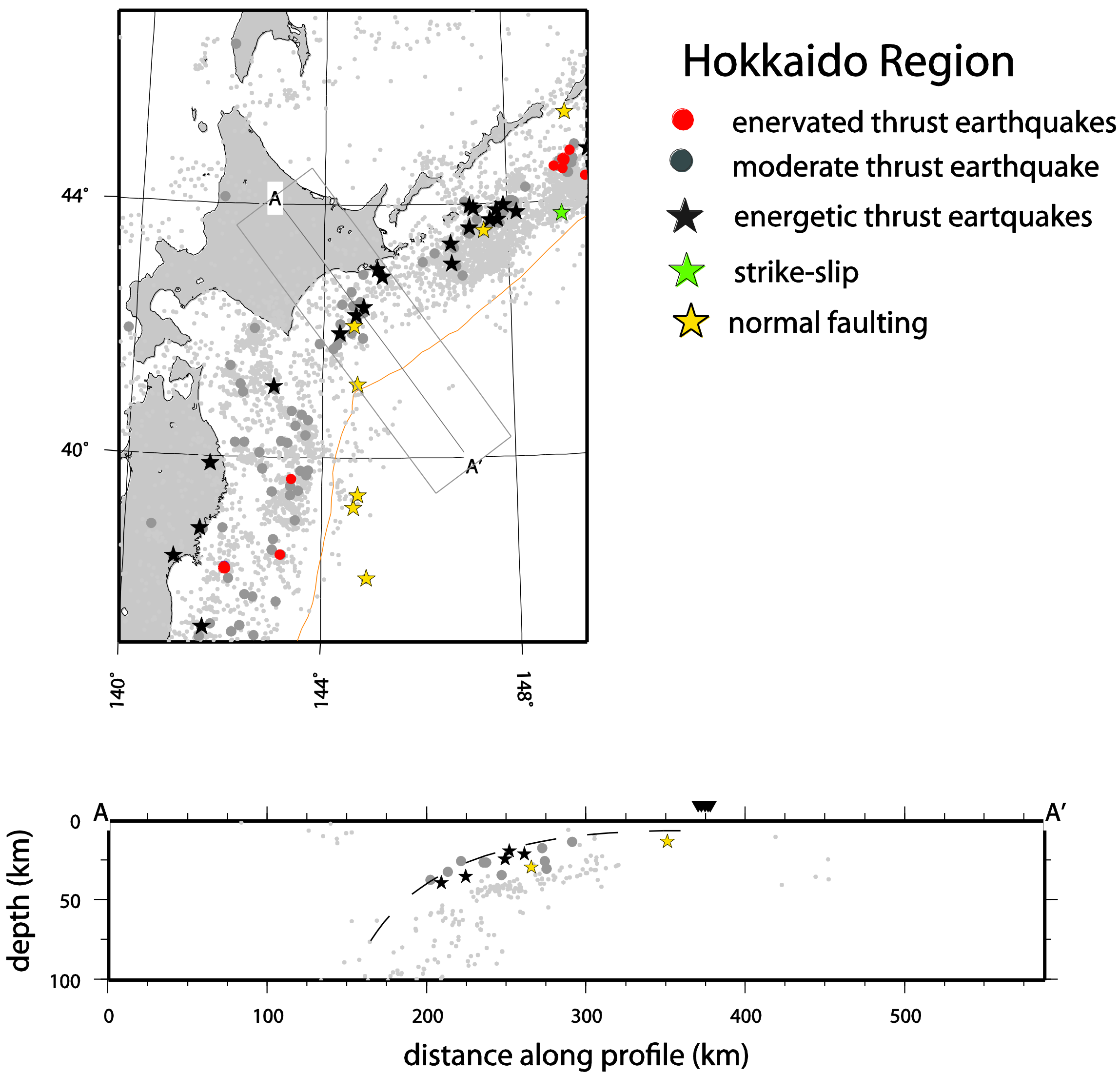
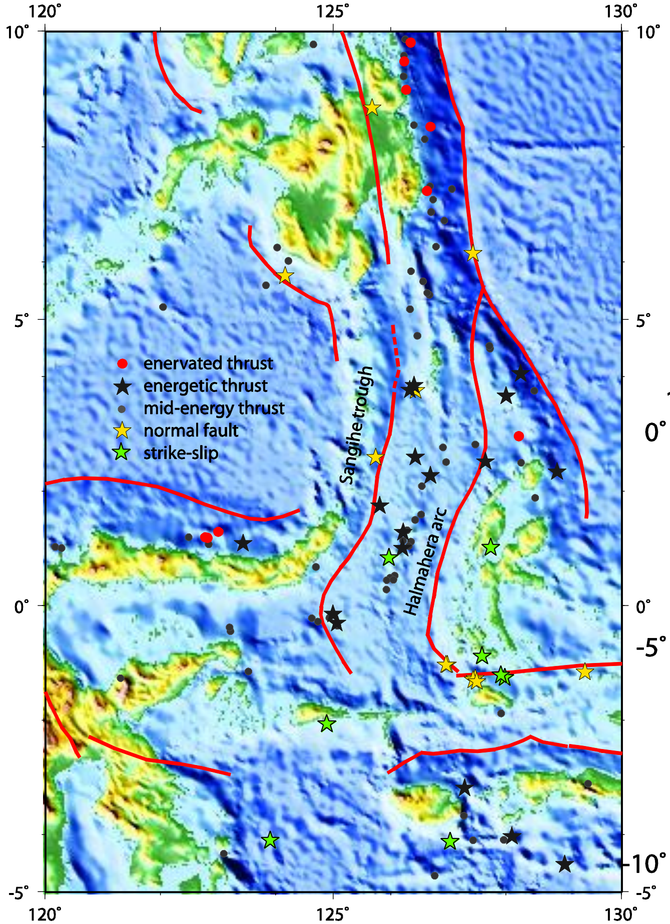


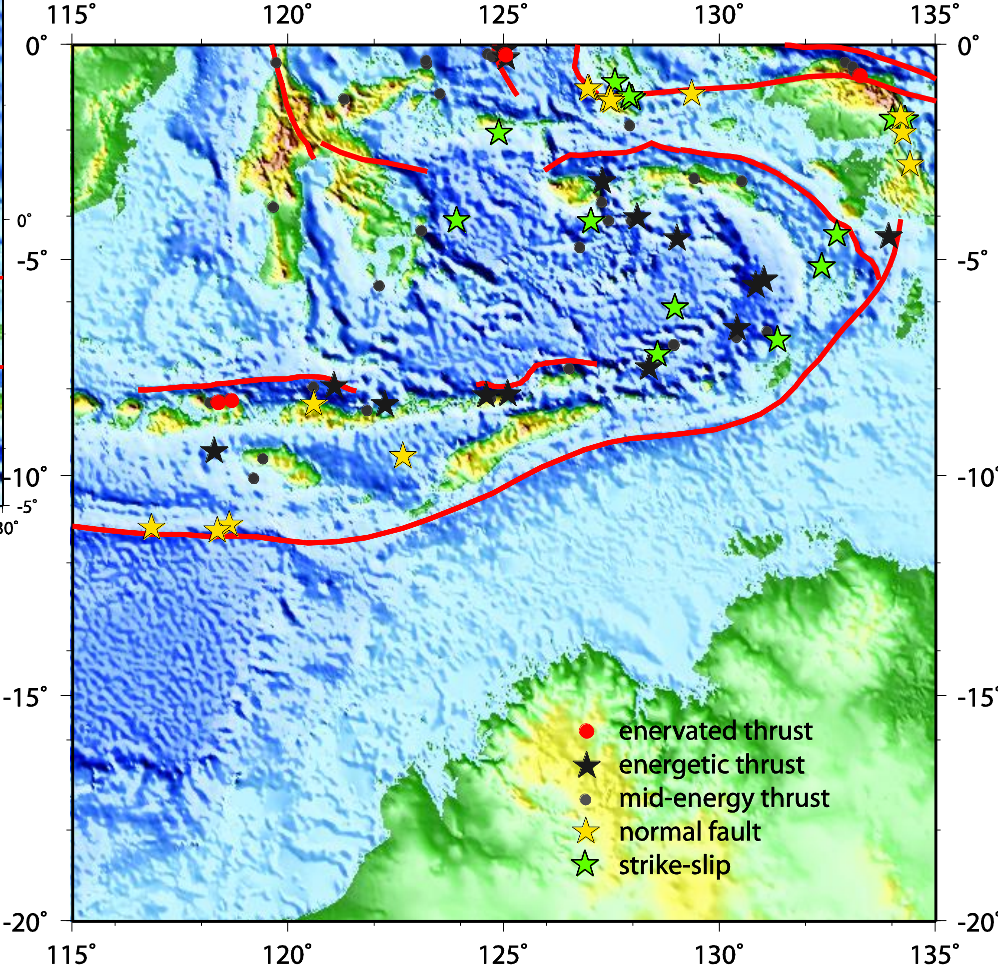
Kuril Region
enervated thrust
energetic thrust
moderate thrust
normal fault
strike-slip
140°
145°
150°
155°
50°
45°
40°


Kurils Region
enervated thrust
moderate thrust
energetic thrust
strike-slip
normal faulting
volcano
48°
44°
40°
144°
148°
152°
A
A′
B
B′
depth (km)
0
50
100
0
100
200
300
distance along profile (km)

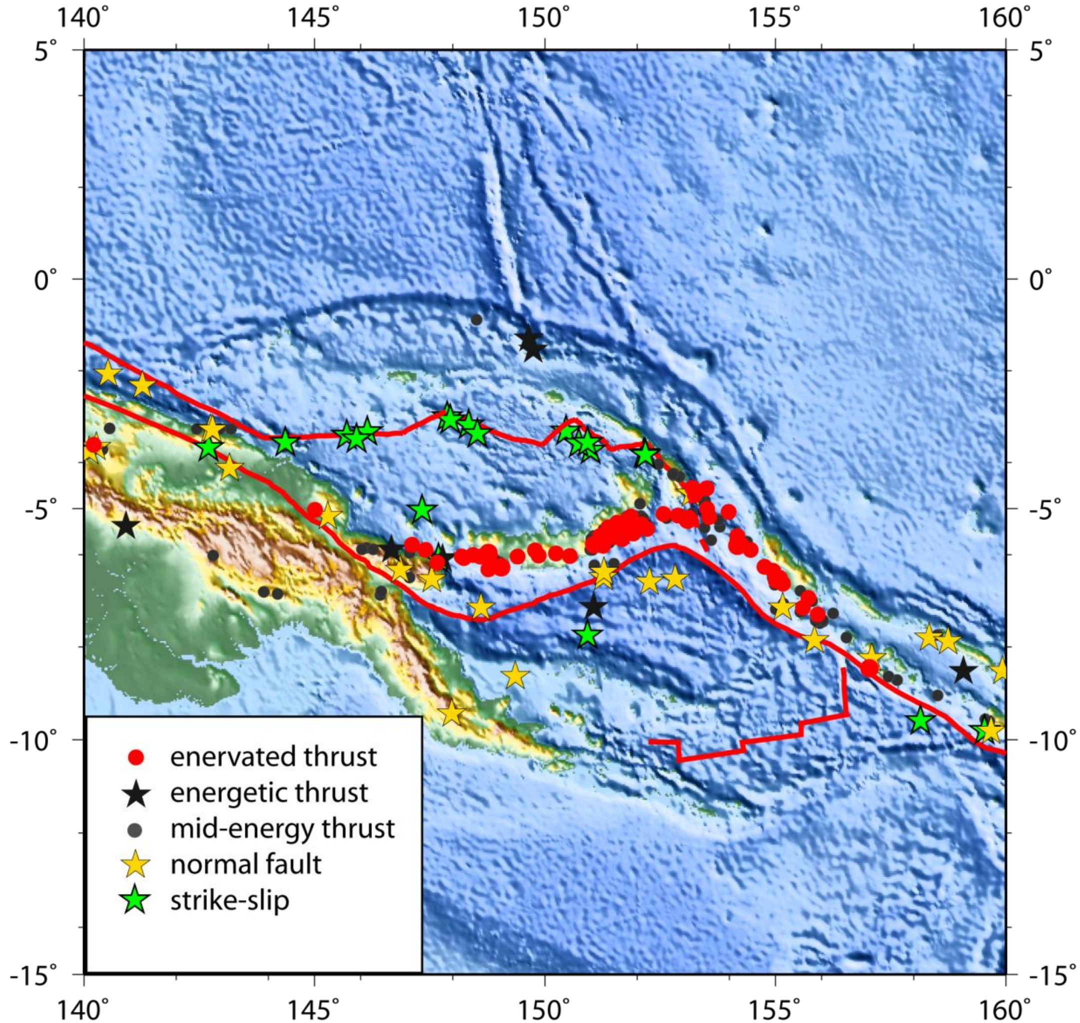

Hokkaido Region
enervated thrust earthquakes
moderate thrust earthquake
energetic thrust eartquakes
strike-slip
normal faulting
44˚
40˚
140˚
144˚
148˚
A
A′
0
50
100
depth (km)
0
100
200
300
400
500
distance along profile (km)

Marine collision zones

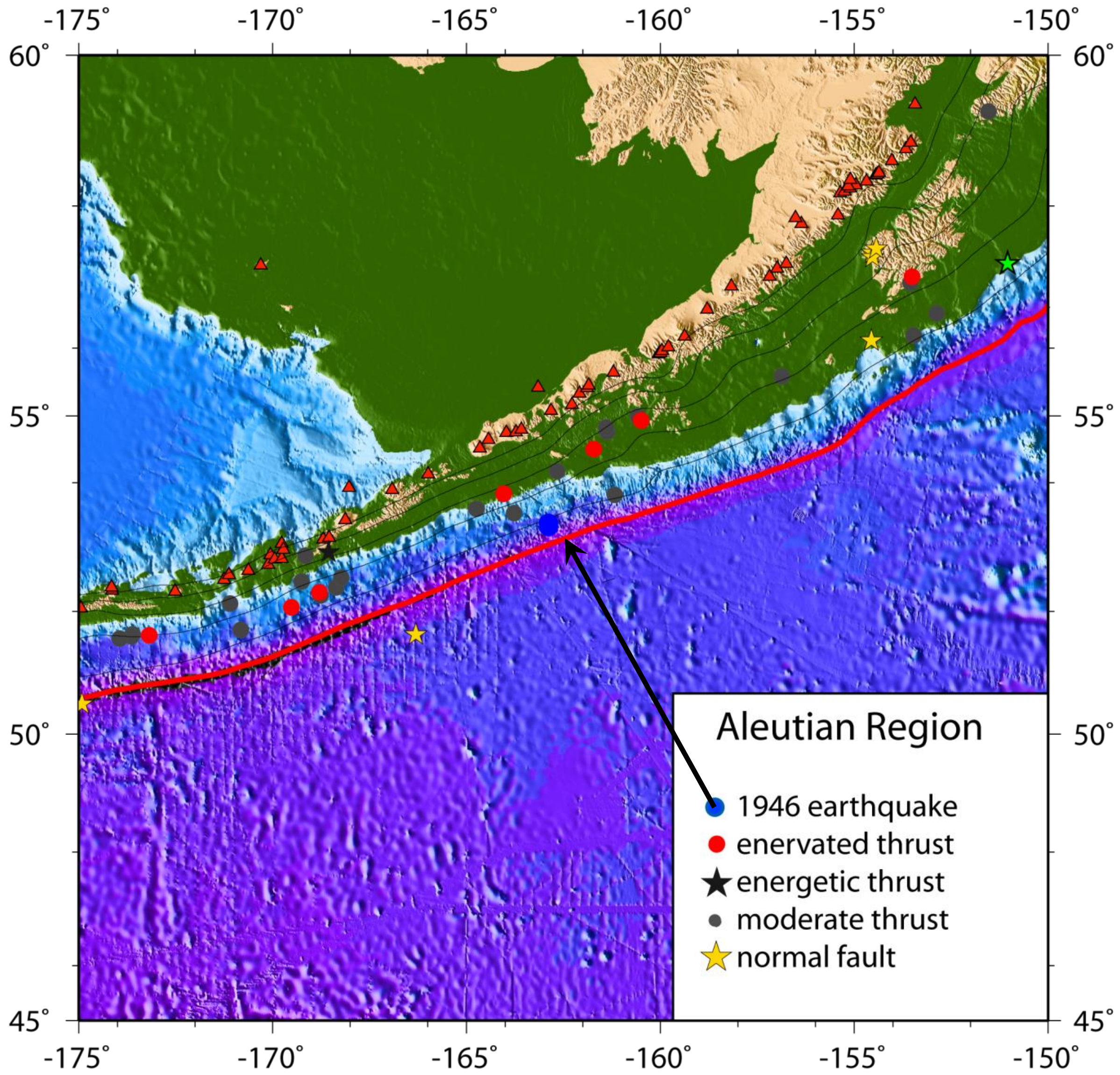


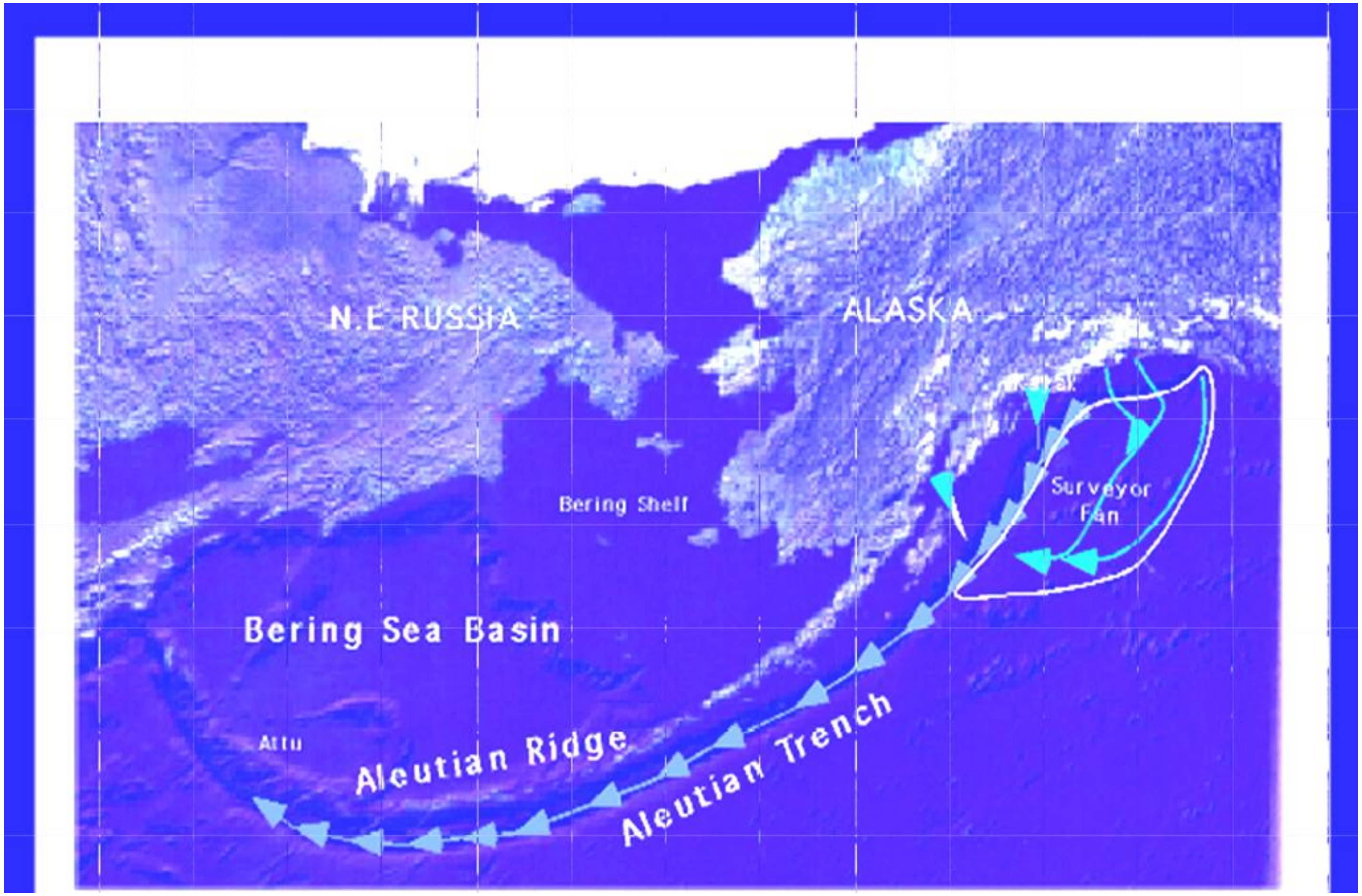


Enervated events in sediment rich subduction zone deeper and further from trench axis

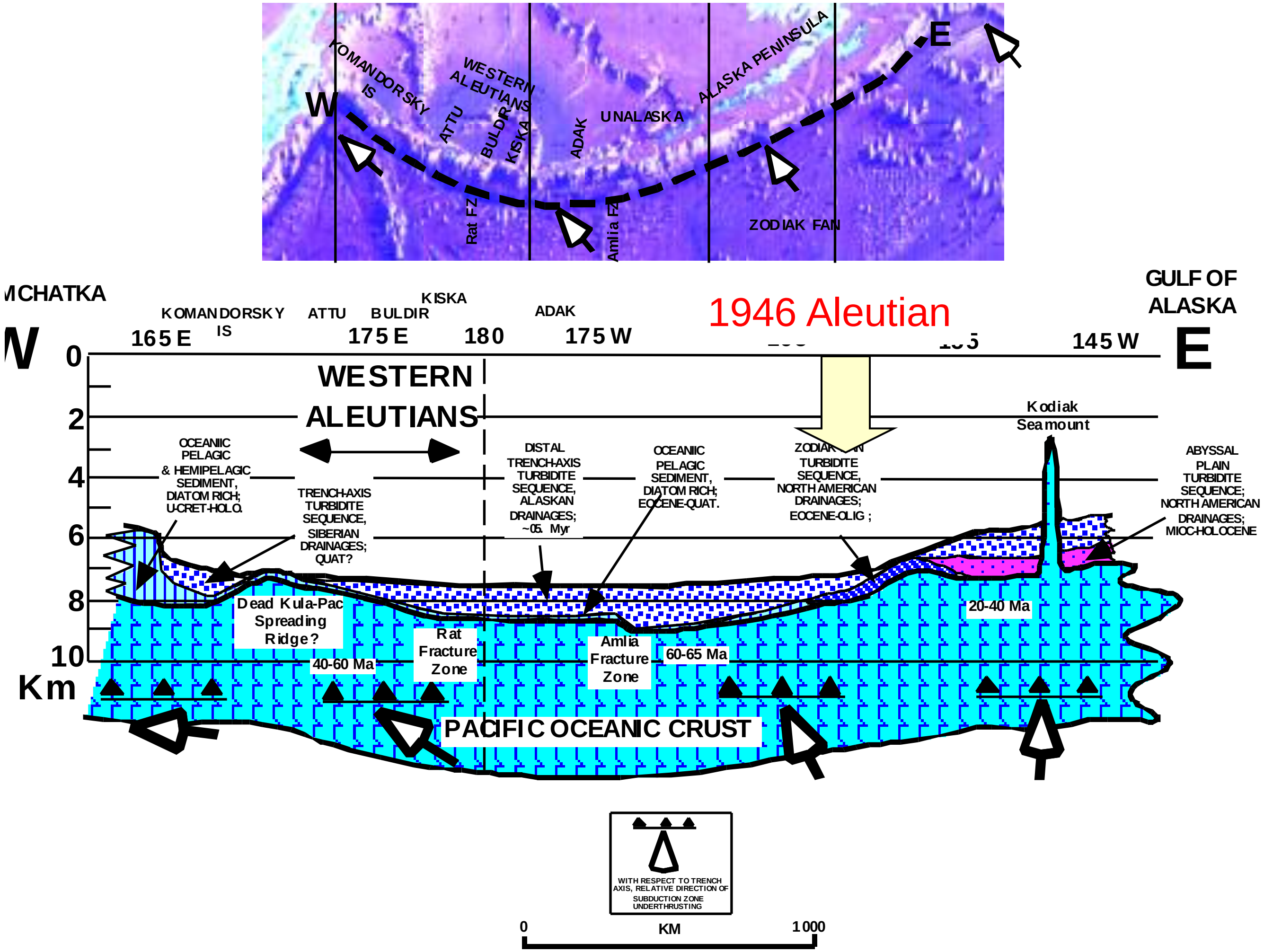


Enervated events at sediment poor trench axes





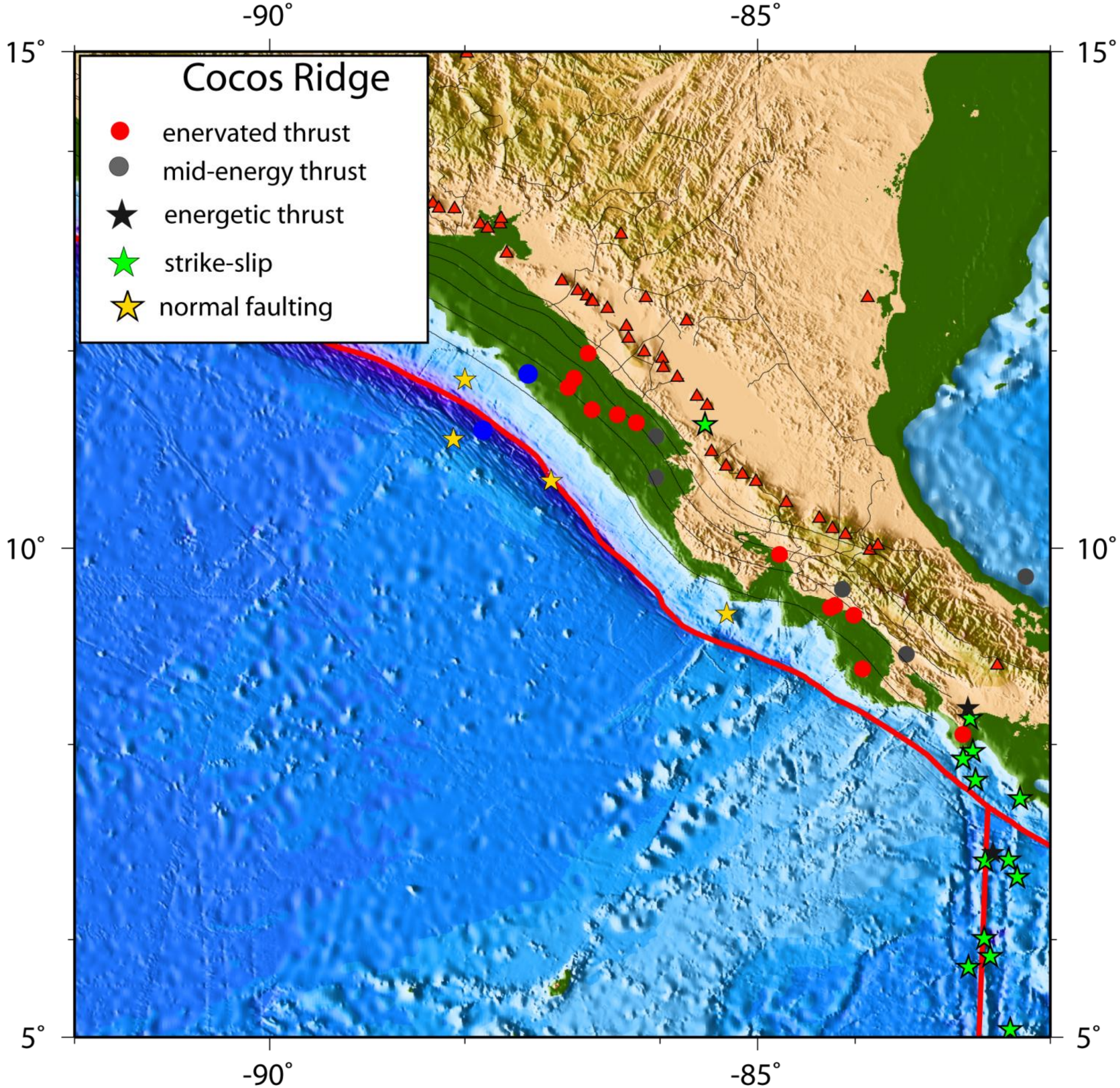
From the USGS Tsunami Source Working Group



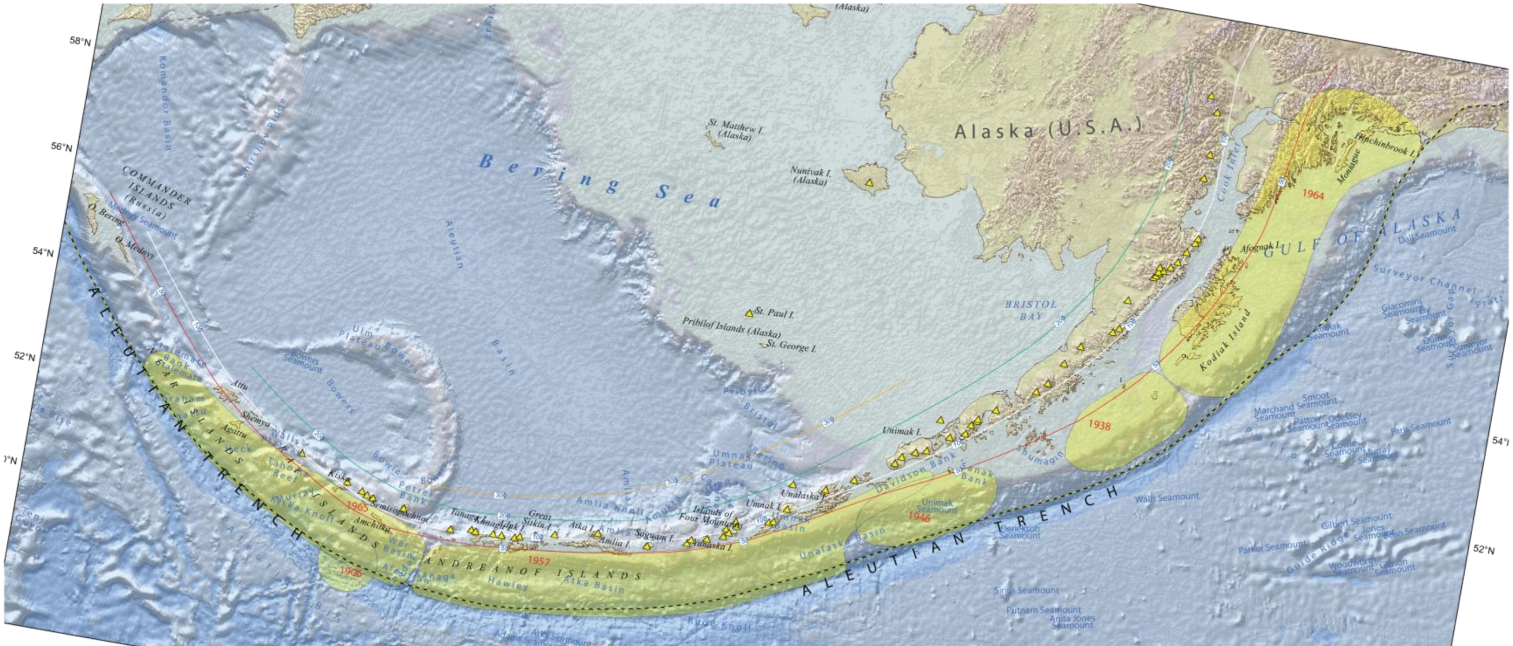
SCHEMATIC E TO W LONGITUDINAL SECTION OF ALEUTIAN TRENCH DISPLAYING THE PRINCIPAL SEDIMENT TYPE ENTERING THE ALEUTIAN SUBDUCTION ZONE

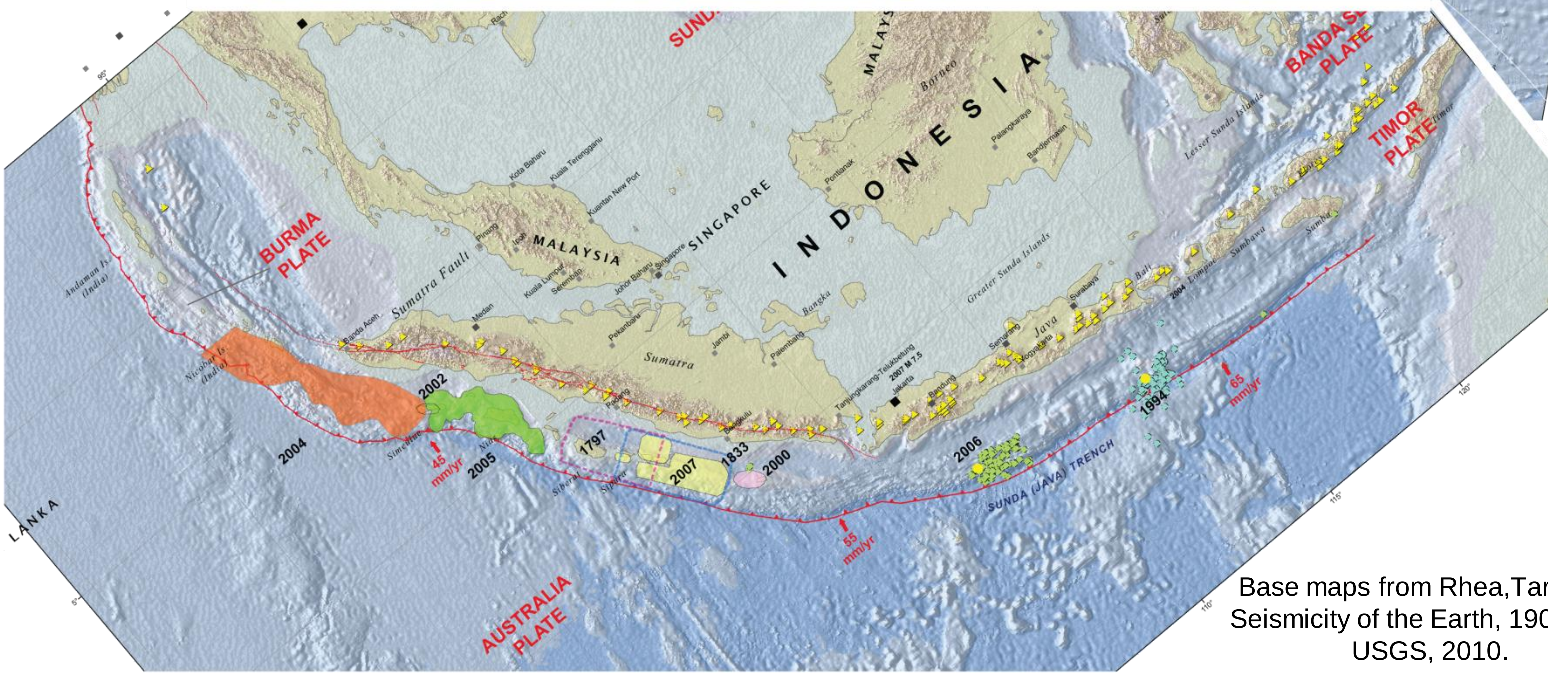
From the USGS Tsunami Source Working Group

Enervated events associated with subduction erosion

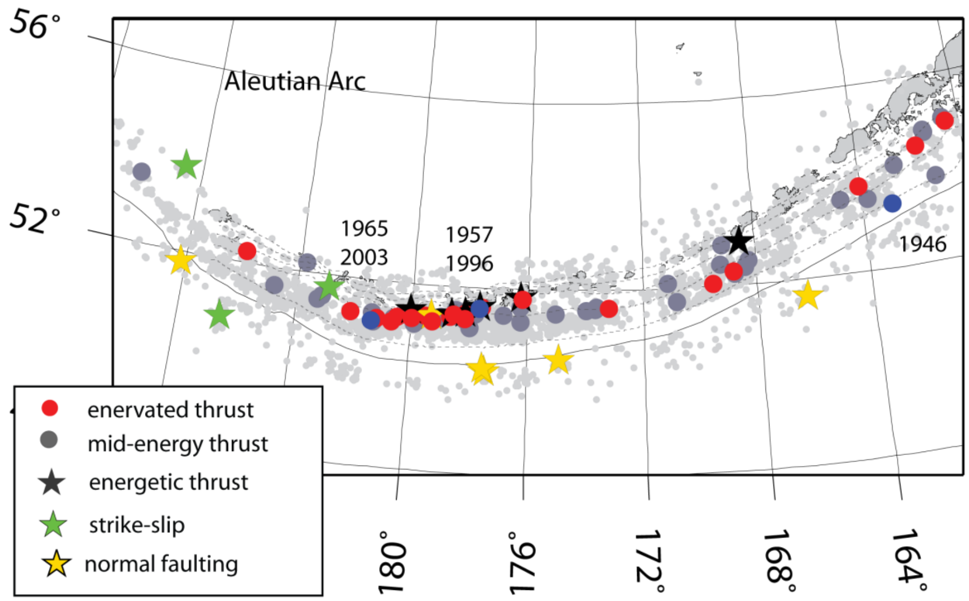


Along-strike comparison of seismotectonics of the Aleutian and Sunda Arcs

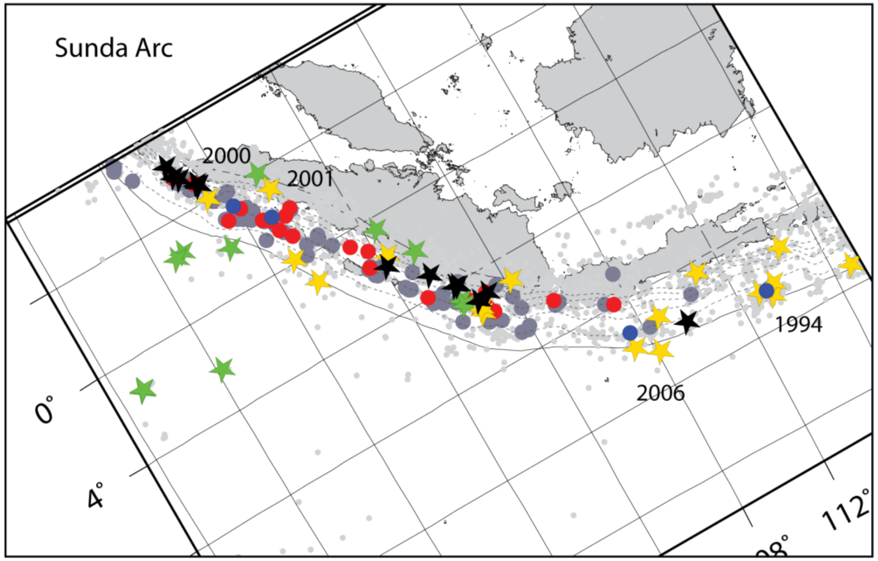




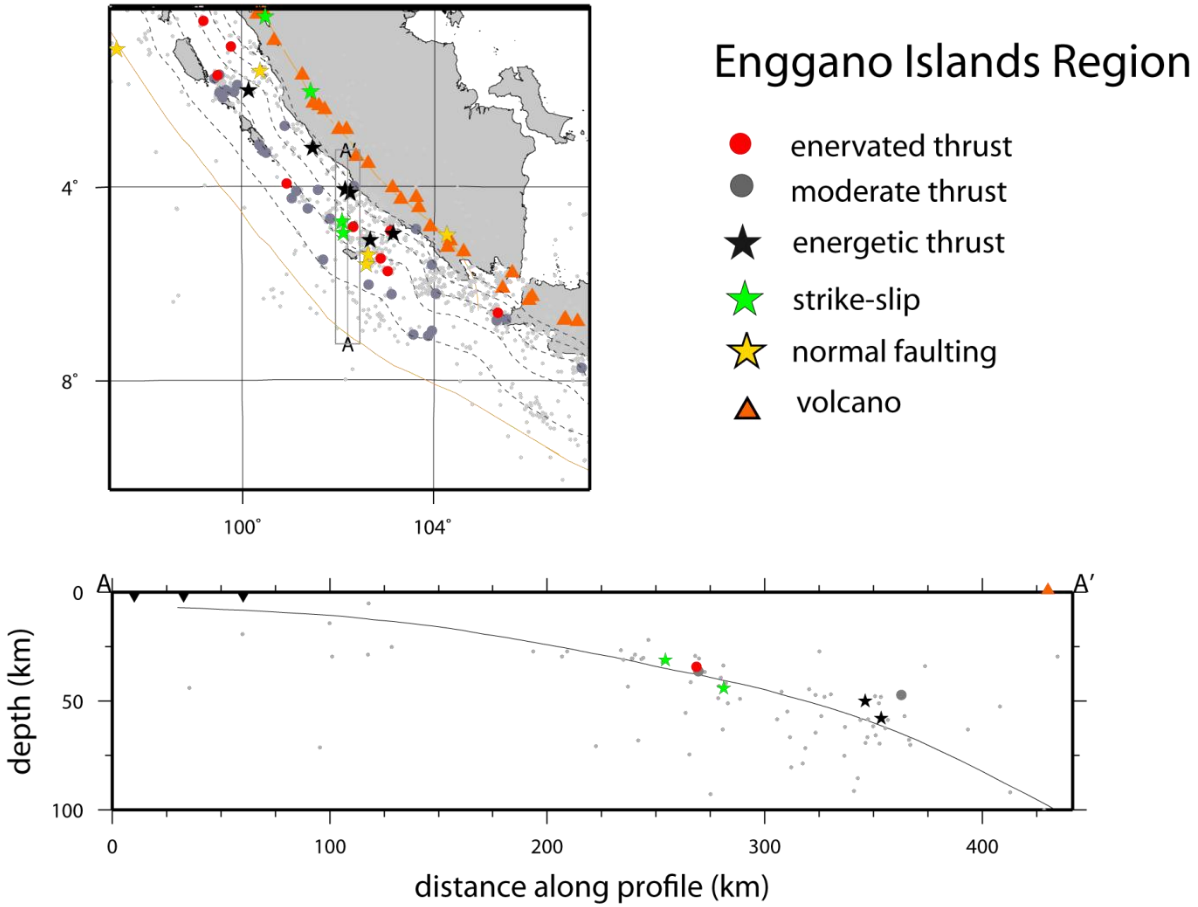
Base maps from Rhea,Tarr,Benz
Seismicity of the Earth, 1900-2007
USGS, 2010.



56°
52°
Aleutian Arc
1965
2003
1957
1996
1946
enervated thrust
mid-energy thrust
energetic thrust
strike-slip
normal faulting
180°
176°
172°
168°
164°

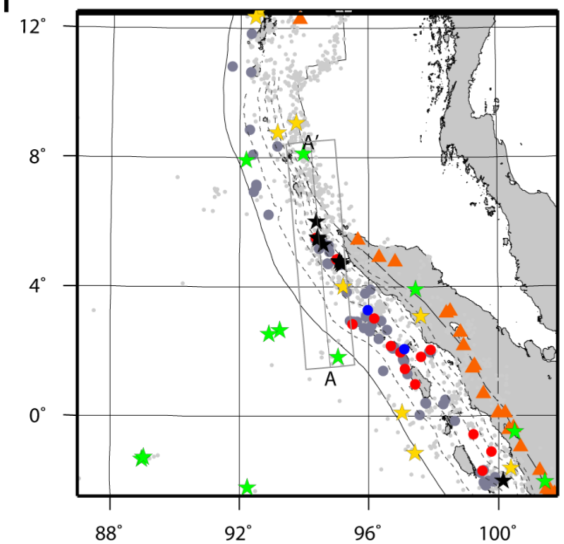


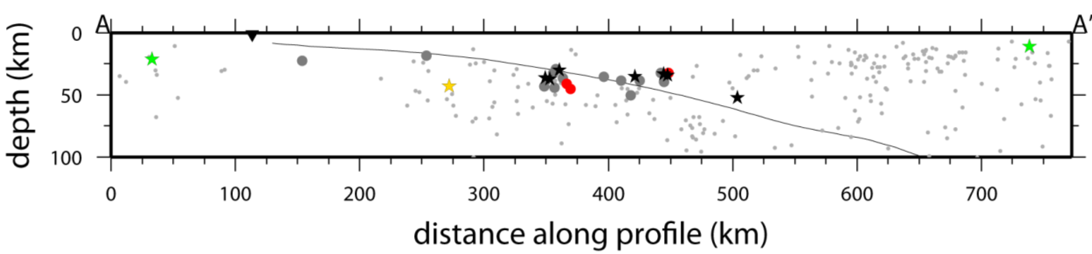
Sunda Arc
2000
2001
1994
2006
0°
4°
112°

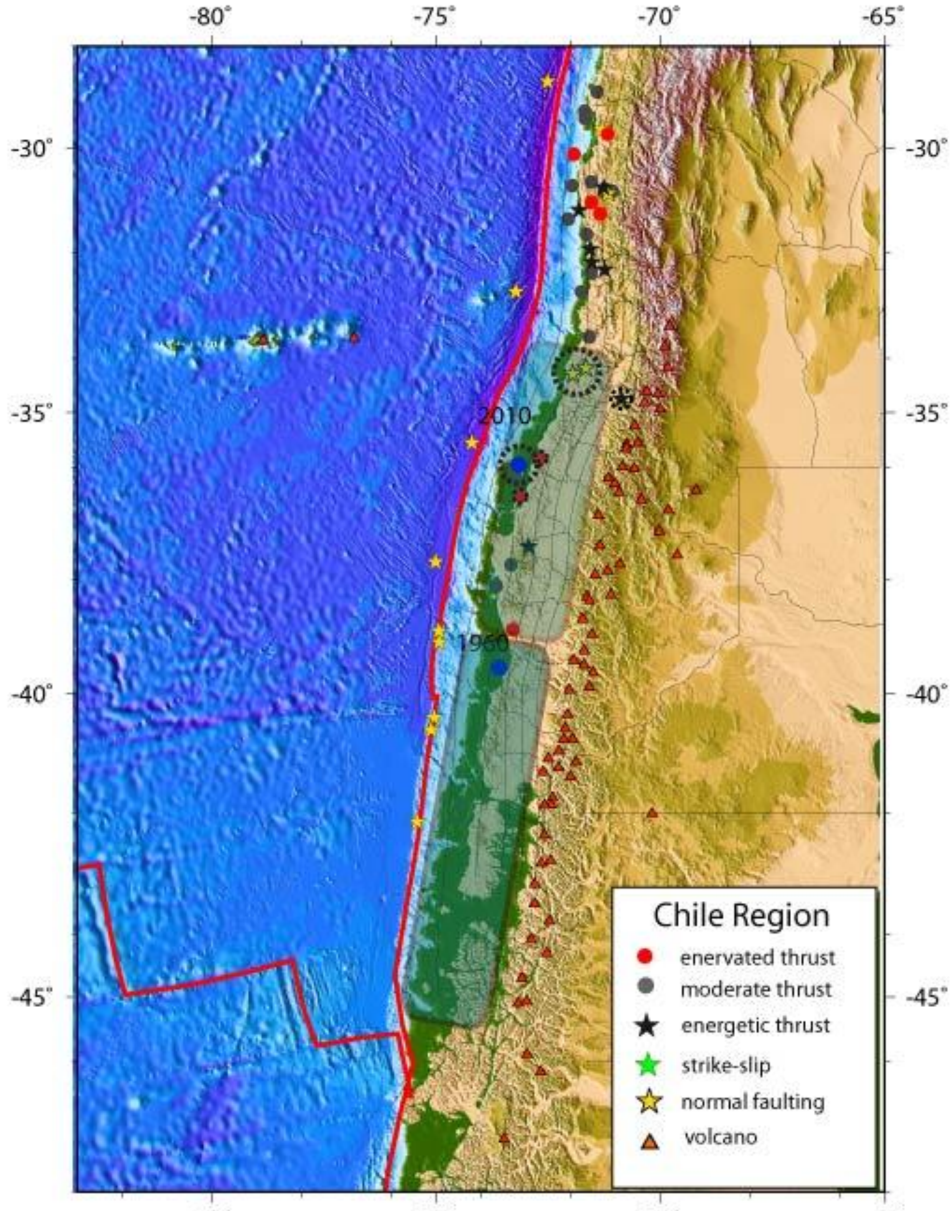

Enggano Islands Region
enervated thrust
moderate thrust
energetic thrust
strike-slip
normal faulting
volcano
4°
8°
100°
104°
A'
A
depth (km)
0
50
100
0
100
200
300
400
distance along profile (km)

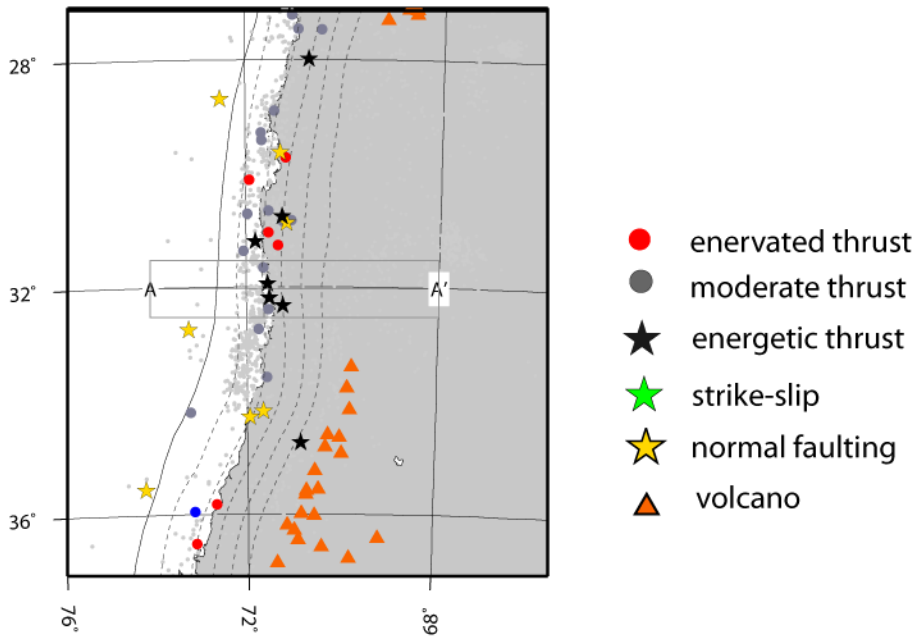
Sumatra Region near Banda Aceh

- enervated thrust
- moderate thrust
- energetic thrust
- strike-slip
- normal faulting
- volcano

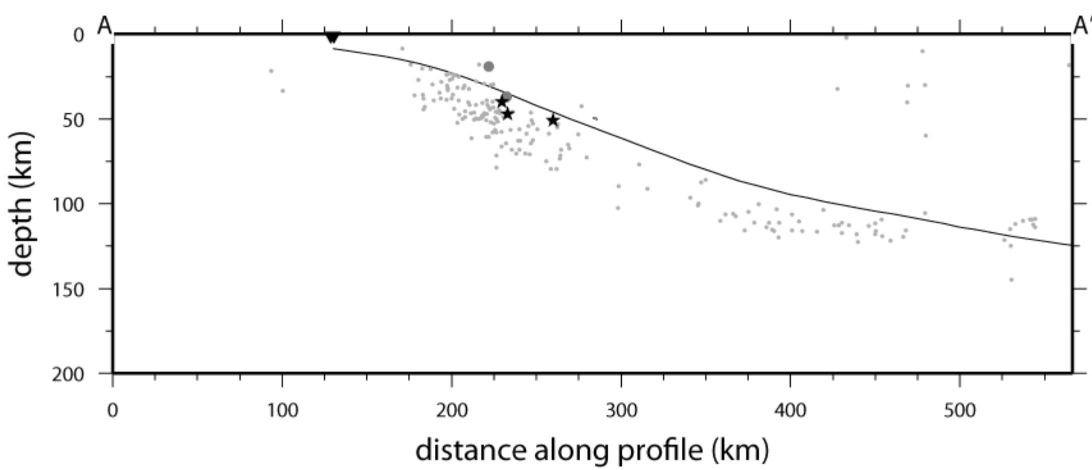





-80°
-75°
-70°
-65°
-30°
-35°
-40°
-45°
2010
1960
Chile Region
enervated thrust
moderate thrust
energetic thrust
strike-slip
normal faulting
volcano



Subduction of Buoyant Feature

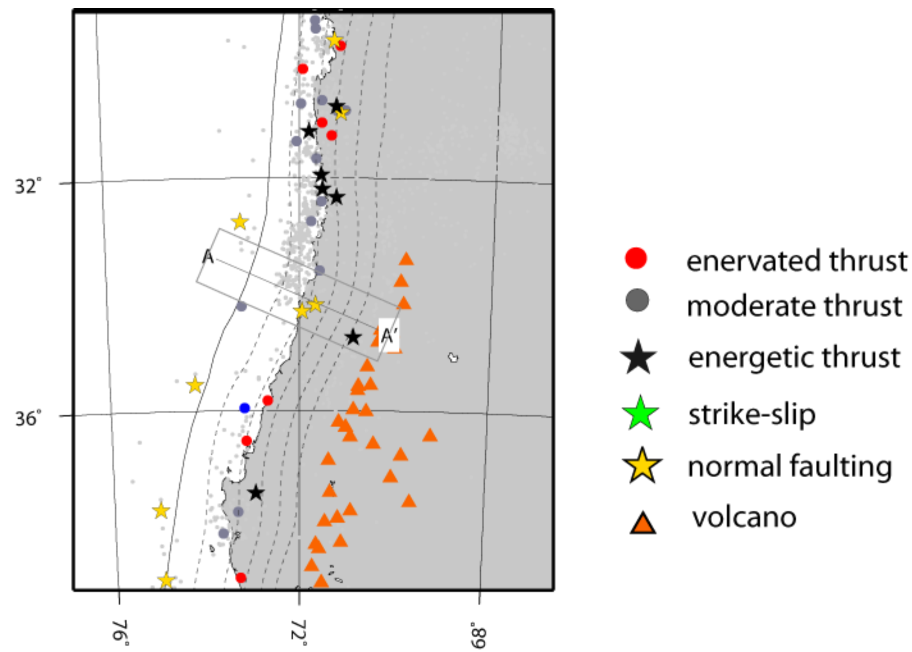


Summary

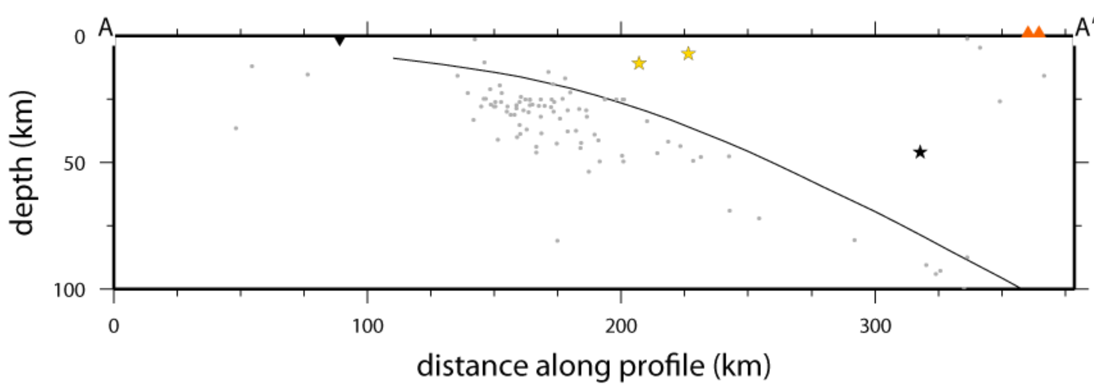
- The global distribution of high (energetic) and low (enervated) Es thrust events is not random, but a function of seismic region and tectonic setting.

- Energetic thrust earthquakes occur in high-deformation settings.
    - Marine and submerged continent-continent collision zones.
    - Bends or cusps in plate boundary.
    - Interface or intraslab; when in proximity to enervated events they are deeper.
    - Occur downdip of subducted fracture zones and ridges on non-slab interface fault surfaces.
- Enervated thrust earthquakes
    - Not always associated with tsunamis.
    - Occur in both sediment-starved and sediment-rich trenches.
    - Downdip of subducted fracture zones and ridges which may transport sediments down the plate interface.

- The correlation of energetic vs. enervated earthquakes (both strike-slip and dip-slip) with tectonic features may enhance our understanding of slab mechanics.



Large Aftershocks of the Chile 2010 Earthquake



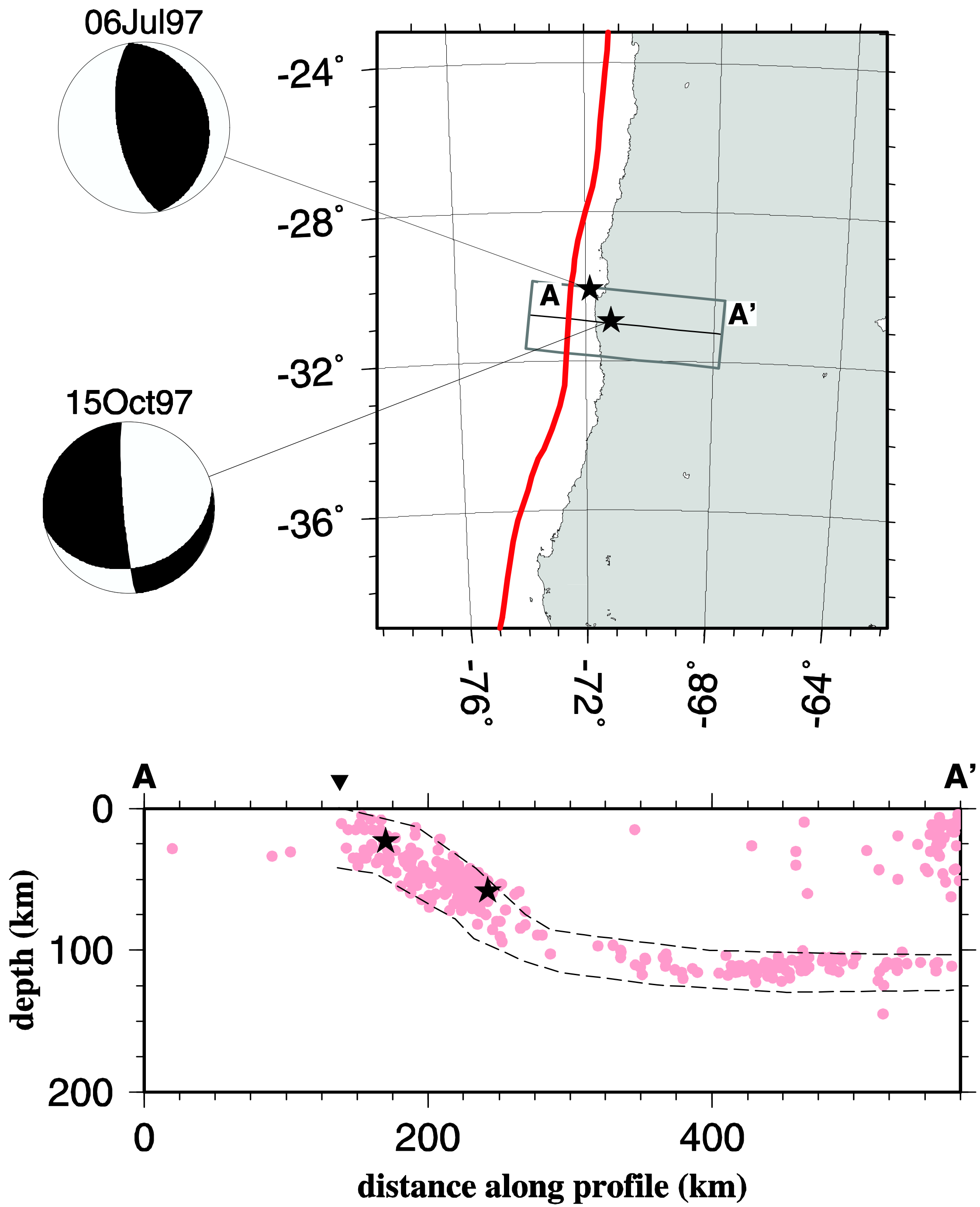
Event	Magnitudes	Deaths	Location	Trench Sediments
1895 Japan	M_{jma}~7.2 M_t ~ 8.2	27,000	FP	Low
1946 Alaska	Mw 8.6	117	FP	Low
1992 Nicaragua	Mw 7.7 Me 6.7	116	Not NP ?	Low
1994 Java	Mw 7.8 Me 6.5	>250	FP	Low
2004 Sumatra	Mw 9.2 Me 8.5	227,000	FP	High?
2006 Java	Mw 7.7 Me 7.1	730	FP	Low

From the USGS Tsunami
Source Working Group

Fault Maturity and Apparent Stress

Less mature faults have little or no accumulated displacement (e.g., rupture in intact or fresh rock).

Mature faults have large cumulative displacements (e.g., the plate interface at a subduction zone).



Choy and Kirby, 2004

Macroseismic reports for Central Chile earthquakes

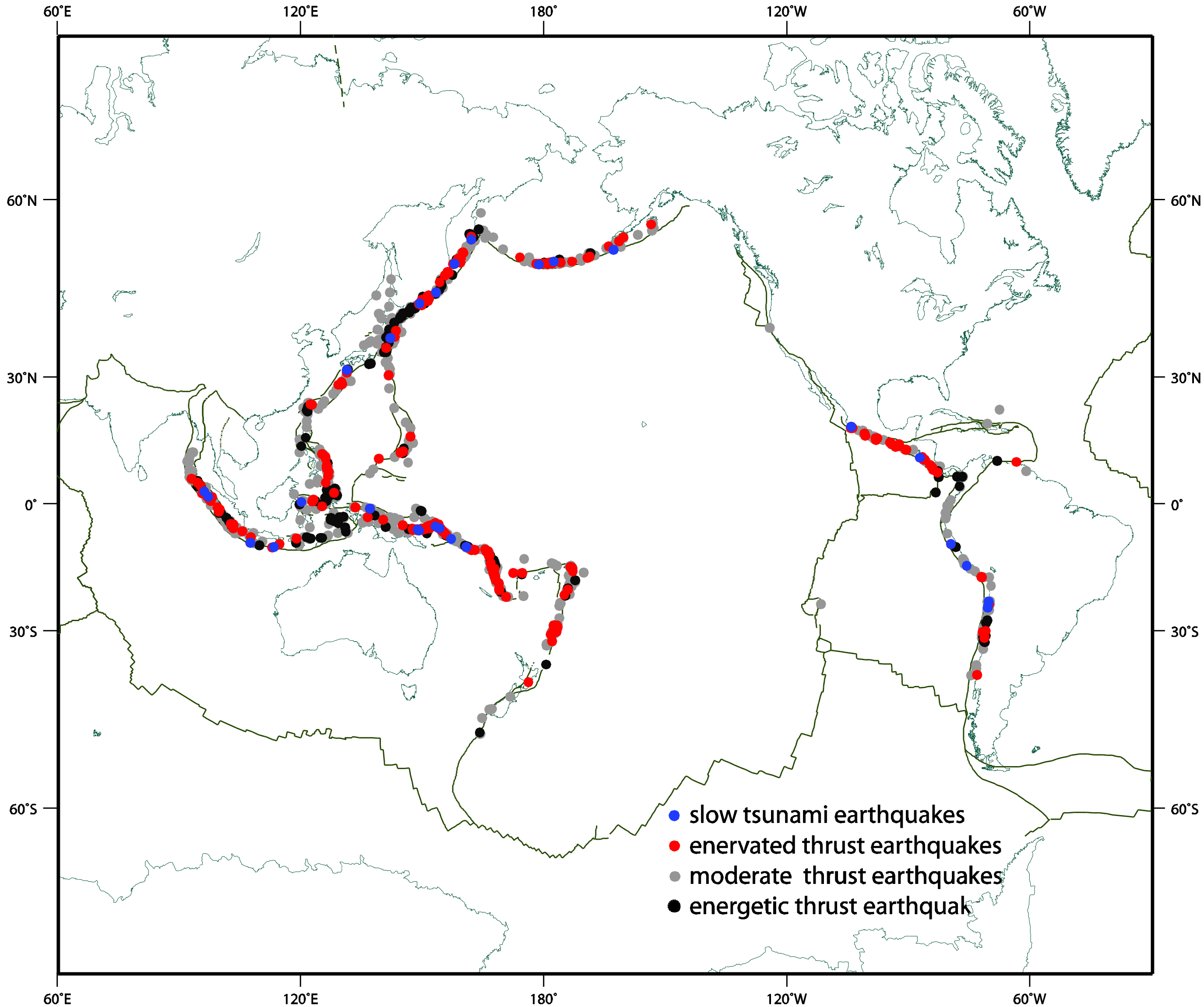
Date	LAT (°)	LON (°)	Dept h (km)	M_e	M_W	m_b	M_S	τ_a MPa	Faulting Type
6 JUL 1997 (1)	-30.0	-71.87	23.0	6.1	6.9	5.8	6.5	0.1	interplate-thrust
15 OCT 1997 (2)	-30.9	-71.22	58.0	7.6	7.1	6.8	6.8	4.4	intraslab-normal

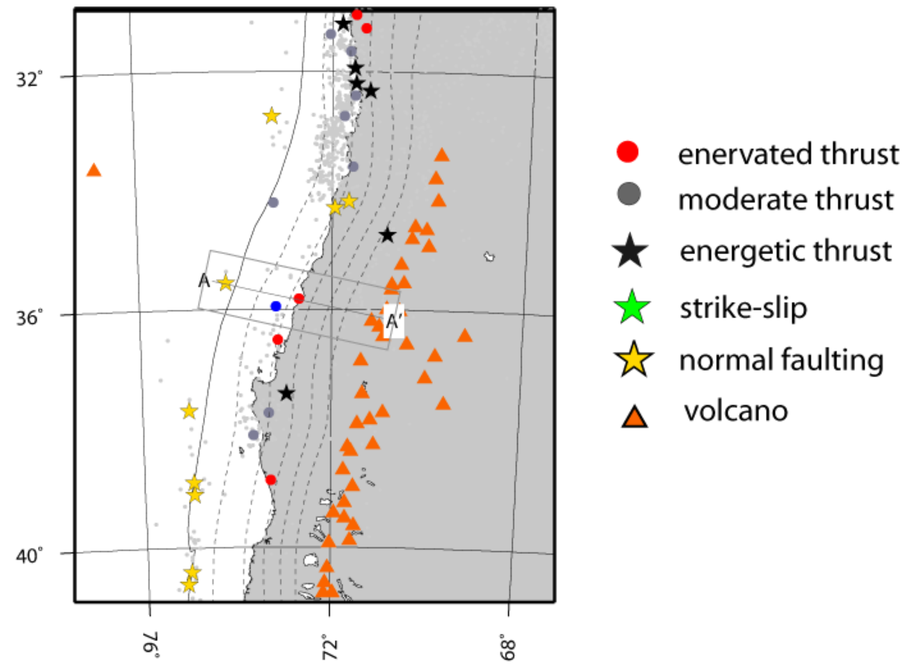
Notes:

(1) Felt (III) at Coquimbo, La Serena, Ovalle and Vicuna.

(2) Five people killed at Pueblo Nuevo, one person killed at Coquimbo, one person killed at La Chimba and another died of a heart attack at Punitaqui. More than 300 people injured, 5,000 houses destroyed, 5,700 houses severely damaged, another 10,000 houses slightly damaged, numerous power and telephone outages, landslides and rockslides in the epicentral region. Some damage (VII) at La Serena and (VI) at Ovalle. Felt (VI) at Alto del Carmen and Illapel; (V) at Copiapo, Huasco, San Antonio, Santiago and Vallenar; (IV) at Caldera, Chanaral, Rancagua and Tierra Amarilla; (III) at Talca; (II) at Concepcion and Taltal. Felt as far south as Valdivia. Felt (V) in Mendoza and San Juan Provinces, Argentina. Felt in Buenos Aires, Catamarca, Cordoba, Distrito Federal and La Rioja Provinces, Argentina. Also felt in parts of Bolivia and Peru.

Radiated Energy of Global Subduction-Thrust Earthquakes





Main Shock Cross-section