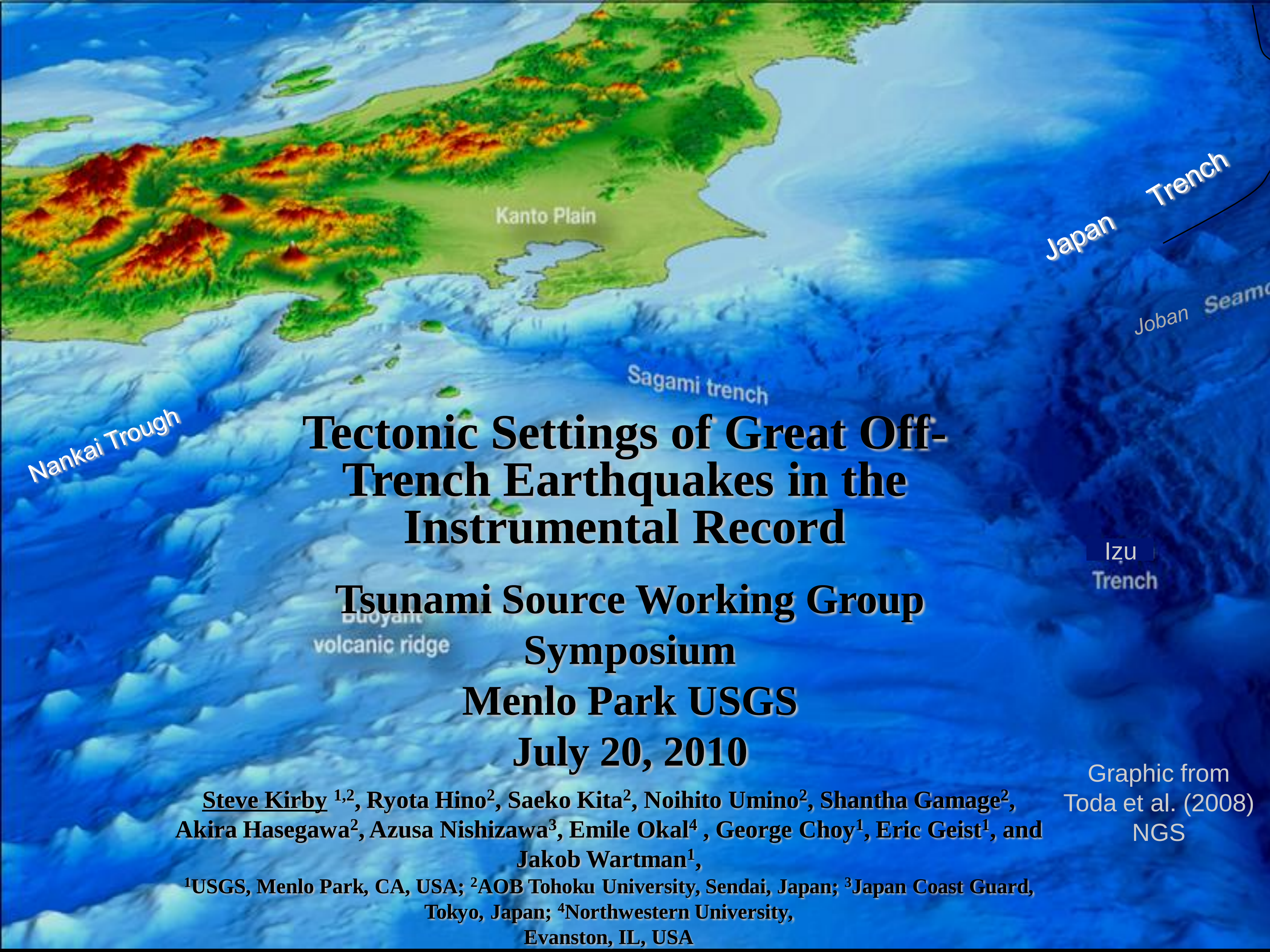


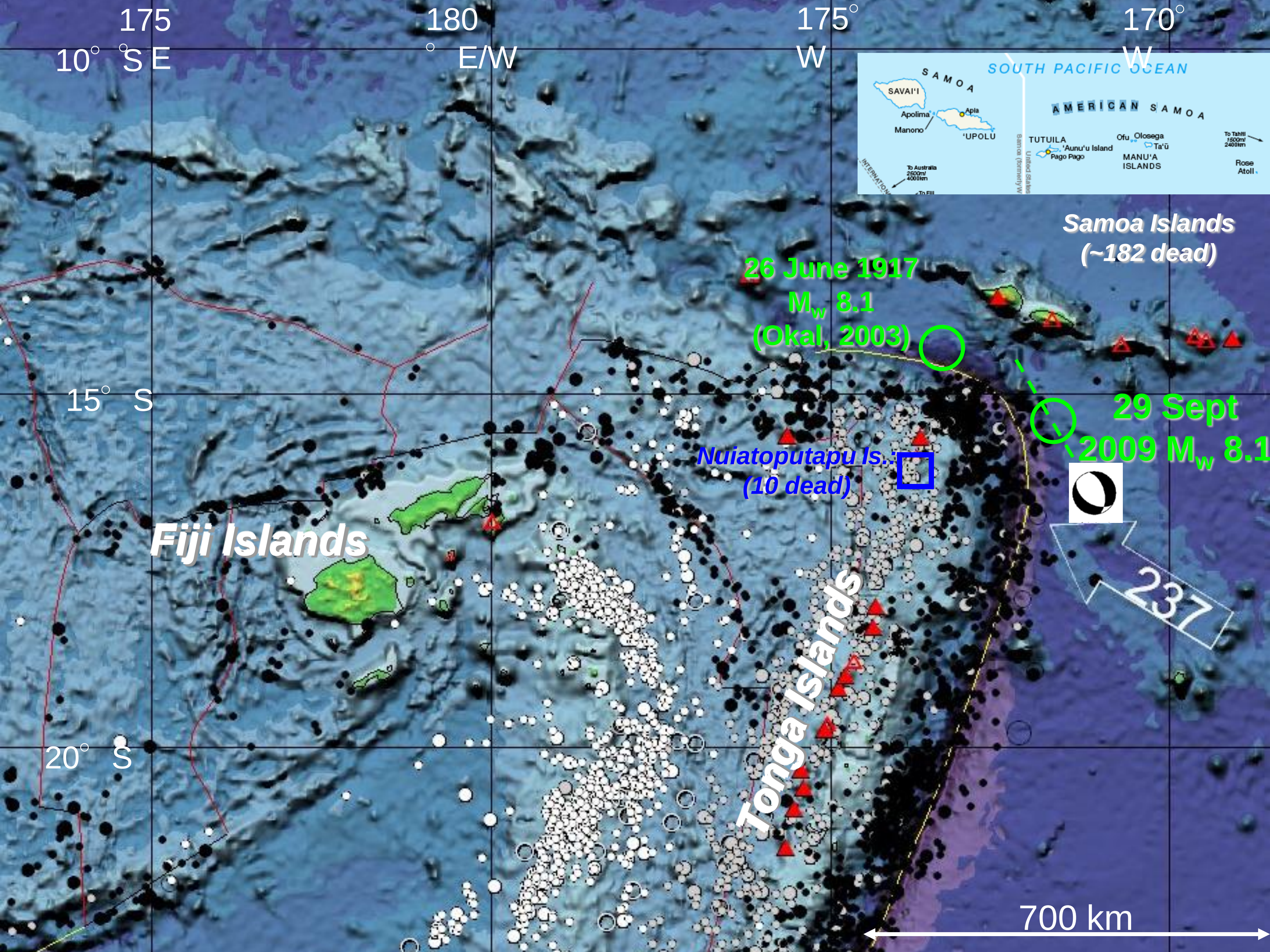
Tectonic Settings of Great Off-Trench Earthquakes in the Instrumental Record

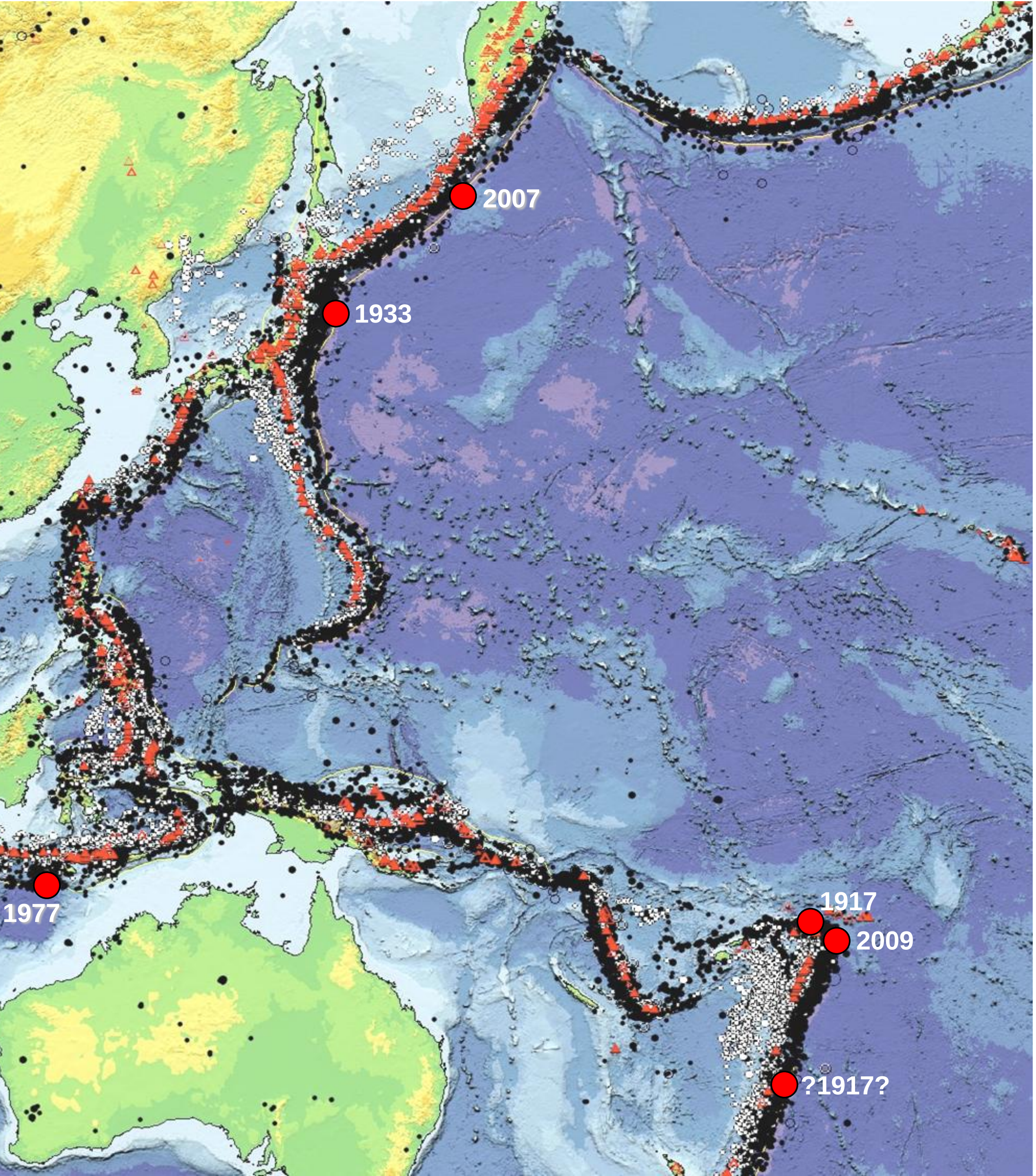
Tsunami Source Working Group Symposium
Menlo Park USGS
July 20, 2010

Steve Kirby[1,2], Ryota Hino[2], Saeko Kita[2], Noihito Umino[2], Shantha Gamage[2], Akira Hasegawa[2], Azusa Nishizawa[3], Emile Okal[4] , George Choy[1], Eric Geist[1], and Jakob Wartman[1],

[1]USGS, Menlo Park, CA, USA; [2]AOB Tohoku University, Sendai, Japan; [3]Japan Coast Guard, Tokyo, Japan; [4]Northwestern University, Evanston, IL, USA

Graphic from
Toda et al. (2008)
NGS


175° E
180° E/W
175° W
170° W
10° S
15° S
20° S
SOUTH PACIFIC OCEAN
SAMOA
SAVAI'I
Apolima
Manono
Apia
'UPOLU
AMERICAN SAMOA
TUTUILA
'Aunu'u Island
Pago Pago
Ofu
Olosega
Ta'ū
MANU'A ISLANDS
Rose Atoll
To Tahiti 1500mi/ 2400km
To Australia 2500mi/ 4000km
To Fiji
INTERNATIONA
Samoa (formerly W
United States
Samoa Islands
(~182 dead)
26 June 1917
M_w 8.1
(Okal, 2003)
29 Sept
2009 M_w 8.1
Nuiatoputapu Is.
(10 dead)
Fiji Islands
Tonga Islands
237
700 km



Features Common to these M ≥ 8 Earthquakes

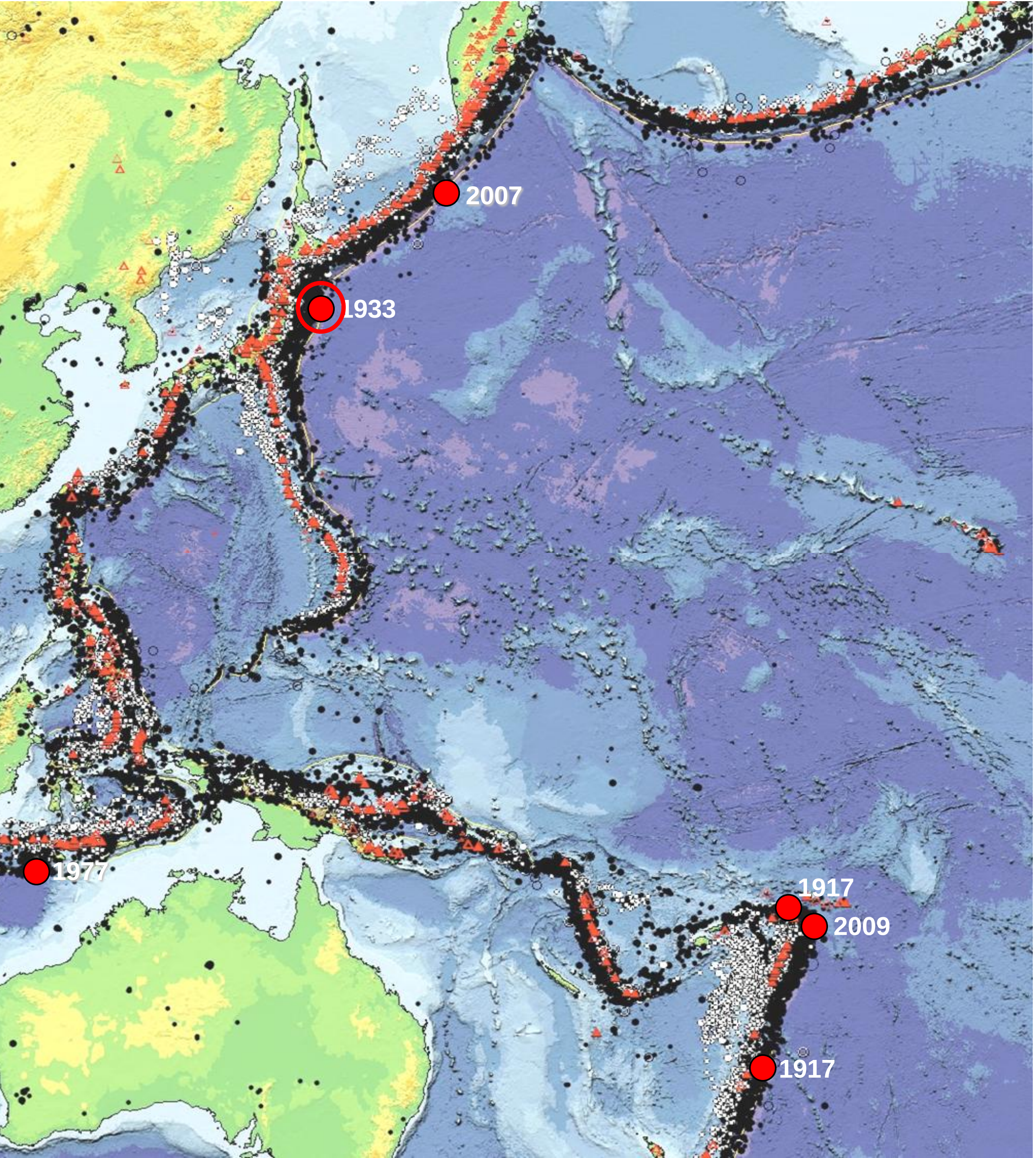
*<u>Incoming plate is Mesozoic in age</u> and hence thermally mature and thick. High stress.

*Where focal mechanisms are known and/or swath maps are available, <u>rupture planes cross-cut seafloor spreading fabric at high angles</u> (> 30°).

*Well-located great earthquakes occur where <u>outer-rise gravity anomalies are positive and large</u>.

*<u>Dip angles on rupture planes are high compared to megathrust earthquakes</u>.

*Combined with the large ocean depths in the epicentral areas, <u>such events should produce bigger tsunamis for a given Mo than megathrust EQ's of similar moment</u>.



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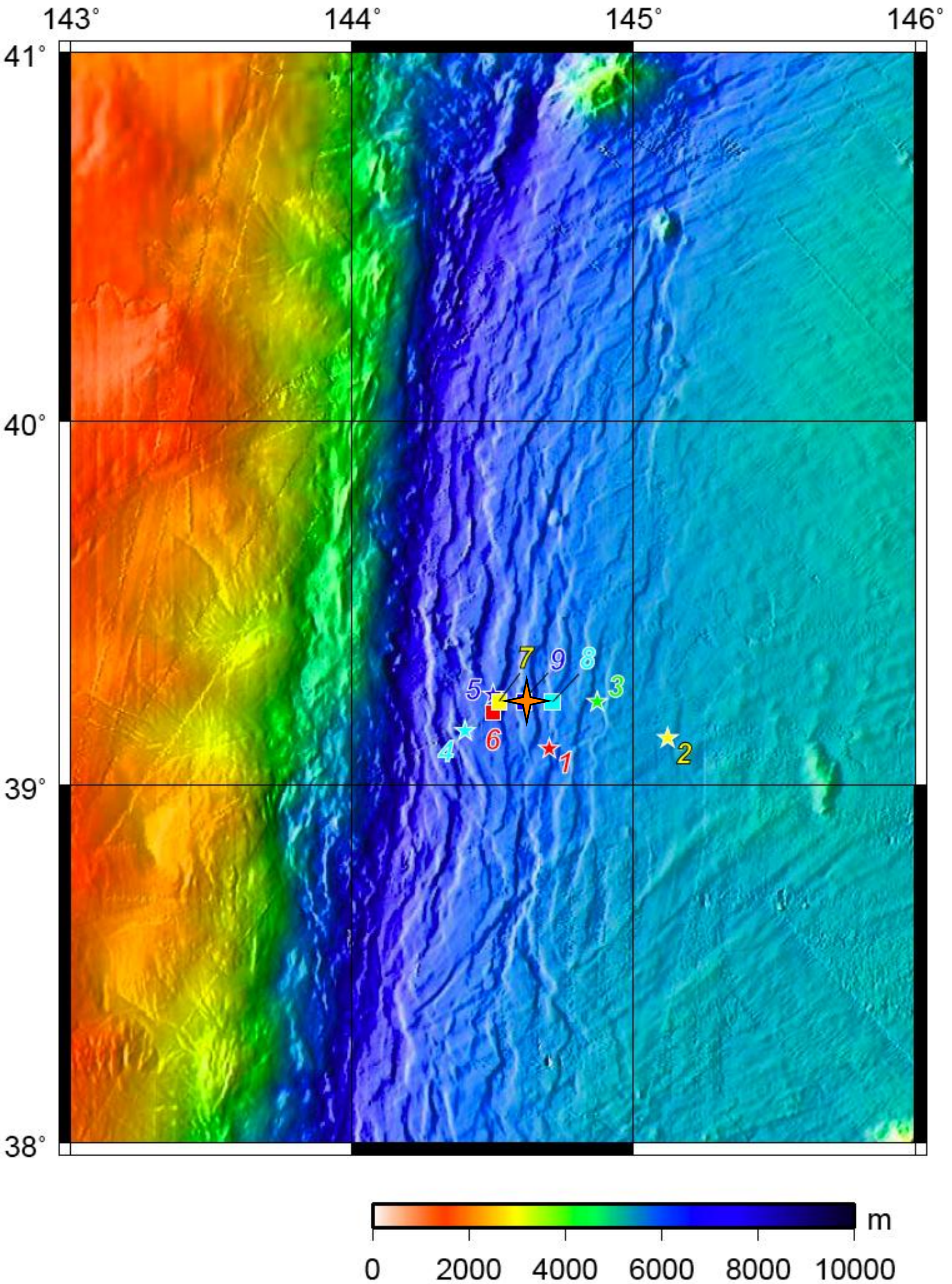
Reported Hypocenters of the 2 March 1933 Sanriku-oki Earthquake

Modern teleseismic hypocenter and OT

✦ ϕ: 39.23° N; λ: 144.61° E
h: < 30 km No depth phases reported.
OT: 17h 30m 56.71 s

1. JMA (1957) ★
2. JMA (2004) ★
3. Honda & Takehama (1933) ★
4. Matuzawa (1935) ★
5. Gutenberg (1956) ★
6. Kanamori (1971) ■
7. Utsu (2000) □
8. Engdahl (EHB: 2004, unpub.) ■
9. Eric Bergman (2004, unpub.) ■

Bathymetry by JHD (Nishizawa, 2009)

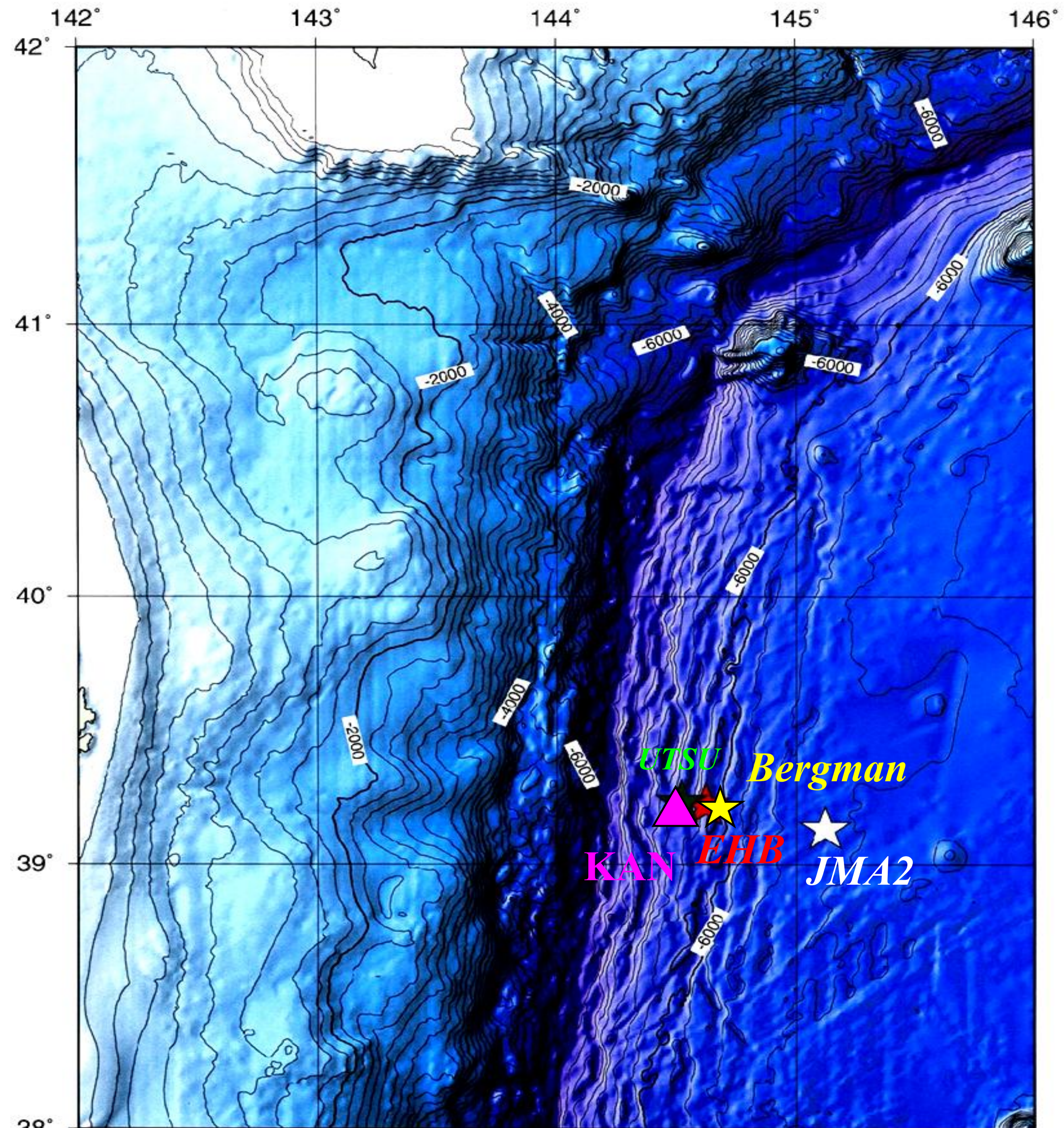


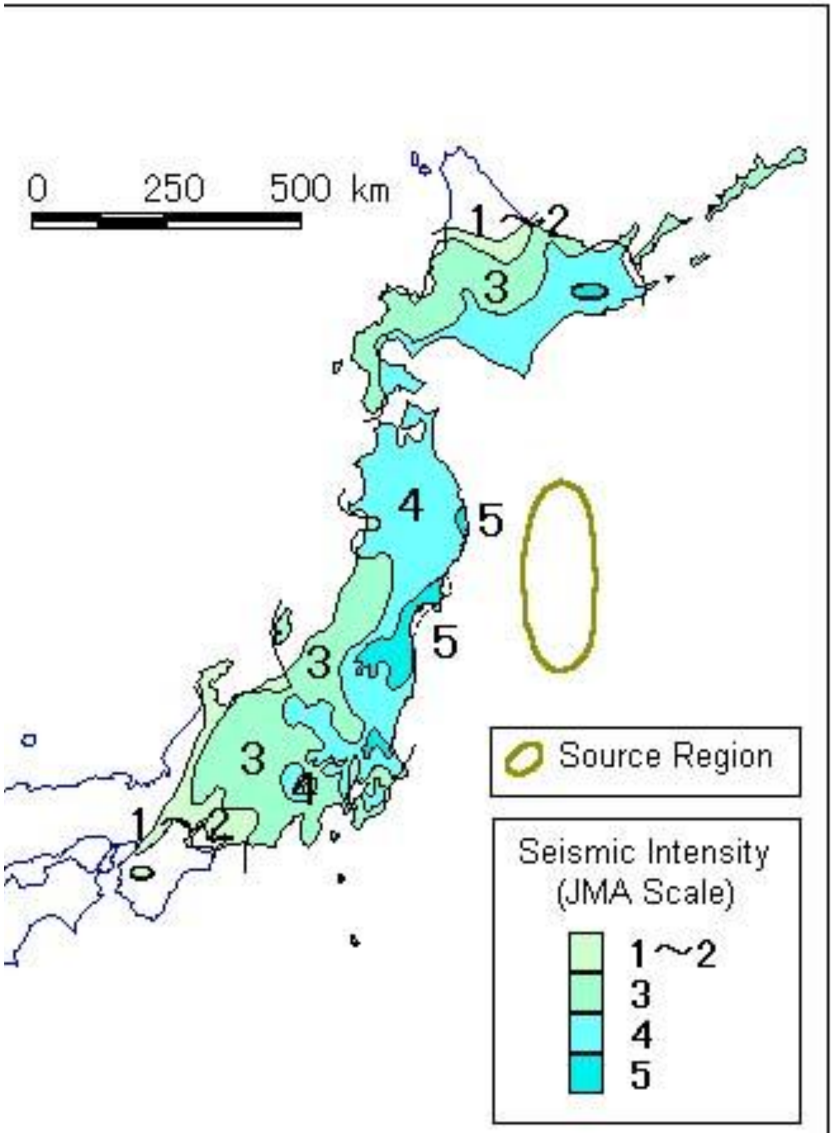
M8.4+ Sanriku-oki Earthquake of 2 March 1933

*Mw 8.4+ largest outer-rise/outer trench slope earthquake in the instrumental record

*Maximum JMA seismic intensity = 5

*3,064 deaths (est.) on Sanriku coast, mostly by the tsunami





Seismological evidence for a lithospheric normal faulting – the Sanriku earthquake of 1933

Hiroo Kanamori

Earthquake Research Institute, University of Tokyo, Tokyo, Japan

Received 10 September 1970. Available online 11 October 2002.

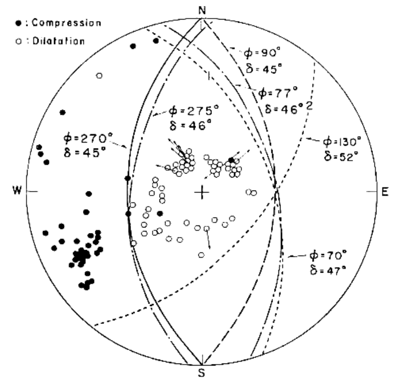


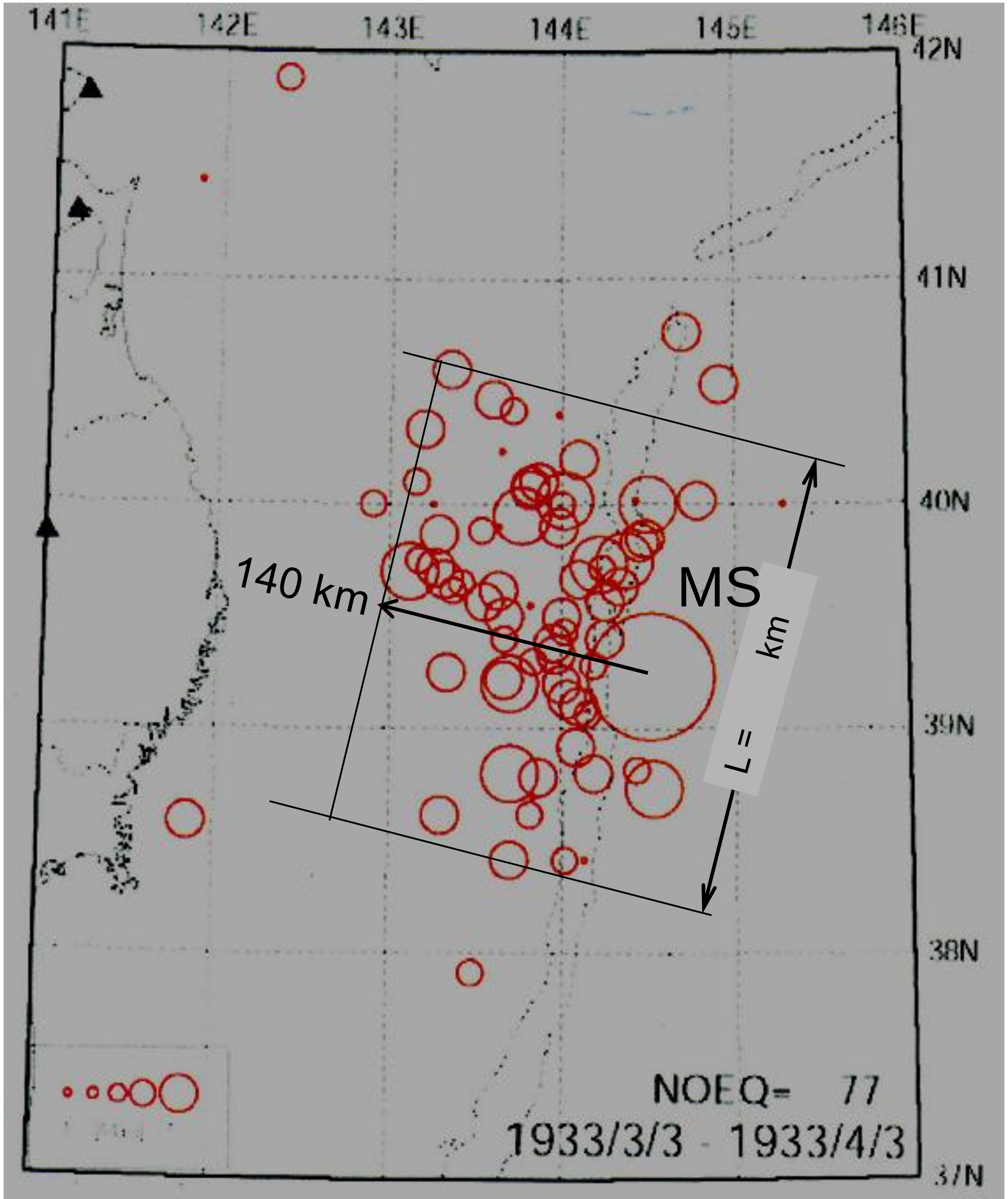
Fig. 4. Stereographic projection of the lower half of the focal sphere on the Wulff grid. ϕ is the dip direction measured clockwise from the north and δ is the dip angle. *P* wave first motion data (open and closed circles) and the polarization angles of *S* waves (arrows) are shown. The dash–dot curves show the solution determined by *S* wave data.

Abstract

The focal process of the Sanriku earthquake of March 2, 1933, is discussed in relation to the bending mechanism of the lithosphere. On the basis of the *P* times obtained at more than 200 stations, it is confirmed that the hypocenter of this earthquake is within the lithosphere beneath the Japan trench. The *P* wave fault plane solution, the amplitude of long-period (100 s) Love and Rayleigh waves and two near-field observations suggest, almost definitely, that the Sanriku earthquake represents a predominantly normal faulting on a plane dipping 45° towards N 90° W. A fault size of 185 × 100 km^2, in agreement with the size of the aftershock area, is required to yield a slip dislocation of 3.3 m, a value consistent with the tsunami data. This result suggests that the fracture took place over the entire thickness of the lithosphere, thereby precluding the possibility that the Sanriku earthquake merely represents a surface tensile crack due to the bending of the lithosphere. This large scale lithospheric faulting is presumably due to a gravitational pull exerted by the cold sinking lithosphere. The fracture probably took place on an old fault plane which had once fractured and healed up. The existence of this fracture zone which decouples, to some extent, the oceanic lithosphere from the sinking lithosphere accounts for the sharp bend of the lithosphere beneath oceanic trenches and also the abrupt disappearance of seismic activity across oceanic trenches. The sharp bend of the lithosphere is therefore a result, not the cause, of great earthquakes beneath oceanic trenches.

Physics of The Earth and Planetary Interiors
Volume 4, Issue 4 , April 1971, Pages 289–300

JMA: One-month aftershocks of the 1933 Sanriku Earthquake



A Mystery - The Large Width of Aftershock Zone:

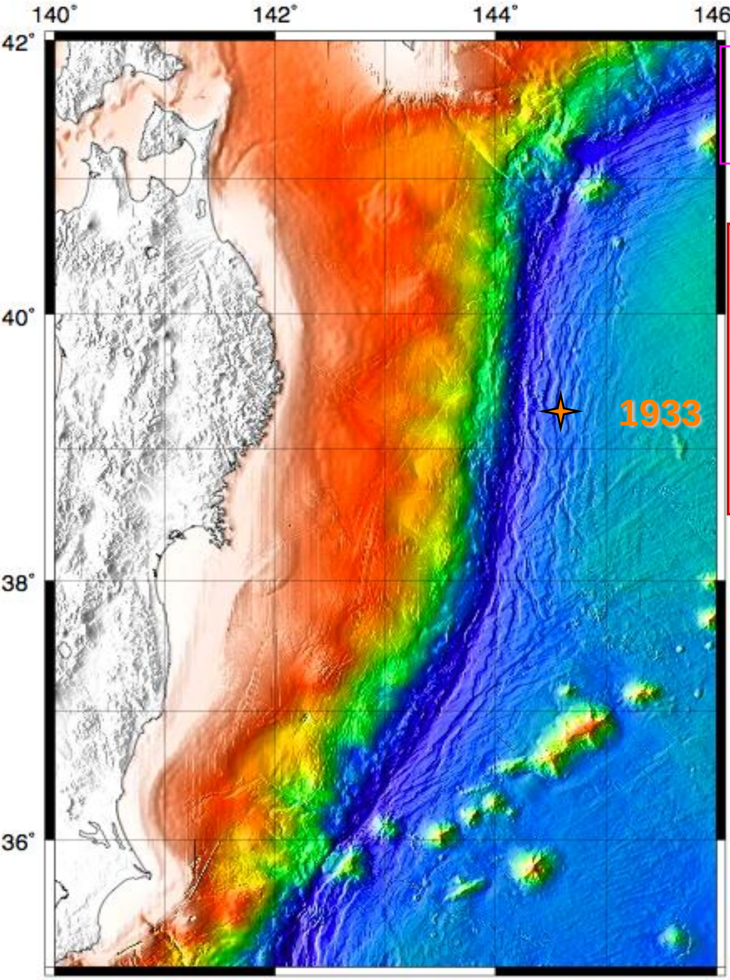
"Aftershocks" east of the Japan Trench represent the effects of stress transfer to the megathrust boundary and to bending deformation of the slab.

Modern Source Models

Moment, M_o 10^{28} dyn-cm (Mw)	Rupture Length L, km	Rupture width W, km	Dip Angle °	Slip, u average, m	Reference
4.3 (8.4)	185	100	45	3.3 m	Kanamori (1971) 100 s sw's
9.5 (8.7)	220	35	45	17.1 m	Okal (1992) M_o , >> 100 s sw's L&W: This Work
8 (8.6)	≈ 280	≈ 50	45	11 m	Kanamori (2009) from very long period PAS record, unpublished

- Normal faulting mechanism ($\phi = 347^\circ$; $\delta = 46^\circ$; $\lambda = 247^\circ$; Kanamori, 1971)
- Maximum depth of rupture (new result):
  25 km below seafloor, 31 km in depth. Gives W = 35 km
- $\mu = 7.2 \times 10^{11}$ dyn/cm^2 shallow upper-mantle rigidity (Kanamori, 1971)

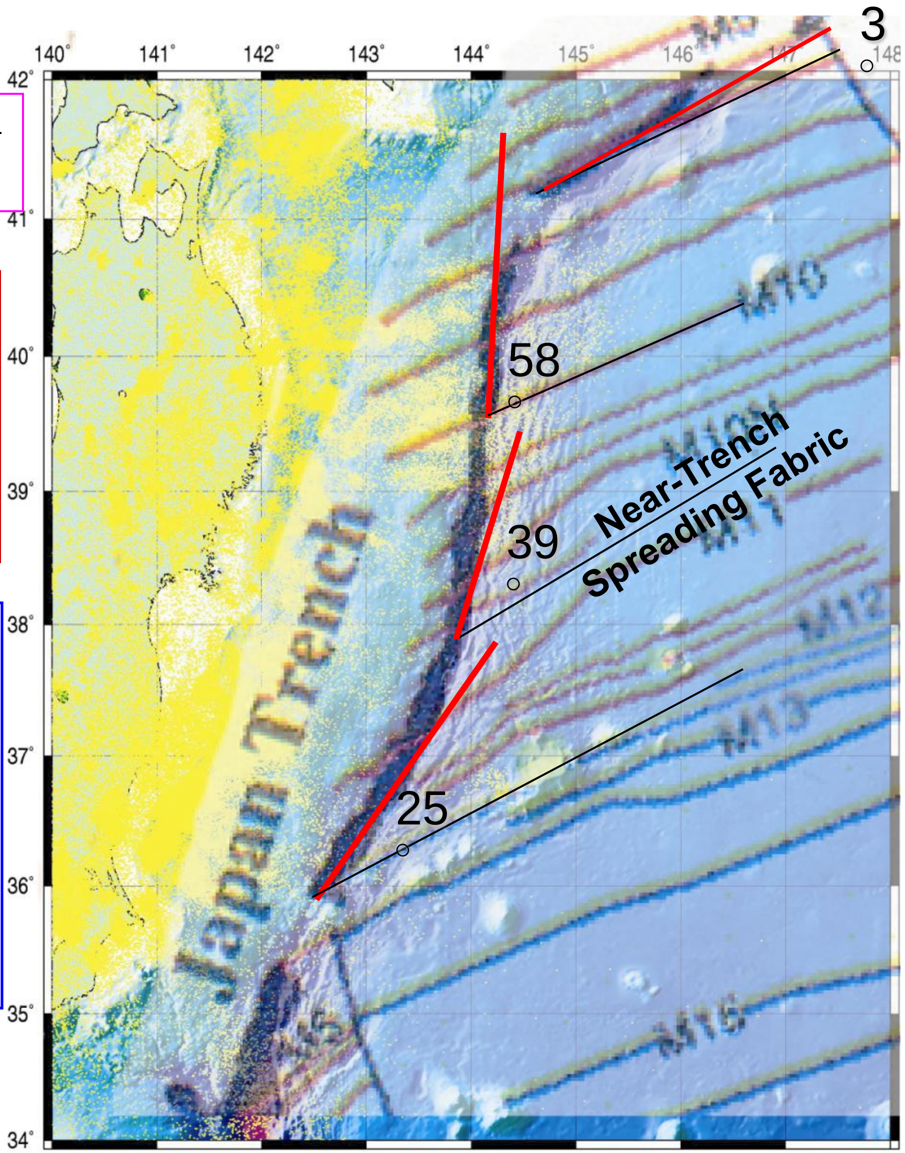
North-South Changes in OR/OTS Fault Scarp Morphology with Trench Obliquity to Magnetic Anomalies and MOR Abyssal Hills

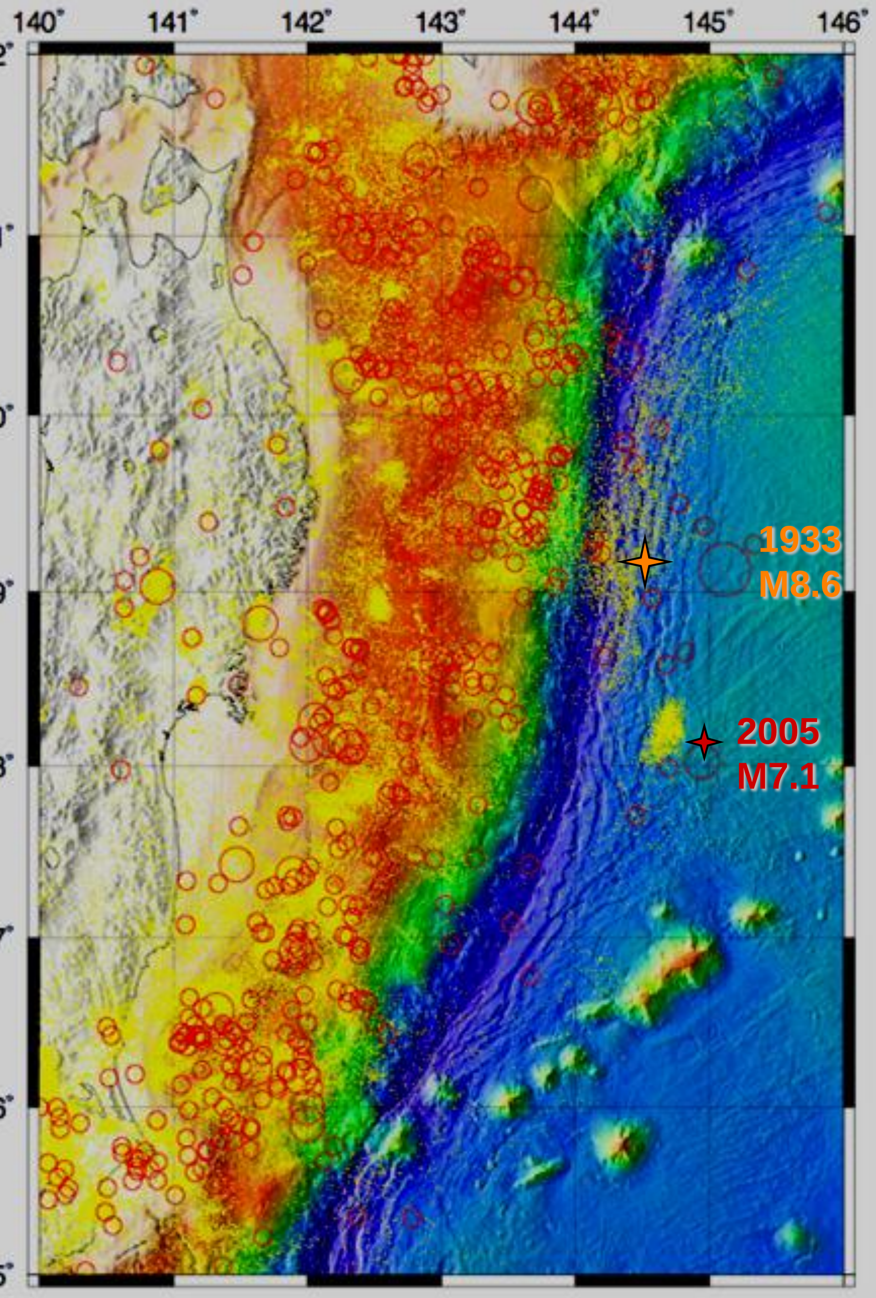


Hokkaido/Kuriles:
Scarps ~// MOR Fabric

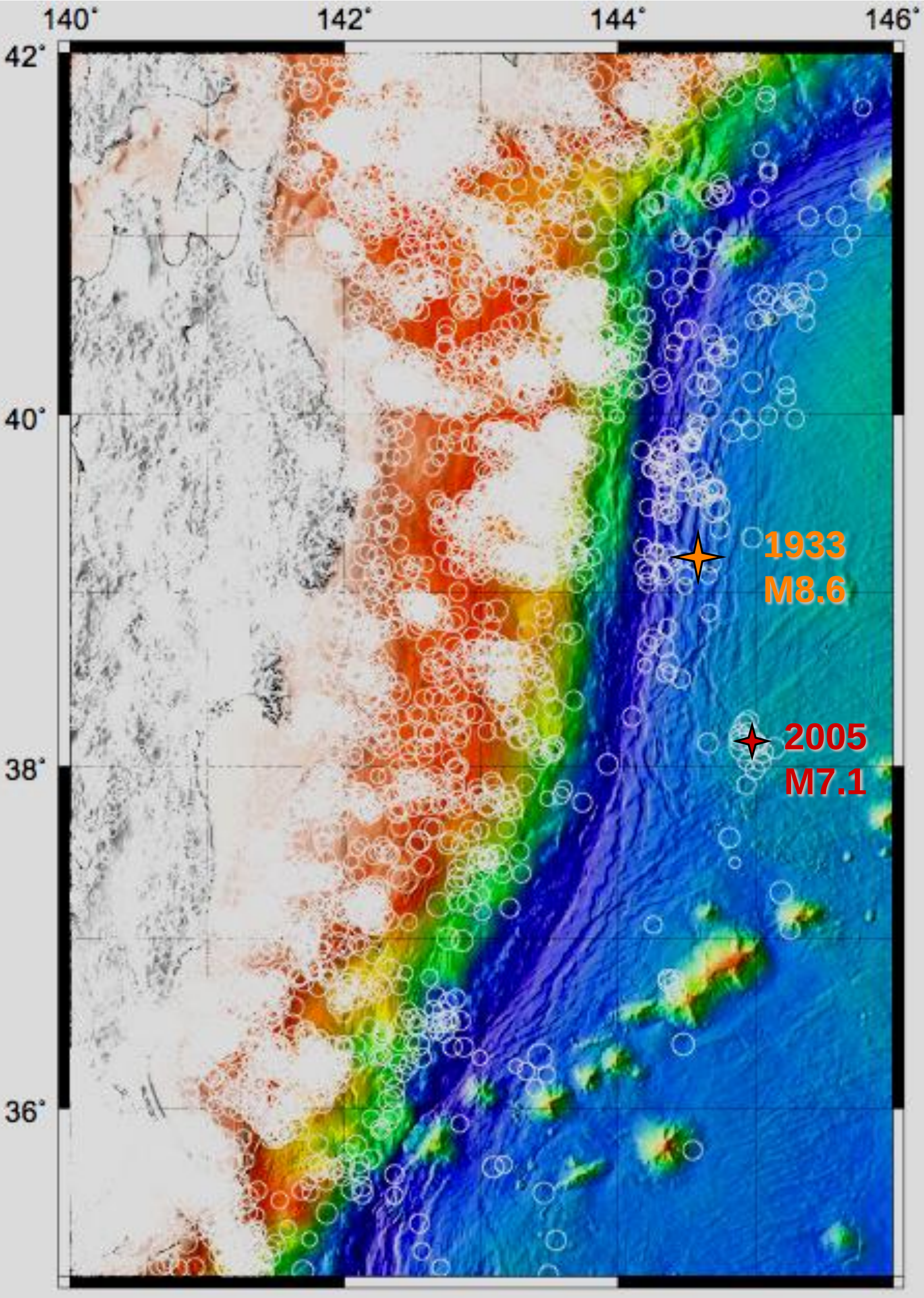
Northern JT:
Scarps ~// trench that cross-cut MOR fabric at high angles

Southern JT:
Zig-zag scarps with segments trench // that cross-cut MOR fabric and segments // MOR fabric

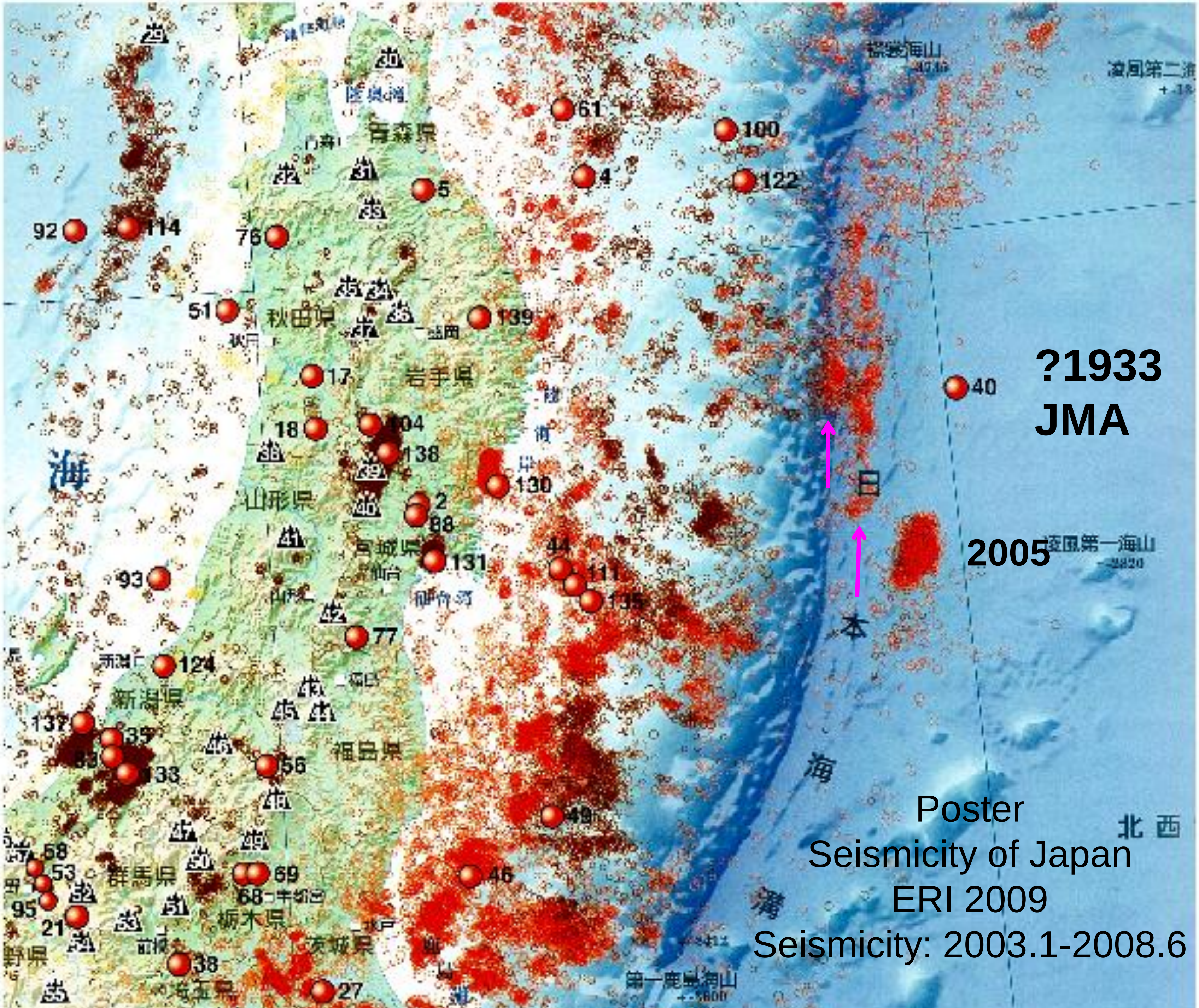




JMA 1923-2008



EHB (1964-2007)



?1933
JMA

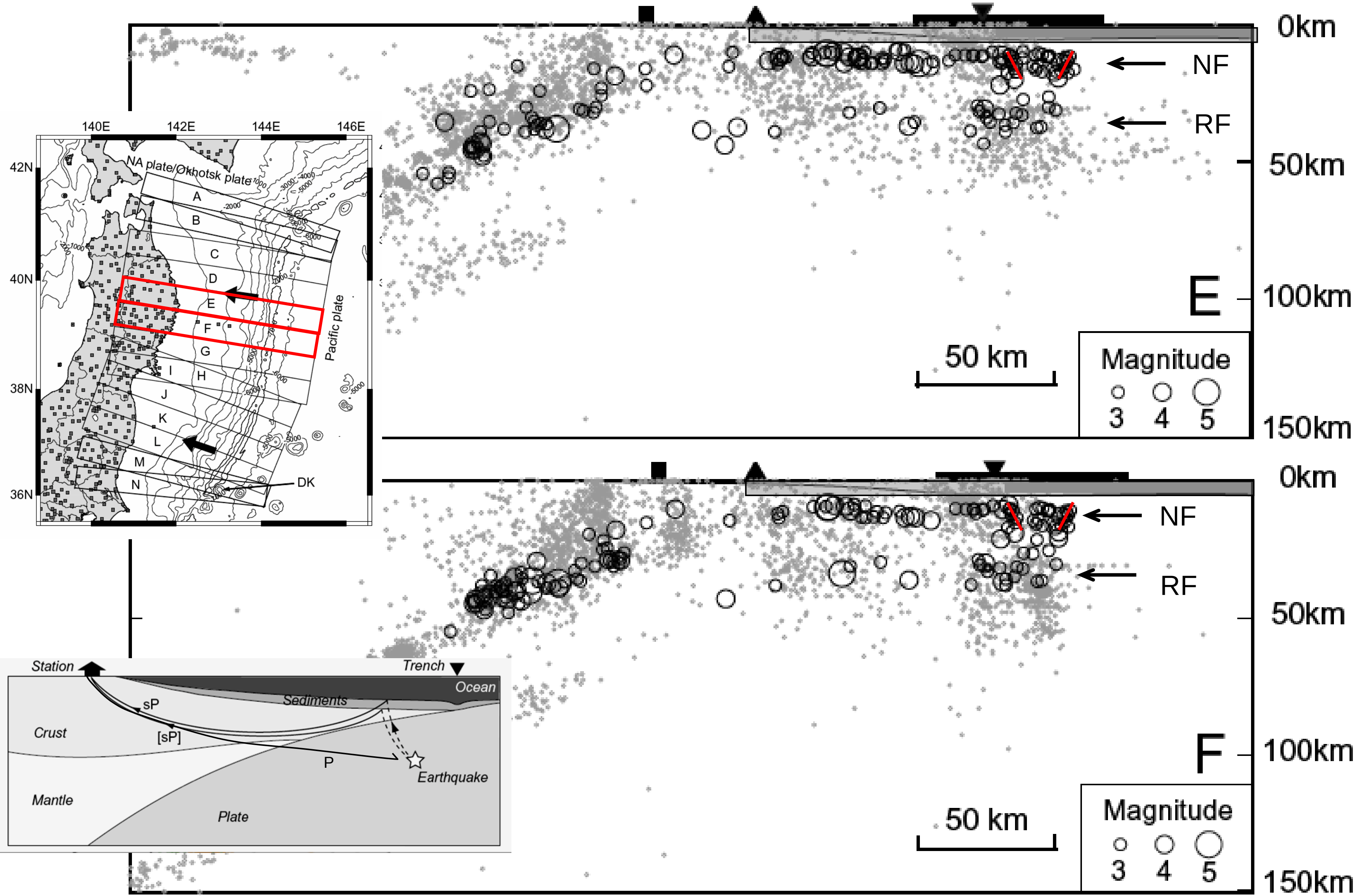
2005

Poster
Seismicity of Japan
ERI 2009
Seismicity: 2003.1-2008.6

Double seismic zone near-trench seismicity based on sP-P depth-phase delays

Upper zone: Normal faulting; Lower zone: Reverse faulting

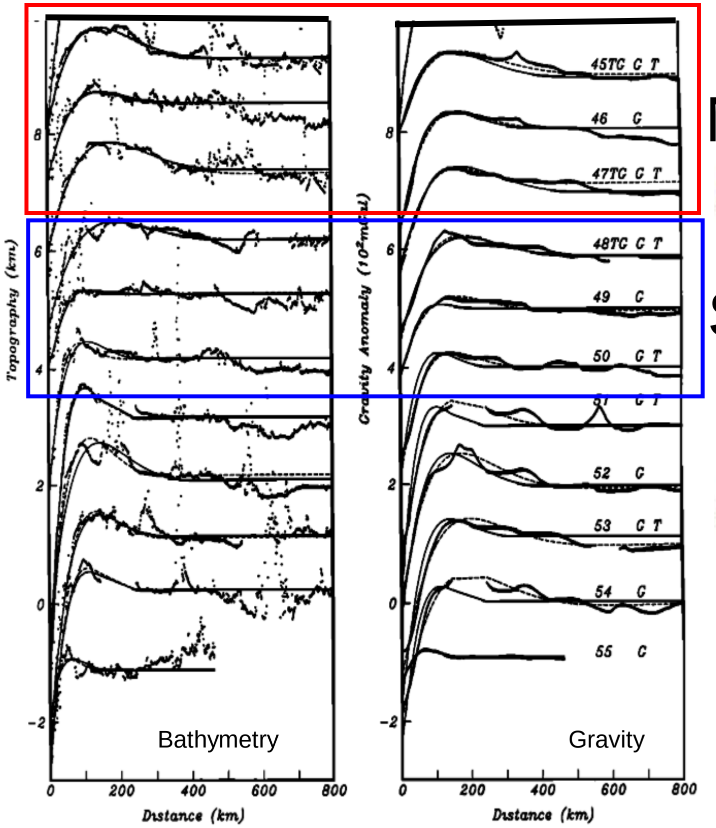
Gamage, Umino, Hasegawa, and Kirby (GJI, 2009)

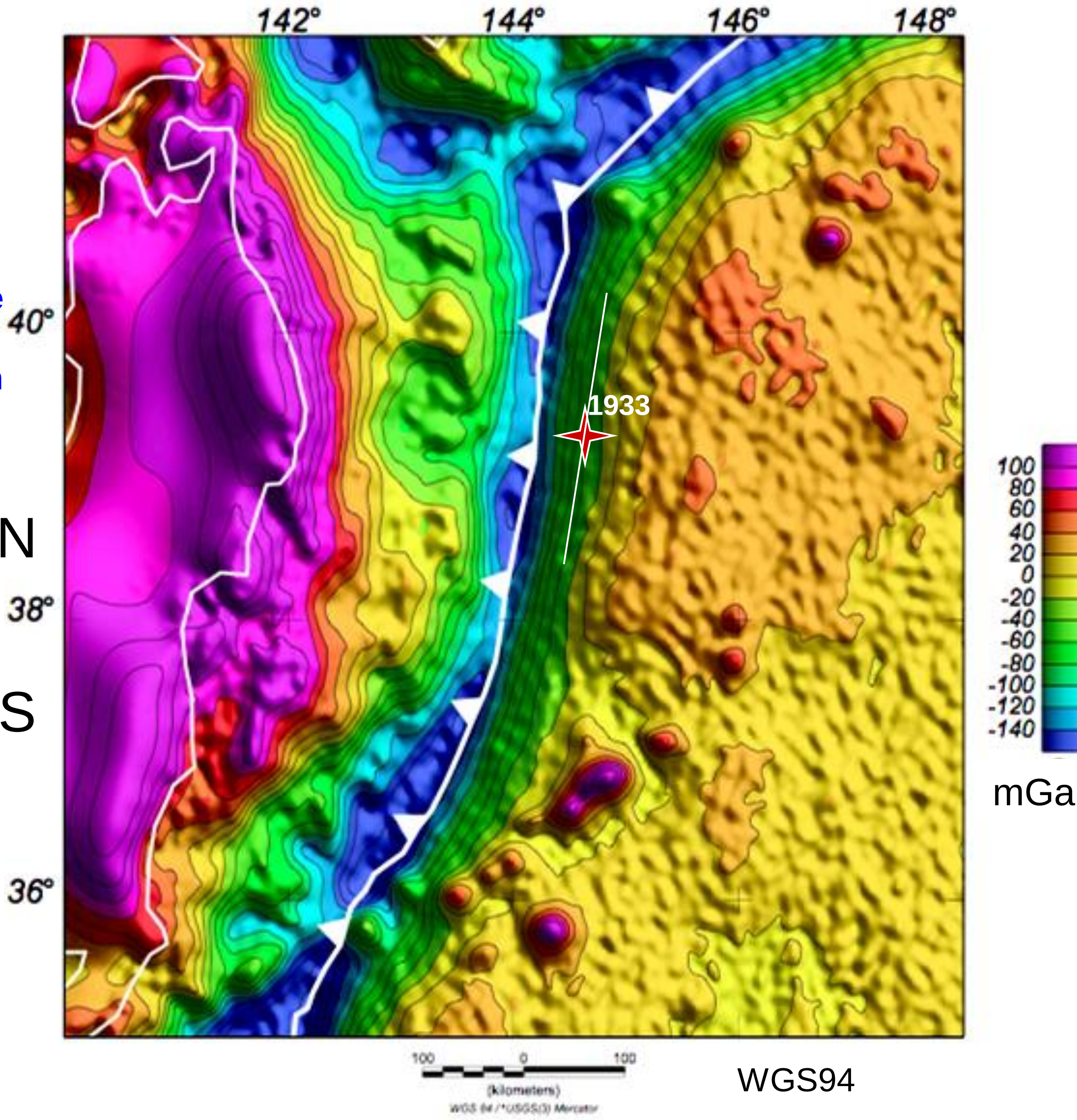


Japan Trench Gravity

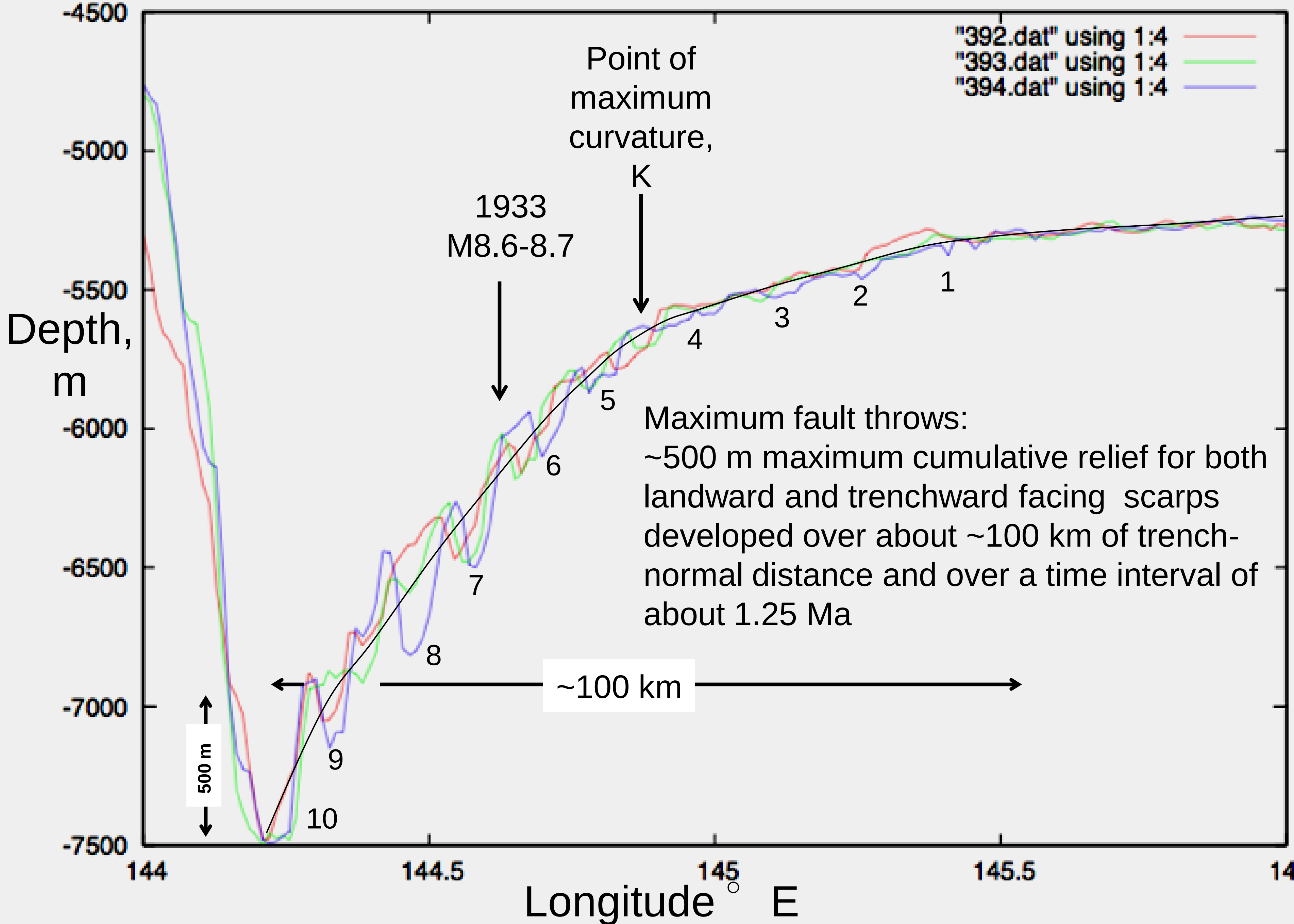
1933 Source Sanriku-oki region of the N. Japan Trench has an <u>exceptionally large outer-rise gravity anomaly and bathymetric relief, among the highest on Earth</u>

Levitt and Sandwell (JGR 1995) flexure model: Estimates of bending resistance for the northern Japan Trench:
M_o = 25 X 10^{16} N; h_e = 60 km; h_m = 70 km





Three Depth Profiles of the Japan Trench in the 1933 Source Region



Maximum fault throws:
~500 m maximum cumulative relief for both landward and trenchward facing scarps developed over about ~100 km of trench-normal distance and over a time interval of about 1.25 Ma

Comparison of Slip Rates for Normal Faulting with Average Megathrust (MT) Slip Rates

- Megathrust average slip rate (PA:OK): 80 mm/a or *80 km/Ma*

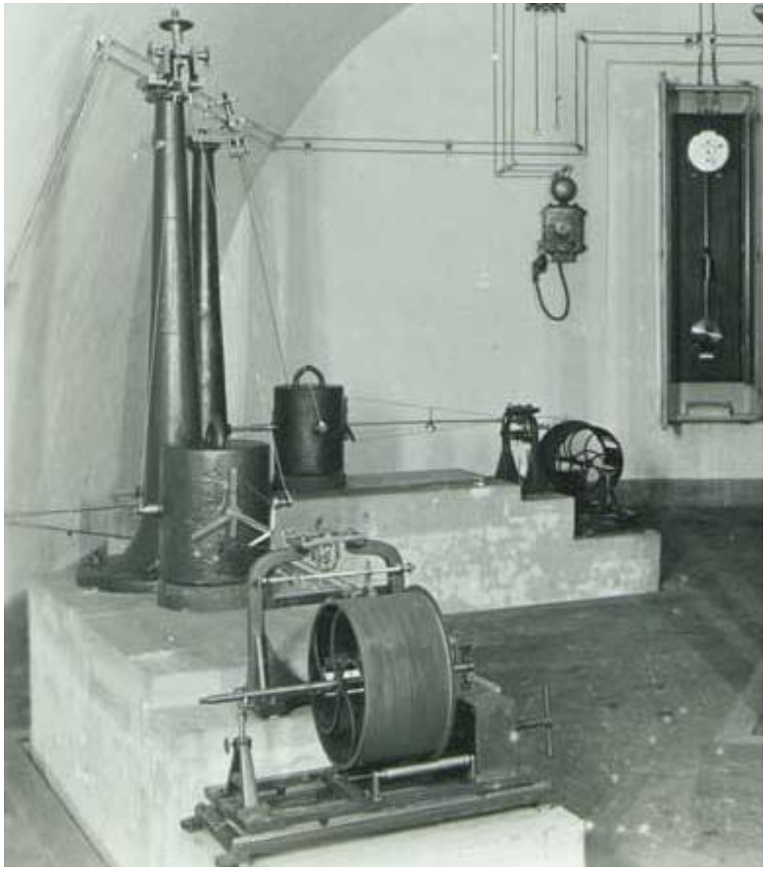
- Normal faulting OR/OTS:
  - *Total cumulative slip on scarps nearest trench: scarps, S ≈ 500 m
  - *Time interval for normal faulting over the outer trench slope of 100 km width:
    T = 100 km/80 km/Ma = 1,250,000 years = 1.25 Ma

Average slip rate = 0.5 km/1.25 Ma = *0.4 km/Ma = 0.4 mm/a* or <u>0.005 of the megathrust slip rate => very slow average slip rate [*But the MT boundary has a very different structure and faulting behavior*]</u>

If most of the slip on these scarps occurs by great OR/OTS earthquakes with average slip, s ≈ 10 m, then a rough average regional return time would be:

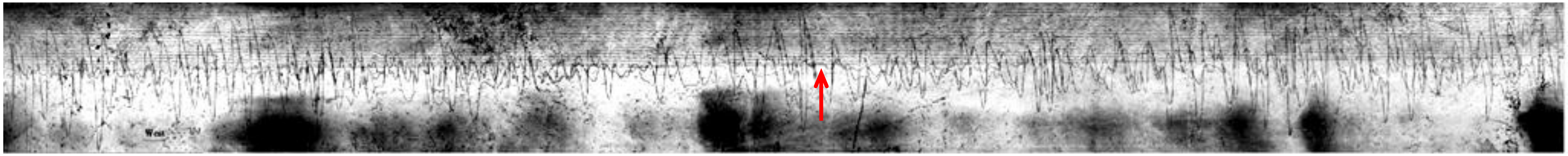
$\Delta T = 10^4$ mm/(0.4 mm/year)/(20 scarps) = 1250 years (a minimum interval, since it neglects the slip contributions of smaller earthquakes and possible fault creep or afterslip).

Thomas A. Jaggar (1871-1953) Founder of the Hawaiian Volcano Observatory and Pioneer in Volcano Seismology and Volcano Science



A Bosch-Omori seismograph like that in the Whitney Vault at HVO in 1933

1916



The 2 March 1933 seismogram written on the E-W Component of the Bosch-Omori seismograph then at HVO

Tsunami Runups from M8.4 Sanriku Japan EQ of 2 March 1933 in Hawai’i and the NE Pacific and Tsunami Forecast by HVO Staff

Other Islands

Oahu Honolulu:	0.3 m
Kukuiula Kauai:	1.2 m
Nawilowili Kauai:	1.2 m
Pakala Kauai:	1.2 m
Lahina, Maui	0.6 m
Midway Is.	?

West Coast N. America (Tide Gage Measurements)

San Francisco (Presido):	0.25 m
Santa Monica:	0.25 m

Smaller waves at Santa Barbara, Los Angeles, Long Beach, La Jolla, and San Diego

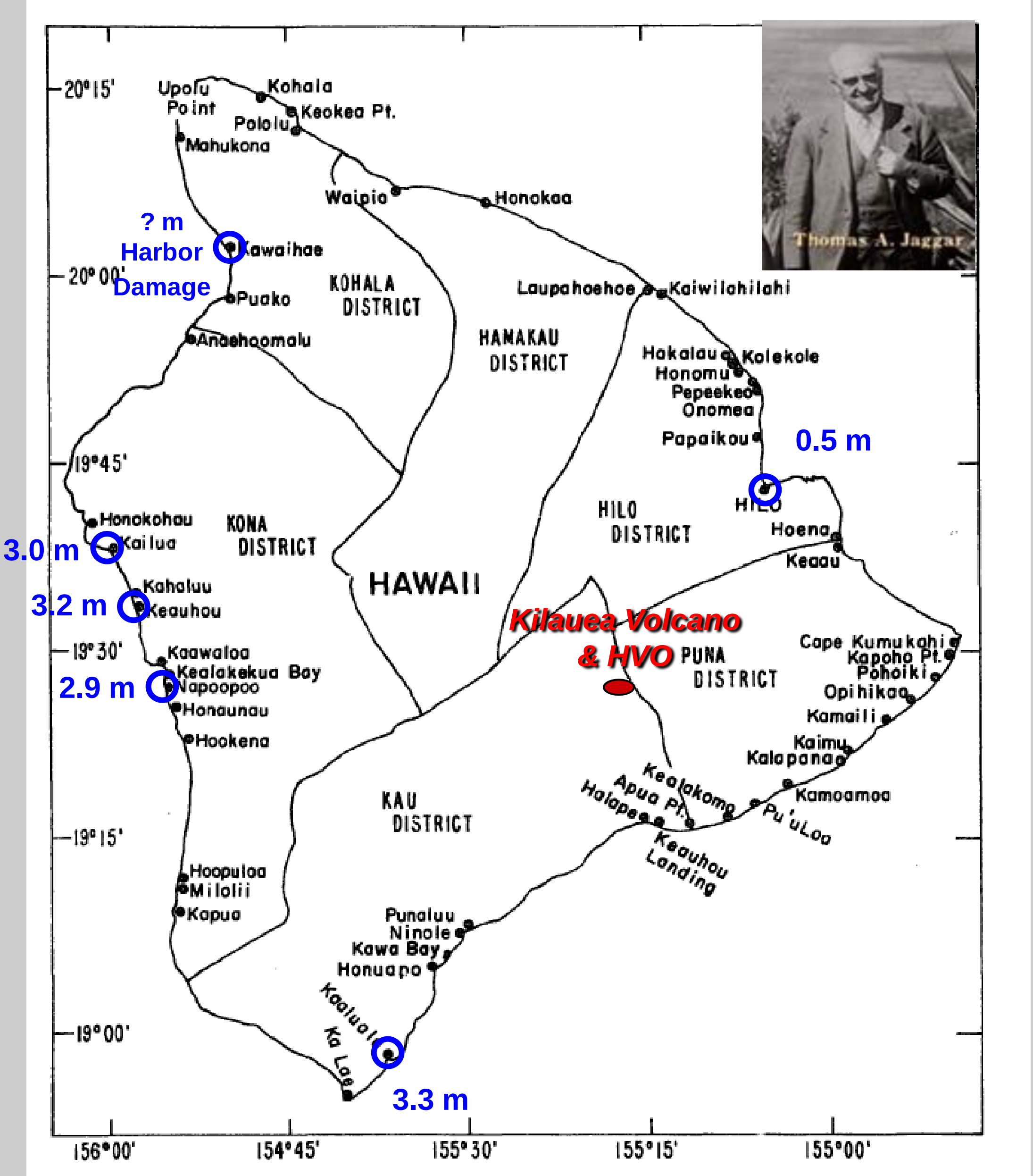
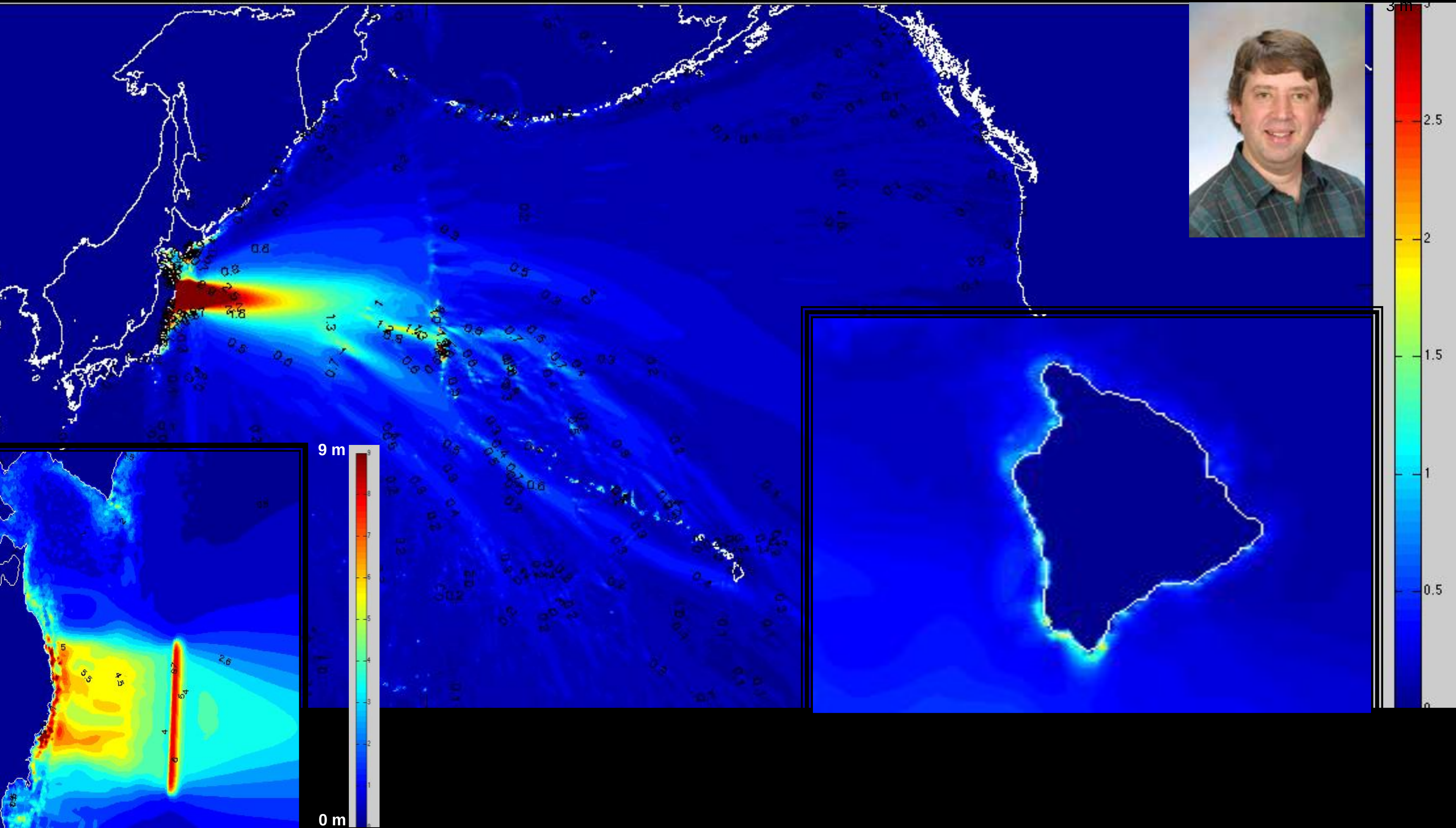


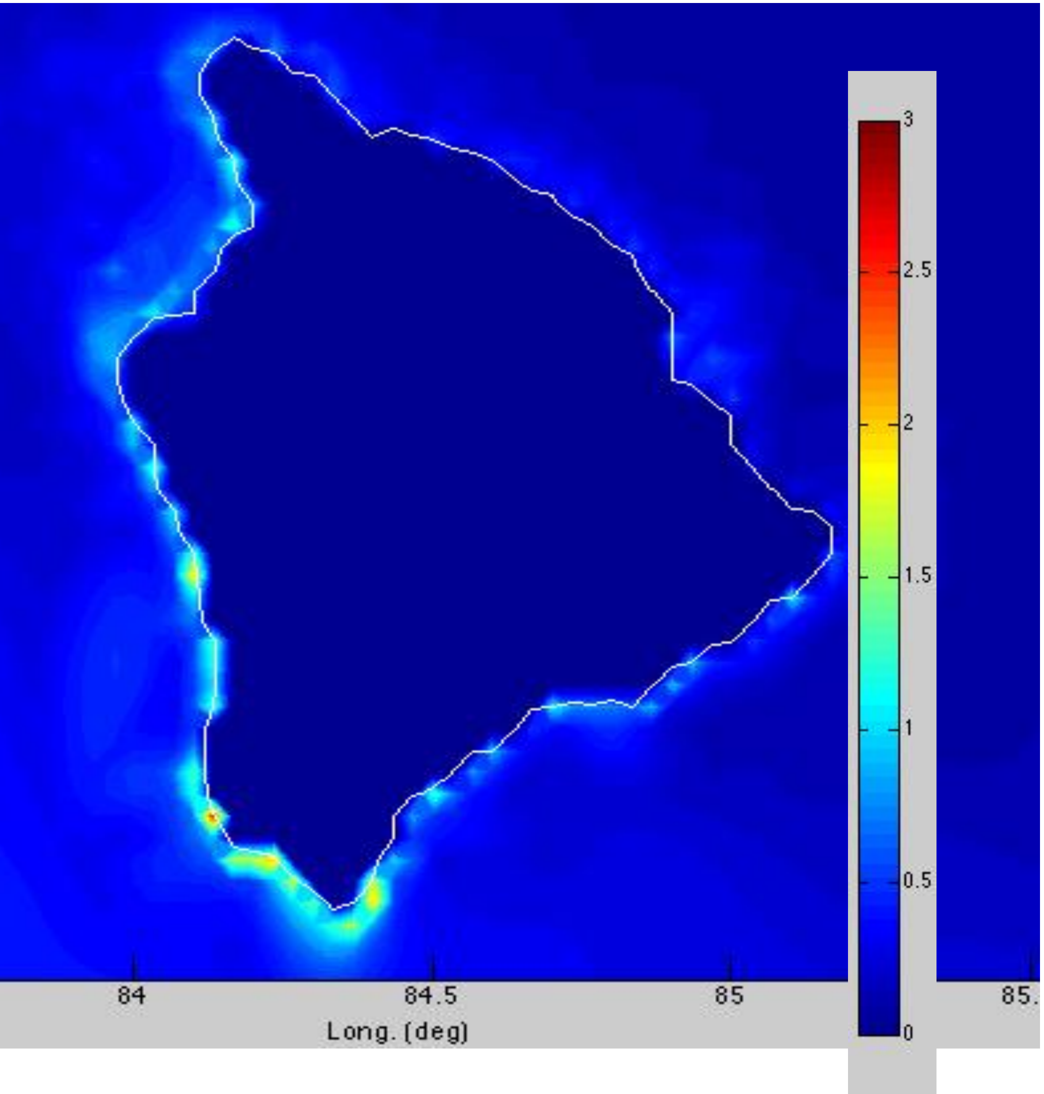
FIGURE 13.—Location map of the Island of Hawaii.

Tsunami Model of the 1933 EQ (Eric Geist)

- **Okal (1992) seismic moment, $M_o = 9.5 \times 10^{28}$ dyn-cm, $M_W = 8.7$**
- **Kirby (2009) Source Dimensions: Length = 220 km; Width = 35 km; Avg. slip = 17.1 m**



Maximum wave heights versus Observed Runups



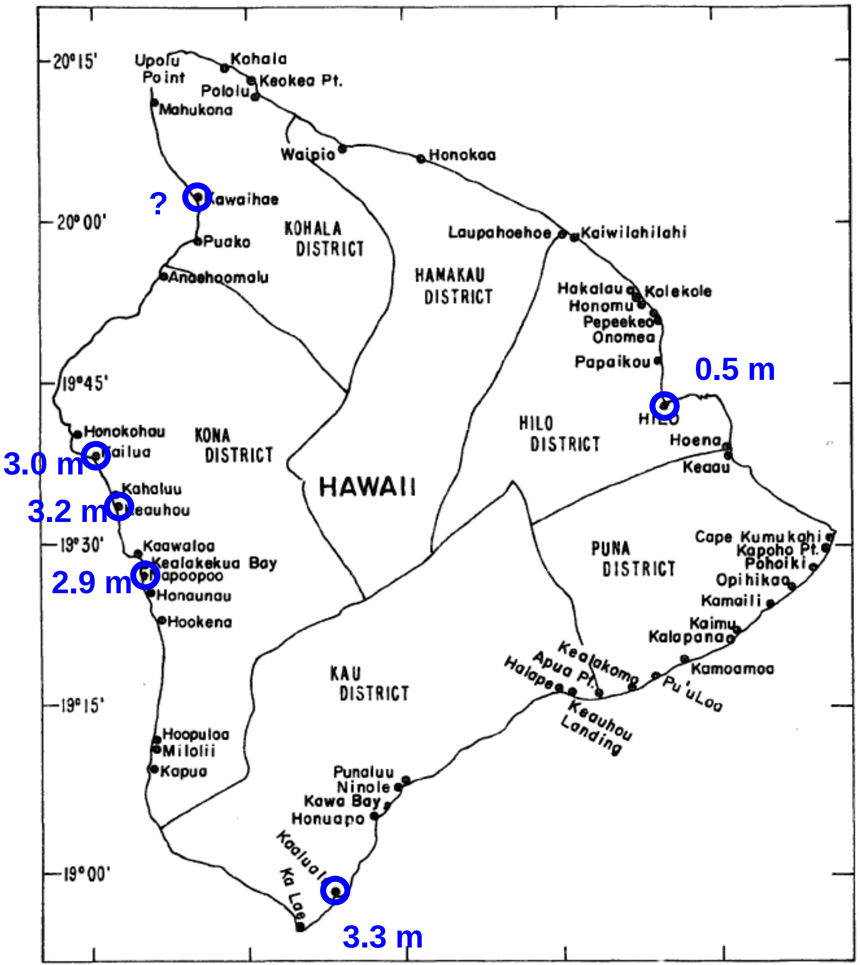
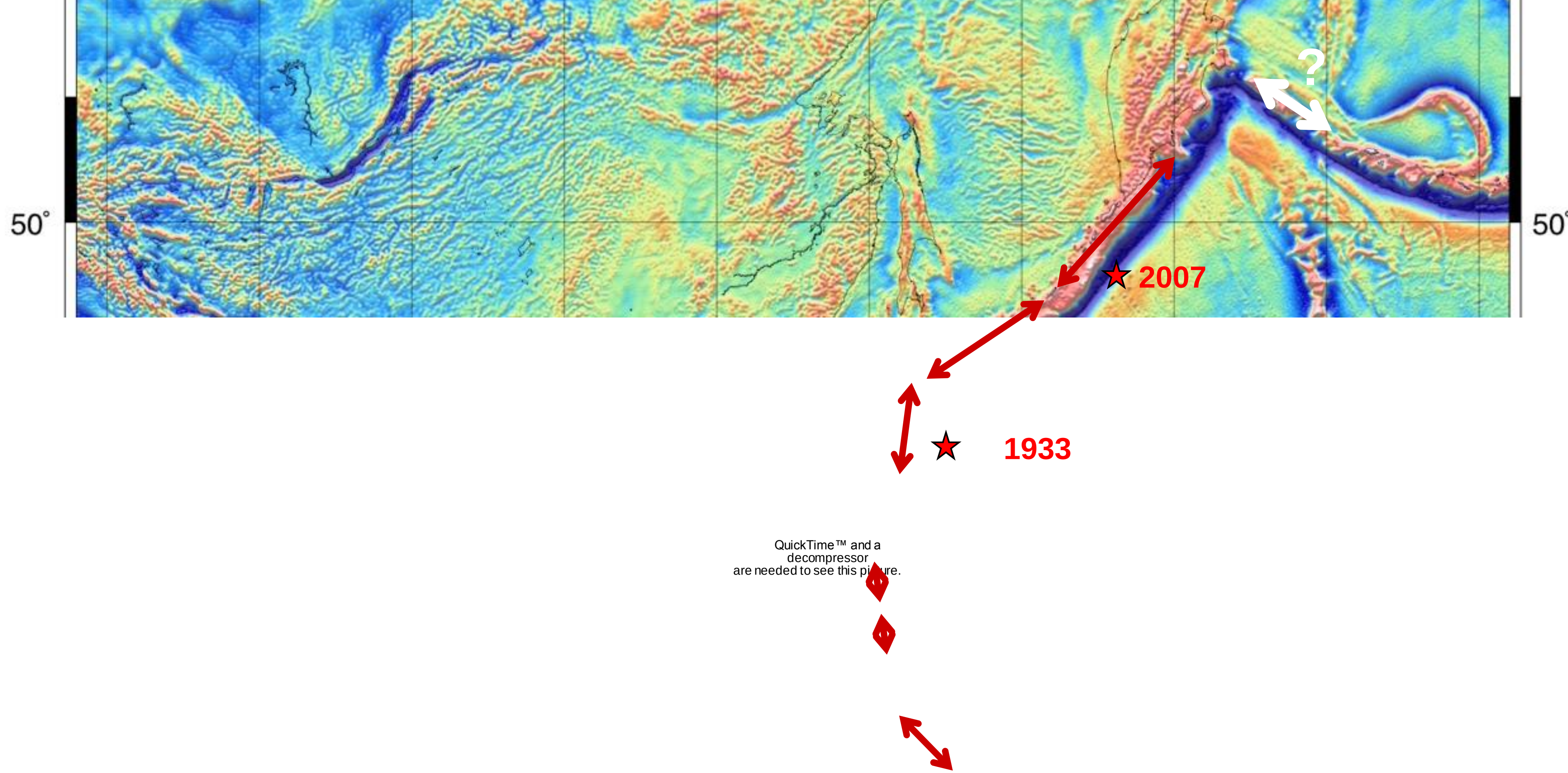
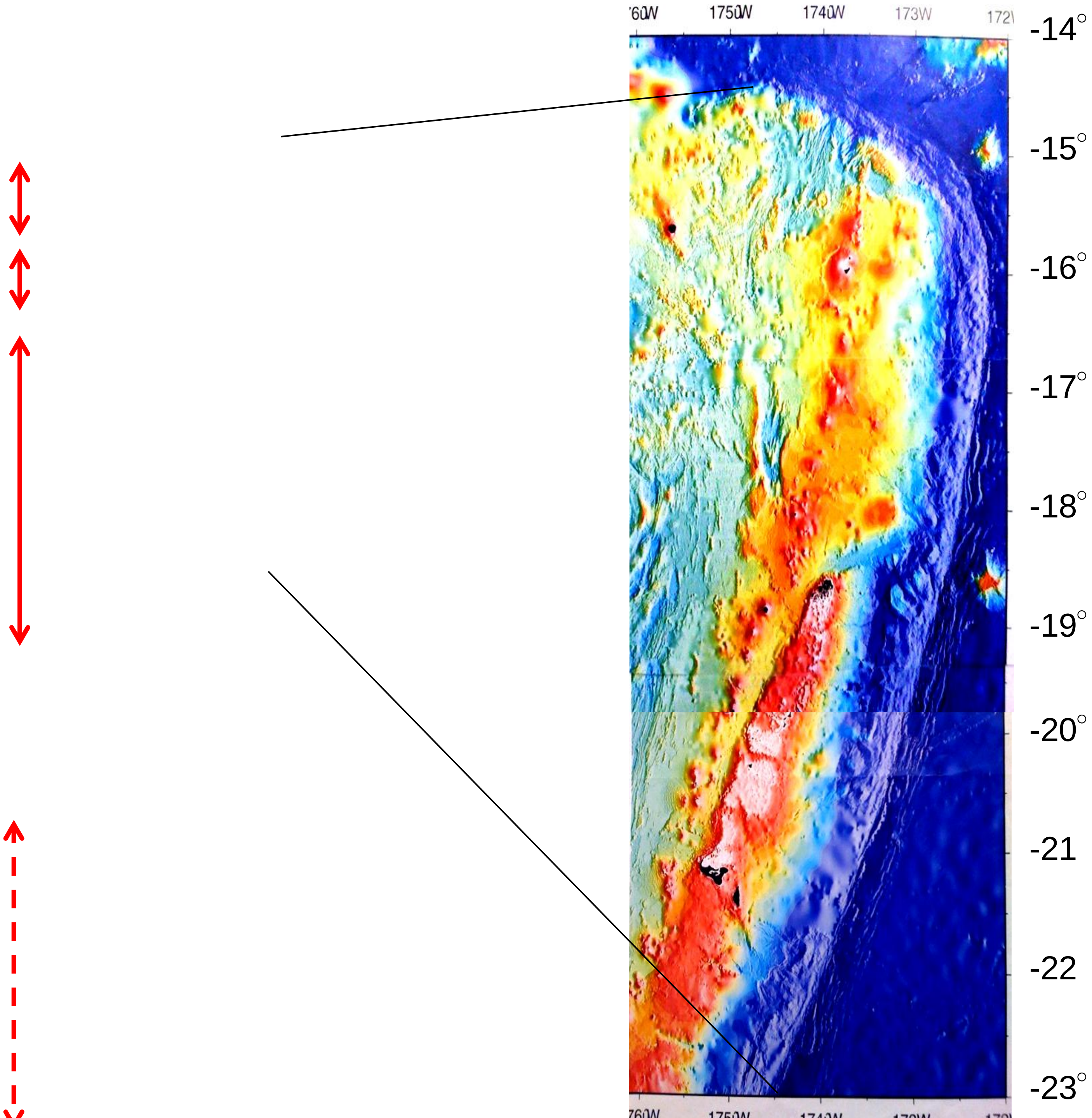


FIGURE 13.—Location map of the Island of Hawaii.

Conclusions: Four Contributing Factors

Event Year Region	Mesozoic Plate Age	Large OR Gravity Anomaly	Large Trench vs. MA angle	Long, straight fault scarps
1933 Sanriku	✓	✓	✓	✓
1977 Sumbawa	✓	✓	✓	?
2006 Kurile	✓	✓	✓	?
2009, 1917 Tonga	✓	✓	✓	✓
1917 Kermadec	✓	✓	✓	?


50°
50°
?
2007
1933



Regions of high potential for future great off-trench tsunamigenic earthquakes

A Fundamental Question:

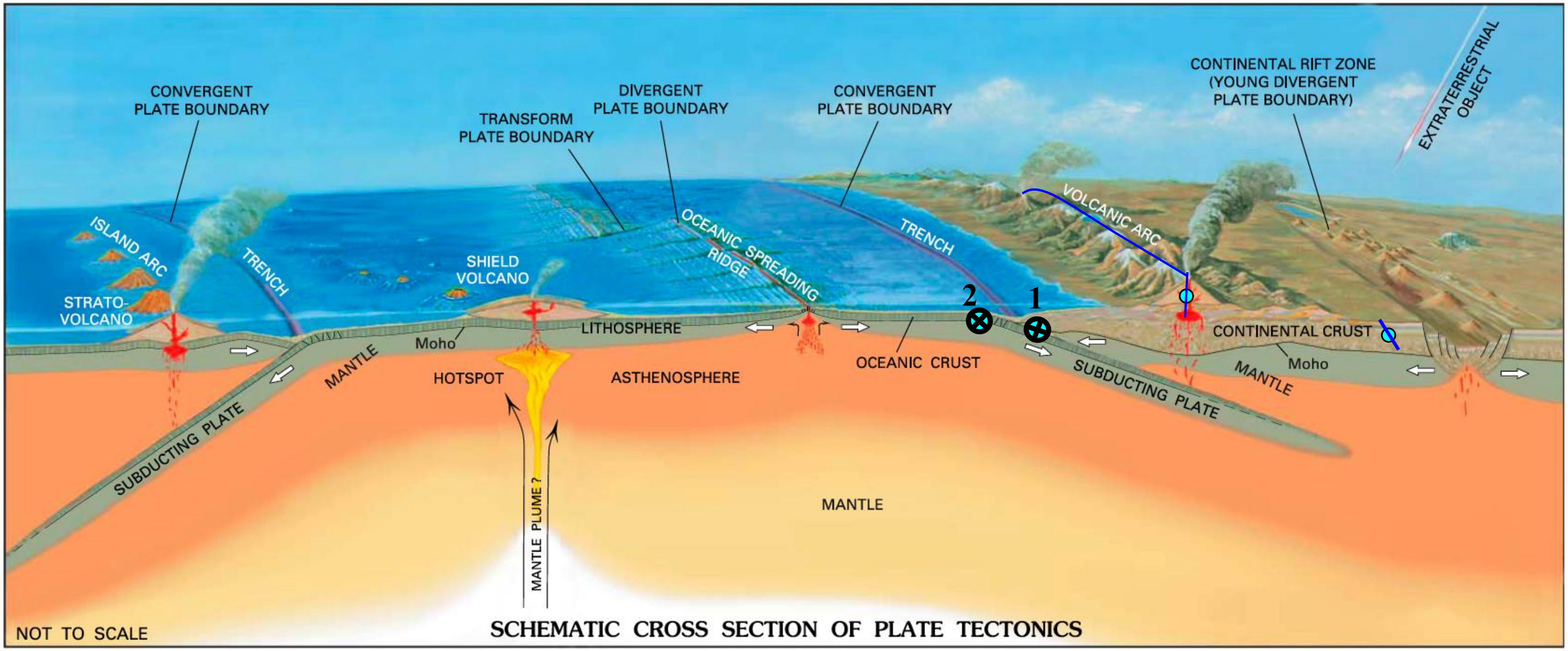
Why do the gravity and bathymetric expressions of the outer rise vary so greatly for lithosphere of basically the same age and convergence rate?

*Effects of ocean island basalt (plume) magmatic activity?

*Effects of transforms and fracture zones?

*Other effects?

Thank you for coming!



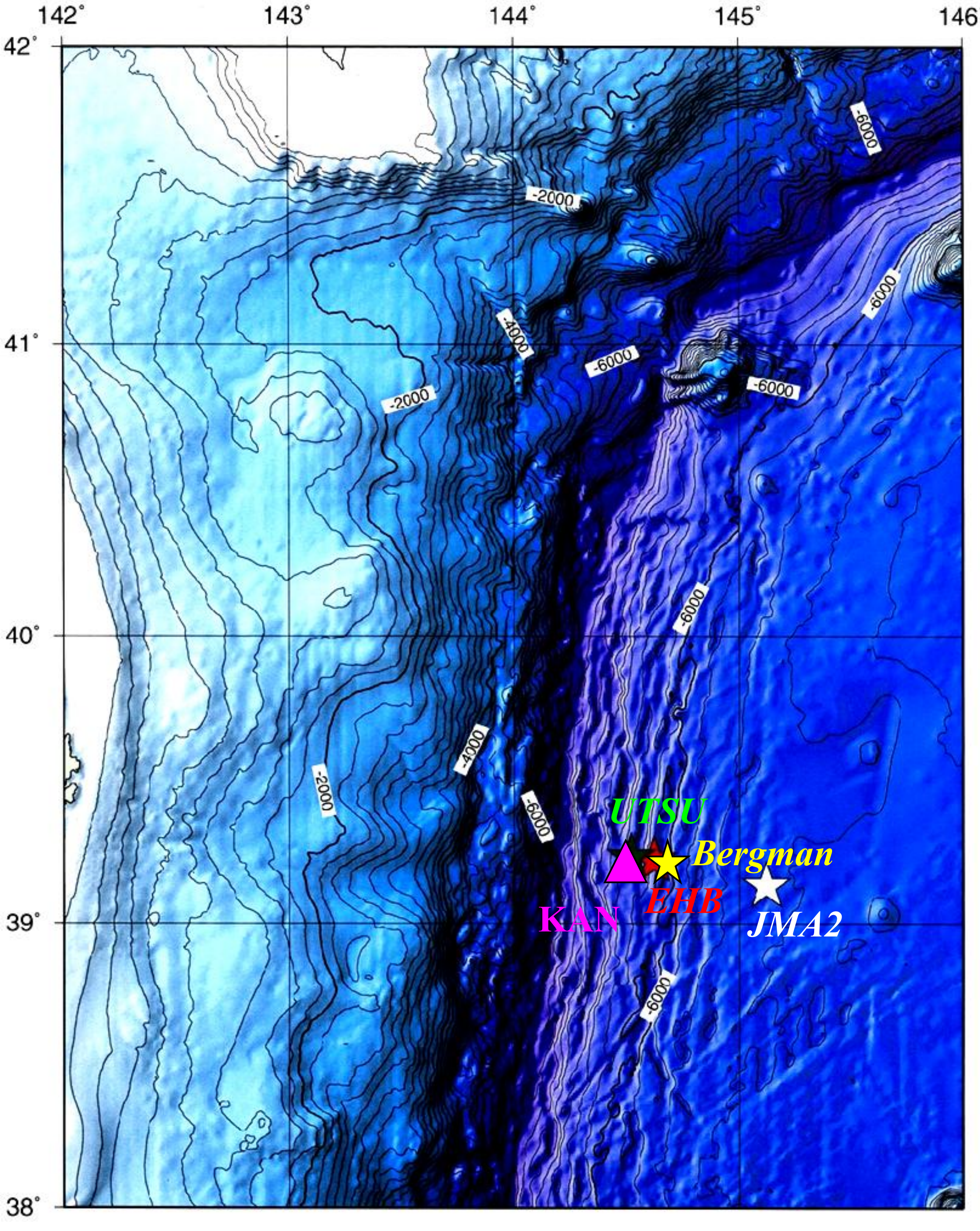
This Dynamic Earth Map and Poster
URL: **http://mineralsciences.si.edu/tdpmap/**

USGS science for a changing world

Smithsonian Institution

U.S. Naval Research Laboratory

The 1933 Sanriku-oki earthquake: An exceptionally well-determined epicenter

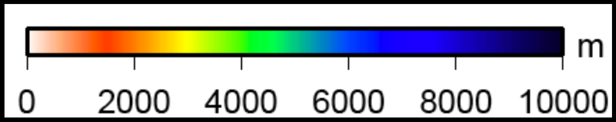


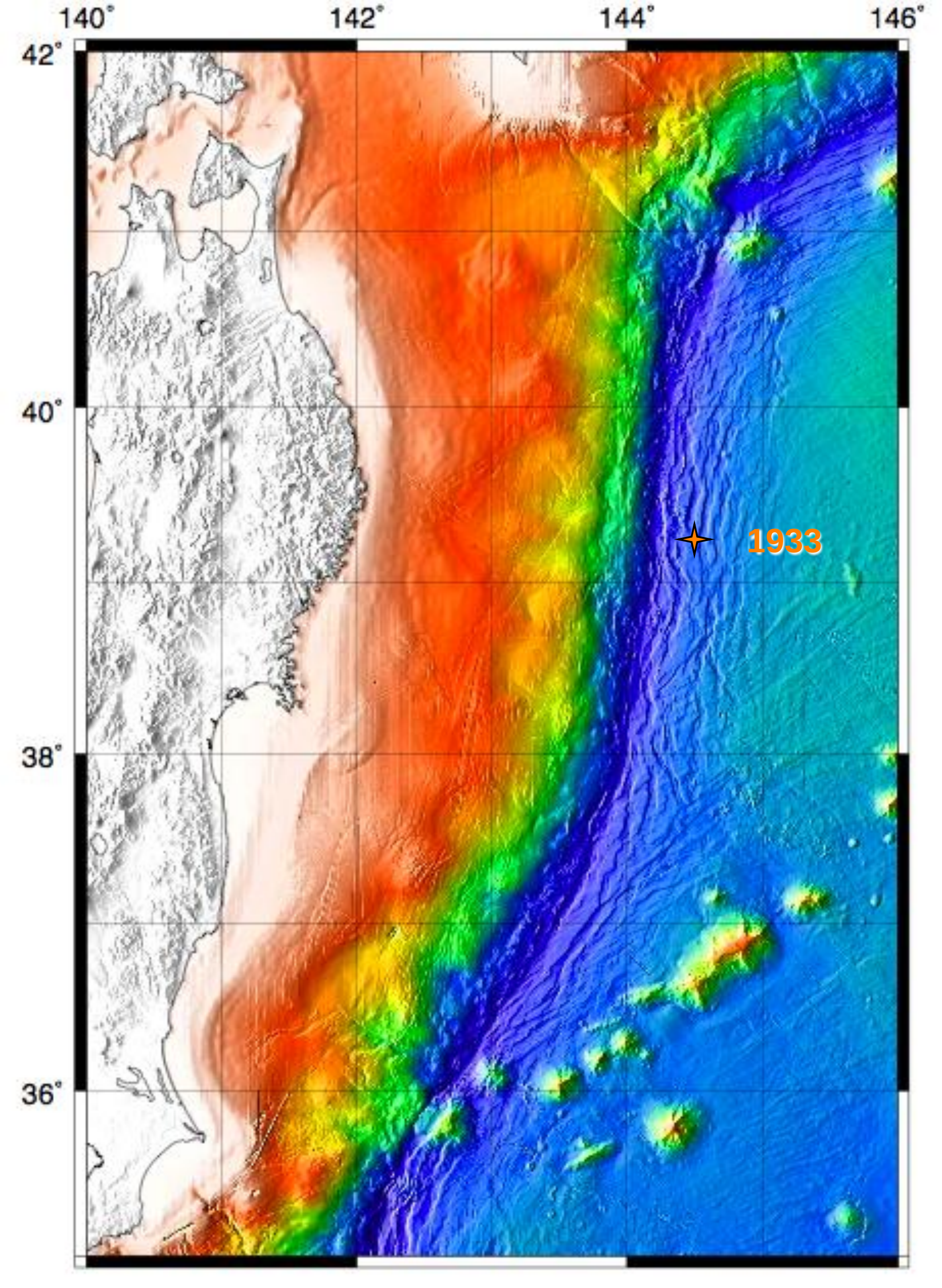
New Integrated Multibeam Sonar Map of the Japan Trench

Azusa Nishizawa[1] and
Ryota Hino[2]

[1]Hydrographic and Oceanographic Department, Japan Coast Guard, Tokyo

[2]Research Center for Earthquake and Volcanic Eruption Prediction, Tohoku University, Sendai





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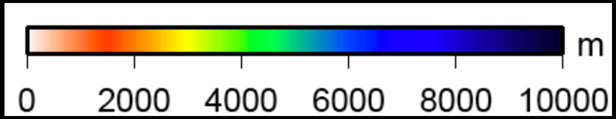
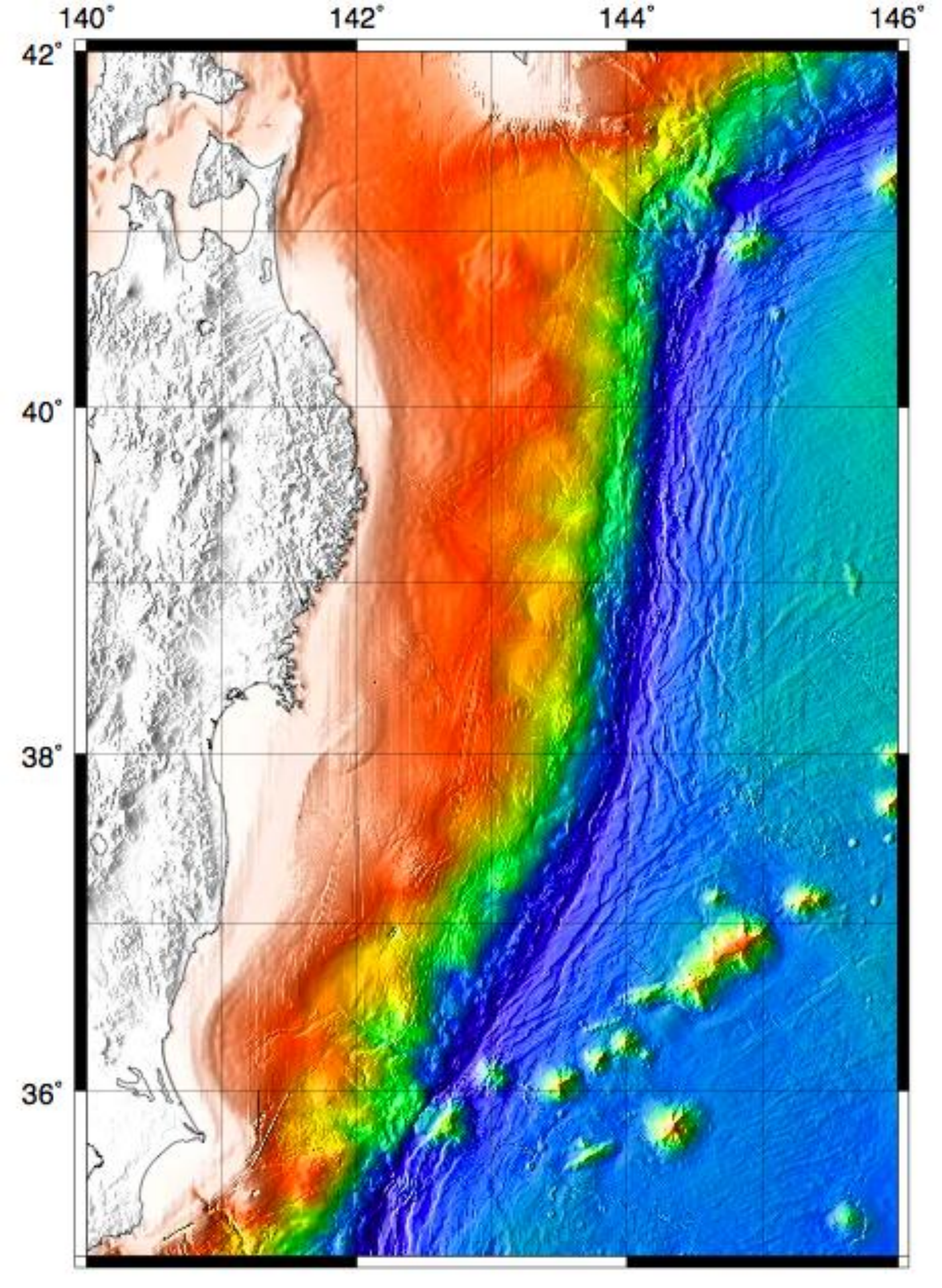
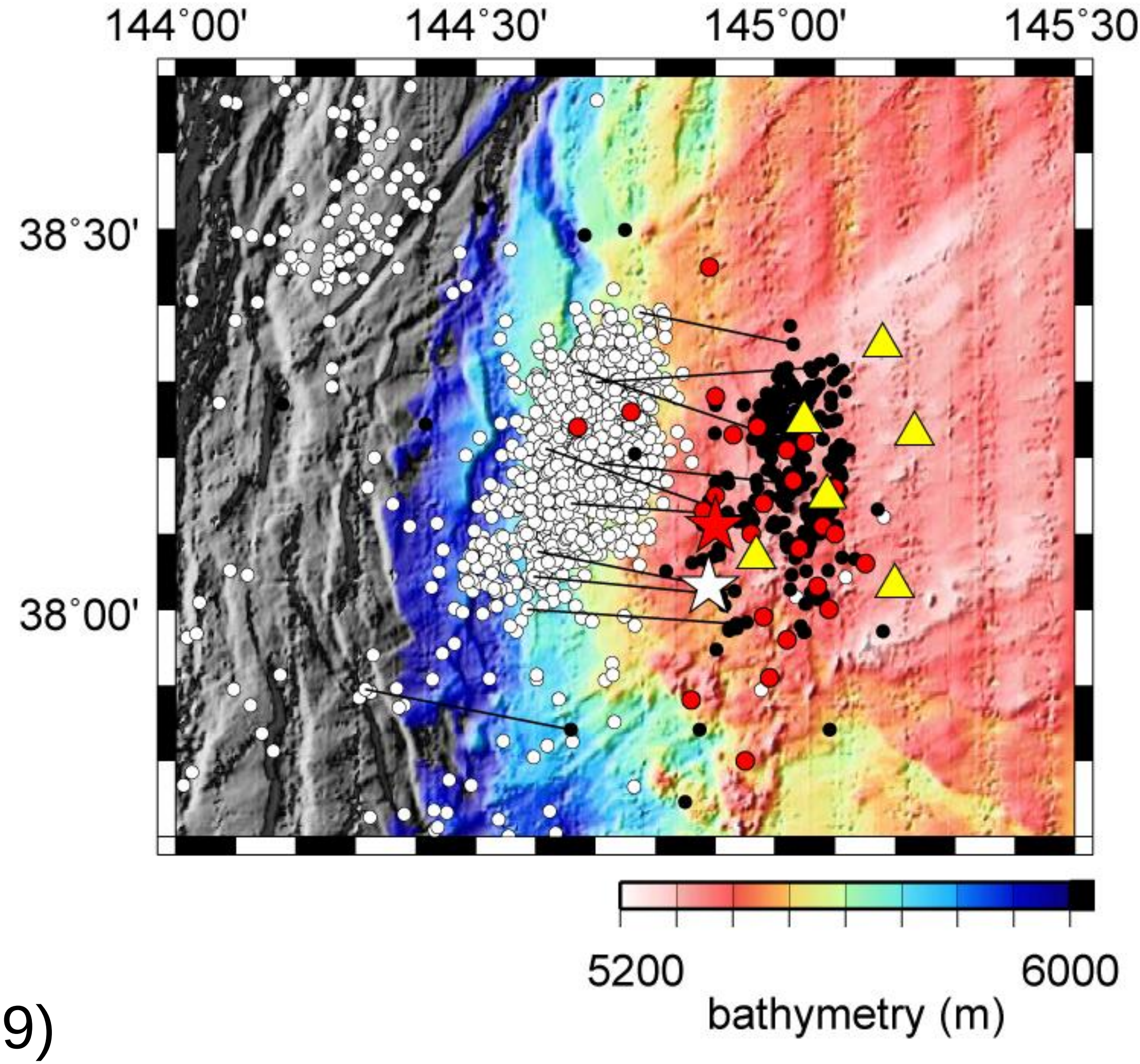




Comparisons of MS and Aftershocks of M7.1 OR Earthquake of 14 Nov 2005

- ★ Engdahl EHB
- ☆ JMA MS (Land network)
- ○ JMA AS's
- ● OBS Deployment 1
- ● OBS Deployment 2
- △ OBS Instrument



Hino et al. (G3, 2009)

Great OR/OTS Earthquake Sources

Date Mw Site	Rupture L, km, from AS's Fault Model	Max rupture D, km below seafloor	Average slip*, m	MOR (MA) Fabric ∧ Trench Azimuth, °	OR Satellite Gravity Anomaly	Plate Age, Ma
2 March 33 8.6 Sanriku Japan	220, 280	30 km (based on AS depths + lack of MS sP depth phase)	17 m	39 - 58°	High	~140
19 Aug 77 8.3 Sumbawa, Indonesia	200	22 km (based on AS depth phases)	~12 m	45°	High	150-160
13 Jan 07 8.1 Kuriles	200, 280	~30	9.6 m modeled	40°	Very High	80-125
29 Sept 09 8.1 Tonga	190, 250	15	~10 m modeled	52°	High	80-125

Criteria: **1)** Plate age > 80 Ma (Mesozoic); **2)** Large outer rise gravity anomaly; **3)** MA∧Tr Az > 30° or < 5° ; **4)** ~Trench || fault scarps