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Title:	The Sendai Earthquake: Great Earthquakes, Tsunami, Nuclear Power, and Global Tectonics
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Form 836 (7/06)

The Sendai Earthquake: Great Earthquakes, Tsunami, Nuclear Power, and Global Tectonics

Terry C. Wallace, Jr., Venkateswara R. Dasari (DV Rao), Paul A. Johnson, Sara C. Scott, Patrcik R. McClure, Frank V. Pabian, Janet Mercer-Smith

On March 11 a major earthquake occurred around 3 pm local time, east of the island of Honshu, Japan. The earthquake is a subduction thrusting event in the Japan Trench which is the convergent plate boundary between the Pacific and North American plates. The earthquake had a moment magnitude of slightly larger than 9.0, making it the fourth or fifth largest earthquake in recorded history. The earthquake epicenter was approximately 120 km east of the Japanese city Sendai. Although shaking was experienced widely across Honshu, the damage associated with the shaking was modest considering the size of the event; however, the earthquake triggered a major tsunami. The tsunami caused extensive damage along 350 km of the eastern coast of Honshu.

The shaking associated with the earthquake triggered an automatic shut down of 11 reactors in Northern Japan. Early reports (which have not been updated) indicate that there was no significant damage associated with the shaking, and diesel generators designed to operate cooling systems started as expected. However, approximately one hour after the earthquake the tsunami arrived on shore and caused some flooding (the extent is still being debated) at two of the reactor sites (Fukushima-Daiichi and Fukushima Daini), and diesel powered systems were interrupted. The tsunami height at both Daiichi and Daini was approximately 10 m, but the diesel pedestals were approximately 5 m above sea level. Pressure inside the containment vessel at Unit 1 of the Daiichi reactor complex increased rapidly with no auxiliary cooling, and ultimately there was a gas (hydrogen deflagration) explosion outside the containment vessel the morning of March 12. The source of the hydrogen is the fuel cladding, which is zirconium based, and oxidizes with steam and produces hydrogen. Ultimately, Tokyo Electric Power Company made the decision to flood the reactor cores with borated seawater in an attempt to prevent partial melting of the fuel rods. Issues continue at Daiichi, and another hydrogen explosion occurred on March 14 in unit 3.

The Sendai Earthquake:

Great Earthquakes, Tsunami, Nuclear Power, and Global Tectonics

Terry C. Wallace, D.V. Rao
Paul Johnson
Sara Scott
Patrick McClure
Frank Pabian

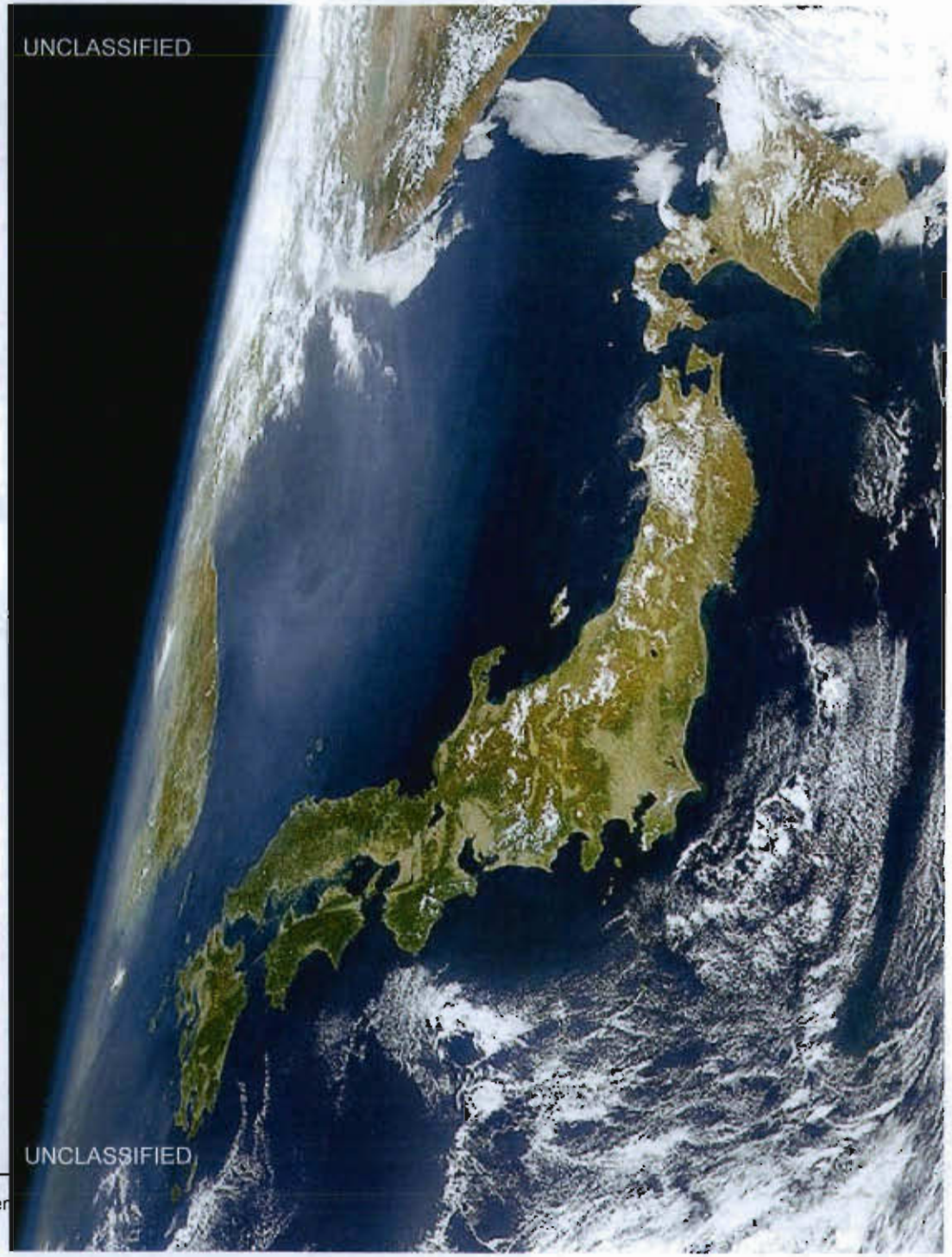

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Plate Tectonics and the Earthquake

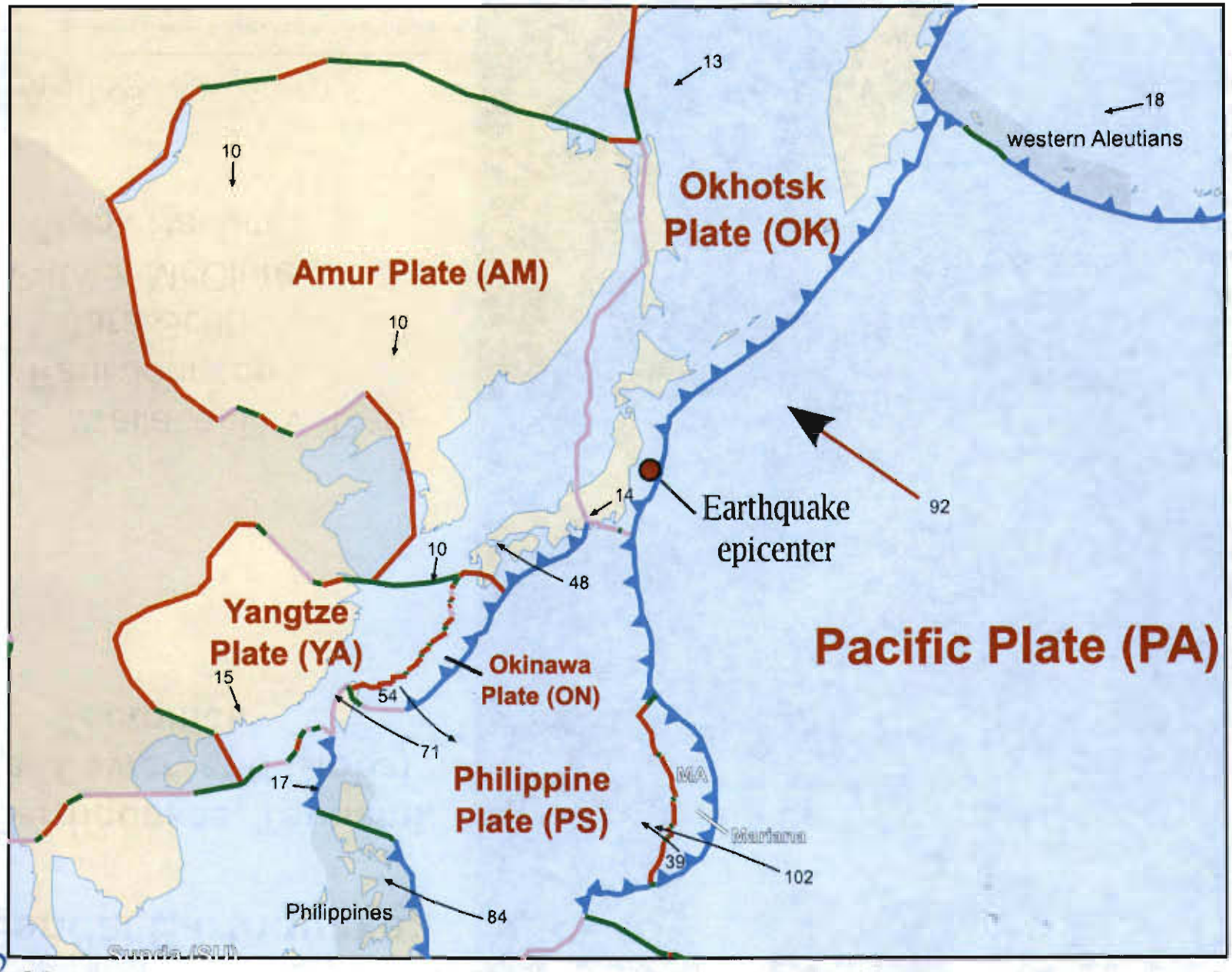

Plate Tectonics and the Earthquake

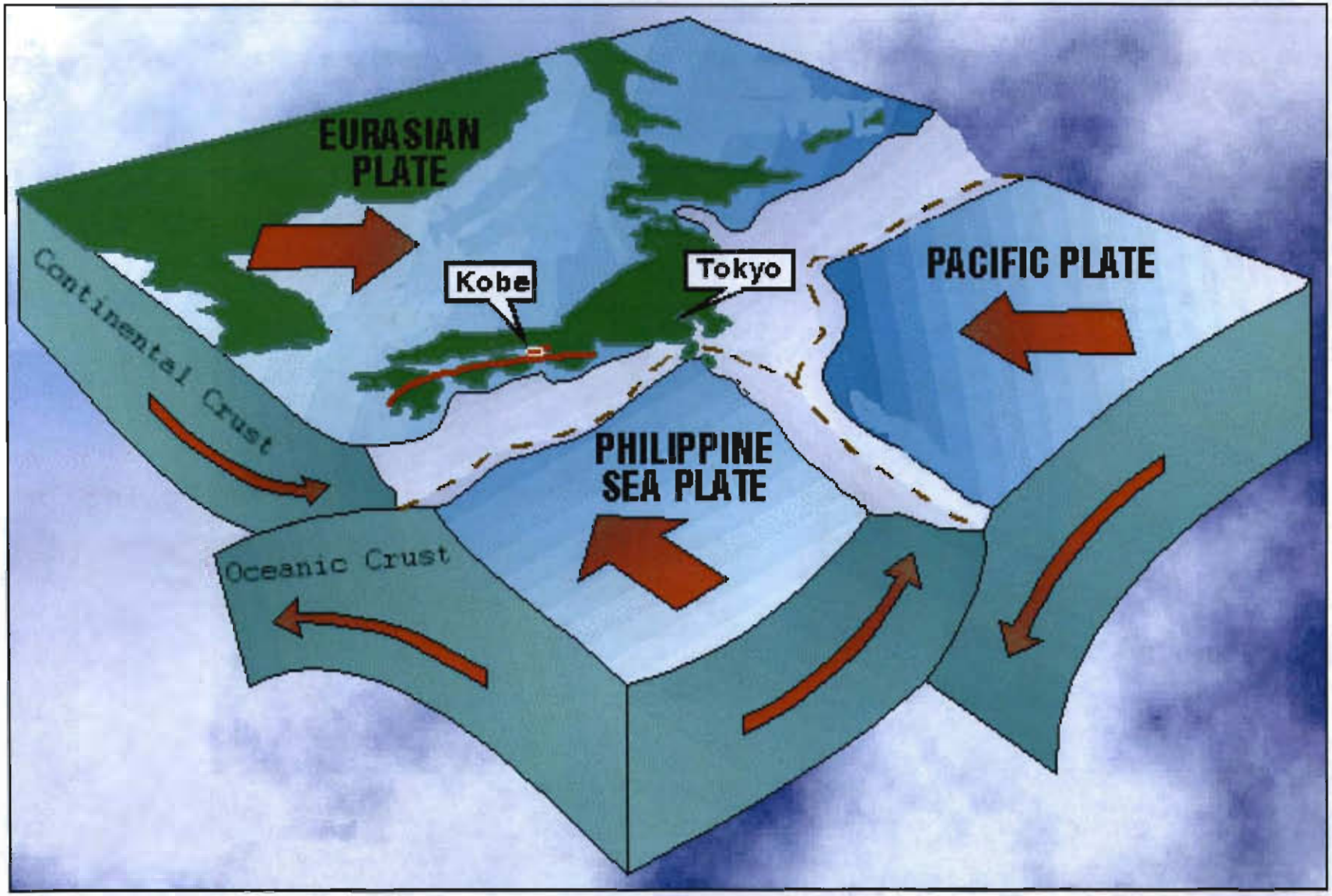

Plate Tectonics and the Earthquake

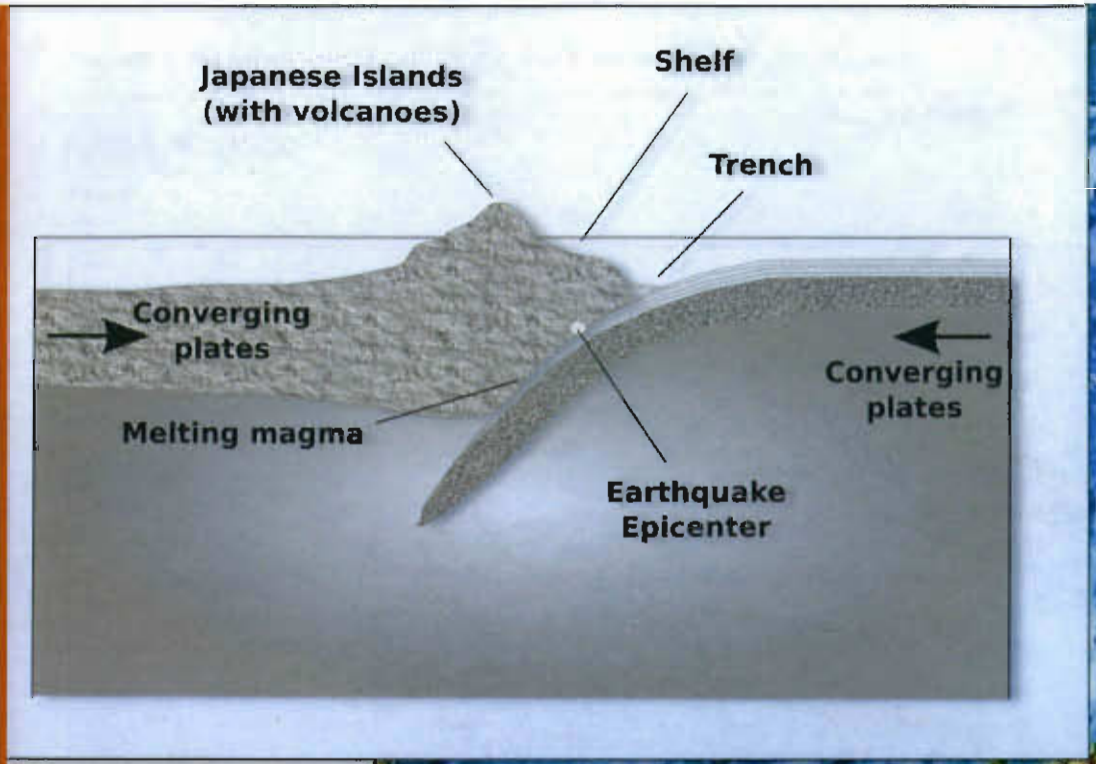

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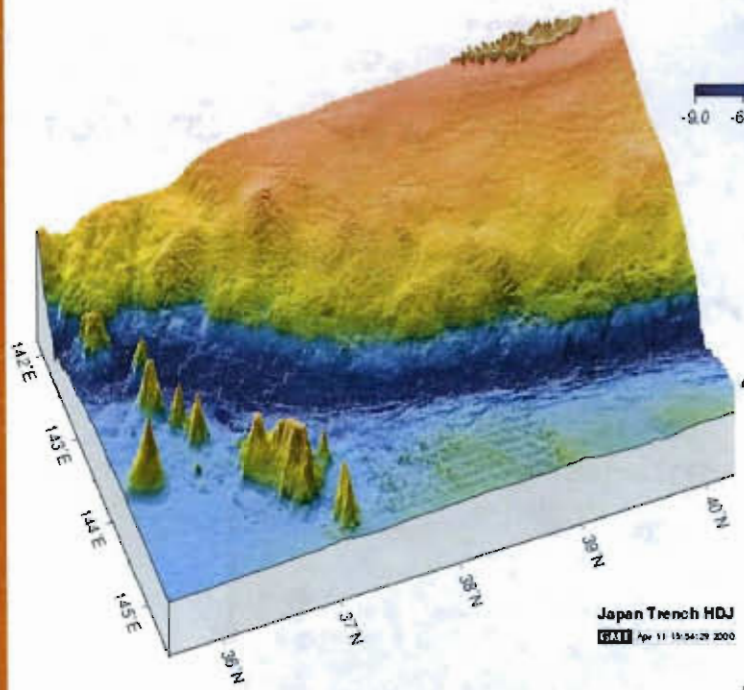
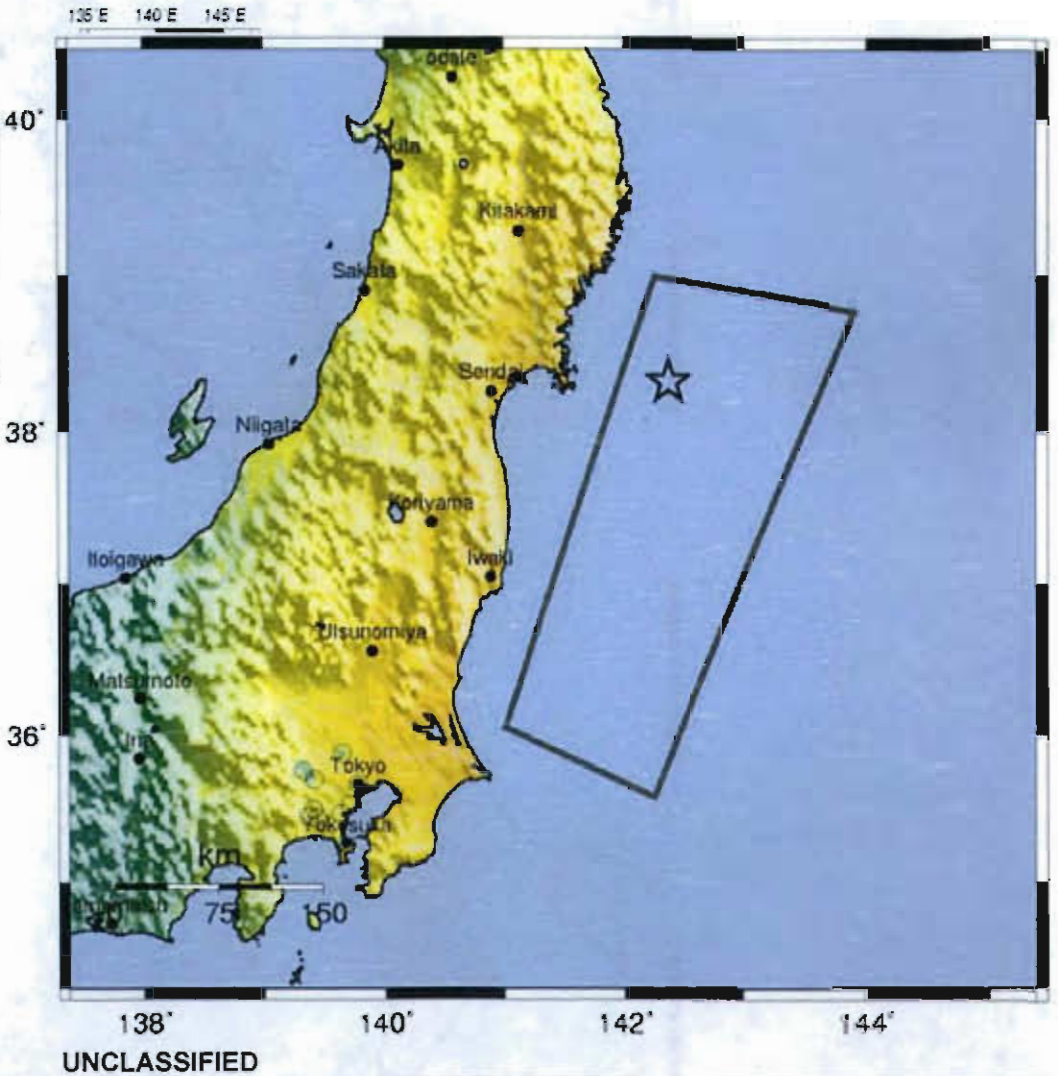
Plate Tectonics and the Earthquake



Modified Mercalli Intensity

X
IX
VIII
VII
VI
V
IV
II-III
I



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Kisi
Primorskaya
Mutankiang
Russia
Vladivostok
Asahikawa
Tomari
Kushiro
Chongjin
Hakodate
Kimchaek
Hirosaki
China
West Asia
Akita
Onagawa
South Korea
Kashiwazaki Kariwa
Nagaoka
Ulchin
Shika
Fukushima Dalichi
Fukushima Daini
Fugen
Tsuruga
Wolsong
Mihama
Shimane
Tokai
Kofu
Kori
Takahama
Monju
Hamaoka
Ohi
Genkai
Ikata
Kochi
Sendai
Miyazaki
Kagoshima
46°
44°
42°
40°
38°
36°
34°
32°
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130°
132°
134°
136°
138°
140°
142°
144°
146°
International Nuclear Safety Center at ANL, Aug 2005

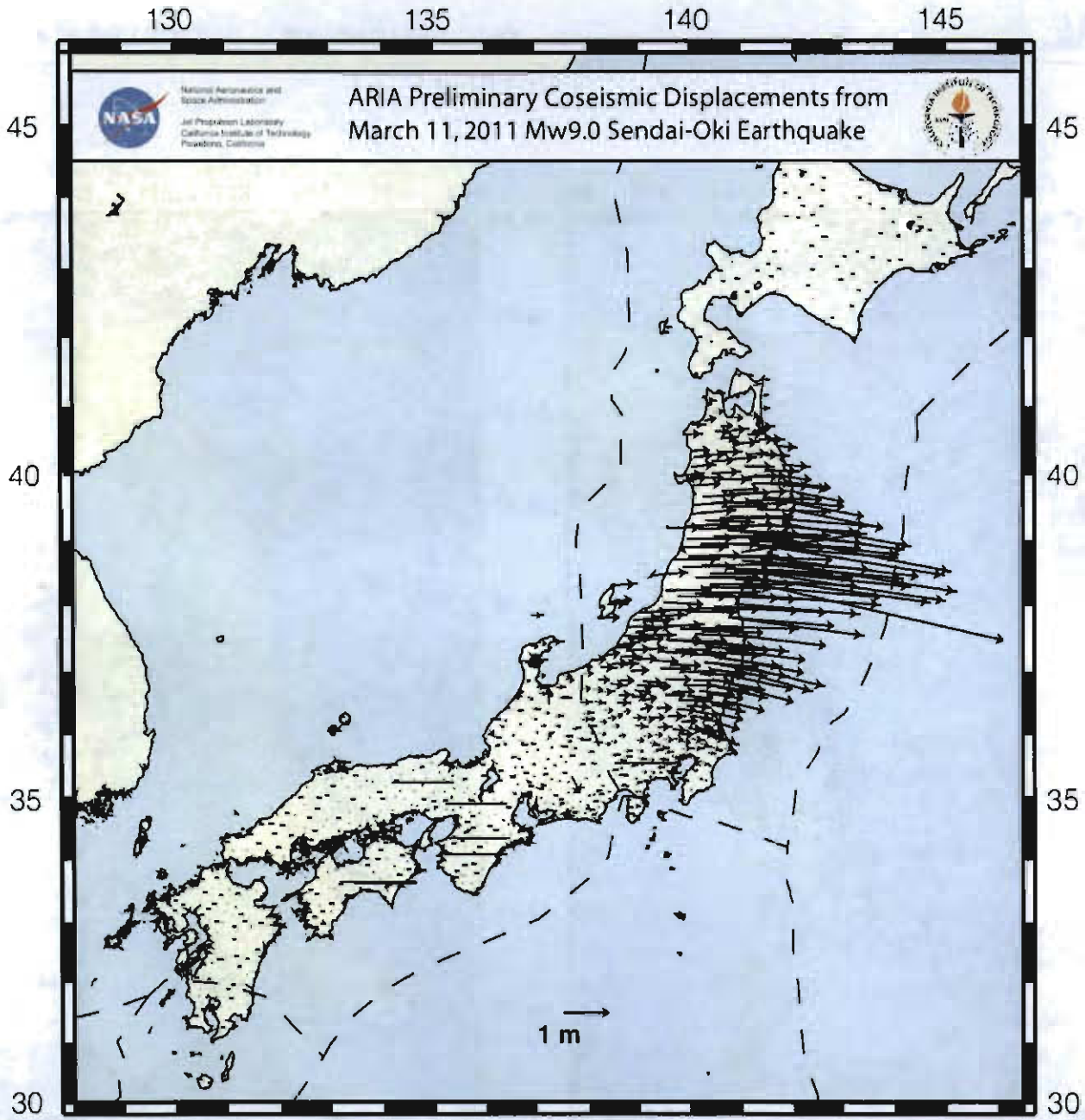

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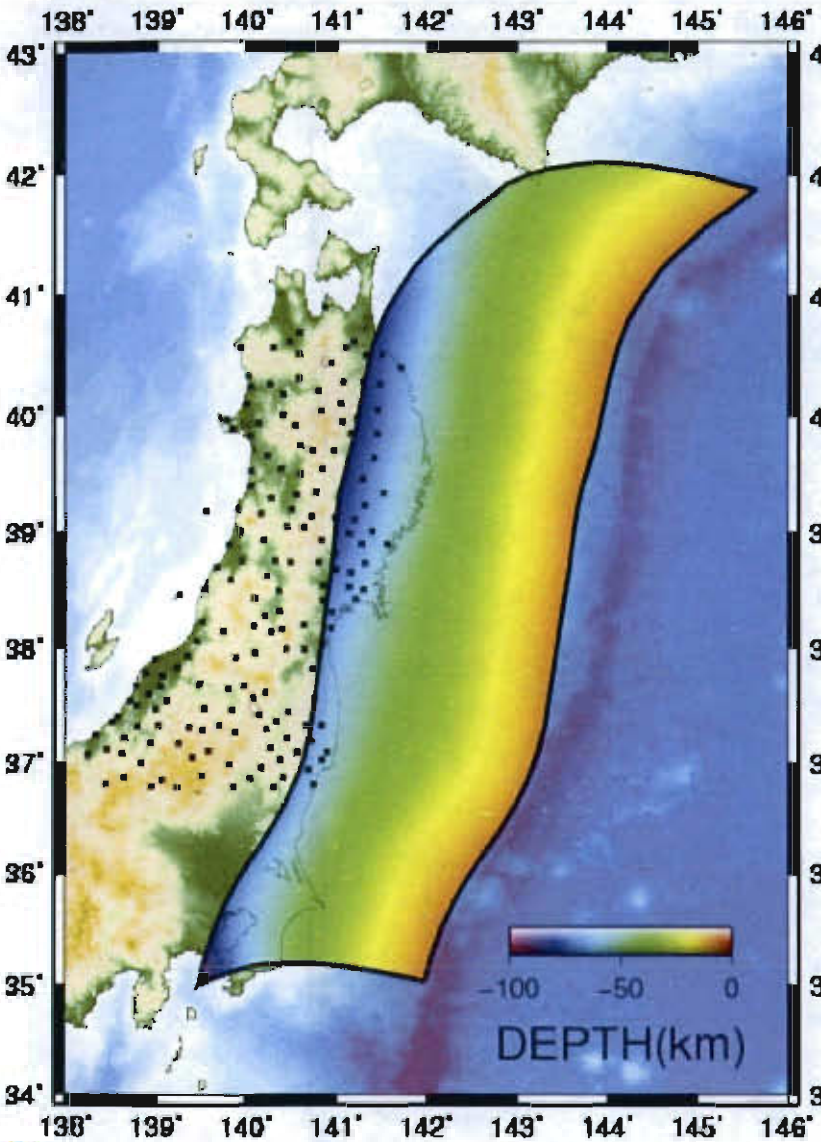
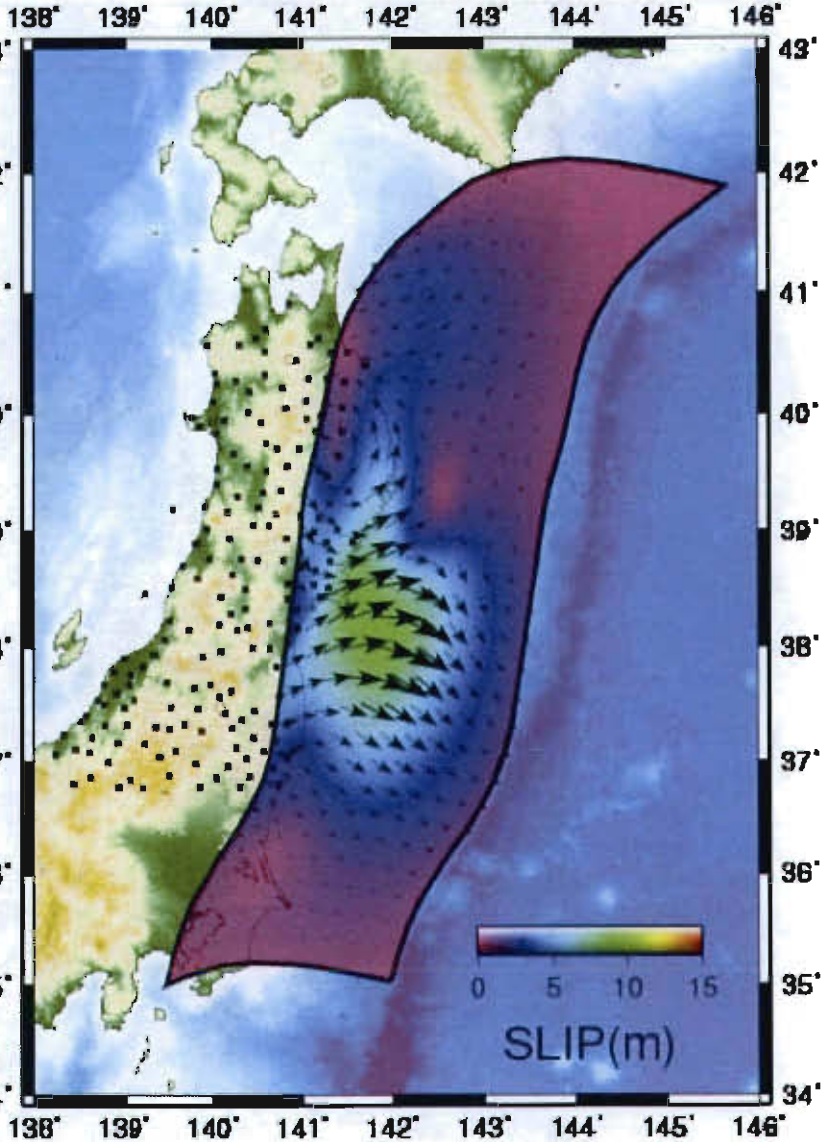
Plate Configuration



Slip Distribution



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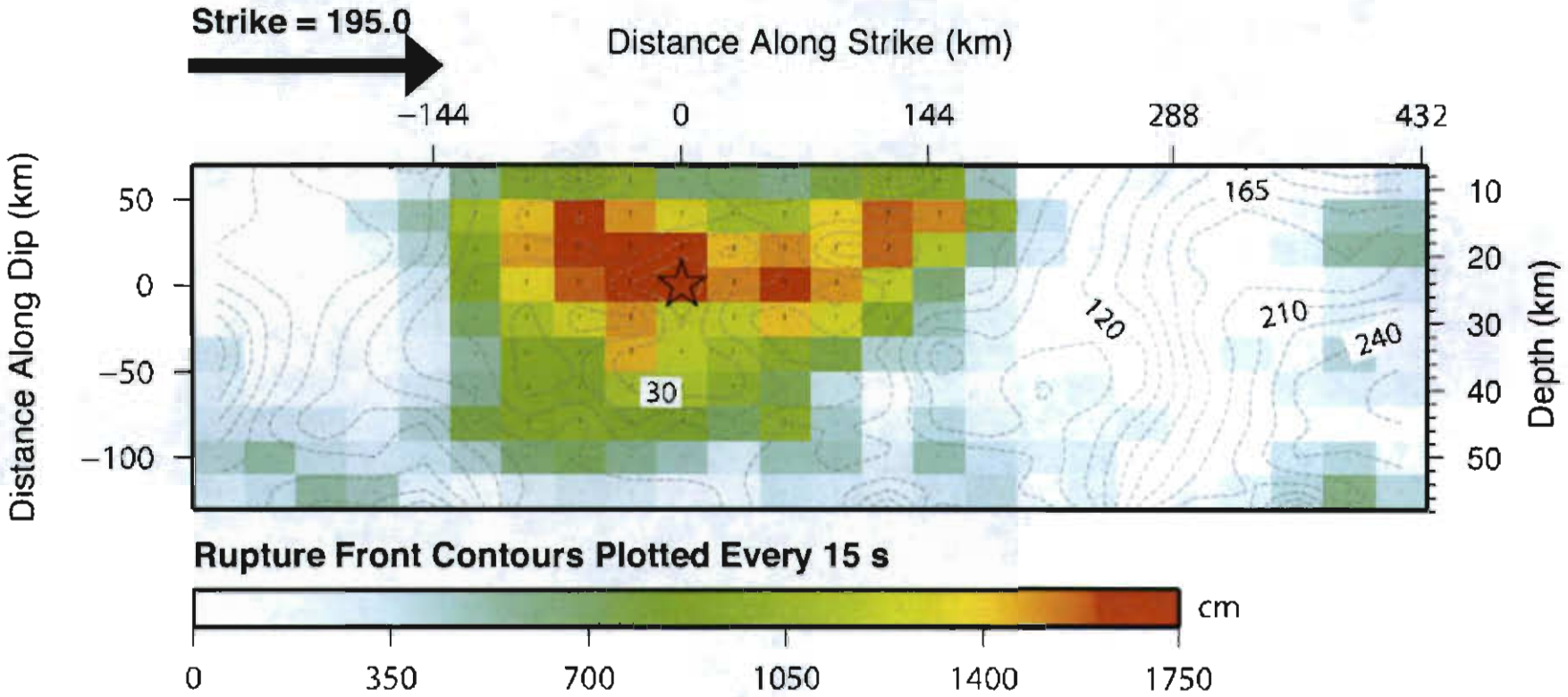
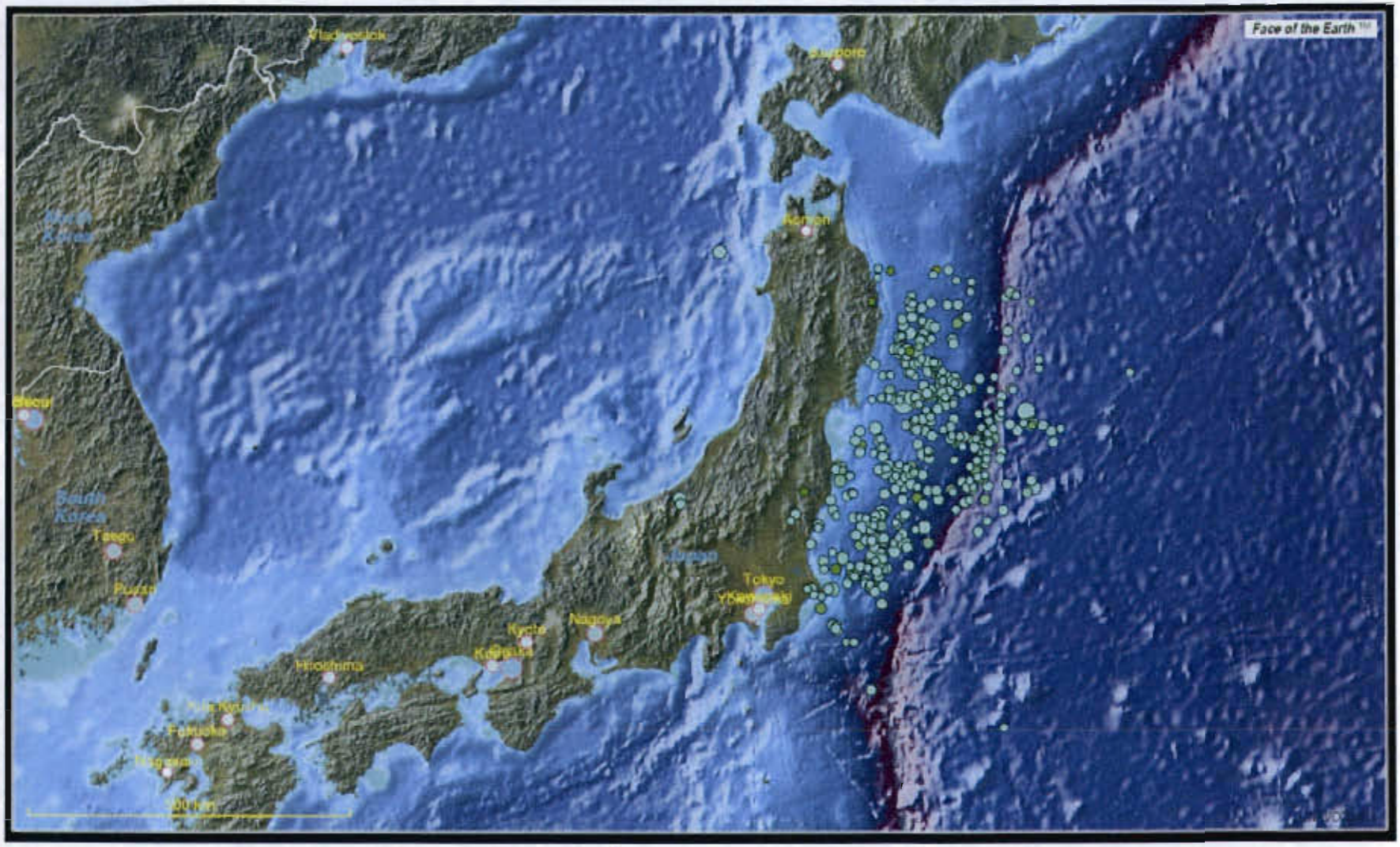

Strike = 195.0
Distance Along Strike (km)
−144
0
144
288
432
Distance Along Dip (km)
50
0
−50
−100
Depth (km)
10
20
30
40
50
165
120
210
240
30
Rupture Front Contours Plotted Every 15 s
cm
0
350
700
1050
1400
1750

Plate Tectonics and Earthquakes



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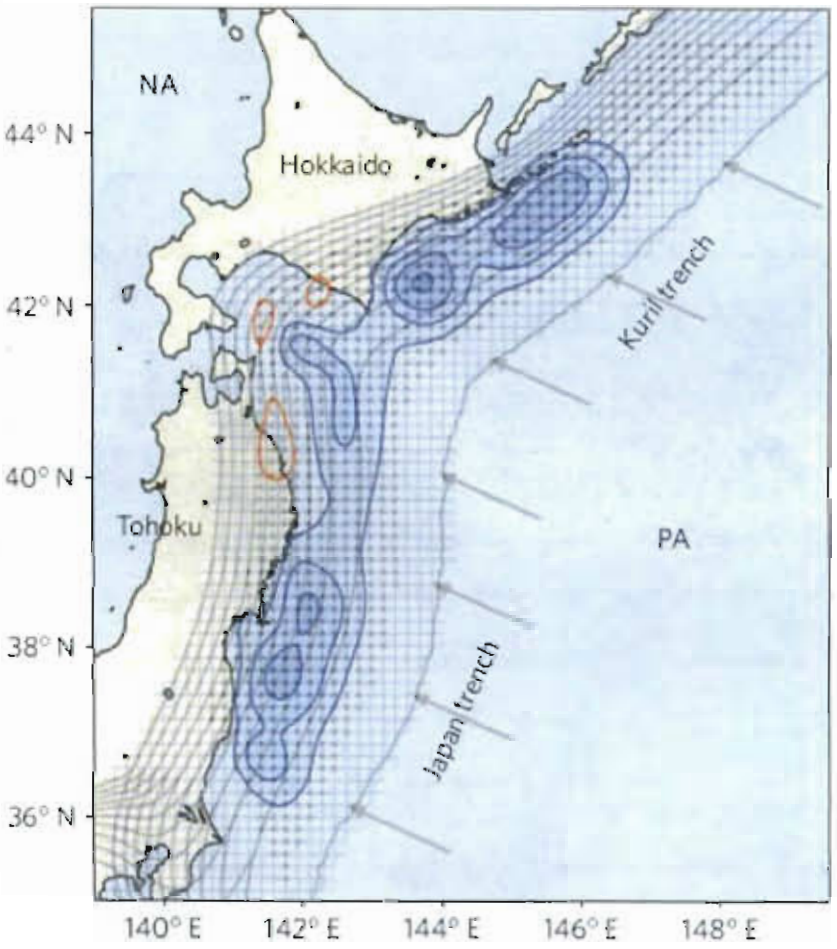
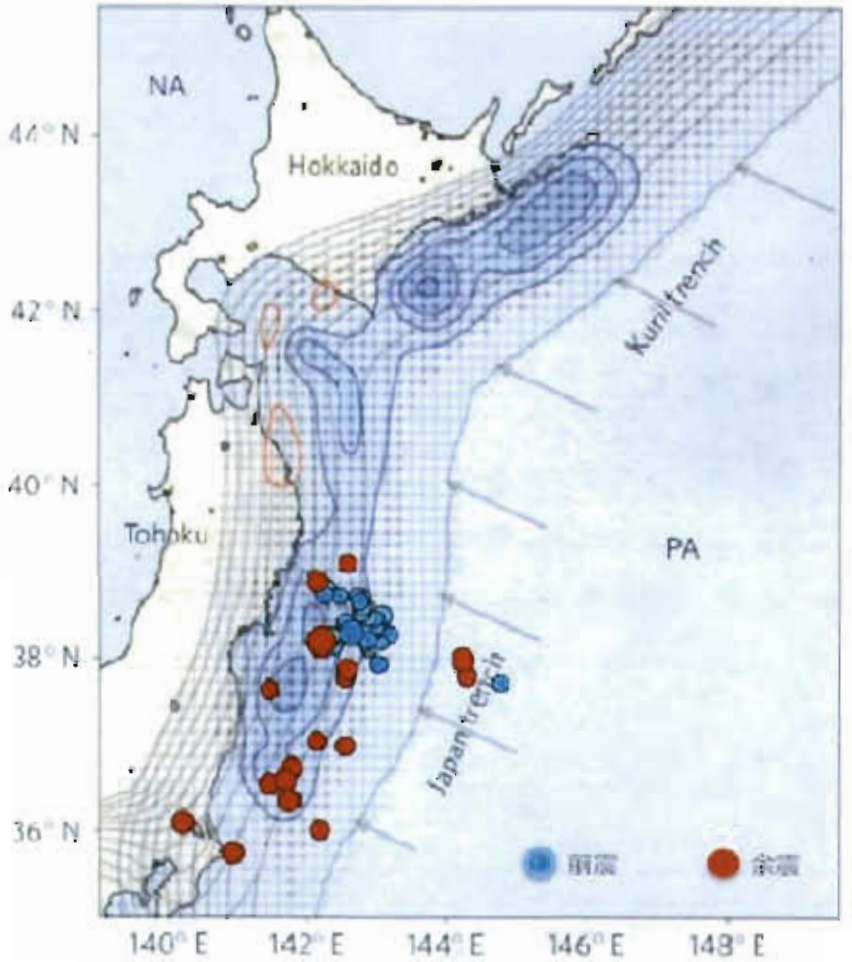
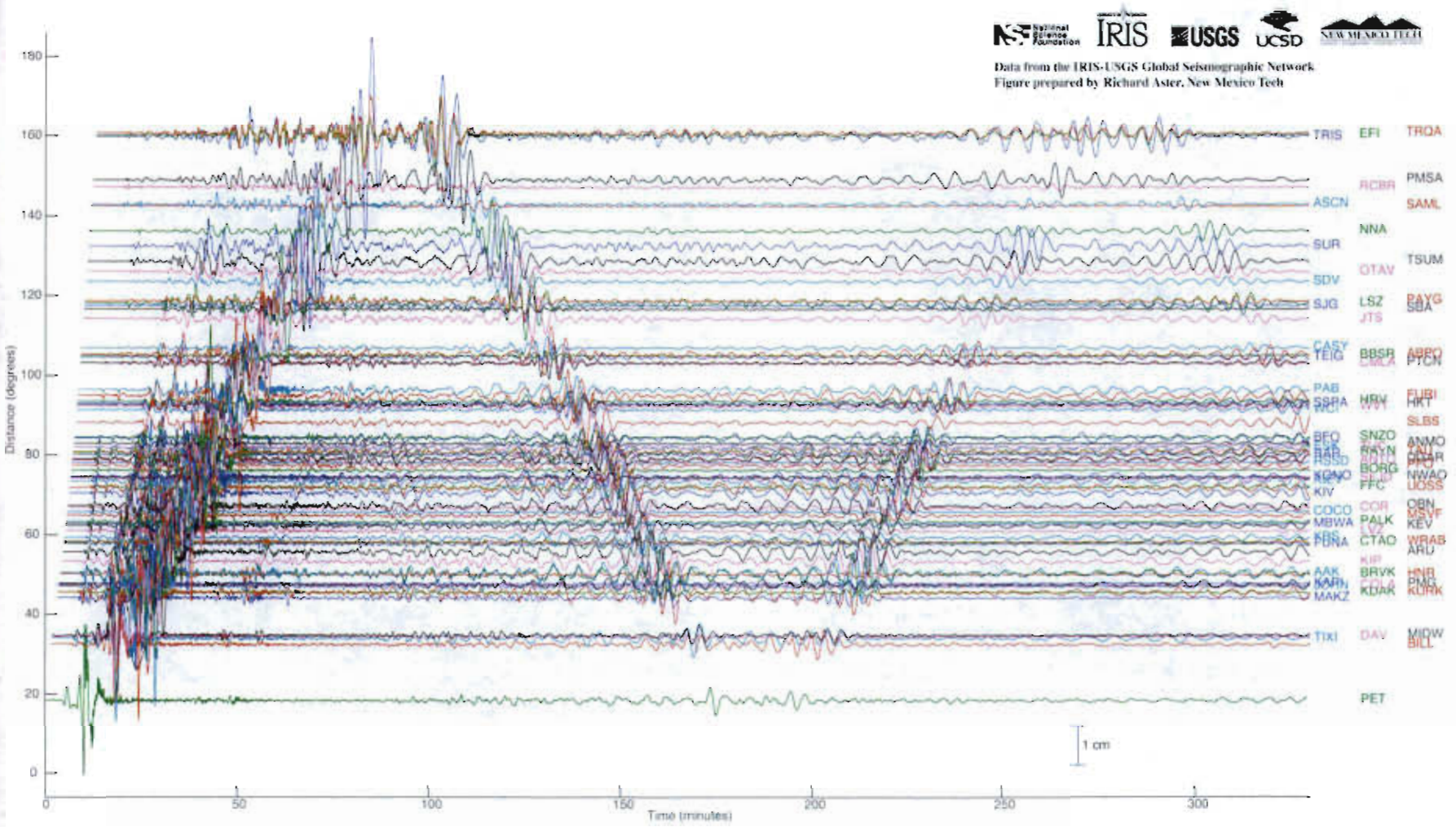
Earthquake is where is was predicted to be – but larger!





Earthquake

Japan Earthquake (M_w = 9.0), Global Displacement Wakefield



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Tsunami

Tsunami

Tsunami

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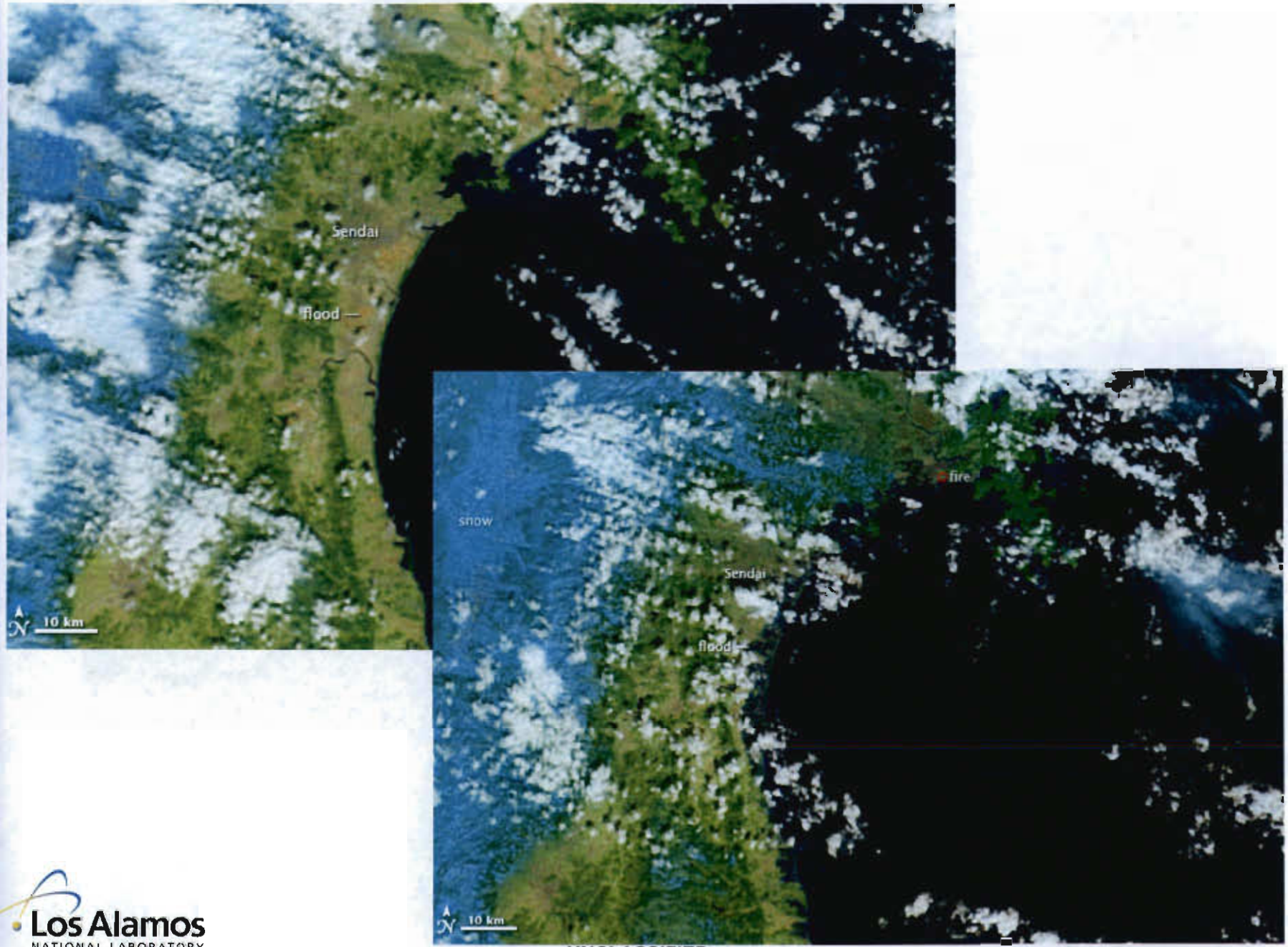
Tsunami



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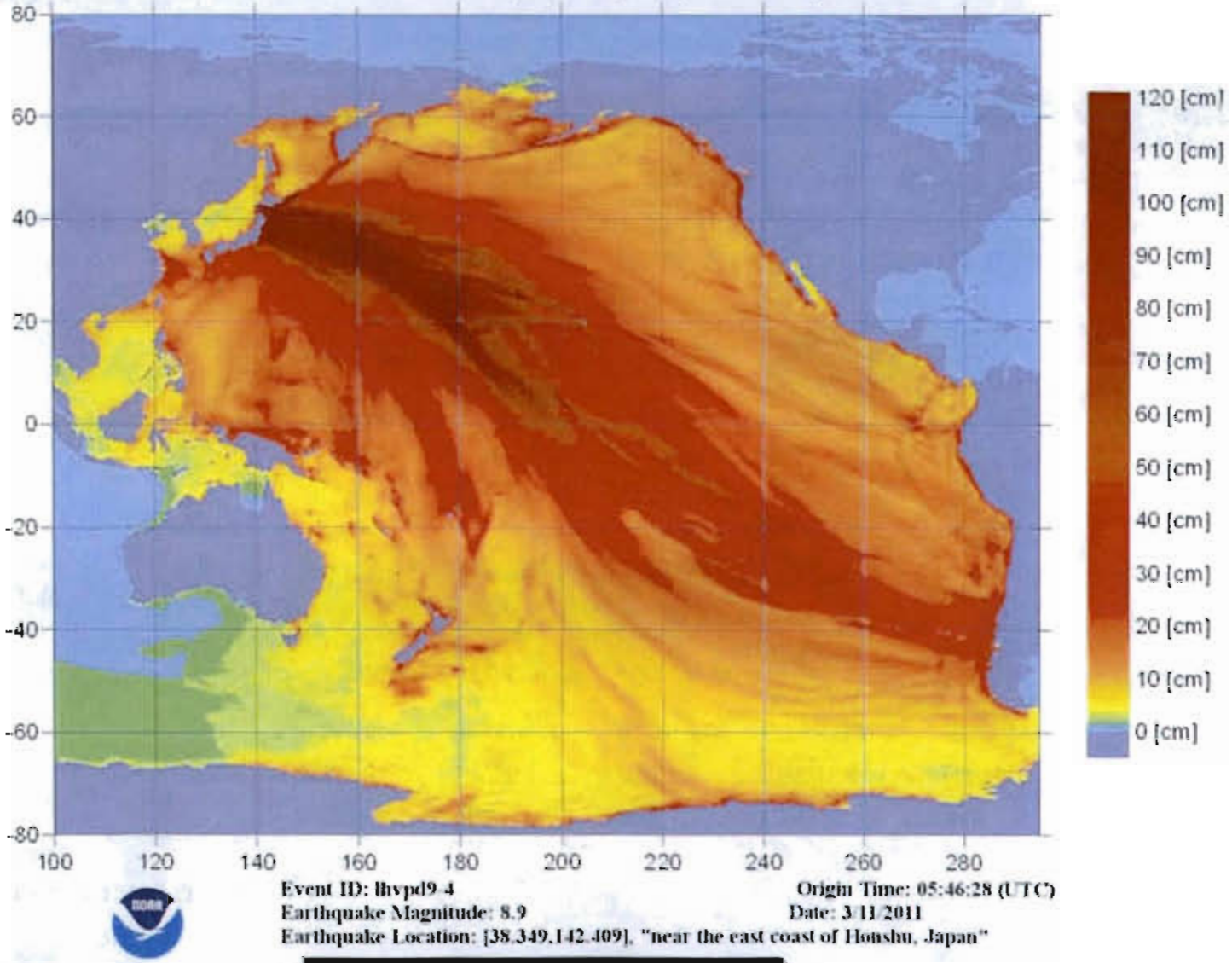
Tsunami

Tsunami

Tsunami Propagation Forecast

Contours of forecasted maximum wave amplitude [cm], detailing tsunami energy propagation



West Coast and Alaska Tsunami Warning Center

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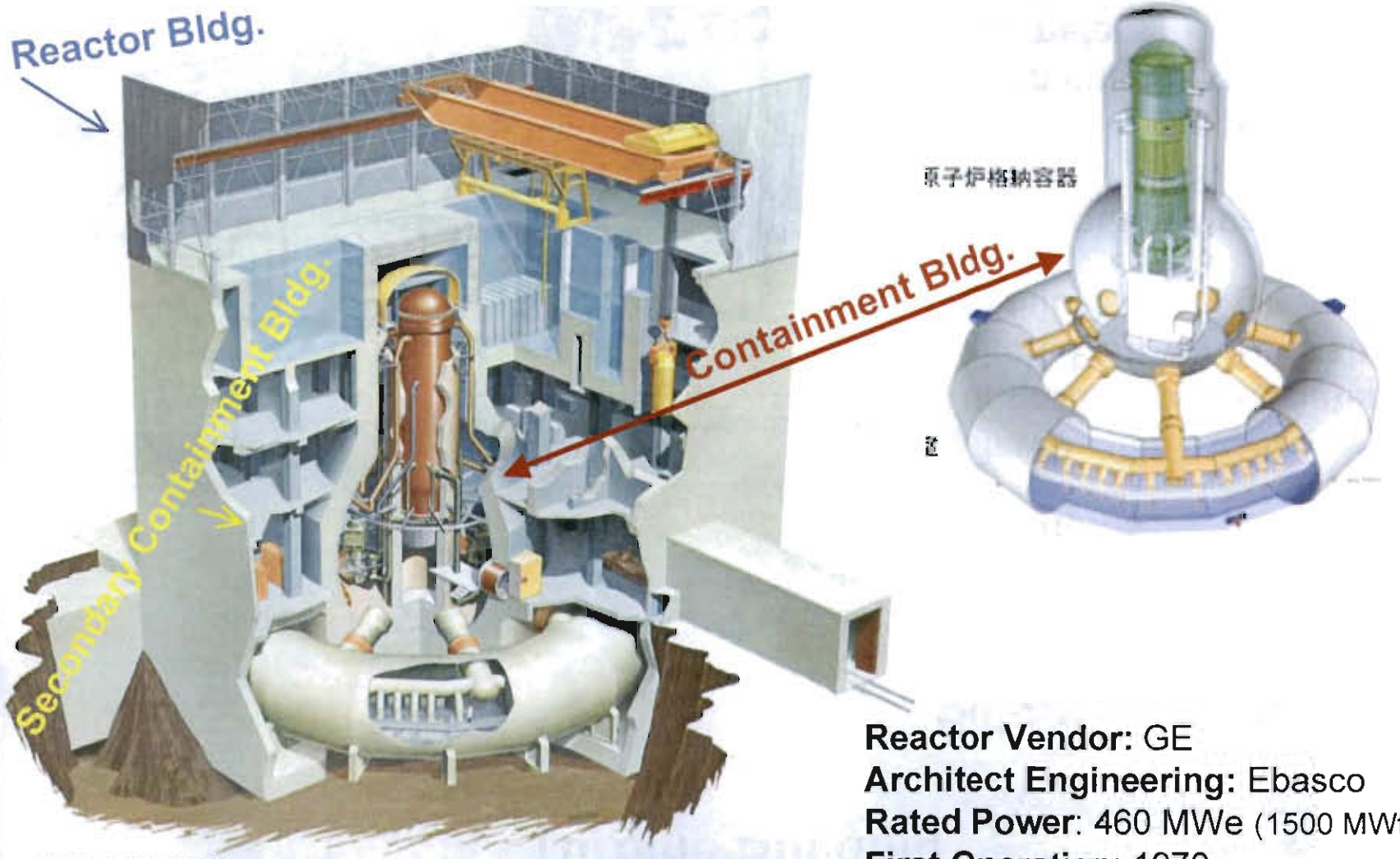
Status of Fukushima 1 Nuclear Power Plant Accident

Status of reactors at 12:30 March 14[43]	1	2	3	4	5	6
Power output (MWe)	460	784	784	784	784	1100
Type of reactor	BWR-3	BWR-4	BWR-4	BWR-4	BWR-4	BWR-5
Status at earthquake	In service	In service	In service	Shut down	Shut down	Shut down
Fuel integrity	Damaged	Damaged?	Damaged	Not damaged	Not damaged	Not damaged
Containment integrity	Not damaged	Not damaged	Not damaged	Not damaged	Not damaged	Not damaged
Core cooling system 1 (ECCS/RHR)	Not functional	Not functional	Not functional	Not necessary	Not necessary	Not necessary
Core cooling system 2 (RCIC/MUWC)	Not functional	RCIC Working	Not functional	Not necessary	Not necessary	Not necessary
Building integrity	Damaged	Not damaged	Damaged	Not damaged	Not damaged	Not damaged
Environmental effect	20 microSievert/hour at 11:44					
Pressure vessel, water level	Unknown	Above core	Unknown	Safe	Safe	Safe
Pressure vessel, pressure	Stable	Stable	Stable	Safe	Safe	Safe
Containment pressure	Stable	Stable	Stable	Safe	Safe	Safe
Sea water injection	Suspended	To be decided	Performed	Not necessary	Not necessary	Not necessary

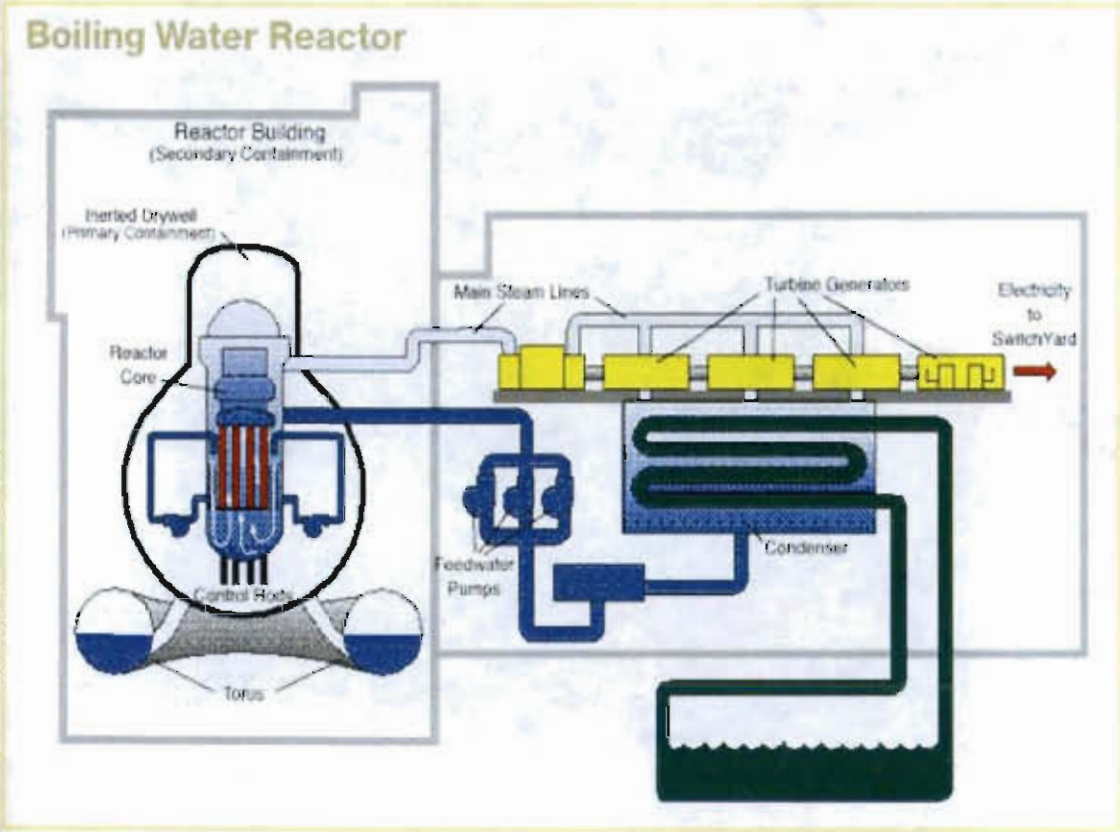
Isometric view of typical BWR-3 w/ Mark I Containment

Before Seismic Event



Reactor Vendor: GE
Architect Engineering: Ebasco
Rated Power: 460 MWe (1500 MWth)
First Operation: 1970

Reactor Vessel, Containment, Reactor Building and Turbine Building



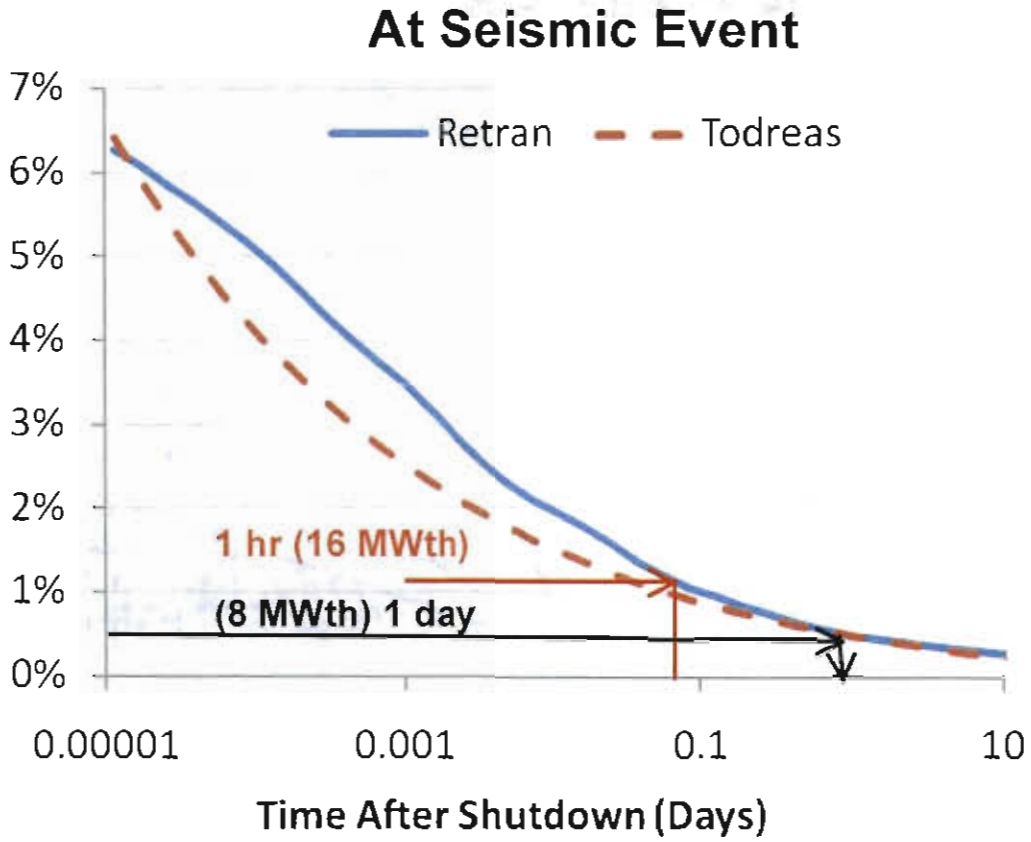
Before Seismic Event

- Designed with 1960's safety codes and standards
- March 2008 TEPCO upgraded its estimates of likely PGA for Fukushima to 600 Gal (0.6 g)
- After Indian Ocean Tsunami NUSA and TEPCO upgraded Tsunami design limit to 5.3 meters
- All units share emergency diesel units

Reactor Scrammed upon Seismic Event

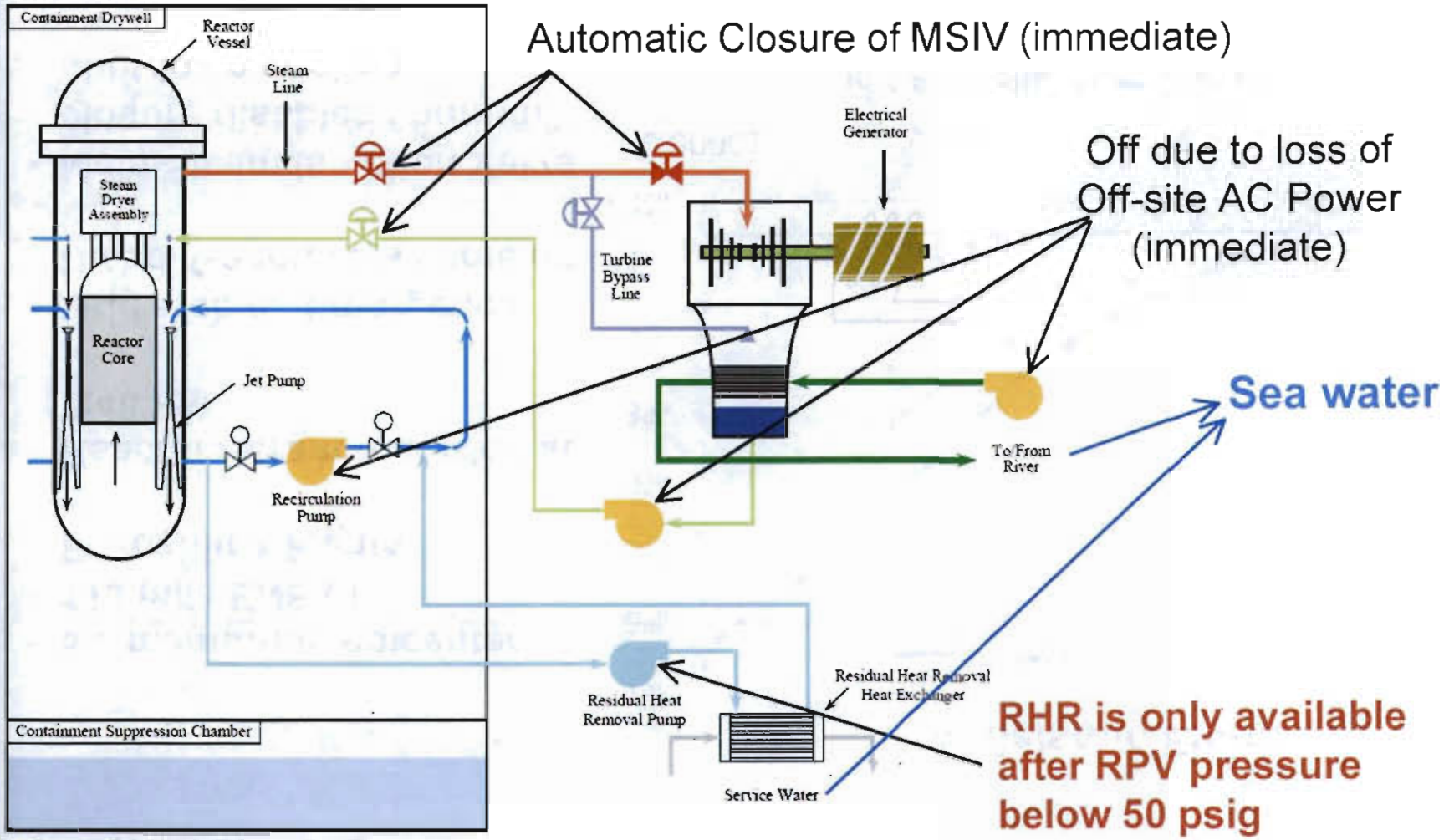
Seismic Activity @ 2:46 PM

- 8.9 magnitude epicenter 110 mile ENE of Fukushima Plants
- Reactor Scram recorded at 2:48 PM
- Grid stable. Emergency Diesel Generators came on
- Main Steam Isolation Valve closure disabled "normal" shutdown cooling



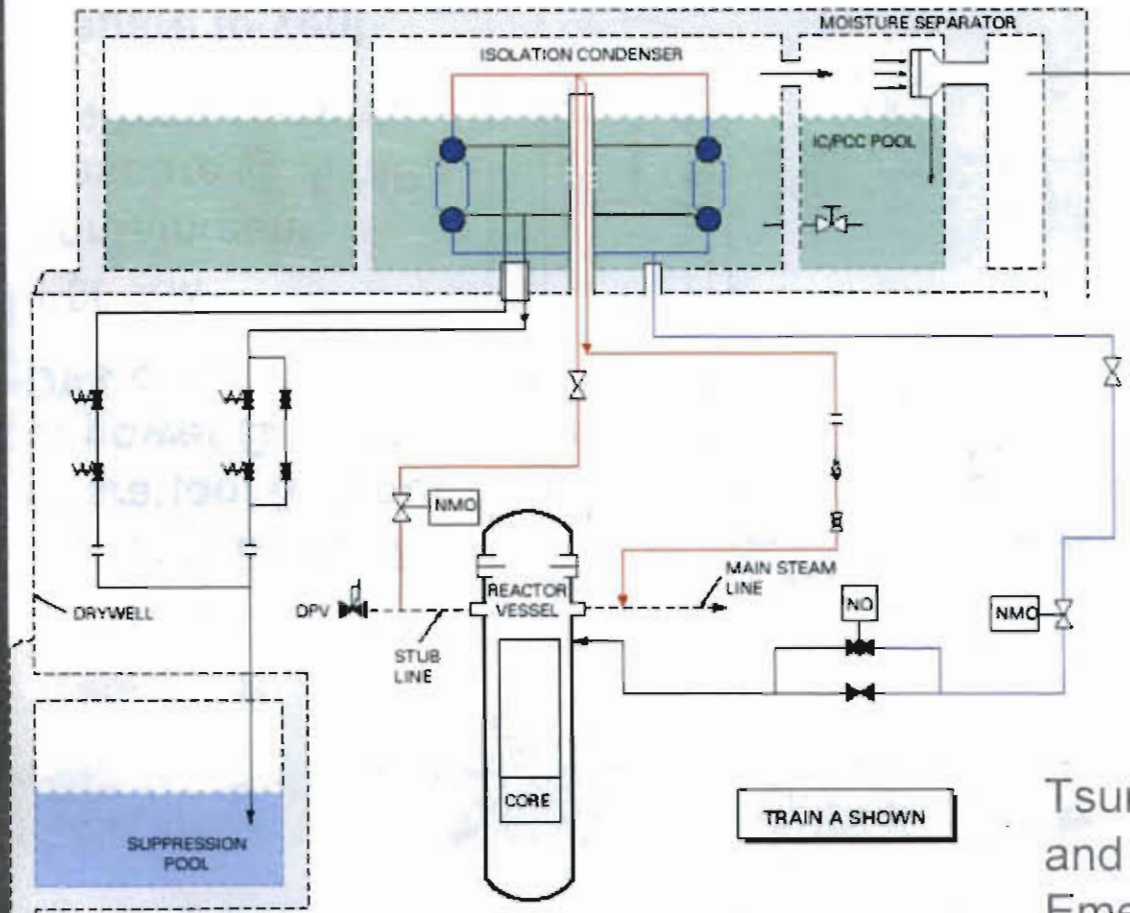
Earthquake disabled normal decay heat removal (Operator trained to respond)

At Seismic Event



Shutdown Cooling Accomplished by Isolation Condenser (2:48 PM – 3:41 PM JST)

Article 1 mandates heightened alert for Emergency Planning Zone -1



Routine Procedure after Seismic Transients

- Slow vessel cooling to minimize thermal shock
- Prepare to go backup if necessary
- (or) Prepare to activate SRV to initiate High Pressure Core Injection

Tsunami hit between 2:46 PM and 3:35 PM (Tsunami impacted Emergency Diesel Generator and Switch Gear)

Reactor Core Isolation Cooling provided necessary heat removal (3:41 PM – 1: 00 AM)

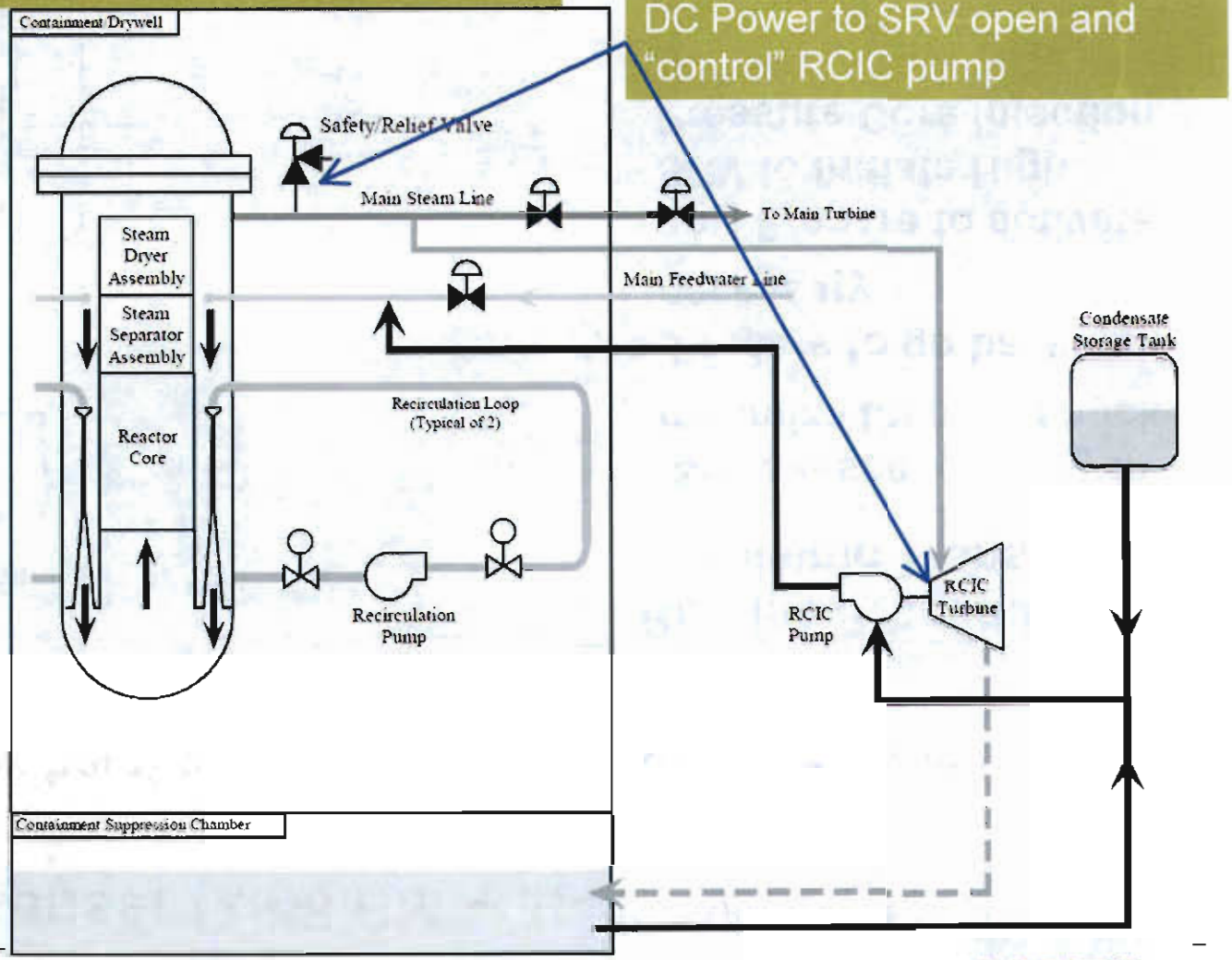
Nuclear emergency situation (EPZ-1 evacuation)

DC Power to SRV open and "control" RCIC pump

DC Battery power sized for 8 hrs of operation. Ran out of power @ 1 AM – DVs estimate

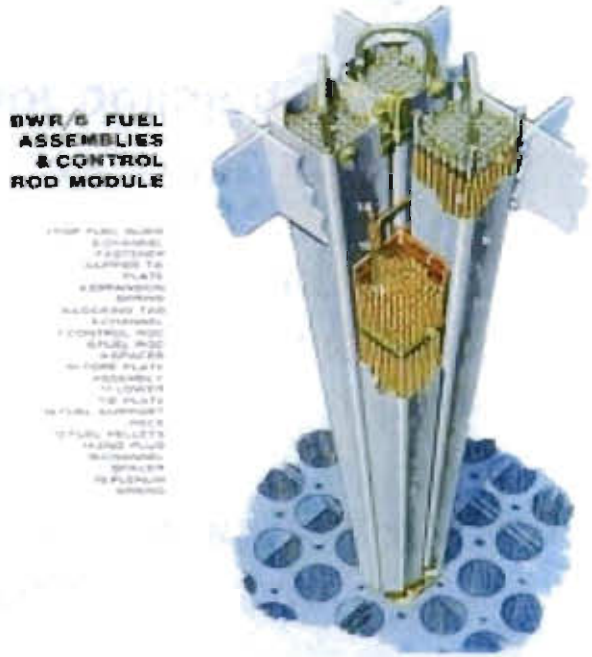
2:00 AM: Containment pressure @ .6 MPa (0.4 Mpa normal)

Prepare to vent containment



Fuel Damage When Water Level Drops Below Top of Fuel

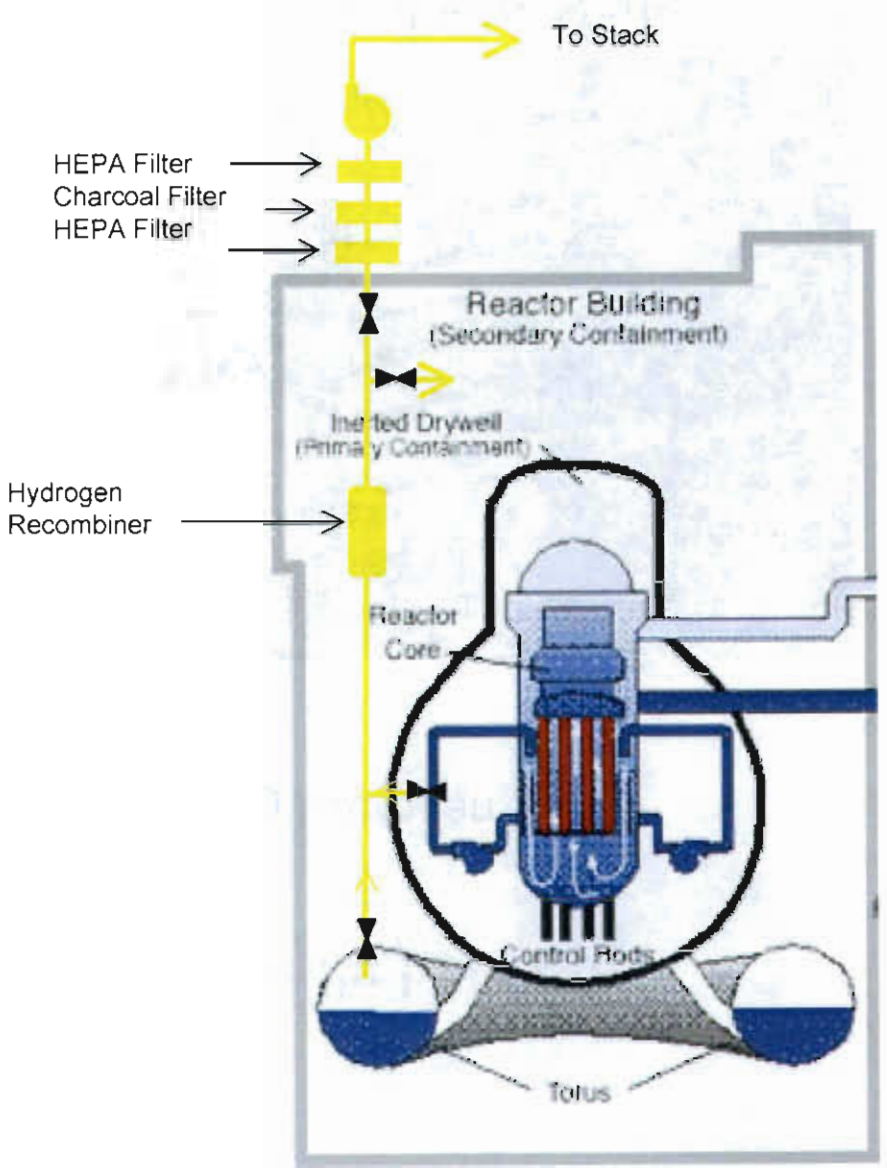
- **As the water level drops the core rapidly heats up**
  - 1100 K, fuel can balloon and burst
  - 1500 K, rapid oxidation of cladding producing hydrogen
  - 1700 K, debris bed formation



TMI Fuel Rods

Venting System

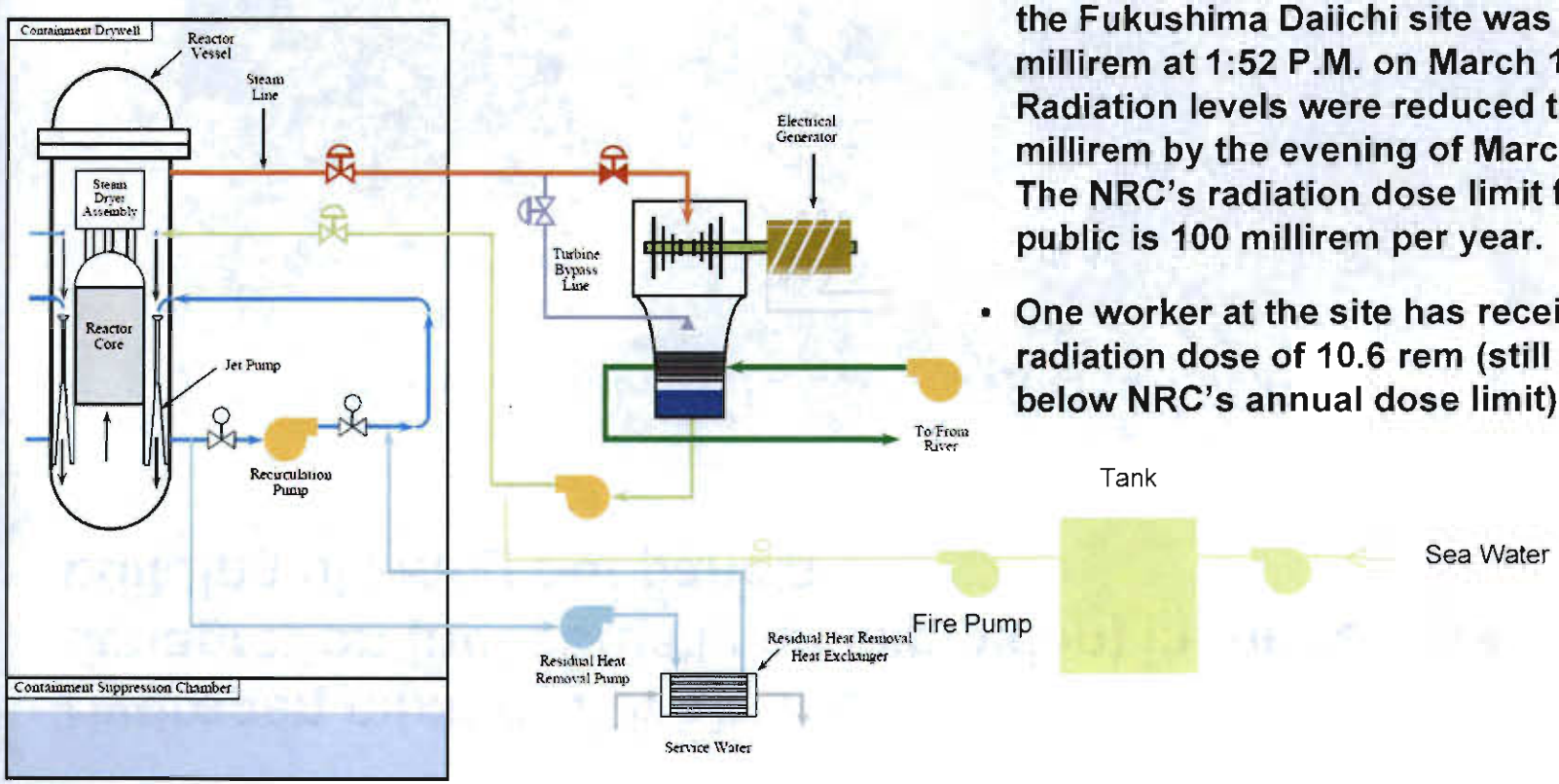
- Maximum containment reached 800 kPa (2 X normal pressure)
- The containment is vented to reduce pressure
- Can vent to the stack or reactor building
- Venting of the containment releases hydrogen to the reactor building
- Hydrogen ignites and explosion occurs



Hydrogen Explosion (cont.)

- Hydrogen mixing with air and a spark source caused a deflagration (not actually an explosion) in the reactor building blowing out panels

Current Mitigation Strategy

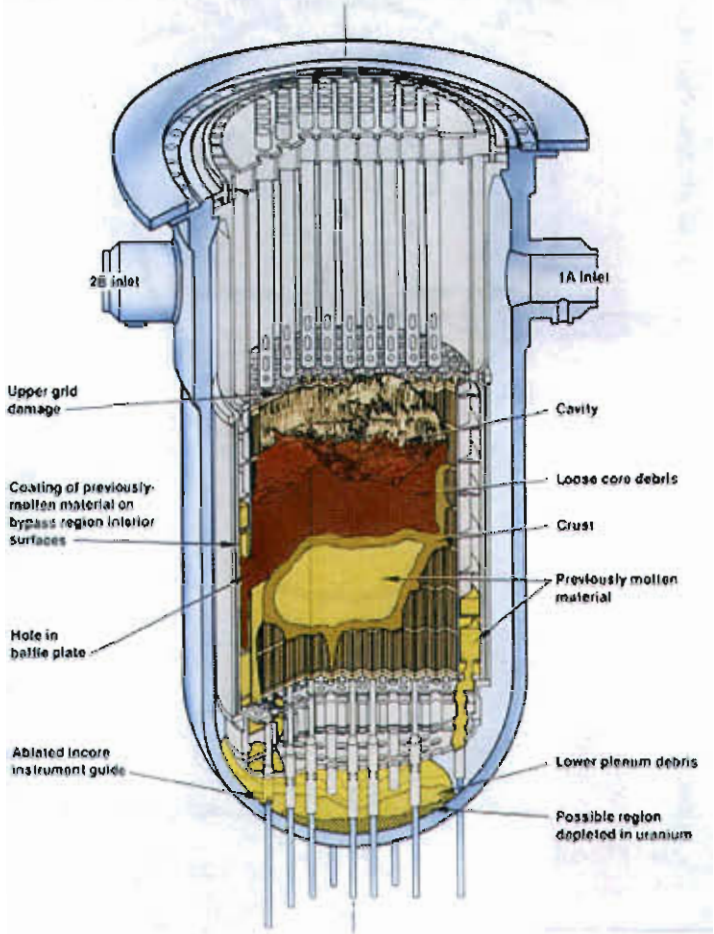


- Public evacuated to 12-mile radius as a precaution
- The highest recorded radiation level at the Fukushima Daiichi site was 155.7 millirem at 1:52 P.M. on March 13. Radiation levels were reduced to 4.4 millirem by the evening of March 13. The NRC's radiation dose limit for the public is 100 millirem per year.
- One worker at the site has received a radiation dose of 10.6 rem (still well below NRC's annual dose limit)

Extent of Core Damage and Release

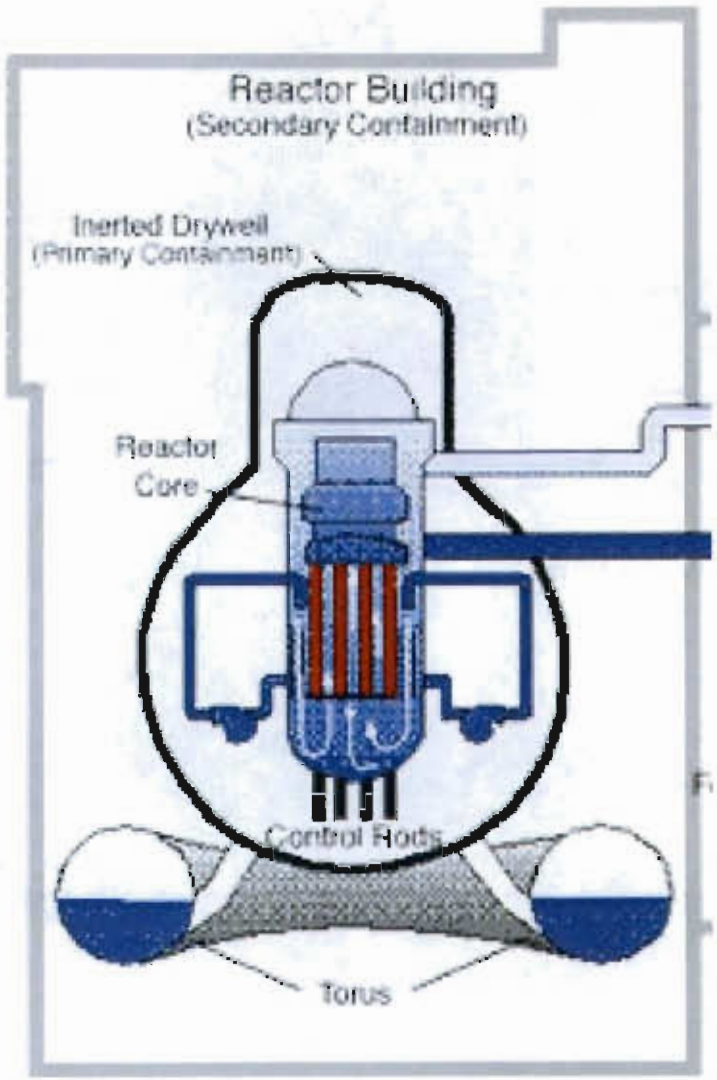
- **Damage to core could range from:**
  - **Oxidized fuel rods with cladding failure (Occurred)**
    - ➢ Gases in fuel cladding gap (Nobles, Iodine, and Cesium) released
  - **Partial fuel melt (Possible)**
    - ➢ Cladding gap releases plus release from fuel as it heats up
  - **Full core melt (Unlikely)**
    - ➢ Release of substantial amount of core radionuclide inventory

TMI-2 Core End-State Configuration

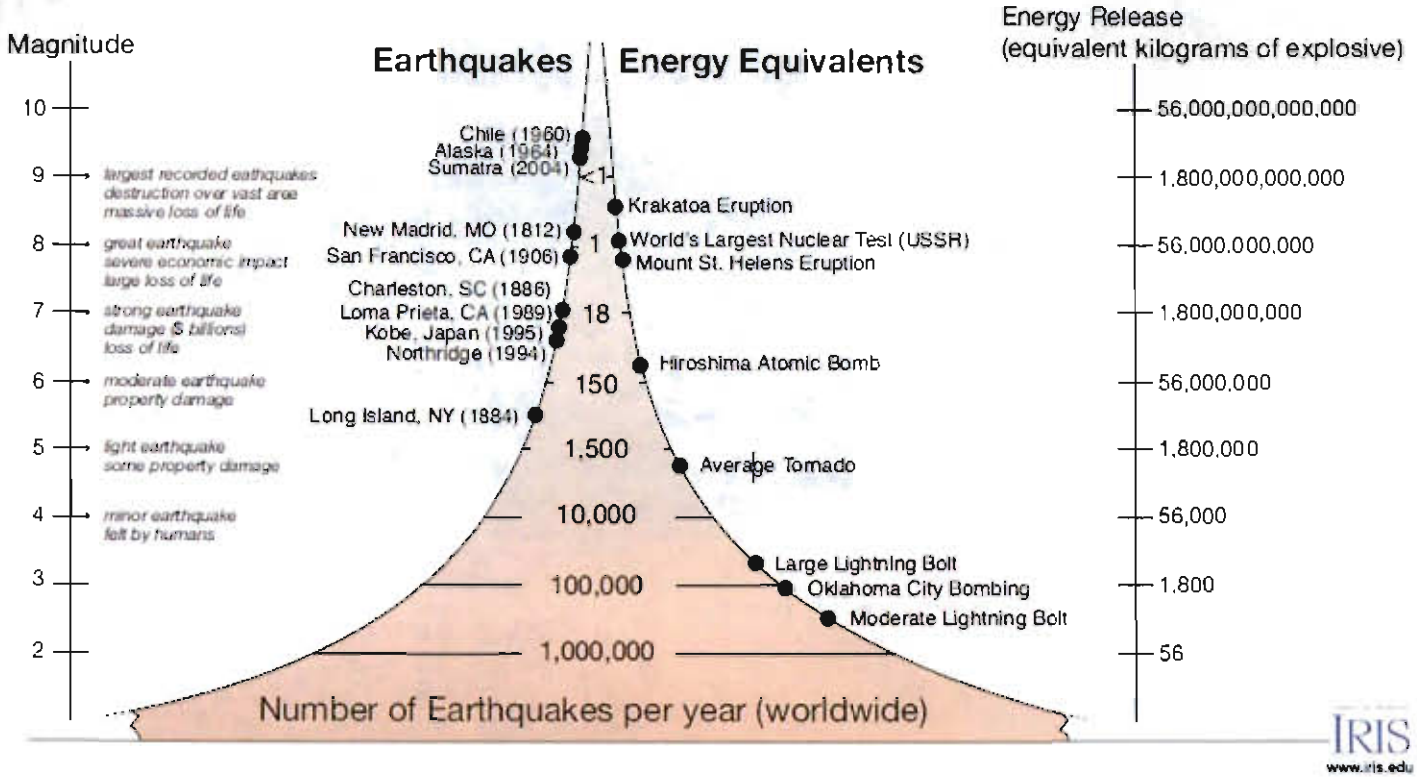


Retention of Fission Products in Containment

- **Containment has NOT failed!**
- **Containment is being vented to prevent failure and control release**
- **Large amounts of fission products will remain in containment**
  - Plated out in reactor vessel walls
  - Held up in suppression pool
  - Plated out in containment walls



The Global Earthquake Cycle: Frequency, Magnitude and Energy

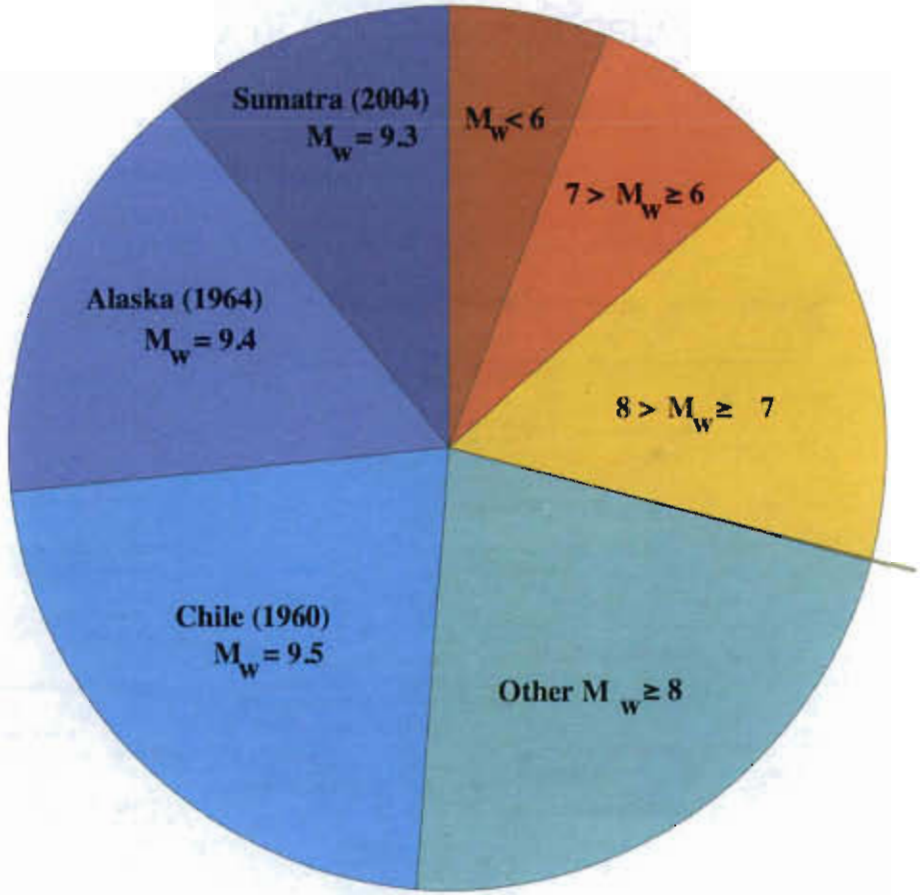


Frequency of Occurrence of Earthquakes

Magnitude	Average Annually
8 and higher	1 [1]
7 - 7.9	15 [1]
6 - 6.9	134 [2]
5 - 5.9	1319 [2]
4 - 4.9	13,000 (estimated)
3 - 3.9	130,000 (estimated)
2 - 2.9	1,300,000 (estimated)

Before Sendai, the seismic moment and energy was dominated by 3 earthquakes.

Global Seismic Moment Release January 1906 - December 2005



Total Moment: 1.0×10^{24} Newton-meters

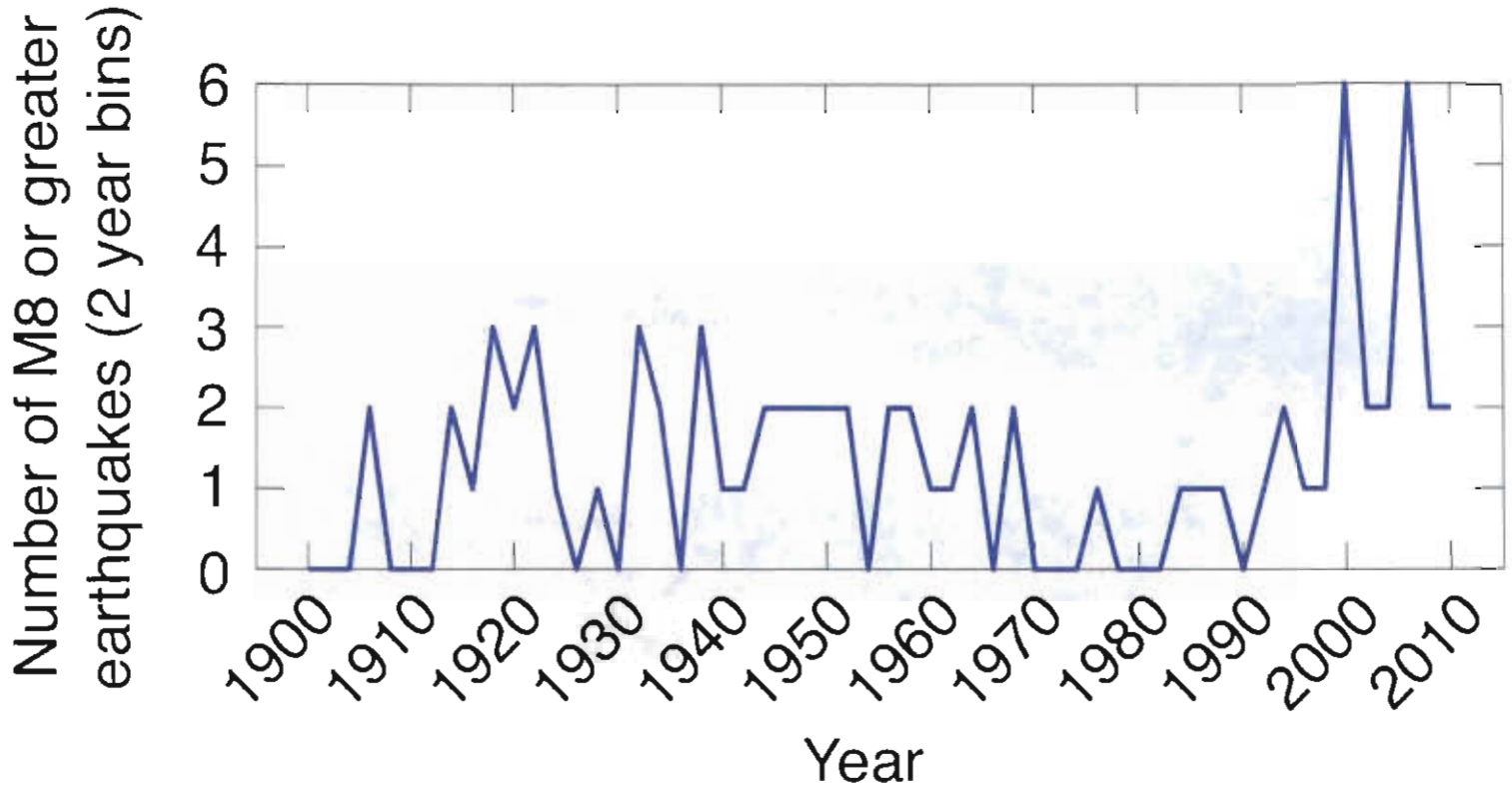
Largest quakes

The world's highest-magnitude earthquakes since 1900:

Location	Year	Mag.
Chile	1960	9.5
Prince William Sound, Alaska	1964	9.2
Off coast of Northern Sumatra	2004	9.1
Kamchatka, Russia	1952	9.0
Honshu Coast, Japan	2011	8.9
Off coast of Ecuador	1906	8.8
Chile	2010	8.8
Rat Islands, Alaska	1965	8.7
Northern Sumatra, Indonesia	2005	8.6
Assam, Tibet	1950	8.6
Andreanof Islands, Alaska	1957	8.6
Southern Sumatra, Indonesia	2007	8.5
Banda Sea, Indonesia	1938	8.5
Kamchatka, Russia	1923	8.5
Chile-Argentina border	1922	8.5

Source: U.S. Geological Survey © 2011 MCT

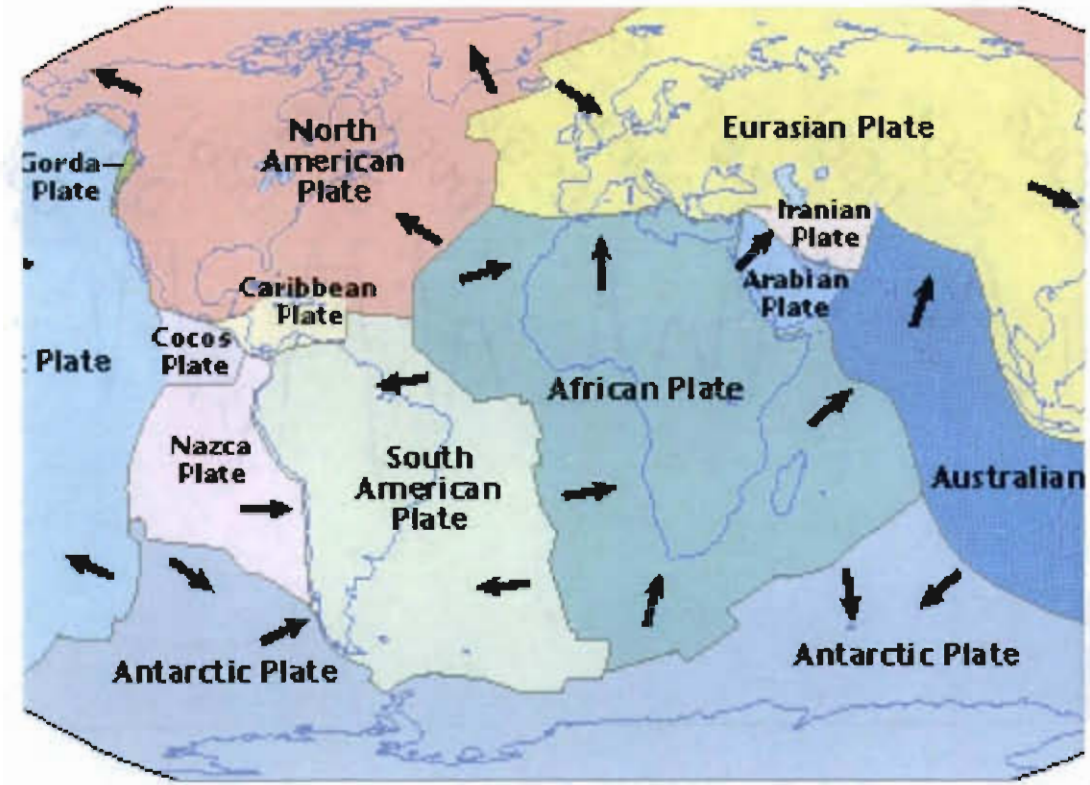
Earthquakes >M8 since 1900



Courtesy Eric Daub

The plate-tectonic paradigm of Earth is based on plates sliding past each other driven by mantle processes.

- Stress builds up and Coulomb failure creates and earthquake.



- The new paradigm is based on *long range interactions* between faults–Earth as elastic system. An earthquake can affect faults far away.

Earthquake Triggering

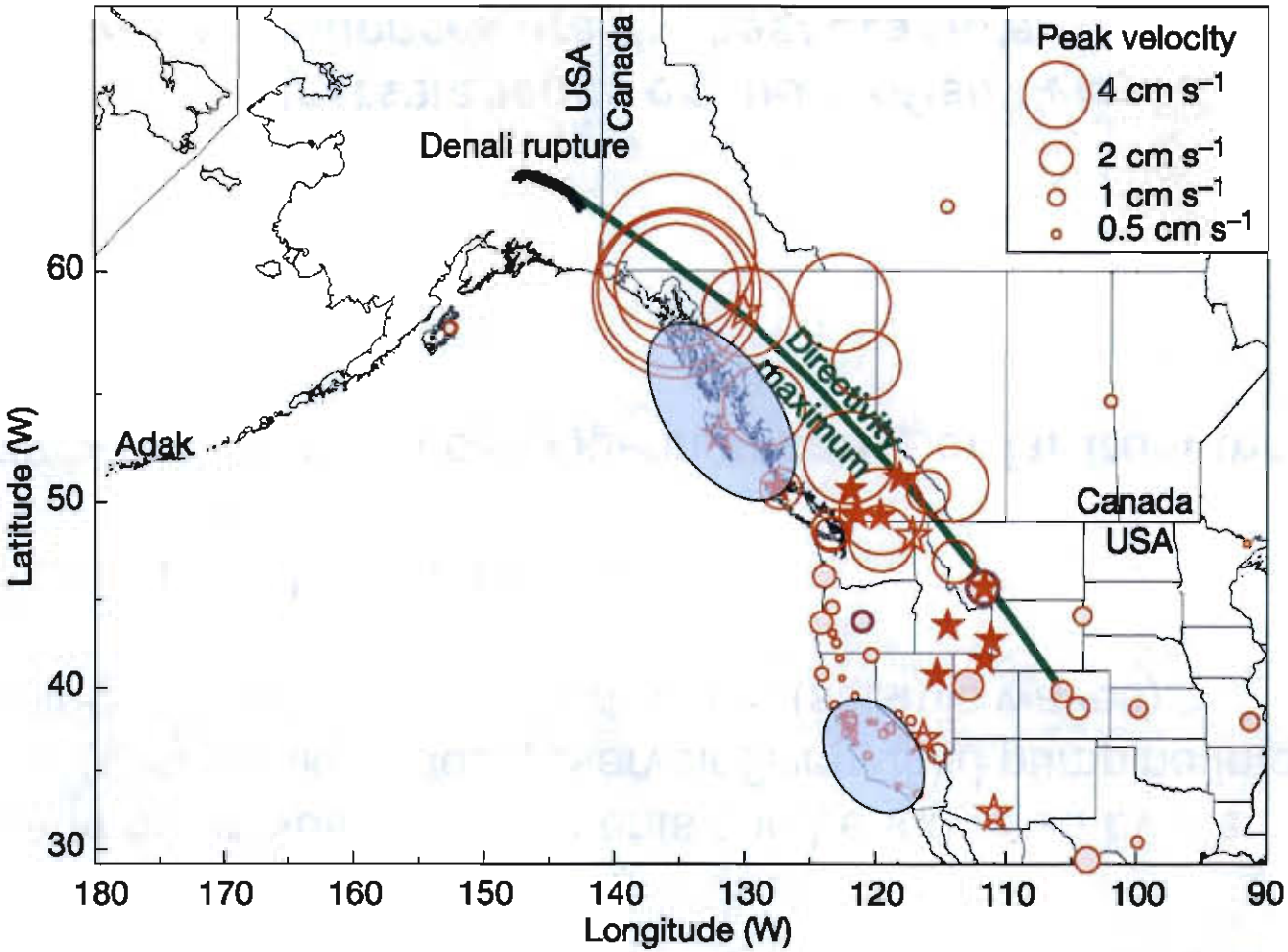
- Earthquakes and other types of slip events can be triggered by static stress changes (earthquake, tides, reservoir filling, fluid pumping into boreholes…) and dynamic wave perturbations (seismic waves).
- Static triggering is a **local phenomenon**.
- Dynamic perturbations can induce triggering **nearby or far from the triggering source**.

All triggering can be instantaneous or, more often delayed – aftershock sequences are the best example.

A Dynamic Earthquake Triggering Scenario

Triggered tremor

Triggered earthquake



Modified from Gomberg *et al.*, ***Nature*** (2004) + Gomberg *et al.*, ***Nature*** (2008)

Dynamic Wave Triggering of other Natural Phenomena

- Japan earthquake triggered volcano eruption In Russia? (*as yet unsubstantiated*)

- Triggering of small earthquakes and "tremor" in the western US reported, but details are not yet available (Joan Gomberg, USGS Seattle Office).

Similar Characteristics in the Pacific Northwest