Seismological analysis of the recent earthquake disasters in New Zealand and Japan: 10 lessons for Switzerland

SED, March 17, 2011

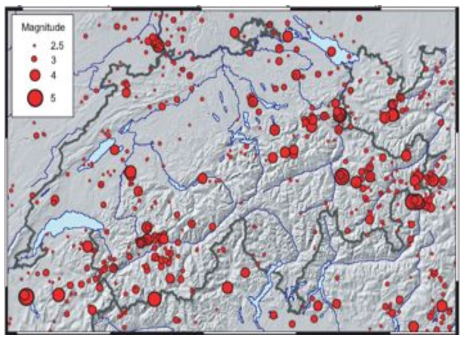
- Common language
- The February 22, M6.3 Christchurch earthquake
- The March 11, M9 Tohoku earthquake
- Comparison between the two earthquakes
- Consequences for nuclear power plants
- 10 Lessons for Switzerland

www.seismo.ethz.ch

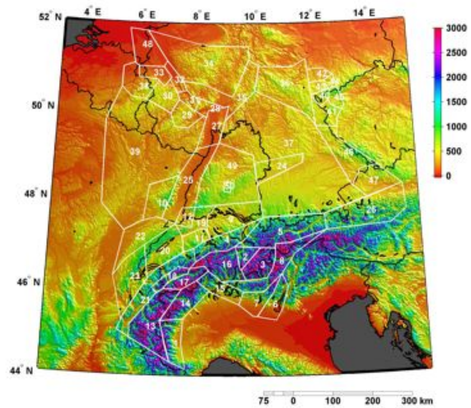
Seismic Hazard Assessment

Main steps in the probabilistic assessment of seismic hazard (PSHA)

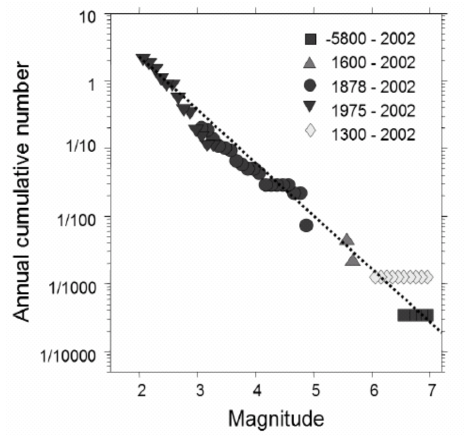
Earthquake catalogue

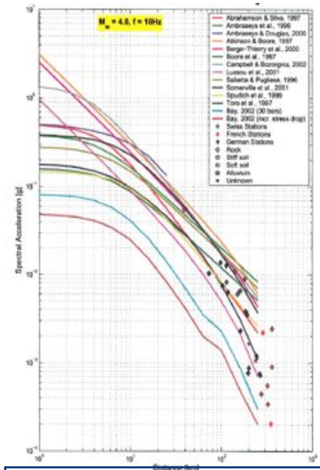


Seismotectonics and active faults

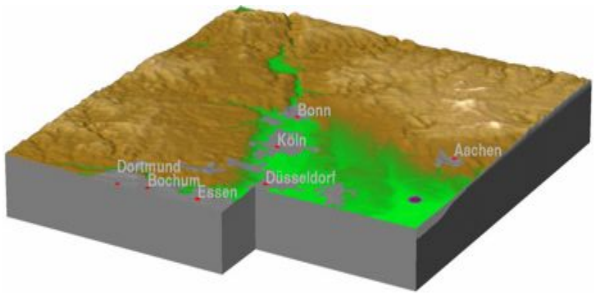


Earthquake activity rates

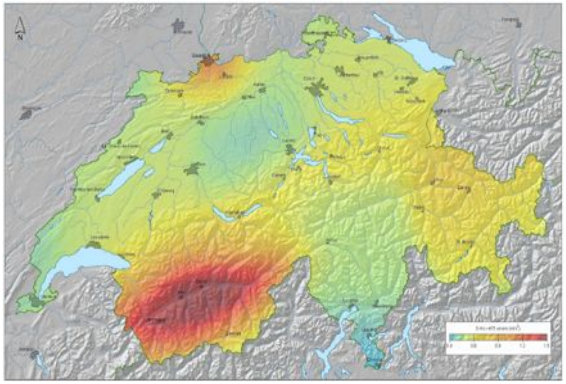




Attenuation of wave height with distance



Shaking scenario with site amplifications

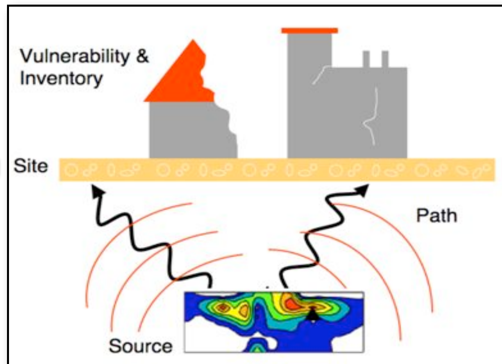


Hazard: ground shaking expected with 10% probability in 50 years

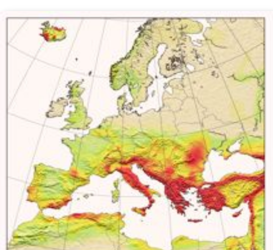
Seismic hazard assessment

Different hazard products can be computed for the long term and short term probability of shaking, and in the aftermath of the earthquake

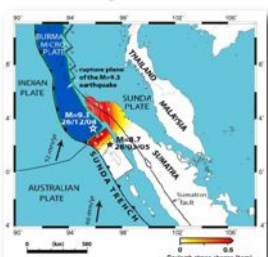
Earthquake



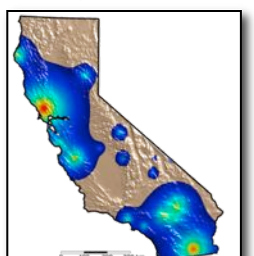
decades | **years** | **days to minutes** | **seconds** | **minutes to hours**



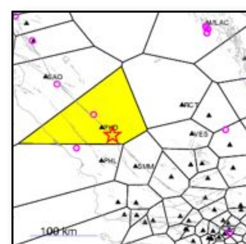
Long-term Hazard Mapping



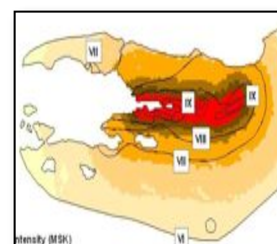
Long-Term Forecasting



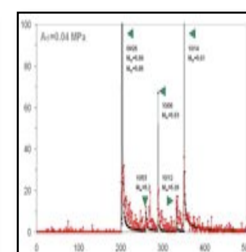
Short-Term Forecasting



Early Warning



ShakeMaps & Rapid Loss



Aftershock Forecasting

From seismic hazard to seismic risk assessment

Seismic hazard

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Local effects

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Exposed value

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Vulnerability

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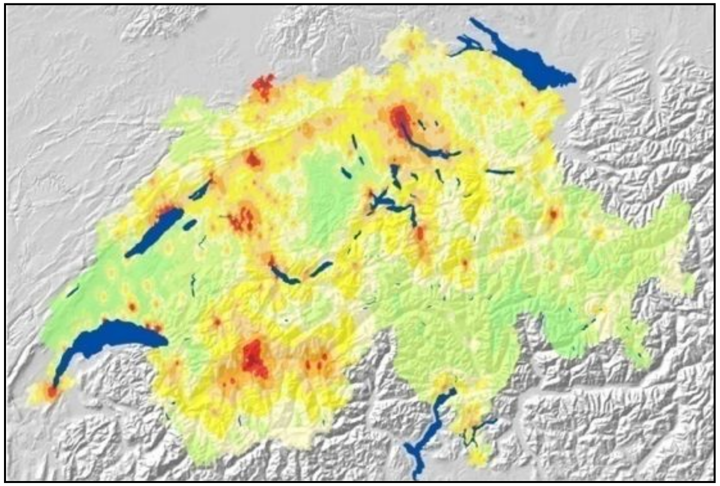
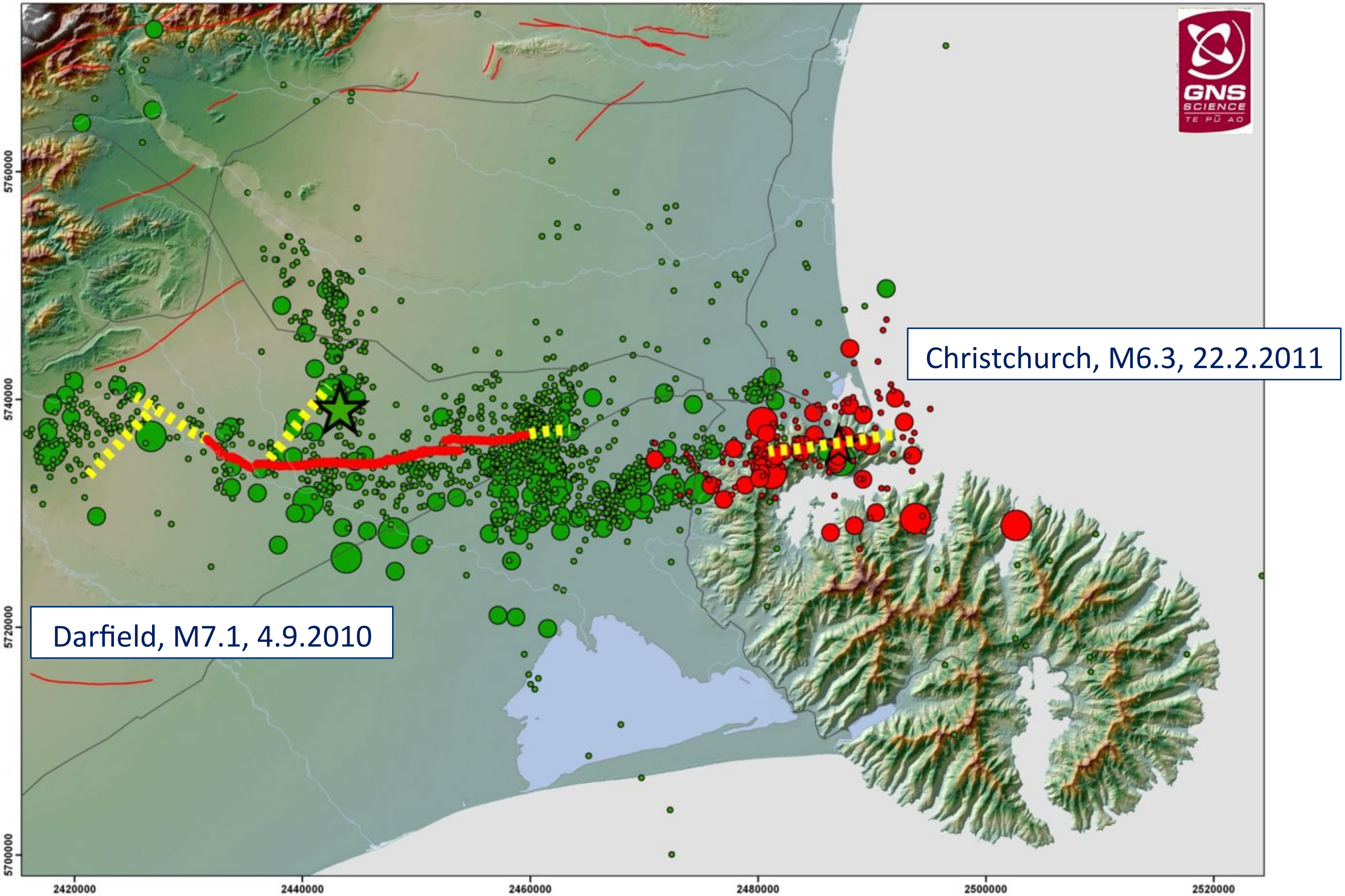


Seismic risk is dominated by economic value and is concentrated in urban areas

GVZ/PartnerRe, 2009

The Christchurch earthquake, February 22, 2011

- Magnitude 6.3
- Depth 5km
- Located East of the M7.1 Darfield earthquake, September 4, 2010
- Both events located on a previously unknown fault, outside of the main recognized seismic areas of New Zealand
- Shaking intensity MMI IX in central Christchurch (d=8km)
- Strong site effects due to local soil conditions (soil class D)
- Shaking largely exceeded local building code
- It was not forecasted/predicted


Christchurch, M6.3, 22.2.2011
Darfield, M7.1, 4.9.2010
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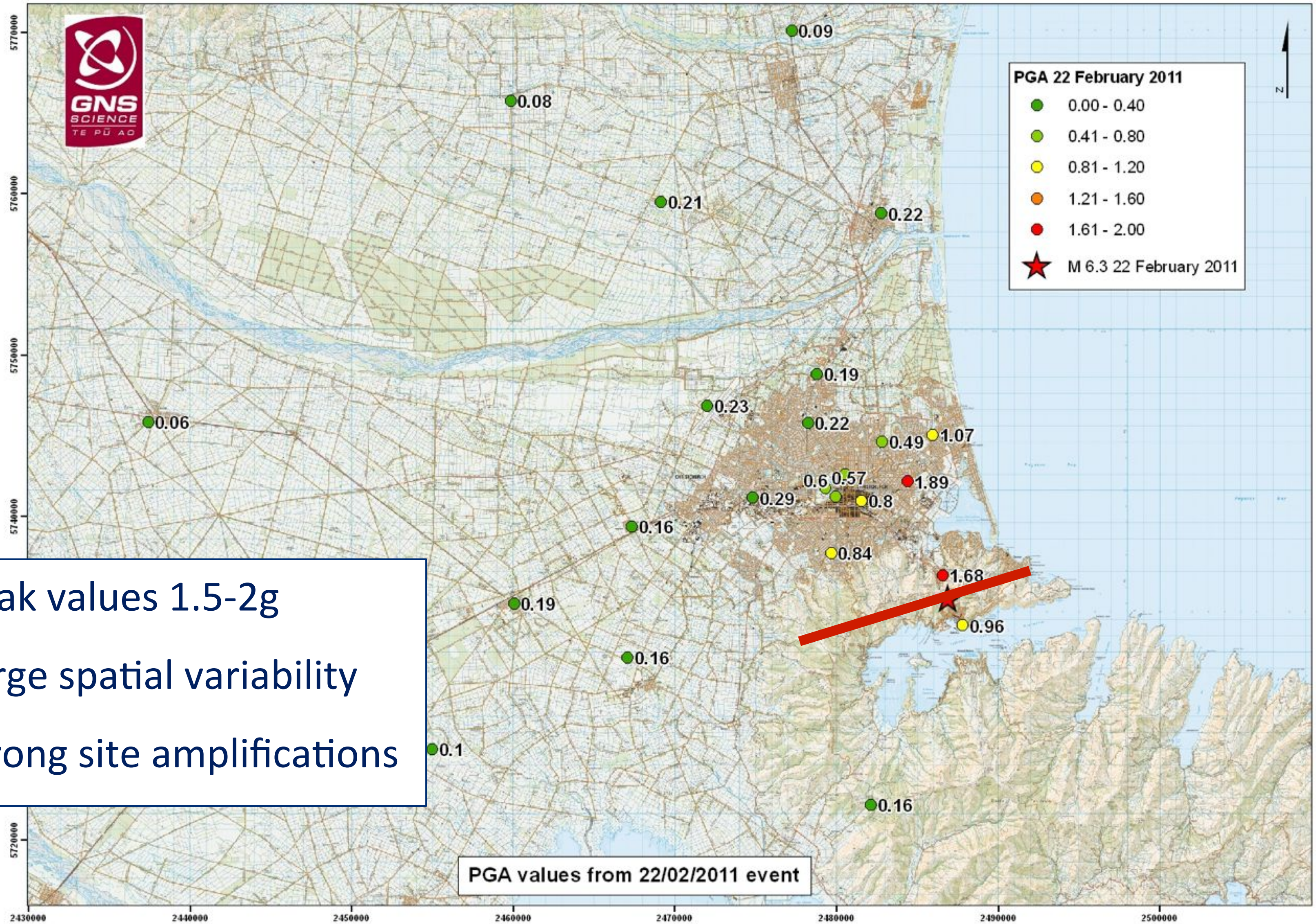
Consequences

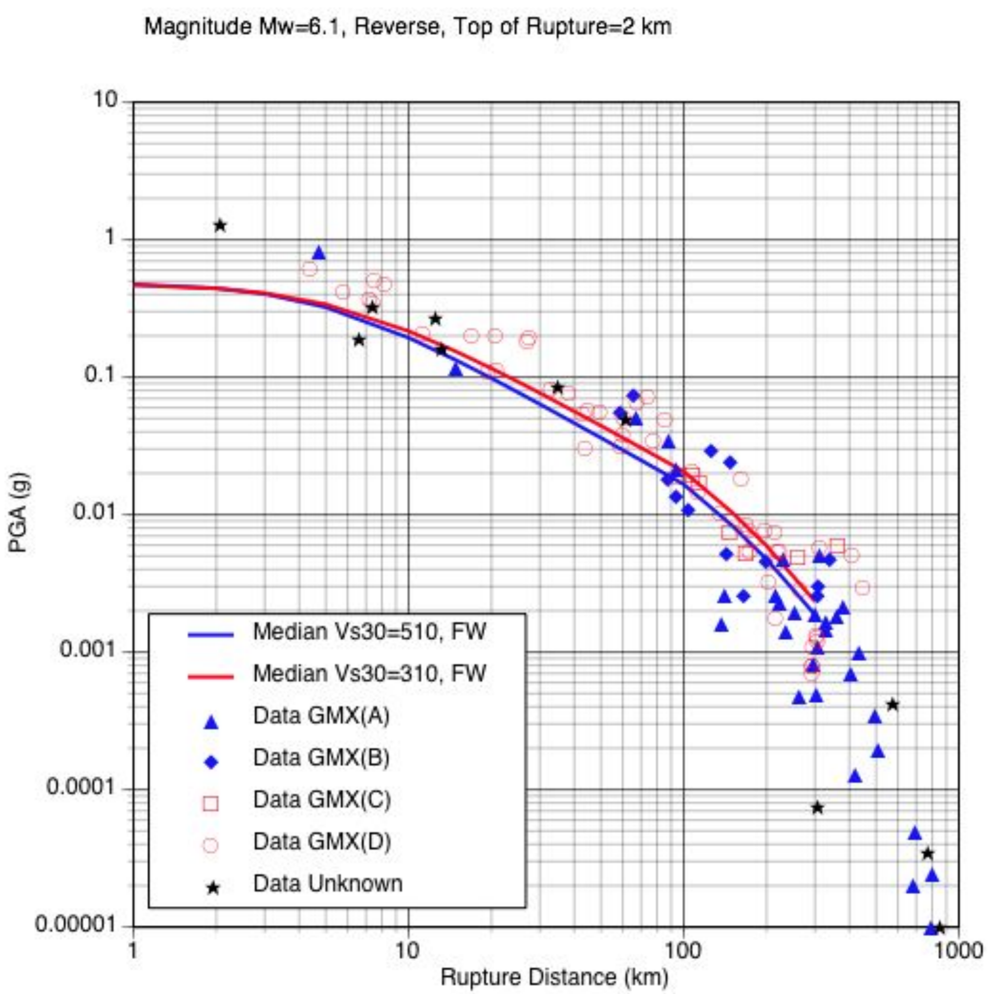
- Casualties 200+
- ~5000 homes uninhabitable
- 13B$ direct damage
- Widespread liquefaction
- Widespread landslides over Port Hills
- Electricity: initially lost to 60% city; after 10 days, 20% without power
- Water Supply: lost to 50% city; after 10 days, 15% without water
- Waste Water: widespread, non-recoverable damage to sewer network and treatment plant

Recorded peak ground motion (PGA)



- Peak values 1.5-2g
- Large spatial variability
- Strong site amplifications

Recorded peak ground motion (PGA)



- Excellent data coverage
- ~50Good site characterization
- Peak values and spatial variability agree with existing models

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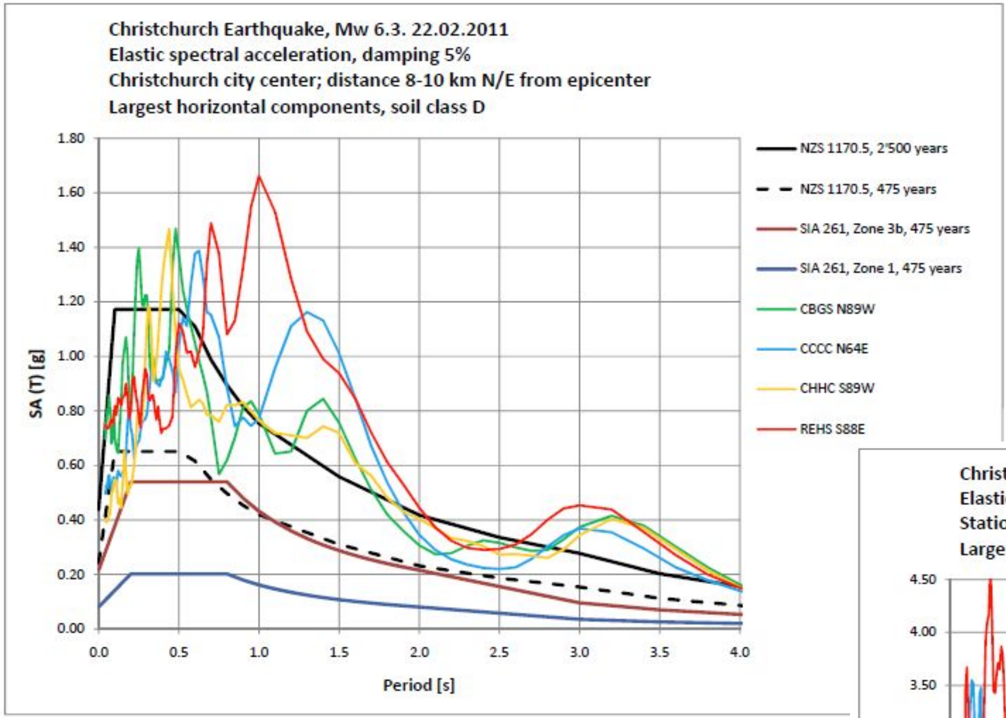
Recorded peak ground motion (PGA)

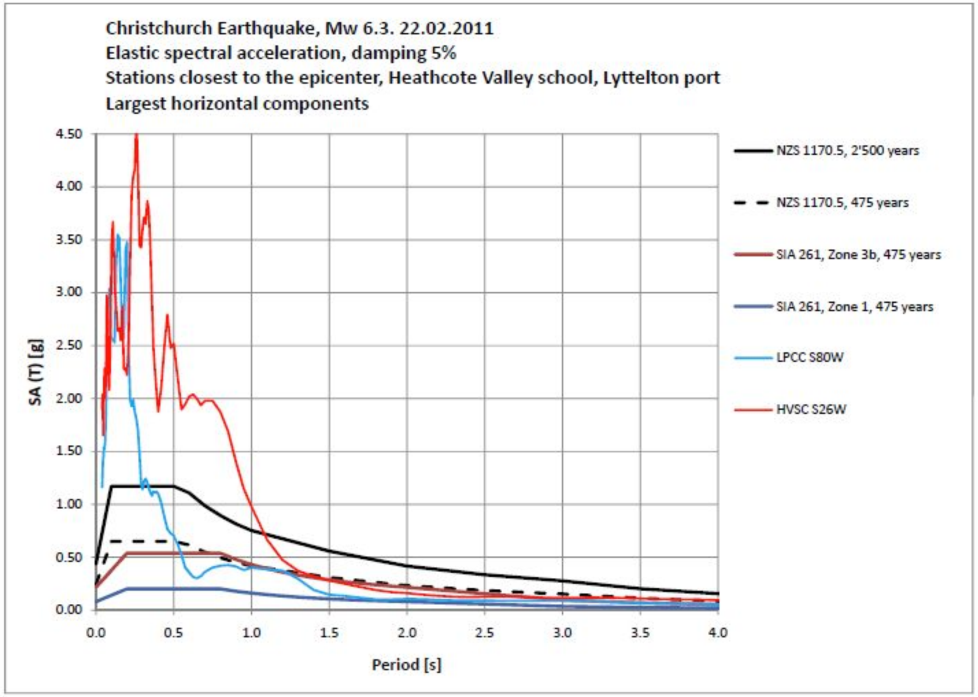


Motions exceed NZ building code

- 475yr by 2-5 times
- 2500yr by 1-3 times

Motions exceed CH building code

- 475yr-zone 3b by 2-7 times
- 475yr-zone 1 by 6-18 times



GNS and B. Duvernay/BAFU

Building damage

Damage from liquefaction and landslides

Water damage in on the corner of Pages Rd and ANZAC Dr. DON SCOTT/The Press

Photo 17. GTH_5787 - House destroyed by rock fall at 54 Raekura Place, Redcliffs (reported fatality site).

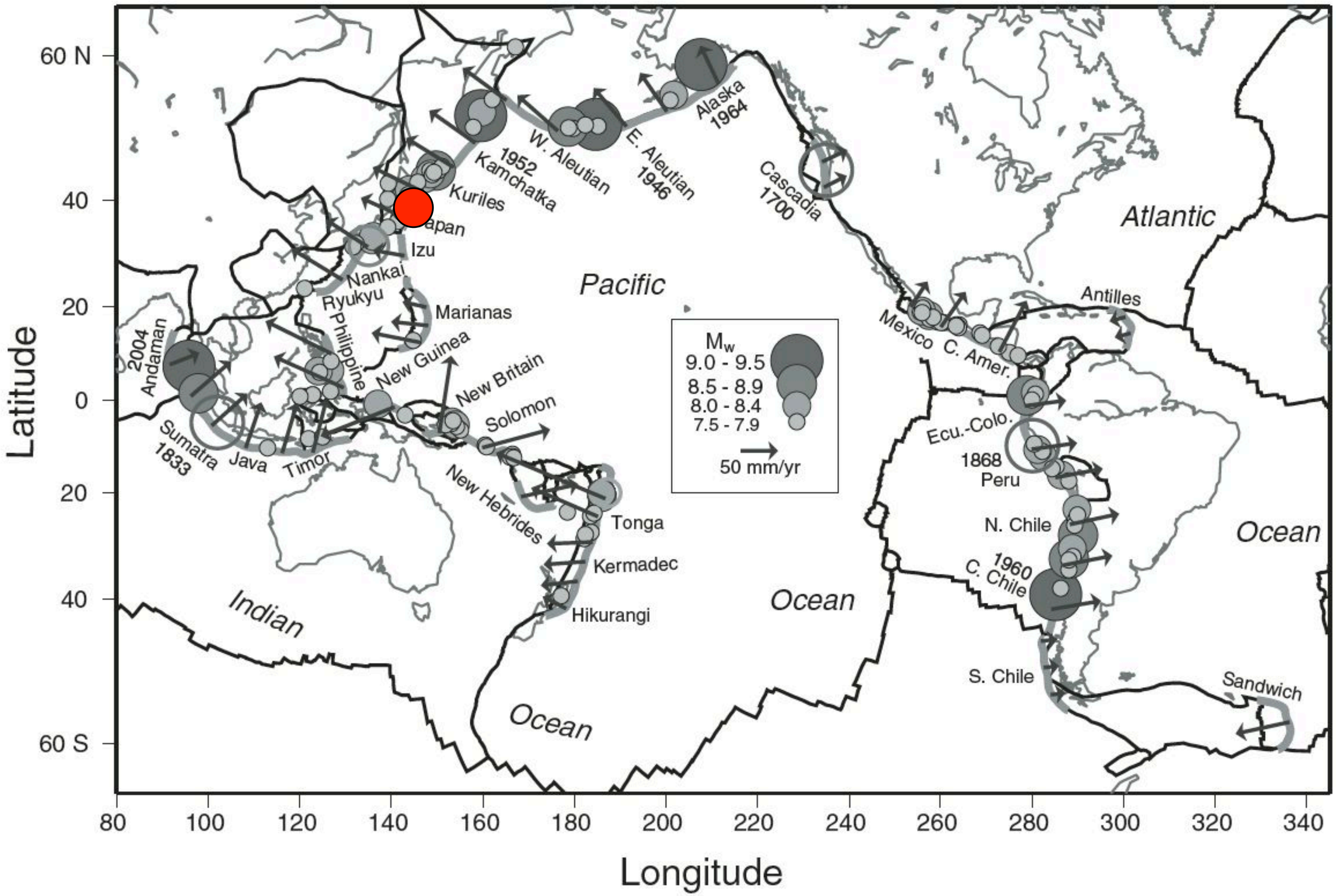
Photo 6. GTH_5708 (Rock falls RSA Building in Wakefield Ave Sumner (rock fall fatality reported at building site left).

Lessons learned

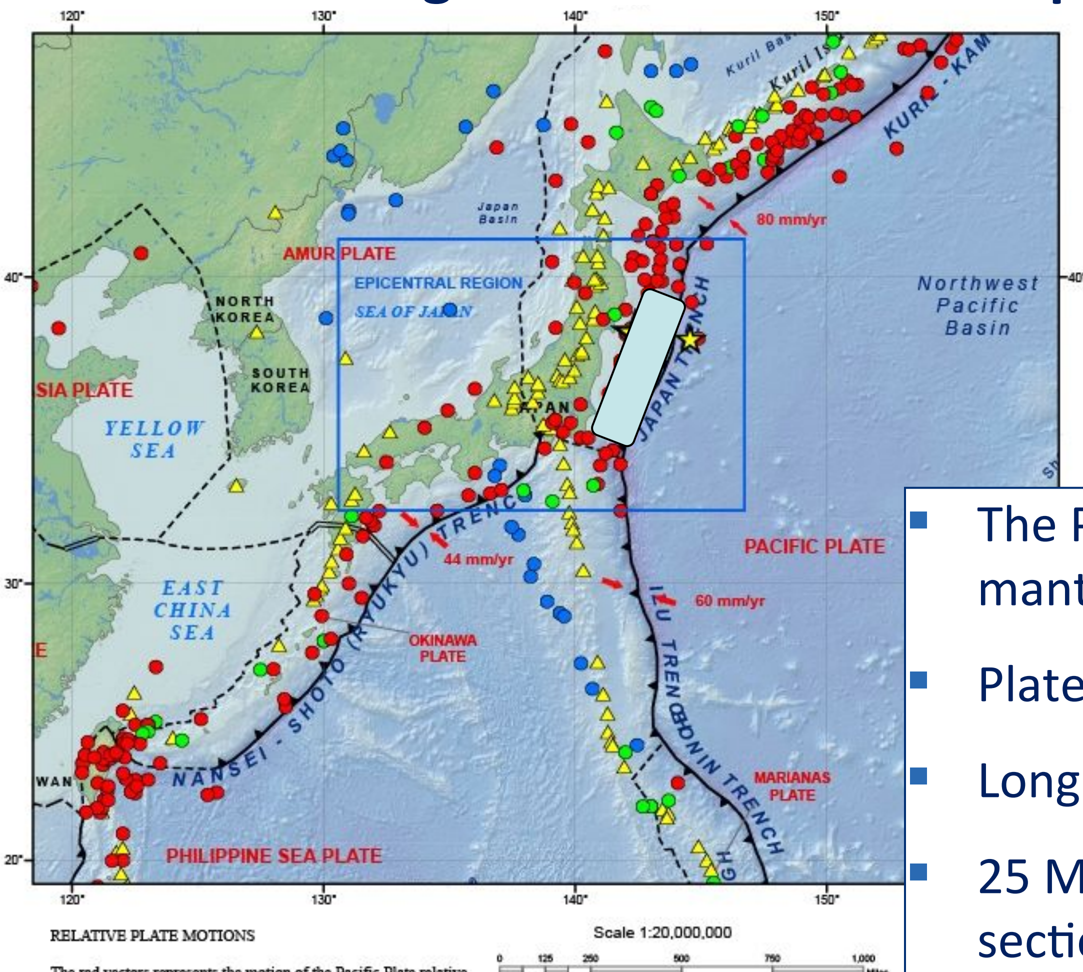
- Ground shaking intensity (much) beyond current design code levels
- Significant ground deformation related losses
  - Liquefaction – housing & infrastructure
  - Landslide – housing
- Damage to residential buildings
  - Hill-side locations damage > average
  - Shaking damage to modern buildings < average
- Damage to non-residential buildings
  - Damage to buildings constructed using older codes
  - Modern buildings (post 1980) performed well
  - Widespread damage to Un-Reinforced Masonry buildings

Tohoku earthquake, March 11, 2011, Magnitude 9

Tectonic setting: M9 on Pacific "ring of fire"

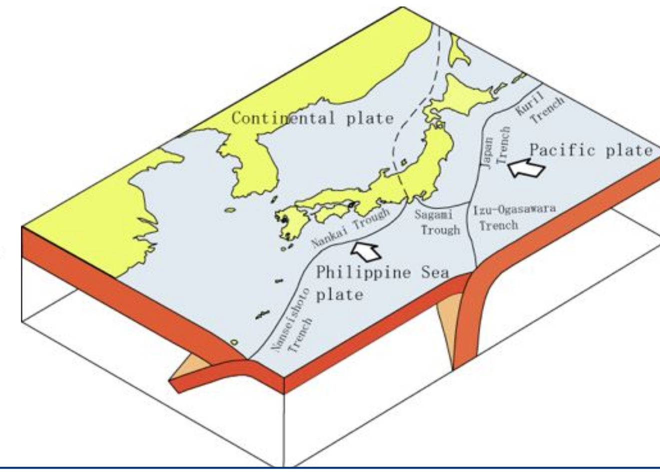


Tectonic setting: subduction of Pacific plate under Honshu



RELATIVE PLATE MOTIONS

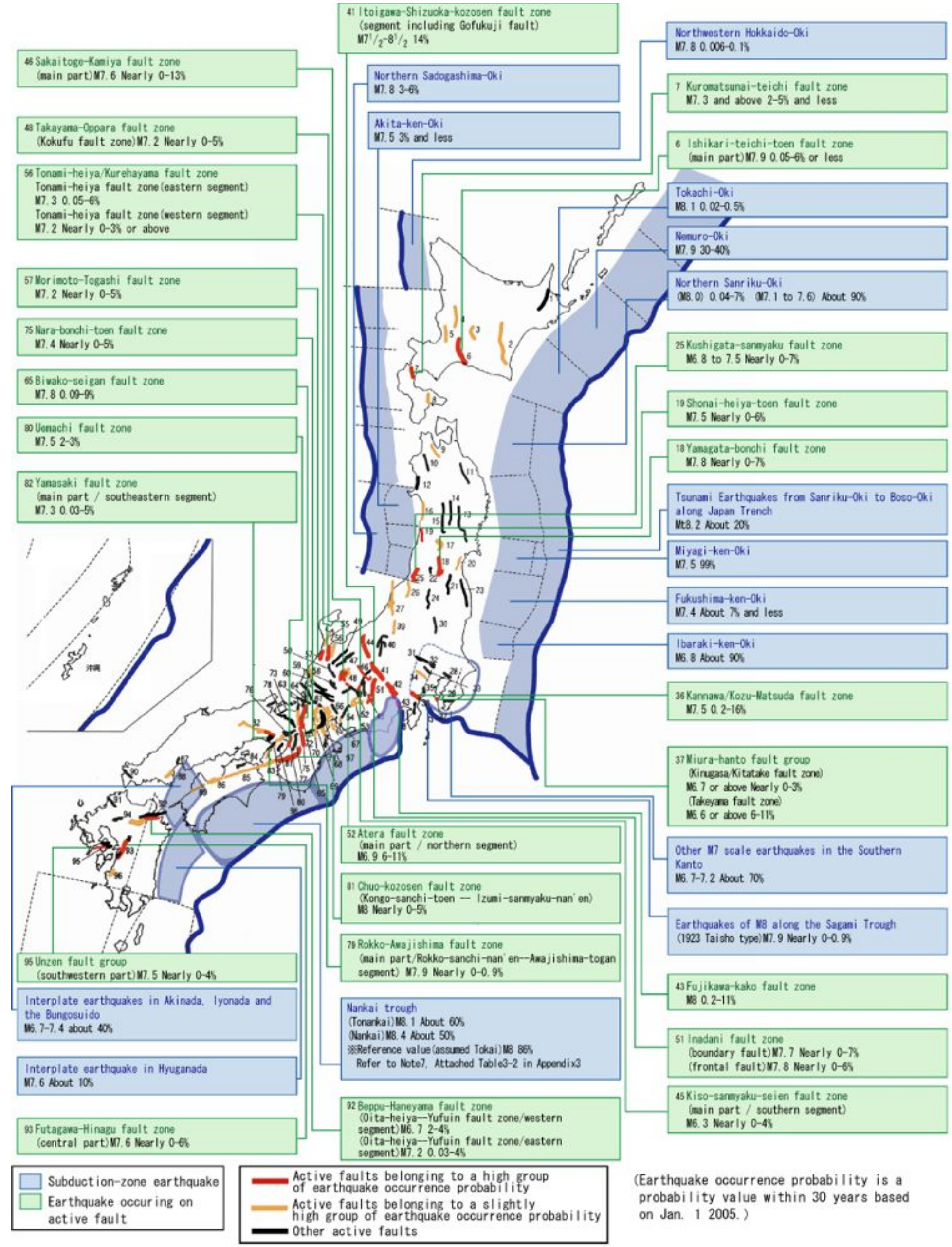
The red vectors represents the motion of the Pacific Plate relative to the Philippine Plate, and the Philippine Plate relative to the Eurasia Plate in the region. The motion of the Pacific Plate is generally 60 mm/yr north westward with respect to the Philippine Plate. The motion of the Philippine Plate is generally 44 mm/yr north westward with respect to the Eurasia Plate.



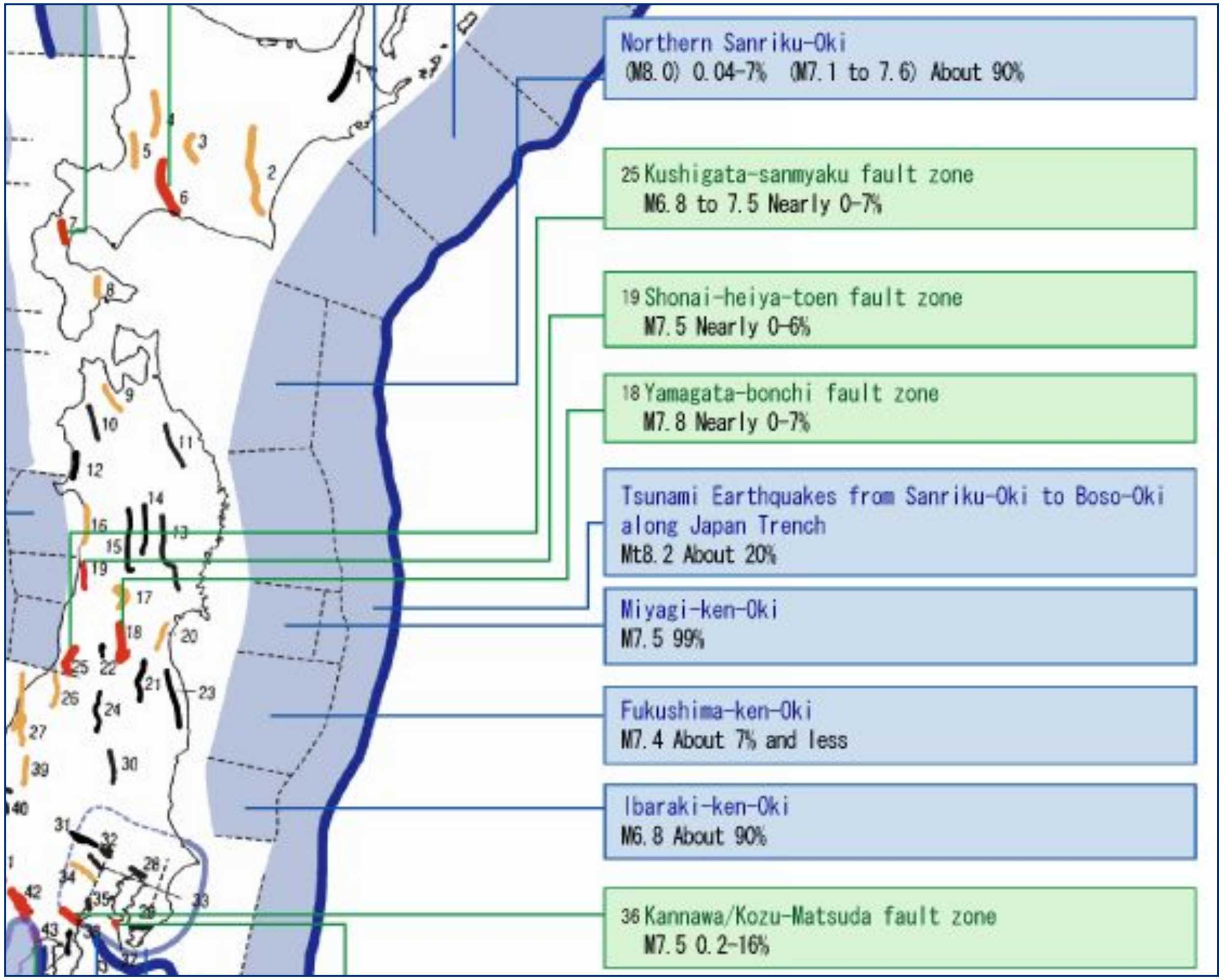
- The Pacific plate sinks deep into the mantle at the Japan trench
- Plate convergence of 8-10 cm/yr
- Long and well known seismic history
- 25 M7+ earthquakes on the Honsu section of the Japan trench since 1900
- The M9 filled a “gap“ in the Western Pacific margin

Active fault model of Japan

- Very detailed characterization, best worldwide
- Maximum Magnitude and probability of occurrence specified for each fault and each segment
- Different treatment of subduction and crustal faults



Active fault model of Japan: Pacific subduction



Mmax 6.8-8.2 on different subduction segments, M9 not considered

Seismic hazard of Japan

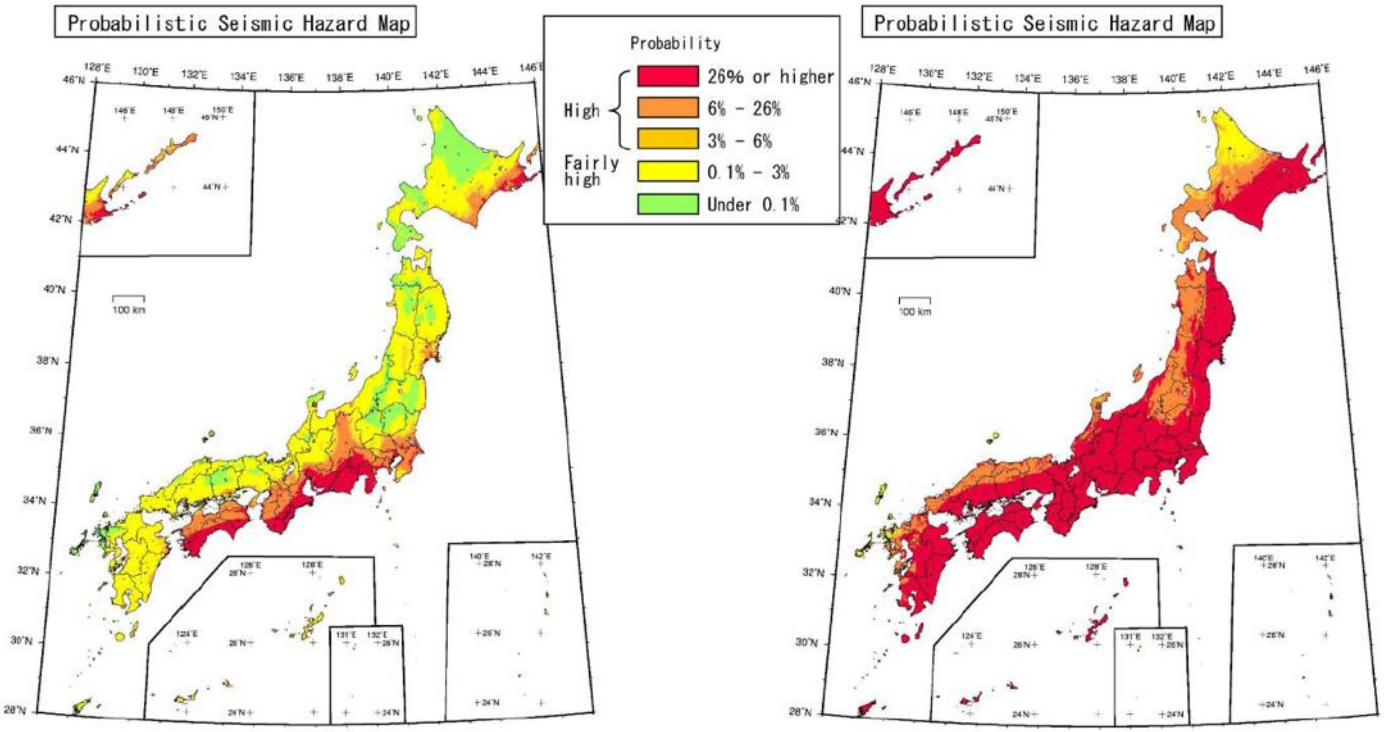


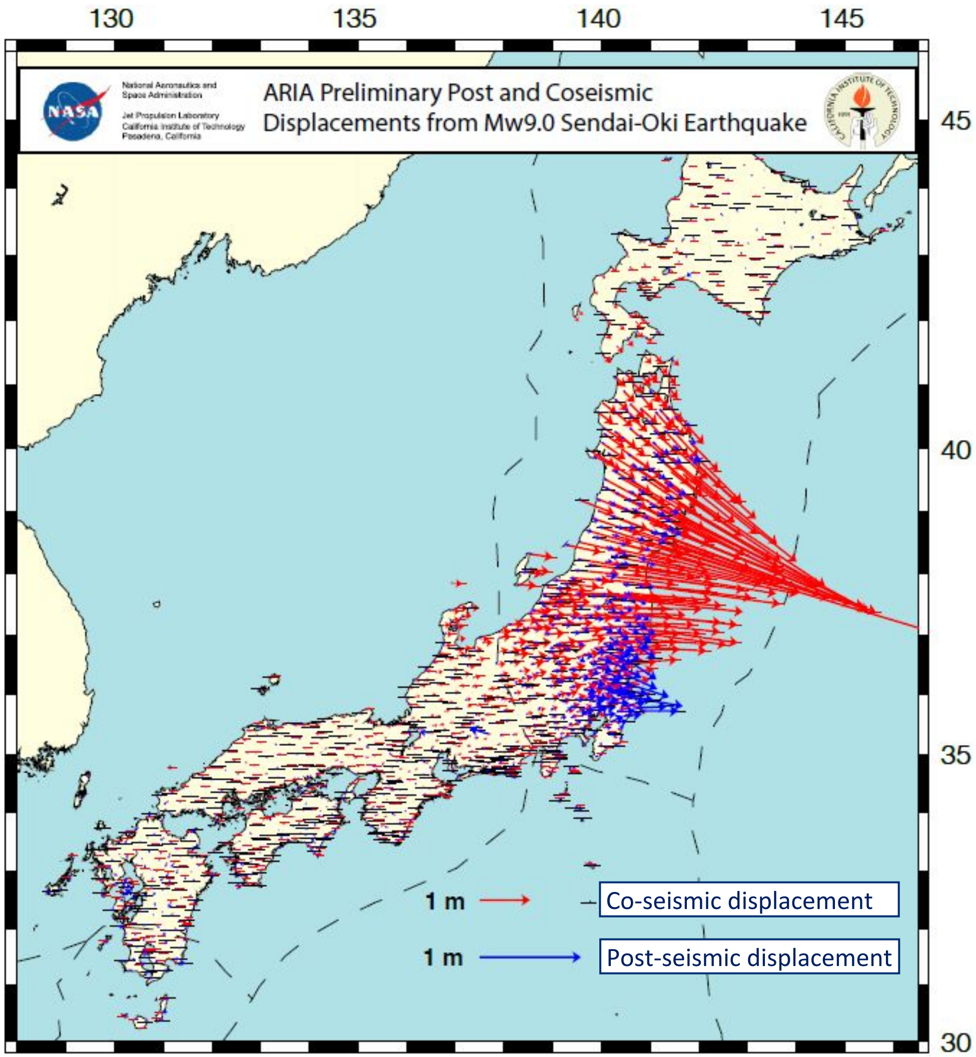
Fig. 3.3.1-2(a) Distribution map of probability of ground motions equal to or larger than seismic intensity 6 Lower, occurring within 30 years from the present (Duplication of Fig. 3.3.1-1 for comparison).
(Start date: January 1, 2005)

Fig. 3.3.1-2(b) Distribution map of probability of ground motions equal to or larger than seismic intensity 5 Lower, occurring within 30 years from the present.
(Start date: January 1, 2005)

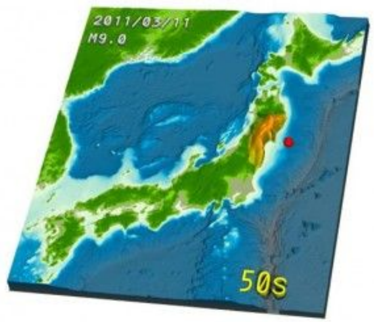
- Pacific subduction is not expected to produce strong shaking (JSI 6-), owing to large distance from the coast (80+ km) and to Mmax limitation

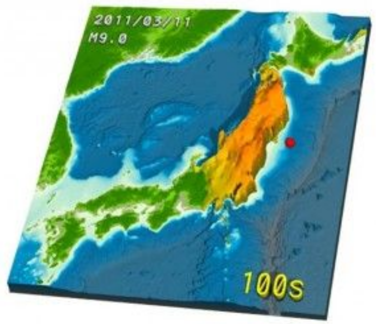
How much did Japan move?

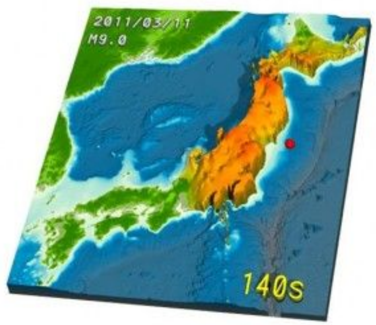
- Seismic slip on the fault up to 18 meters
- Northern Honshu moved East by ~5 m during the event, and 0.5 m after the event
- The axis of rotation of the Earth shifted by ~10 cm

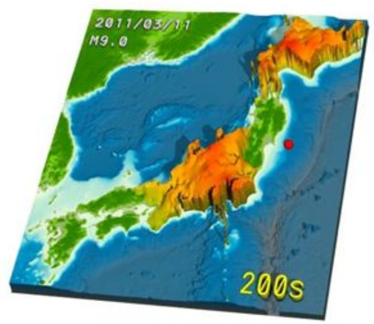


Seismic shaking



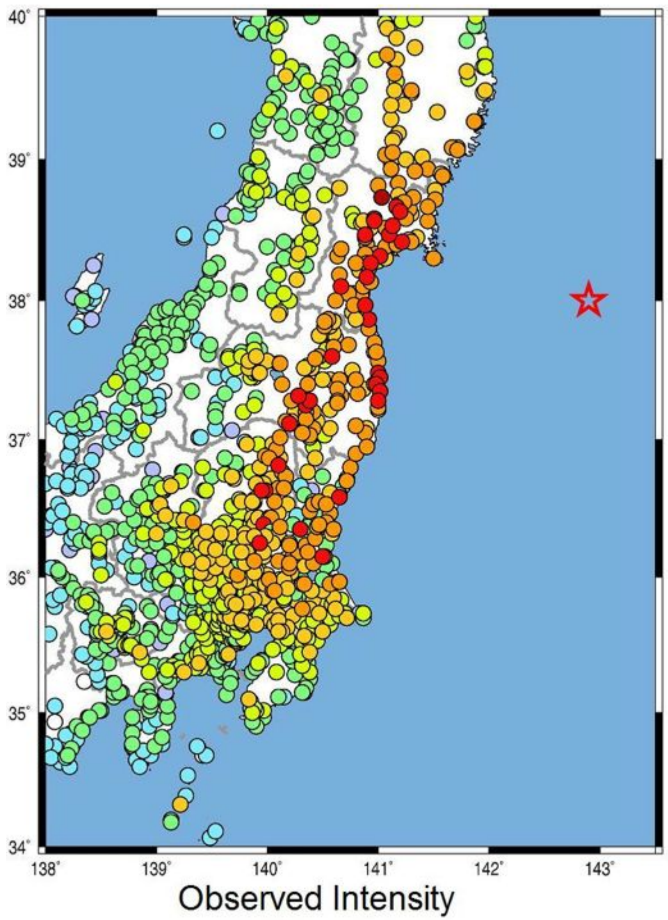


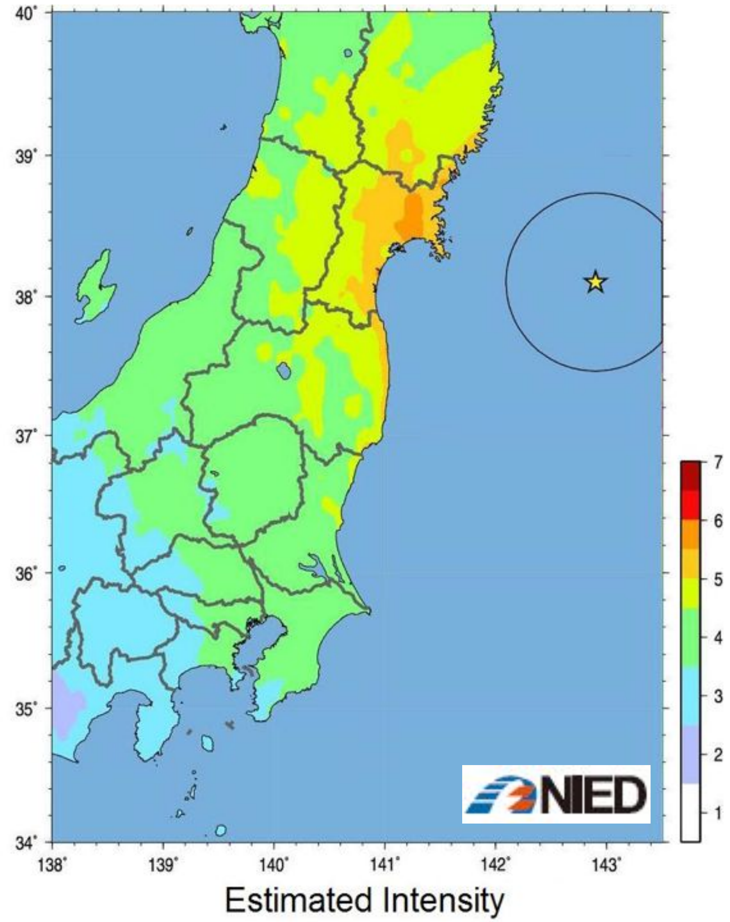




- Earthquake rupture propagated to the South along the Japan trench and lasted ~150 seconds
- First seismic waves reached the coast after ~20 seconds
- Strong ground shaking lasted up to 120 seconds
- After 100 seconds, the whole Northern Honshu was shaking
- After 200 seconds, strong motions in Northern Honshu ceased and the shaking was propagating to Hokkaido and southern Honshu

Strong motion intensity (JSI)

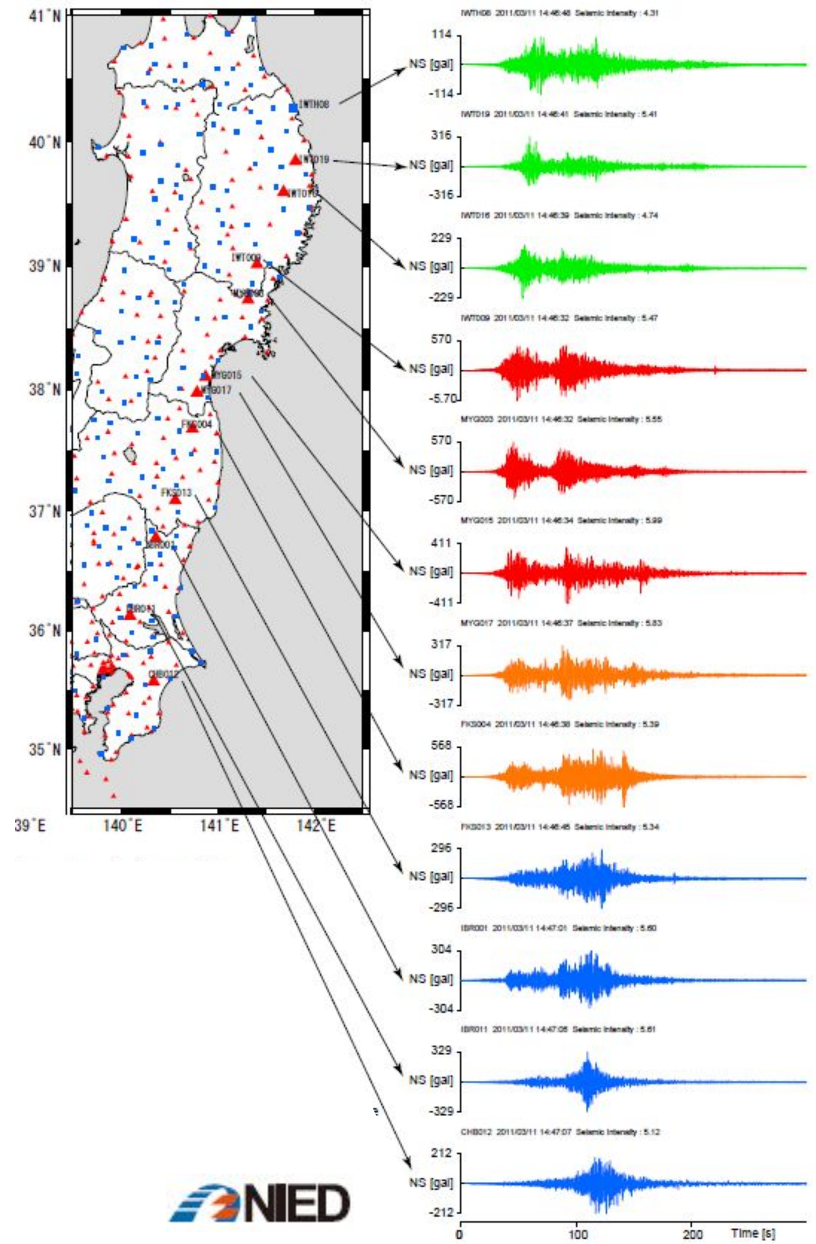




- Observed values of JSI 6+ released for the coastal area, but the effects of tsunami not yet clear

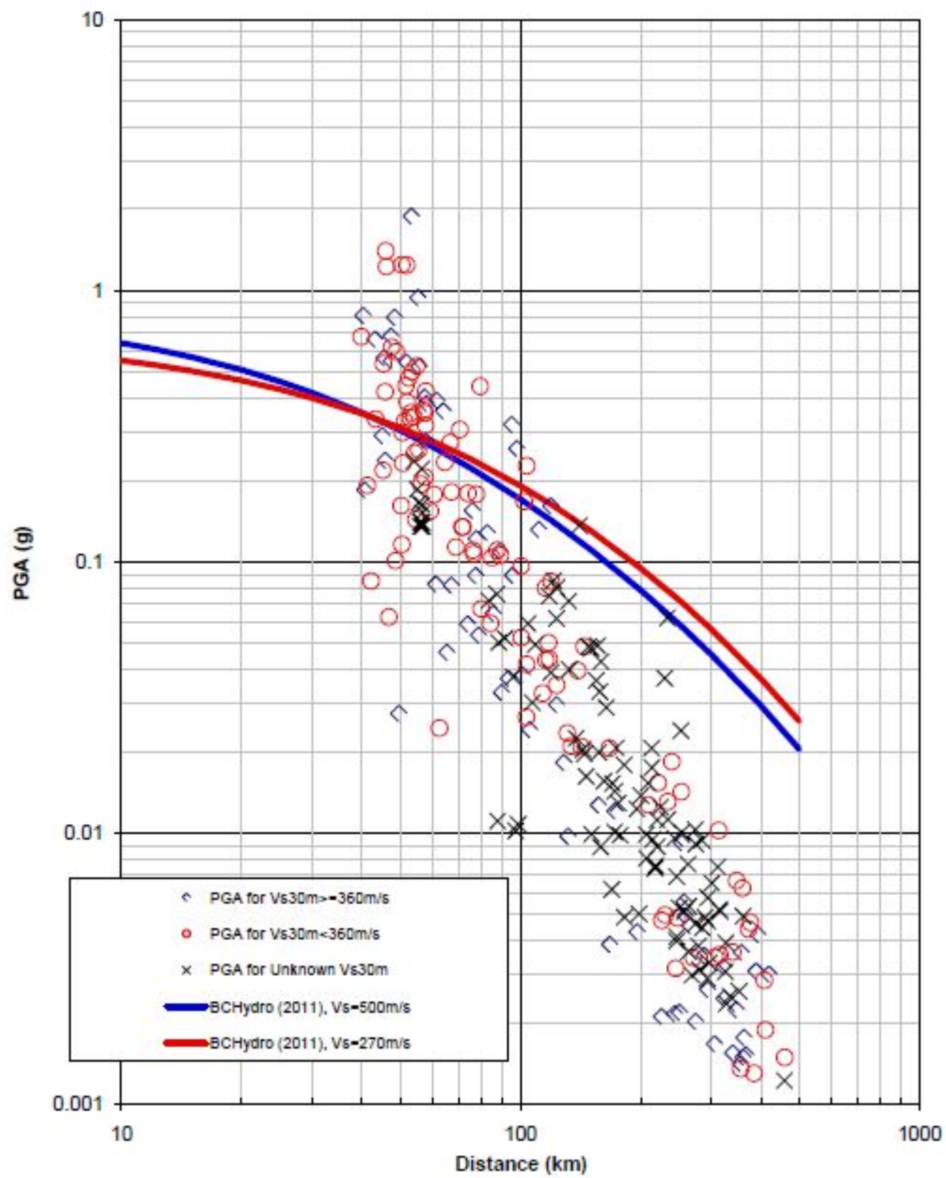
Recorded strong-ground motions

- Exceptional data coverage
- Consistent traces across Honshu
- Peak motions in the range 0.2-1.5g for the closet stations, at 60-100 km distance from the fault
- Very long duration of strong motions, up to 120 seconds



Was the shaking too large?

- Minimum distances to fault of 50-60km
- Peak values in the 0.06-1.2g range
- Peak values agree with models for a M9 subduction event at distances of 60-100 km from the fault
- Peak values are smaller than existing models for larger distances
- Spatial variability of peak values high (factor 20), but not unexpected



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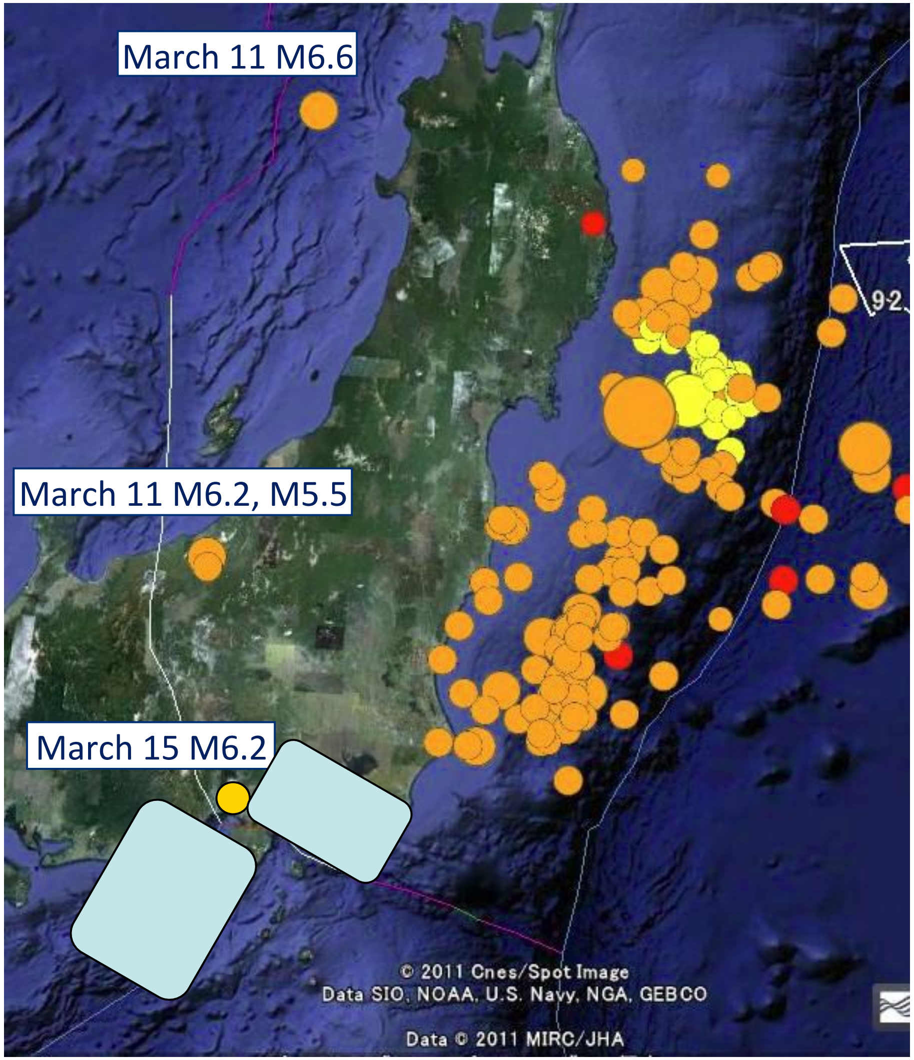
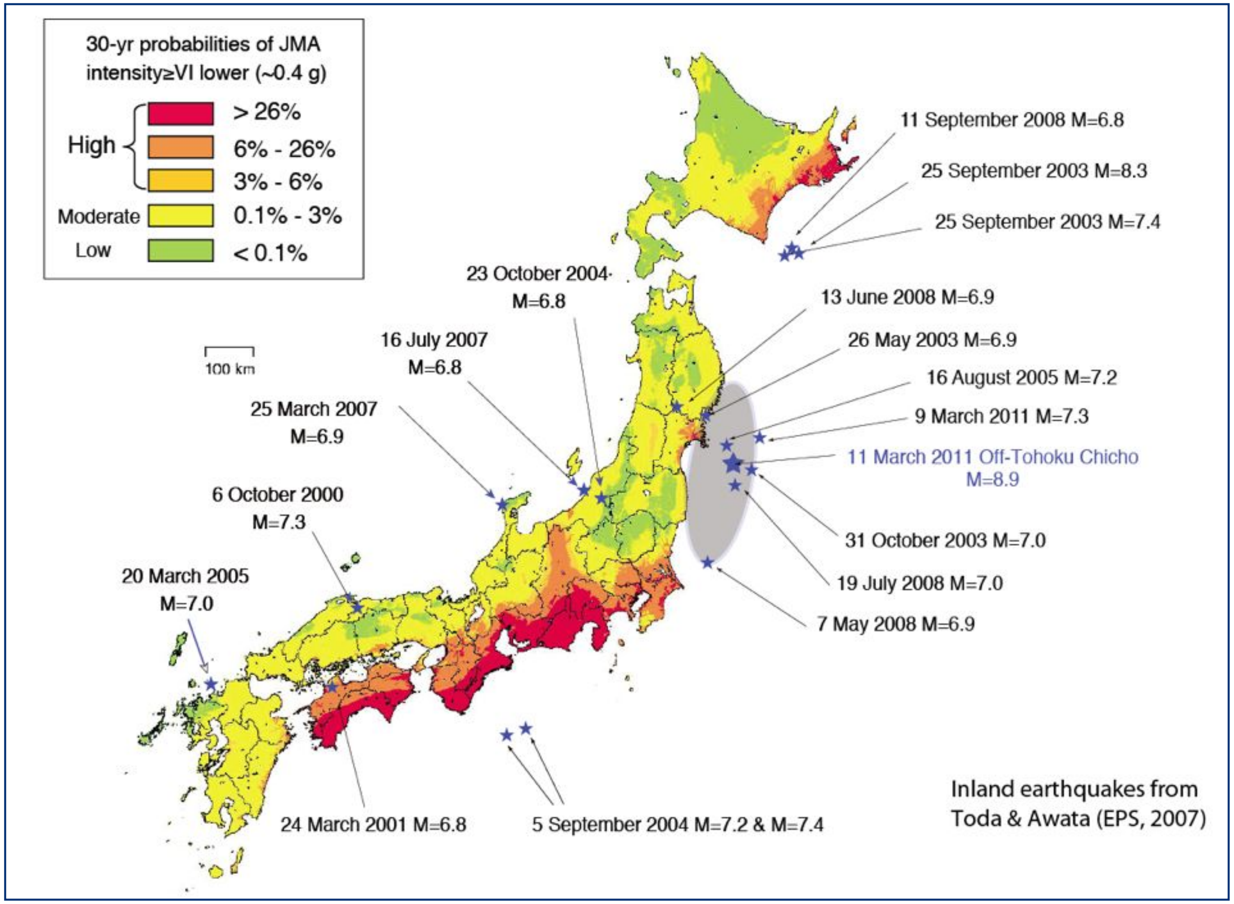
Danger of aftershocks and triggered events

- Aftershocks cover the whole faulted area, largest so far M7.9
- Aftershocks will continue, possible M8+, but are not expected to pose additional risk
- Various inland faults have been activated, including a M6.6 in Niigata (with tsunami alert) and a M6.2 in Shuzuoka (with Tokyo alert)
- The Tokai and Nankai sources have not yet moved and pose the largest danger, with Mmax 7.9 and 8.2, and close to the Tokyo area



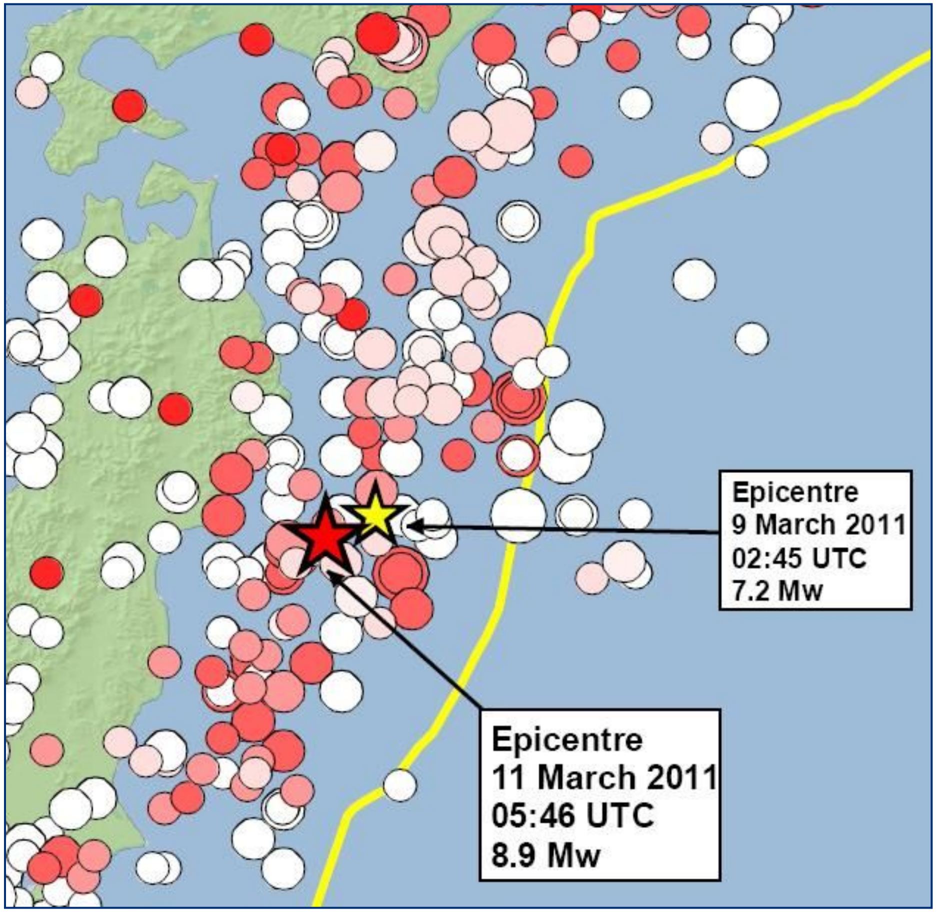
Could the Tohoku earthquake be expected?



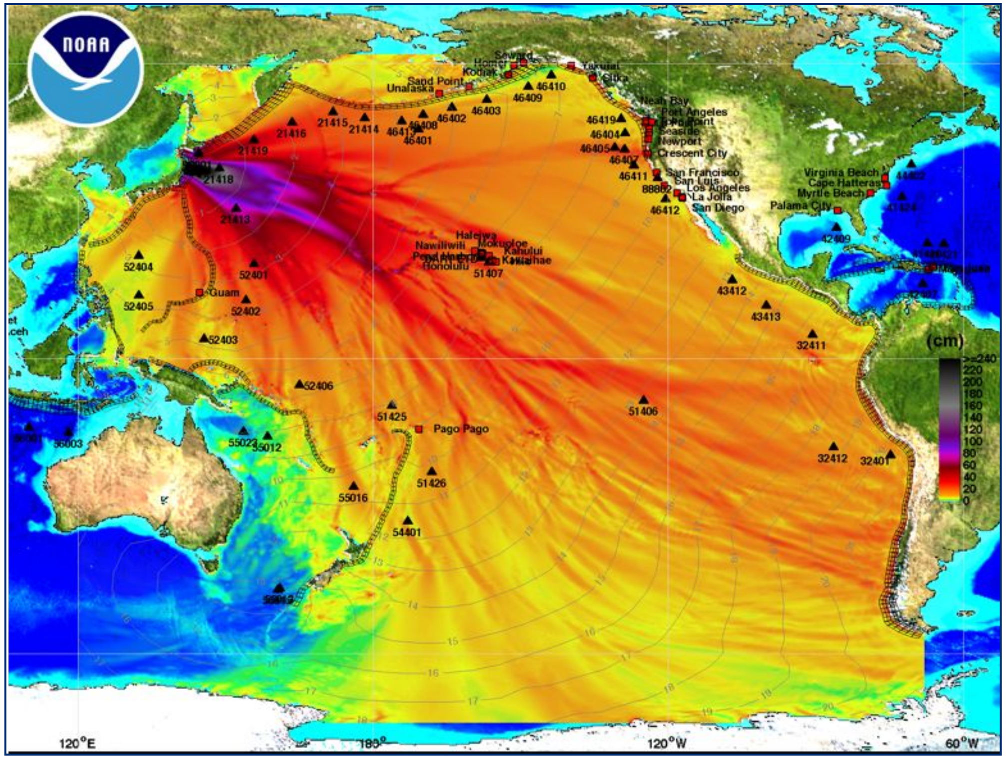
- Most of the M7+ earthquakes of the past ten years, including the Tohoku M9 event, were located outside of the most active identified zones
- In the last ten years, two large subduction events occurred in Hokkaido (M8.3) and Nankai (7.4), in addition to the M9 Tohoku event

Could we have predicted the Tohoku event?

- Too early to say, it will take time to analyse all data
- The M9 was preceded by a M7.2 event on March 9, in the vicinity of the March 11 hypocenter
- The M7.2 was not identified as a foreshock, but 24 similar M7+ events have been recorded on the Japan trench in the past century, one every four years on average
- As a precautionary measure, the M7.2 event could have been used to put critical infrastructures under alert

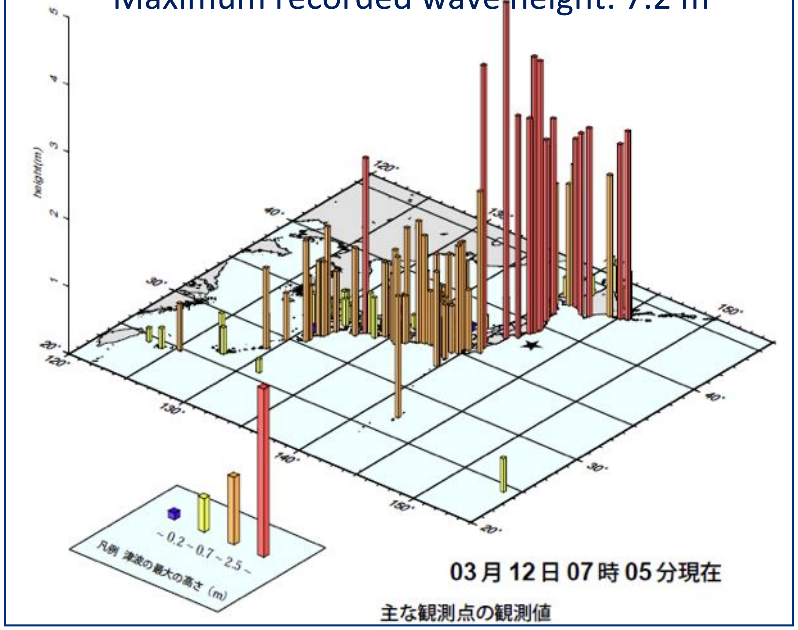


Tsunami



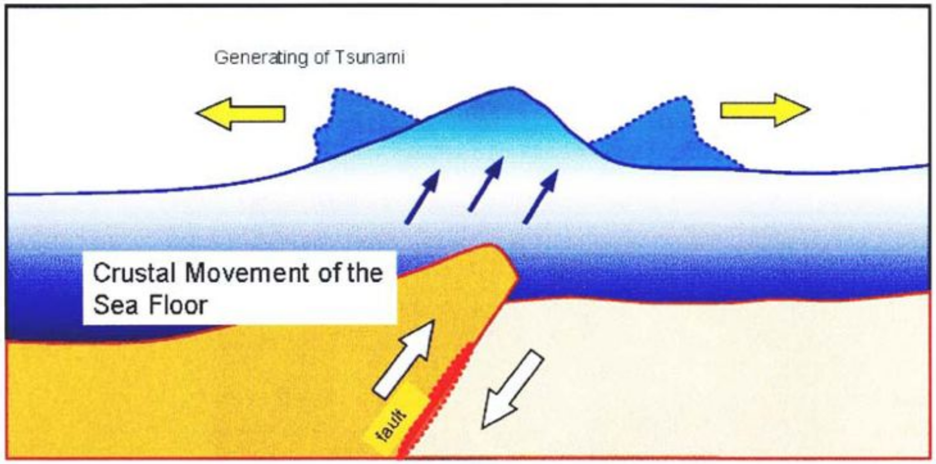
- Every known M9 subduction earthquake has produced a massive tsunami, but only few M8 event produce significant tsunamis
- Given the magnitude 9, the tsunami height and extension were not surprising

Maximum recorded wave height: 7.2 m

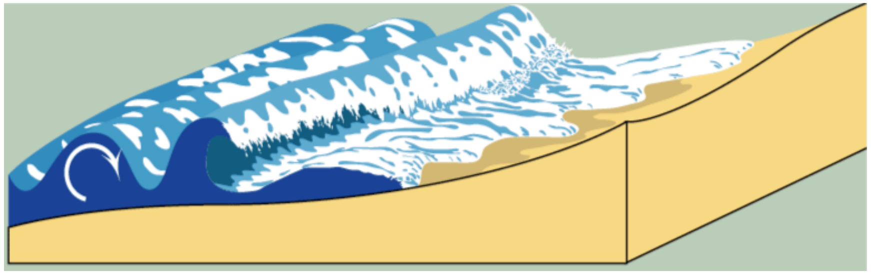


Tsunami generation

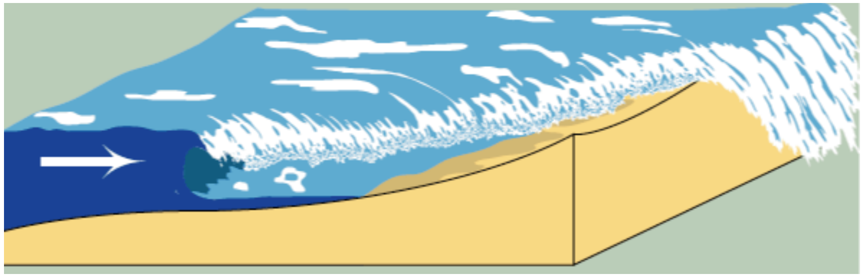
- The tsunami is produced by the displacement of the ocean bottom produced by the earthquake
- The tsunami is preceded by waves, but it looks more like a tide than a wave; the water remains high for 15-20 minutes and flows deep into the land



Sea wave



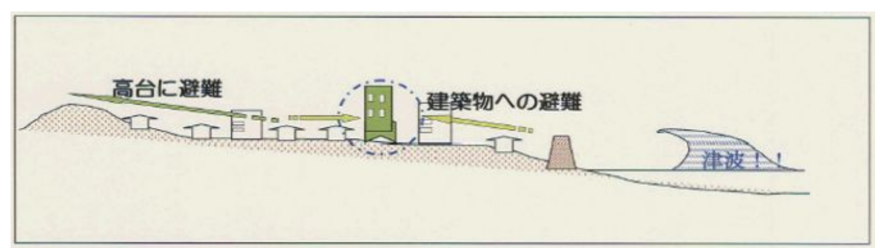
Tsunami



Tsunami history and protection in Japan

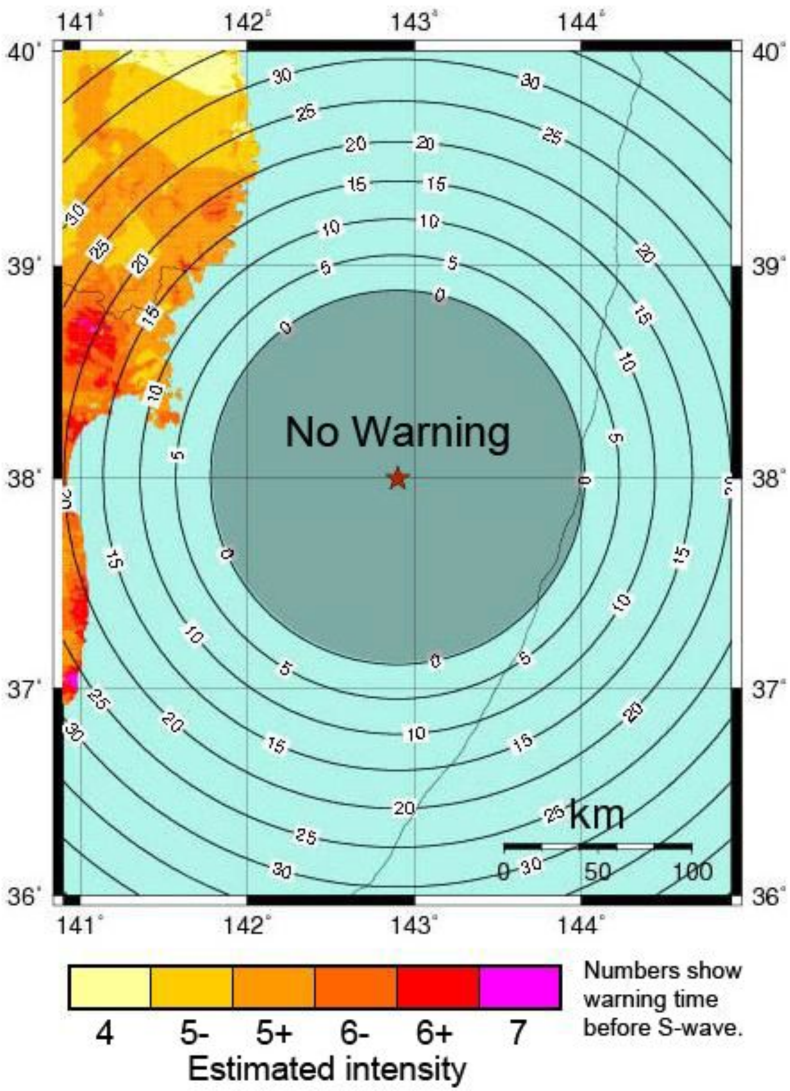
The science and engineering of tsunami protection were born in Japan and are implemented there as nowhere else on Earth

Year	Name of Earthquake	Max Wave Height (m)	Dead and Missing
684	Nankai	-	Many
1896	Meiji Sanriku	38.2	22,000
1933	Sanriku	28.7	3,064
1944	Tonankai	9	1,223
1946	Nankai	6.5	1,432
1960	Chile	8.1	142
1964	Niigata	4.9	26
1983	Nihonkai Chubu	13	104
1993	Hokkaido Nansei-oki	31.7	230



Early warning and alert

- Warning and alert worked well
- Early warning was released to infrastructures (AKWs, Shinkansen, harbour tsunami protections, ...) 8 seconds after the arrival of the first seismic waves on the shore; 20-60 seconds warning times were possible
- Tsunami waves arrived only 30-50 minutes after the start of the earthquake and after the general alert
- Earthquake damage was not high and did not impede tsunami evacuations
- Too many tsunami warnings in past years may have created a sense of false safety



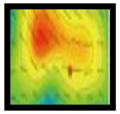
Lessons from the Tohoku earthquake

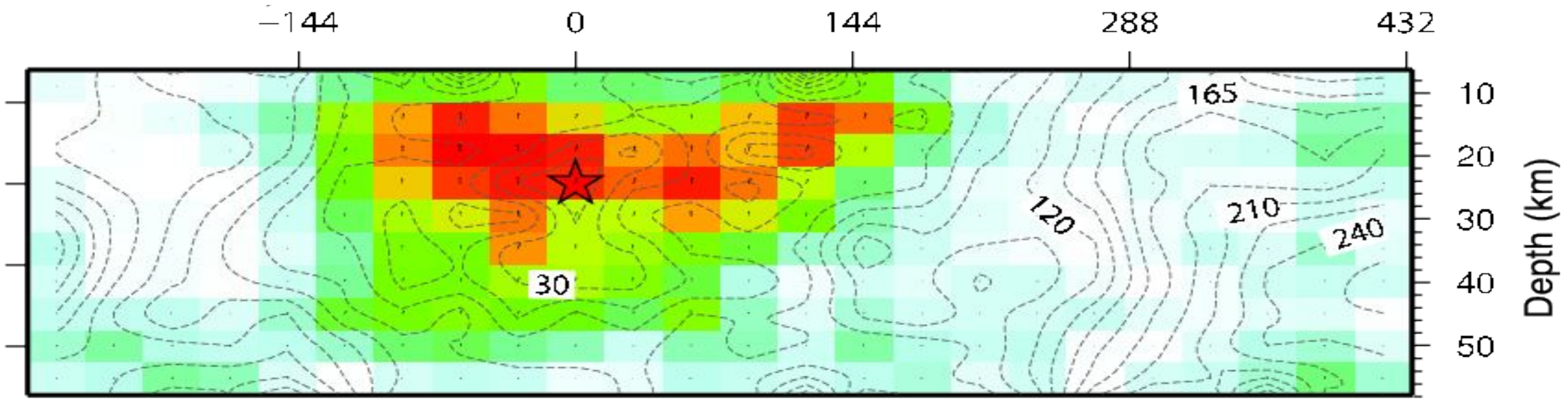
- The maximum magnitude of the earthquakes on the Japan trench had been underestimated by the Japanese scientists; a M9 on the Japanese trench cannot be considered as an exception; with a plate convergence of 8mm/yr, a M9 event, with 18m slip, can be expected every few centuries.
- The shaking produced by the earthquake agrees with expectations for a M9 event, and is not much higher than it would have been produced by a M8 event.
- The amplitude and extend of the tsunami were not surprising considering the magnitude 9.
- The seismic shaking did not produce large damage, owing to the good construction practice, to the level of preparation and to the distance to the fault. The damage was due to the tsunami, which exceeded the expected heights and the protection measures over a long coastline.

Comparing the two events: seismic sources

A M9 event releases much more energy - 20 ‘000 more - than a M6.3 event. This depends on the size of the fault and the amount of slip.

Christchurch: M6.3, slip 1m, source area 30*10km

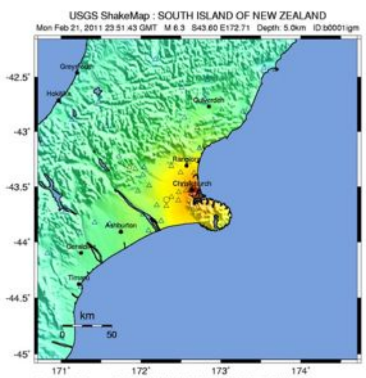


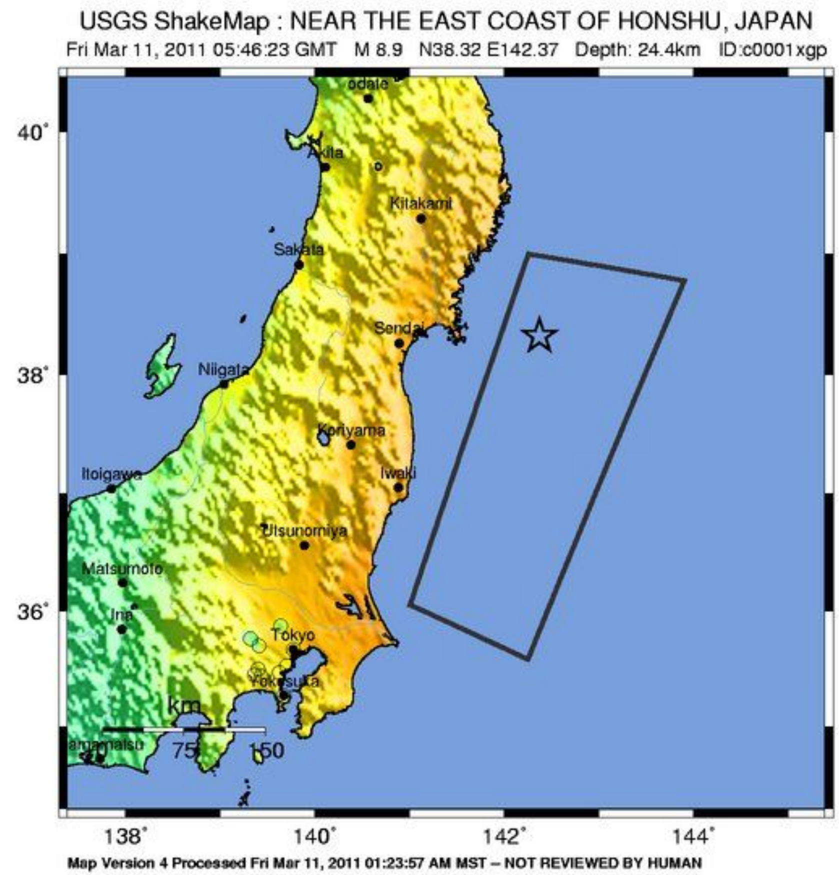


Tohoku: M9, slip up to 18m, source area 300*40km

Comparing the two events: affected surface

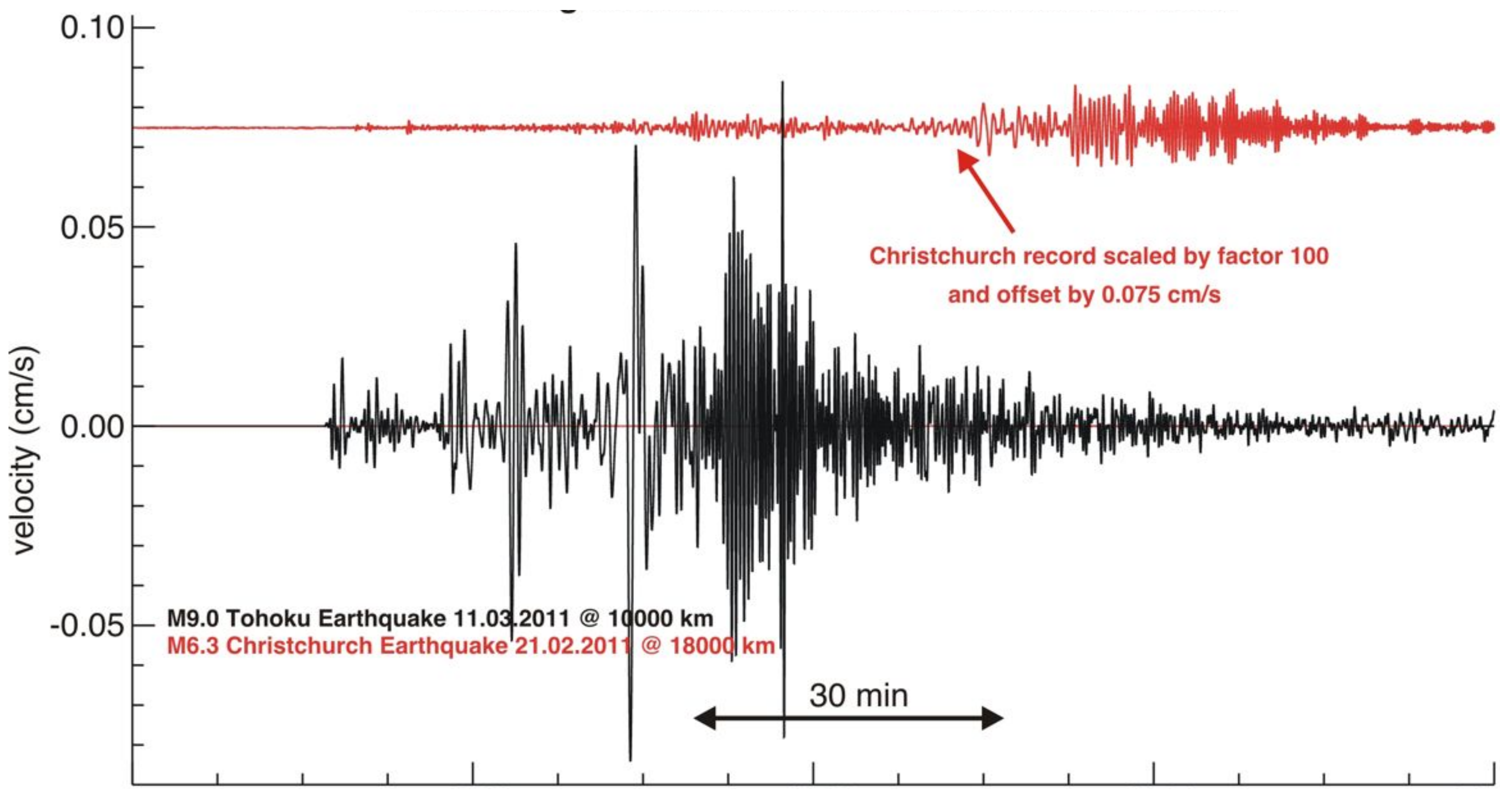
- The area of strong ground shaking was ~5*5 km2 for the M6.3 Christchurch event and ~400*100 km2 for the M9 Tohoku event, 1600 times larger





PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

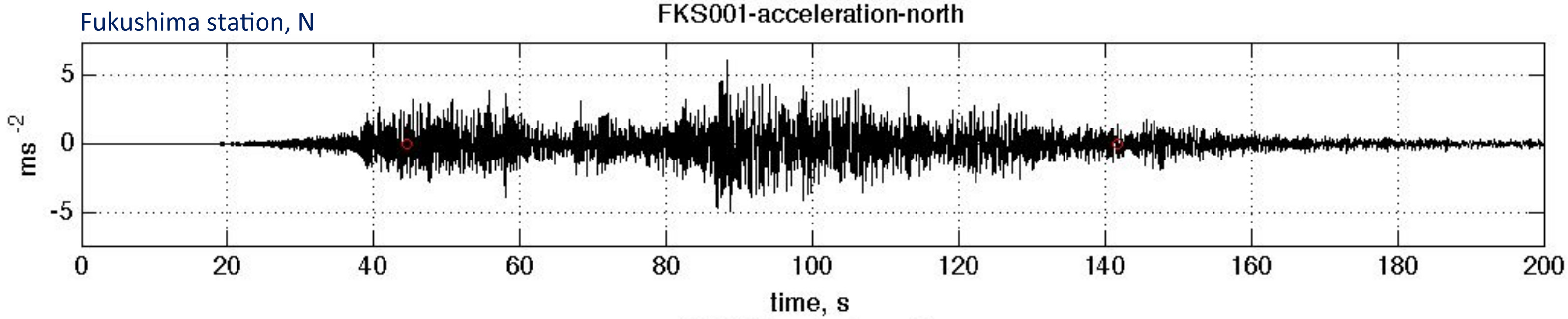
Comparing the two events: seismic signals recorded in Zurich



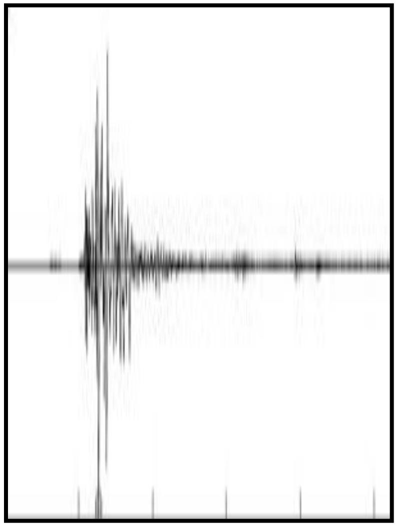
- Both events were well recorded in Switzerland; for the Tohoku event, the whole Switzerland moved up and down by 2 cm for more than an hour
- The seismic waves of the Tohoku M9 event will continue to travel around the Earth for weeks

Comparing the two events: close-distance seismic signals

Fukushima station, N



Heathcote school, Z



- Tohoku M9: distance 70 km, peak motion 0.4g, duration 120 seconds
- Christchurch M6.3: distance 2km, peak motion 1.5g, duration 8 seconds
- Even if the magnitude was much lower, the peak motions of the Christchurch event were higher than those of the Tohoku event, given the close distances

Safety of NPPs in Japan: the 2007 Niigata M6.6 earthquake

- In 2007, the M6.6 Niigata earthquake damaged the Kashiwasaki-Kariwa TEPCO NPP, the largest plant of the world
- The event produced peak ground motions of 0.67 g and extensive deformation, cutting off roads and water pipelines
- Of the seven reactors, five are still offline and will most likely have to be replaced
- The NPP cores were not damaged by the shaking, but the damage around the plant and in peripheral systems was so extensive that fires could not be put off and the plant could not be further operated
- Following that event, the Japan government increased the reference design value for nuclear installations from 0.25g to 2g
- In 2008, two smaller plants were damaged by earthquakes in central Japan

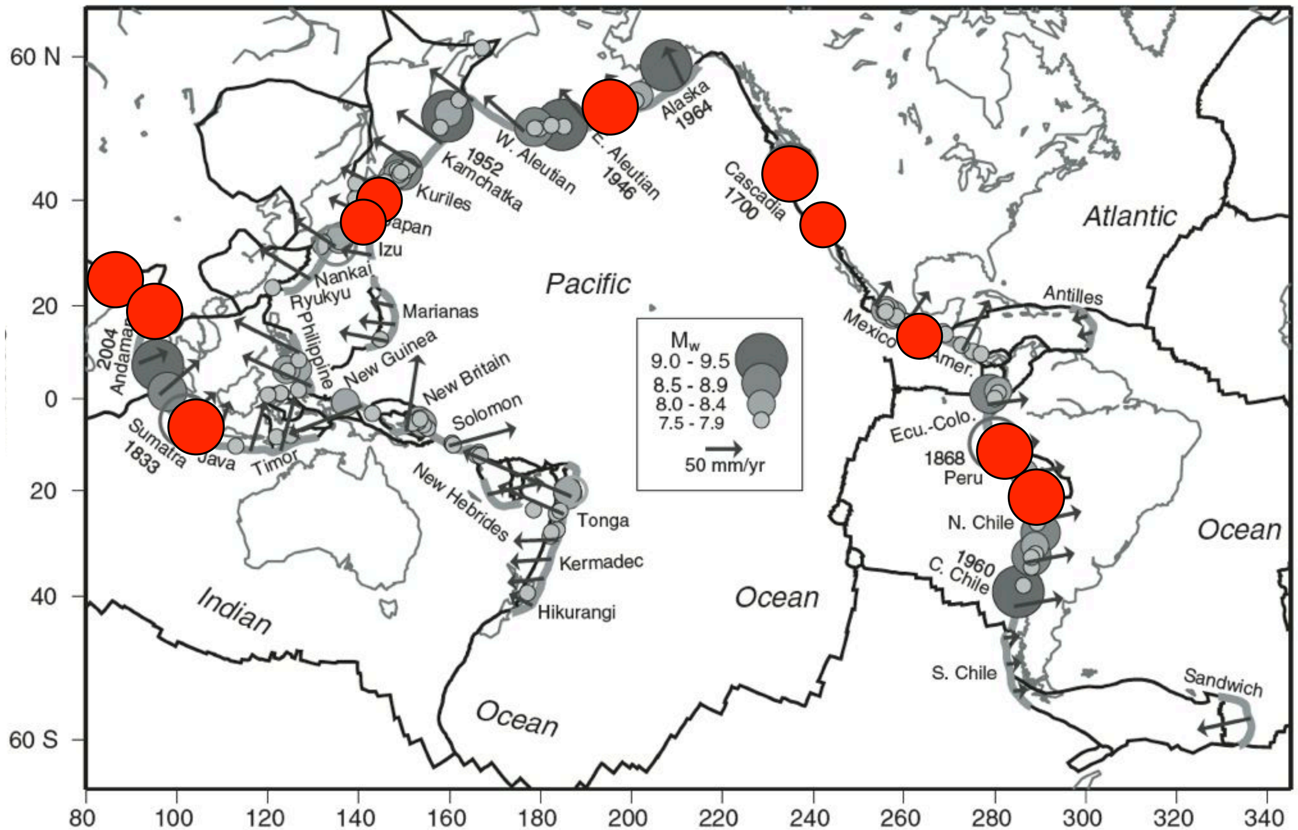
USGS Open File Report 2007-1365

Safety of NPPs in Japan: the 2011 Tohoku M9 earthquake

- The catastrophic consequences of the Tohoku earthquake are still ongoing, and information are fragmentary
- The event produced peak ground motions of 0.3-0.5 g inside the plants; these values are well within the design parameters; no or minimal damage was expected and is believed to have taken place
- All plants in the area successfully performed the safety shut-down (11 reactors)
- The plant was protected against tsunami; however, the emergency diesel generator was flooded and the main diesel tank of the emergency generator (located outside the protected area) was washed away
- The Daiichi plant is still without electricity and appropriate cooling system after 6 days, due to the extensive damage produced by the tsunami

Expected future large earthquakes

Earthquake prediction is not yet possible, but the attention is concentrated on key hotspots, identified as seismic gaps (Costarica, Nankai, Peru, California, Aleutians, Cascadia) or triggered by recent large earthquakes (SE Sumatra, Burma and Assam after the 2004 Andaman Sea event; Tokai after the 2011 Tohoku event)



10 lessons for Switzerland

1. M9 events or the type of strong-motions produced by the Tohoku event are not possible in Switzerland.
2. M6.3 events like the Christchurch earthquake are possible and expected in Switzerland every 80-100 years. M6 events are the main contributor to Swiss hazard for normal houses; M6.5-7 events are the main contributor for the hazard of critical infrastructures.
3. The motions recorded in the Christchurch earthquake largely exceed the parameters of the Swiss building code. We should consider increasing the level of protection in the building code from 475 years to 1000 years, at least for urban areas.
4. The seismic building codes in Japan and New Zealand worked very well, with minimum damage to new houses; it is urgent that the Swisscode (SIA261) becomes obligatory for all cantons of Switzerland, with appropriate verification mechanisms.
5. The open availability of high-quality, dense data is the key to understand the complexity of events such as the Christchurch and Tohoku earthquakes; Switzerland should actively pursue the installation of monitoring stations and warning systems in cities as well as in critical infrastructures (AKW, dams, geothermal projects, buildings).

10 lessons for Switzerland

6. We need to take a more conservative approach in the identification of rare, extreme events, taking into consideration the failures in New Zealand (unidentified fault) and Japan (unidentified potential for M9 events).
7. Swiss lakes have a history of damaging tsunamis (i.e. Luzern 1601) which have never been taken into proper consideration; a comprehensive hazard and risk analysis for urban areas on Swiss lakeshores is needed.
8. The risk associated to near-surface or surface break of identified faults as well as of possible deep shearing zones still needs to be evaluated
9. The vast damage to key Japanese infrastructures (AKWs, dams, harbours, communication, ...) confirms the intrinsic vulnerability of modern society to large earthquakes; comprehensive, end-to-end risk assessments are required to verify the level of seismic risk for critical infrastructures in Switzerland.
10. The economic damage produced by events such as the M6.3 Christchurch event (13B$) poses the urgent need to evaluate the economic risk and install appropriate financial mechanisms (i.e. obligatory insurance coverage) to cover rare, potentially disastrous events in Switzerland.