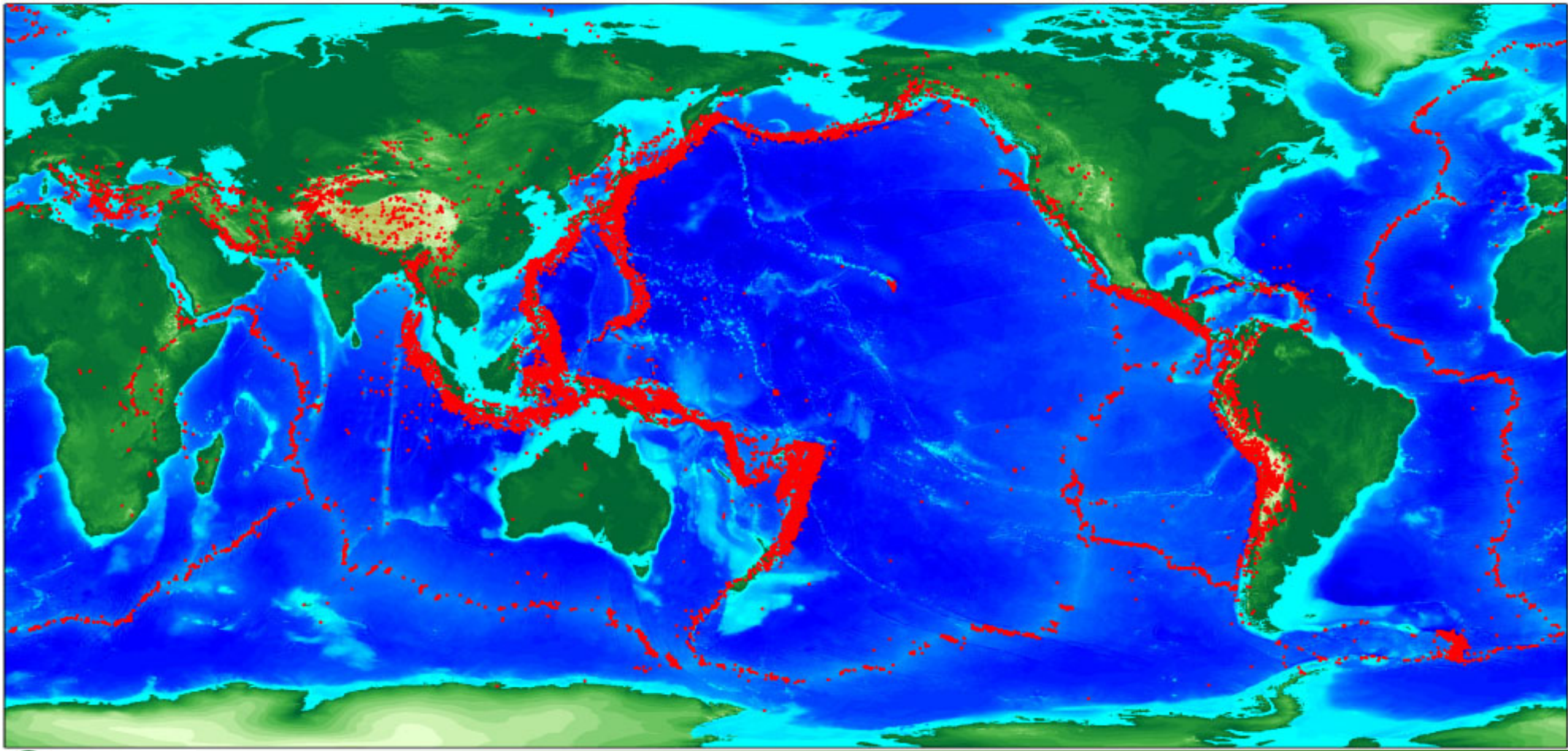
Japan's experience on improving nuclear installation safety challenged by external events; the Noto Peninsula earthquake

Koshun Yamaoka

Commissioner, Nuclear Regulation Authority, Japan

Where is Japan ? Its geological environment

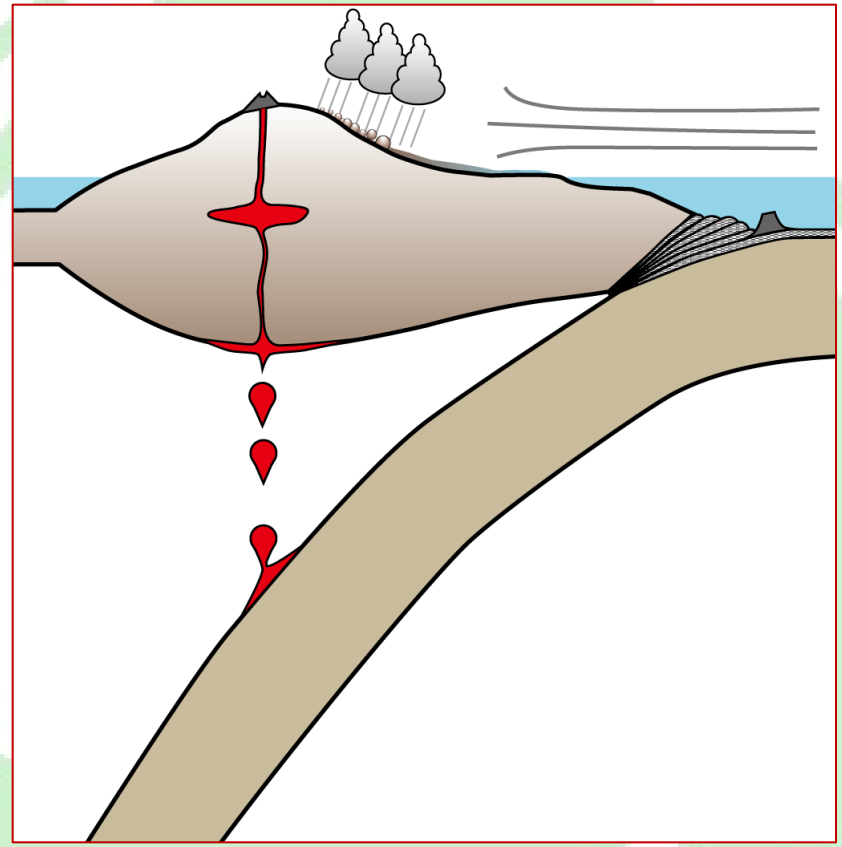


NRA Japan
Nuclear Regulation Authority

1997-2005 M>5 from Harvard Earthquake catalog. Base map from ETOPO1 DEM.

Why Japan has so many natural disasters.

Japan is in a subduction zone where Pacific and Philippine Sea plates subduct beneath the islands.



Geological processes

- Interplate earthquakes
- Inland earthquakes by the force of plate motion
- Volcanism by magma production above the subducted plate
- Accretion of oceanic sediment to the islands
- Rapid uplift of the islands to build high mountain system

Meteorological processes

- Heavy rains enhanced by the topographic high in the environment of the monsoon or typhoon (tropical storm)
- Mass movement and flooding by the heavy rain and steep slopes

Most public debate on nuclear safety concerns natural hazard, especially, earthquake and tsunami hazards.

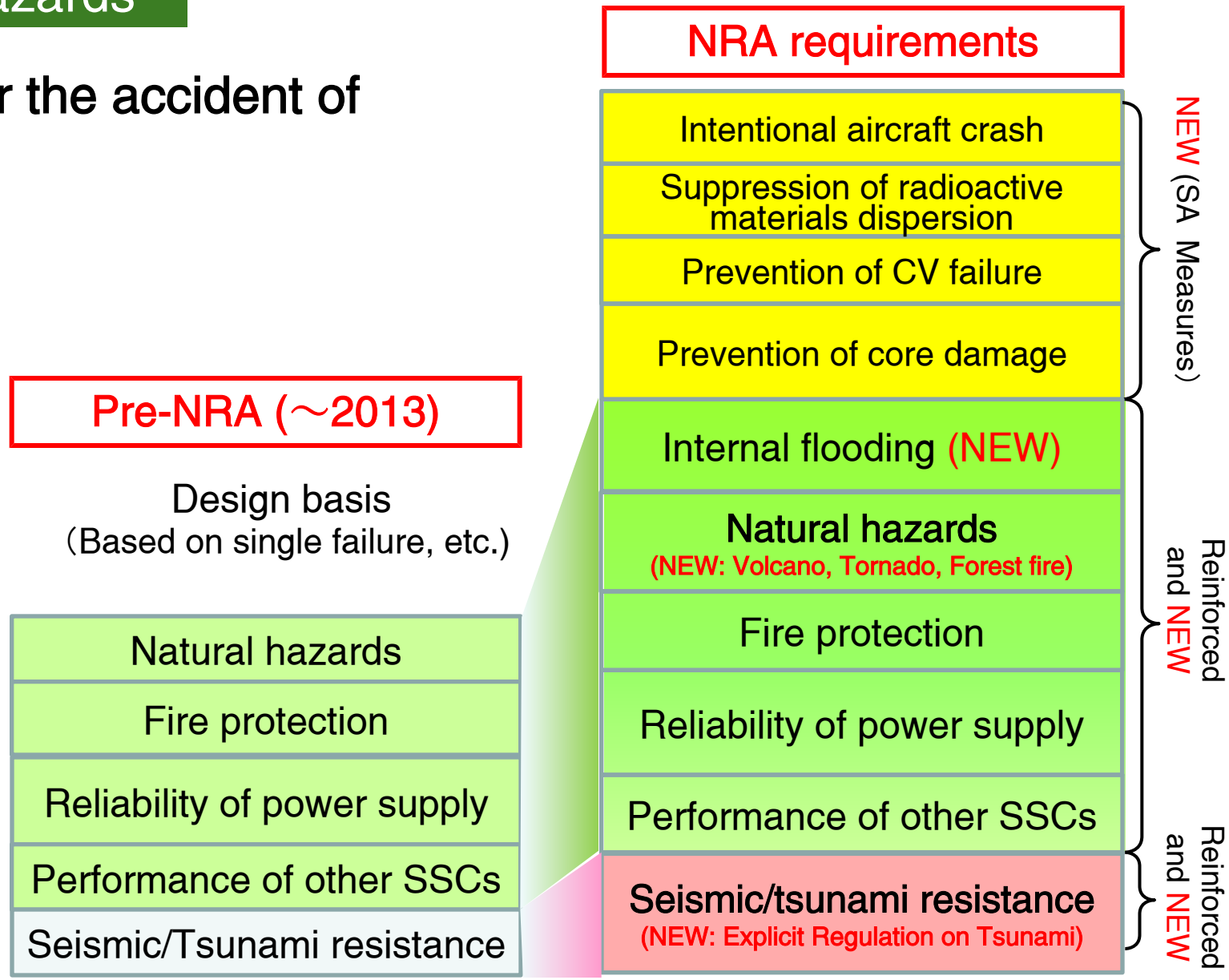
NRAís Regulation on External Hazards

New regulatory requirements after the accident of Fukushima Daiichi NPP

Tsunami hazard was treated as events accompanied with earthquakes and considered as a part of seismic design in the previous 2006 NSC standards,

New requirements developed by NRA in 2013.

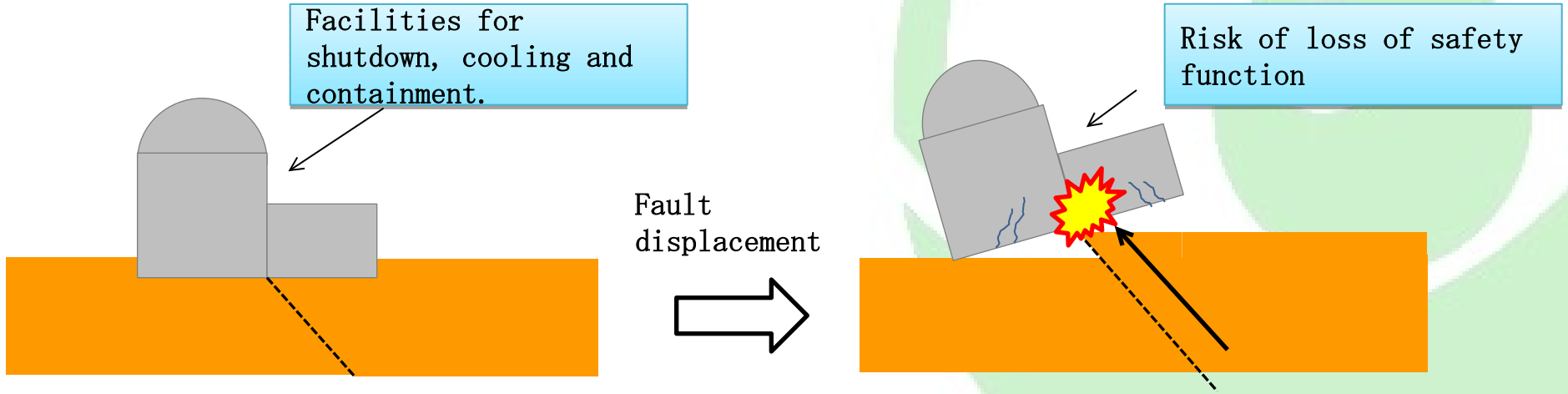
NSC: Nuclear Safety Commission (1978 - 2012)
NRA: Nuclear Regulation Authority (2012 -)



Reference: NRA HP, The 13th NRA Commission Meeting (3 July 2013) Reference materials (partially modified)
https://www.nra.go.jp/data/000070101.pdf

(1) Strict Regulation for Capable Faults

- Important facilities shall be constructed on the ground without outcrop of capable faults.
- ìCapable faultsî shall be determined as those whose activities since the late Pleistocene (approx. 120k to 130k years ago or later) cannot be denied.

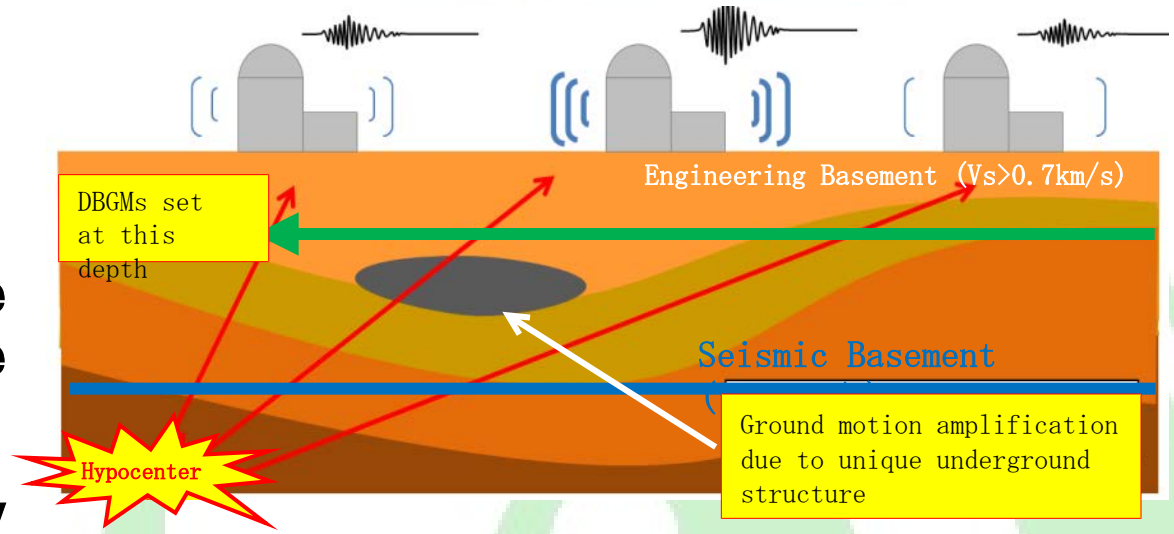


- Displacement of the fault under important facilities like Reactor Building may cause damage on the building.
- Even if the damage of the building is avoided, safety function can be lost.
  NRA ruled that the Tsuruga NPP-2 reactor does not meet the regulatory standards in 2024, because the licensee could not clear the concerns about the existence of active faults under the facility.

NRAís Regulation on External Hazards

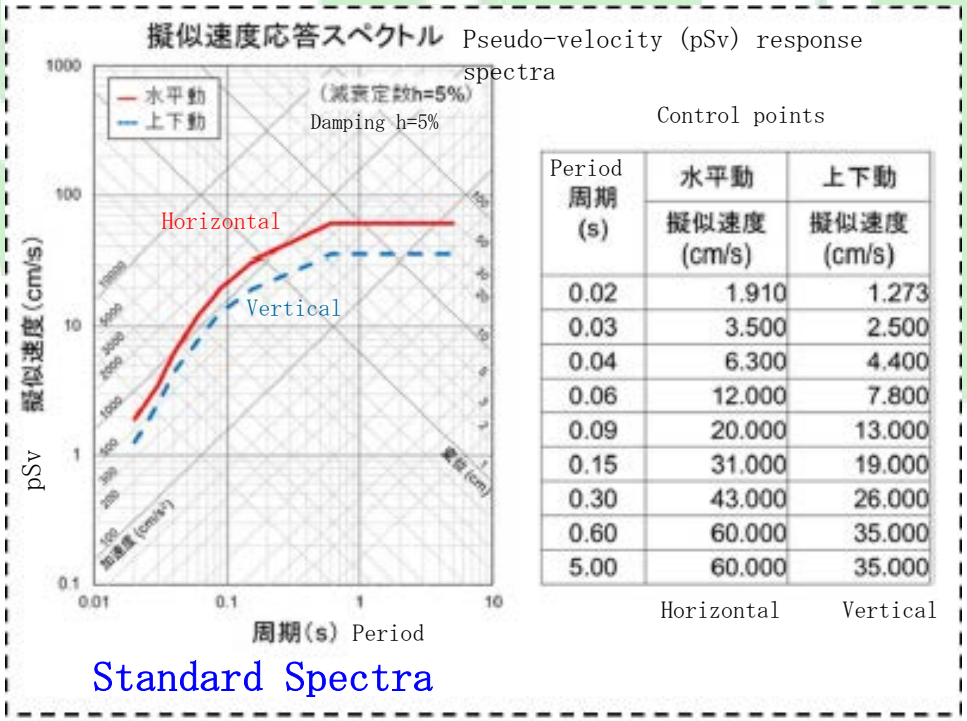
(2) Enforced Regulation for Ground Motions

- **3D evaluations of the subsurface structure** are required for fear of amplification of seismic motion due to irregular structures beneath NPP site.
- **Standard Spectra** are introduced for diffuse seismicity (unidentified seismic sources).



- In 2017, the NRA set up *the Study Team on Evaluation for Ground Motions without Identification of Seismic Sources* to create the Standard Spectra, which is included into NRA's regulatory requirements.

New design bases are developed at four NPPs (*Genkai*, *Sendai* NPPs and others) by considering both the Standard Spectra and site conditions.



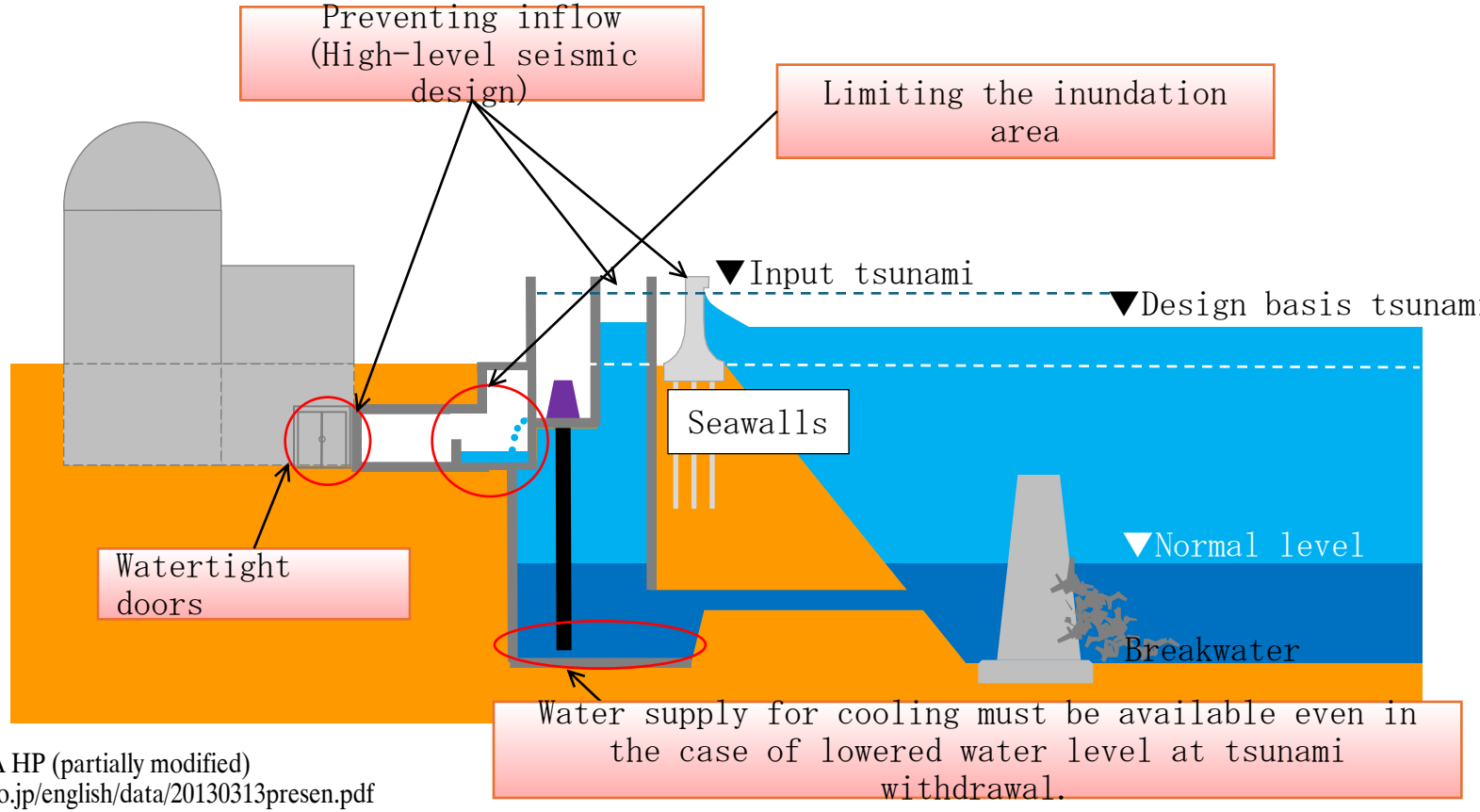
Standard Spectra

(3) Strict Regulation for Tsunamis

ï Define ìDesign Basis Tsunamiî that exceeds the largest in the historical and archeological records.
ï Requirements for multiple protective measures.

- Design Basis Tsunamis approved by the NRA have been conservatively developed.

The design basis tsunami height at *Onagawa* NPP has been raised from the pre-NRA value of 9.1m to the current value of 23.1m.



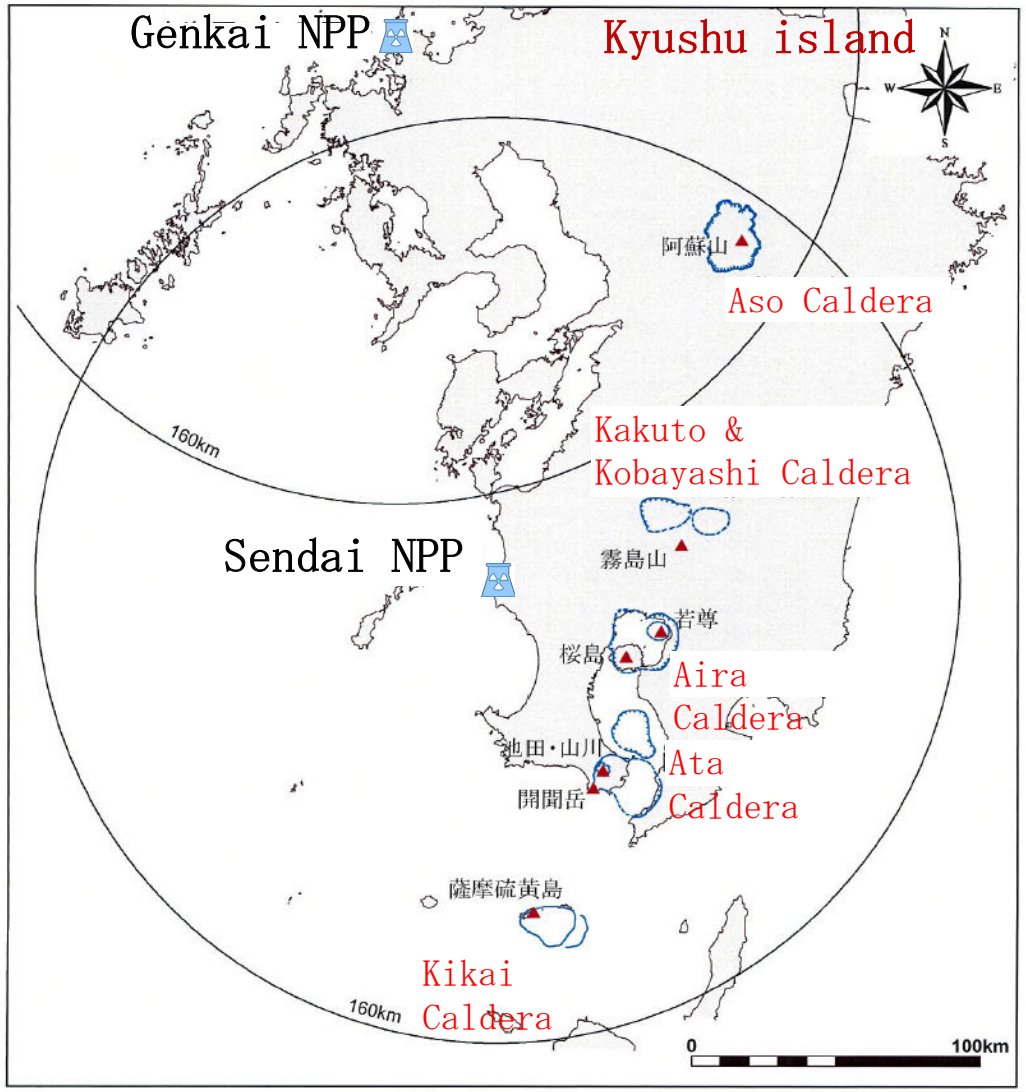
Reference: NRA HP (partially modified)
http://www.nsr.go.jp/english/data/20130313presen.pdf

(4) New Regulation for Volcanoes

- **The licensee shall survey Quaternary volcanoes within a 160km distance from the NPP and evaluate their activities.**

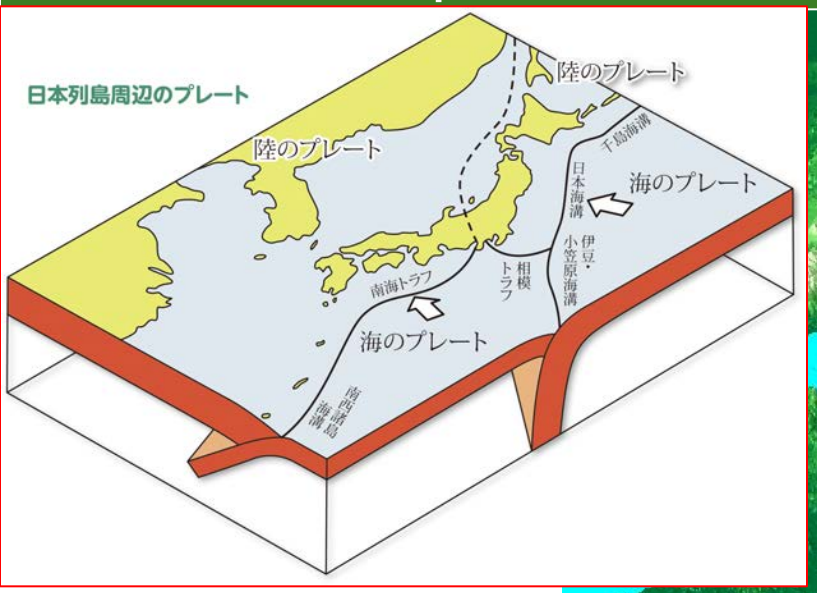
- Pyroclastic density current (PDC) is one of the representatives of the phenomena for which **no engineering solutions are available.** Especially, PDCs by gigantic caldera forming eruptions are of great interest.
- Improbability of such events during the operation period of NPP is evaluated based on subsurface structure as well as eruption histories.
- Seismic and geodetic monitoring of the target volcanoes are required to make sure the stability of the volcano condition.

This is the case for *Sendai*, *Genkai* and *Tomari* NPPs, *Rokkasho* Reprocessing Plant and Recyclable Fuel Storage at *Mutsu*.



Modified from the FY2023 Monitoring Evaluation Report by the Kyushu Electric Power Company.
https://www.data.go.jp/view/NRA100006322?contents=NRA100006322-002-004#pdf=NRA100006322-002-004

Recent and expected Earthquakes in and around Japan



Tectonic plates around Japan

Headquarters for Earthquake Research and Promotion, Government of Japan. https://www.static.jishin.go.jp/resource/figure/figure003003.jpg

2xxx Hokkaido

2007 Niigata

2024 Noto Pen. Eq.

2011 Tohoku Eq.

Pacific Plate

2016 Kumamoto

20xx Nankai Trough Eq.

Philippine Sea Plate

Base map created using ETOPO1

NPP in operation or under licensing.

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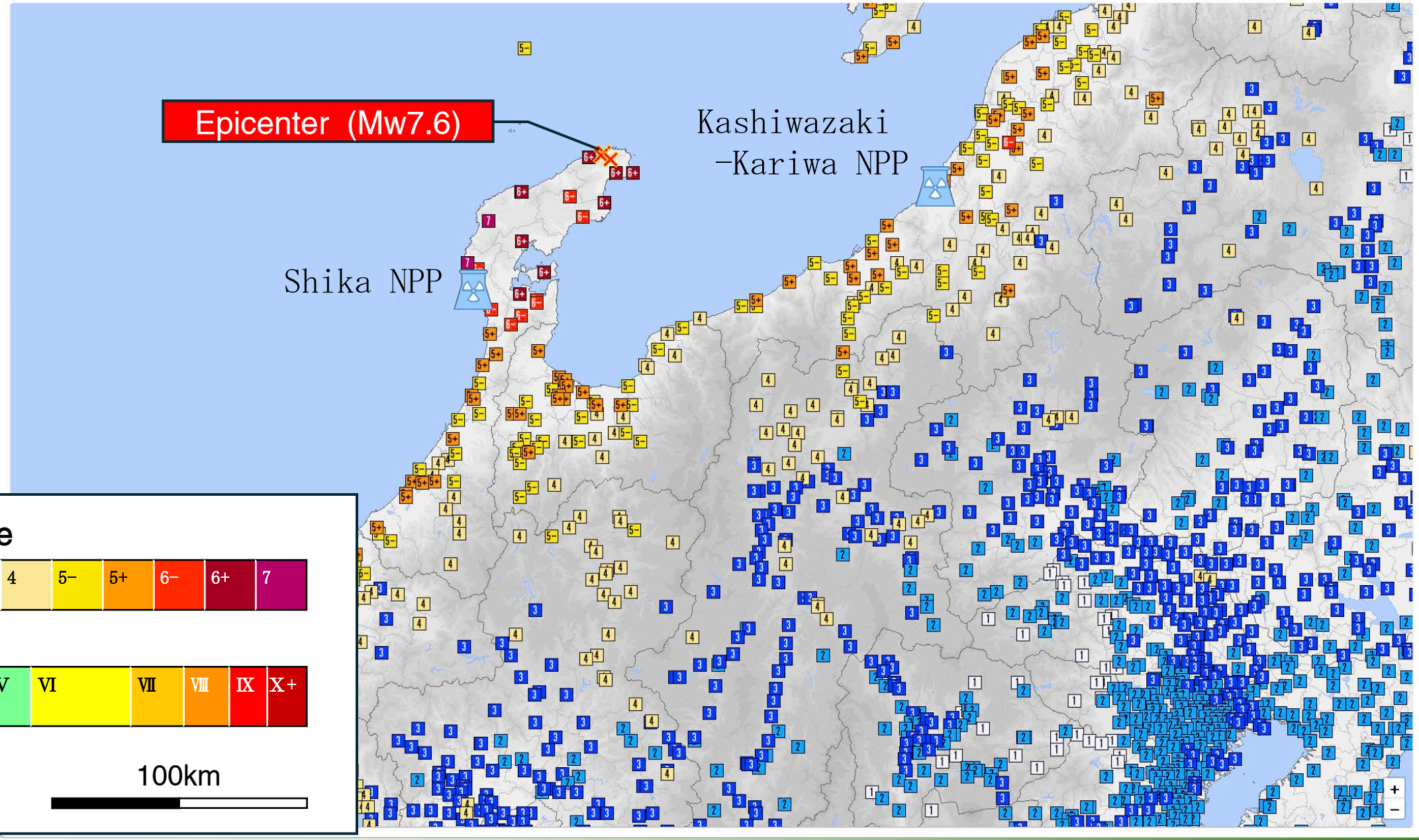
2024 Noto Peninsular Earthquake ñ Seismic Intensity



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Nuclear Regulation Authority

From JMA Shindo Database

2024 Noto Peninsular Earthquake ñ Ground motion at the site

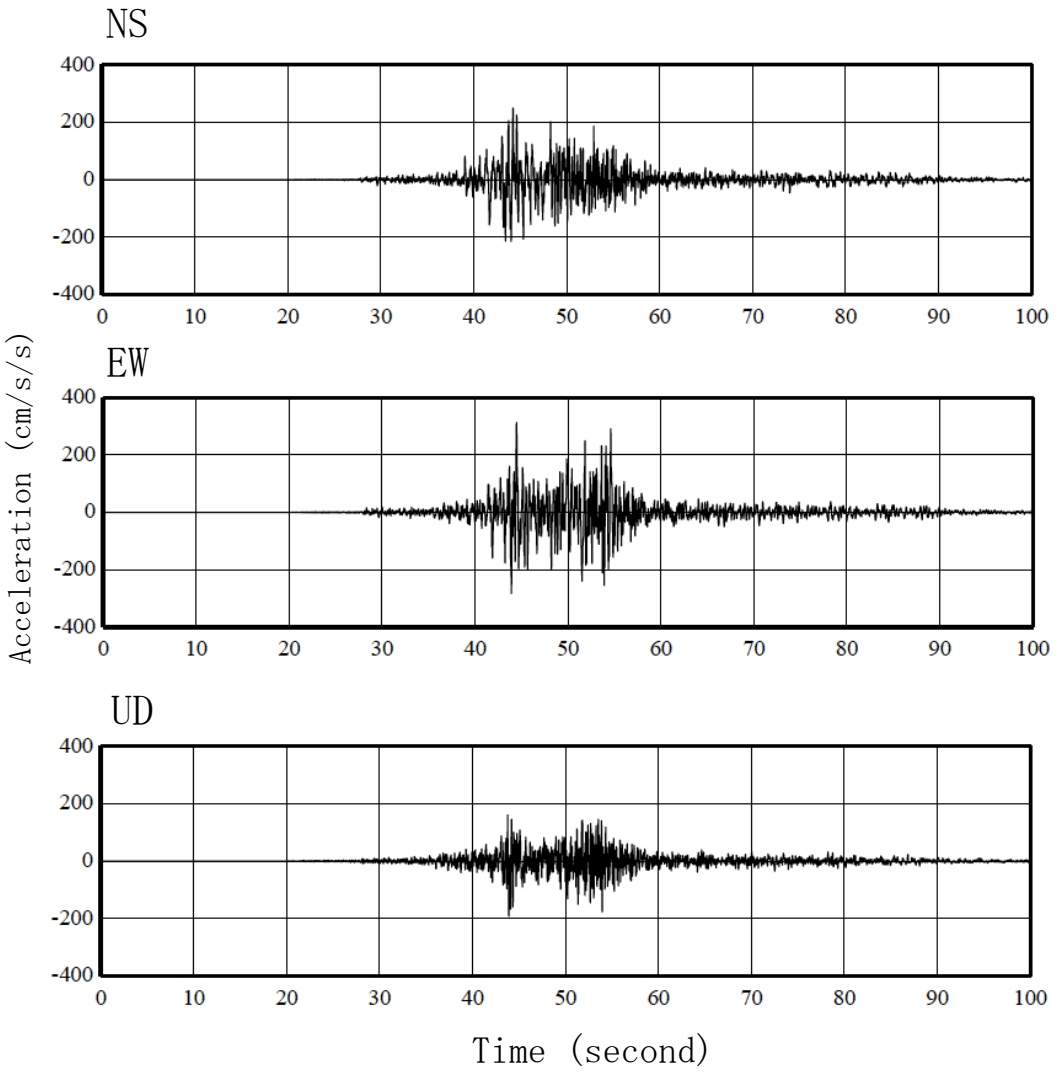
Earthquake ground motion at -10m of Shika NPP site.

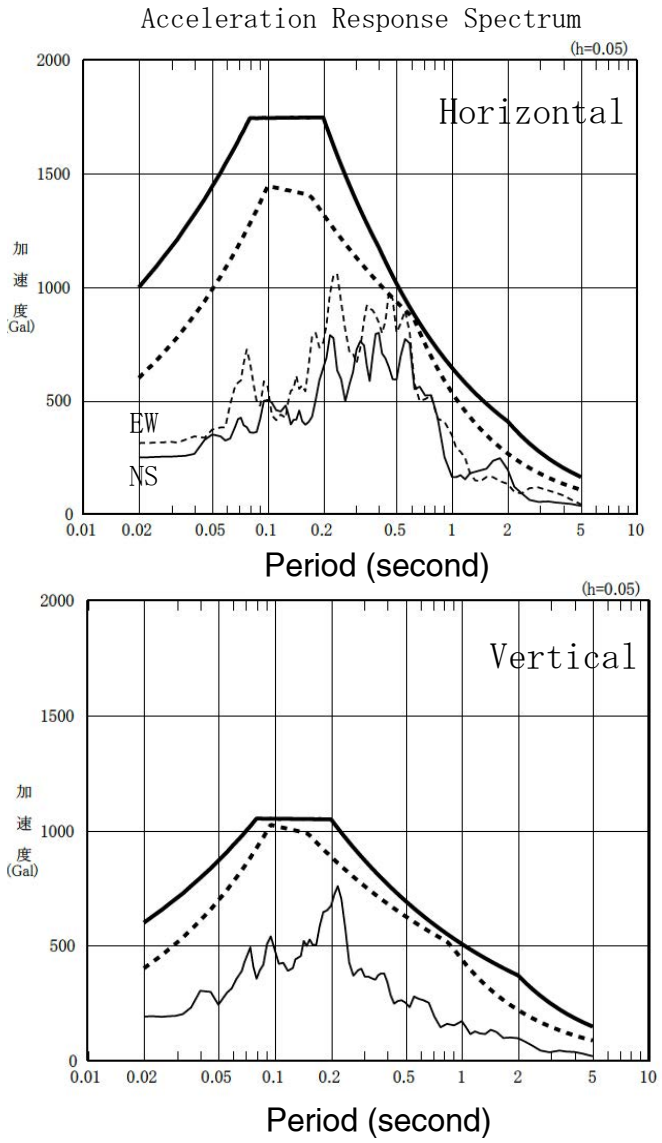
Long duration of strong ground motion caused by long fault.

Within the range of design basis ground motion.

Some Damages are reported in the Shika NPP

- Transformers of 1480MVA and 50MVA were broken.
- Shaking-induced subsidence in some part of the site.
- Tsunami water level rise in the intake pit was 3m, which is within the design limit.





Hokuriku Electric Power Company https://www.da.nra.go.jp/detail/NRA045000841

Four issues arose in the Noto Peninsular Earthquake

1. **Length of Capable Fault**
   - Multi-segment and bi-lateral rupture over 150km distance
   - Multi-segment rupture was assessed before the earthquake.

2. **Coastal uplift**
   - Reverse faulting close to the coastline causing 4m uplift at maximum.
   - Topography generating process, as suggested by previous geographical studies.

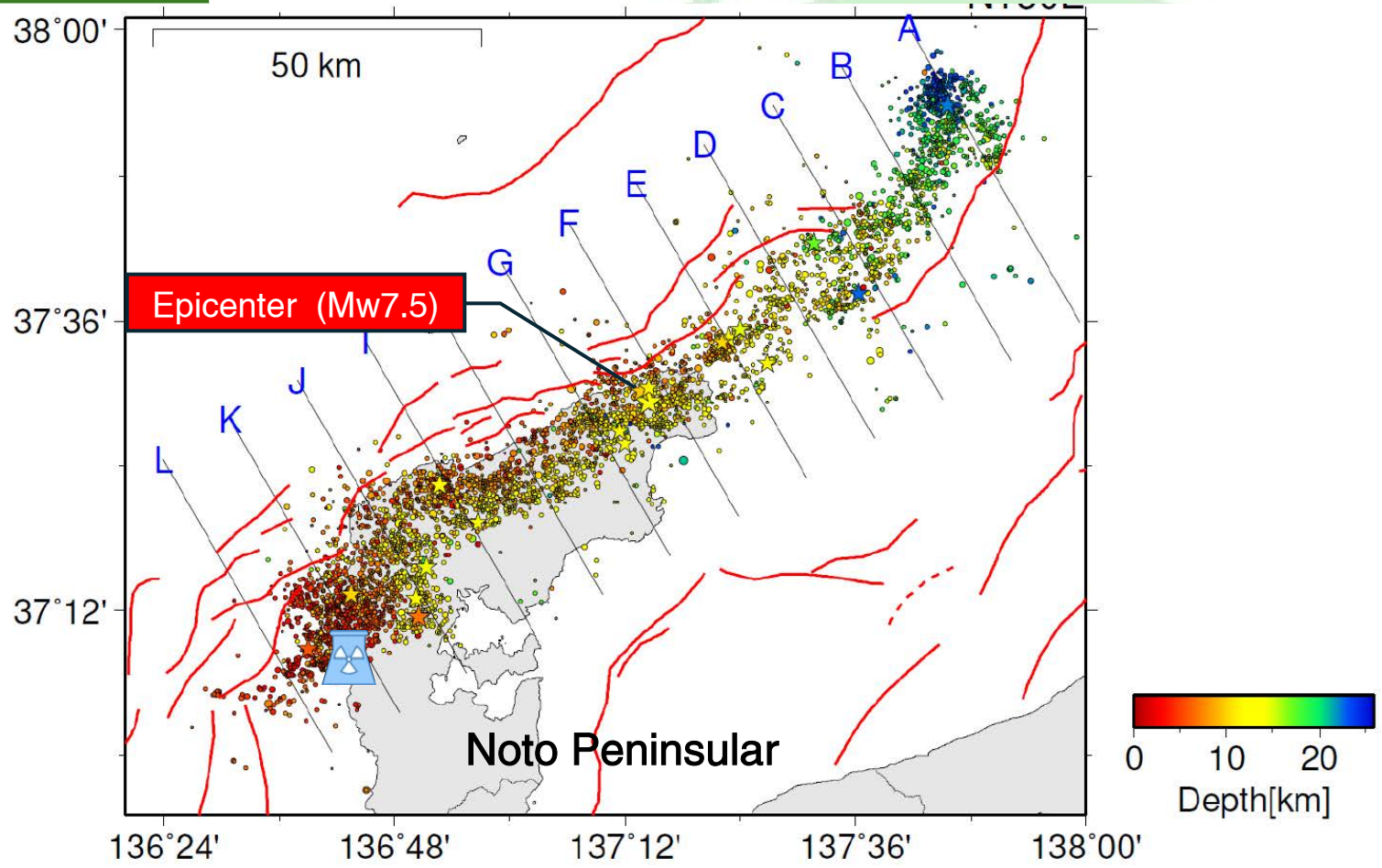
3. **Accompanying faulting**
   - Surface faulting was observed away from the earthquake fault.
   - This kind of accompanying faulting were found in the past event with InSAR.

4. **Multi hazard risk**
   - People near NPPs became more aware of simultaneous occurrence of nuclear and earthquake disaster.
   - 18/116 monitoring stations failed.
   - Guide on *Indoor Sheltering in Place* was discussed in NRA.

Length of Capable Fault ñ After shocks

Mw7.5 earthquake along the northern coast of the Noto Peninsular

- Rupture length was estimated to be 150 km, which connected a series of fault segments.
- The rupture occurred along the faults which are already identified.
- South-dipping fault beneath the peninsular are seen, although north-dipping fault ruptured in the northeastern end, as expected.



Aftershock Distribution

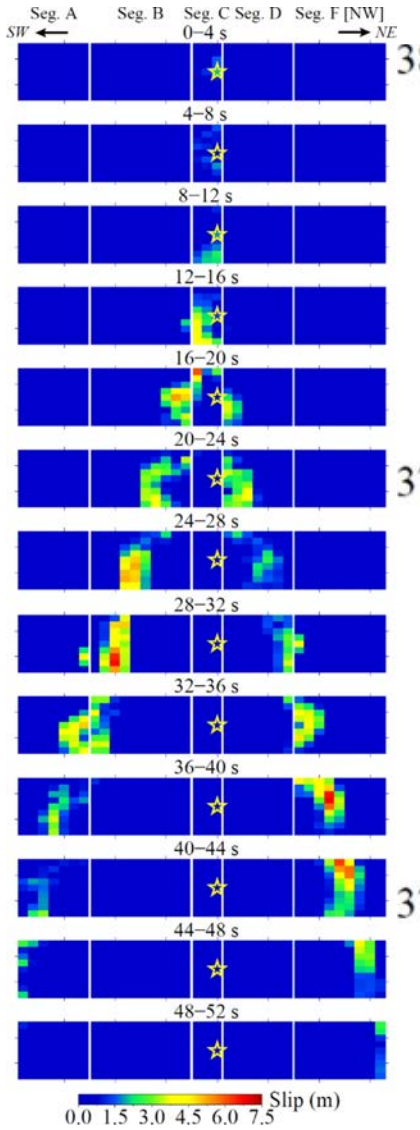
by Japan Meteorological Agency (JMA) in the report of the Headquarters for Earthquake Research Promotion. https://www.static.jishin.go.jp/resource/monthly/2024/2024_08.pdf

Fault trace

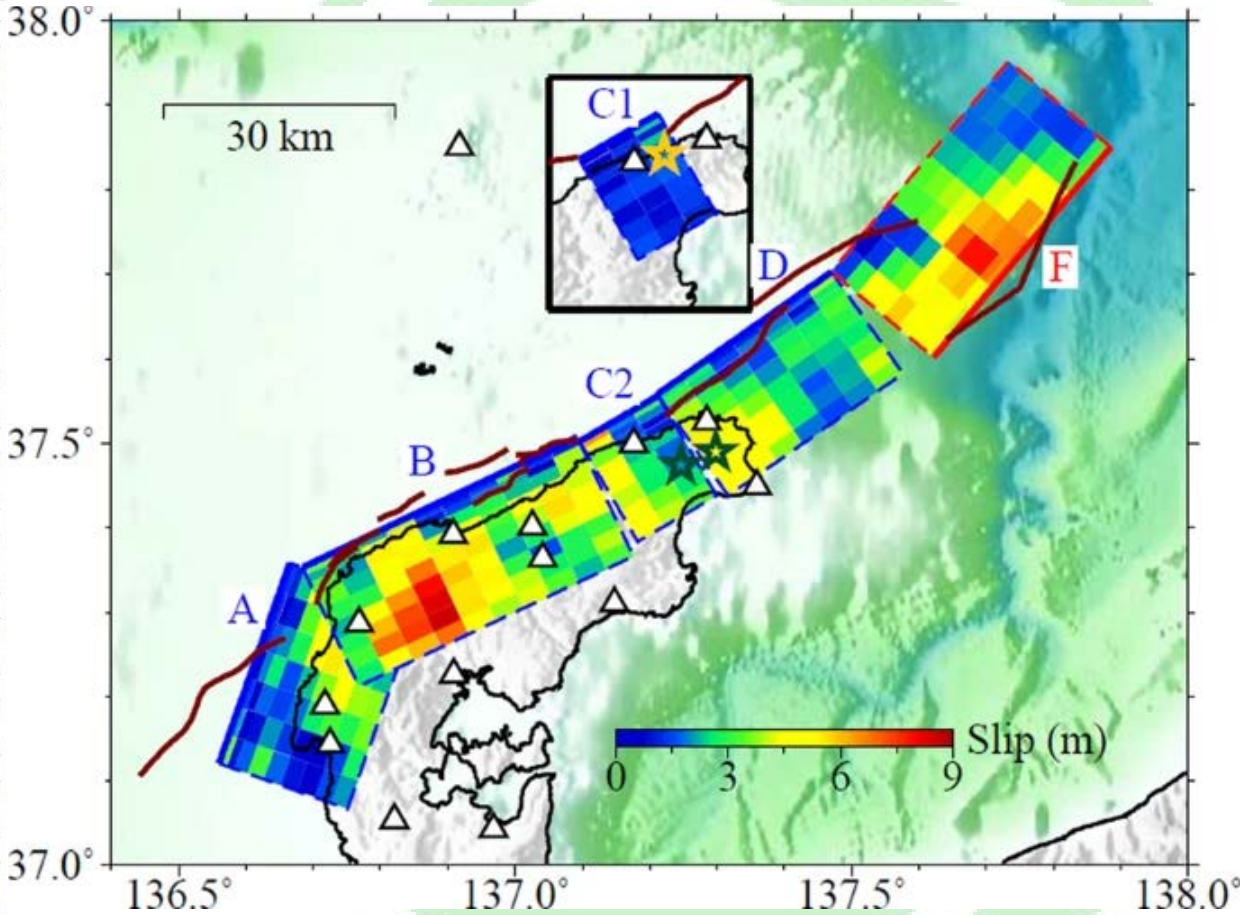
Length of Capable Fault ñ Fault rupture model

Several models of fault rupture are proposed.

- Typical models that are commonly accepted show that the main part of the fault consists of southeast dipping fault with reverse movement except for the easternmost part, which is northwest dipping fault.
- The rupture starts near the northeastern tip of the peninsular to propagate bi-laterally toward the northeast and southwest.
- Total length of time for rupturing is about 50 seconds, which produced long shaking.



Guo et al. (2024, EPS)



Guo et al. (2024, EPS)

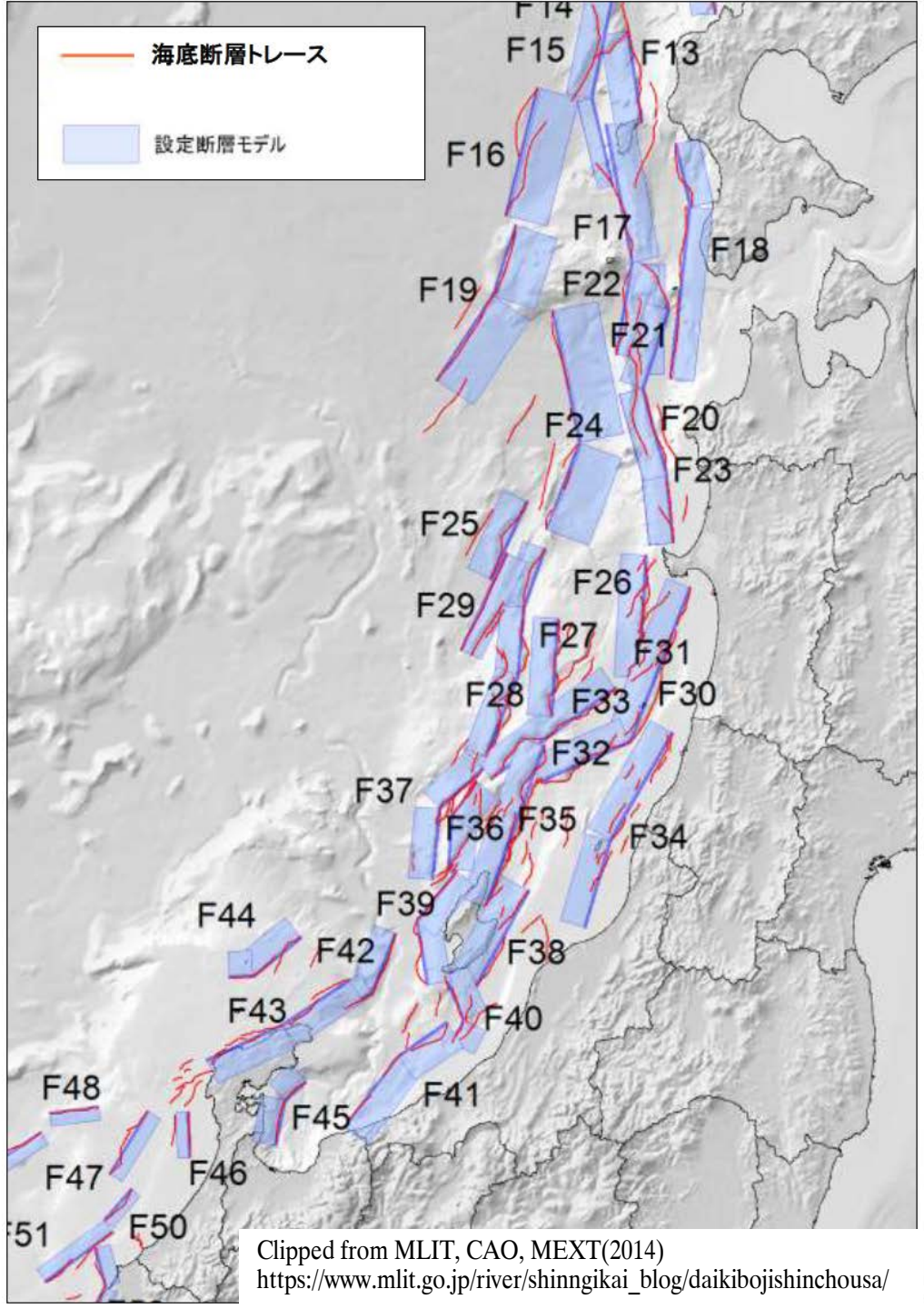
Length of Capable Fault
ñ Evaluation before the earthquake.

Tsunamis also hit the coastal area of the Japan Sea as well as Pacific Ocean.

Major earthquakes hit the eastern margin of the Japan Sea area as Shakotan Eq. 1940 (Mw7.6), Niigata 1964 (Mw7.6), Off Akita 1983 (Mw7.7) and Off SW Hokkaido 1993 (Mw7.7).

Capable faults in the eastern margin of Japan Sea had been evaluated by the government (MLIT, Cabinet Office, MEXT) in 2014.

The fault area of the 2024 Noto Pen. Earthquake (Mw7.5) almost coincides with the previously evaluated faults, i.e. F43 & F42.

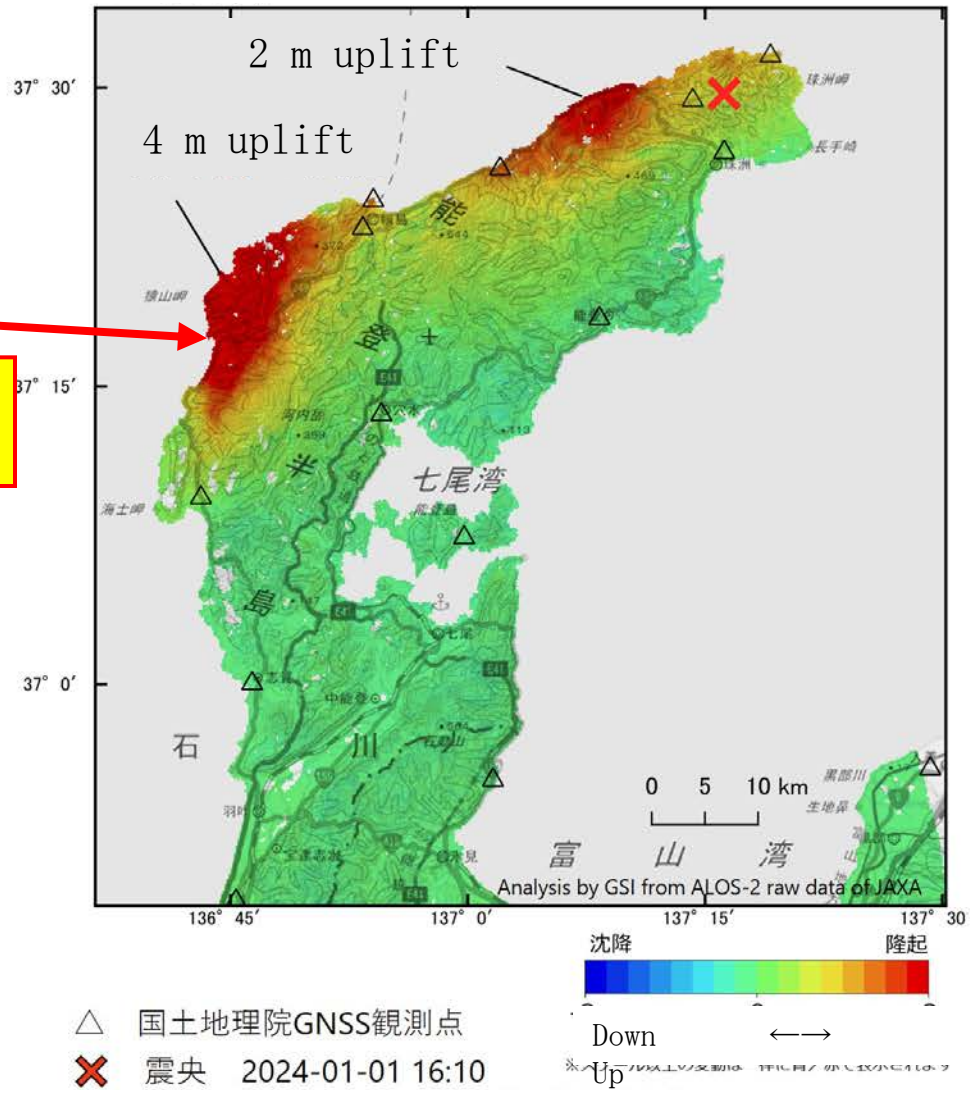


Clipped from MLIT, CAO, MEXT(2014)
https://www.mlit.go.jp/river/shinngikai_blog/daikibojishinchousa/

Coastal Uplift

- Crustal deformation by InSAR with ALOS-2 observation (GSI,JAXA)
- Maximum uplift is 4m at the NW coast.
- Land area increased by 4.74 km^2 (GSI, 2025)

Vertical movement by InSAR
(Analysis by GSI from ALOS-2 data of JAXA)

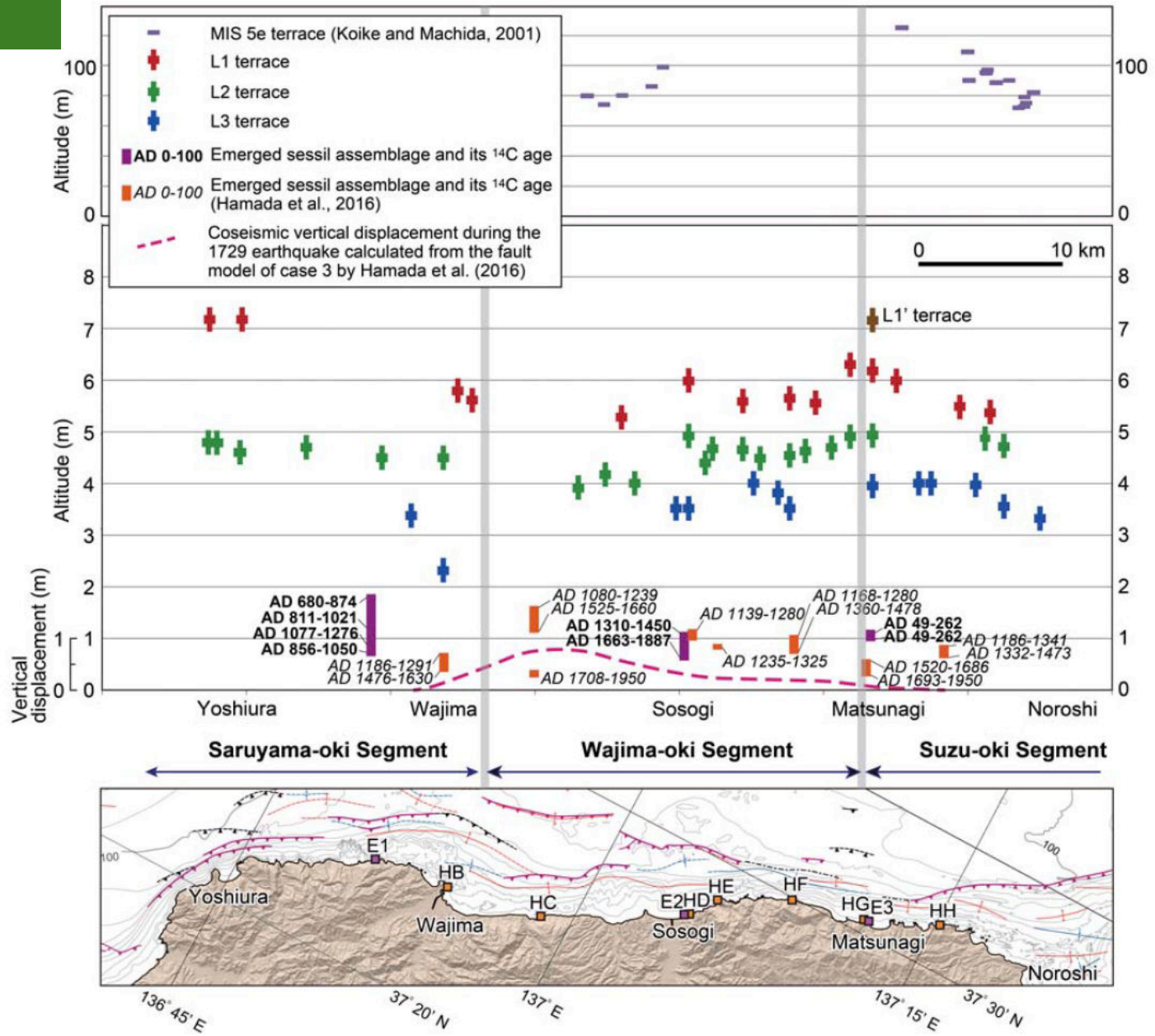


English explanation added to the figure in
https://www.gsi.go.jp/uchusokuchi/20240101noto_insar.html

Coastal uplift ñ past earthquakes

Three major marine terraces were identified (Shishikura et al. 2020) along the north coast.

- Each terrace represents the uplift corresponding to a past earthquake which was multi-segment rupturing like the 2024 earthquake.
- A smaller uplift corresponds to the earthquake of AD1729 (Hamada et al. 2015).
- The multi-segment rupture occurred every 900-1400 years, with some smaller events in between.

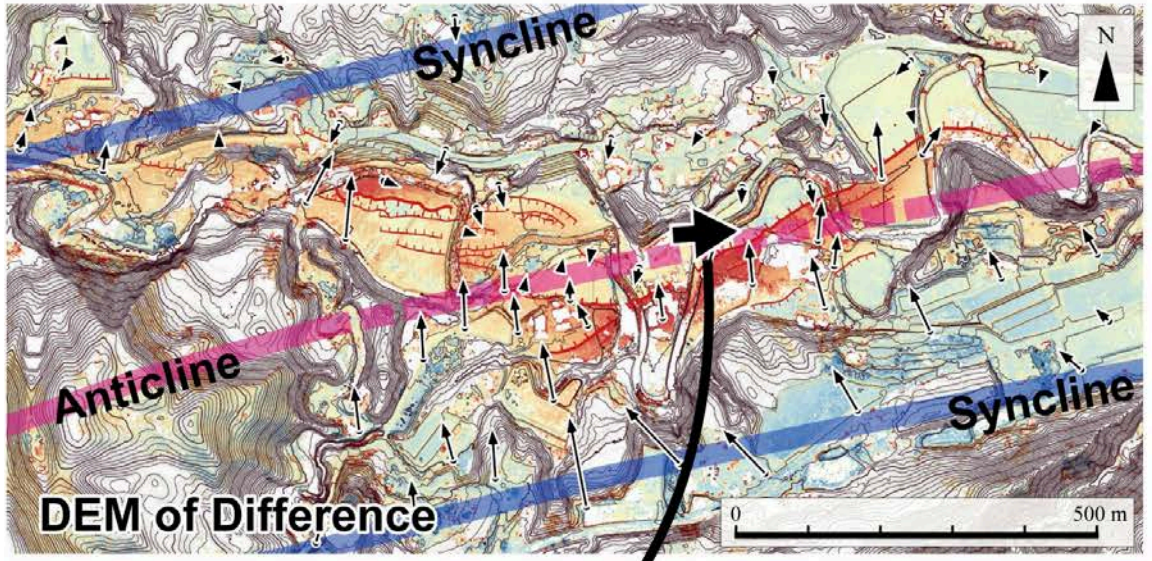


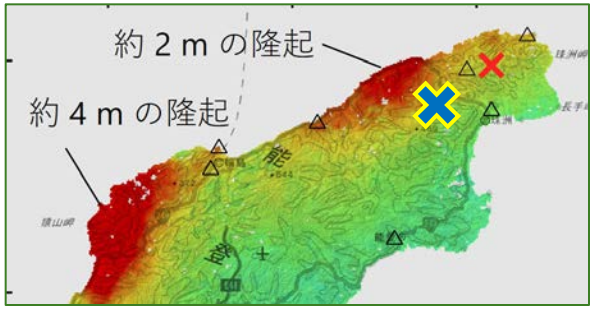
Shishikura et al. (2020, Active Fault Research)

Accompanying faulting

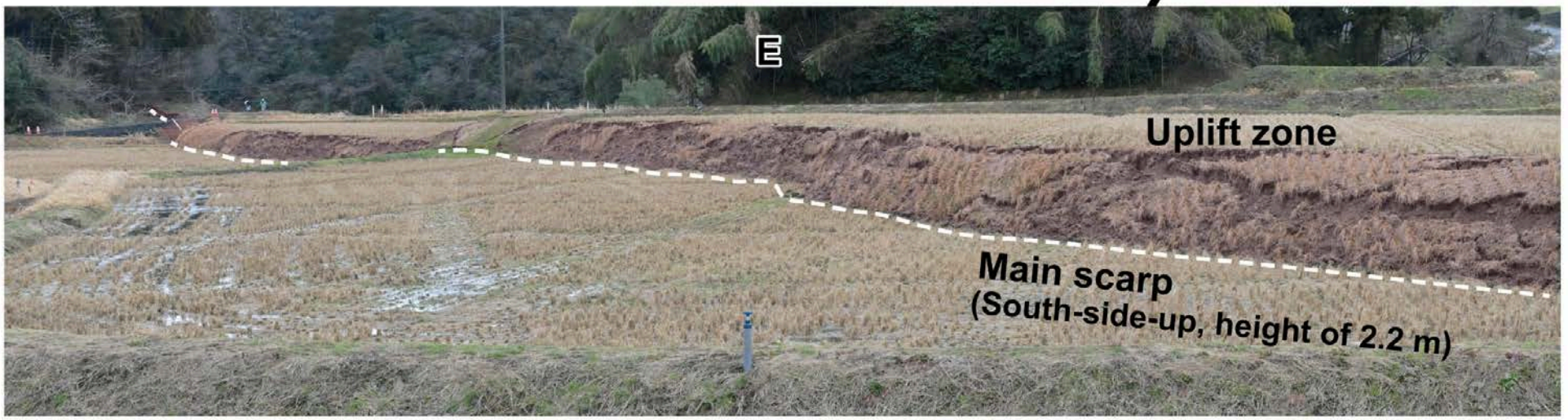
Faulting with a displacement of about 2m was found apart from the source fault of the Noto Pen. Earthquake.

- The faulting was caused by regional land slides, (Nakamura et al. 2024, Komura et al. 2025) which may be triggered by strong ground motion of the earthquake.
- Some of the faults slipped along the pre-existing fault surface.





Location of ìAccompanying Faultingî



Base map selected from https://www.gsi.go.jp/uchusokuchi/20240101noto_insar.html

Yoshida et al (2024, Remote Sensing)

Accompanying faulting ñ Also in Kumamoto Eq. 2016

Damages by the 2024 Noto Pen. Earthquake

(as of 2025.8.5, Cabinet Office of Japanese Government)

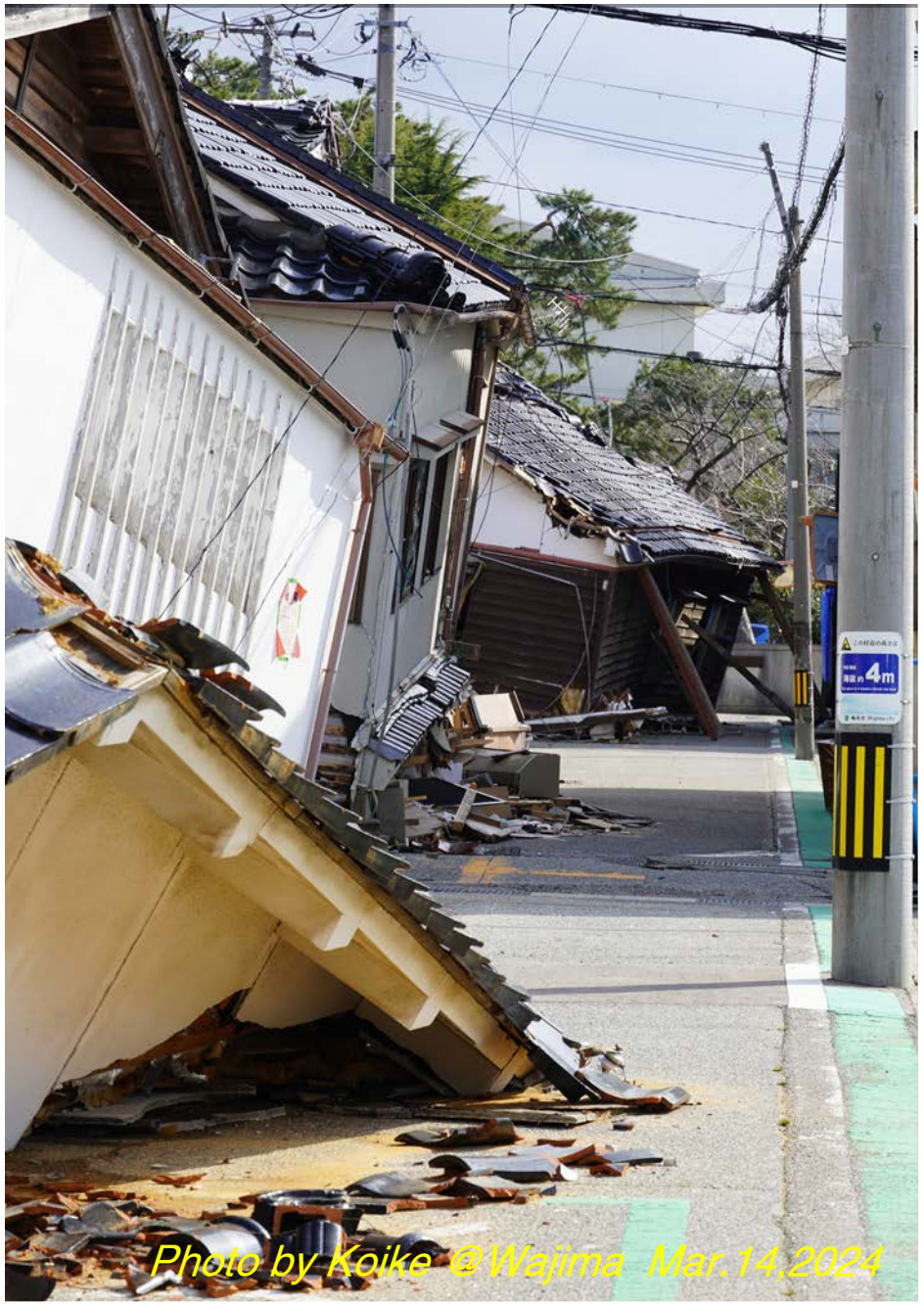
- Casualties
  - Fatalities 634
  - Injuries 1398
- Collapsed houses
  - Destroyed 6532
  - Damaged 23680
- Road closure (due to blockage or collapse)
  - National Road 40
  - Prefectural Road 145

A building of Japanese lacquerware company was toppled over.

Raising awareness for multi-hazard risk

Earthquake damages may prevent the people from effective sheltering or evacuation.

- Residents could be trapped inside collapse houses.
- Collapsed houses could block evacuation routes.

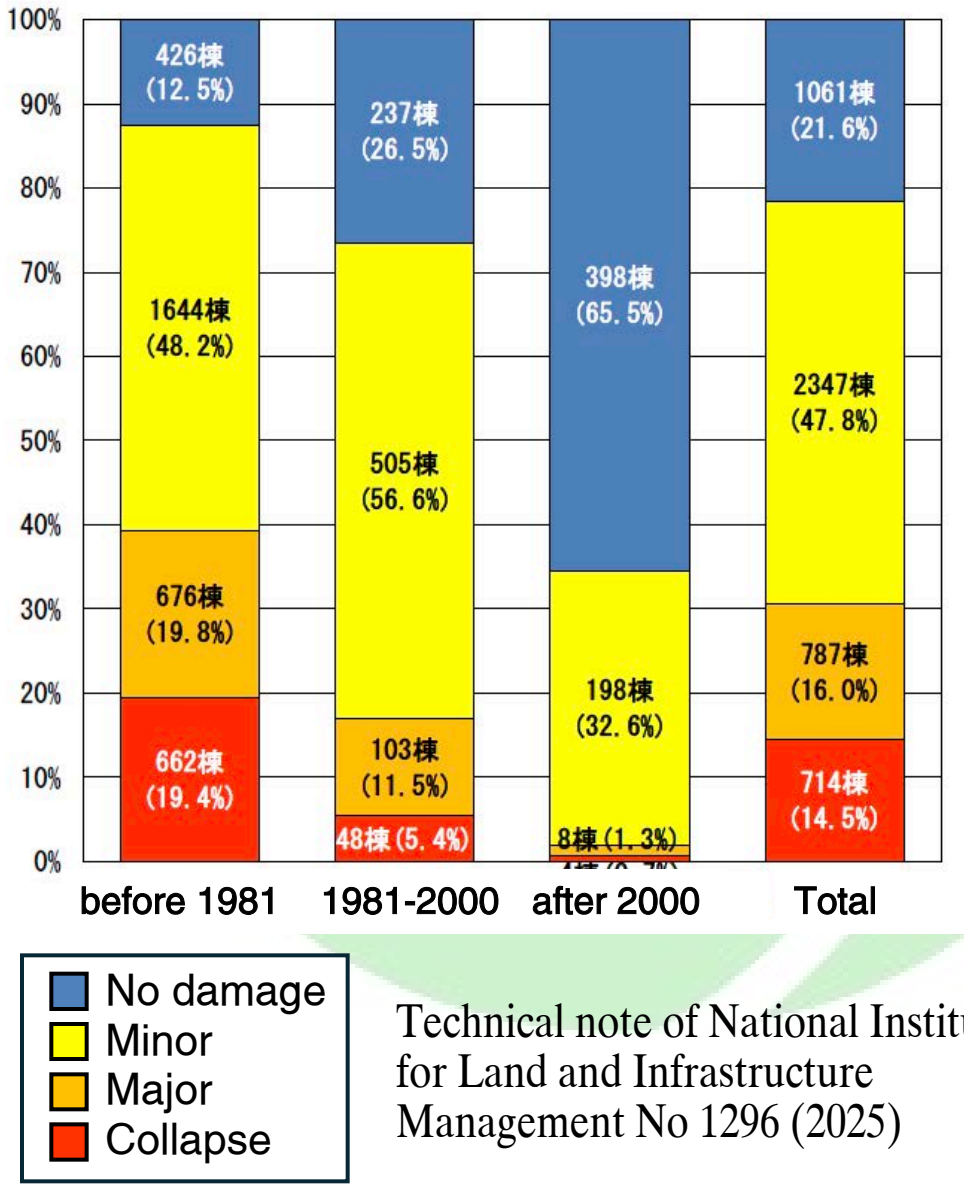


Raising awareness for multi-hazard risk

Low rate of earthquake resistant houses in the Noto area made the damage of wooden houses increase.

- Majour revision of Japanese Building Codes are made in 1981.
- 46% (Wajima) and 51%(Suzu) of wooden houses are build before 1981.
- Minor update in 2000 for wooden houses.
- Minor damage for the houses which were build after 2000.

Damage statistics of wooden houses in the Noto area



Technical note of National Institute for Land and Infrastructure Management No 1296 (2025)

Raising awareness for multi-hazard risk

Road Closure

- Even the high-grade road, which is a major connection route in the peninsular, was destroyed.
- Some small villages are isolated due to landslides or rockfalls on community roads.
- These damages could block the transportation of emergency supplies as well as evacuations.

Raising awareness for multi-hazard risk - Guide for *Sheltering in Place*

NRA established the Review Team on the *Sheltering in Place* in the event of nuclear emergency in March 2024, in response to the discussion with the local governor. (Final report published in March 2025)

- *Sheltering in place* is regarded as a key protective action within UPZ (5 to 30 km from NPP site).
- Three-day duration of indoor sheltering are recommended, because the government recommends three-day supply of emergency food in preparation for natural disasters.

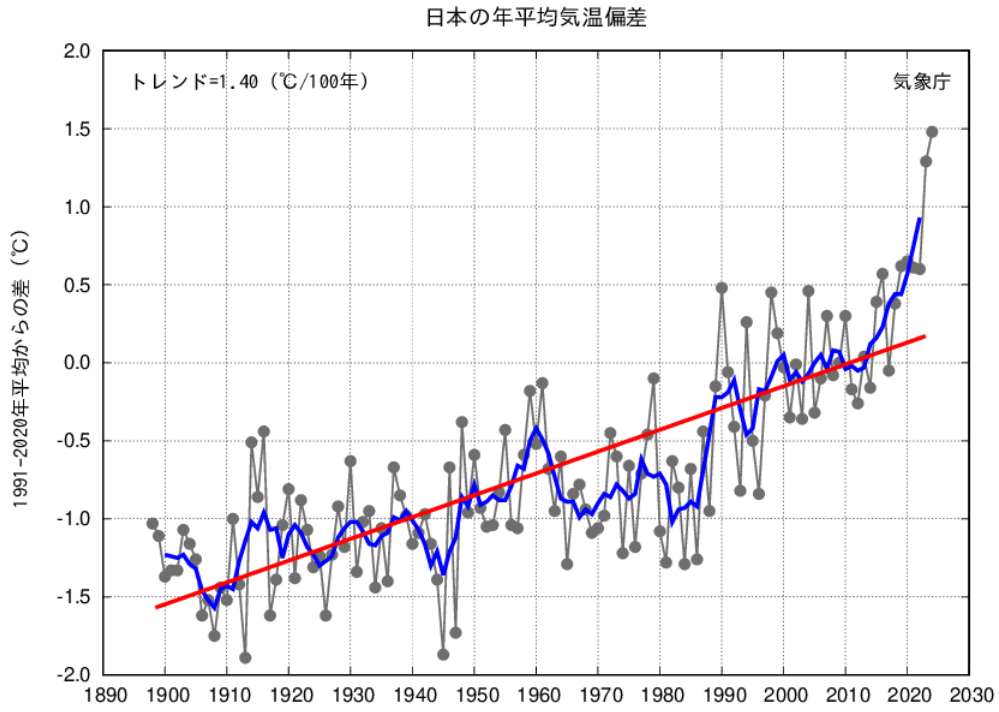
NRA intends to strengthen collaboration with relevant ministries and agencies responsible for natural disaster preparedness.

Ensuring NPP Safety against Extreme Meteorological Hazards

Regional changes in the intensity and frequency of climate extremes generally scale with global warming.
(in IPCC 6th report, Chapter 11)

Some effects of climate extremes are relieved by the natural environment specific to Japan.
Some measures for climate extremes to NPP sites in Japan are covered by the measures for earthquakes and tsunamis.

- High temperature <= Relieved by the Sea-side location of NPPs
- Sea level change <= Included in the measures for crustal uplift of subsidence by earthquakes.
- High tide by storm surge <= Included in the measures for tsunami.



Annual deviation of mean temperature in Japan (JMA)

Ensuring NPP Safety against Extreme Meteorological Hazards

The NRA regulations require that impacts of external hazards other than earthquakes and tsunamis shall be evaluated and measures be taken to prevent any damage from such hazards.

Recent meteorological record in Japan (JMA)

Wind speed of 75m/s is estimated in the tornado in Shizuoka. (2025.9.5)

1-hour rain of 153mm was recorded in Chiba. (1999.10.27)

1-day rain of 922.5 mm was recorded in Kanagawa. (2019.10.12)

High temperature of 41.8℃ was recorded in Gunm.a (2025.8.5)

An example of safety evaluation required by the NRA regulati

External hazard values at annual exceedance probability of 10^{-6} for *Sendai* NPP

External Hazard	Event considered	Hazard values of 10^{-6}/year	Design value
High winds including tornadoes	Tornadoes (Wind speed)	104.7 m/s	100.0 m/s
Lightening strike	Lightning strike (Maximum lightning strike current)	369 kA	150 kA
Weather	High temperature (Outdoor temperature)	39.4 ℃	33.0 ℃
	Low Temperature and freezing (Outdoor temperature)	-10.5 ℃	-7.0 ℃
	Snowfall (snow accumulation)	99.4 cm	30.0 cm
	Rainfall (1-hour rainfall)	251.0 mm	160.0 mm

Sunada & Azetsu (2024), SMiRT 27, Yokohama.

Concluding Remarks

A Mw7.5 Earthquake ruptured offshore faults along the northern part of the Noto Peninsular, causing large damage to roads and houses in the Noto region.

The faulting uplifted the northern coast of the peninsular.

1. It reminds us the importance of careful assessment on the continuity of fault segments as well as possible triggering onto neighboring faults.
   - Comparable capable fault can be assessed under the current NRA regulation.
   - Evaluation of offshore faults in the Japan Sea are still being conducted.

2. Large crustal uplift that may affect the sea water intake.
   - NRA has confirmed the NPP safety in the case of sudden uplifts.

3. Accompanying faulting was found apart from the earthquake fault.
   - Careful examination, including the evaluation of soil stability, is required.

4. The road and house damage raised the awareness of the potential threat of multi hazards by earthquakes and SA of NPP.
   - NRA created a guide on the indoor sheltering in place in response to NPP severe accident.
   - Emergency response plan for multi-hazards should be established in relationship among relevant institutions.