NOAA TSUNAMI FORECAST DEVELOPMENT

Vasily Titov
NOAA Center for Tsunami Research
Pacific Marine Environmental Laboratory

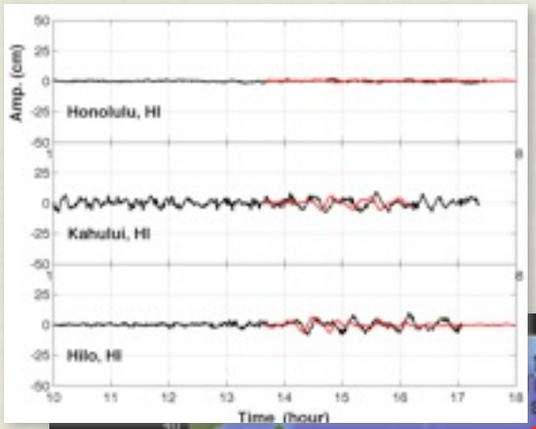
TSUNAMI FORECAST

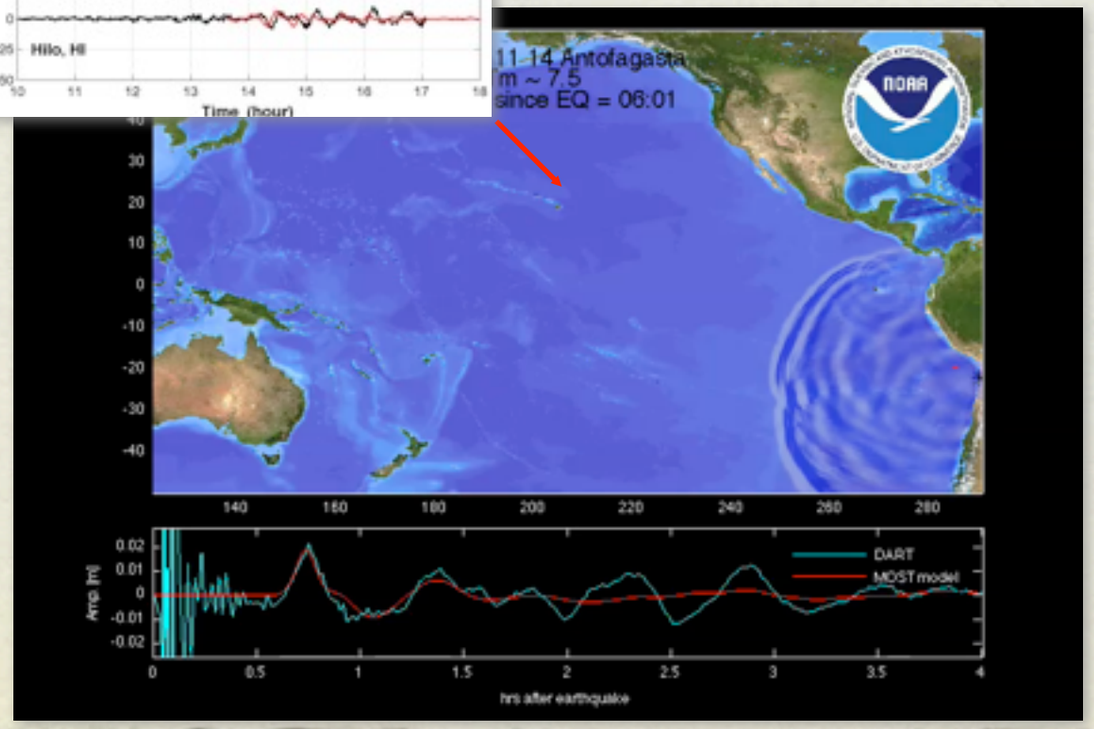
Real-time:

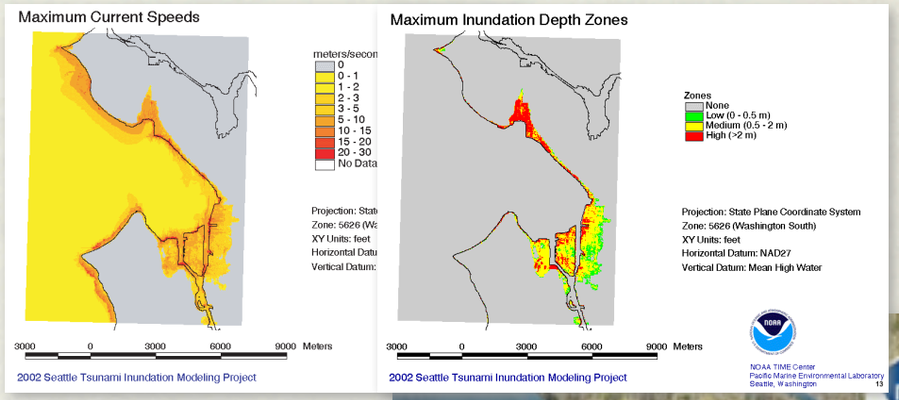
- Event-specific
- Real-time event assessment
- Real-time impact assessment before tsunami arrival

Long-term:

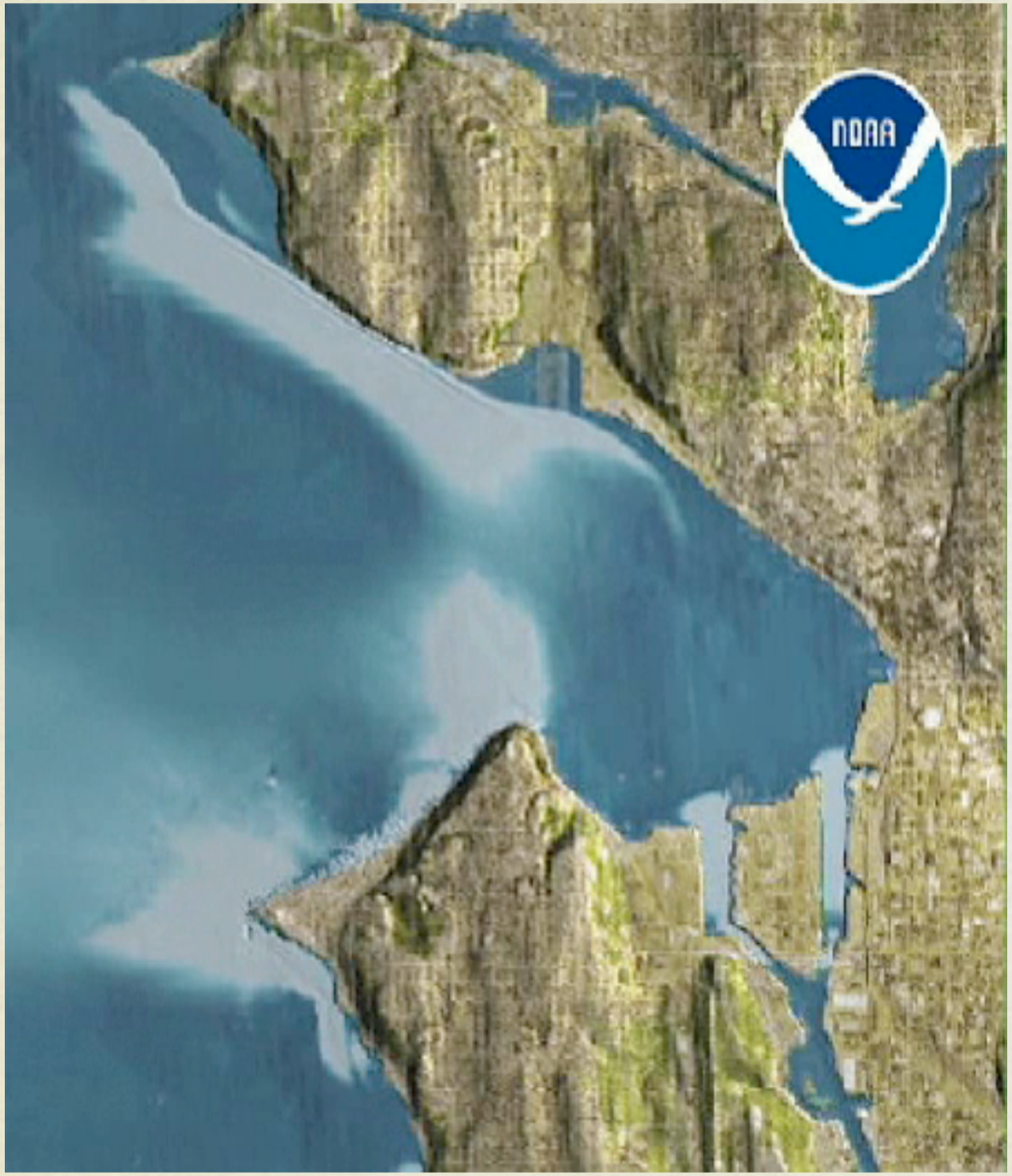
- Site-specific
- Probable Maximum Tsunami
- Multiple scenarios for PTHA
- Comprehensive Hazard Assessment

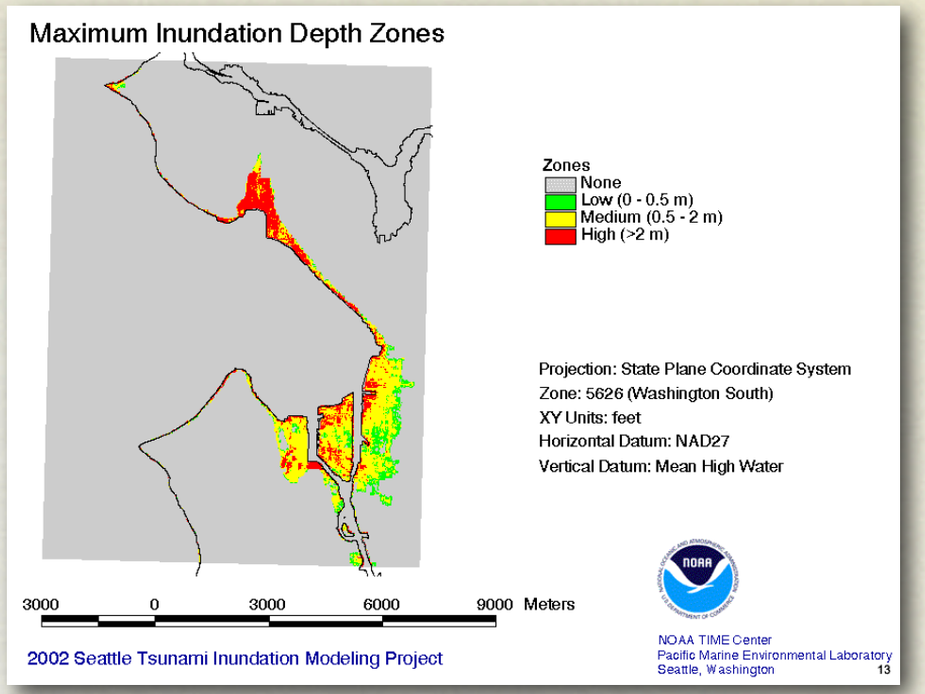


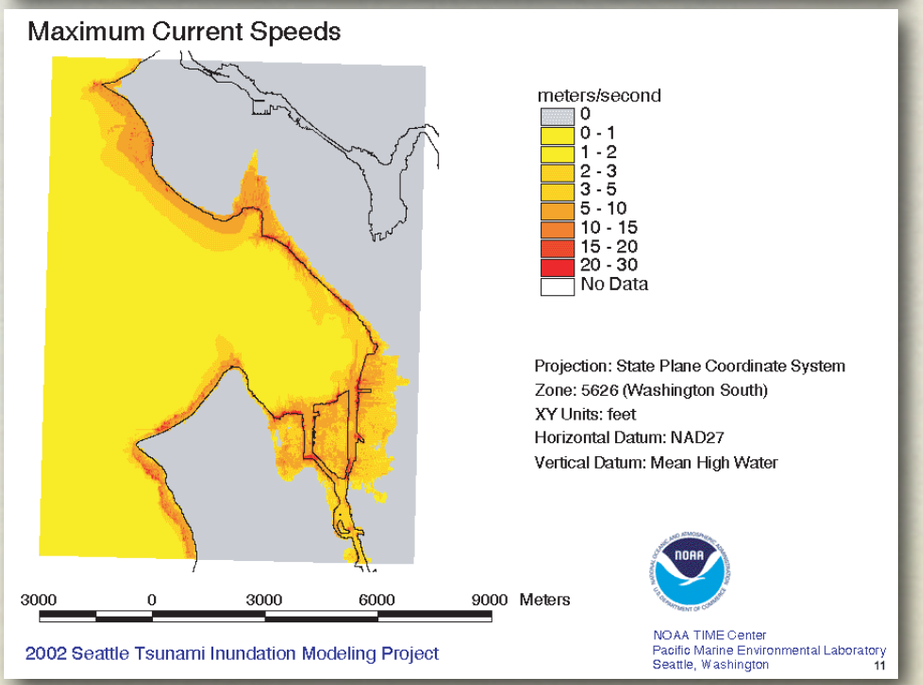




LONG-TERM FORECAST: HAZARD ASSESSMENT







WASHINGTON STATE DEPARTMENT OF
Natural Resources
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Ron Teissere - State Geologist

NOAA TIME Center
Pacific Marine Environmental Laboratory
Seattle, Washington

WASHINGTON DIVISION OF GEOLOGY AND EARTH RESOURCES
OPEN FILE REPORT 2003-14

Tsunami Hazard Map of the Elliott Bay Area, Seattle, Washington: Modeled Tsunami Inundation from a Seattle Fault Earthquake

by
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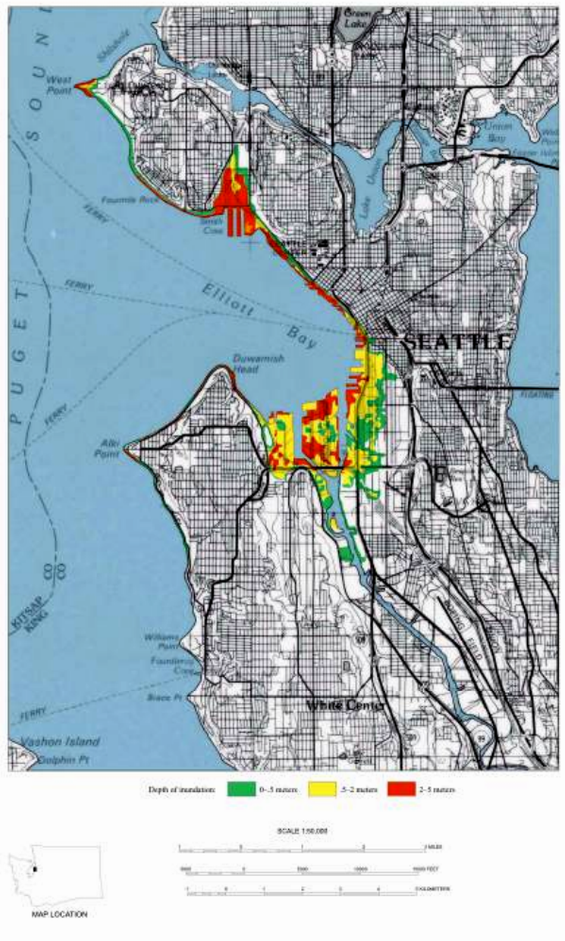

INTRODUCTION

In 1995, Congress directed the National Oceanic and Atmospheric Administration (NOAA) to develop a plan to protect the West Coast from tsunamis generated locally. A panel of representatives from NOAA, the Federal Emergency Management Agency (FEMA), the U.S. Geological Survey (USGS) and the five Pacific coast states wrote the plan and submitted it to Congress, which created the National Tsunami Hazard Mitigation Program (NTHMP) in October of 1996. The National Tsunami Hazard Mitigation Program is designed to reduce the impact of tsunamis through warning guidance, hazard assessment, and mitigation. A key component of the hazard assessment for tsunamis is delineation of areas subject to tsunami inundation. This map is part of a series of tsunami inundation maps produced by the Washington Department of Natural Resources, Division of Geology and Earth Resources, in cooperation with the Washington Emergency Management Division, as a contribution of the National Tsunami Hazard Mitigation Program (Walsh and others, 2003a,b; 2002a,b; 2000). These maps are produced using computer models of earthquake-generated tsunamis from nearby seismic sources. The modeling for this map was done by the Center for the Tsunami Inundation Mapping Efforts (TIME) at NOAA's Pacific Marine Environmental Laboratory in Seattle for a scenario earthquake on the Seattle fault.

THE SEATTLE FAULT

Geographic features now known to be associated with the Seattle fault have been noted for many years. Vancouver (1798) noted that the fault-uplifted bedrock wave-cut platform at Restoration Point (Fig. 1, Location 1) on Bainbridge Island "did not possess that beautiful variety of landscape, being an almost impenetrable wilderness of lofty trees" that characterized the rest of his explorations in Puget Sound. Kimball (1897) described the Newcastle Hills (Fig. 1, Location 2), part of the hanging wall of the fault, as a "postglacial eruption". Dunell and others (1965) interpreted the large gravity and magnetic anomalies through central Puget Sound and the associated abrupt change in the sedimentary section thickness as an active fault with about 11 km of displacement. Rogers (1970) collected additional gravity and magnetic data across the structure and named it the Seattle–Bremerton fault. Grover (1978) demonstrated that the uplift at Restoration Point (Fig. 1, Location 1) was Holocene in age and Bucknam and others (1992) showed that there was an uplift of 7 meters produced on the fault about 1,000 years ago.

In 1996, the first of a series of lidar (Light Detection And Ranging) surveys was flown over Bainbridge Island. This and subsequent lidar missions have enabled scientists to locate splays of the fault in a number of places accurately enough to dig trenches (Bucknam and others, 1999; Nelson and others, 2002). Lidar mapping and trenching have enabled scientists to accurately map the amount of uplift on the fault in some places. Also in 1996, the U.S. Geological Survey began several large-scale geophysical studies. An aeromagnetic study of the Puget Sound (Blakely and others, 1999, 2002) enabled more accurate location of the fault along its entire length. Seismic reflection and tomographic studies, such as SHIPS (Seismic Hazards Investigations in Puget Sound) and other geophysical studies in Puget Sound have greatly increased the understanding of the fault characteristics at depth (Pratt and others, 1997; Johnson and others, 1999; Brocher and others, 2001, ten Brink and others, 2002; Van Wagoner and others, 2002), although considerable uncertainties and controversy remain.

There also is substantial evidence that earthquakes on the Seattle fault can generate tsunamis. Atwater and Moore (1992) showed that tsunamis inundated part of Whidbey Island (Fig. 1, Location 5) and West Point (Fig. 1, Location 4) about 1000 years ago, and Jacoby and others (1992) showed that a tree in the tsunami deposit at West Point died in the same season of the same year as a drowned forest carried into Lake Washington by a huge landslide from Mercer Island, strongly implicating the A.D. 900–930 event. A discontinuous sand layer along Snohomish delta distributaries—Ebey Slough, Steamboat Slough, Union Slough, and Snohomish River (Fig. 1, Location 6)—also probably was deposited by the tsunami from the large A.D. 900–930 earthquake on the Seattle fault (Bourgeois and Johnson, 2001).

MODELING

Tsunami inundation shown on the map is based on a computer model of waves generated by the Seattle fault (Titov and others, in press). The model used is the finite difference model of Titov and Synolakis (1998), also known as the Method of Splitting Tsunami (MOST) model (Titov and Gonzalez, 1997). It uses a grid of topographic and bathymetric elevations and calculates a wave elevation and velocity at each gridpoint at specified time intervals to simulate the generation, propagation and inundation of tsunamis in the Elliott Bay area.

In this MOST model study, the tsunami is generated by a Seattle fault deformation model that simulates the A.D. 900–930 event as a credible worst-case scenario of magnitude 7.3. The magnitude was chosen to be consistent with the 2002 USGS update of the National Seismic Hazard Maps (Frankel and others, 2002). Parameter values are based on Brocher and others (2001), Calvert and Fisher (2001), and ten Brink and others (2002).

The slip distribution was constrained, through trial-and-error, to match available field estimates of vertical displacement at three sites—Alki Point (Fig. 1, Location 3; +4 m), Restoration Point (Fig. 1, Location 1; +7 m) and West Point (Fig. 1, Location 4; –1 ±0.5 m).

Titov and others (in press) also modeled a M7.0 event, and the tsunami inundation values and patterns were essentially the same as for the M7.3 event. No doubt this is due to the fact that the deformation patterns and values were very similar for both events, since they were each constrained by field estimates at the three sites. Also, the smaller ground displacement zone of the M7.3 event forms a more concentrated tsunami source that compensates for its smaller overall displacement.

The computed tsunami inundation is shown on the map in three color-coded depth ranges—0–0.5 m, 0.5–2 m, and greater than 2 m. These depth ranges were chosen because they are approximately knee-high or less, knee-high to head-high, and more than head-high. The limit of tsunami inundation is the landward edge of the green zone. In previous maps, we have shown only the edge of inundation, but for this map, much higher resolution bathymetric and topographic data were available. Figure 2 also shows current velocities in two zones—less than or greater than 1.5 meters/second (~3 miles/hour), which is the current speed at which it would be difficult to stand. Within this zone, computed velocities locally exceed 20 meters/second (~40 miles/hour). Computed wave heights in Elliott Bay were approximately 6 meters. Figure 3 shows a time progression of the wave across Elliott Bay at 30-second intervals. Note that because Harbor Island is uplifted by the earthquake, the Duwamish Waterway initially drains rapidly before the wave reflects off the north side of the bay and then inundates the Harbor Island area.

Table 1. Segment (west to east) parameters for magnitude 7.3 Seattle fault earthquake models. The vertical deformation pattern is shown in Figure 1.

Segment	Depth (km)	Length (km)	Width (km)	Strike (°)	Dip (°)	Slip (m)
1	0.5	15.2	20	87.9	60	1
2	0.5	6.5	20	86.6	60	7
3	0.5	8.9	20	94.0	60	12
4	0.5	3.2	20	126.8	60	11
5	0.5	11.5	20	99.3	60	4
6	0.5	14.9	20	81.0	60	1

LIMITATIONS OF THE MAP

Because the nature of the tsunami depends on the initial deformation of the earthquake, which is poorly understood, the largest source of uncertainty is the input earthquake. The earthquake scenario used in this modeling was selected to honor the paleoseismic constraints, but the next Seattle fault earthquake may be substantially different from these. Sherrod and others (2000) show that an uplift event at Restoration Point predating the A.D. 900–930 event was smaller. Trenching of subsidiary structures to the Seattle fault that are thought to be coseismic with the main fault trace (Nelson and others, 2002) indicate that there were at least two earthquakes in the 1500 years before the A.D. 900–930 event. These, however, did not produce prominent uplifted wave-cut platforms similar to the one made by the A.D. 900–930 event, suggesting that significant earthquakes have occurred on the fault that had different and smaller uplifts in central Puget Sound.

Another significant limitation is that the resolution of the modeling is no greater or more accurate than the bathymetric and topographic data used. This can be up to 50 meters horizontally, although high-resolution multibeam data (Gardner and others, 2001) is available for Elliott Bay and 2-foot contour topography is available for the city of Seattle.

The model run does not include the influences of changes in tides and is referred to mean high water. The tidic stage and tidal currents can amplify or reduce the impact of a tsunami on a specific community. In Elliott Bay, the mean spring tide range is about 11 feet and can be as much as about 16 feet (NOAA, accessed at http://co-ops.nos.noaa.gov/co-ops.html, June 25, 2003). This means that, while the modeling can be a useful tool to guide evacuation planning, it is not of sufficient resolution to be useful for land-use planning.

ACKNOWLEDGMENTS

This project was supported by the National Tsunami Hazards Mitigation Program (NTHMP) in cooperation with the city of Seattle and the Washington Emergency Management Division. Information about NTHMP is available at http://www.pmel.noaa.gov/tsunami-hazard/. Discussions with Tom Pratt, Brian Sherrod, and Craig Weaver (all USGS, Seattle) were invaluable for calibrating the fault source model. Karl Wegmann and Steve Palmer, both Washington Division of Geology and Earth Resources, provided helpful reviews.

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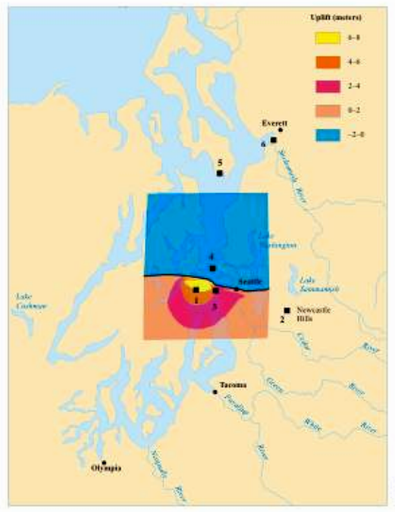


Figure 1. (left) Map showing Seattle fault and associated ground deformation model used in this study. Numbered locations are localities mentioned in text. 1, Restoration Point; 2, Newcastle Hills; 3, Alki Point; 4, West Point; 5, Camus Bay; 6, Snohomish Delta.

Figure 2. Computed current velocity zones. Note that velocities are highest along the shoreline and in narrow channels. One meter/second is ~2.2 mph.

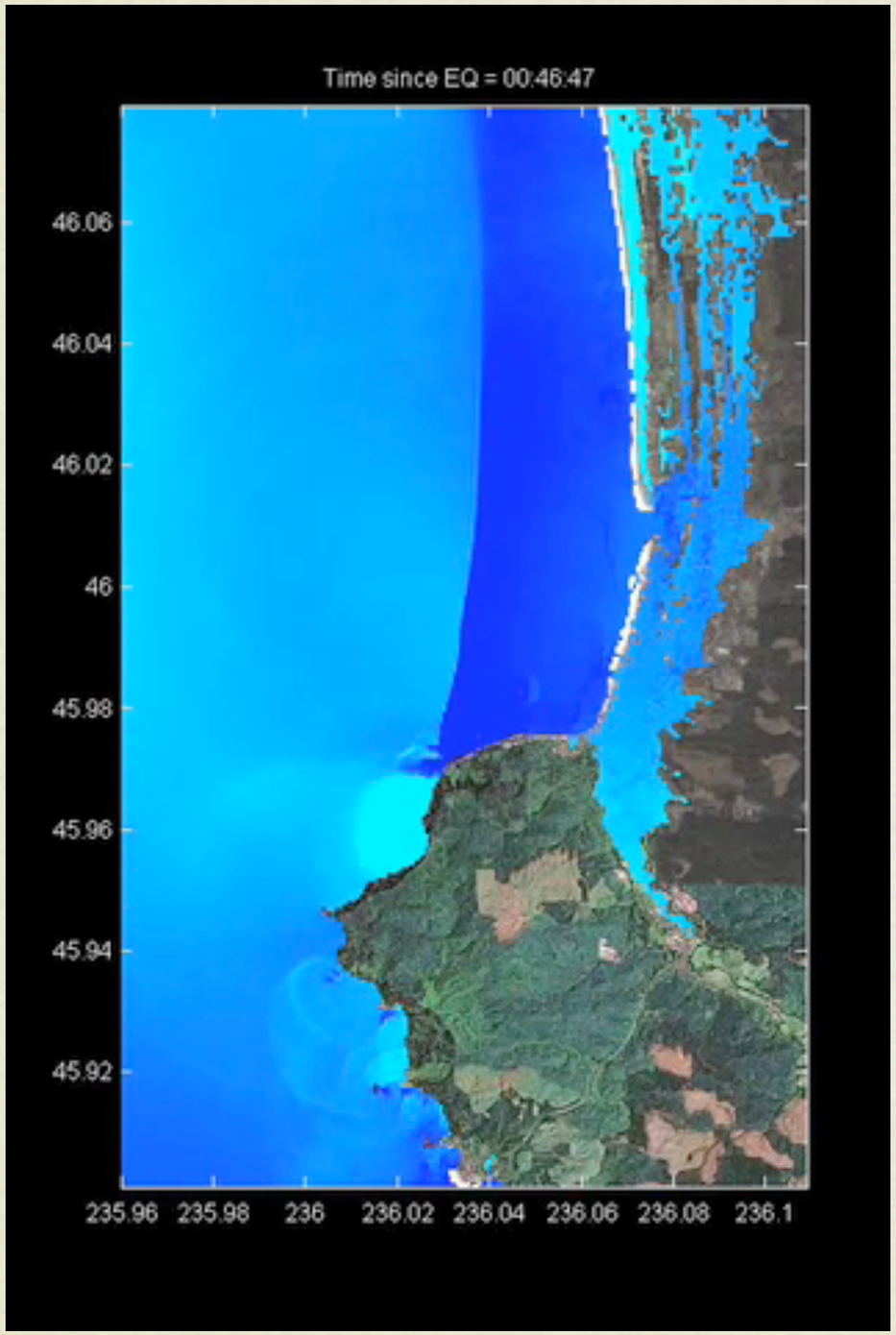
Figure 3. Freeze frames of animation of modeled tsunami at 30-second intervals (from left to right). The wave crest is colored pale blue. Note that because Harbor Island is uplifted by the earthquake, the Duwamish Waterway initially drains rapidly before the wave reflects off the north side of the bay and then inundates the Harbor Island area.

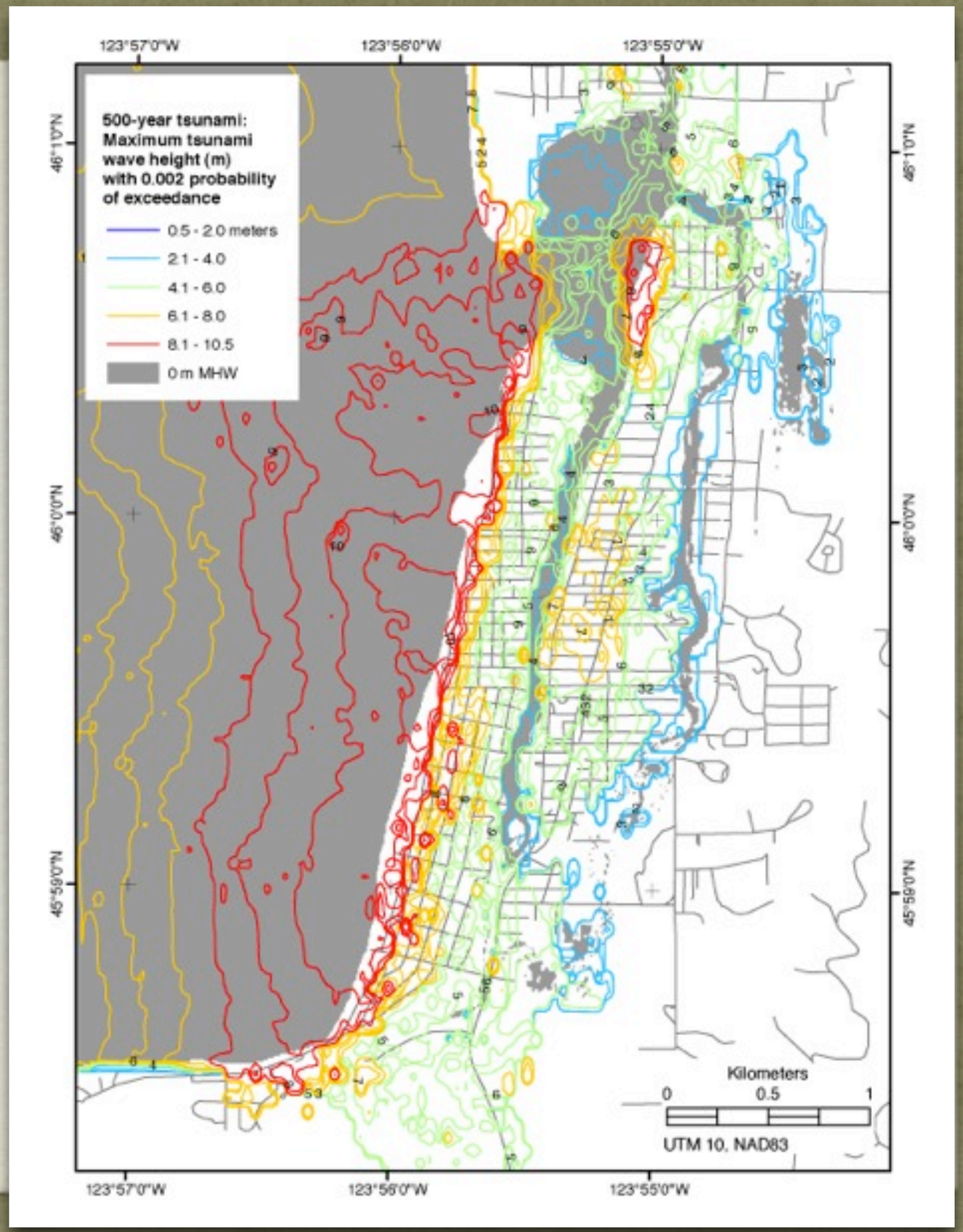
The phenomenon we call "tsunami" (soo-NAH-mee) is a series of traveling ocean waves of extremely long length generated by disturbances associated primarily with earthquakes occurring below or near the ocean floor. Underwater volcanic eruptions and landslides can also generate tsunamis. In the deep ocean, their length from wave crest to wave crest may be a hundred miles or more but with a wave height of only a few feet or less. They cannot be felt aboard ships nor can they be seen from the air in the open ocean. In deep water, the wavor may reach speeds exceeding 500 miles per hour.

Tsunamis are a threat to life and property to anyone living near the ocean. For example, in 1992 and 1993 over 2,000 people were killed by tsunamis occurring in Nicaragua, Indonesia and Japan. Property damage was nearly one billion dollars. The 1960 Chile Earthquake generated a Pacific-wide tsunami that caused widespread death and destruction in Chile, Hawaii, Japan and other areas in the Pacific. Large tsunamis have been known to rise over 100 feet, while tsunamis 10 to 20 feet high can be very destructive and cause many deaths and injuries.

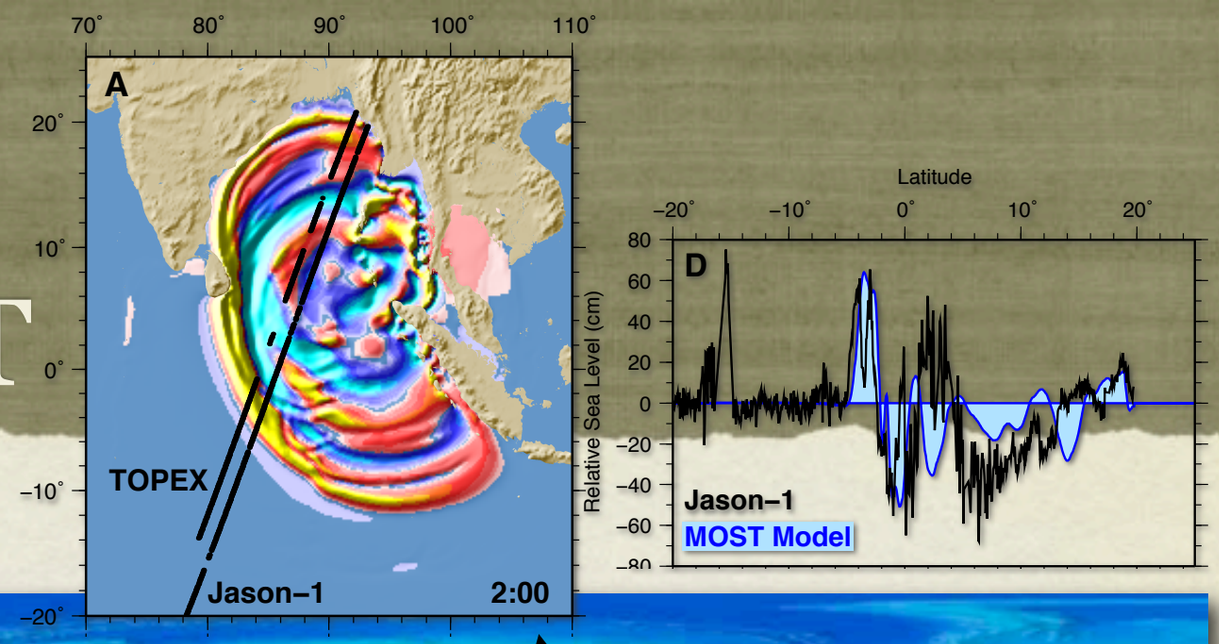
From Tsunamis—The Great Waves
by the U.S. Department of Commerce,
National Oceanic and Atmospheric Administration,
National Weather Service, Intergovernmental Oceanographic Commission,
and International Tsunami Information Center
Accessed at http://www.nws.noaa.gov/om/brochures/tsunami.htm on 8/27/02

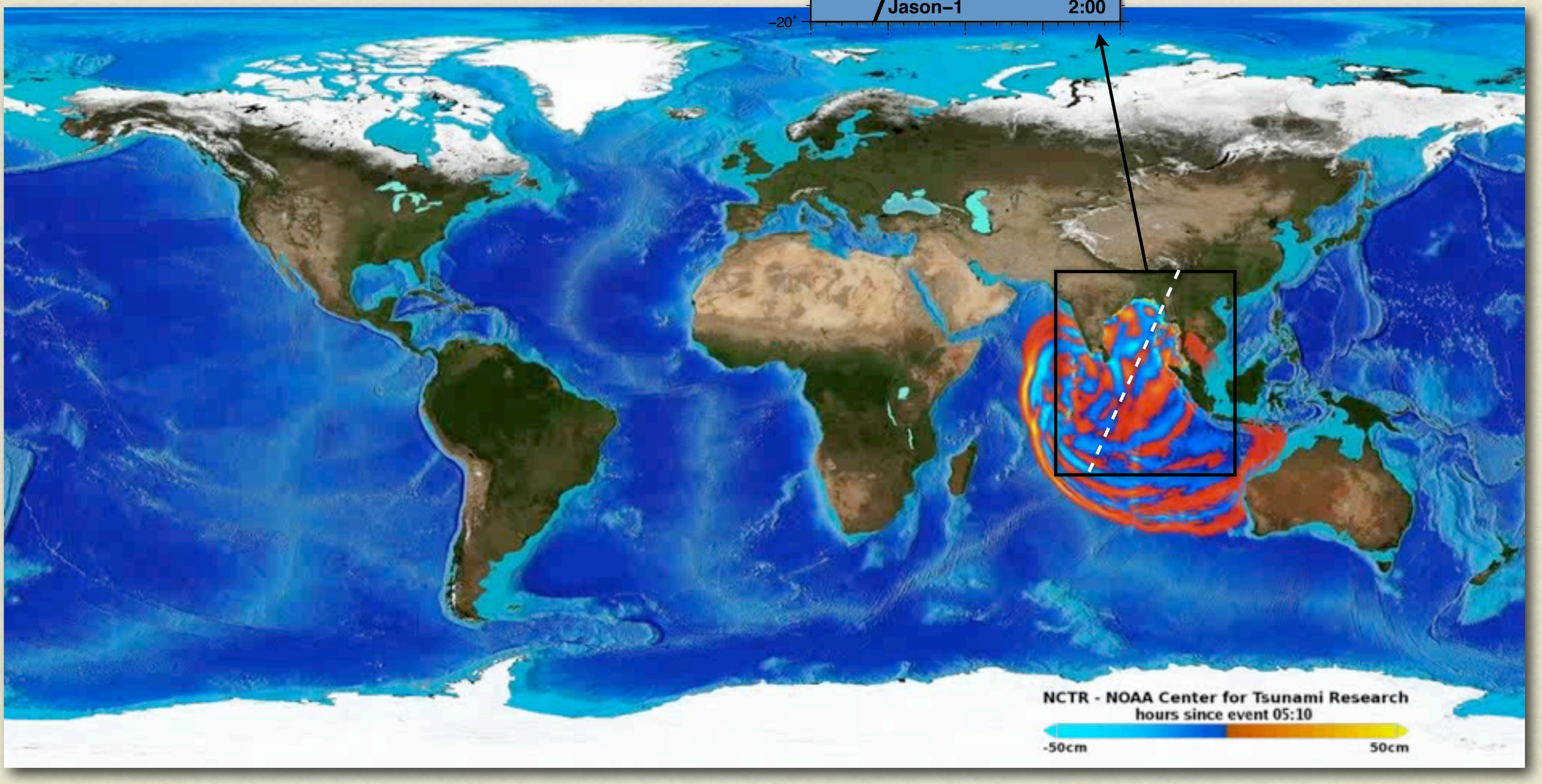
PROBABILISTIC ASSESSMENT





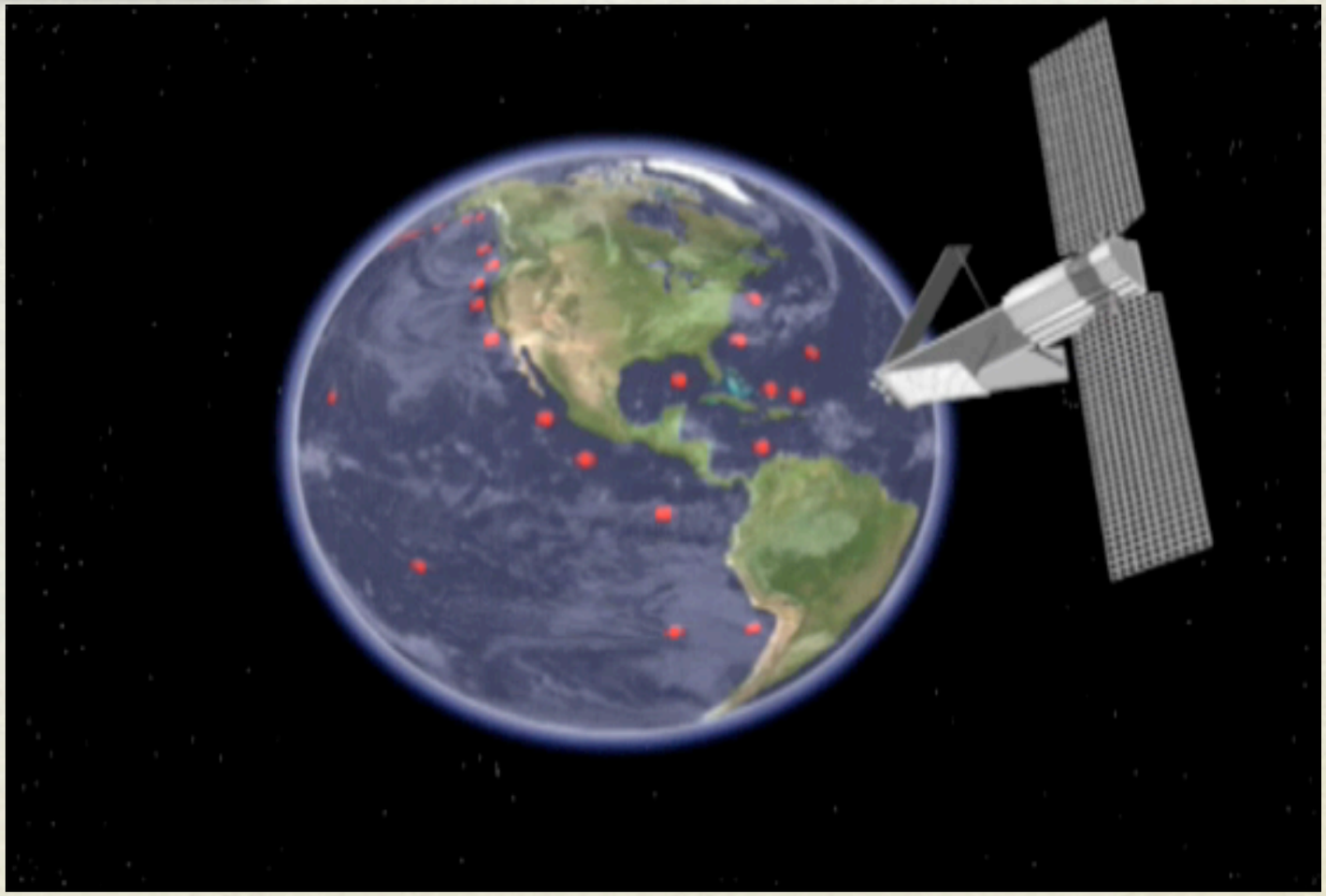
THE CHALLENGE: REAL-TIME MODEL FORECAST





TSUNAMI REAL-TIME DETECTION

Deep-ocean Assessment and Reporting for Tsunamis (DART)



NOAA Tsunami Forecast

Detection

▲ Tsunameters

Inversion

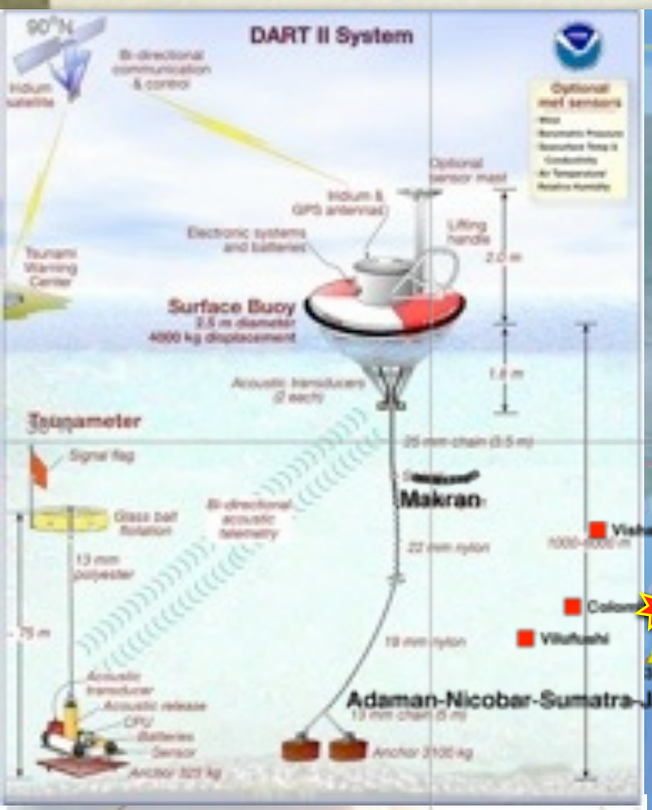
▬ model database

Coastal forecast

■ Flooding forecast

Verification

✸ Tsunami events



Forecast tests:

- 17 real-time tests
- 13 data tests
- over 30 global test events

MARCH 11, 2011
JAPAN TSUNAMI

Vasily Titov
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Pacific Marine Environmental Laboratory

WORST TSUNAMI IN JAPAN HISTORY

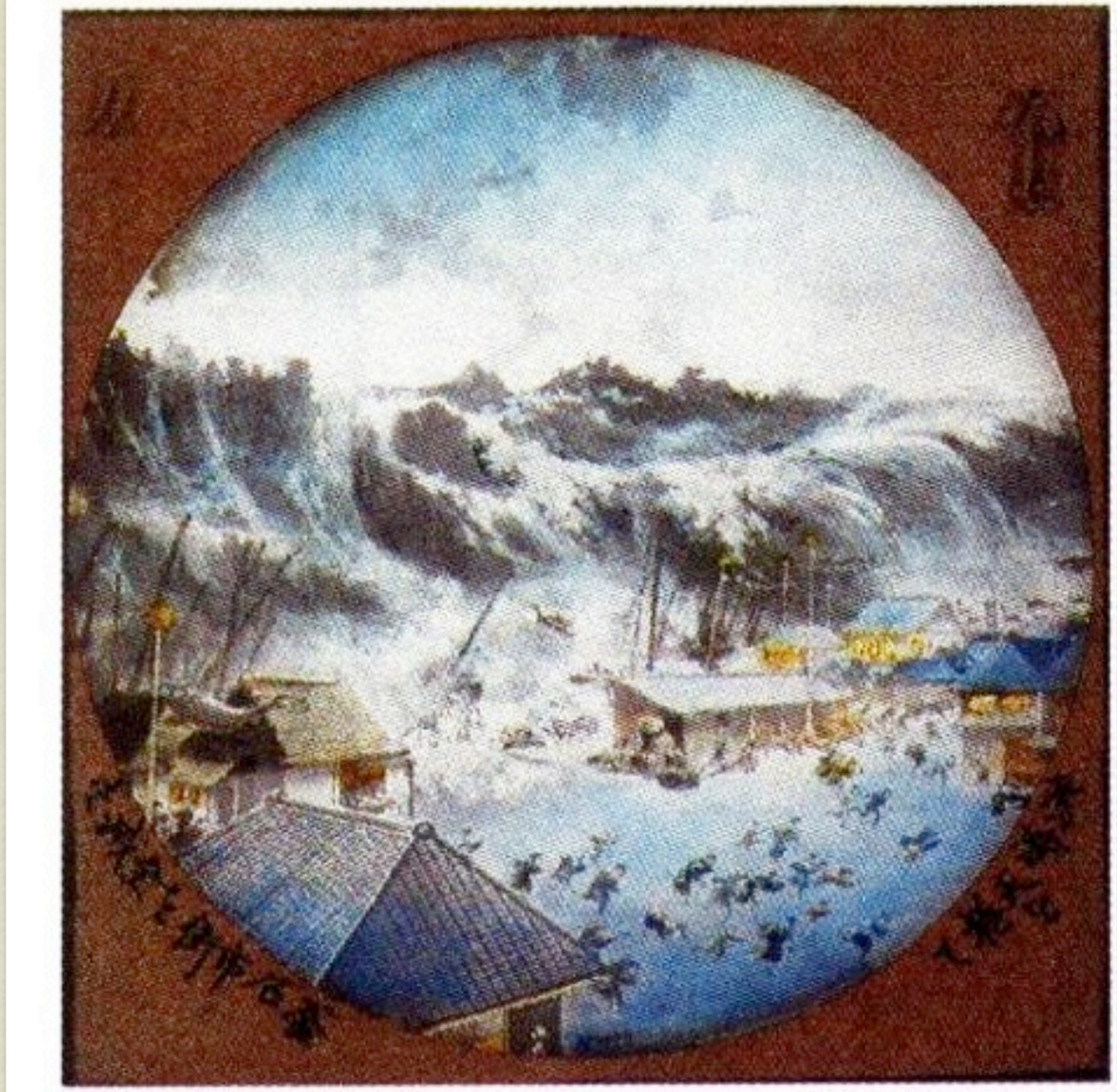
SOME FACTS

- Vast majority of damage is due to the tsunami
- Possibly the worst tsunami in Japan (1896 Sanriku, 22,000 deaths)
- Estimates of over 20,000 dead
- Estimates of over $250B damage
- Substantial impact in US (flooding, people killed, tens of millions of damage)
- Flooding and damage in Chile 22 hrs after earthquake
- Assessments of damage around the Pacific continues
- Second worst ever NPP incident caused by the tsunami

JAPANESE HISTORICAL TSUNAMIS

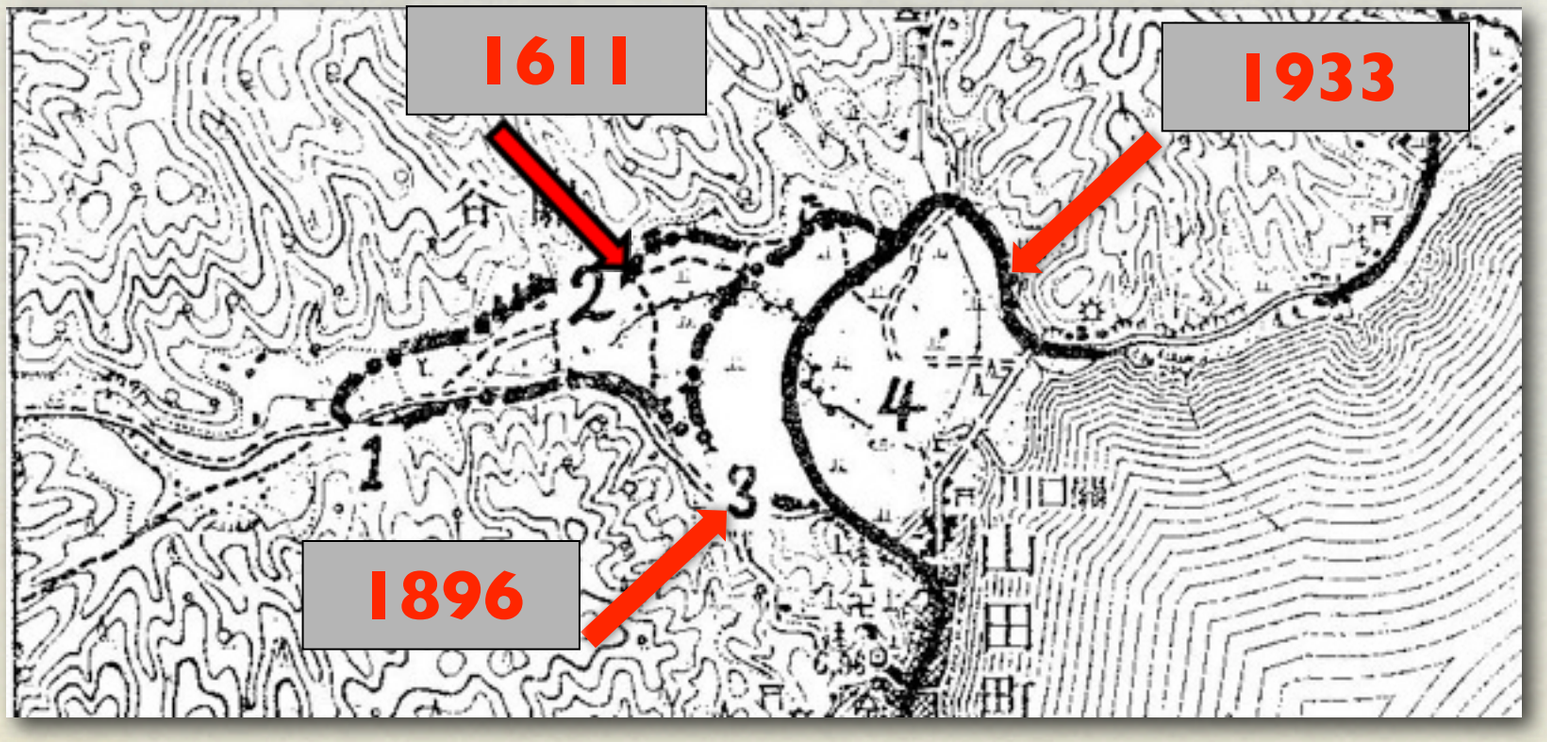
Year	Earthquake Magnitude	Number of Deaths	Water Height (m)
869	8.6	1,000	
1611	8.1	5,000	25
1616	7.5	200	2
1793	8.3	732	5
1896	7.6	27,122	38
1933	8.4	3,022	29
2011	9.0	18,000	40

PICTURES SOLD AFTER 1896 TSUNAMI



From field guide, 3rd International Tsunami Field Symposium, April, 2010, Tohoku University, Sendai
Trip leaders: Nobuo Shuto, Fumihiko Imamura

BOUGASAWA AREA



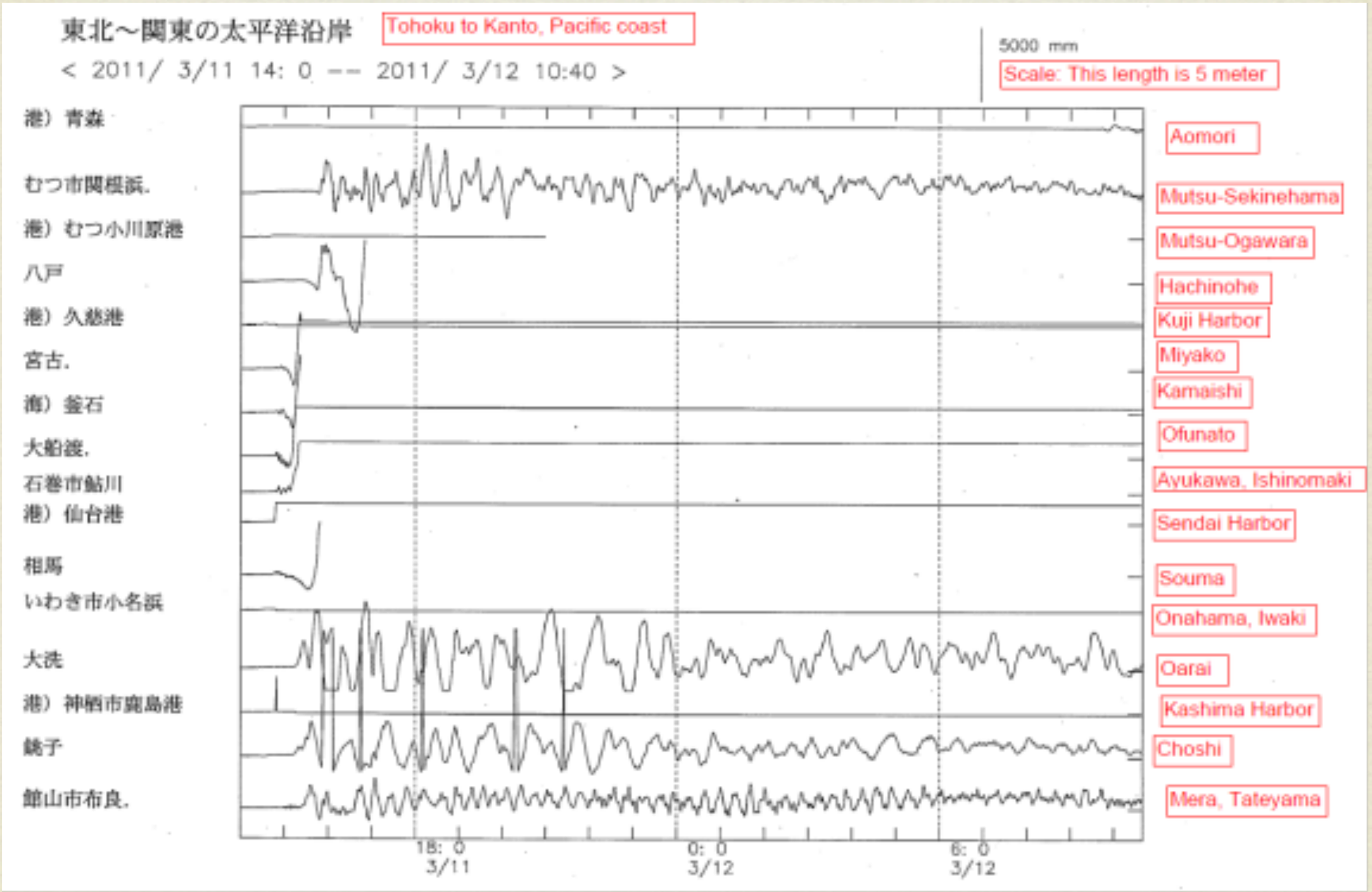
Credit:

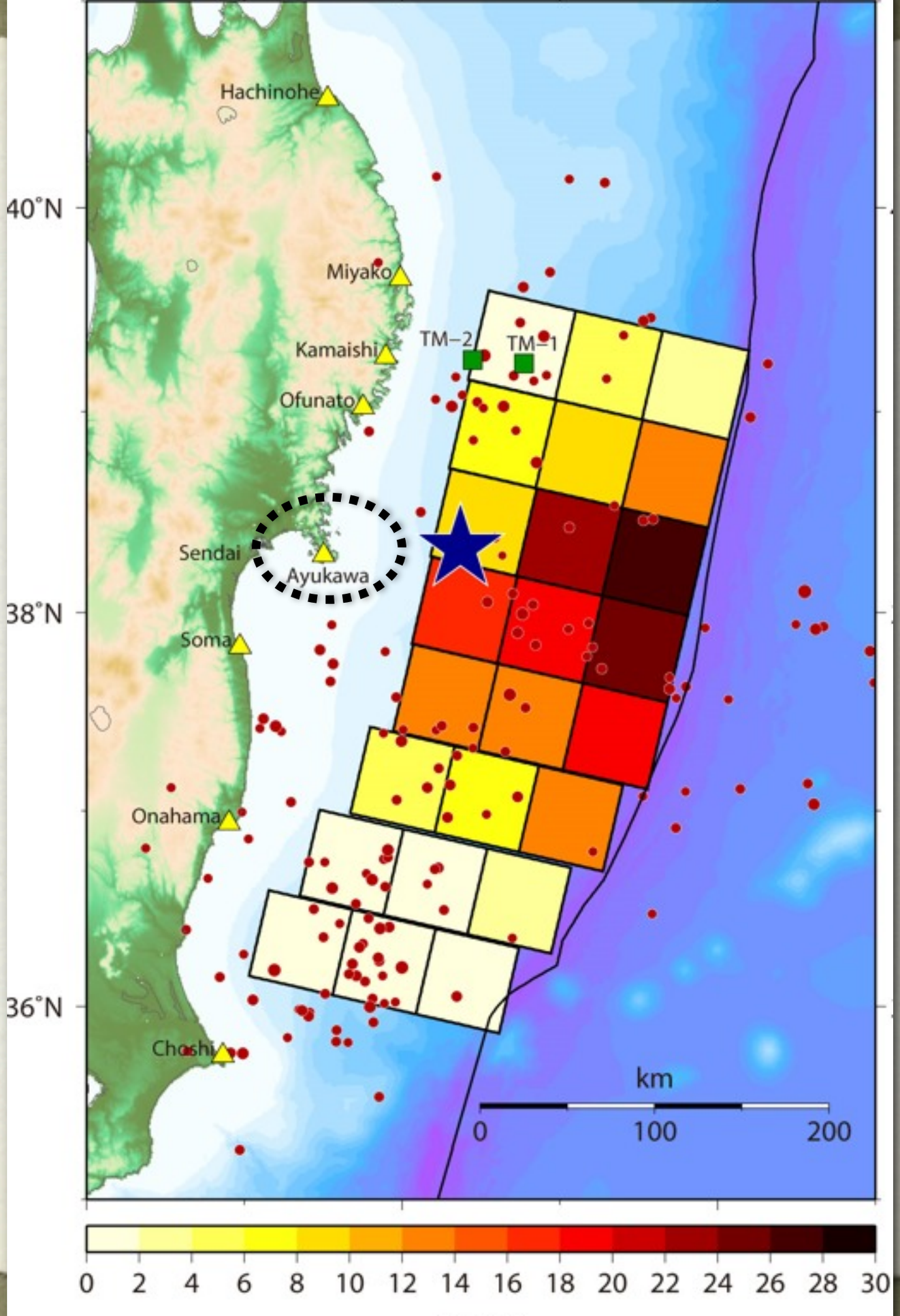
N. Shuto

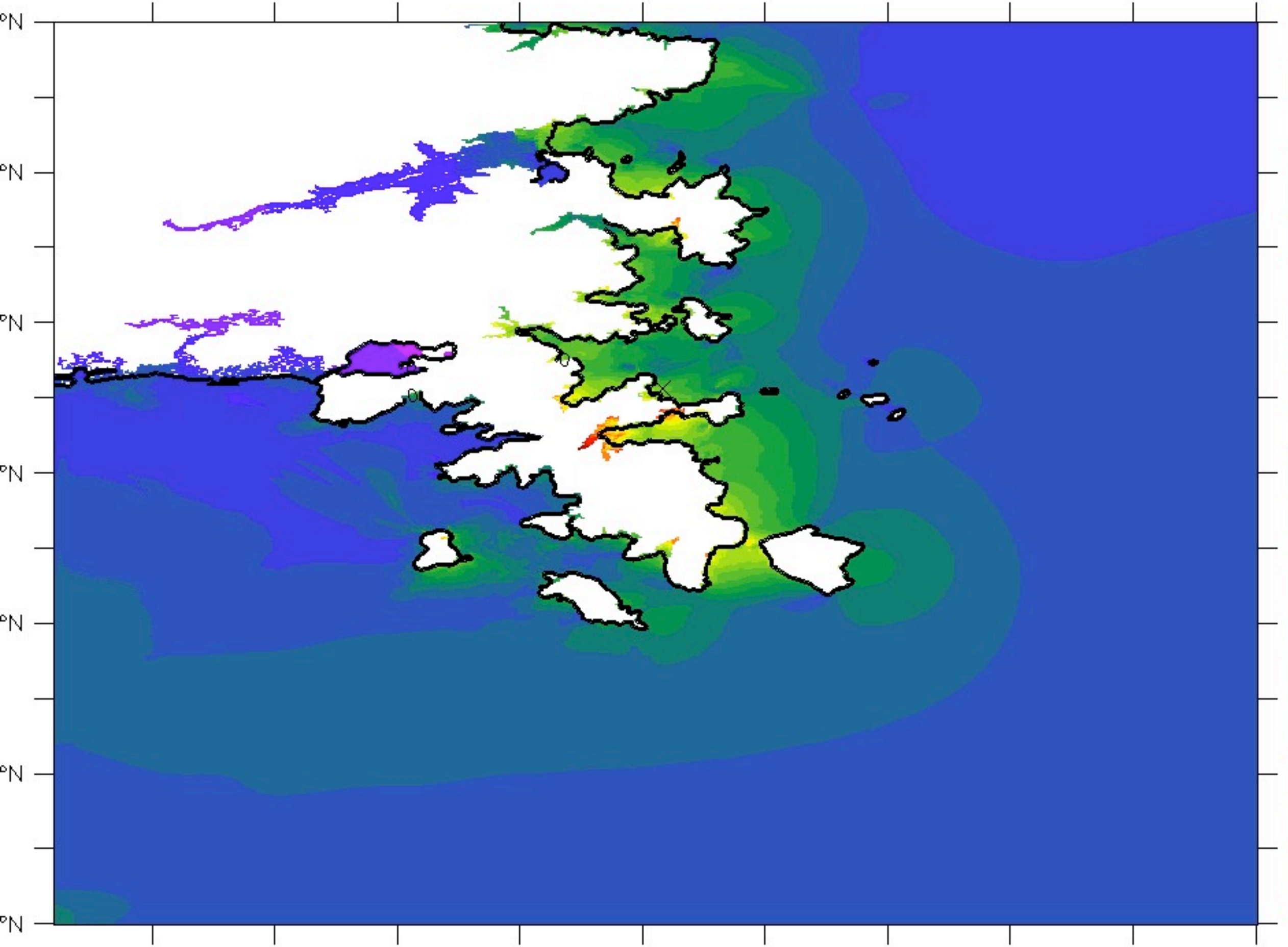
and

F. Imamura

Tsunami recorded at Japanese sea level stations



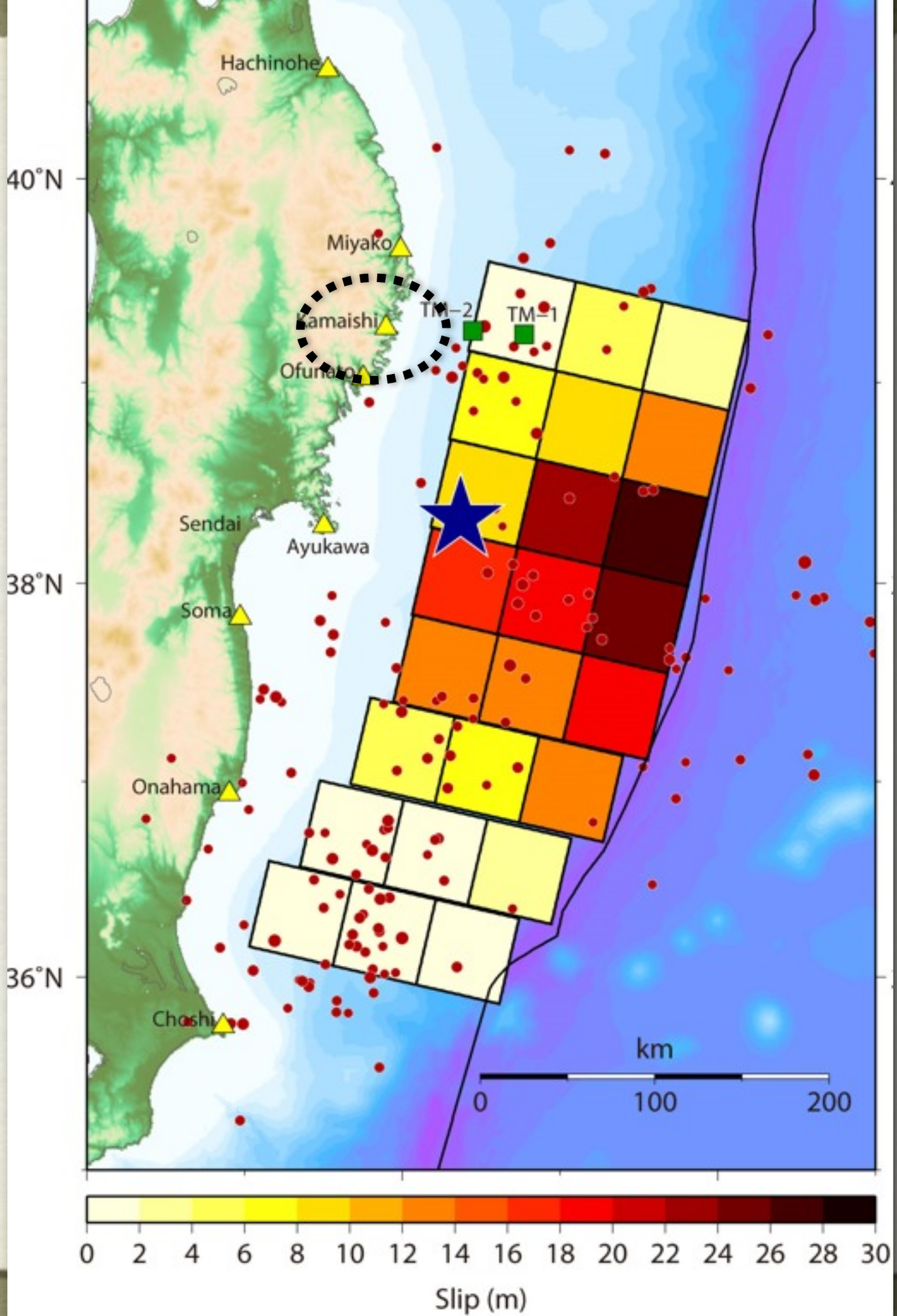

Hachinohe
Miyako
Kamaishi
Ofunato
Sendai
Ayukawa
Soma
Onahama
Choshi
TM−2
TM−1
40°N
38°N
36°N
km
0
100
200
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30


°N
°N
°N
°N
°N
°N

Natori Kashima Arahama Fujitsuka Daiichi Soma Sendai Yagawahama

Before 8/8 After

The city of Yagawahama in Miyagi in 2007 and after the earthquake. (Photo: Google Inc./Bloomberg)


Hachinohe
40°N
Miyako
Kamaishi
TM−2
TM−1
Ofunato
Sendai
Ayukawa
38°N
Soma
Onahama
36°N
Choshi
km
0
100
200
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Slip (m)

Kamiashi City

Before

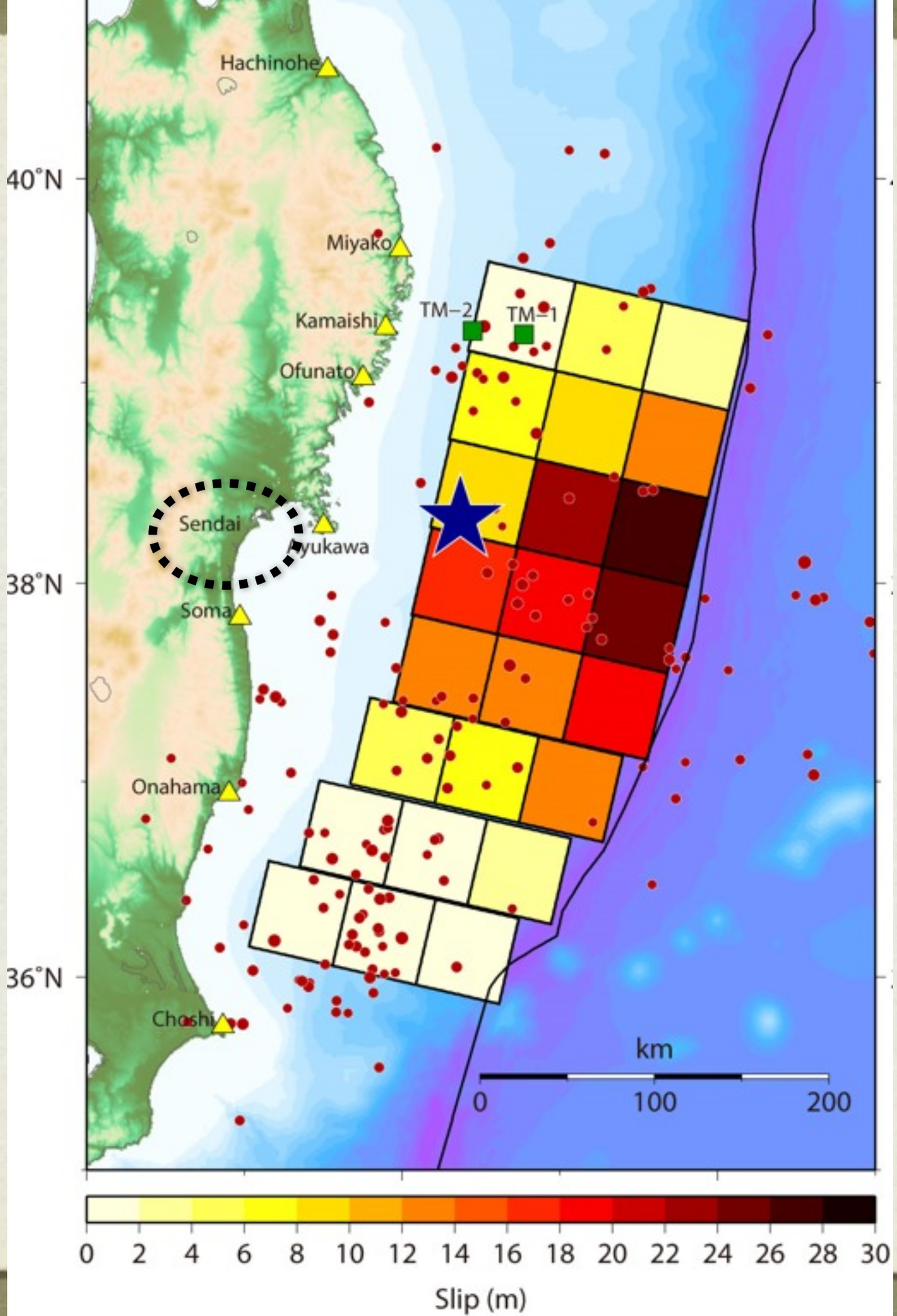
After

Kamaishi Video

Kamaishi City

Kamiashi City Seawall

Kamaishi City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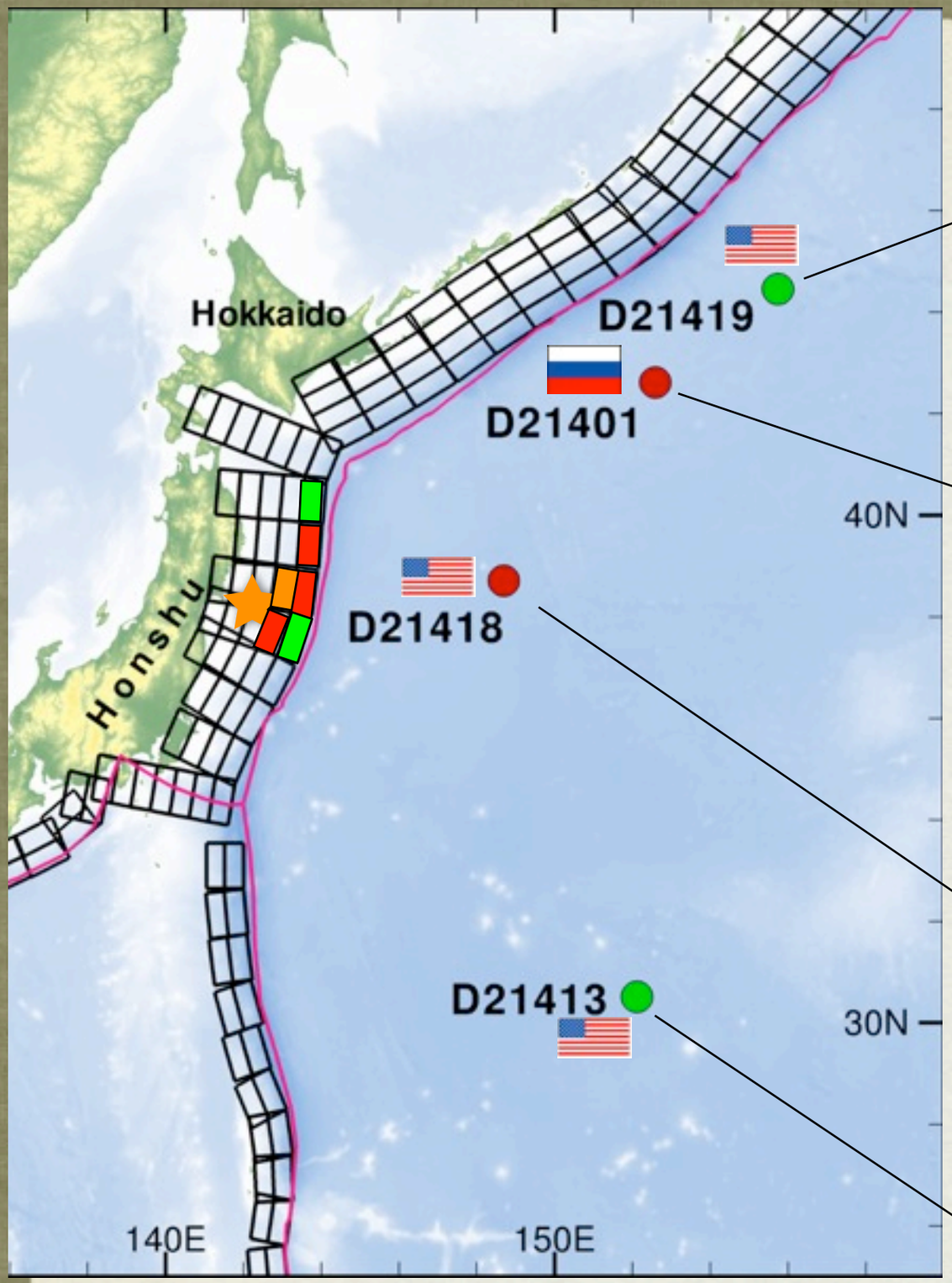
40°N
Miyako
Kamaishi
Ofunato
TM−2
TM−1
Sendai
Iwakawa
38°N
Soma
Onahama
36°N
Choshi
km
0
100
200
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Slip (m)

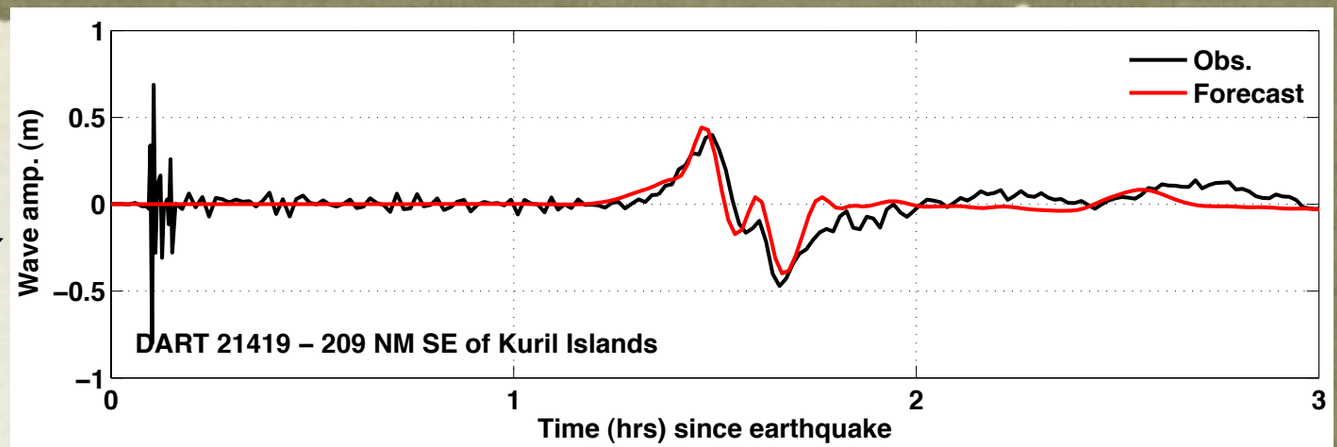
SENDAI

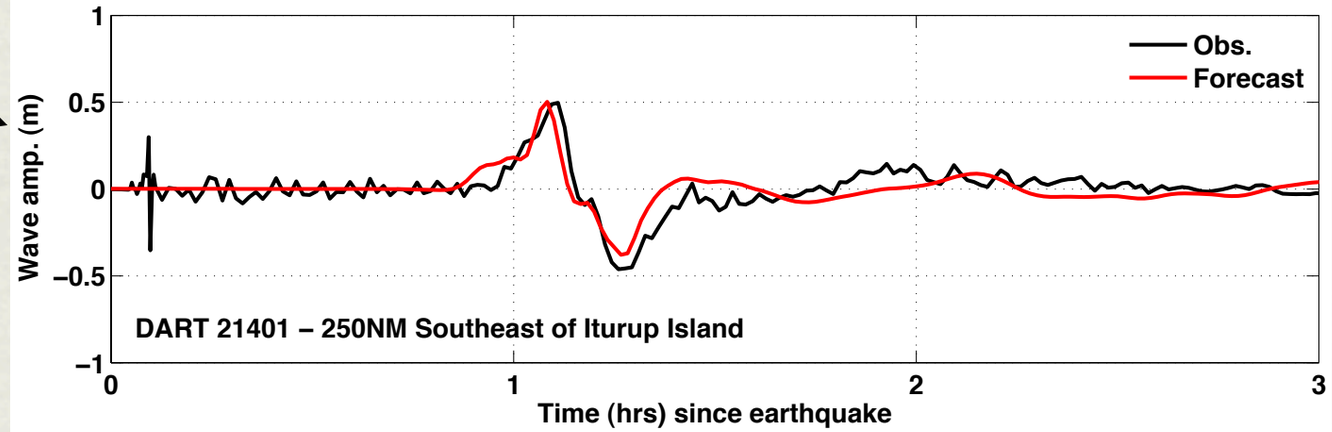
Sendai

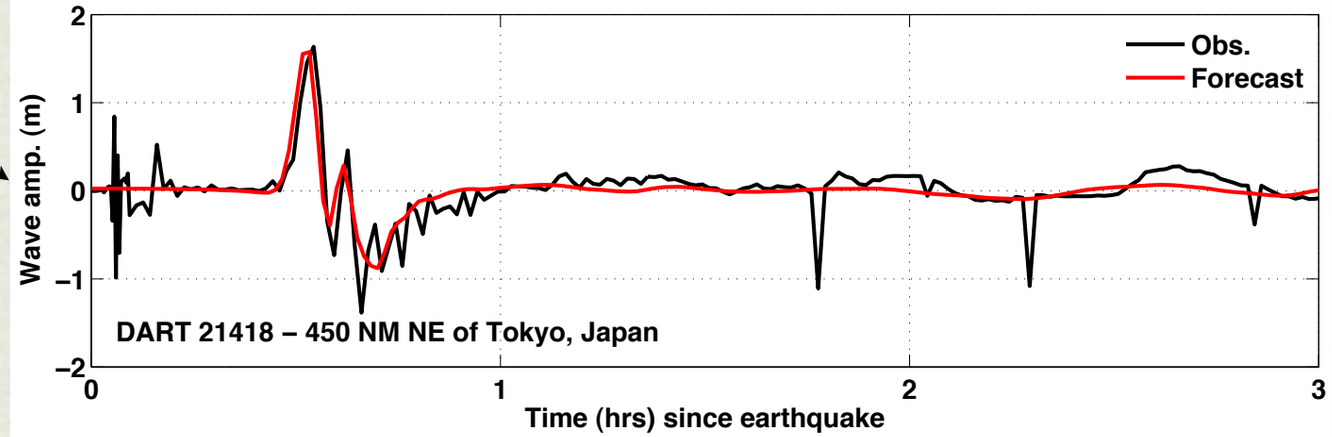
Sendai

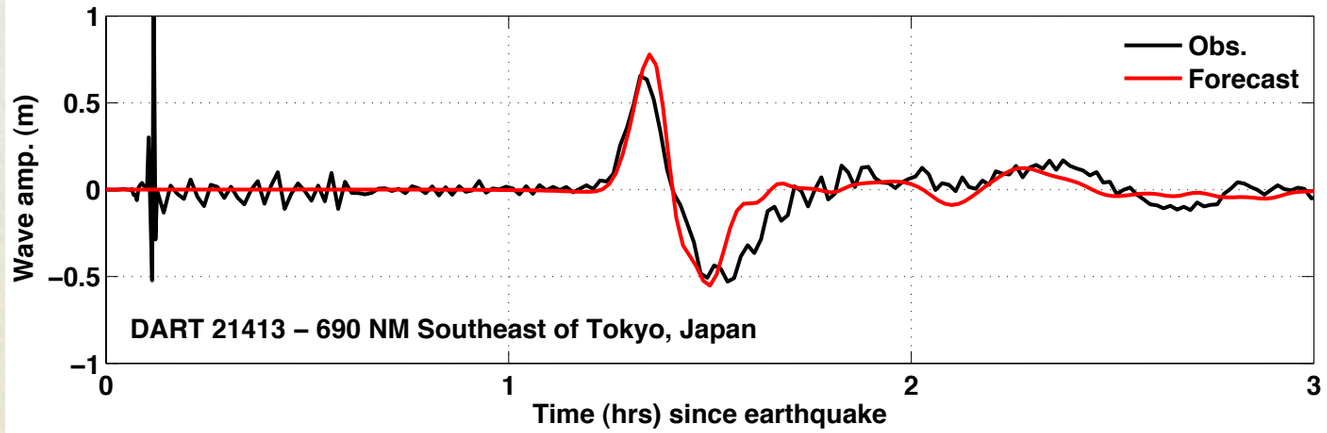
Sendai



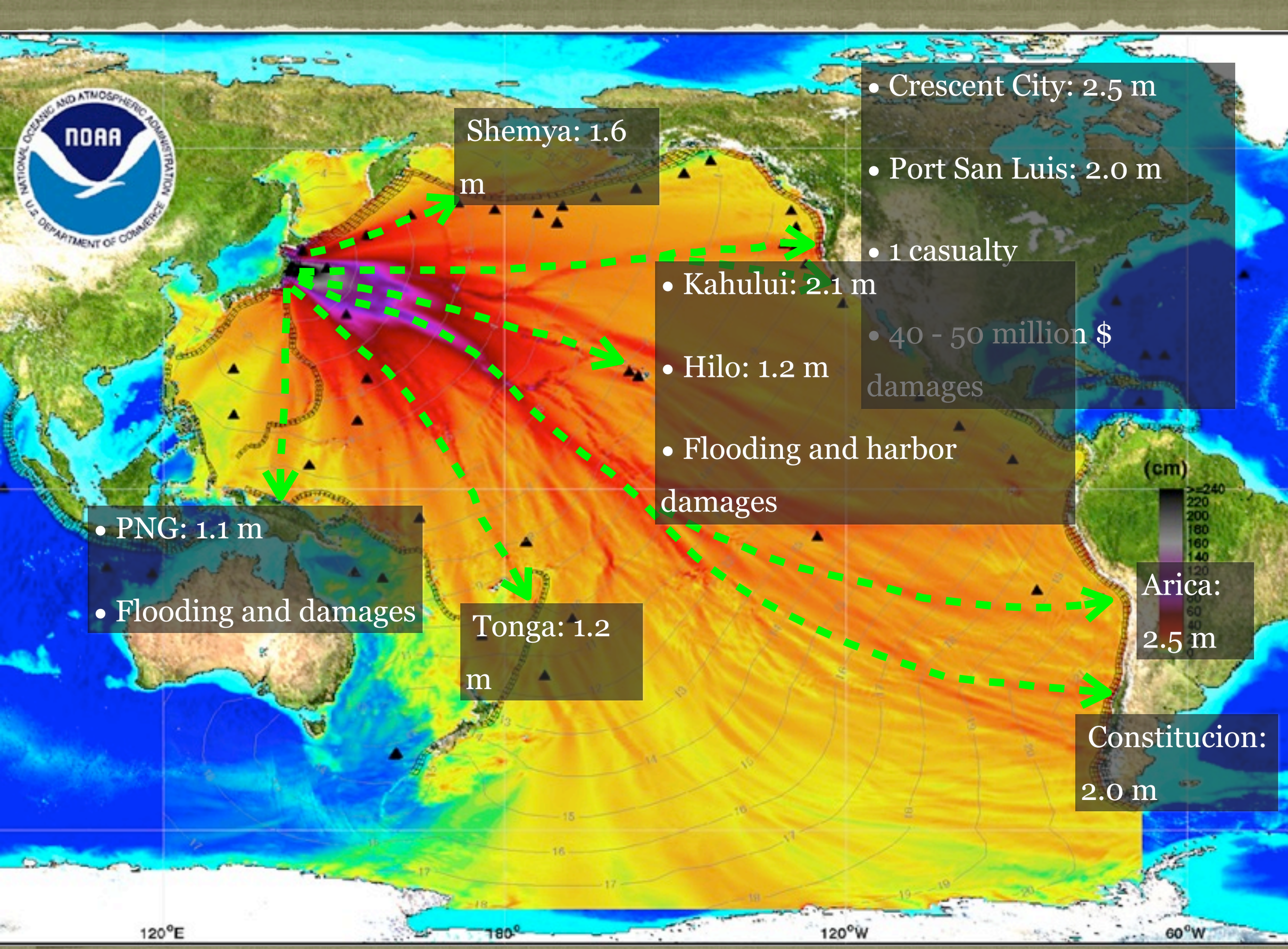


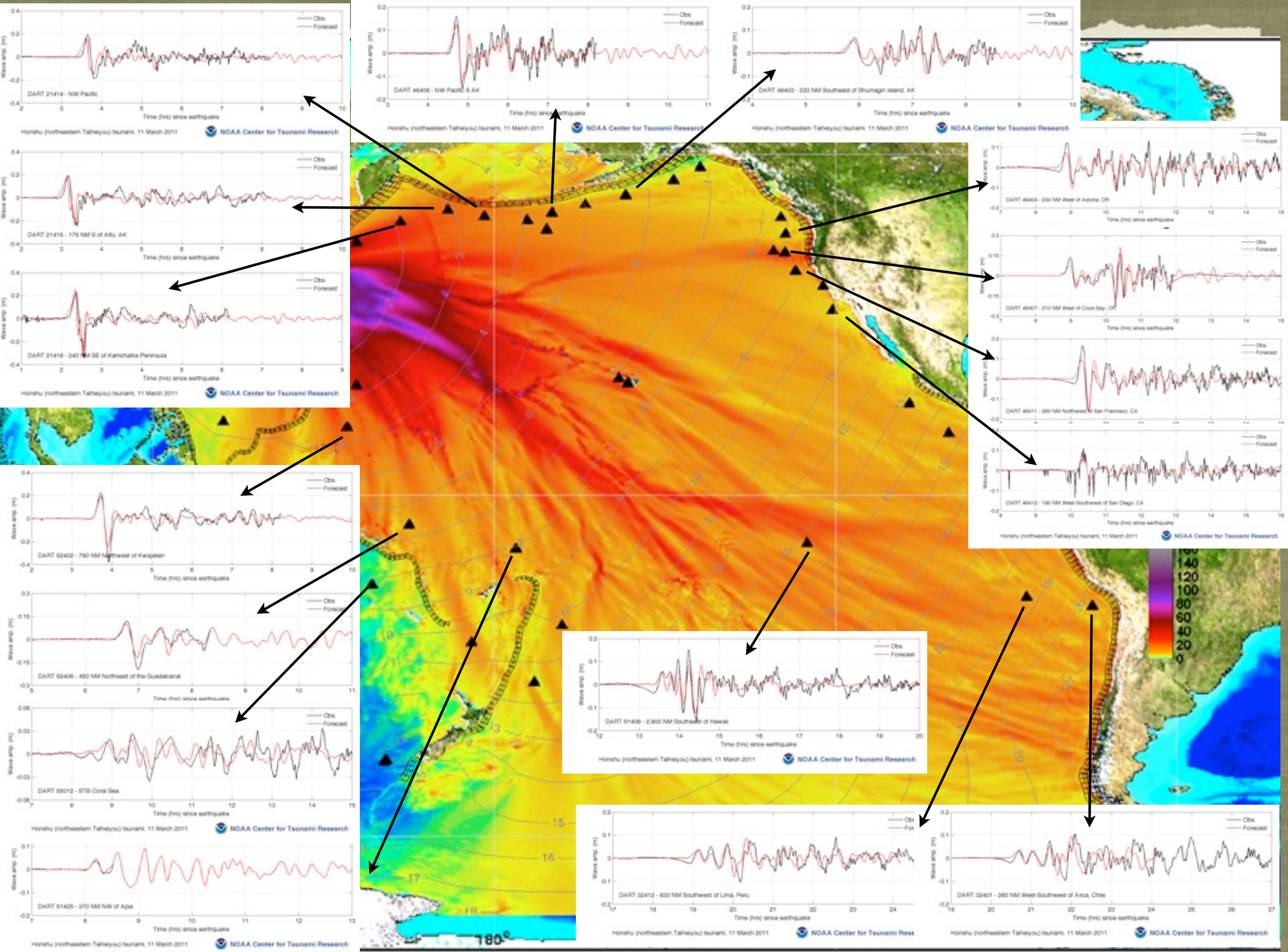




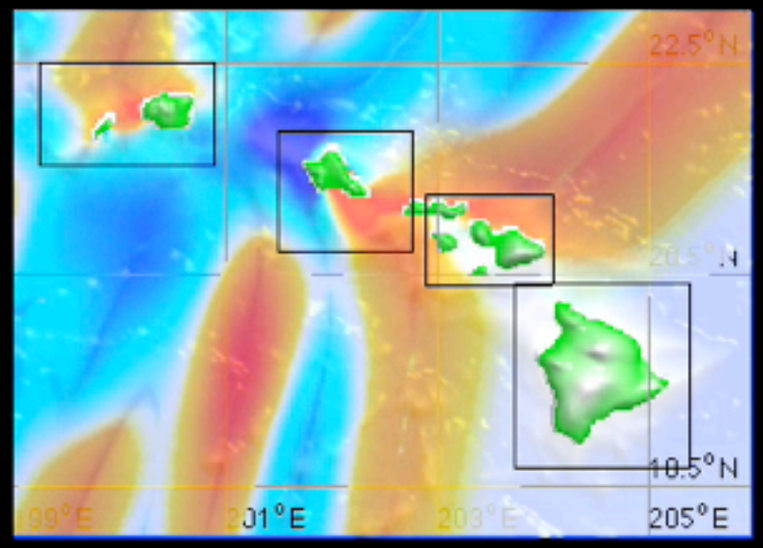


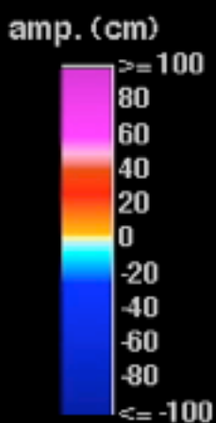
Inverting tsunami source from DART buoy measurements


Shemya: 1.6 m
• Crescent City: 2.5 m
• Port San Luis: 2.0 m
• 1 casualty
• Kahului: 2.1 m
• 40 - 50 million $ damages
• Hilo: 1.2 m
• Flooding and harbor damages
• PNG: 1.1 m
• Flooding and damages
Tonga: 1.2 m
Arica: 2.5 m
Constitucion: 2.0 m
(cm)
>=240
220
200
180
160
140
120
100
80
60
40
0
120°E
180°
120°W
60°W


DART 21414 - NW Pacific
DART 46406 - NW Pacific S AK
DART 46403 - 220 NM Southeast of Shumagin Island, AK
DART 21415 - 175 NM S of Attu, AK
DART 21416 - 240 NM SE of Kamchatka Peninsula
DART 46404 - 230 NM West of Astoria, OR
DART 46407 - 210 NM West of Coos Bay, OR
DART 46411 - 260 NM Northwest of San Francisco, CA
DART 46412 - 190 NM West-Southwest of San Diego, CA
DART 52402 - 790 NM Northwest of Kwajalein
DART 52406 - 450 NM Northeast of the Guadalcanal
DART 55012 - STB Coral Sea
DART 51425 - 370 NM NW of Apia
DART 51406 - 2,900 NM Southeast of Hawaii
DART 32412 - 630 NM Southwest of Lima, Peru
DART 32401 - 260 NM West-Southwest of Arica, Chile
Obs.
Forecast
Wave amp. (m)
Time (hrs) since earthquake
Honshu (northeastern Taiheiyou) tsunami, 11 March 2011
NOAA Center for Tsunami Research
180°

NCTR





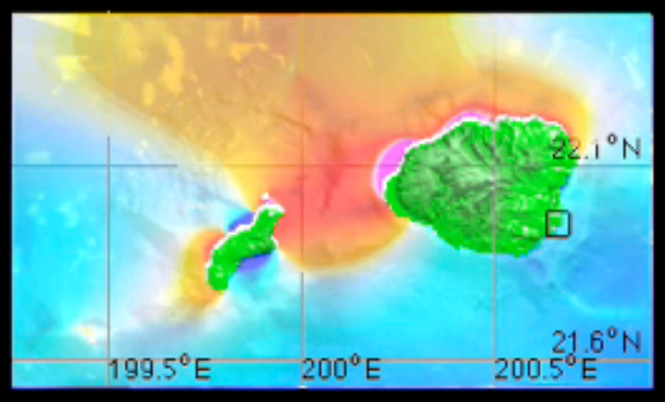
Honshu Tsunami

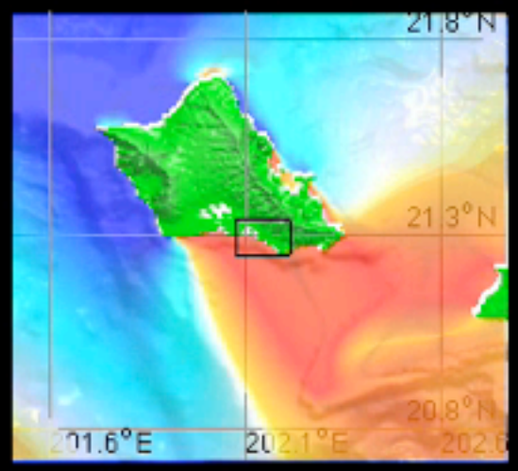
2011 03 11 05:46:23 UTC

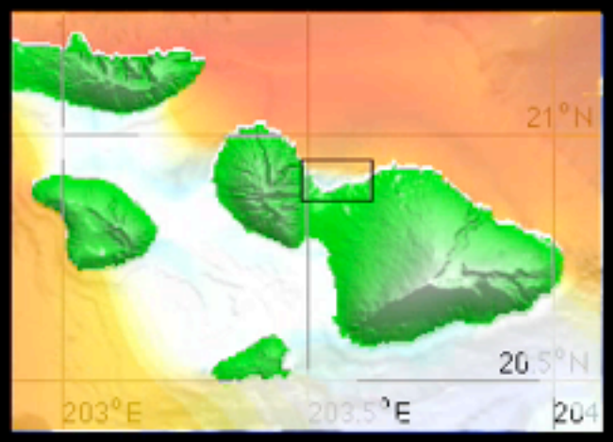
07h33m46s

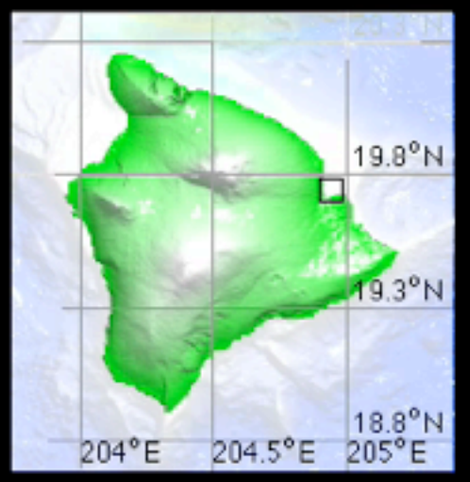
forecast

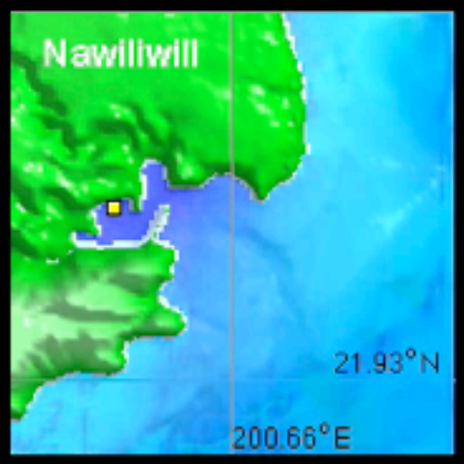
observation

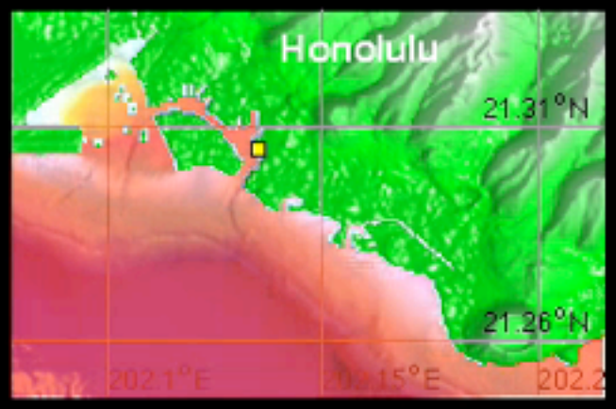


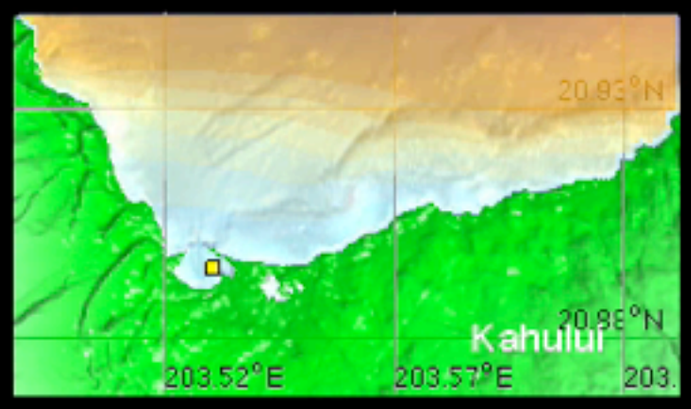


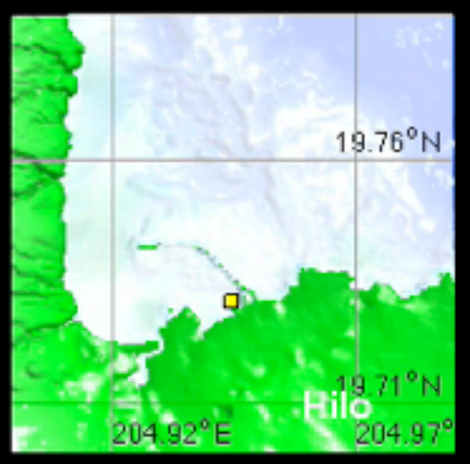


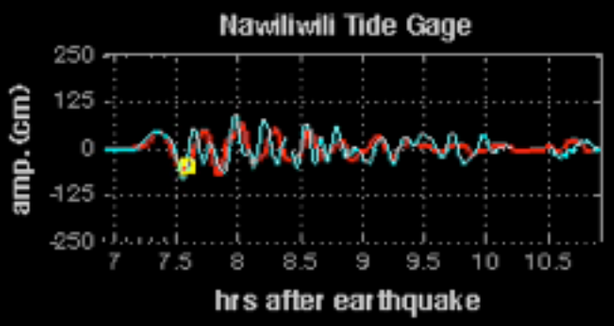


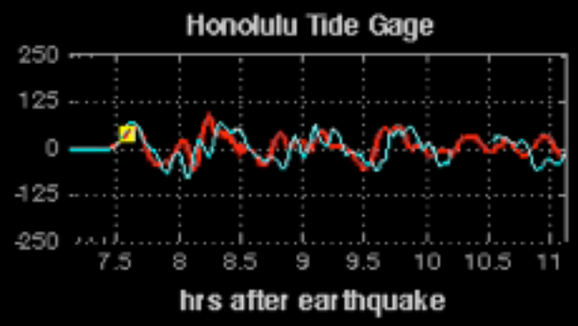


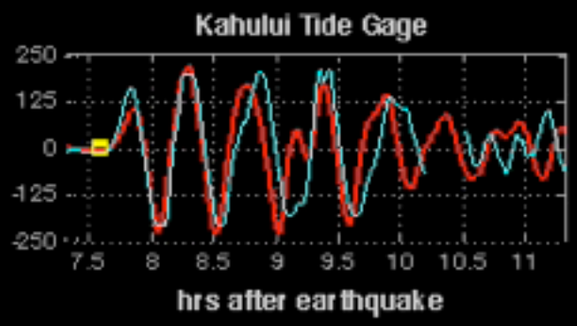


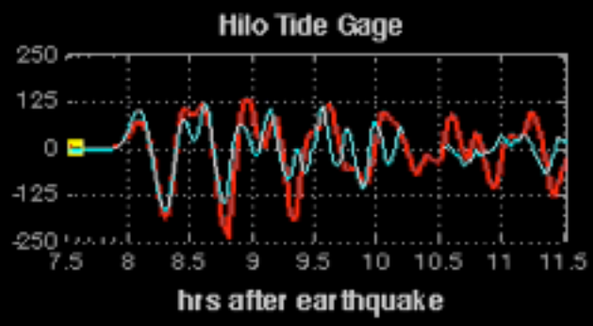




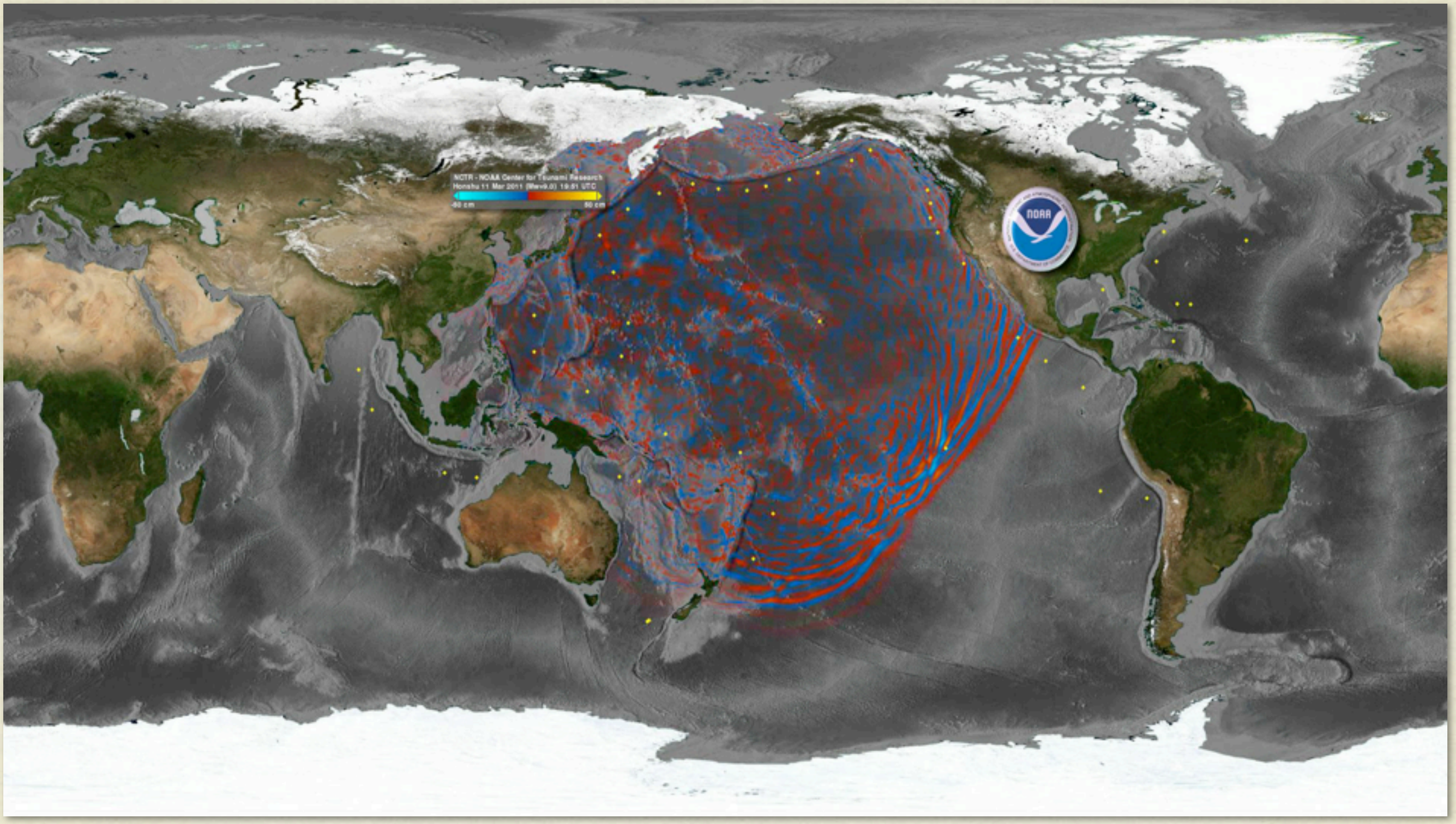




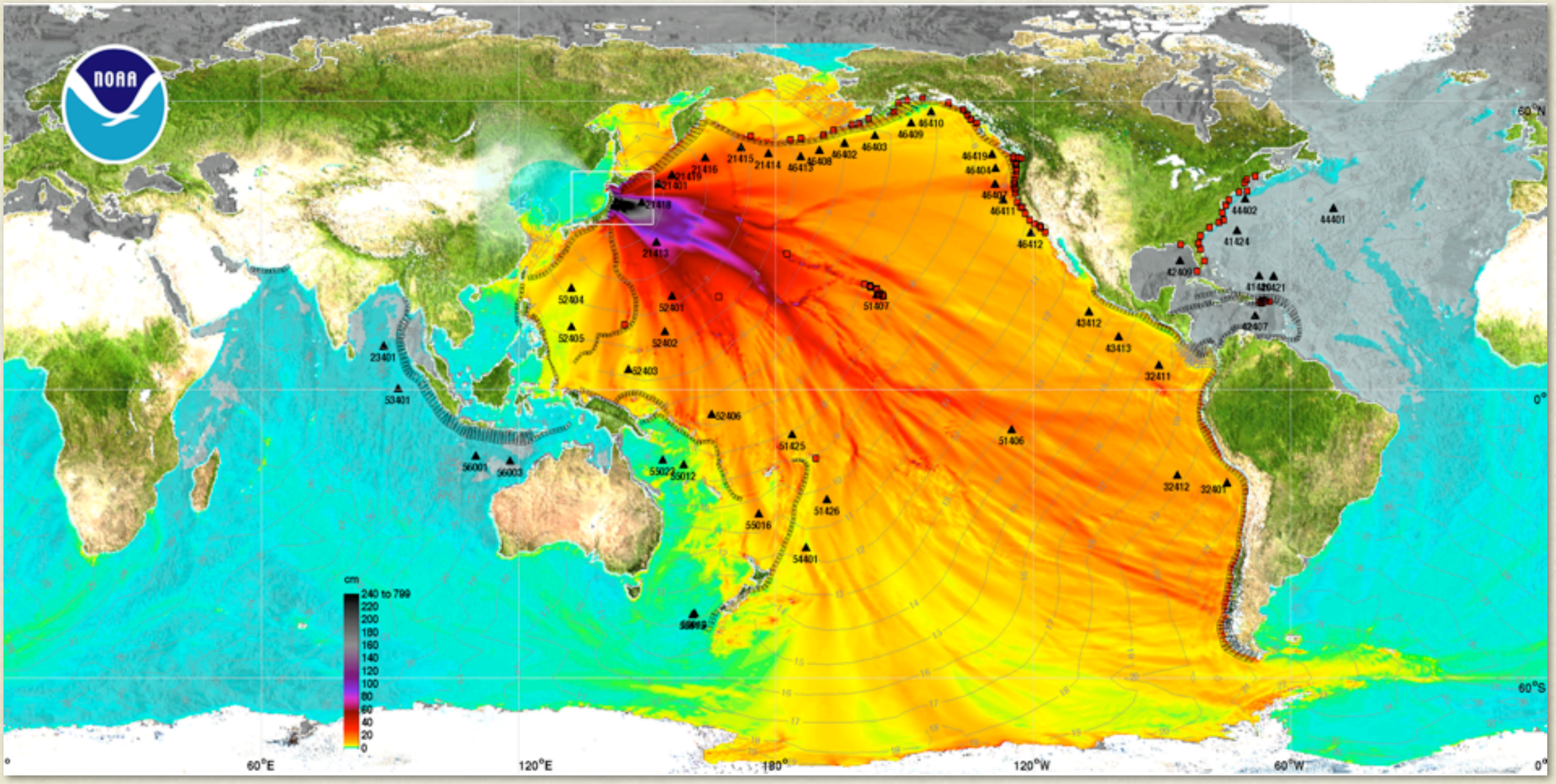




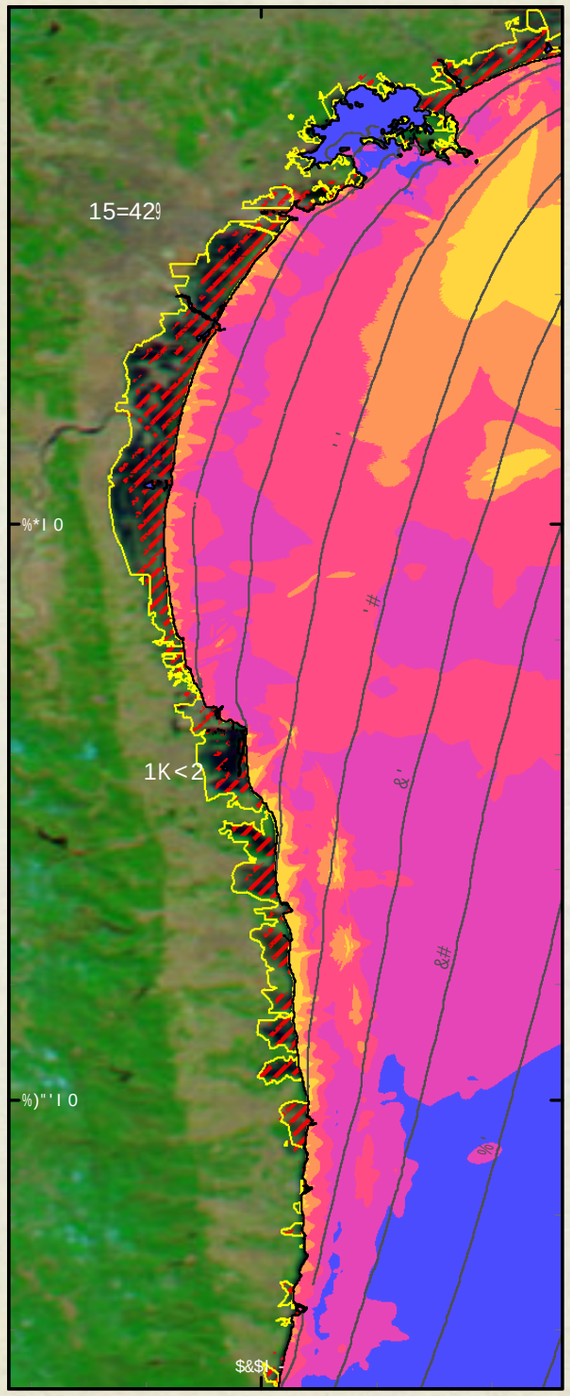
MODEL FORECAST



MODEL FORECAST



LOCAL FORECAST TEST



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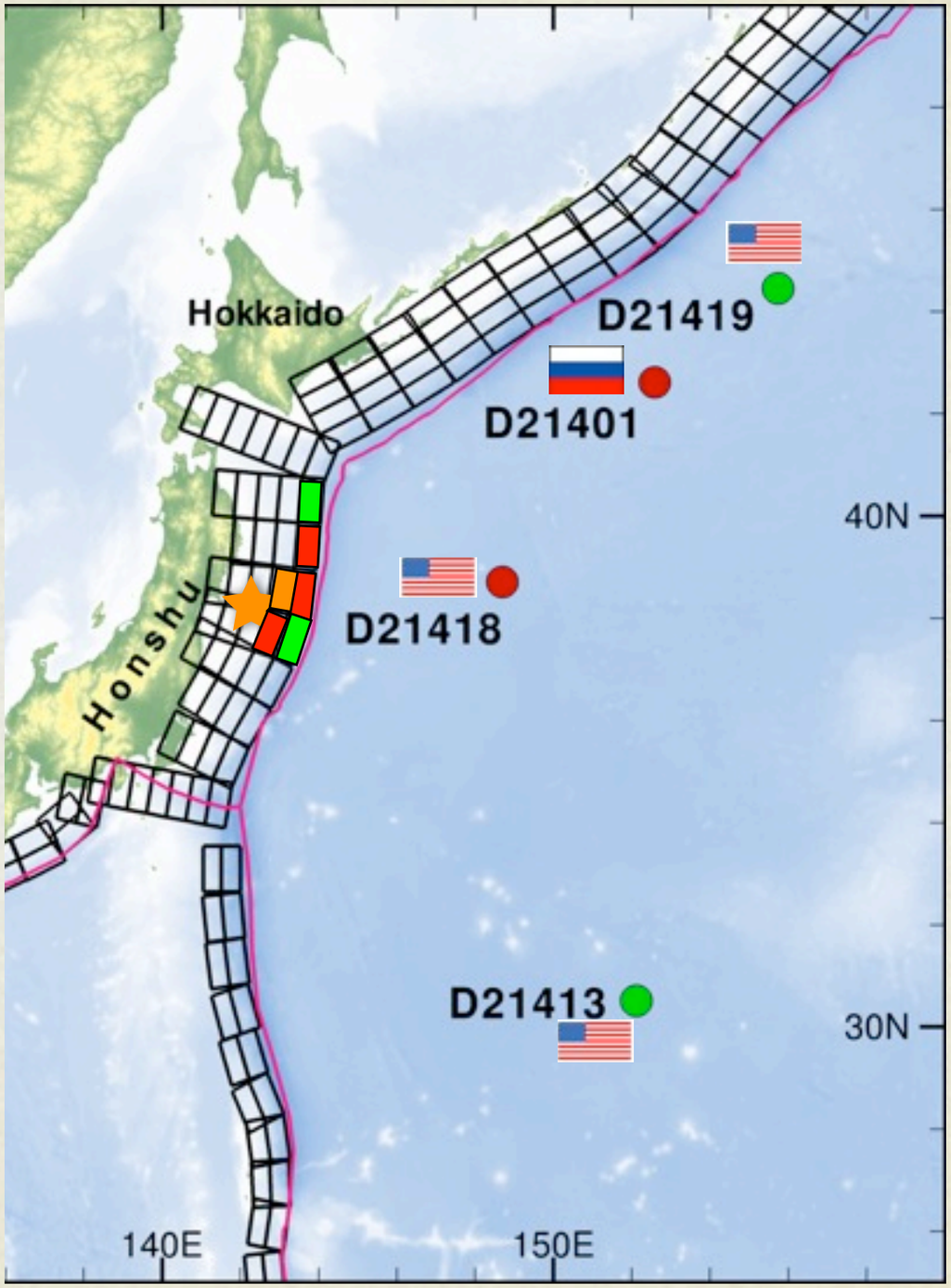

DISCUSSION

- PMEL Forecast Method performed “better than expected”
  - DART data was the first and only tsunami data for hours after the earthquake
  - Quality of DART data in the near-filed led to a robust forecast quickly
  - Model forecast performed well
  - ISSUE: tide predictions are necessary for accurate inundation predictions
- Implications for Local (near-field) forecast
- Increasing interest in site-specific forecasts (NRC, NAVY, Local EM, International…)
- What is the role of warning and forecast for near-field coastlines?