Development of a GNSS-Enhanced Tsunami Early Warning System

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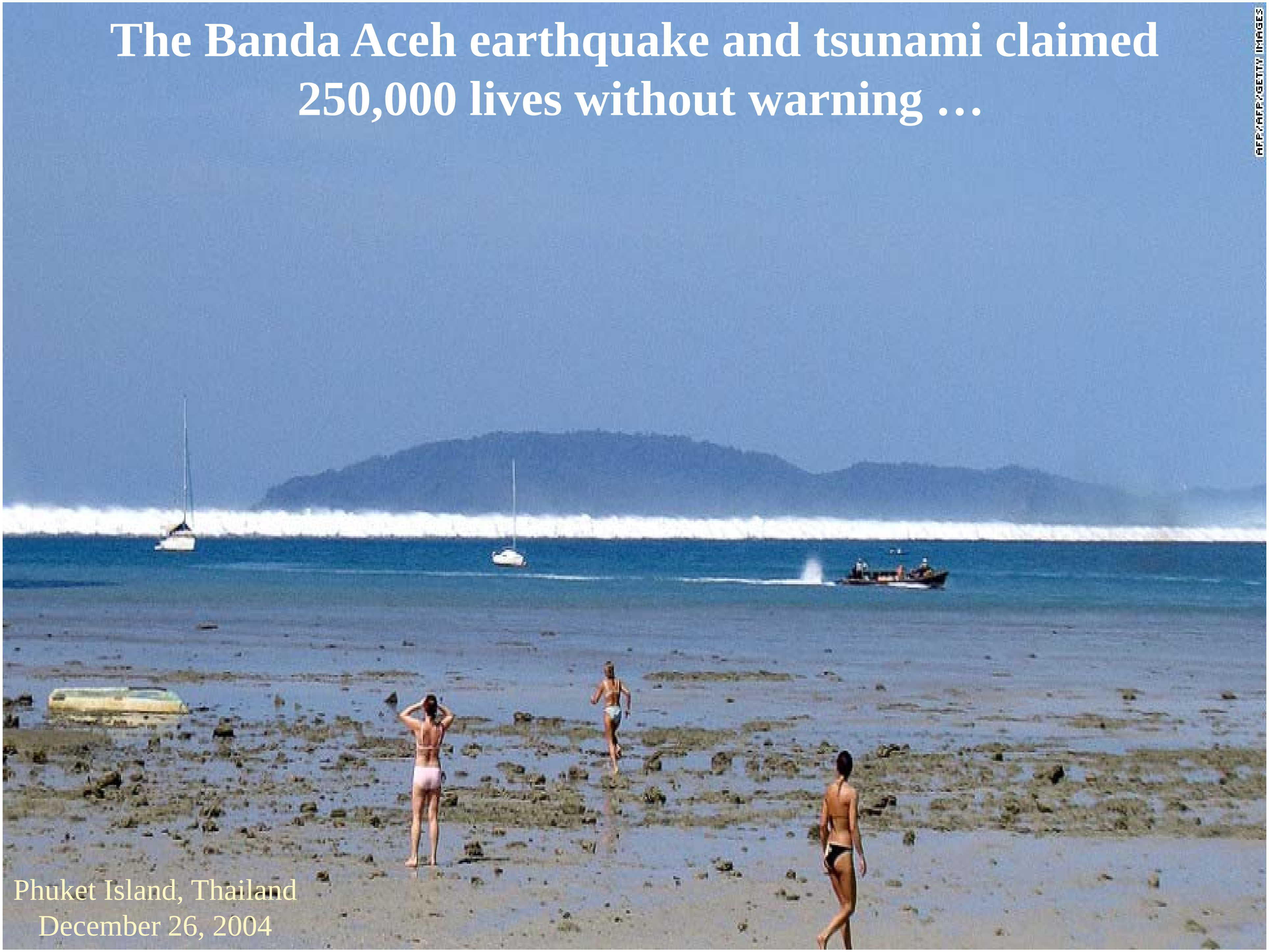
Dr. Yehuda Bock *UC San Diego*
Dr. David Green *NASA Headquarters*
Dr. Tony Song *Jet Propulsion Laboratory*
Dr. Attila Komjathy *Jet Propulsion Laboratory*
Plus many many more.

The Banda Aceh earthquake and tsunami claimed 250,000 lives without warning …



Phuket Island, Thailand
December 26, 2004

What questions are asked when there is an earthquake in tsunami prone regions?

Where was the earthquake? **Lat/Lon/Depth**

How large was it? **Accurate Magnitude**

Could the earthquake generate a tsunami?
Nature of earthquake – thrust, normal, strike-slip, oblique

Was there a tsunami? **DART buoys, other**

How much time do communities have before the tsunami makes landfall? **Tsunami energy modeling**

How far will the tsunami come onshore?

How deep will the water be?
Subsidence measurements and inundation modeling

Real-time GNSS can help address many of these questions for most earthquakes

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Subsidence measurements and inundation modeling

Measurement of the land surface deformation
Measurement perturbations in the ionosphere
Improves latency and accuracy of models
Next generation models include coastal subsidence

} Real-Time GNSS

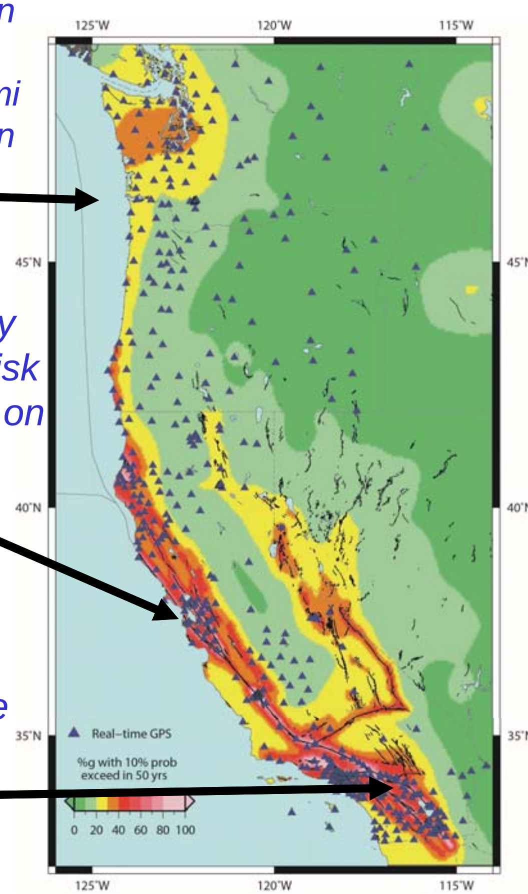
The READI Working Group

- **R**eal-Time **E**arthquake **A**nalysis for **D**isaster m**I**tigation network (READI): ~750 GPS stations, a NASA driven project
- Super set of GNSS networks maintained by (sorted according to largest to smallest number of stations):
  - UNAVCO/PBO
  - CWU/PANGA
  - USGS/Pasadena-SCIGN & Menlo Park
  - UC Berkeley/BARD
  - Scripps Institution of Oceanography/SCIGN
  - JPL/Caltech

Cascadia Subduction Zone – Mw 9.0 earthquake & tsunami similar to 2011 Japan events

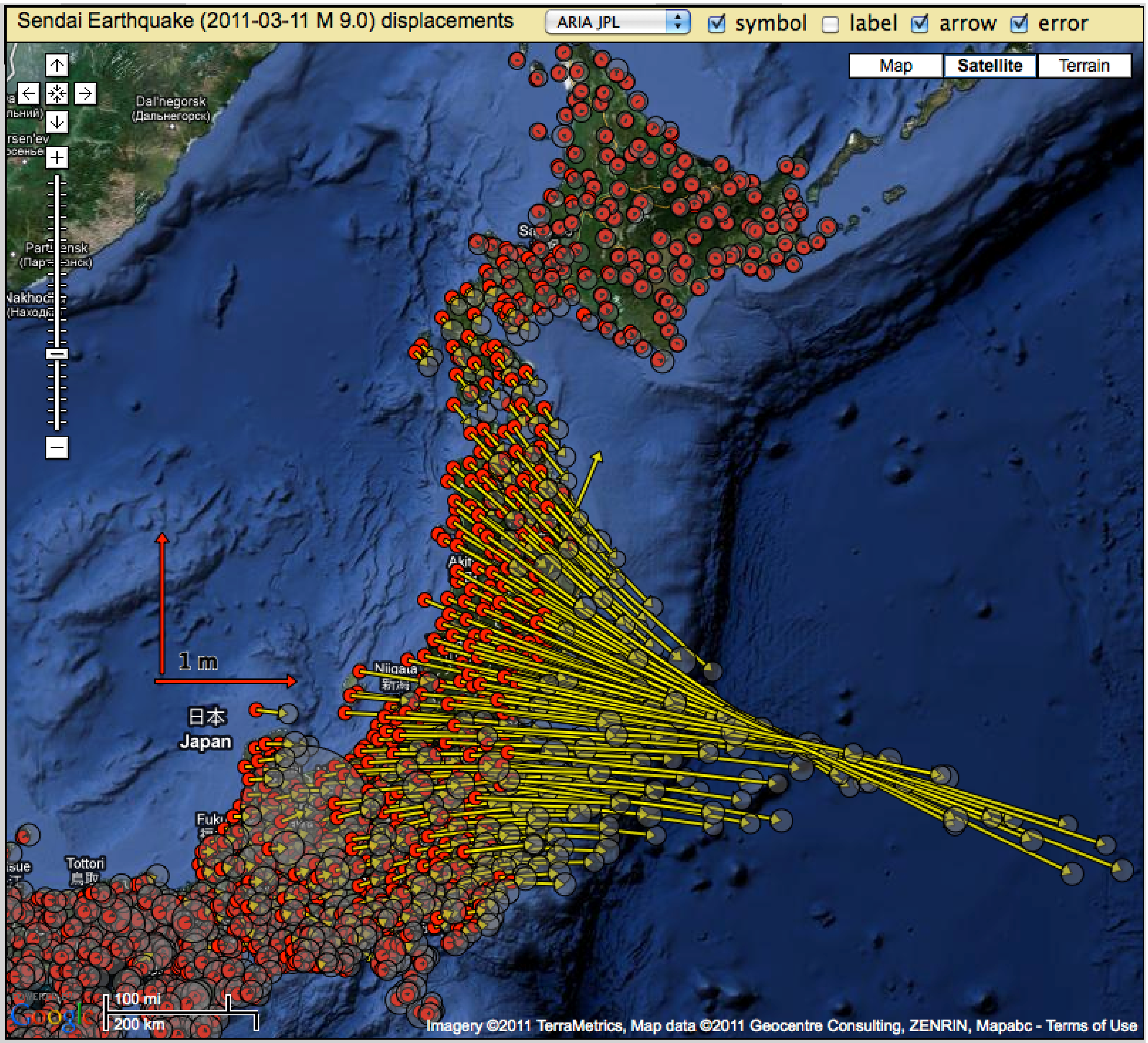
San Francisco Bay Area – Increasing risk of large earthquake on Hayward fault

Southern San Andreas fault – overdue for large earthquake



Jet Propulsion Laboratory
California Institute of Technology

GNSS Earthquake and Tsunami Early Warning



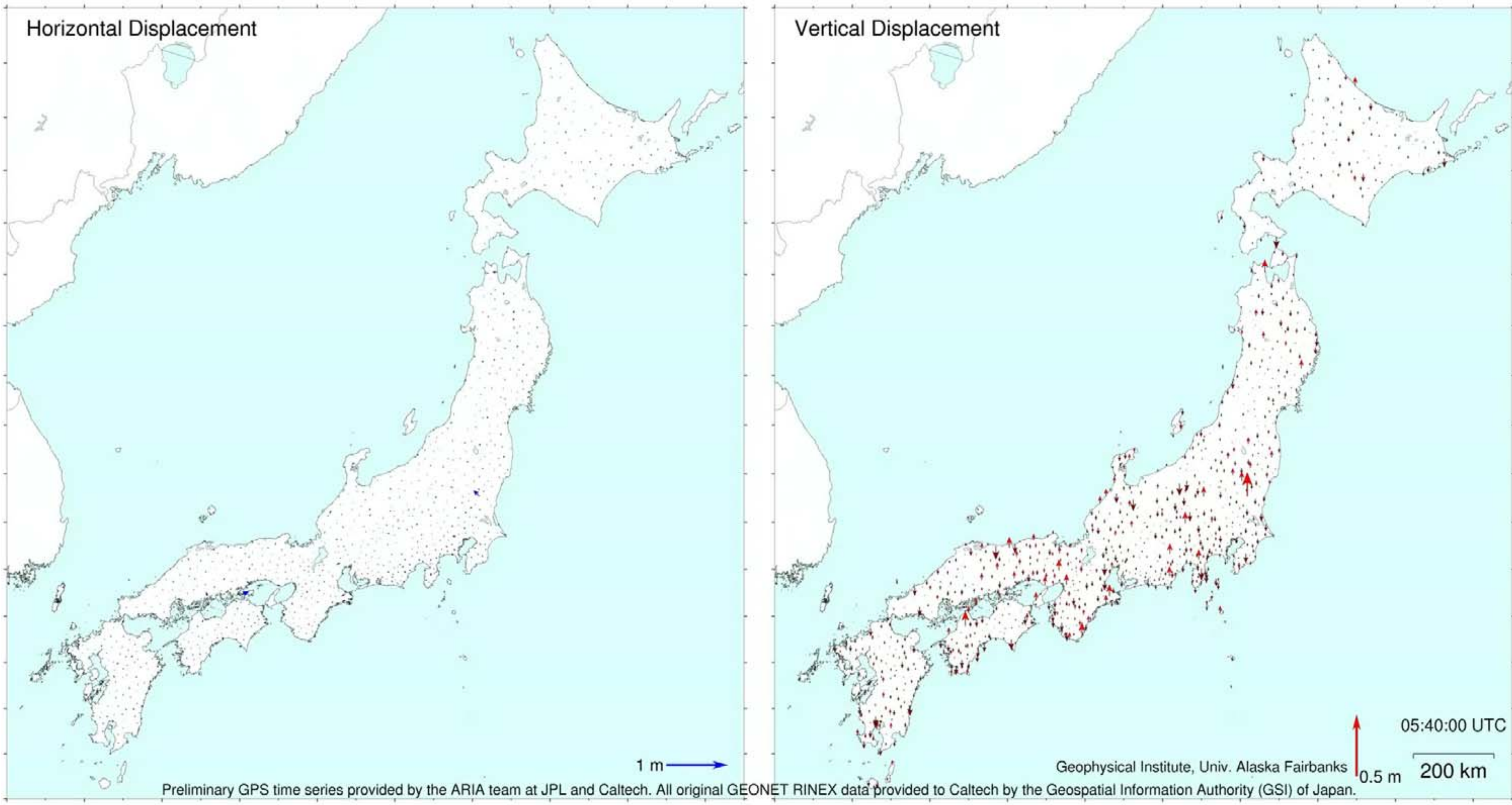
Data courtesy of the Geospatial Information Authority of Japan GSI

GEONET GPS Array

Great East Japan Earthquake and Tsunami

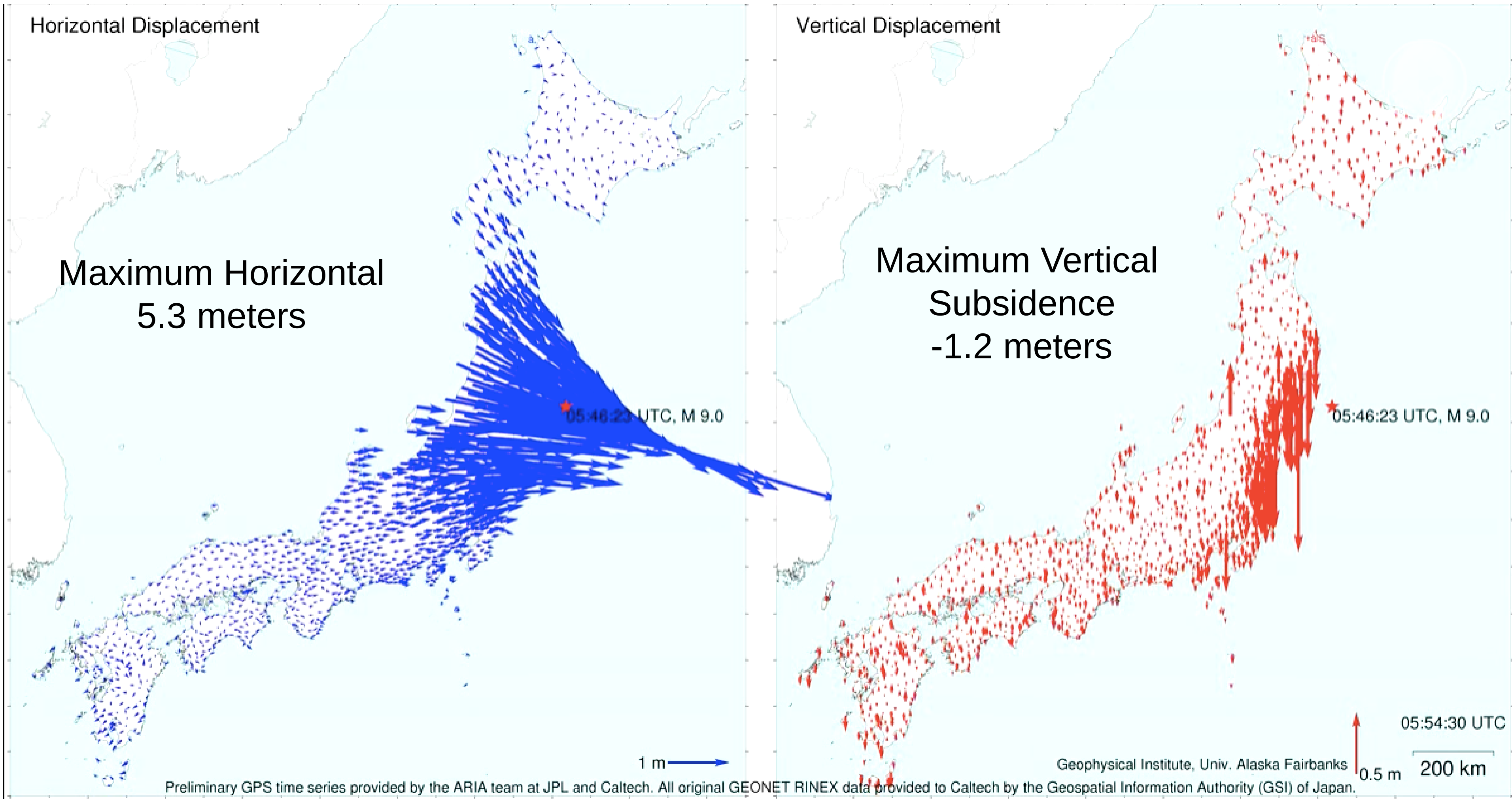
Maximum GPS displacement ~5 meters

GSI GEONET GPS Array Earthquake Displacement Pattern



http://gps.alaska.edu/ronni/sendai2011.html: Ronni Grapenthin

GSI GEONET GPS Array Earthquake Displacement Pattern



http://gps.alaska.edu/ronni/sendai2011.html: Ronni Grapenthin

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AFP/AFP/GETTY IMAGES

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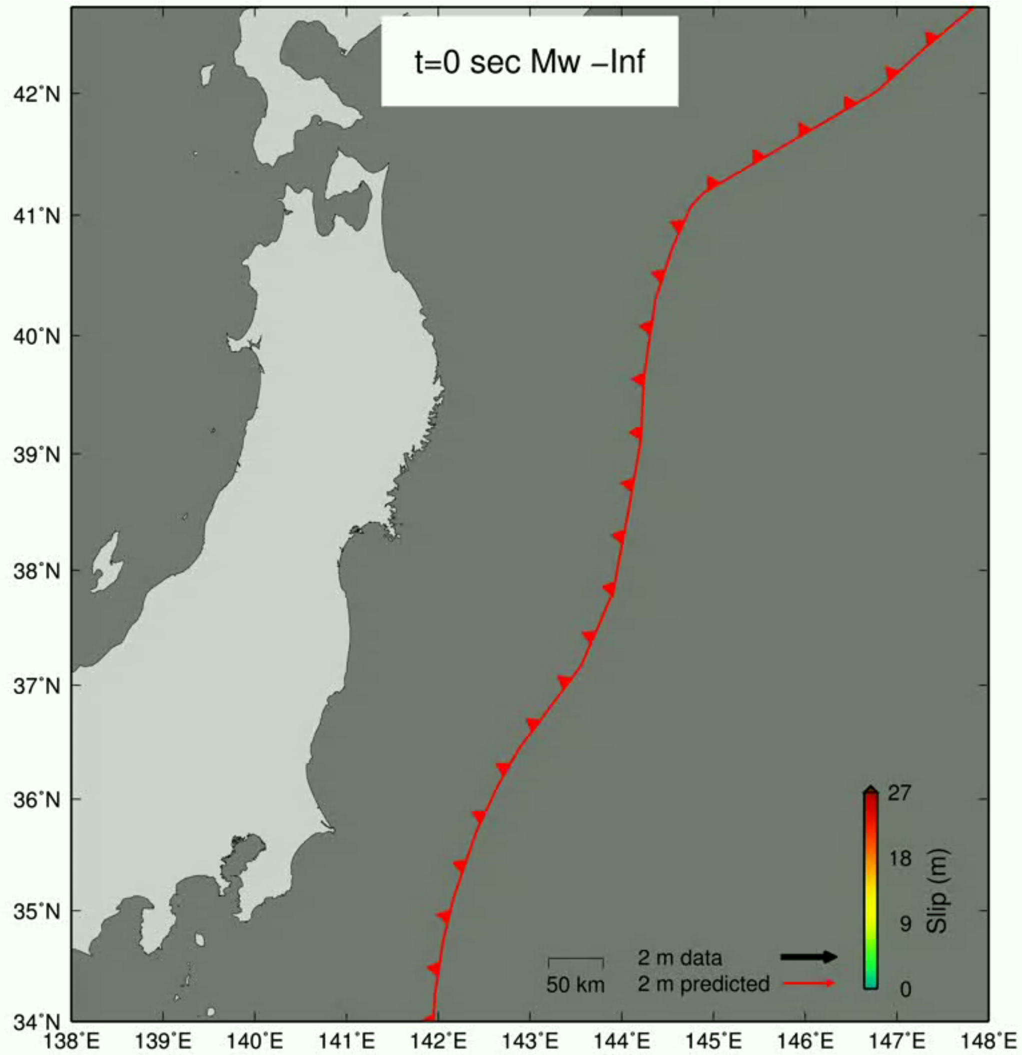
Real-Time GNSS for Rapid Earthquake Magnitude Determination and Fault Slip Distribution



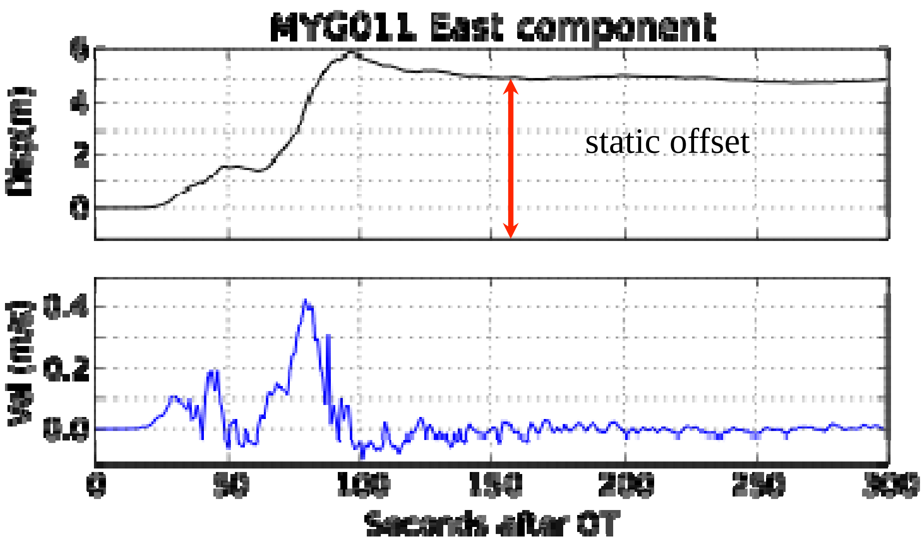
Case 1 – model determines fault location

S. E. Minson et al, 2013
JGR

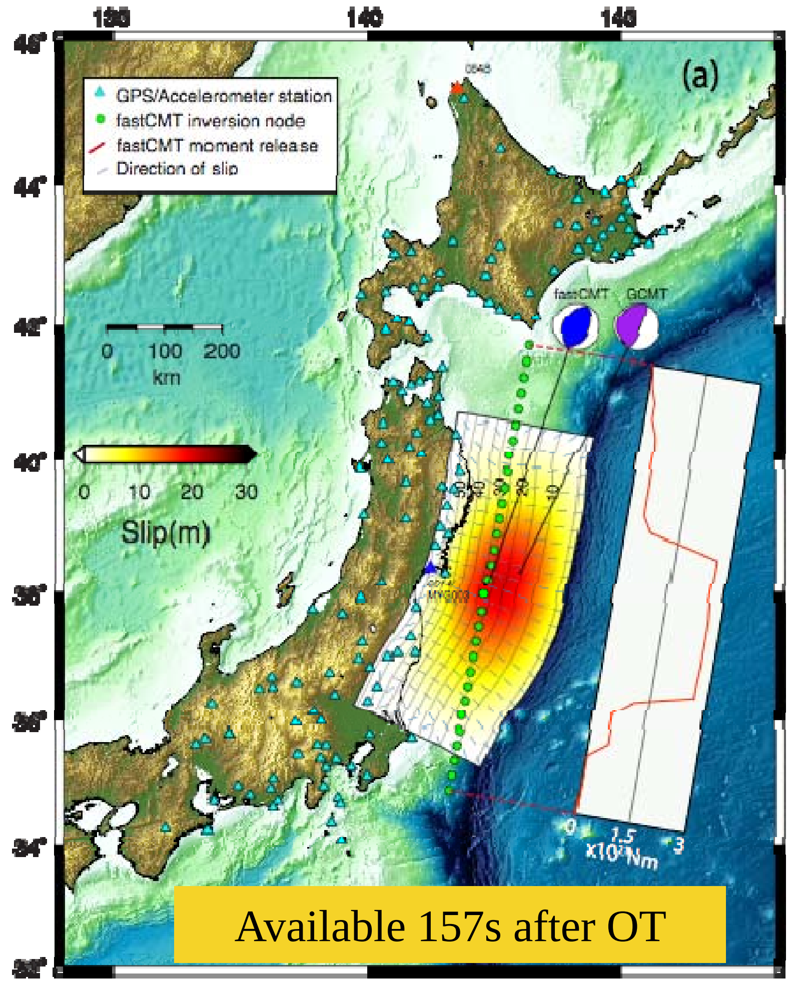
GNSS Static Slip Model 157 seconds

- Magnitude estimates from seismic data-only tend to saturate for large events.
- Regional seismic data are band limited, they cannot adequately capture long periods in real-time.

  - Create rapid models with the GNSS <u>static</u> field
    - **Static = simple and fast**



2011 Mw 9 Great East Japan Earthquake

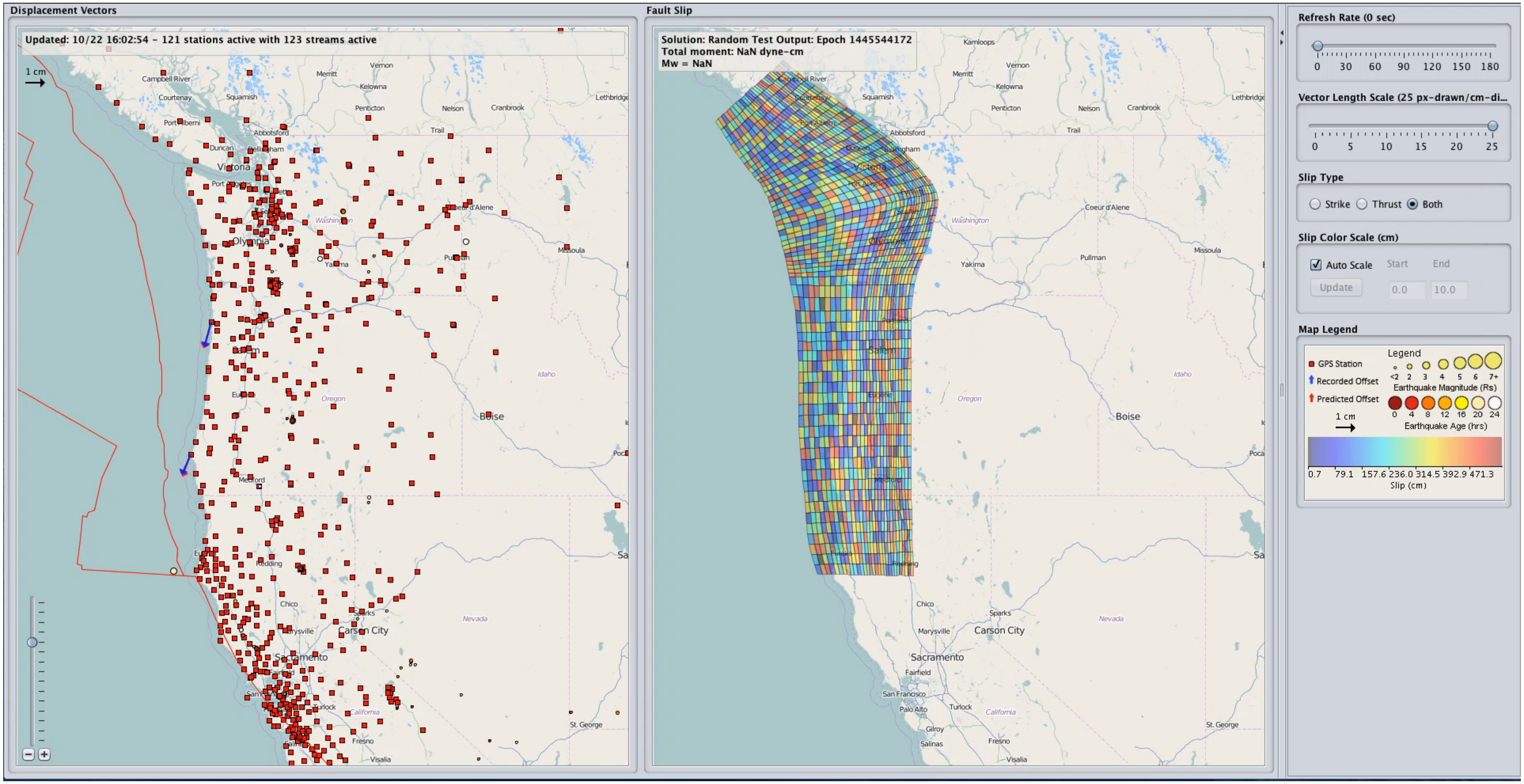


Source: Melgar et al., GRL, 2013

GNSS Earthquake Source Model for a Predefined Fault

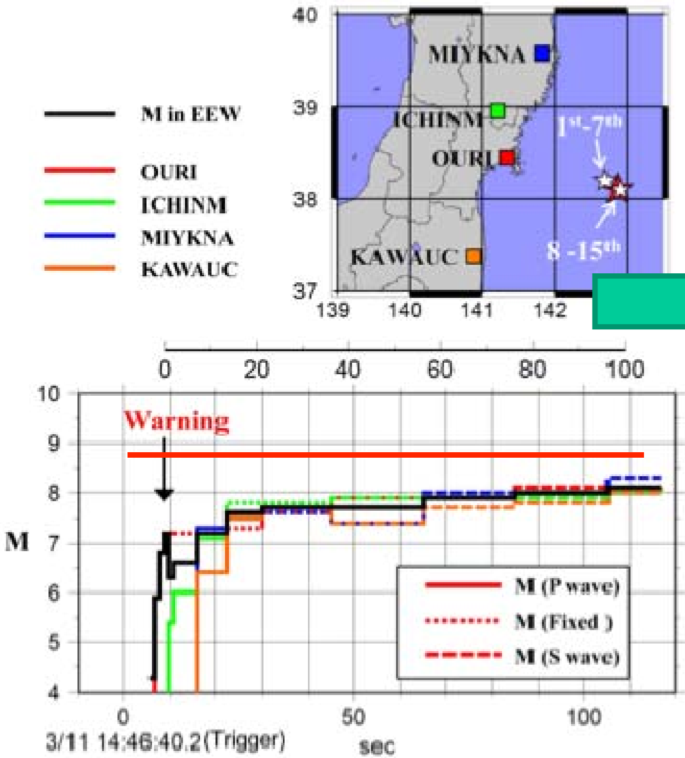
Case 2 –Real-time displacements on a fixed fault surface

Prototype running in real-time on a fixed fault surface

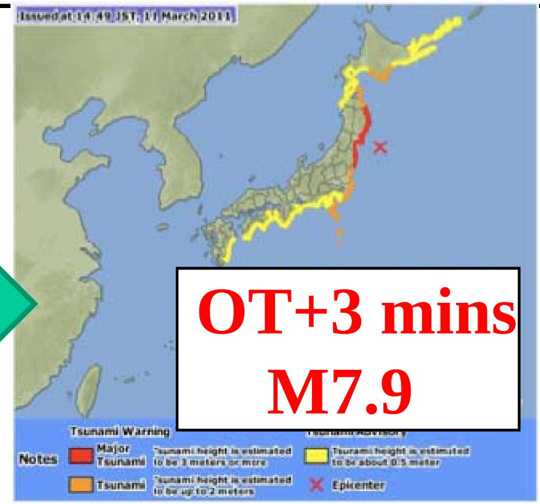


Developed by the READI Working Group

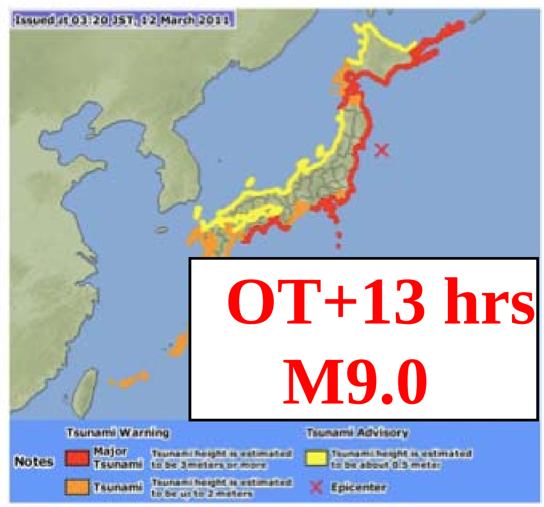
Japanese Response to 2011 Mw9 Tohoku-oki Earthquake



Hoshiba et al, 2011, EPS



Japan seismic data => magnitude => tsunami impact based on precomputed database

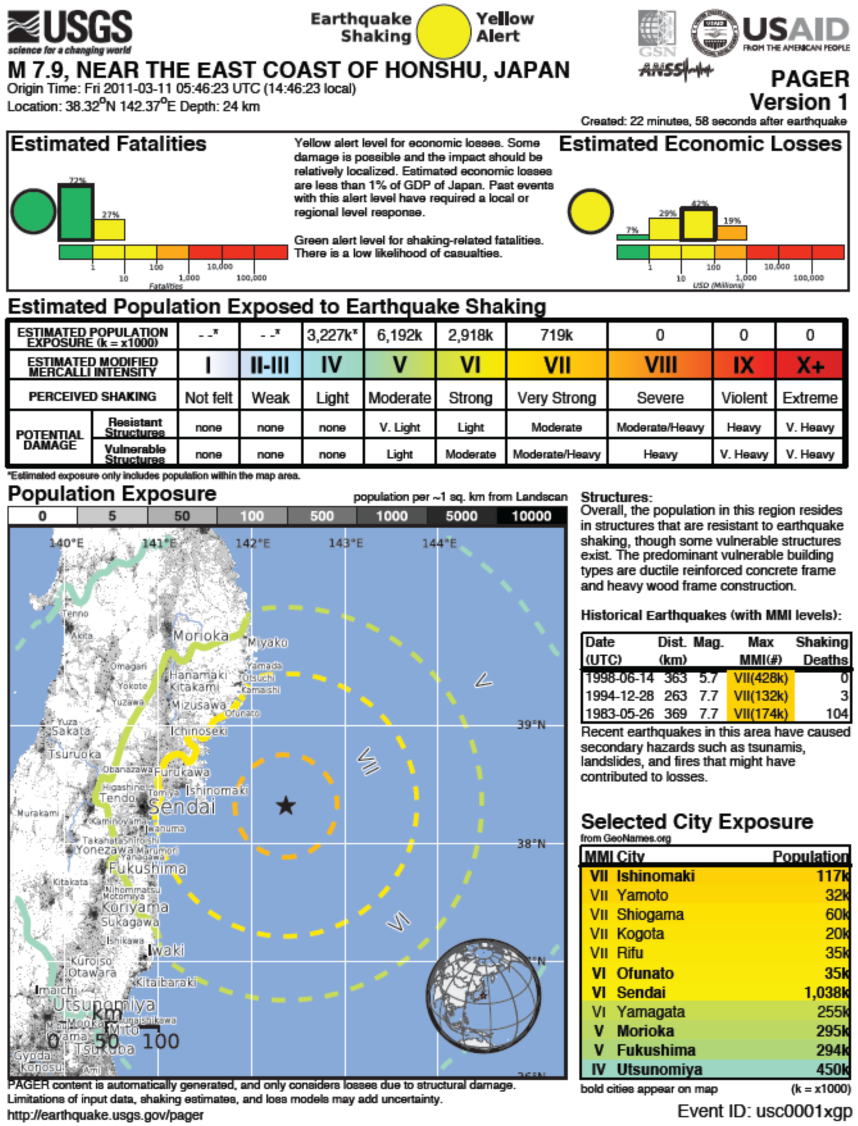


Japan seismic data & teleseismic data => magnitude => tsunami impact based on precomputed database

Ozaki et al, 2011, EPS

USGS Results for 2011 Tohoku-oki Earthquake from Teleseismic Data

23 minutes after OT



USGS — science for a changing world | Earthquake Shaking: Yellow Alert | USAID, FROM THE AMERICAN PEOPLE | GSN | ANSS

M 7.9, NEAR THE EAST COAST OF HONSHU, JAPAN

Origin Time: Fri 2011-03-11 05:46:23 UTC (14:46:23 local)

Location: 38.32°N 142.37°E Depth: 24 km

PAGER Version 1

Created: 22 minutes, 58 seconds after earthquake

Estimated Fatalities | **Estimated Economic Losses**

Yellow alert level for economic losses. Some damage is possible and the impact should be relatively localized. Estimated economic losses are less than 1% of GDP of Japan. Past events with this alert level have required a local or regional level response.

Green alert level for shaking-related fatalities. There is a low likelihood of casualties.

Estimated Population Exposed to Earthquake Shaking

ESTIMATED POPULATION EXPOSURE (k = x1000)		- -*	- -*	3,227k*	6,192k	2,918k	719k	0	0	0
ESTIMATED MODIFIED MERCALLI INTENSITY		I	II-III	IV	V	VI	VII	VIII	IX	X+
PERCEIVED SHAKING		Not felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	Resistant Structures	none	none	none	V. Light	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy
	Vulnerable Structures	none	none	none	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy	V. Heavy

*Estimated exposure only includes population within the map area.

Population Exposure — population per ~1 sq. km from Landscan: 0, 5, 50, 100, 500, 1000, 5000, 10000

Structures: Overall, the population in this region resides in structures that are resistant to earthquake shaking, though some vulnerable structures exist. The predominant vulnerable building types are ductile reinforced concrete frame and heavy wood frame construction.

Historical Earthquakes (with MMI levels):

Date (UTC)	Dist. (km)	Mag.	Max MMI(#)	Shaking Deaths
1998-06-14	363	5.7	VII(428k)	0
1994-12-28	263	7.7	VII(132k)	3
1983-05-26	369	7.7	VII(174k)	104

Recent earthquakes in this area have caused secondary hazards such as tsunamis, landslides, and fires that might have contributed to losses.

Selected City Exposure

from GeoNames.org

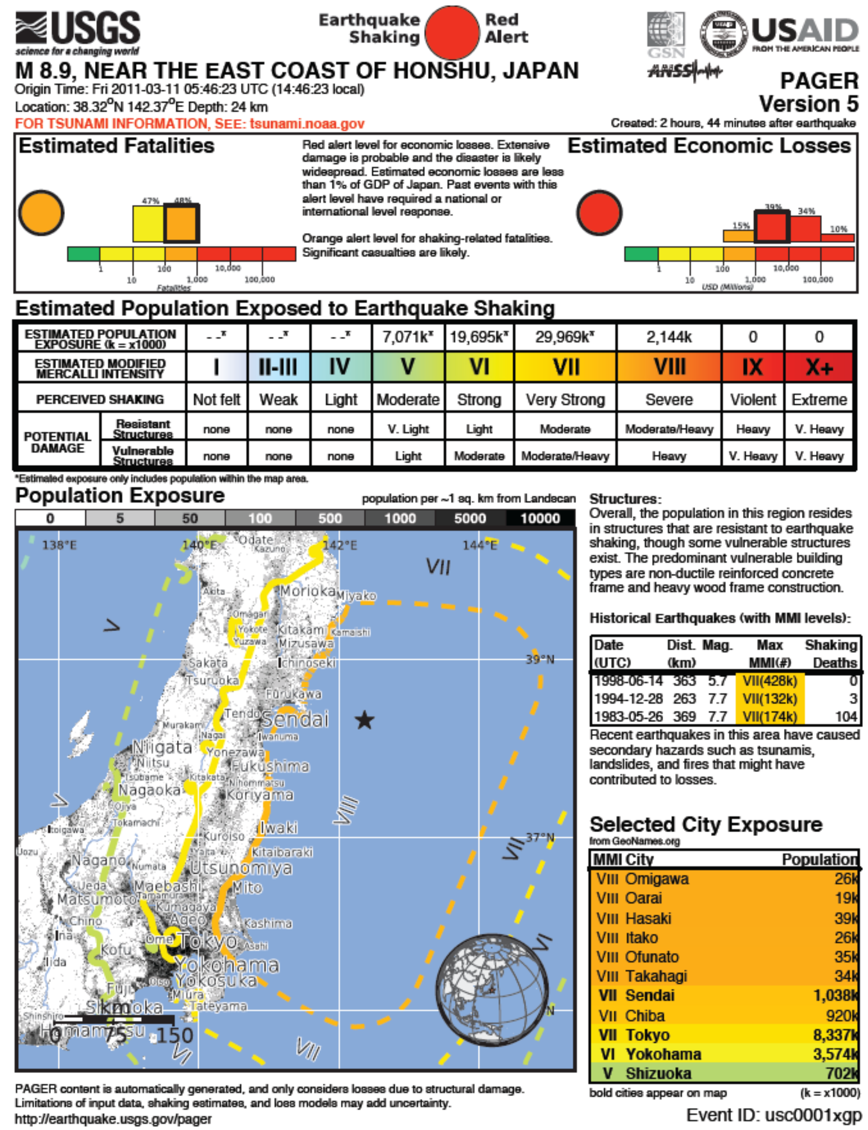
MMI	City	Population
VII	Ishinomaki	117k
VII	Yamoto	32k
VII	Shiogama	60k
VII	Kogota	20k
VII	Rifu	35k
VI	Ofunato	35k
VI	Sendai	1,038k
VI	Yamagata	255k
V	Morioka	295k
V	Fukushima	294k
IV	Utsunomiya	450k

bold cities appear on map (k = x1000)

PAGER content is automatically generated, and only considers losses due to structural damage. Limitations of input data, shaking estimates, and loss models may add uncertainty. http://earthquake.usgs.gov/pager

Event ID: usc0001xgp

2 hrs 44 minutes after OT



USGS — science for a changing world | Earthquake Shaking: Red Alert | USAID, FROM THE AMERICAN PEOPLE | GSN | ANSS

M 8.9, NEAR THE EAST COAST OF HONSHU, JAPAN

Origin Time: Fri 2011-03-11 05:46:23 UTC (14:46:23 local)

Location: 38.32°N 142.37°E Depth: 24 km

FOR TSUNAMI INFORMATION, SEE: tsunami.noaa.gov

PAGER Version 5

Created: 2 hours, 44 minutes after earthquake

Estimated Fatalities | **Estimated Economic Losses**

Red alert level for economic losses. Extensive damage is probable and the disaster is likely widespread. Estimated economic losses are less than 1% of GDP of Japan. Past events with this alert level have required a national or international level response.

Orange alert level for shaking-related fatalities. Significant casualties are likely.

Estimated Population Exposed to Earthquake Shaking

ESTIMATED POPULATION EXPOSURE (k = x1000)		- -*	- -*	- -*	7,071k*	19,695k*	29,969k*	2,144k	0	0
ESTIMATED MODIFIED MERCALLI INTENSITY		I	II-III	IV	V	VI	VII	VIII	IX	X+
PERCEIVED SHAKING		Not felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	Resistant Structures	none	none	none	V. Light	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy
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MMI	City	Population
VIII	Omigawa	26k
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VIII	Hasaki	39k
VIII	Itako	26k
VIII	Ofunato	35k
VIII	Takahagi	34k
VII	Sendai	1,038k
VII	Chiba	920k
VII	Tokyo	8,337k
VI	Yokohama	3,574k
V	Shizuoka	702k

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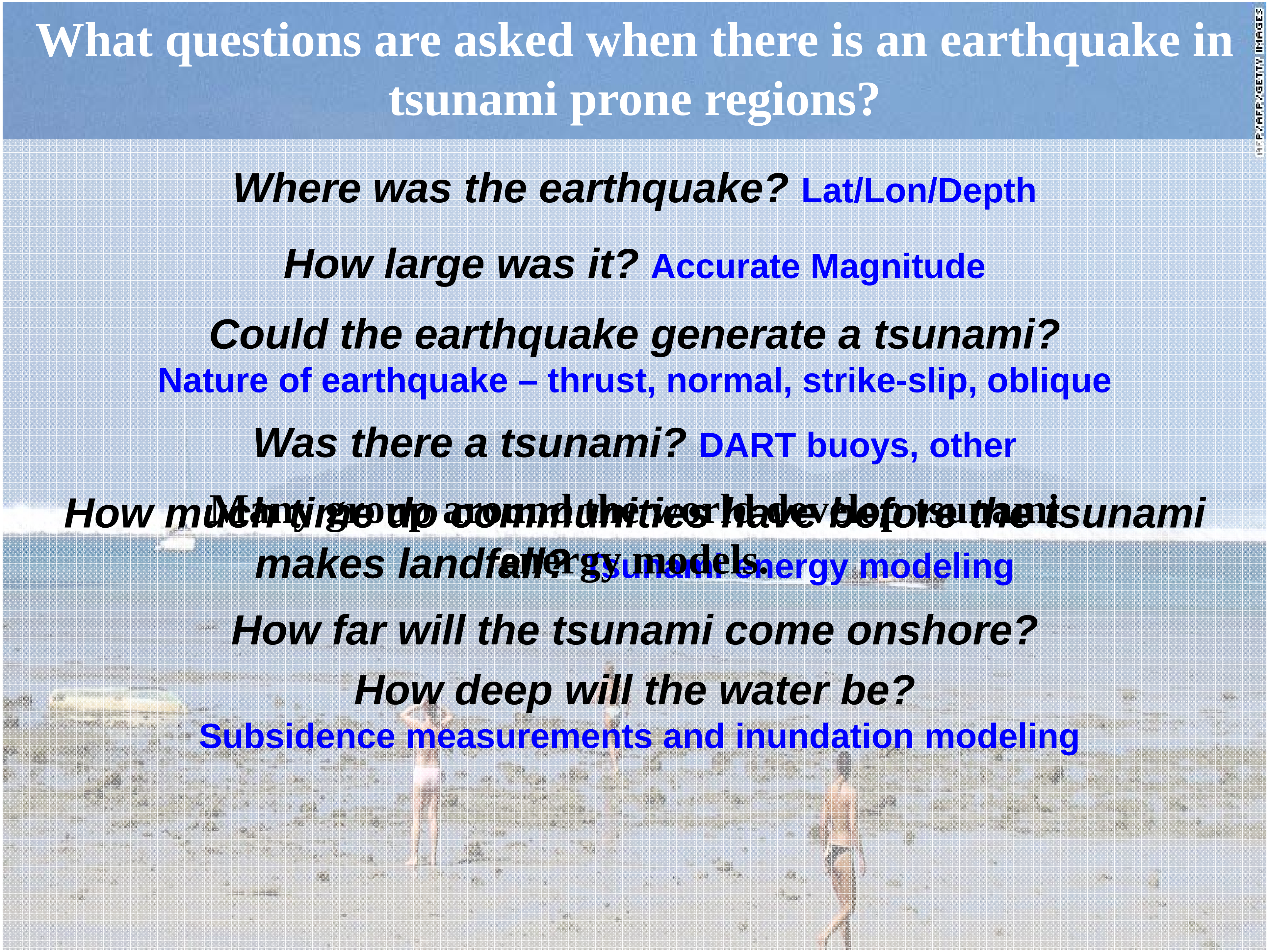
PAGER content is automatically generated, and only considers losses due to structural damage. Limitations of input data, shaking estimates, and loss models may add uncertainty. http://earthquake.usgs.gov/pager

Event ID: usc0001xgp

Hayes et al., 2011, SRL



What questions are asked when there is an earthquake in tsunami prone regions?

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How large was it? **Accurate Magnitude**

Could the earthquake generate a tsunami?
Nature of earthquake – thrust, normal, strike-slip, oblique

Was there a tsunami? **DART buoys, other**

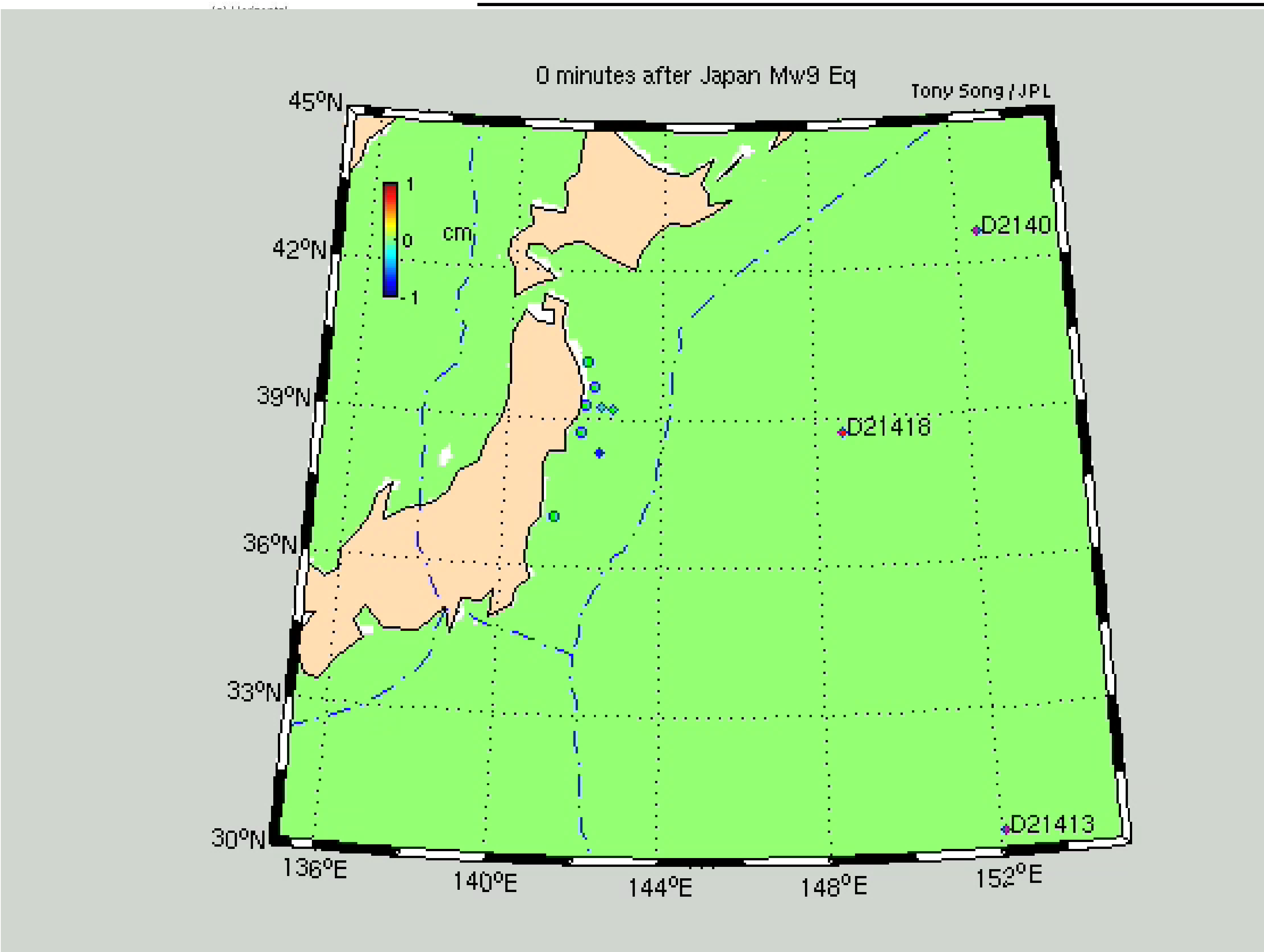
How much time do communities have before the tsunami makes landfall? **Tsunami energy modeling**

Many group around the world have develop tsunami energy models.

How far will the tsunami come onshore?

How deep will the water be?
Subsidence measurements and inundation modeling

The 2011 Tohoku-Oki Tsunami



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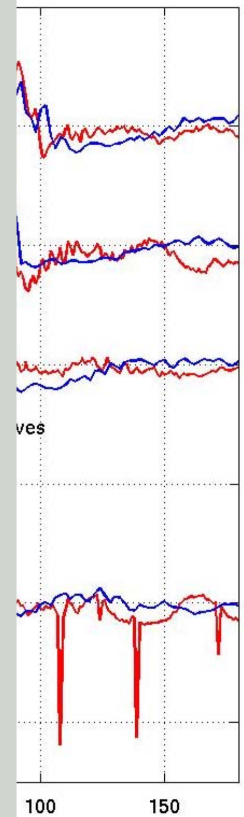

Bawden, NASA HQ

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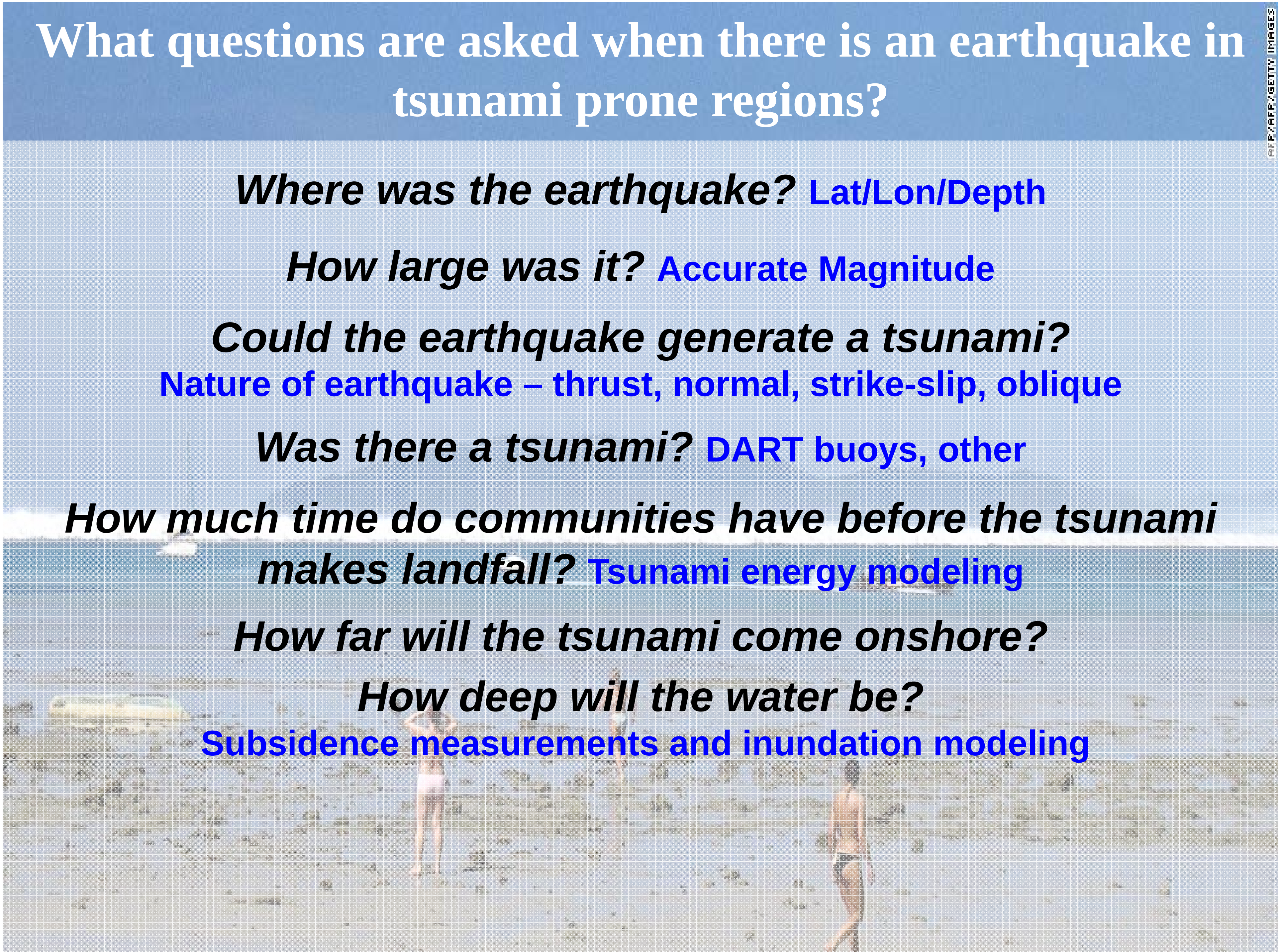

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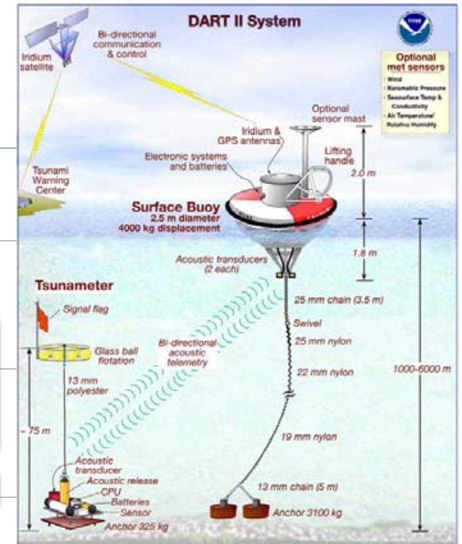
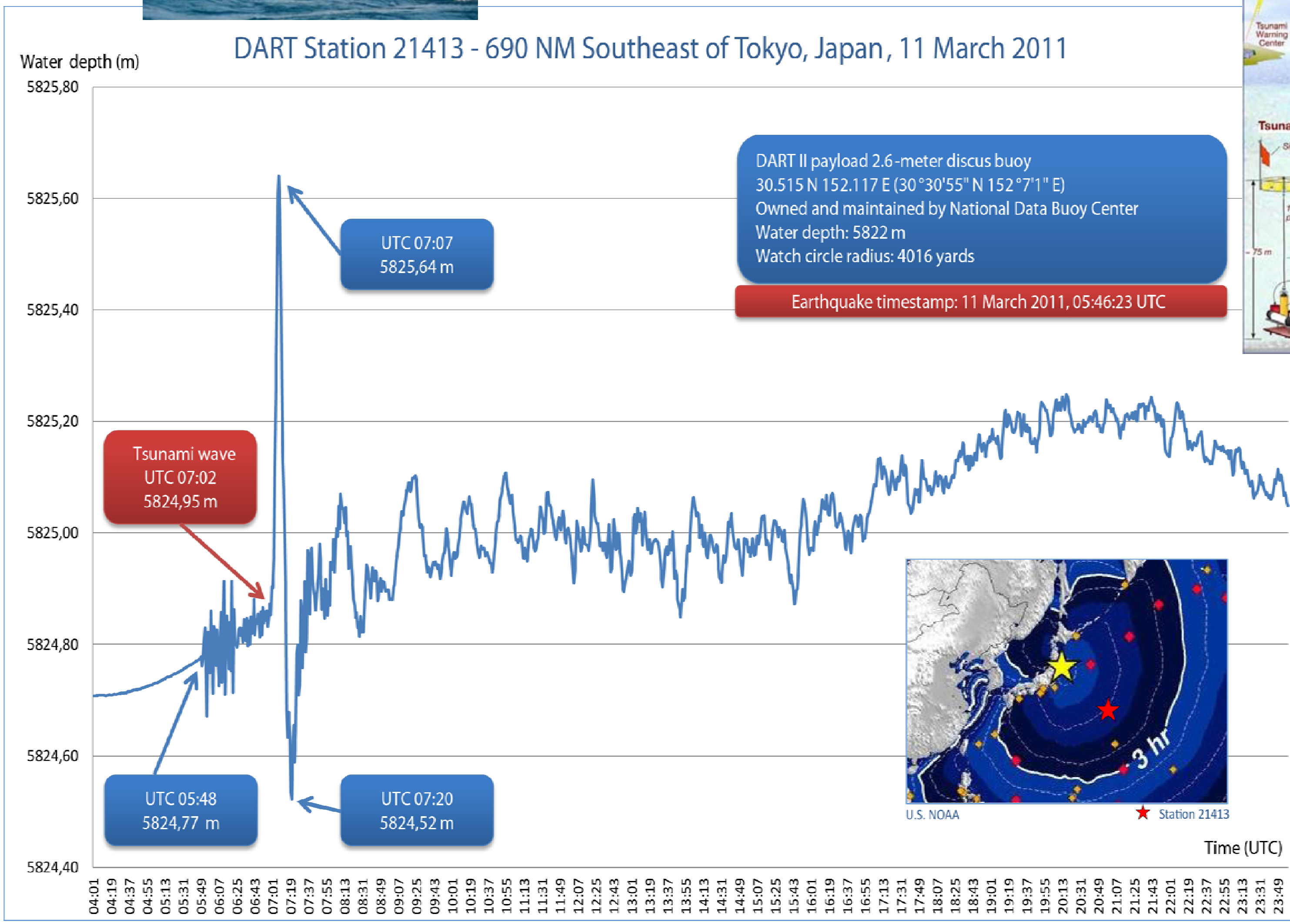
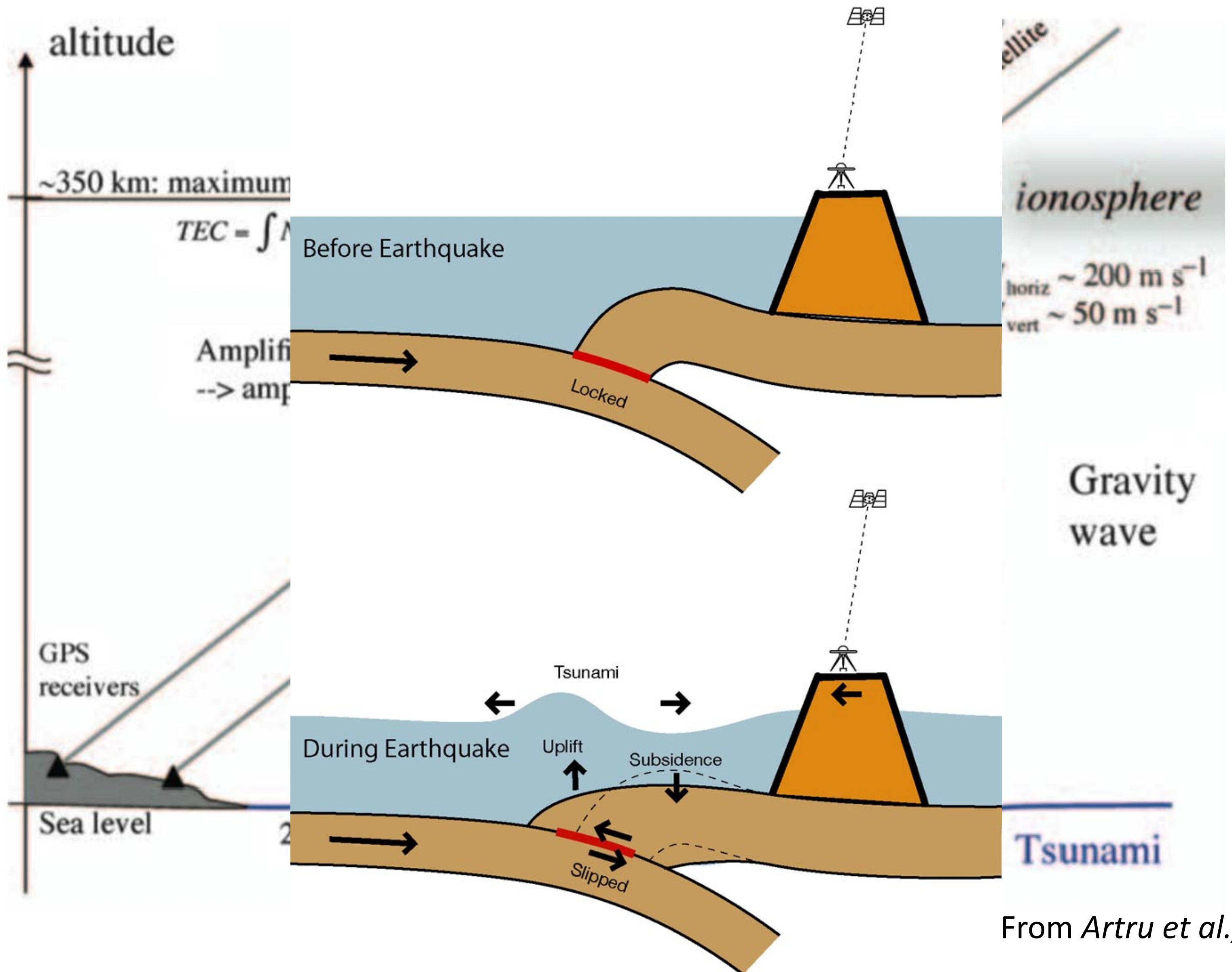
Currently – DART Buoys are only way to track tsunamis in open ocean



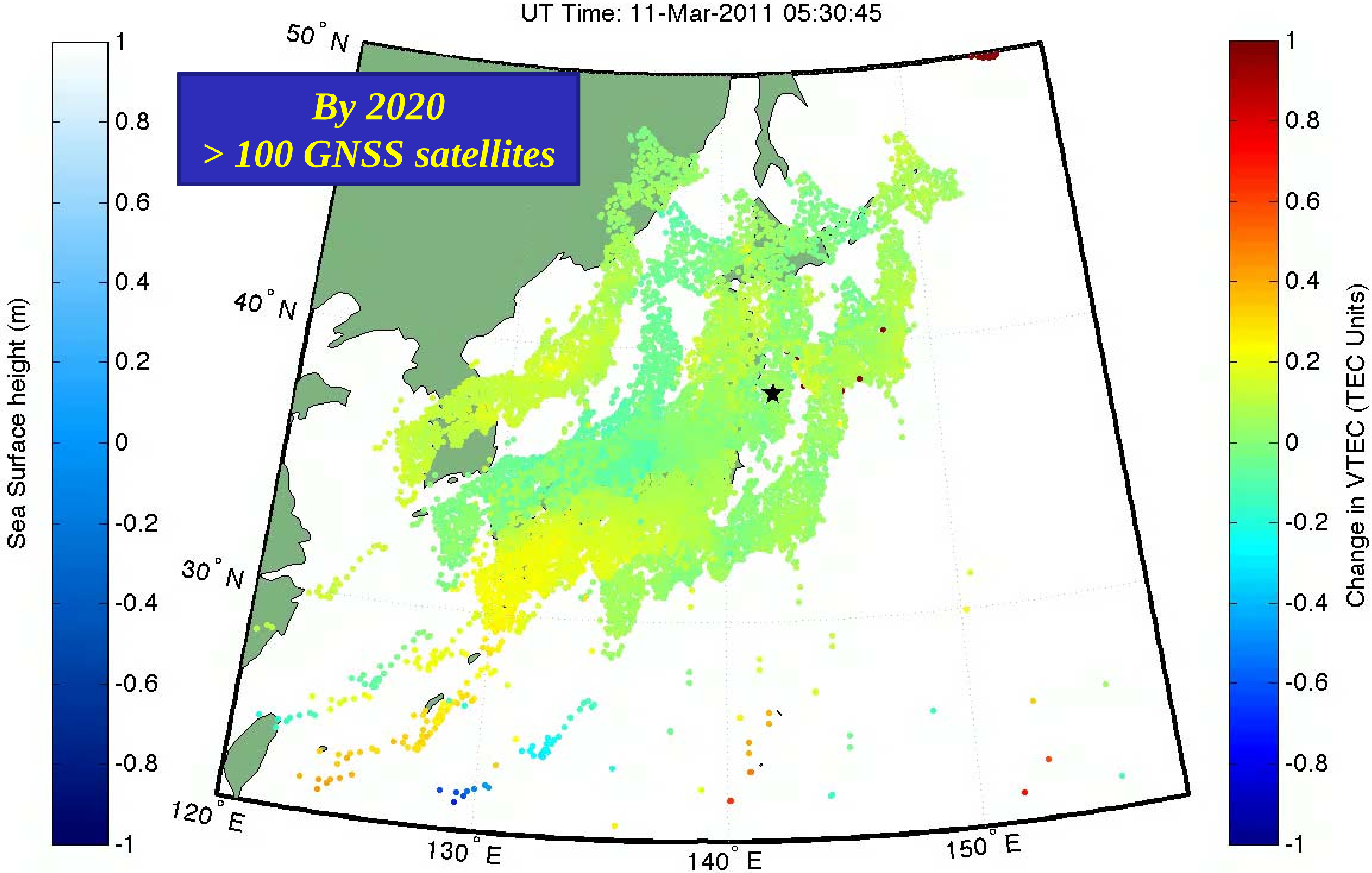


The Tsunami Generated Displacement of the Ocean Surface Couples to the Ionosphere



From *Artru et al.,* 2005

GSI's GEONET Captured the Ionospheric Coupled Waves and Imaged the Tsunami Generation and Propagation



Ionospheric Response to Mw 9.0 Tohoku Earthquake and Tsunami in Japan on March 11, 2011, A.Komjathy, D.A.Galvan, M.P Hickey, P.Stephens, Mark Butala, and A.Mannucci, (http://visibleearth.nasa.gov/view.php?id=77377)

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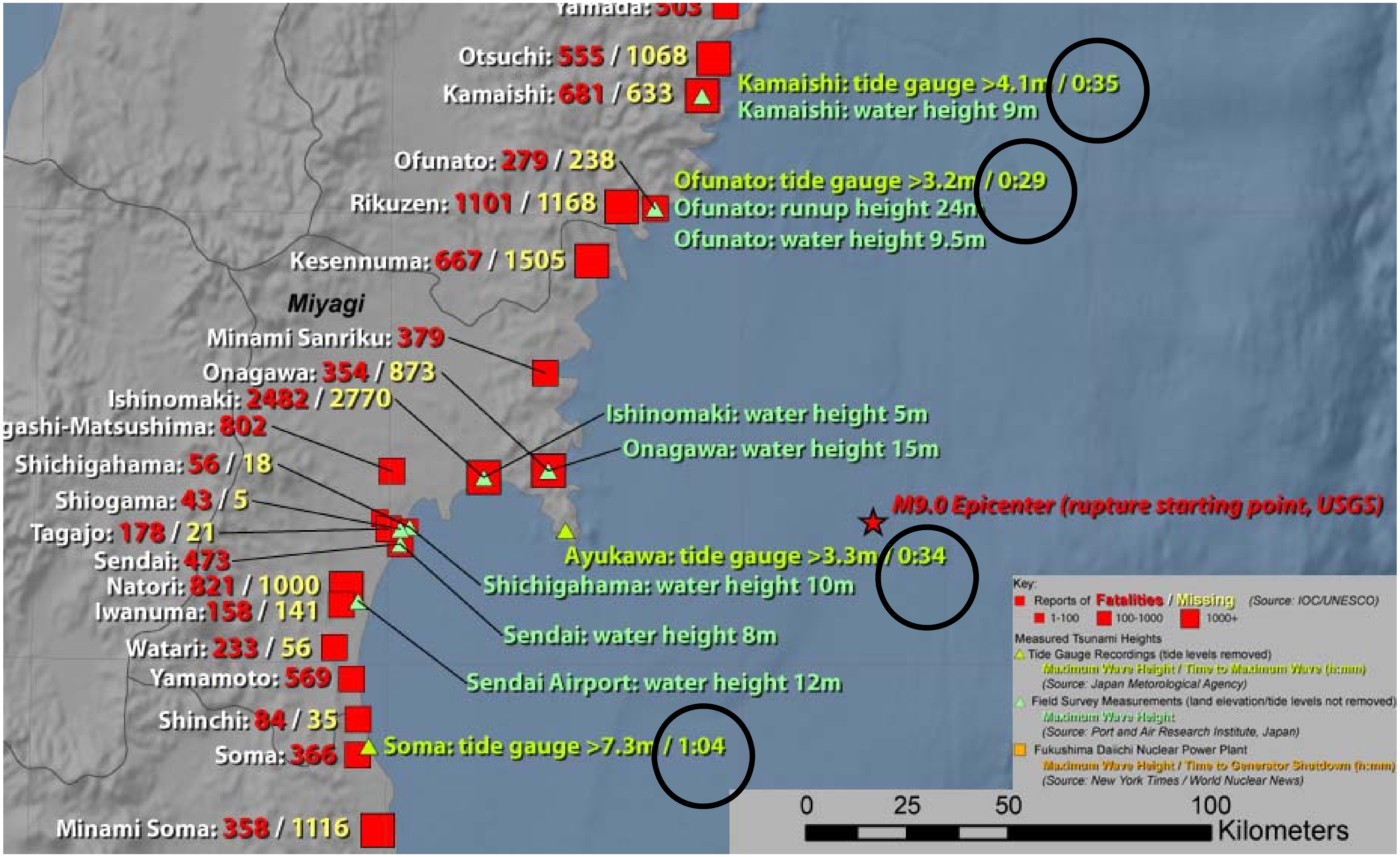
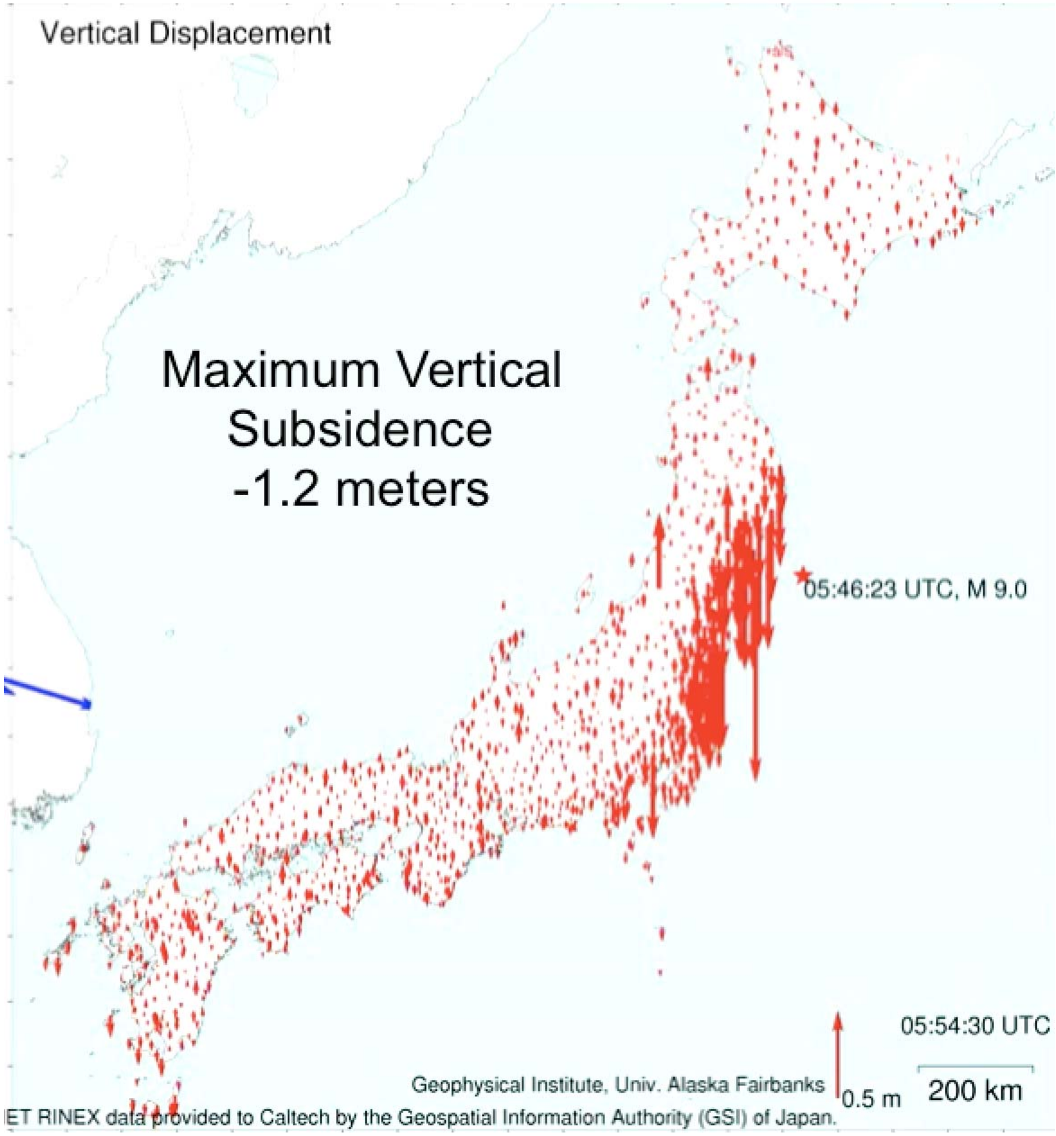
Tsunami travel times for 2011 Mw 9.0 Tohoku-oki earthquake



Dynamic Coastal Inundation Maps
rtGNSS + Tsunami Rise-Up models



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Real-Time GNSS
Measurement of the land surface
Measurement perturbations in the ionosphere
Improves latency and accuracy of models
Next generation models include coastal subsidence

GNSS Earthquake and Tsunami Early Warning

Expanding the earthquake and tsunami early warning globally requires access to **shared *real-time*** GNSS data in areas that are:

- Seismically active
- Coastal communities that may be impacted by a tsunami

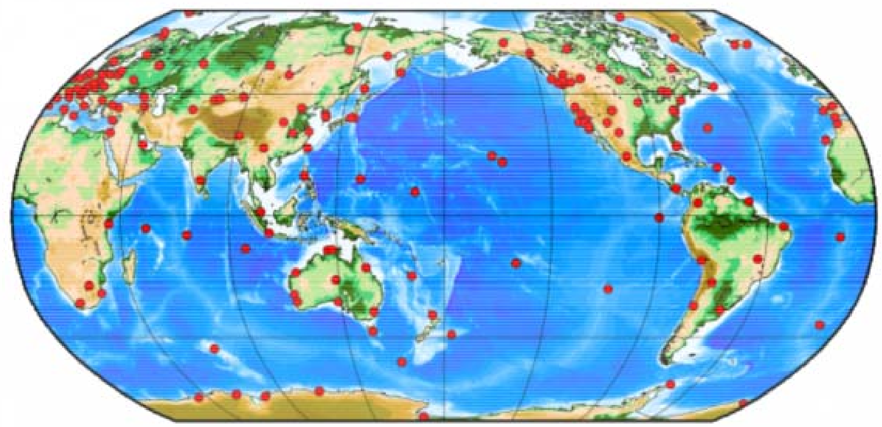
Partnership with regional/national tsunami and earthquake early warning Centers.

- The GNSS Early Warning approach enhances current capabilities

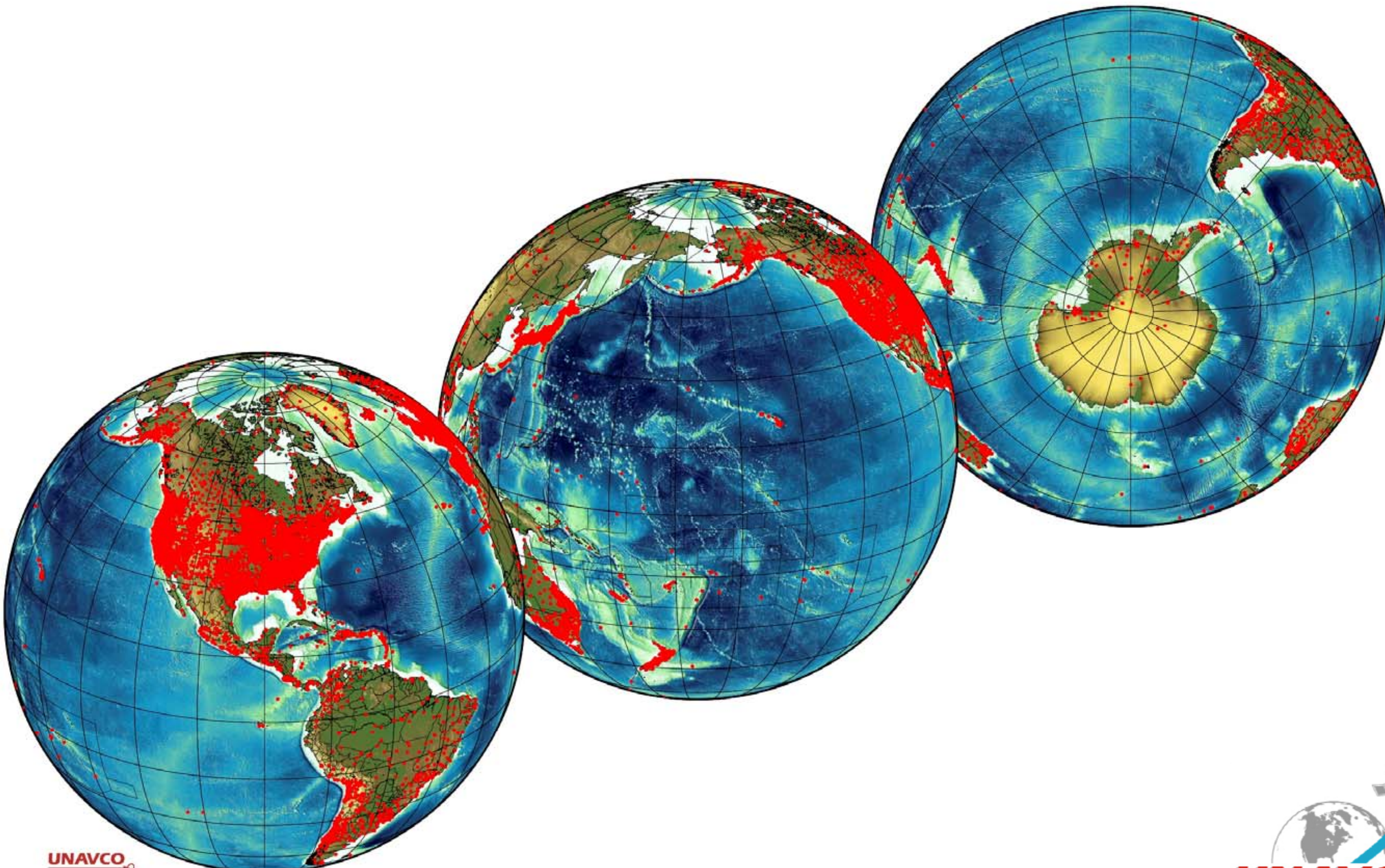
Partnership with the International GNSS and Earth Observation's communities

- ICG – UN International Committee on Global Navigation Satellite Systems + UNOOSA
- IGS – International GNSS Service
- GGOS – Global Geodetic Observing System
- GEO – Group on Earth Observations
- CEOS – Committee on Earth Observation Satellites

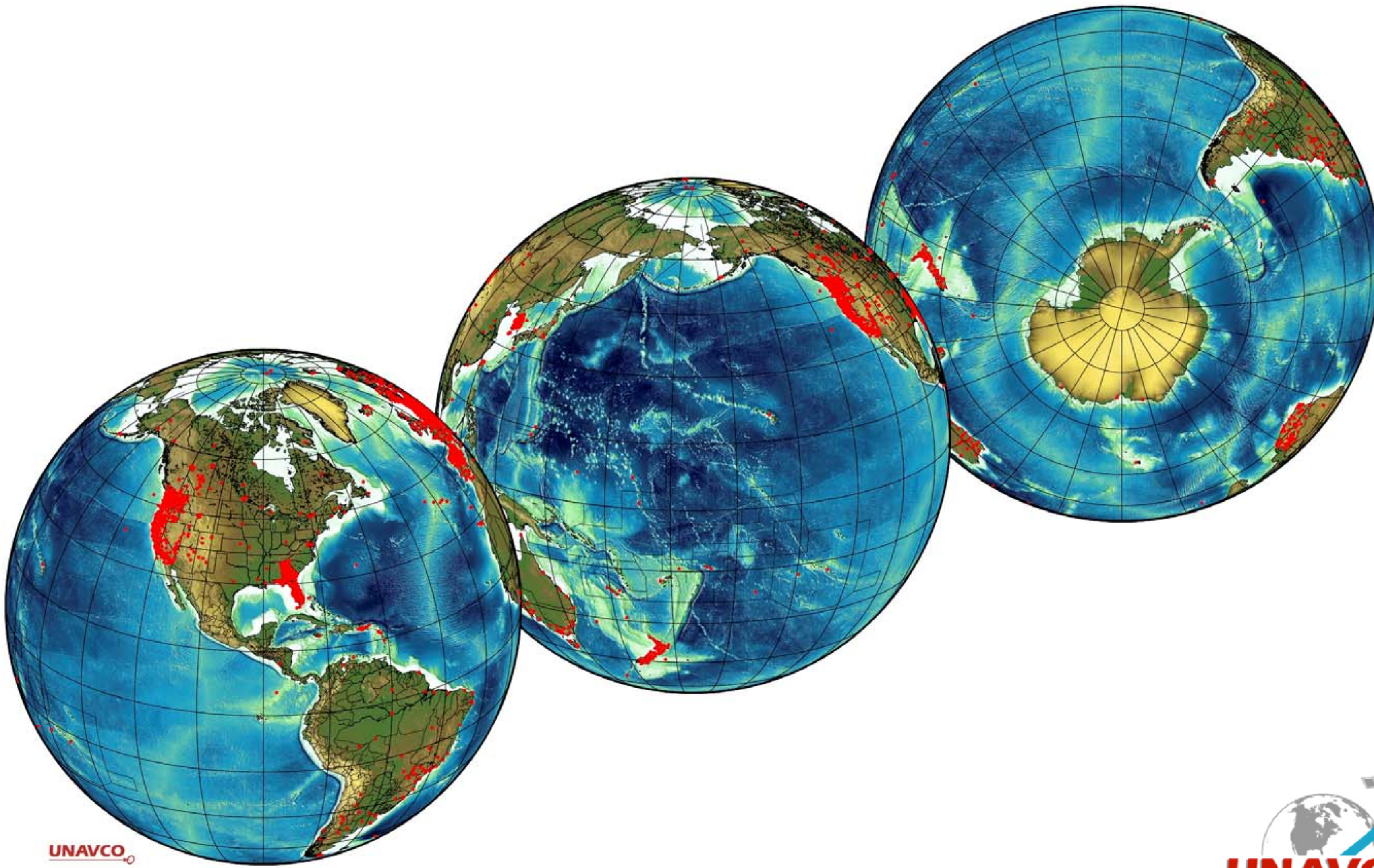
GGOS/IGS Real-TimeNetwork



Known and Publically Accessible Continuous GNSS sites – 14,667

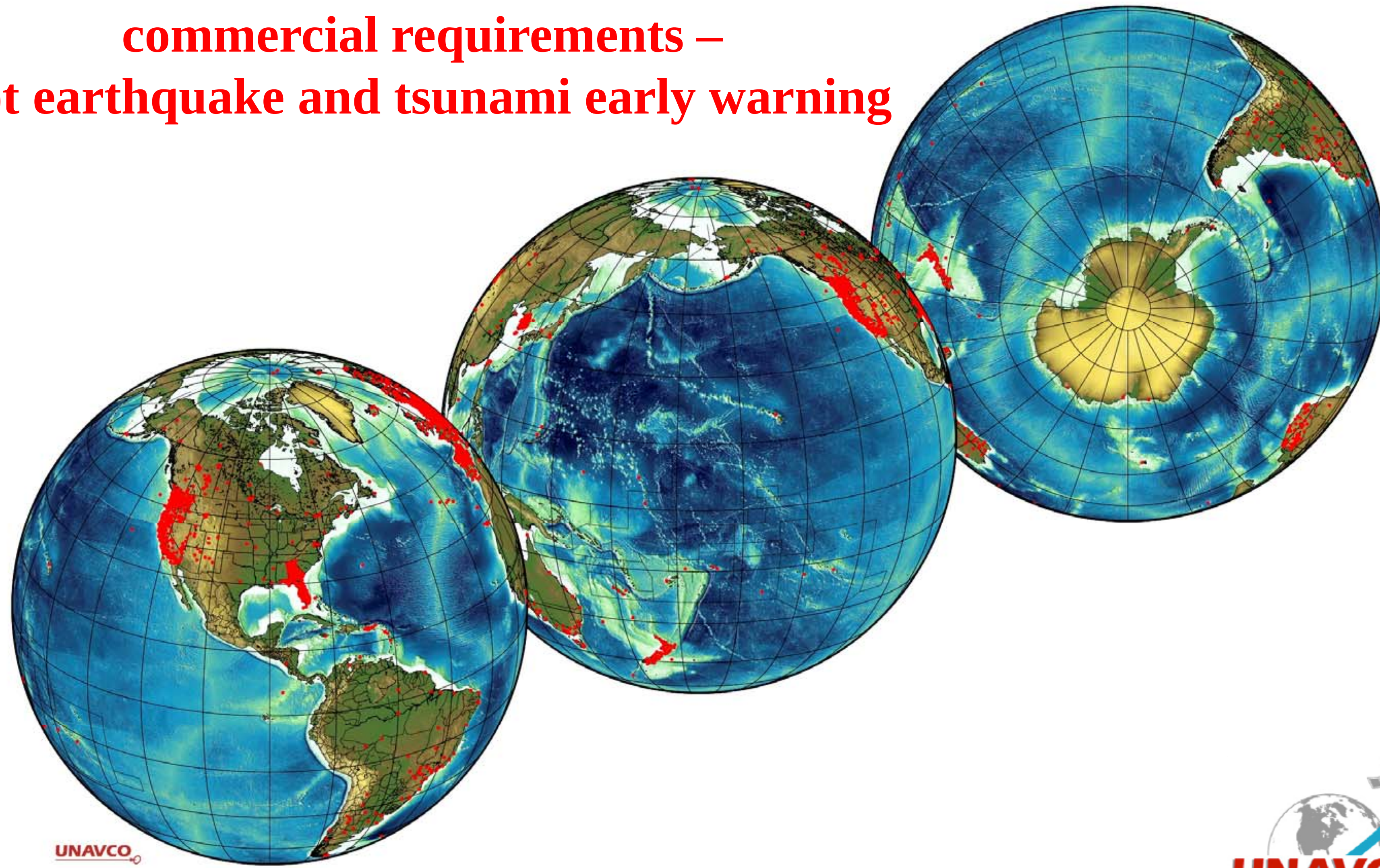


Known and Publically Accessible
Real-Time GNSS sites – 2,287



Available Real-Time GNSS sites – 2,287

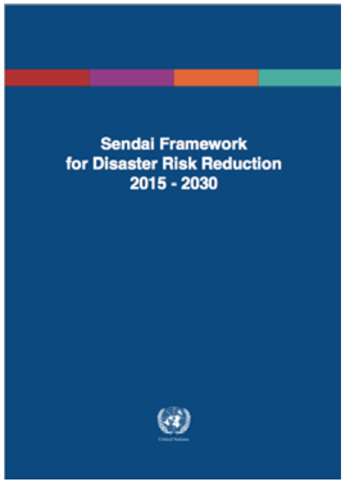
Most were installed for science or commercial requirements –
Not earthquake and tsunami early warning



GNSS Earthquake and Tsunami Early Warning

SENDAI FRAMEWORK FOR DISASTER RISK REDUCTION

A real-time GNSS network would support a number of goals described the Sendai Framework



18. ***To support the assessment of global progress in achieving the outcome and goal of the present Framework, seven global targets have been agreed.***

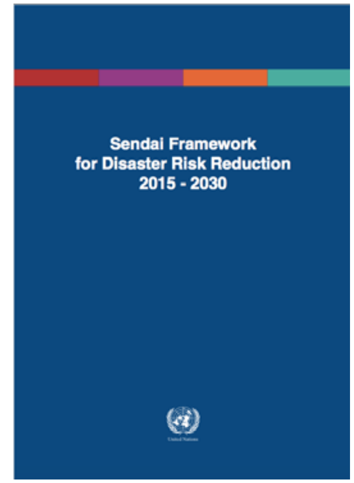
(a) Substantially ***reduce global disaster mortality*** *by 2030, aiming to lower the average per 100,000 global mortality rate in the decade 2020–2030 compared to the period 2005– 2015;*

(f) Substantially ***enhance international cooperation*** *to developing countries through adequate and sustainable support to complement their national actions for implementation of the present Framework by 2030;*

(g) Substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to people by 2030.

GNSS Earthquake and Tsunami Early Warning

SENDAI FRAMEWORK FOR DISASTER RISK REDUCTION



A real-time GNSS network would support a number of goals described Sendai Framework

IV. Priorities for action

***20. Taking into account the experience gained through the implementation of the Hyogo Framework for Action, and in pursuance of the expected outcome and goal, there is a need for focused action within and across sectors by States at local, national, regional and global levels in the following four priority areas*:**

Priority 1: Understanding disaster risk.

GNSS 99.99% of the time
Scientific Research

Priority 2: Strengthening disaster risk governance to manage disaster risk.

Priority 3: Investing in disaster risk reduction for resilience.

Priority 4: Enhancing disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation and reconstruction.

Gerald Bawden

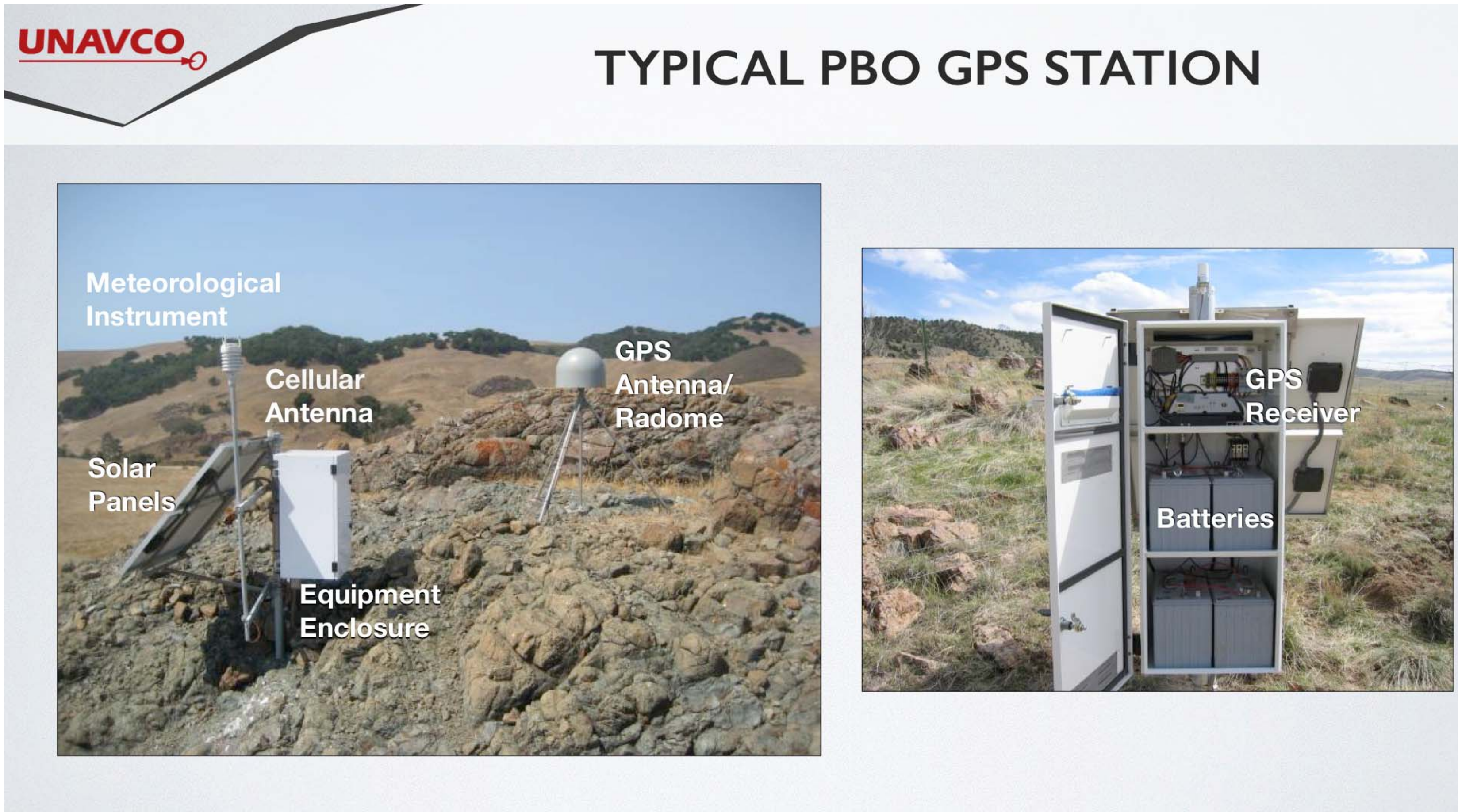
Gerald.W.Bawden@NASA.gov

Backup Slides

GNSS Site Installation Costs

Costs to build a PBO-quality station:

- Deep Drilled-Braced Monument ~$50K/station
- Shallow Drilled-Braced Monument ~$25K/station



GNSS Site Yearly Costs

UNAVCO

COST PER STATION PER YEAR

	Mean	Median	Min	Max	number of stations (n)
All Stations	$5.8k	$5.5k	$3.9k	$13.7k	1100
Critical Stations	$6.1k	$5.5k	$4.0k	$13.7k	331
Volcanic Targets	$7.9k	$6.7k	$4.1k	$13.7k	102
Alaska Stations	$8.6k	$7.5k	$4.9k	$13.7k	140
Low Strain Targets	$5.2k	$5.2k	$4.0k	$8.4k	260
High Strain Targets	$5.5k	$5.4k	$4.0k	$9.8k	628
Stable North America	$5.0k	$5.0k	$3.9k	$7.2k	28
Snow/Soil Moisture Targets	$5.7k	$5.4k	$4.0k	$13.2k	149

GNSS Site Yearly Costs

UNAVCO

MEAN COST PER STATION (1100 STATIONS)

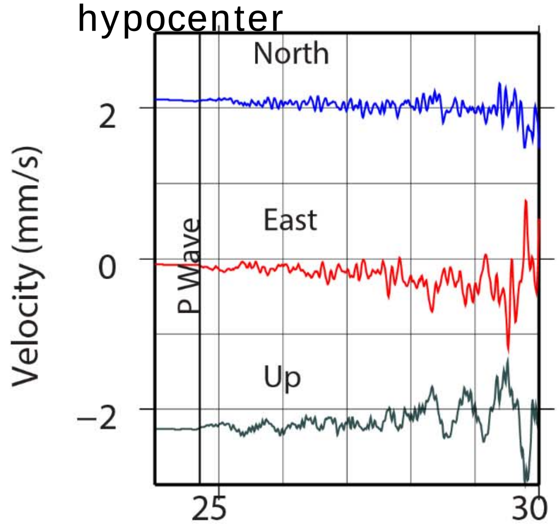
	Mean Cost Per PBO Station Per Year
Field Operations Fixed Costs (Facilities, Storage, Shipping)	$255
Sub-Award Data Processing	$365
Archiving and Data Operations (staff, servers, software, etc)	$899
Realtime Data Handling	$305
Field Travel	$626
Labor (with fringe)	$1,267
Materials/Supplies/Equipment	$471
Station Permitting	$469
Data Communications	$386
Indirect Rate (15.79%)	$796
TOTAL	**$5.8k**

Global Navigation Satellite System (GNSS) will increase to over 110 satellites by 2020

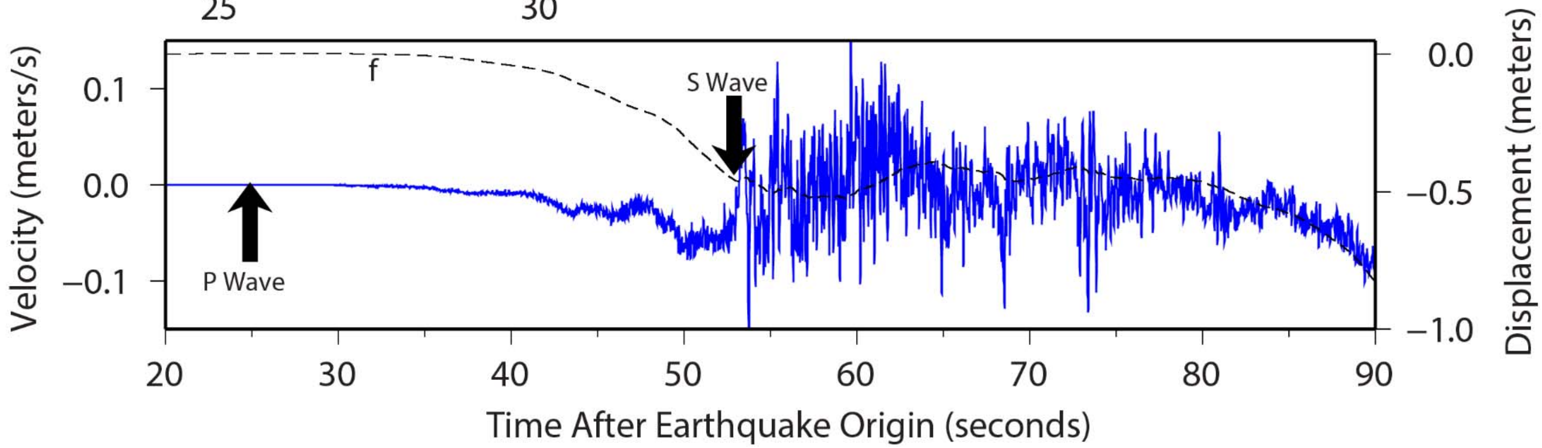
Next Generation of GNSS will Include Accelerometers

Seismogeodetic Earthquake Early Warning at Scripps Institute of Oceanography

2011 Tohoku-oki earthquake
GEONET GPS station 0914 and
K-NET accelerometer MYG003,
155 km from the JMA
hypocenter

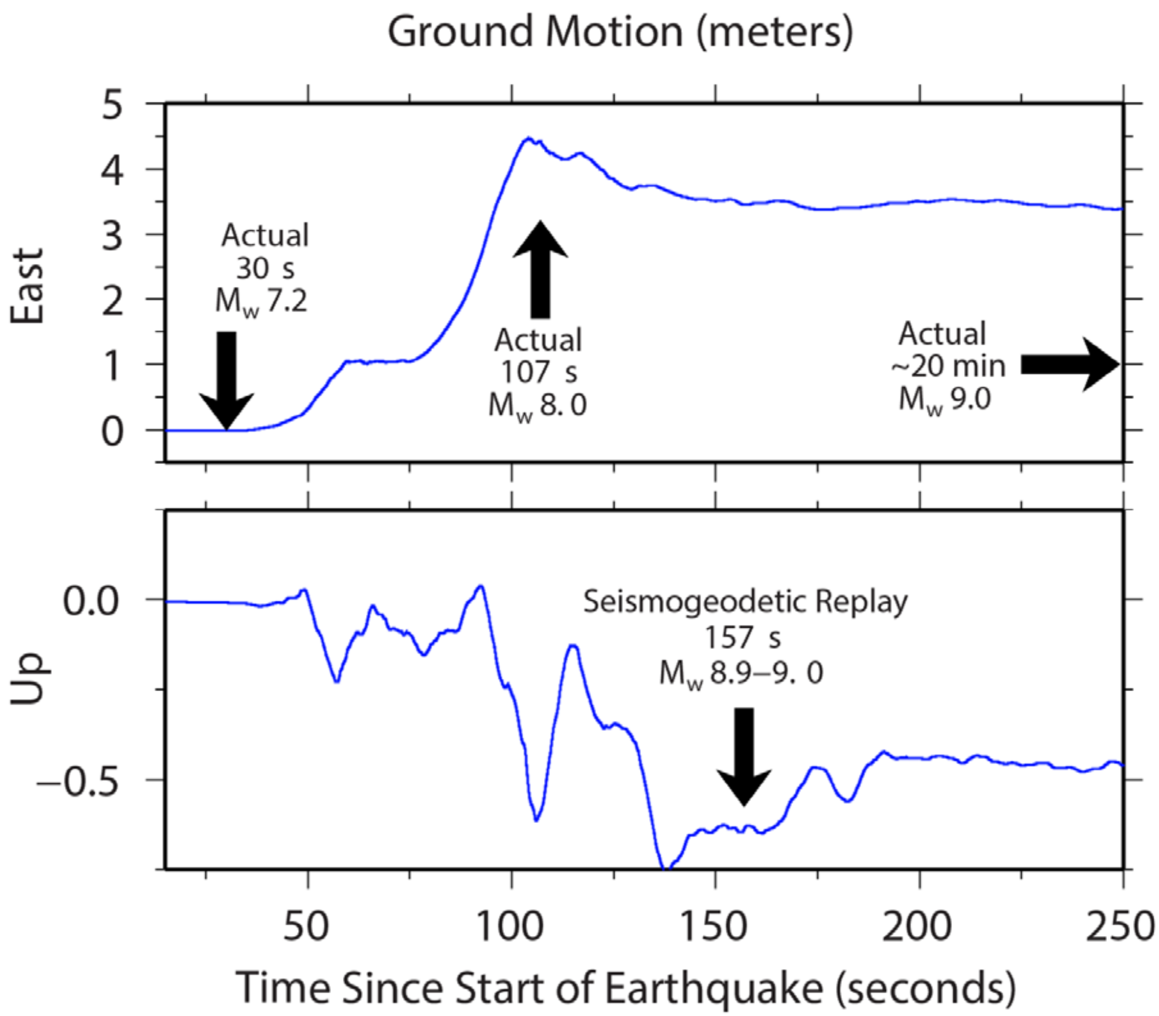


Seismogeodesy detects arrival of seismic *P* (primary) waves used in earthquake early warning to predict arrival and intensity of more damaging *S* (secondary) and surface waves, better than accelerometers alone for large earthquakes, because of magnitude saturation of latter (Crowell et al., GRL, 2013)



Source: Melgar et al., GRL, 2013

Seismogeodetic Displacements and Magnitude Estimation



Seismogeodesy improves on traditional seismic monitoring by accurately determining magnitude of large (> M 7) earthquakes without saturation and by estimating both ground motions and permanent displacements

2011 Tohoku-oki earthquake
GEONET GPS station 0914 and K-NET accelerometer MYG003, 155 km from the JMA hypocenter

Source: Melgar et al., GRL, 2013

Components of a Real-Rime GNSS Tsunami Early Warning System

- **GNSS sites located in seismogenic region *streaming* phase and range in real-time**
- Precise Point Positioning (PPP) estimates calculated and accessible in real-time
- Dynamic change detection algorithms – in real-time
- Earthquake source modeling – in real-time
- Tsunami source modeling – in real-time
  - Continued iterations as new GNSS data are available
  - Continued iterations as other data become available
- Integration of the rtGNSS derived source model into warning assessment and protocols
  - Initial rtGNSS solution
  - Iterative rtGNSS solutions
- Tsunami run-up modeling
  - Including GNSS vertical deformation measurements
- Ionosphere-tsunami linkage – wave propagation