The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2333-13

Workshop on Science Applications of GNSS in Developing Countries (11-27 April), followed by the: Seminar on Development and Use of the Ionospheric NeQuick Model (30 April-1 May)

11 April - 1 May, 2012

Role of GNSS in Advancing Natural Hazards Monitoring and Risk Assessment: Earthquakes, Fault Zones, Volcanoes and Landslides

HOTHEM Larry Dalton

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Reston VA 20192
U.S.A.

Role of GNSS in Advancing Natural Hazards Monitoring and Risk Assessment:

Earthquakes, Fault Zones, Volcanoes and Landslides

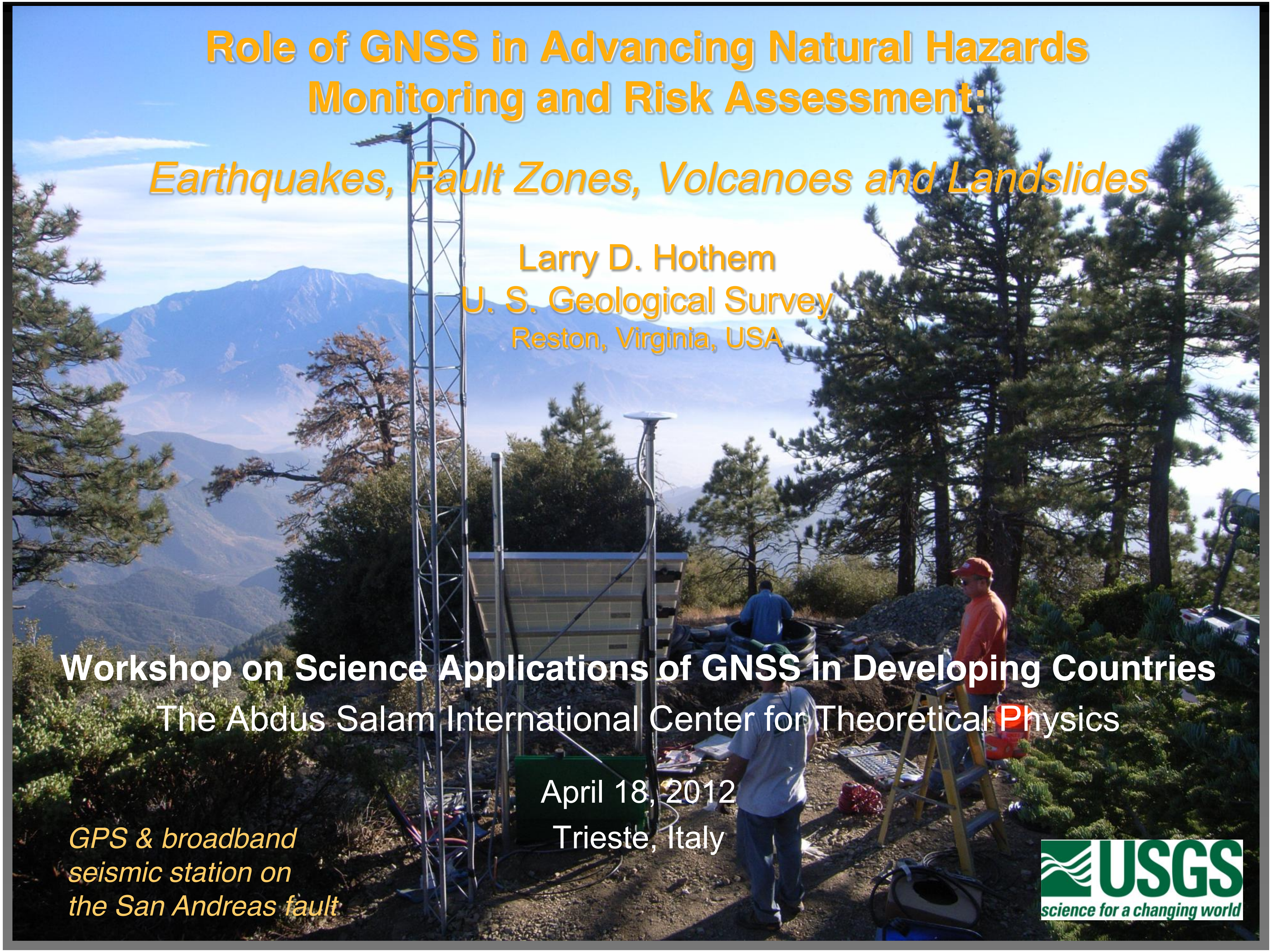
Larry D. Hothem
U. S. Geological Survey
Reston, Virginia, USA

Workshop on Science Applications of GNSS in Developing Countries

The Abdus Salam International Center for Theoretical Physics

April 18, 2012

Trieste, Italy



GPS & broadband seismic station on the San Andreas fault

Acknowledgement

Kenneth W. Hudnut, Ph.D.

- Geodesy Coordinator – U.S. Earthquake Hazards Program Council
- Leader: Southern San Andreas Fault Evaluation (SoSAFE) Project
- Email: Hudnut@usgs.gov
- Website: http://urbanearth.gps.caltech.edu/ken-w-hudnut/

and many others

USGS Mission Areas

New Organization Structure, effective: 1 October 2010

Focused on some of the most significant issues society faces, in which natural science can make a substantial contribution to the well-being of the Nation and the world:

- **Climate and Land Use Change**
- **Core Science Systems**
- **Ecosystems**
- **Energy and Minerals**
- **Environmental Health**
- **Natural Hazards**
- **Water**

USGS science is founded on data quality.

http://www.usgs.gov/natural_hazards/

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Start with Science
- Climate and Land Use Change
- Core Science Systems
- Ecosystems
- Energy and Minerals, and Environmental Health
- Natural Hazards
- Science Quality and Integrity
- Water

Our Contacts

Natural Hazards

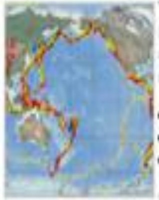
On October 1, 2010, the USGS is realigning its organizational structure around the themes identified in the USGS Science Strategy. One of these new themes, or mission areas, is "Natural Hazards". This mission area brings together the following existing Bureau programs.

Help shape the future of USGS science by weighing in on our Science Strategy planning process.

Natural Hazards

Every year in the United States, natural hazards cost lives and billions of dollars in damage. The U.S. Geological Survey (USGS) provides policymakers and the public with a clear understanding of natural hazards and their potential threats to society, and assists with developing smart, cost-effective strategies for achieving preparedness and resilience. See "Natural Hazards—A National Threat" Fact Sheet.

Earthquake Hazards



The Earthquake Hazards Program (EHP) is part of the National Earthquake Hazards Reduction Program (NEHRP) led by the National Institute of Standards and Technology (NIST). Earthquakes pose significant risk to 75 million Americans in 39 States. The EHP provides information and products for earthquake loss reduction, including hazard and risk assessment, and comprehensive real-time earthquake monitoring.

- Real-time RSS Feeds
- Earthquake Notification Service
- Did You Feel It?

"Earthquake Hazards – A National Threat" Fact Sheet

Volcano Hazards

The overall objectives of the Volcano Hazards Program are to advance the scientific understanding of volcanic processes and to lessen the harmful impacts of volcanic activity. The Volcano Hazards Program monitors active and potentially active volcanoes, assesses their hazards, responds to volcanic crises, and conducts research on how volcanoes work. The Program also issues warnings of potential volcanic hazards to responsible emergency-management authorities and to the populace affected.

- Current Alerts for U.S. Volcanoes

"Volcano Hazards – A National Threat" Fact Sheet

Landslide Hazards

The mission of the Landslide Hazards Program (LHP) is to provide information that leads to the reduction of losses from landslides and increase in public safety through improved understanding of landslide hazards and strategies for hazard mitigation. In pursuit of the program mission, the LHP conducts landslide hazard assessments, pursues landslide investigations and forecasts, provides technical assistance to respond to landslide emergencies, and engages in outreach activities.

- Advisories
- Real-time Monitoring

"Landslide Hazards – A National Threat" Fact Sheet
"Wildfire Hazards – A National Threat" Fact Sheet

Global Seismographic Network

The Global Seismographic Network (GSN) is a permanent digital network of state-of-the-art seismological and geophysical sensors connected by a telecommunications network. The GSN provides near-uniform, worldwide monitoring of the Earth, with over 150 modern seismic stations distributed globally. The GSN was formed in partnership among the USGS, the National Science Foundation (NSF) and the Incorporated Research Institutions for Seismology (IRIS).

- Station Status

Geomagnetism

The mission of the Geomagnetism Program is to monitor the Earth's magnetic field. Using ground-based observatories, the Program provides continuous records of magnetic field variations covering long timescales; disseminates magnetic data to various governmental, academic, and private institutions; and conducts research into the nature of geomagnetic variations for purposes of scientific understanding and hazard mitigation.

- Real-time Data

"Monitoring the Earth's Magnetic Field" Fact Sheet

Coastal and Marine Geology

The Coastal and Marine Geology Program conducts research on changes in the coastal and marine environment, whether naturally occurring or human induced. Changes in this environment can endanger our quality of life, threaten property, pose risk to fragile environments, and affect livelihoods. The management challenge faced by all coastal communities is to balance the competing needs of citizens, government, industry, and the environment. Sound marine science is critical for making such management decisions.

- Floods
- Tsunamis
- Hurricanes

"Flood Hazards – A National Threat" Fact Sheet
"Tsunami Hazards – A National Threat" Fact Sheet
"Hurricane Hazards – A National Threat" Fact Sheet

Natural Hazards Impacts

- **Earthquakes** have the highest potential for causing catastrophic casualties, property damage, and economic disruption.
- Over 75 percent of declared Federal disasters are related to **floods**.
- More than half of the U.S. population lives within 50 miles of a coast. Many of these areas, especially the Atlantic and Gulf coasts, will be in the direct path of future **hurricanes**.
- **Landslides** affect every State, causing $3.5 billion dollars annually in damages and between 25 and 50 deaths.
- The United States faces significant **tsunami** threats to the West Coast, Hawaii, Alaska, and island territories in the Caribbean and the Pacific.
- The United States has 169 active **volcanoes** capable of producing a wide range of hazards that threaten people and infrastructure on the ground as well as aircraft in flight.
- In 2004, **wildfires** burned more than 8 million acres in 40 States.

USGS Science Seeks to Achieve

- Rapid **earthquake** impact assessments delivered to emergency managers
- Real-time **flood** inundation mapping to support emergency response
- Predictions of coastal impacts 48 hours before **hurricane** landfall
- Better predictions of where and when **landslides** will occur
- **Tsunami** risk maps for all coastal areas that may be at risk
- Early detection of **volcanic** activity to allow maximum response time
- Real-time **wildfire** condition information to support rapid firefighting activity

Integrated information about multiple hazards are useful for reducing loss of life and property from natural hazards.

Natural Hazards Monitoring Program

Geodesy and Deformation Activities

Mission statement

The USGS Earthquake Hazards Program monitors the Nation's earthquakes, studies *why they occur* and how they shake the ground, provides quantitative earthquake-hazard assessments, helps promote loss-reduction measures using these results, and provides crucial scientific information to assist emergency responders when earthquakes occur.

Geodetic observations and research
are required to fulfill the
USGS Earthquake Program mission

Role of geodesy in the USGS Hazards Program

- **Overview**
  - USGS geodetic activities in support of USGS hazards program (research in earthquakes, volcanoes, landslides, subsidence, etc.).
- **Geodetic Measurement and Monitoring Technologies**
  - **Global Navigation Satellite Systems (GNSS)**
    - **Global Positioning System (GPS)**
  - LIDAR – airborne and ground based tripod
  - Digital photography – airborne and spaceborne
  - Radar - InSAR and PSInSAR
  - Gravity – absolute, relative and airborne
- **Applications**
  - High-precision LIDAR mapping of the San Andreas Fault
  - Monitoring land surface deformation; landslides
  - Volcanoes
  - Measurements of water level changes
  - Subsidence measurements

Uses of GNSS to Fulfill Statutory Roles in USGS Hazards Mission Area

- USGS is delegated federal responsibility to **provide notifications and warnings for e**arthquakes, volcanic eruptions, and landslides.
- **Seismic networks** support NOAA’s tsunami warnings.
- **Streamgages and storm surge monitors** support NOAA’s flood and severe weather (including hurricane) warnings.
- **Geomagnetic observatories** support NOAA and AFWA geomagnetic storm forecasts.
- **Geospatial information** (mapping and GIS) supports response operations for wildfire and many other disasters.





USGS
science for a changing world

Geodetic Observations and the National Earthquake Hazards Research Program

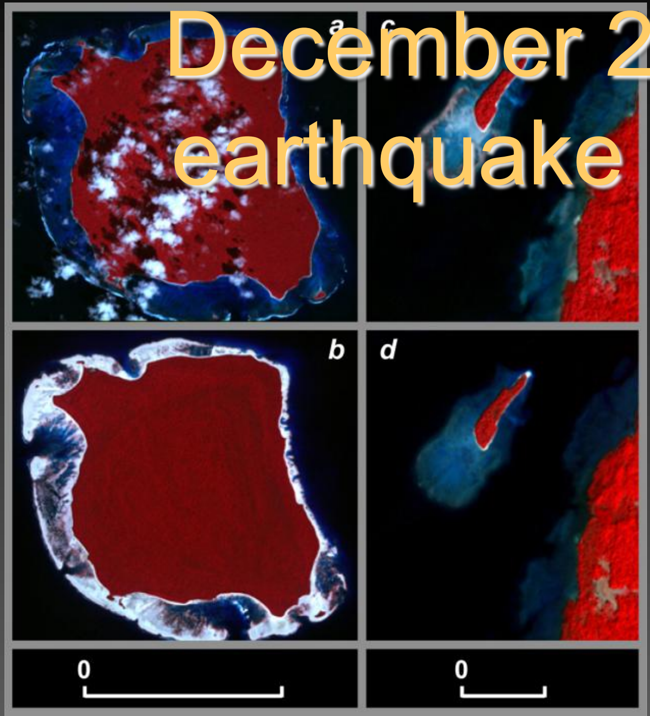
- **Improve quantification of seismic hazards**
  - *quantify the long-term strain accumulation and release along active fault systems*

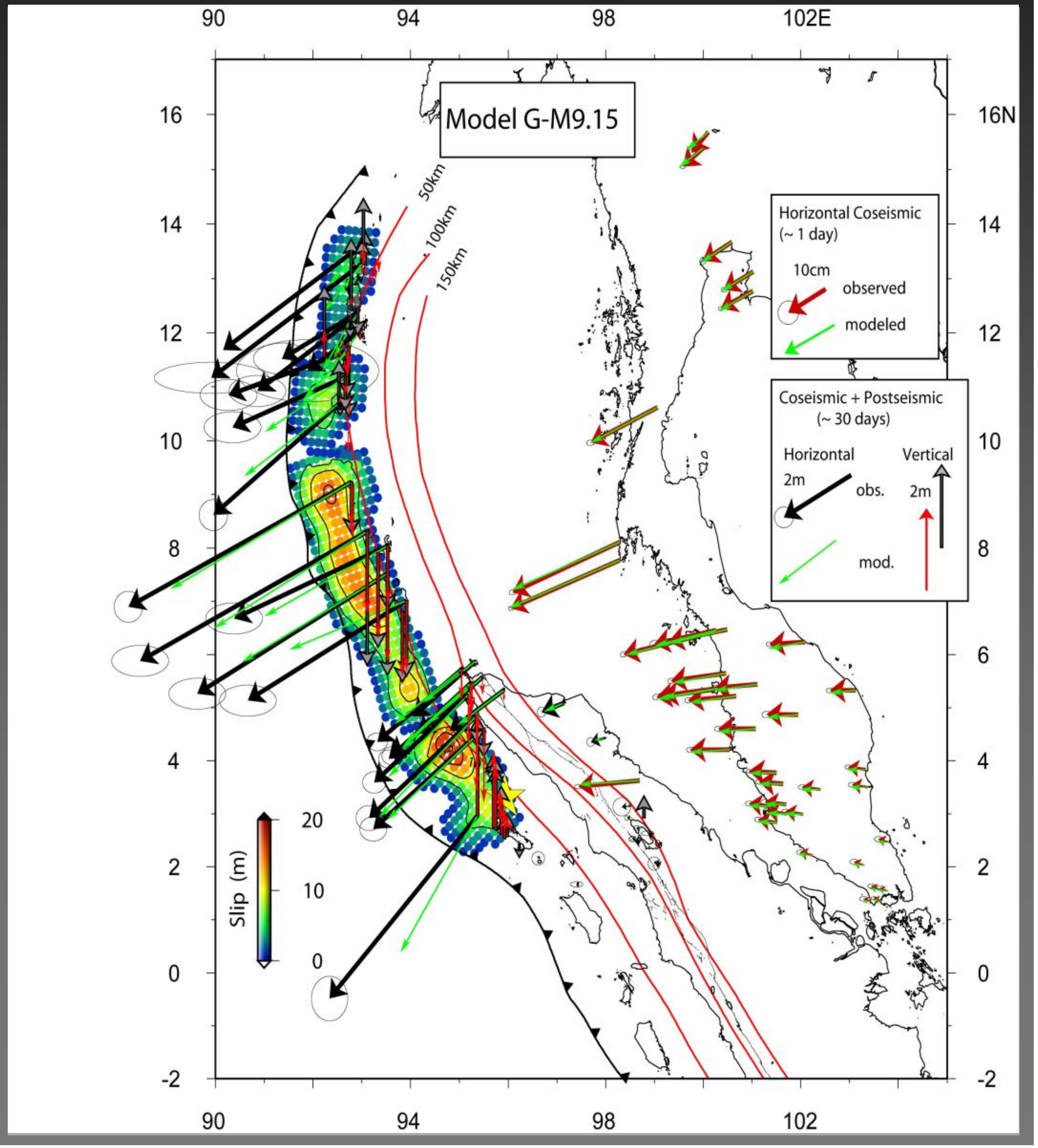
- **Modernization and expansion of real-time earthquake notification and monitoring systems**
  - *rapid assessment of the earthquake source*

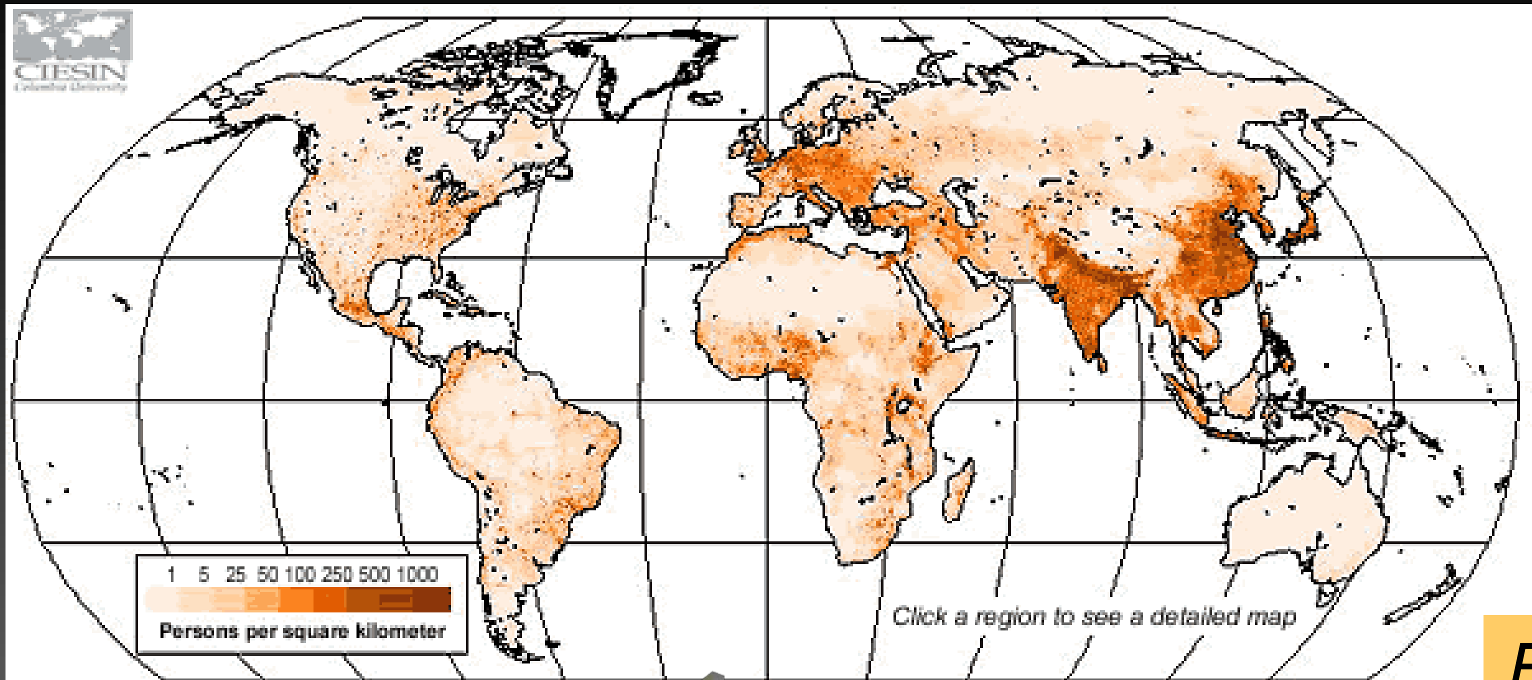
- **Achieve better scientific understanding of earthquake processes and effects**
  - *understanding the range of earthquake-related phenomena between seimic and geologic temporal bands*

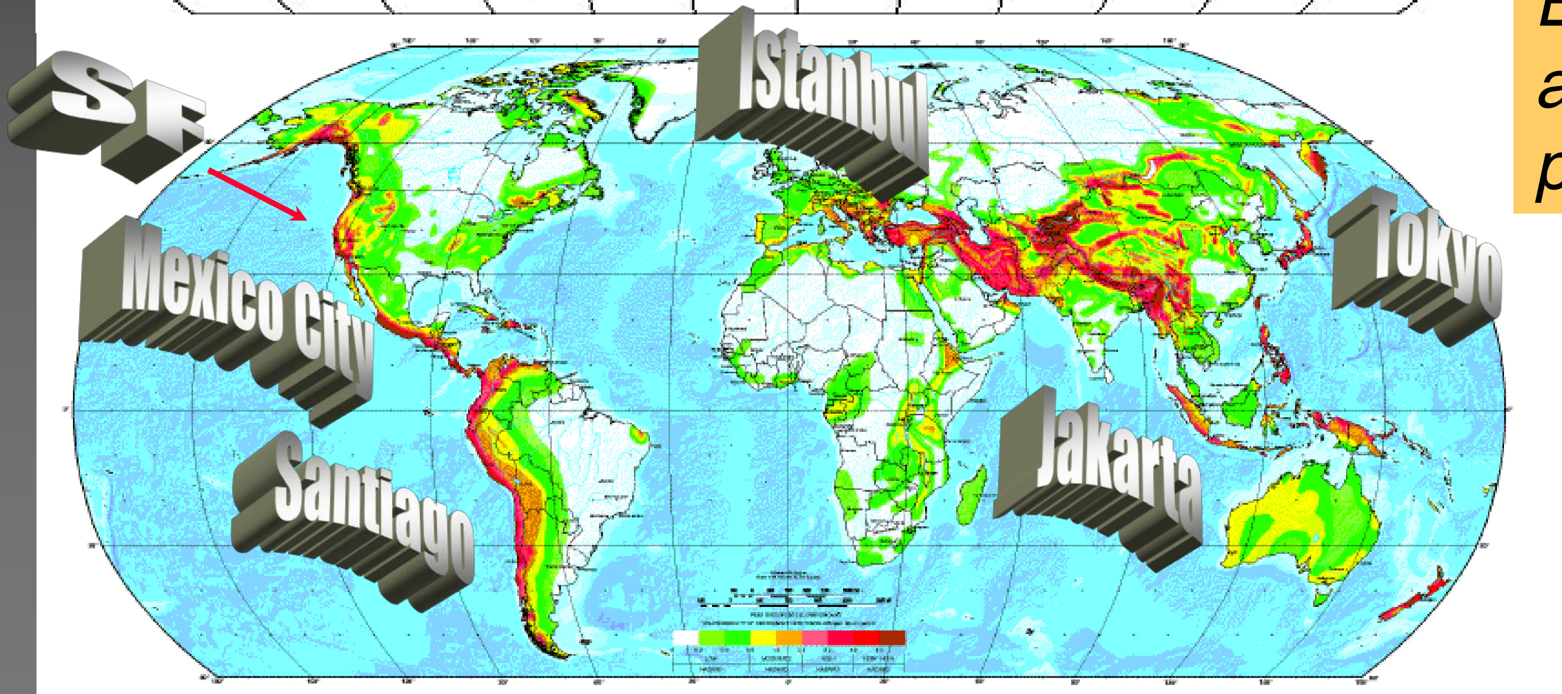
GNSS is a critical component

December 26, 2004 Sumatra-Andaman earthquake and Indian Ocean Tsunami



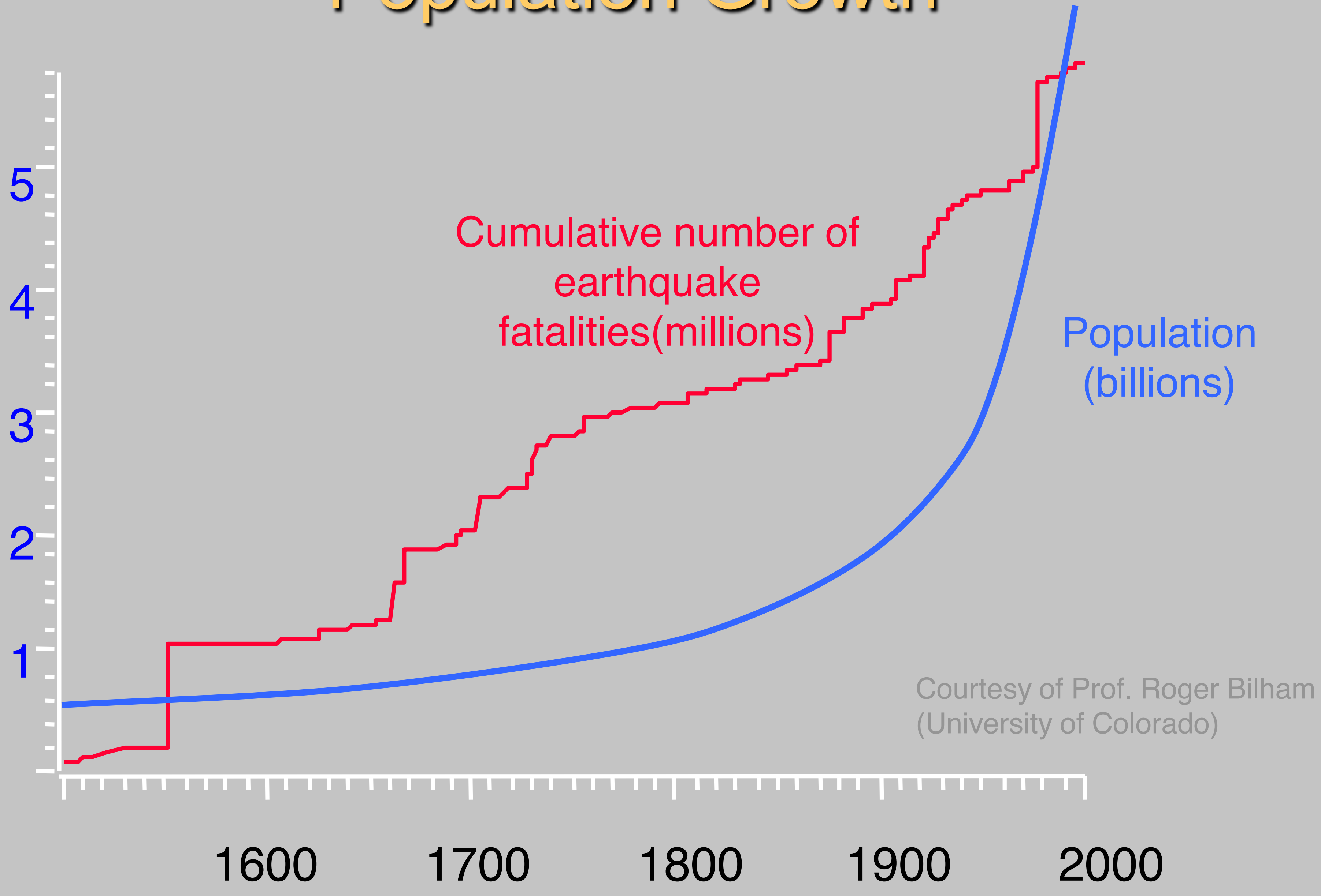




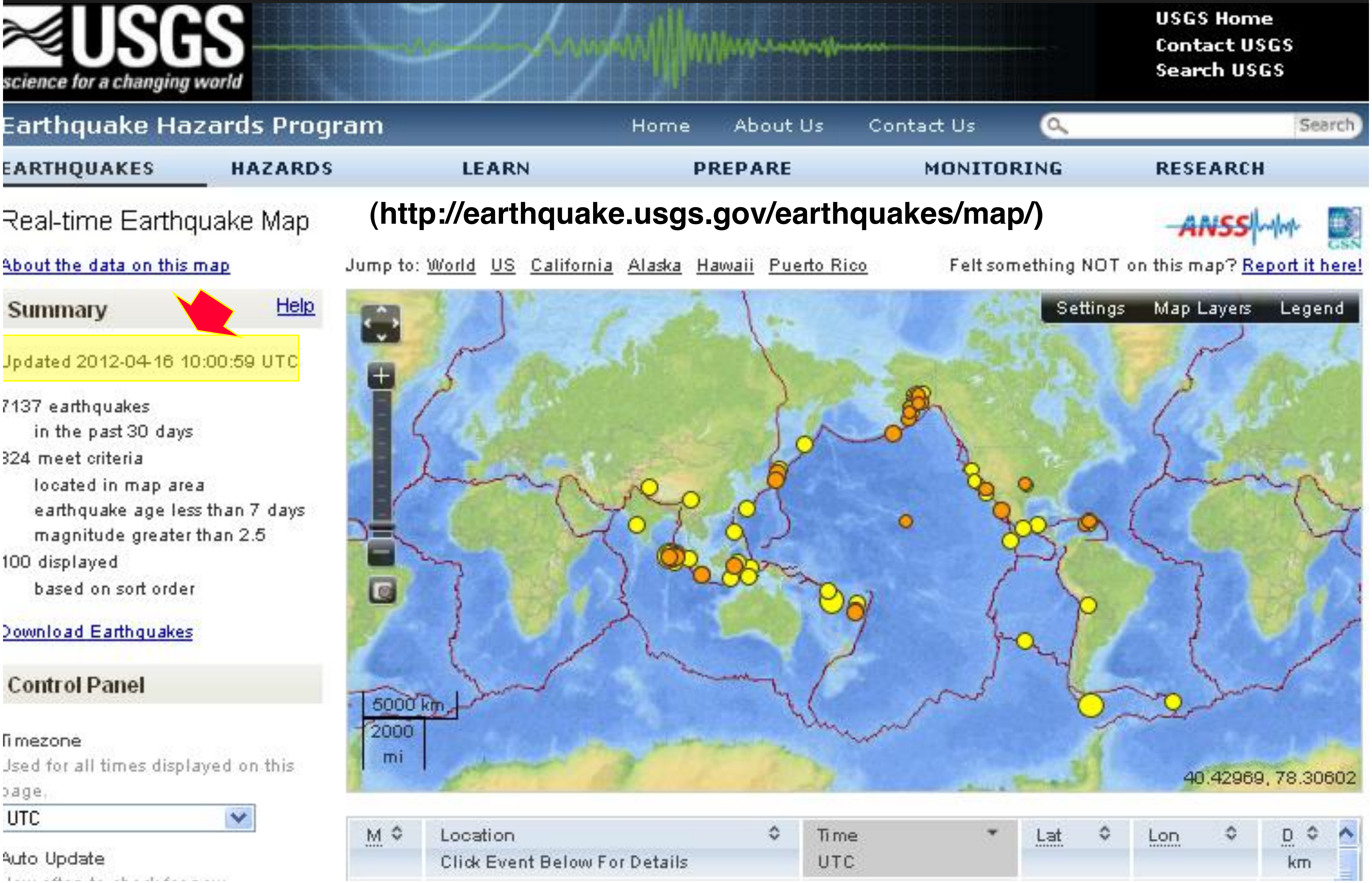


Earthquakes are a global problem

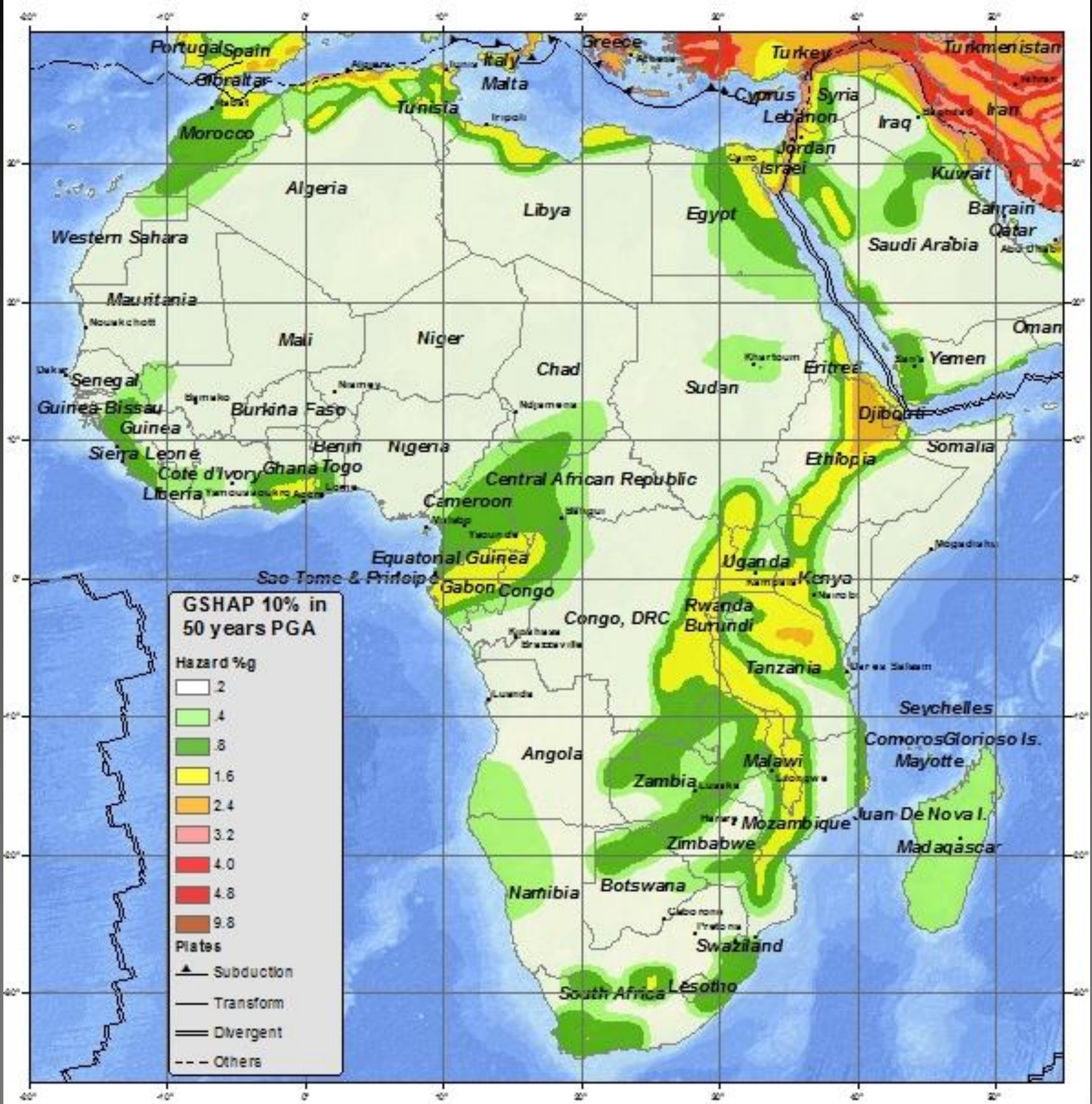
Earthquake Fatalities and Population Growth



GNSS precise time reference for accurate earthquake location worldwide - vital for tsunami alerts



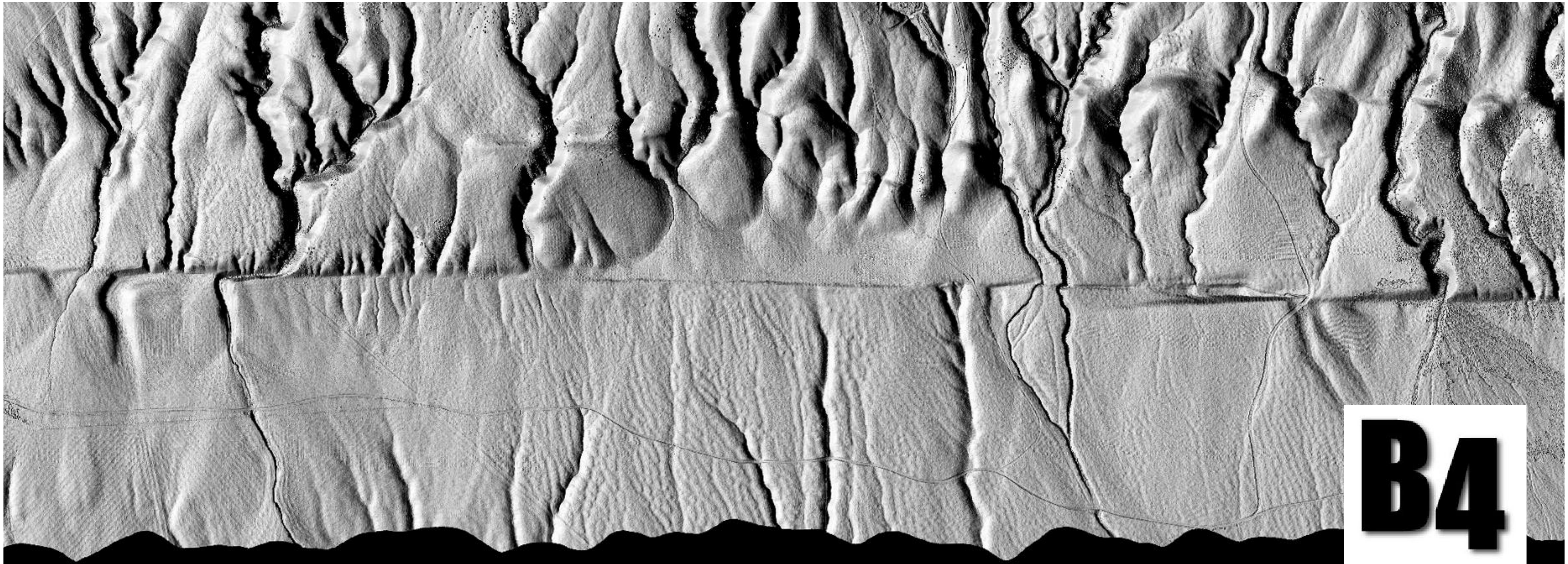
Seismic Hazards Map of Africa

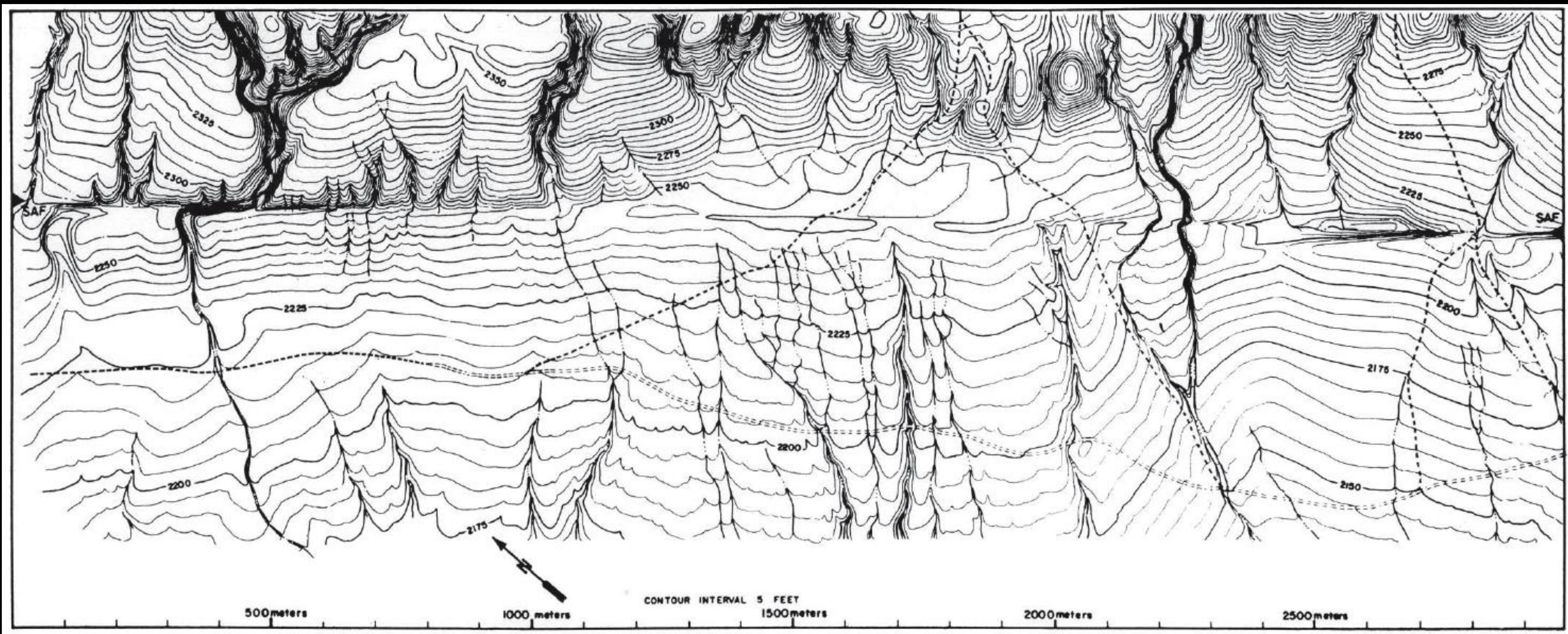


GSHAP – Global Seismic Hazard Assessment Program

San Andreas fault

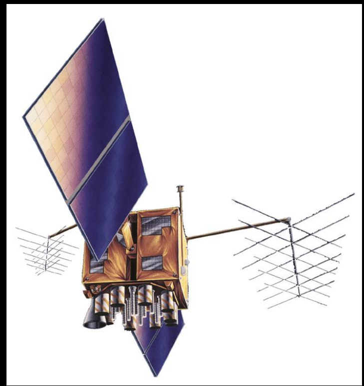
- 35 mm/yr slip rate;
  - >70% of plate motion
  - 1685, 1812, 1857 eq's
- Big Bend compression
  - 1971 Sylmar (M 6.7)
  - 1994 Northridge (M 6.7)
- California is now very heavily 'wired' with many GPS stations
- GPS measures plate motion strain accumulation and large earthquake displacements
- 'Natural laboratory' to study future 'Big Ones'
- B4 - Imaged by airborne LiDAR - ***GPS was crucial!***


B4


SAF
SAF
2350
2325
2300
2300
2275
2250
2250
2225
2225
2200
2175
2275
2250
2225
2200
2175
2150
CONTOUR INTERVAL 5 FEET
500meters
1000 meters
1500meters
2000meters
2500meters

SCIGN
SOUTHERN CALIFORNIA INTEGRATED GPS NETWORK

GPS



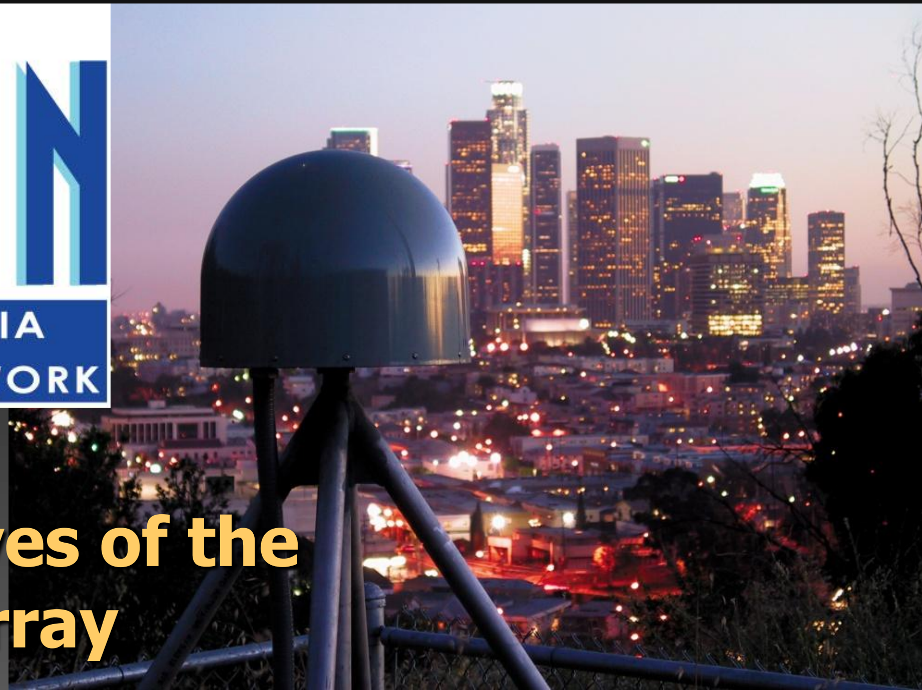
GPS network measures plate tectonic motions to an accuracy of better than **1 mm/yr**

We can see whether the motion is 'slow and steady,' or perhaps more interestingly it may sometimes accelerate or decelerate

W. M. Keck Foundation NASA NSF USGS science for a changing world

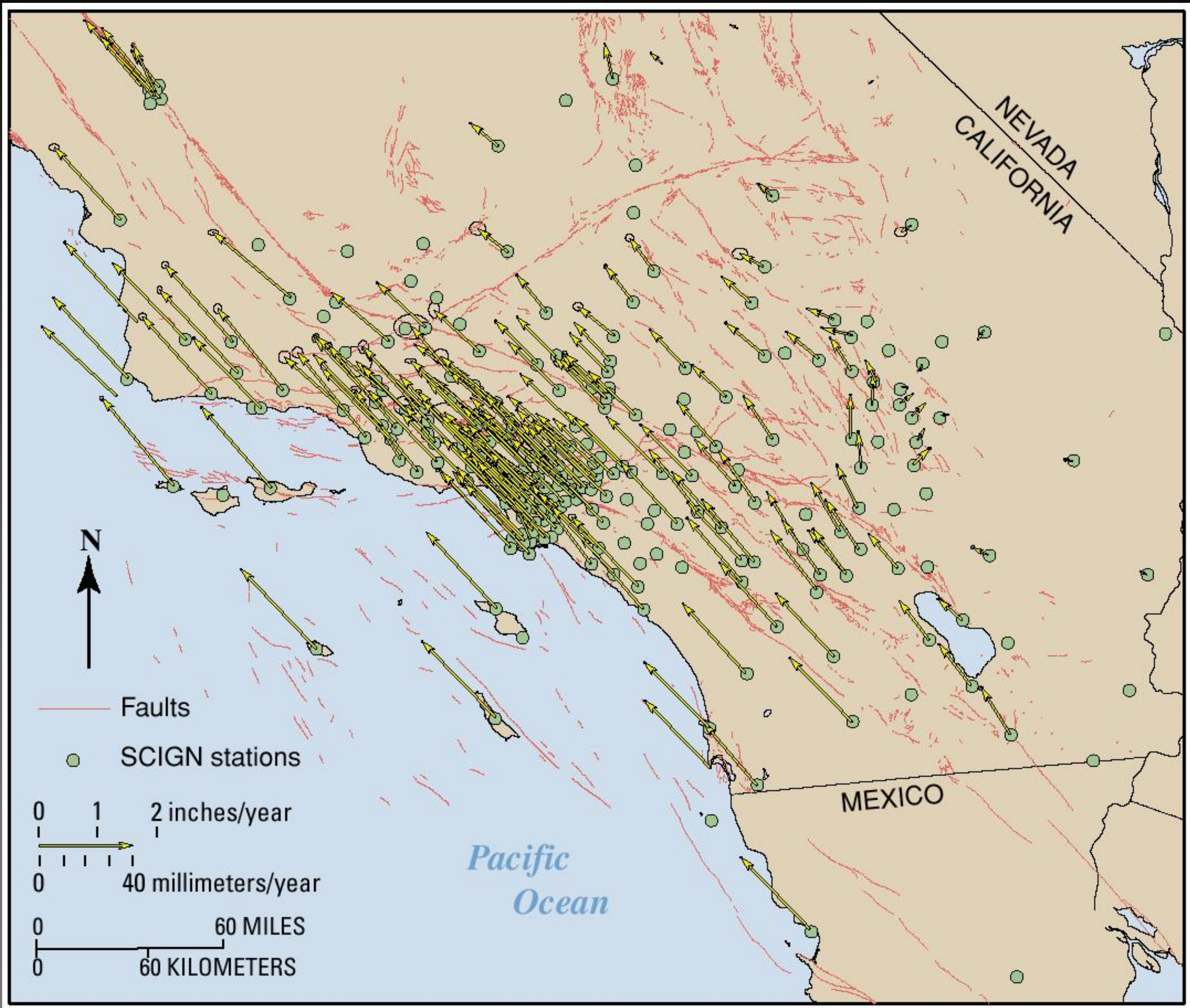
SCIGN

SOUTHERN CALIFORNIA INTEGRATED GPS NETWORK

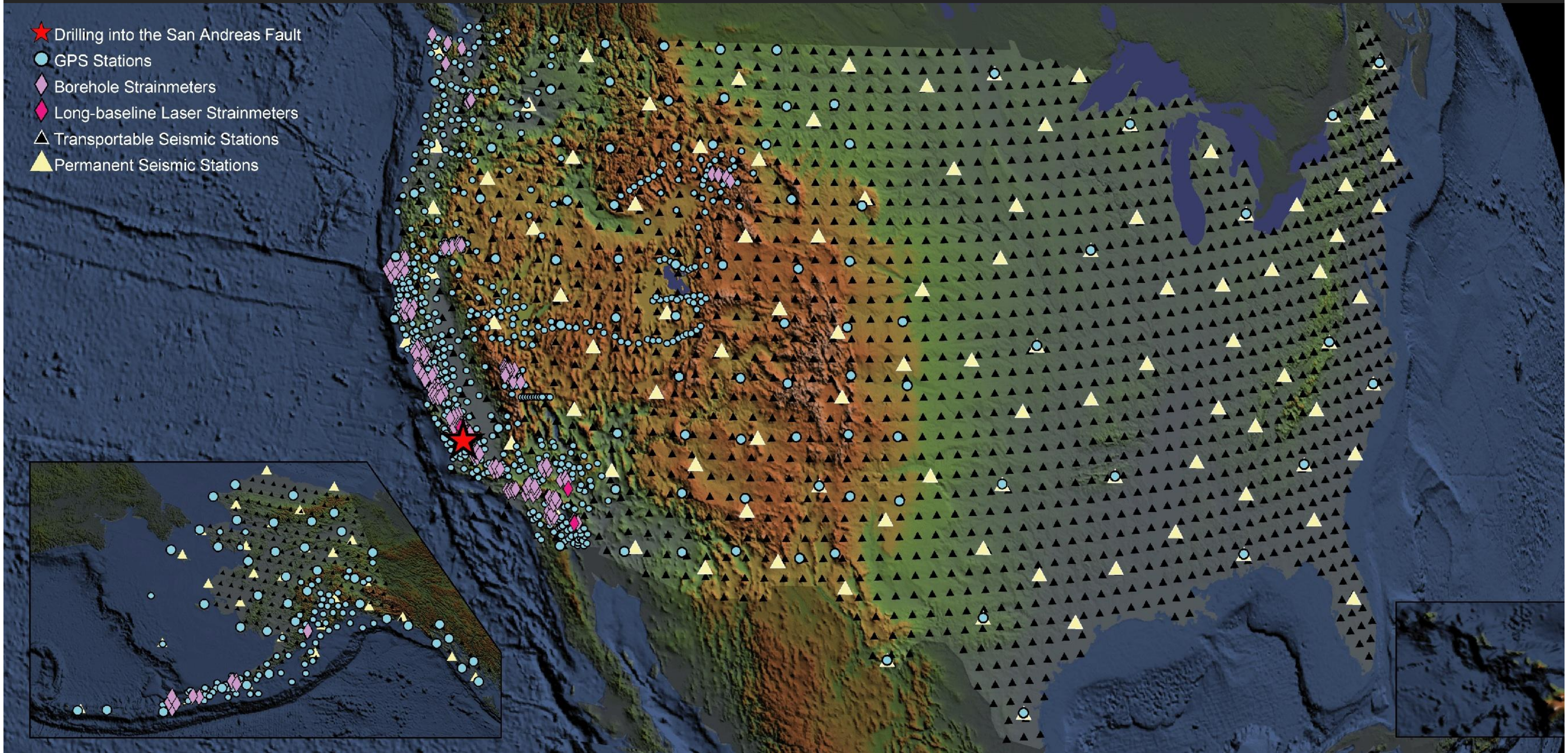


Major objectives of the SCIGN array

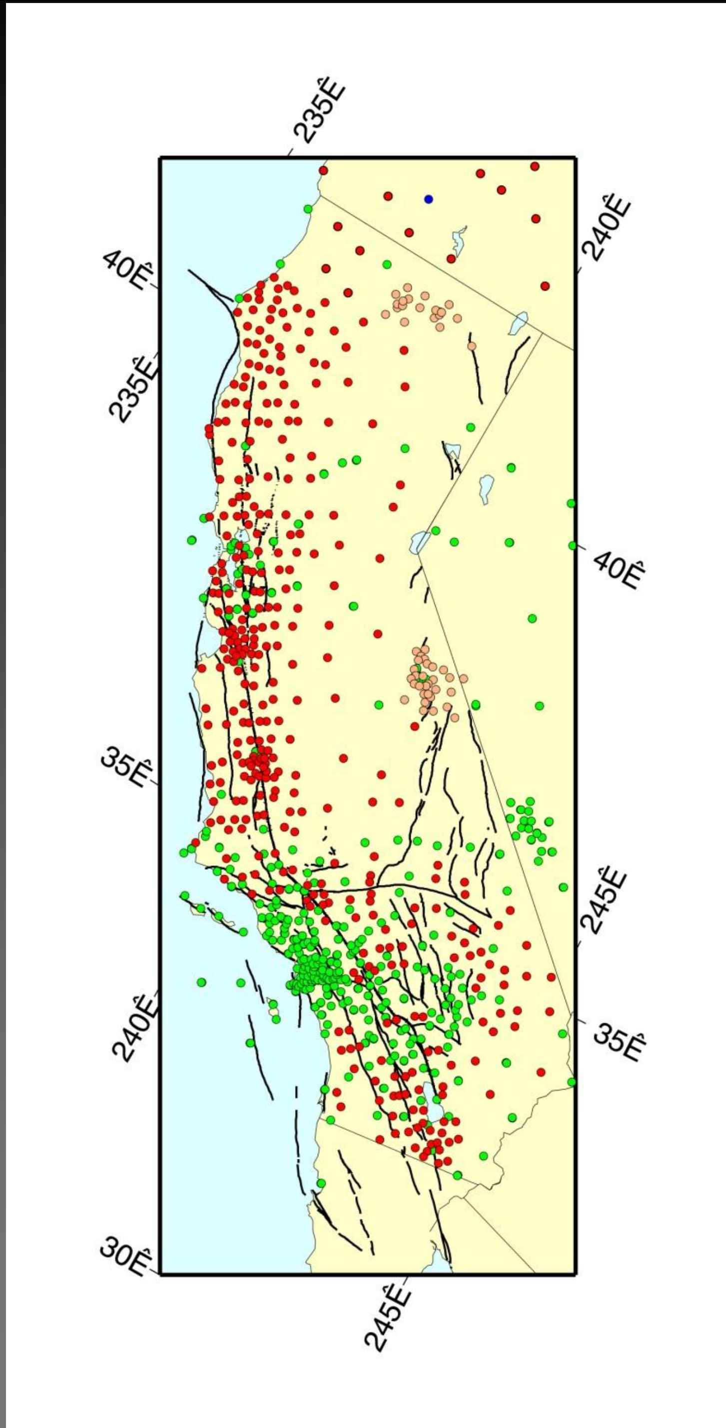
- To provide regional **coverage for estimating earthquake potential** throughout Southern California
- To **identify active blind thrust faults** and test models of compressional tectonics in the Los Angeles region
- To **measure local variations in strain rate** that might reveal the mechanical properties of earthquake faults
- In the event of an earthquake, **to measure permanent crustal deformation** not detectable by seismographs, as well as the response of major faults to the regional change in strain


NEVADA
CALIFORNIA
MEXICO
Pacific Ocean
N
Faults
SCIGN stations
0 1 2 inches/year
0 40 millimeters/year
0 60 MILES
0 60 KILOMETERS

earthscope
PROJECT



National Science Foundation
WHERE DISCOVERIES BEGIN



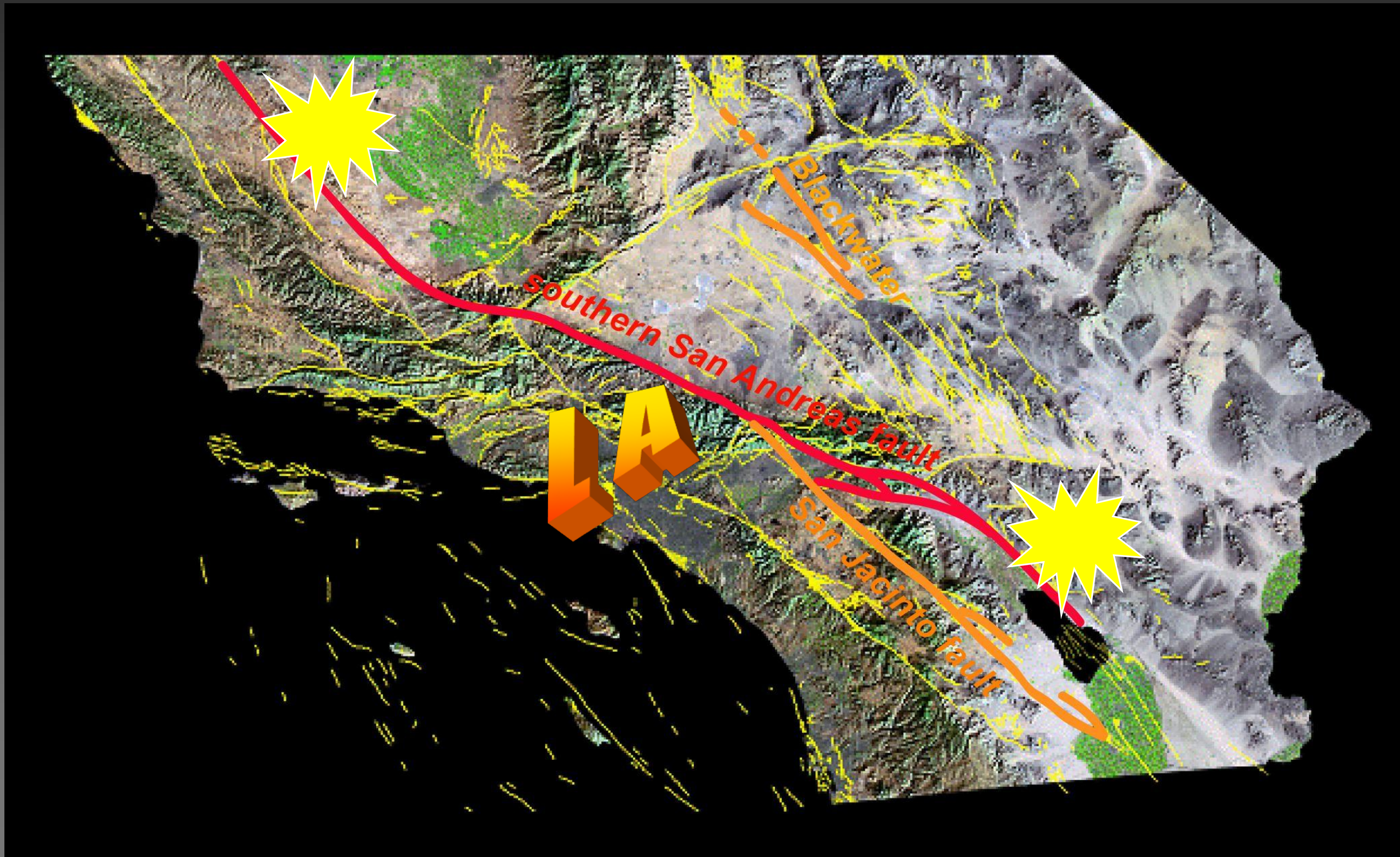
A New View Into Earth
earthscope

Plate Boundary Observatory

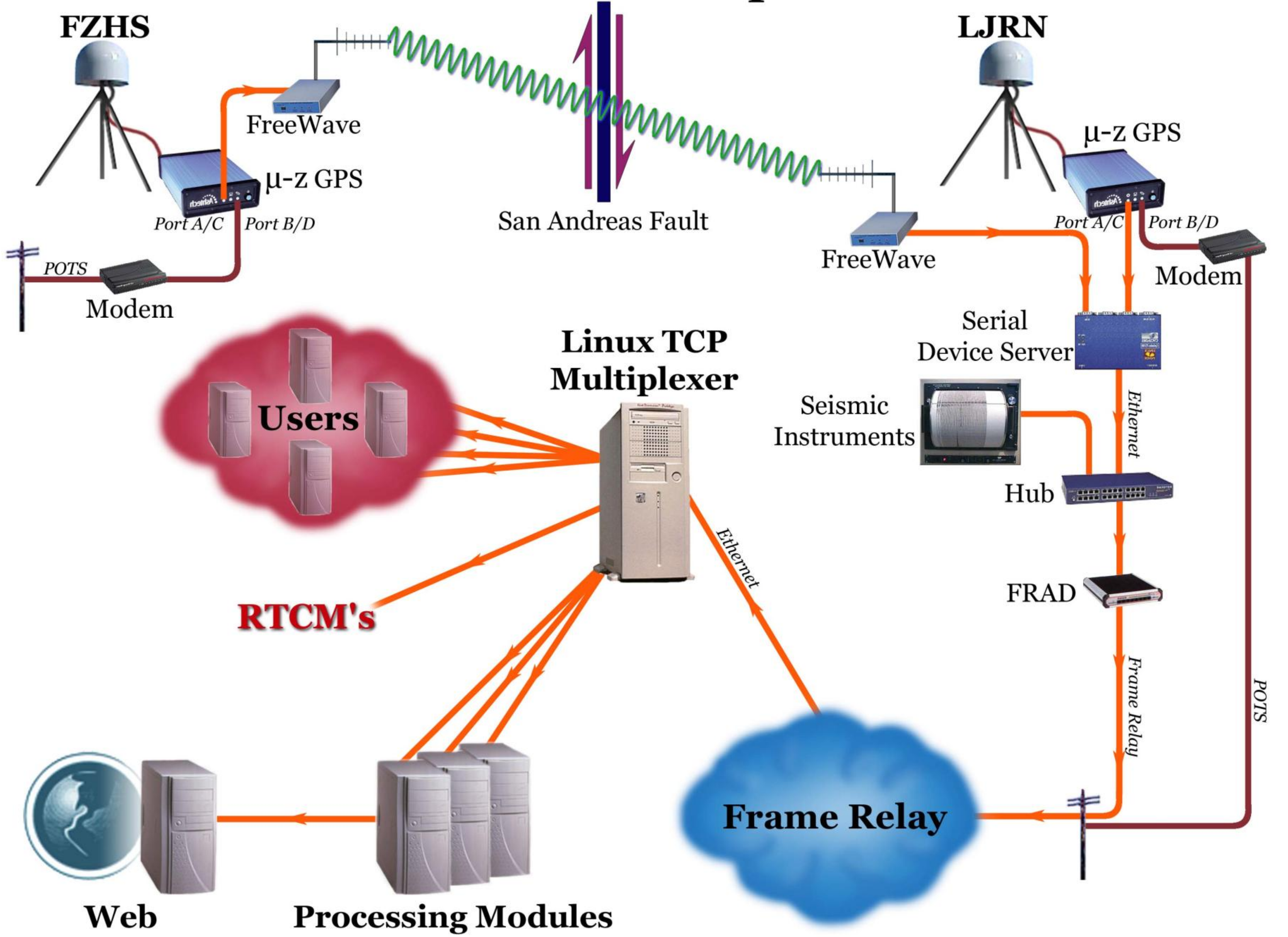
San Andreas plan

GNSS station clusters along San Andreas fault, especially along transitions from creeping to locked sections

San Andreas – Earthquake monitoring strategy
Detect possibly the “big one”
~120 km from Los Angeles (LA)



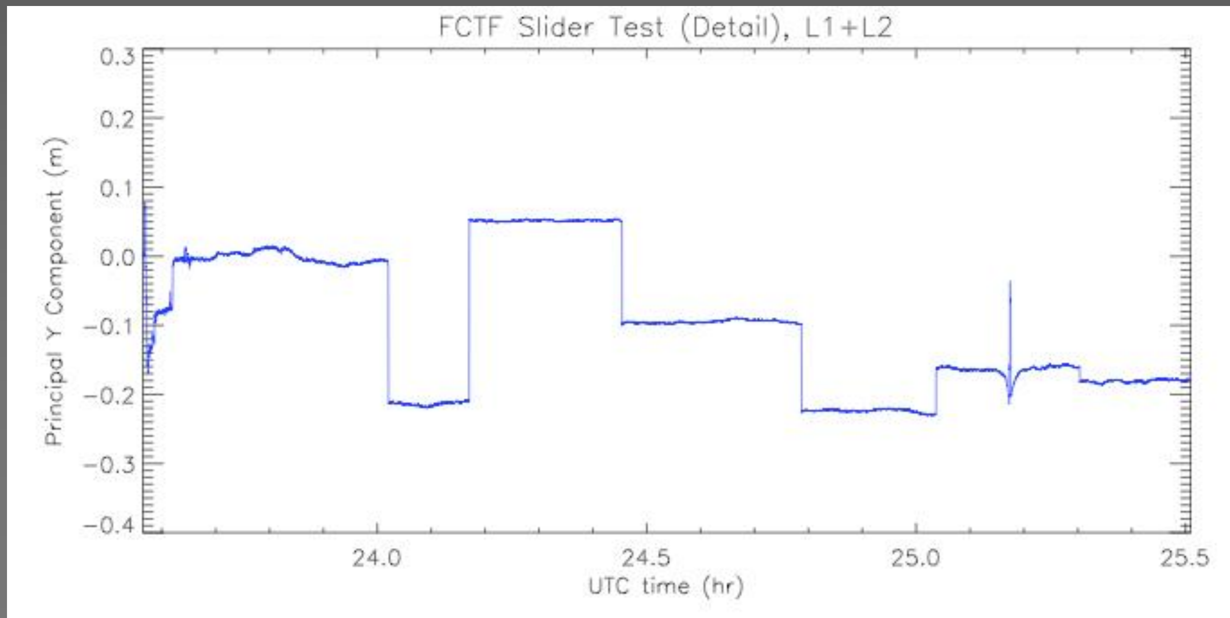
Real-Time GPS Slip Sensor



Real-time GNSS Precise Point and Relative Positioning

Goal: achieve accuracies at the millimeter level or better

- There is progress, but step tests and other basic testing have revealed issues of gross errors, delayed convergence, and noise
- Required is a robust and precise real-time GNSS measurement capability at the millimeter level
    - May require integration of sensors; such as inertial aiding

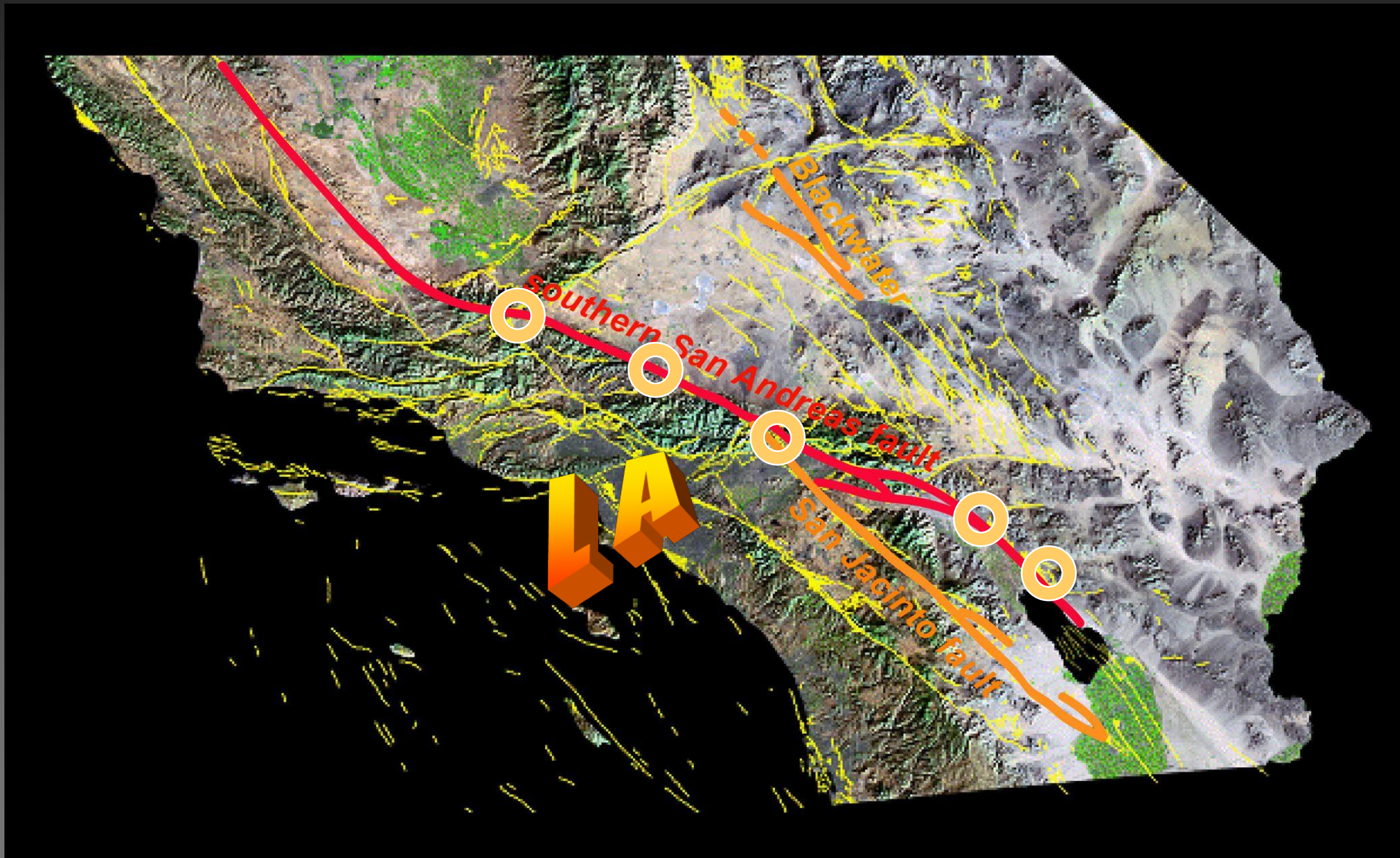


Lone Juniper Ranch and Frazier Park High School

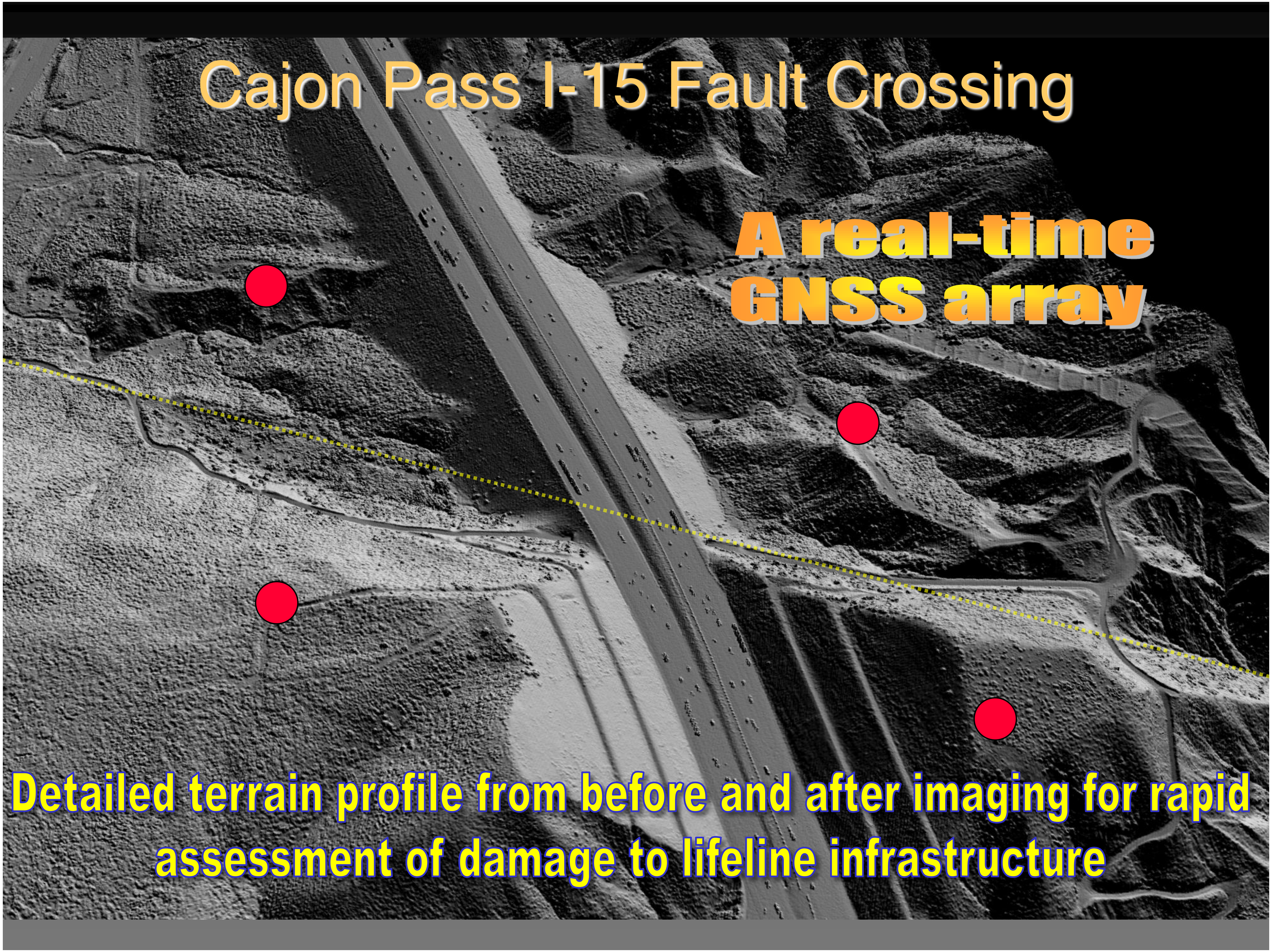
GPS fault slip sensor; recording rate up to 10 Hz

Stations spans the San Andreas fault near Gorman, California

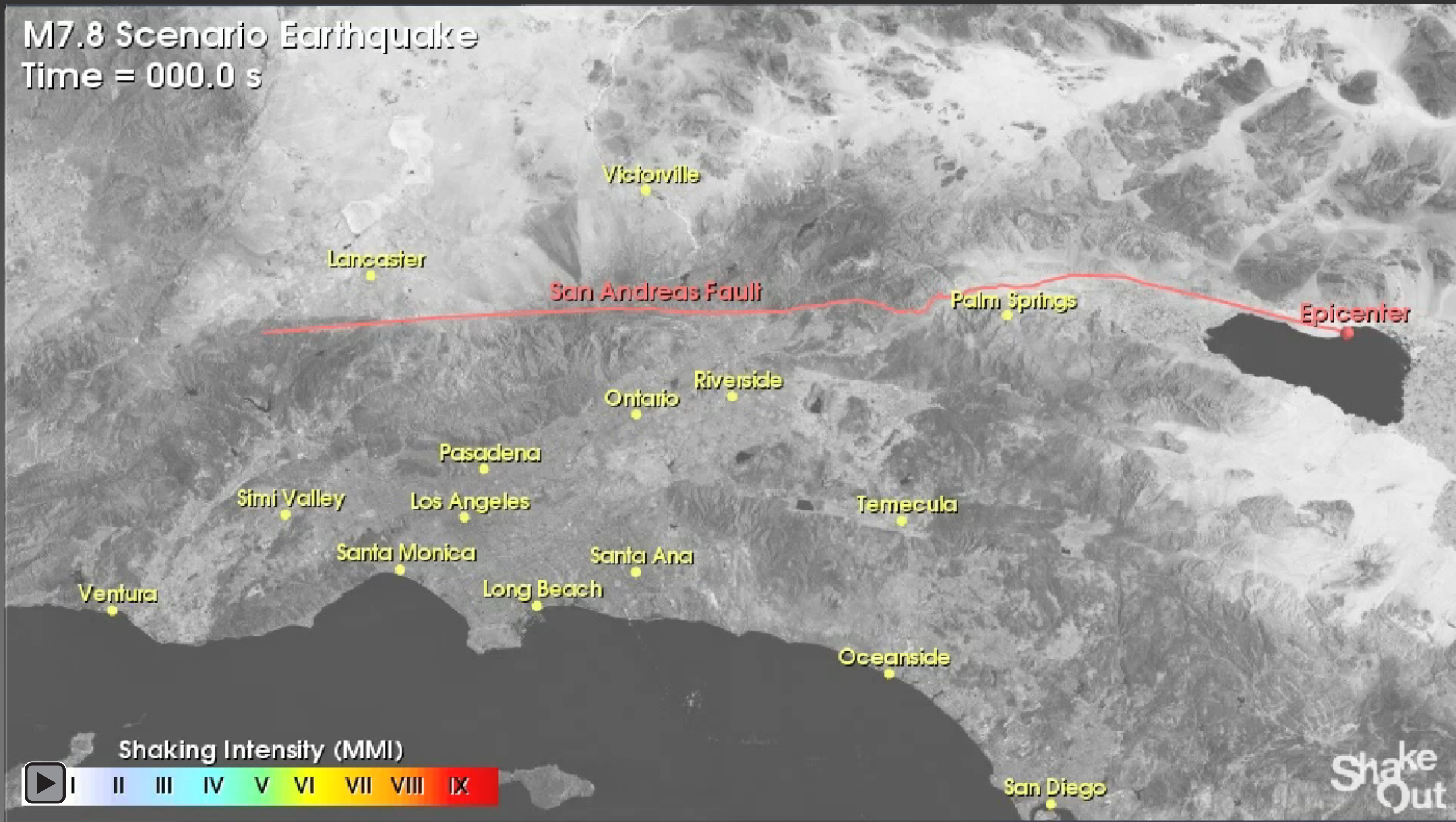
San Andreas - instrument major lifeline infrastructure crossings



GNSS augmented with accelerometer arrays


Cajon Pass I-15 Fault Crossing
A real-time GNSS array
Detailed terrain profile from before and after imaging for rapid assessment of damage to lifeline infrastructure

USGS Earthquake Shakeout Drill
10:00 AM, November 13, 2008



PAUSE

Movie

of

Shakeout Demonstration

Tangshan, China

1976 - M 7.5

255,000

people died

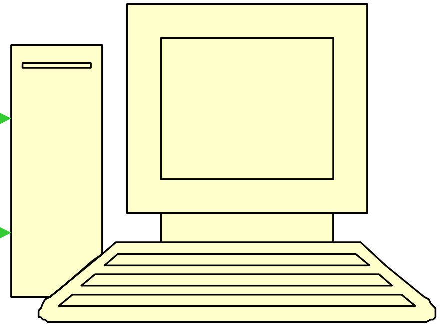
(official)

Northridge, CA
1994 - it *can*
happen here

Earthquakes Don't Kill People, Buildings Do...

REAL-TIME DAMAGE ASSESSMENT

- Satellite
- Telemetry
- Internet

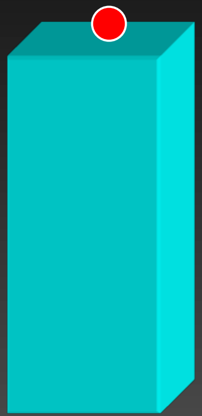


Courtesy of
Erdal Safak (USGS)

SENSOR PACKAGE

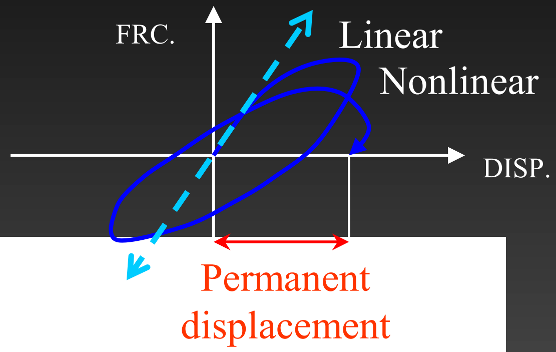
-Accelerometer
-Tiltmeter
-GPS sensor

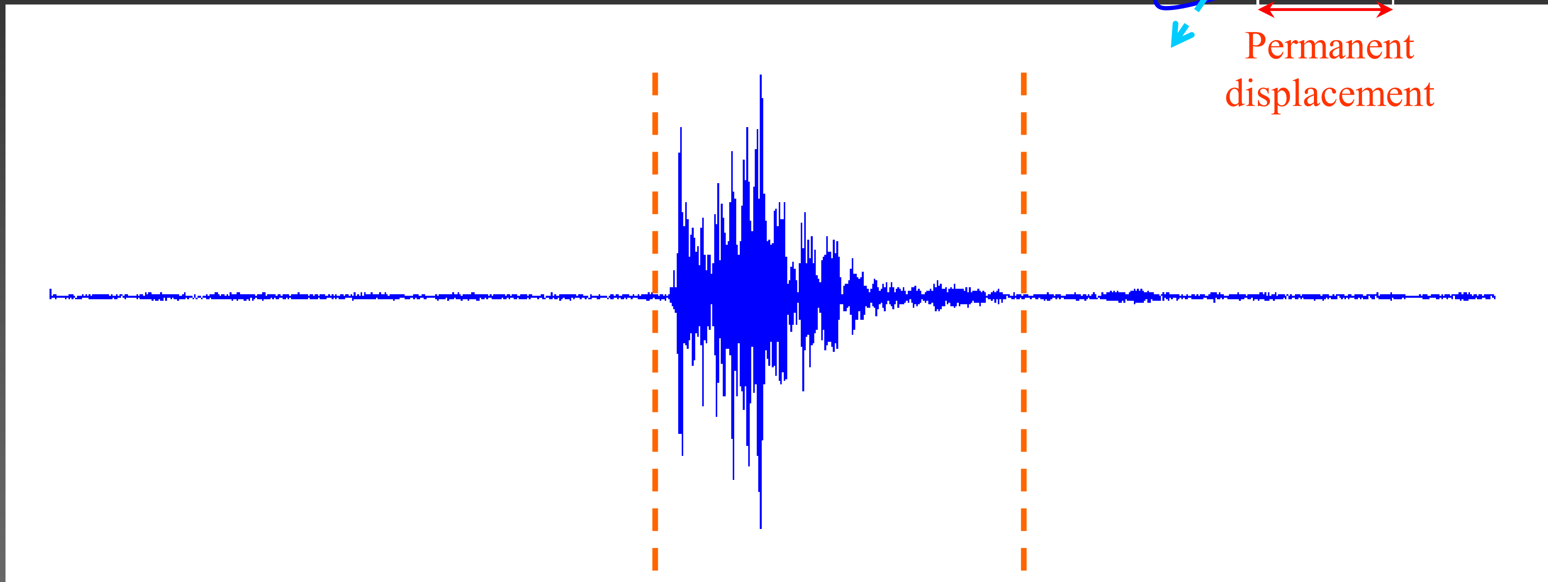
Automated Tagging and Real-Time Damage Distribution Maps



GNSS monitor on roof of building

Multiple sensor package:
- Acceleration / Velocity
- Displacement (GNSS)
- Rotation (tilt-meter)





Pre-earthquake:
- Reference static displacement
- Reference static rotation
- Mean and variance of dynamic characteristics

During earthquake:
- Changes in dynamic characteristics
- Hysteretic behavior
- Damage initiation

Post-earthquake:
- Permanent static displacement
- Permanent static rotation
- Mean and variance of dynamic characteristics

March 11, 2011 Japan earthquake

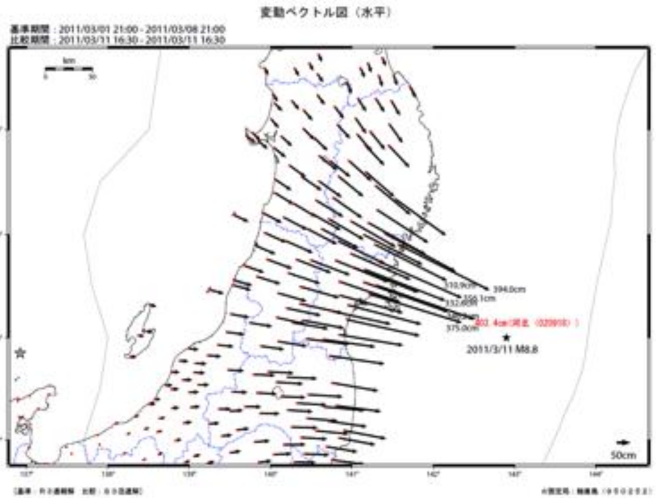
Initial GPS results from GSI showed 2.6 meters shift

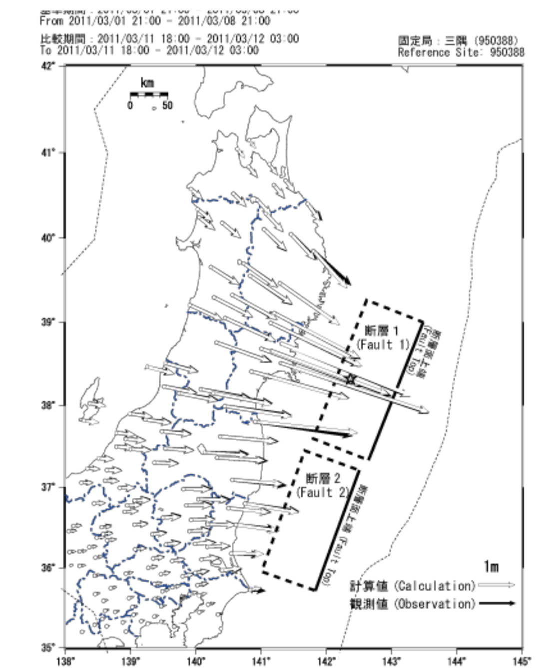
Later results gave maximum GPS offset of **4.034 m** (that's 13 feet)

Data were openly available and other groups quickly confirmed these results

Movies made of the displacements to help visualize the information

The





星印は USGS の震央（142.369°，38.322°）
A Star indicates an epicenter released from USGS (142.369°, 38.322°)

矩形断層 2 枚での推定結果
Two rectangular faults with uniform slip are assumed.

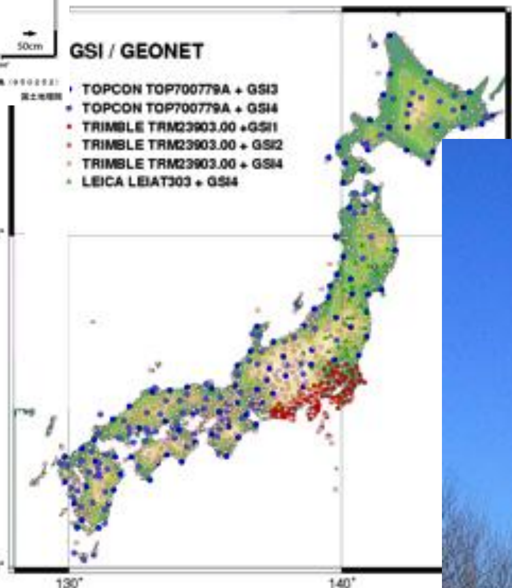
西側に傾き下がる逆断層．モーメントマグニチュードは北側（断層 1）が 8.7，南側（断層 2）が 8.2．2 つ合わせて 8.8（暫定）．
West-dipping reverse fault. Total moment magnitude: Mw8.8. (Northern segment: Mw=8.7, Southern segment: Mw=8.2)

断層の長さは南北に約 200km の断層 1 と約 180km の断層 2 で合計約 380km．総延長はおよそ 400km.
Total major rupture length: ~400 km (Fault Length: Northern segment ~200 km / Southern segment ~180 km)

	緯度 Lat	経度 Lon	上端深さ Depth (Fault Top) km	長さ Length km	幅 Width km	走向 Strike	傾斜角 Dip	すべり角 Rake	すべり量 Slip m	Mw
断層 1	39.00°	143.49°	10.0	199	85	202°	18°	97°	27.7	8.7
断層 2	37.21°	142.51°	10.1	176	82	201°	15°	81°	5.9	8.2

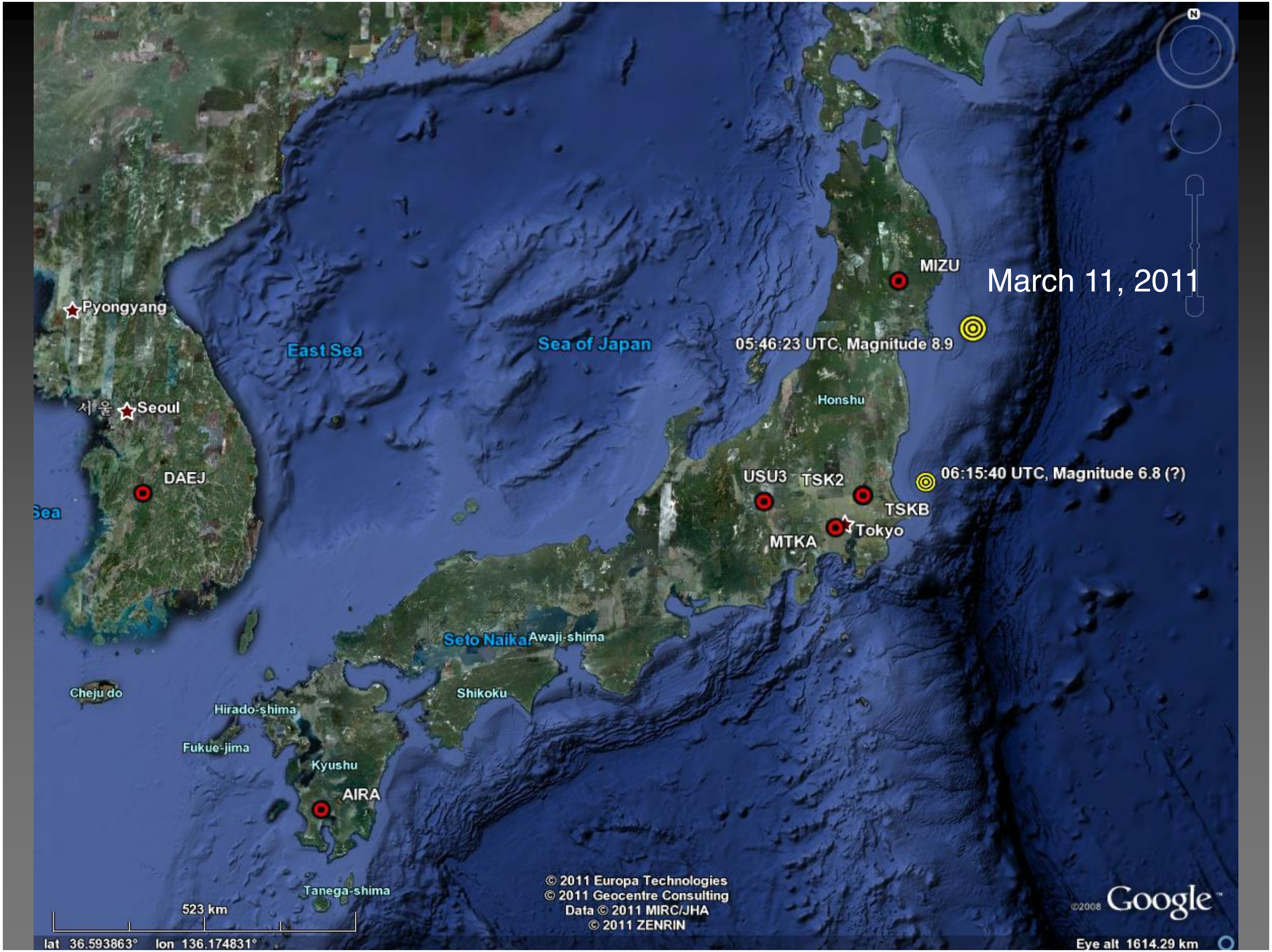
国土地理院資料
Geospatial Information Authority of Japan

In the 1990s, Japan coordinated with US on construction of continuously-operating GPS stations (similar to S. California). Japan built a network of over 1000 GPS stations called **GEONET.**

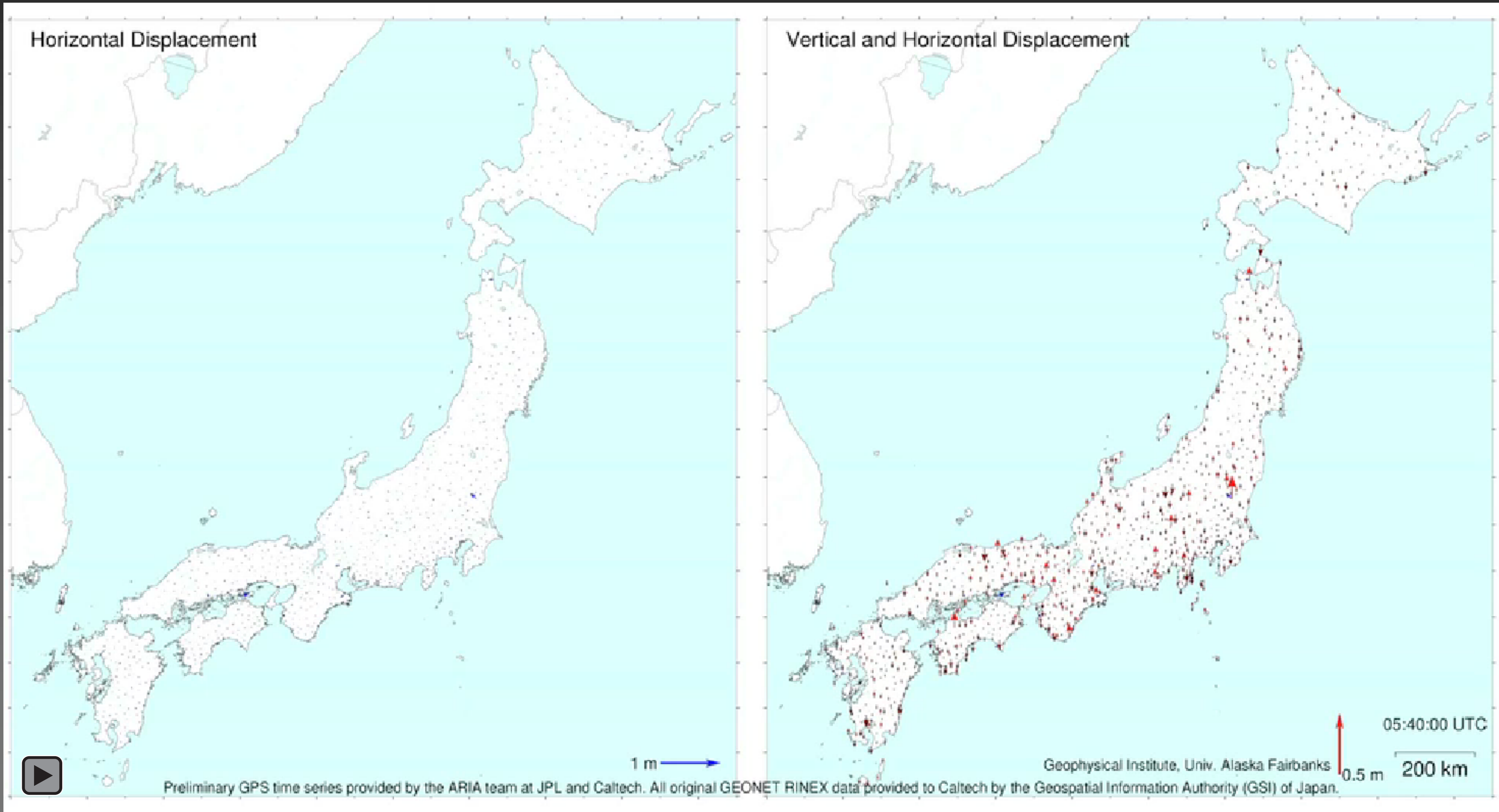


Post-seismic:

re-adjustments will go on for years, GPS is the best way to examine it


March 11, 2011
05:46:23 UTC, Magnitude 8.9
06:15:40 UTC, Magnitude 6.8 (?)
MIZU
USU3
TSK2
TSKB
MTKA
Tokyo
DAEJ
AIRA
Pyongyang
서울
Seoul
East Sea
Sea of Japan
Honshu
Sea
Seto Naikai
Awaji-shima
Shikoku
Kyushu
Cheju do
Hirado-shima
Fukue-jima
Tanega-shima
523 km
lat 36.593863° lon 136.174831°
© 2011 Europa Technologies
© 2011 Geocentre Consulting
Data © 2011 MIRC/JHA
© 2011 ZENRIN
©2008 Google
Eye alt 1614.29 km

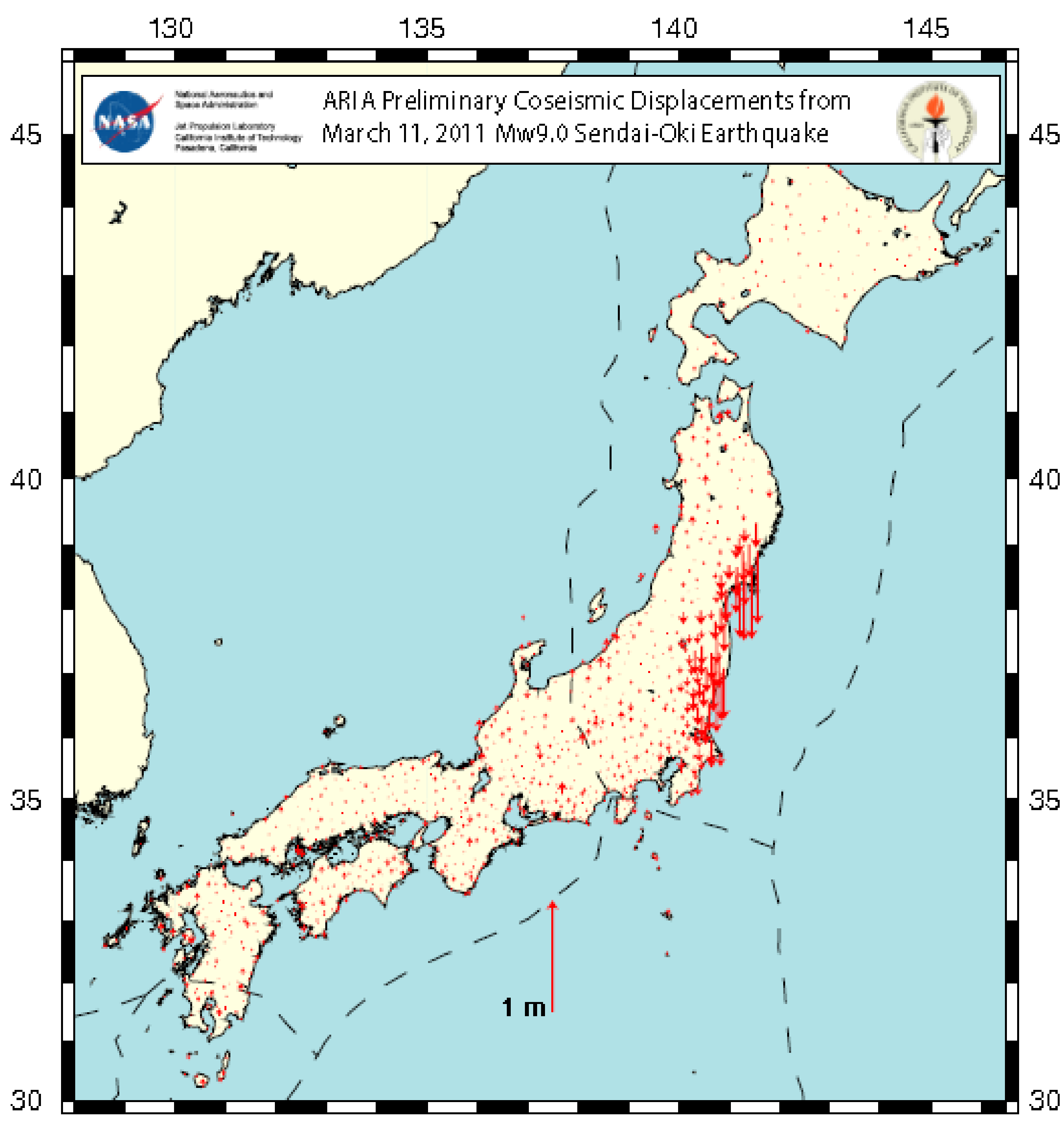
GNSS from GSI, Japan; M8.9 Tohoku



PAUSE

Movie
of
Horizontal and Vertical Displacements

GPS time series

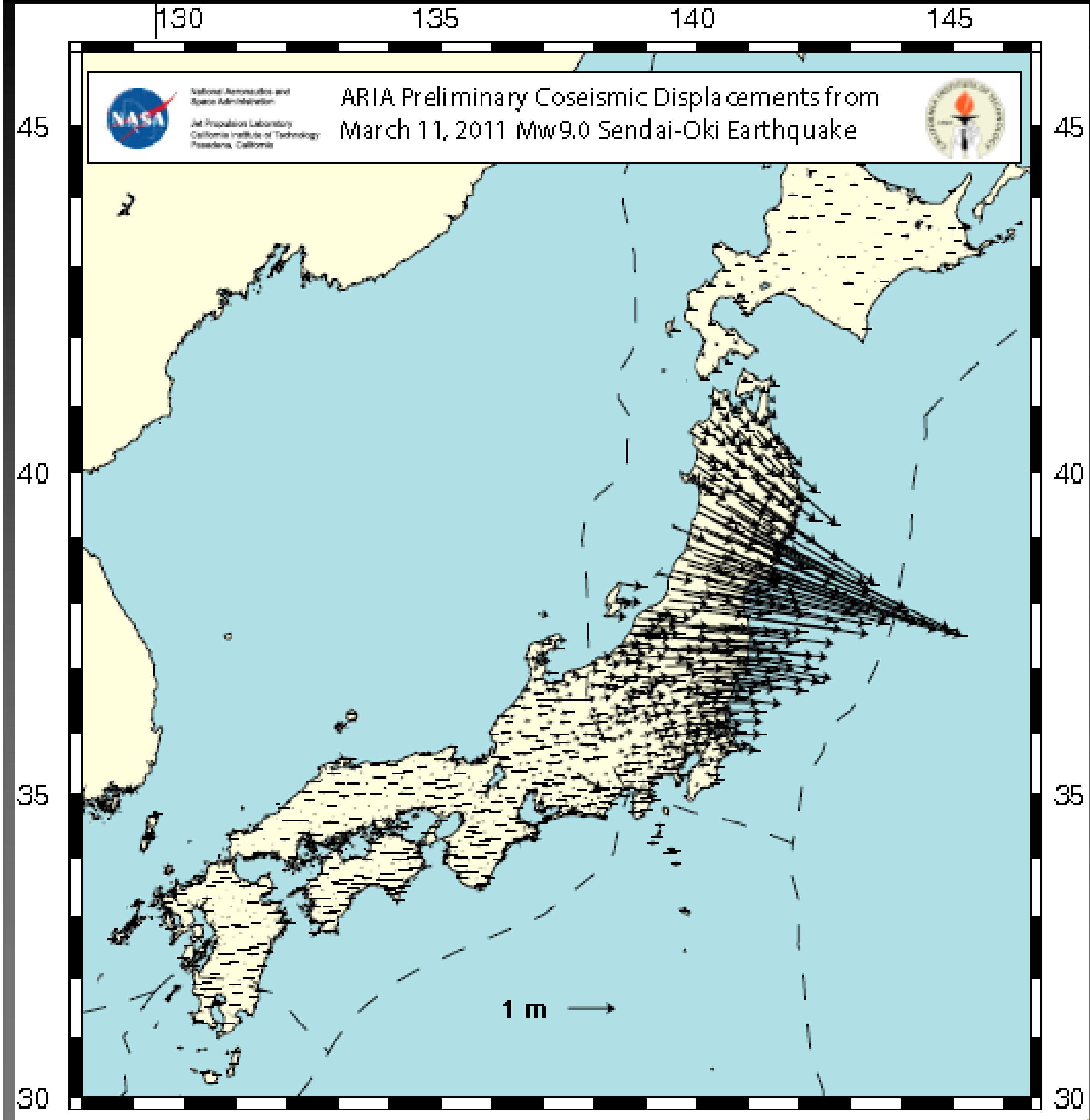


Vertical Displacements

Difference between estimated positions of GEONET stations at 05:00 and 06:30 UTC on March 11, 2011

Solutions by JPL and Caltech.

GPS 1 Hz data in RINEX format provided by the Geospatial Information Authority (GSI) of Japan.



Horizontal Displacements

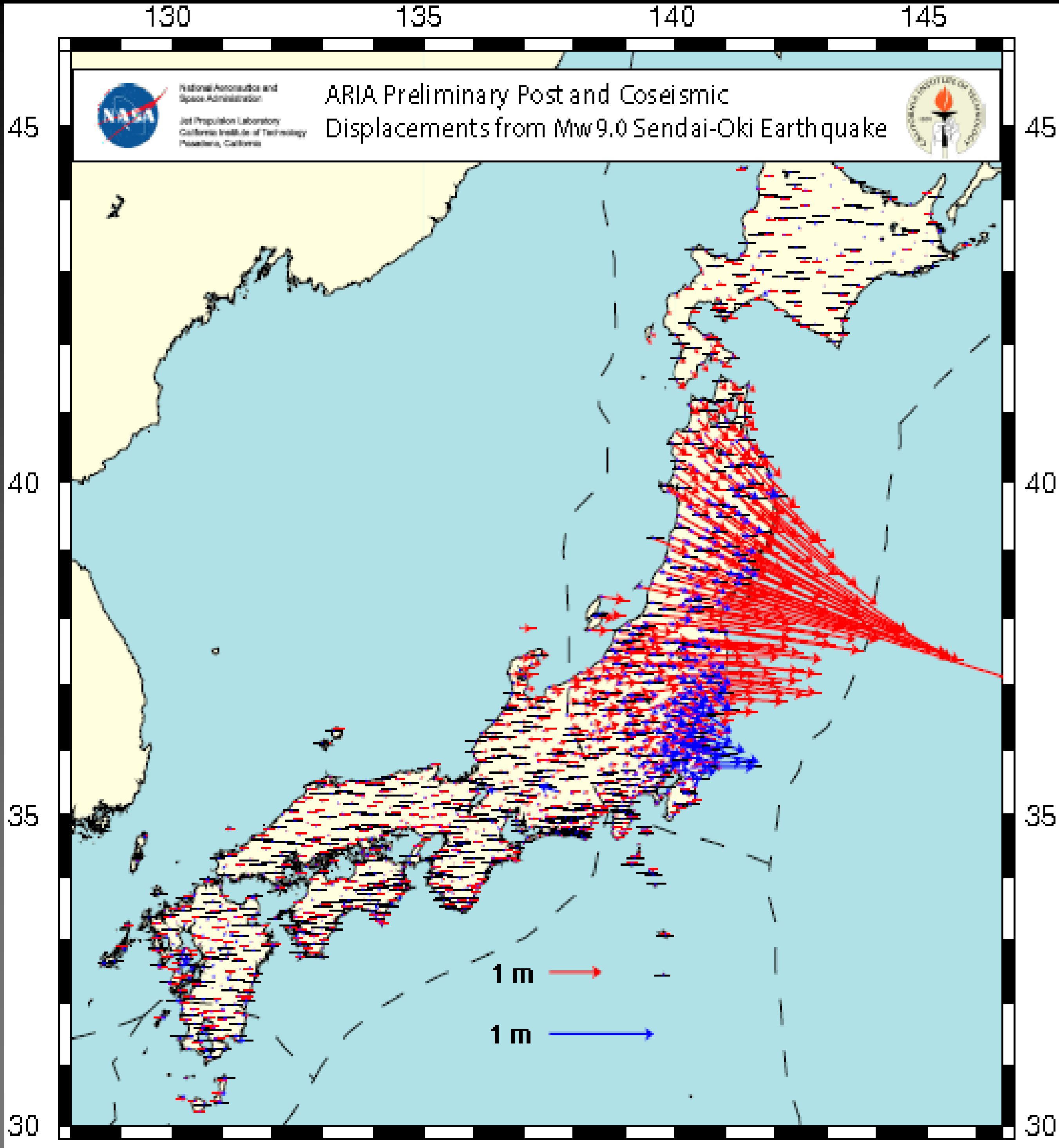
Difference between estimated positions of GEONET stations at 05:00 and 06:30 UTC, March 11, 2011

Bars at end of vector show 95% error estimate.

Solutions by JPL and Caltech.

GPS 1 Hz data in RINEX format provided by the Geospatial Information Authority (GSI) of Japan.

Horizontal Displacements

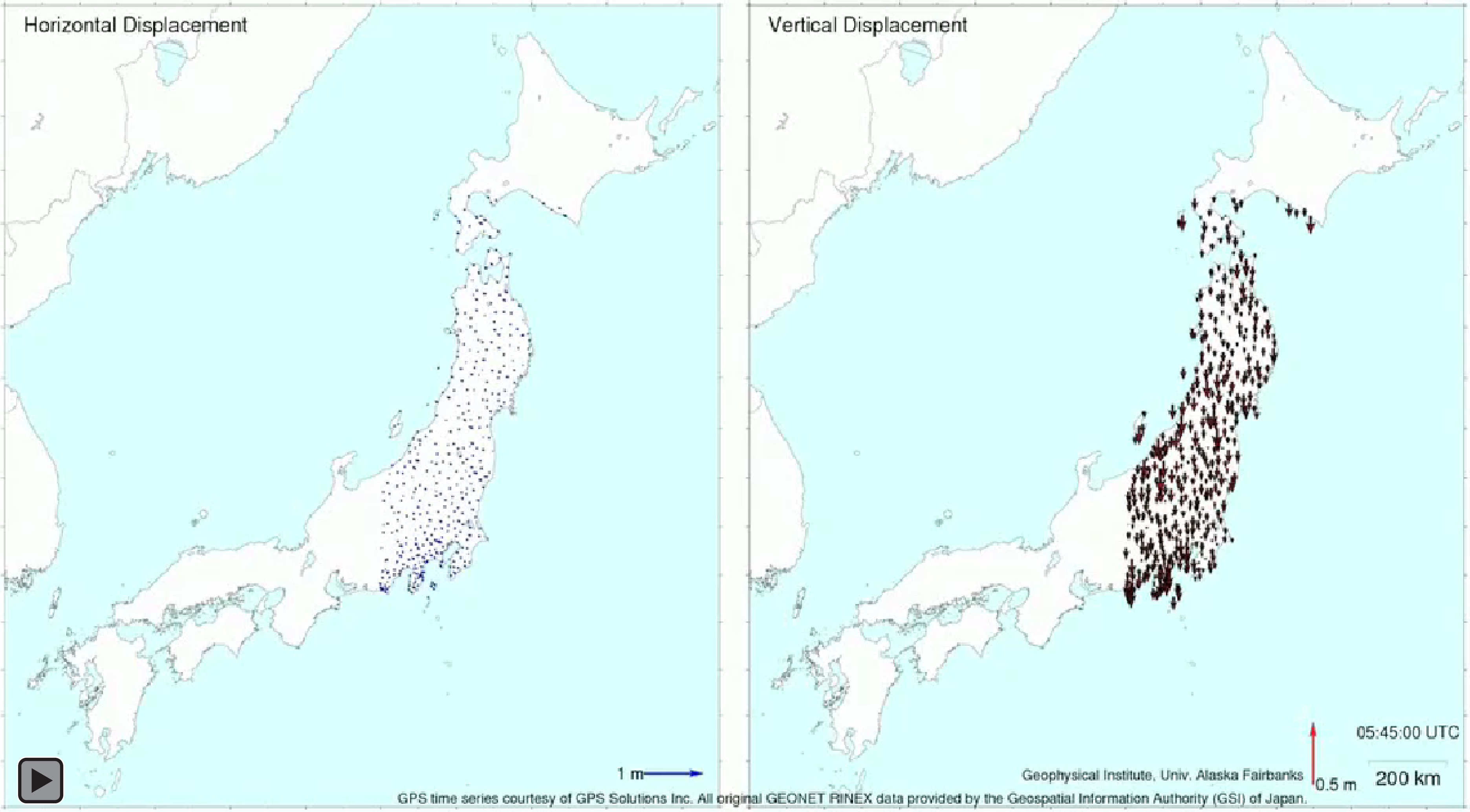


Displacements of position estimates for GEONET stations from 05:00 to 06:30 UTC, March 11, 2011.

Coseismic displacement in red. First 8 h of postseismic motion in blue.

Bars at end of vector - 95% error estimate.

GPS 1 Hz data in RINEX format provided by the Geospatial Information Authority (GSI) of Japan.



Horizontal Displacement
1 m
Vertical Displacement
05:45:00 UTC
Geophysical Institute, Univ. Alaska Fairbanks
0.5 m
200 km
GPS time series courtesy of GPS Solutions Inc. All original GEONET RINEX data provided by the Geospatial Information Authority (GSI) of Japan.

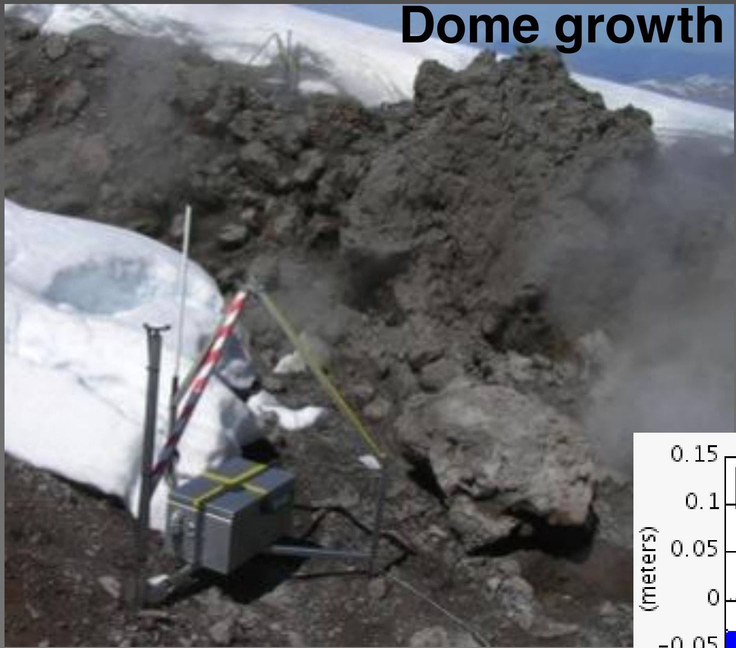
Will the operation of GNSS or GPS receivers at stations located in vicinity of potential Earthquakes be affected by major Earthquakes such as occurred on 11 March 2011 in Japan?

GNSS uses for volcano monitoring

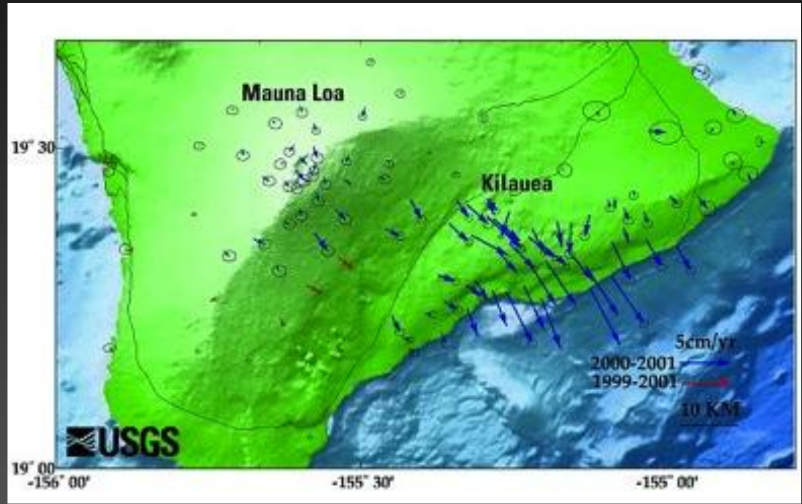
- Key component of volcano monitoring for flank movements and lava dome growth
- Integral part of **US National Volcano Early Warning System**
- Over 300 continuous operating GPS units are currently in use by USGS volcano observatories (most telemeter GPS data in real-time; many are **Plate Boundary Observatory** stations)

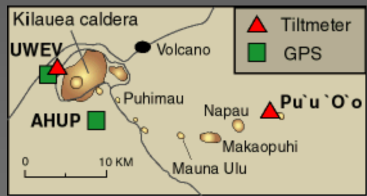
USGS
science for a changing world

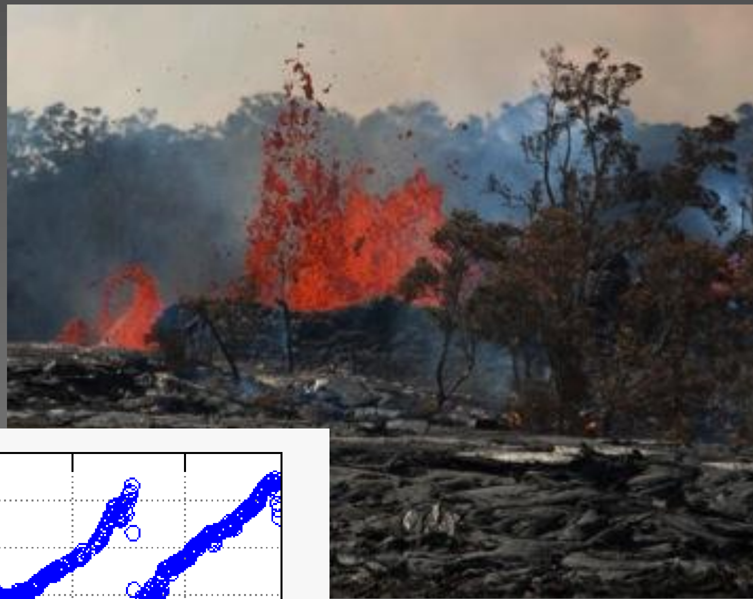
USGS uses precise GPS measurements for eruption monitoring of volcanoes

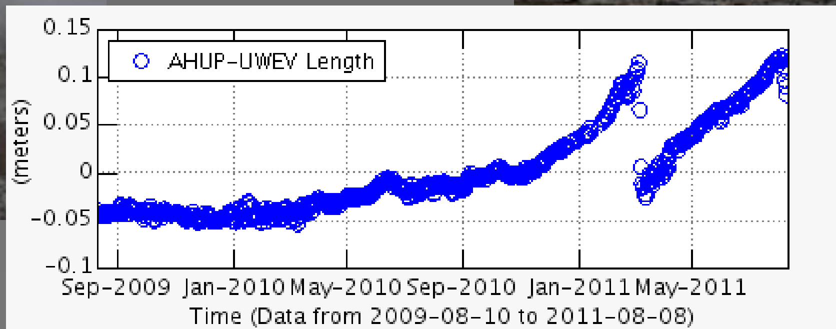


Motions of volcanoes' flanks can indicate the arrival of new magma; GPS is used to monitor changes in activity.









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science for a changing world

GNSS for hazards management

- GNSS is an essential enabling technology for the mapping and precise monitoring needed to accomplish science missions in support of hazard warnings.
- In the aftermath of a significant disaster event, GNSS is critical in support of new mapping and geopositioning incident features is essential in support of immediate response (e.g., support Urban Search & Rescue) as well as for long-term recovery (e.g., organizing debris removal).

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science for a changing world

GNSS is benefiting humanity, such as for: Earthquake and Tsunami safety

- Global earthquake observation and tsunami alerts
- Airborne imagery positioning for fault zone characterization & damage assessment
- Tracking plates and strain accumulation and release (PBO)
- Earthquake early warning & rapid slip observation at lifeline fault crossings
- Building monitoring and damage assessment; automatic 'tagging'
- Fault displacement and tsunami buoy measurement

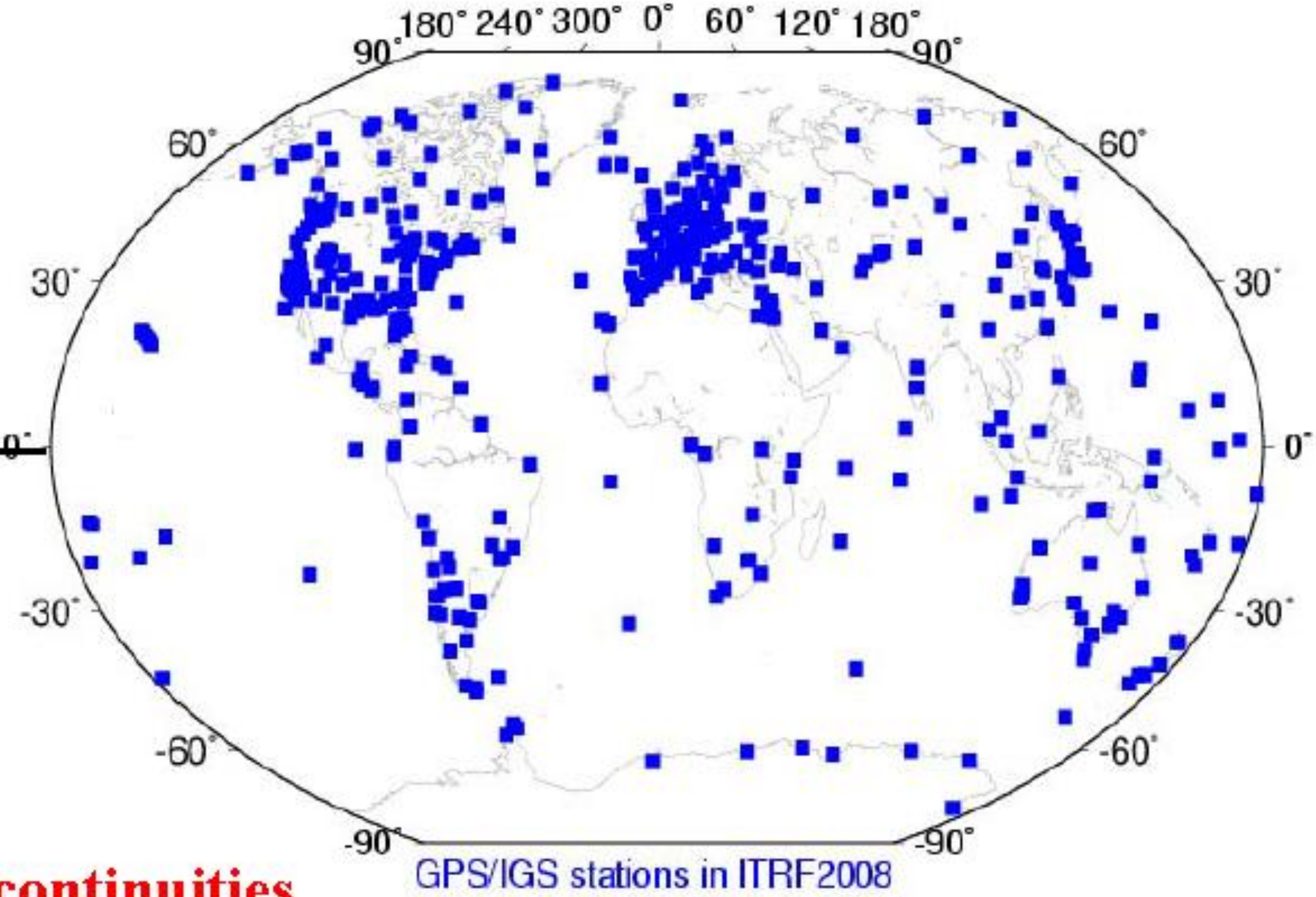
Nearly everything we do is helped by GNSS

- **GNSS will become even better than it is currently for these applications**
  - GPS L2C, L5 and L1C will improve over current capabilities
  - Future multi-GNSS solutions: GLONASS, QZSS, Galileo and other GNSS
- **GNSS may be improved beyond currently planned system enhancements**
  - Aiding through internet or wireless will enhance real-time precise results
  - Added signals could nearly eliminate the real-time ambiguity resolution problem


Thank You

International Terrestrial Reference Frame (ITRF)

ITRF2008: GPS/IGS Site distribution

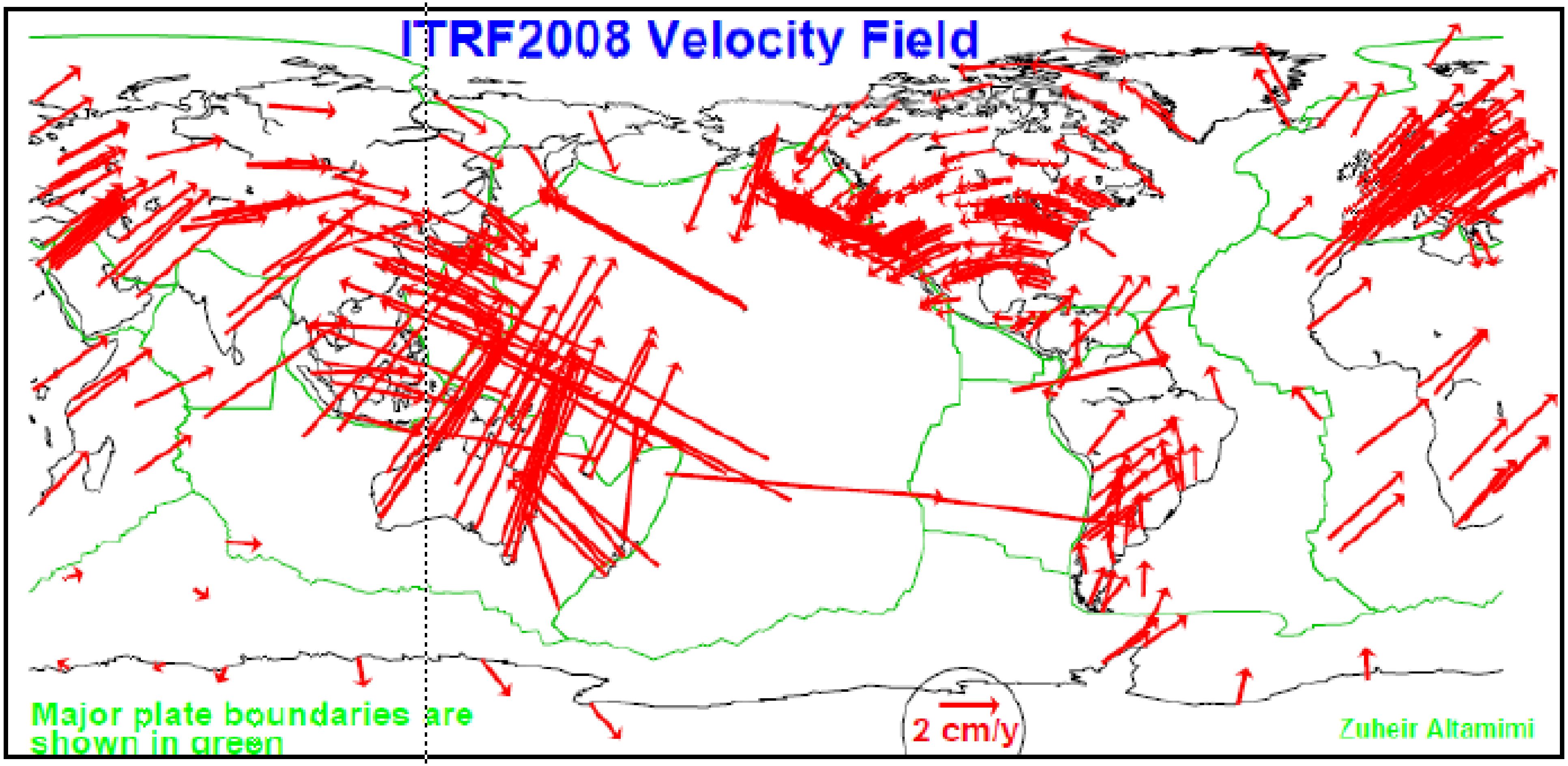


390

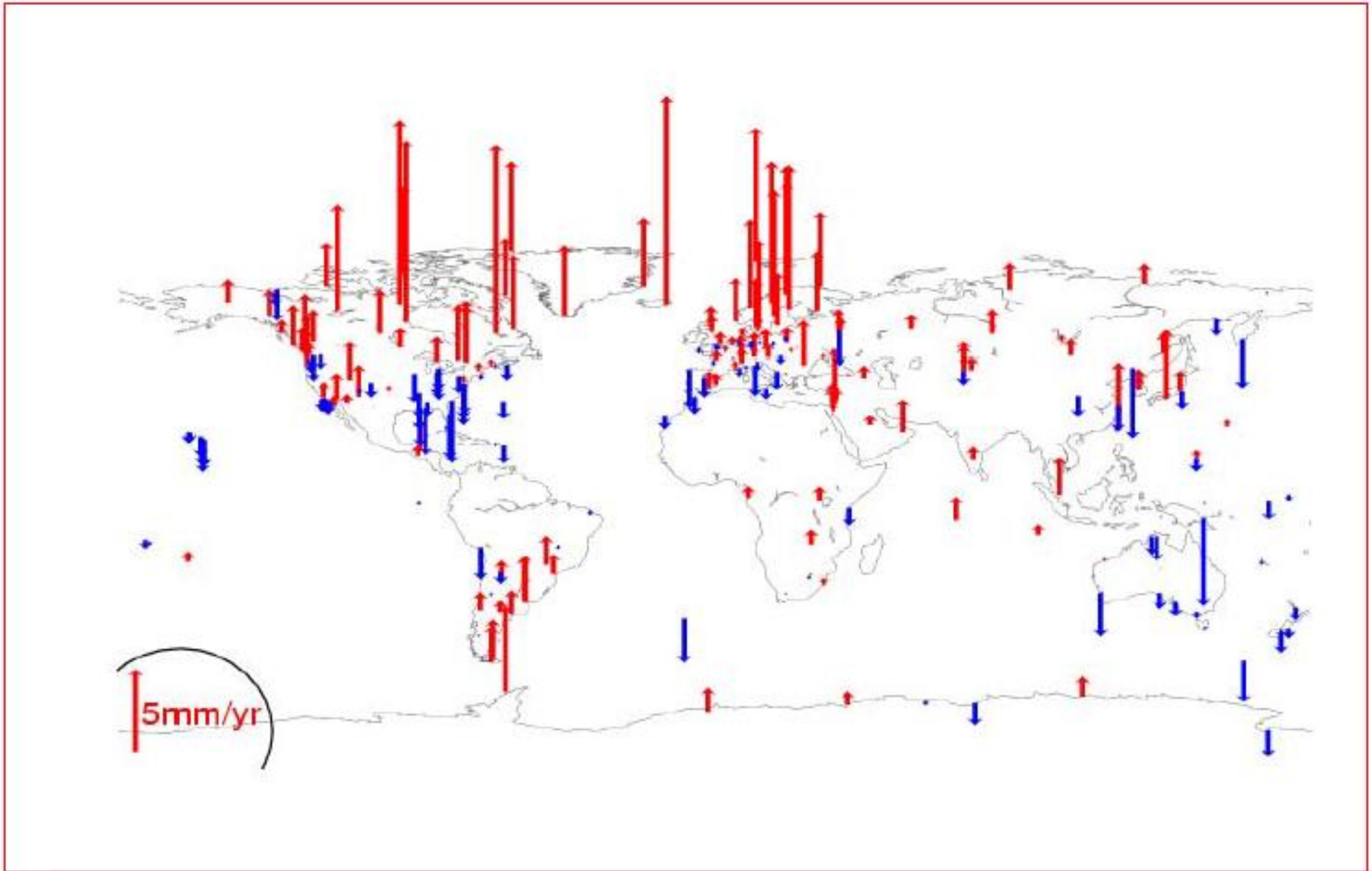
102

550 discontinuities

ITRF2008 Horizontal Velocity Field

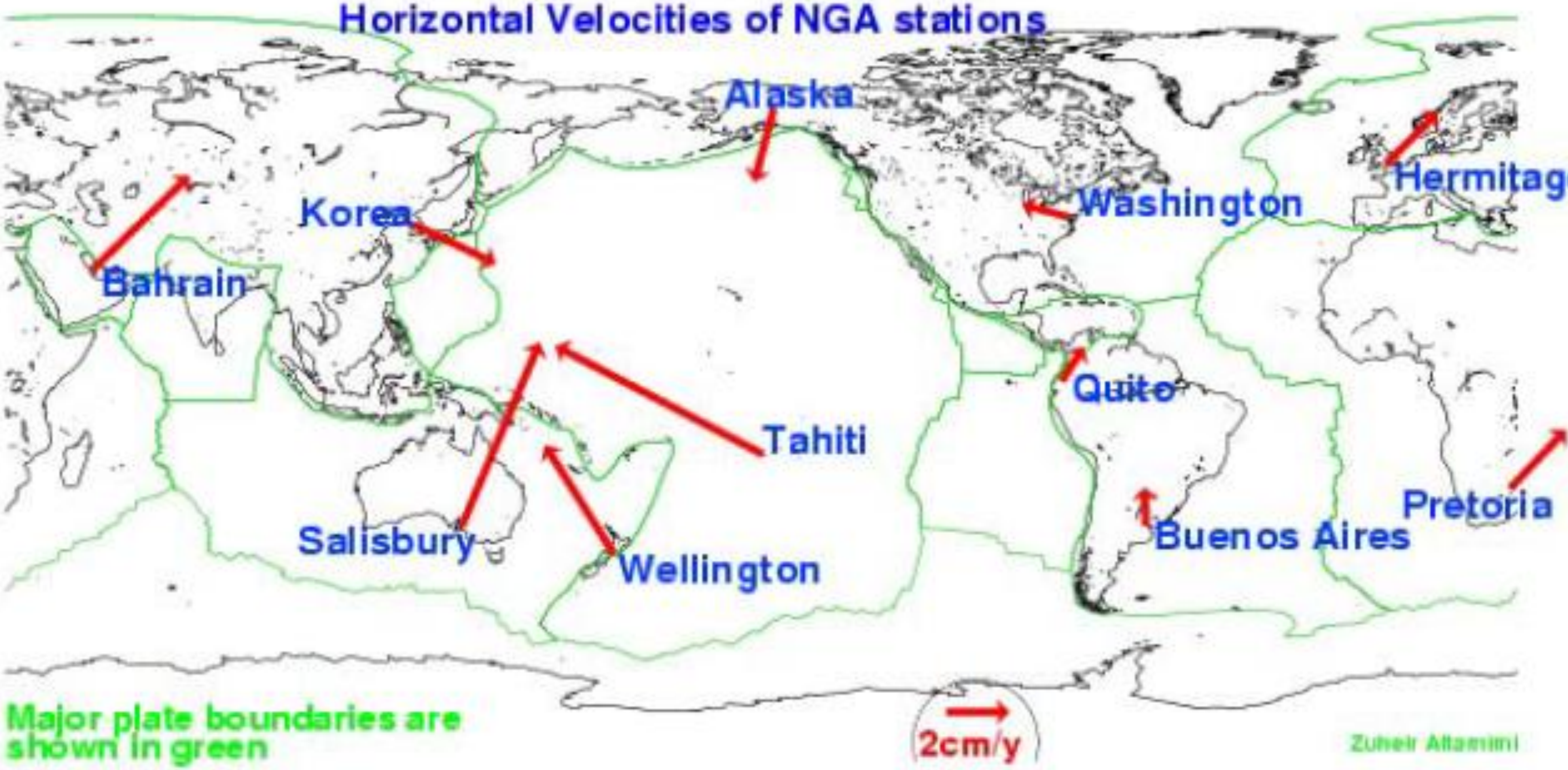


ITRF2008 Vertical Velocity Field



WGS84 - NGA Stations in ITRF2008

NGA: National Geospatial-Intelligence Agency



$$X(t) = X(t_0) + \dot{X}(t - t_0)$$