Low-Latency Earthquake Displacement Fields for Tsunami Early Warning and Rapid Response Support

Hans-Peter Plag, Geoffrey Blewitt
Nevada Bureau of Mines and Geology and Seismological Laboratory
University of Nevada, Reno, NV, USA

University of Nevada, Reno
Statewide • Worldwide

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- What are the information needs for disaster reduction?
- What can surface displacements contribute?
- What are the resulting (observational) requirements
- Where are we today?
- Where should we go and what can IGS contribution?

Information Needs for Disaster Reduction

The Key Applications:
- Early Warning for Disaster Reduction
- Disaster Assessment for Response and Rescue Planning
- Subsequent Hazard Development for Warning and Response Planning

The Main Challenges:
- Offshore earthquakes mainly kill through tsunamis
- 80% of fatalities occur due to late response
- Aftershocks and other post-event hazards are a thread to population and response and rescue teams

The Main Questions to answer after a major earthquake has occurred:
- If offshore: Where and when will a devastating tsunami hit a coast?
- Where occurred significant damage during the earthquake?
- Where will the main aftershocks occur?

Contributions from Surface Displacements

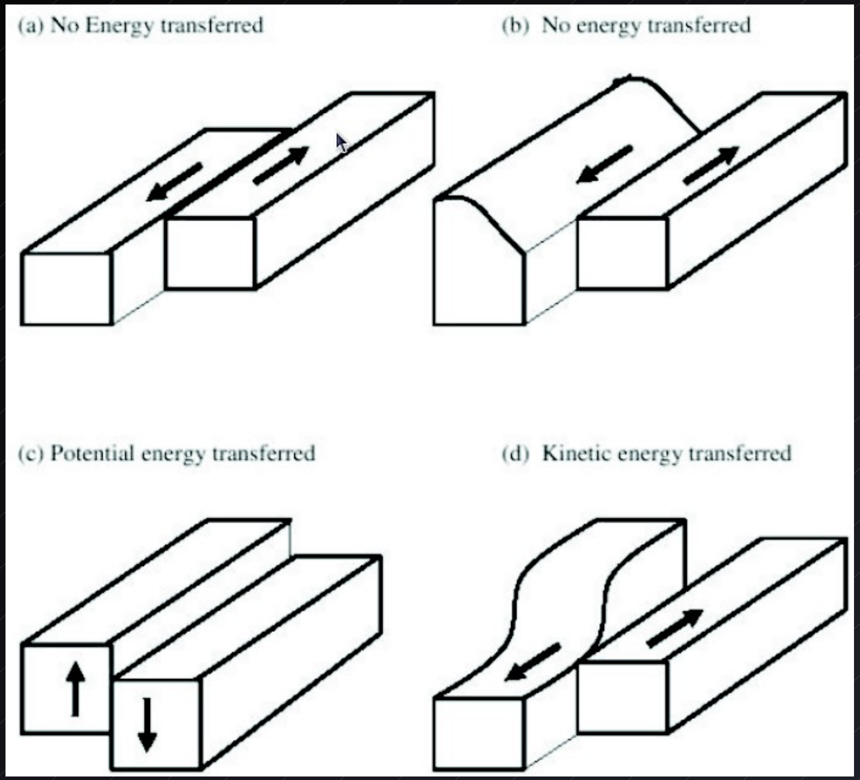
Tsunami Early Warning:
Unbiased magnitude estimates and surface displacement field allow:
- Determination of tsunami potential;
- Improve tsunami propagation predictions;
- Reduce false alarms and missed alarms.

Disaster Assessment for Response and Rescue Planning:
Combination of seismic and geodetic data can improve “shakemaps” for damage assessments

Aftershocks:
Co-seismic and post-seismic displacements inform on stress field changes and potential locations of aftershocks, particularly those on faults others than those that ruptured.

The Requirements: Tsunami Early Warning

Tsunami generation potential:
sea floor displacement determines the potential and kinetic energy transferred to the ocean.



Rapid knowledge of displacement field allows more accurate assessment of tsunami generation potential and supports warning decisions.

Displacement field-based tsunami indicators have the potential to reduce false alarms associated with magnitude-based indicators (Song, 2010).

Courtesy Yuhe T. Song

Tsunami scale as a function of tsunami energy:

$$S_T = 2 \times (\log_{10} \sqrt{E_T} - 5) \equiv \log_{10} E_T - 10 \quad (4)$$

Tsunami energy as function of displacements:

$$\Delta PE = \frac{1}{2} g \rho \Delta h^2 \Delta x \Delta y, \quad (5)$$

Potential energy

$$\Delta KE = \frac{1}{2} \rho \{\Delta u_b(z)^2 + \Delta v_b(z)^2\} \Delta x \Delta y \Delta z, \quad (6)$$

Kinetic energy

If we knew the off-shore displacement field and the rise time, we could determine the tsunami scale (Song, 2007).

The off-shore displacement field is also an important input for tsunami propagation models.

The Requirements: Tsunami Early Warning

How can we determine the off-shore displacement field?

Computation based on seismic CMT: point source, not available with low latency

Empirical extrapolation of (near-field) GPS stations:

$$\Delta E(r) = \Delta E_j \exp\left(r_j^2 - r^2\right) + \Delta e_{j2} \quad (1)$$

$$\Delta N(r) = \Delta N_j \exp\left(r_j^2 - r^2\right) + \Delta n_{j2} \quad (2)$$

$$\Delta U(r) = \alpha\sqrt{\Delta E(0)^2 + \Delta N(0)^2}\left\{\exp\left(-ar^2\right) - \sqrt{\frac{\pi}{4a}}\exp(-r)\right\} \quad (3)$$

Song (2007).

Computation based on geodetic source model: determination of geodetic source model

GPS station network:
- low-latency station
- displacements

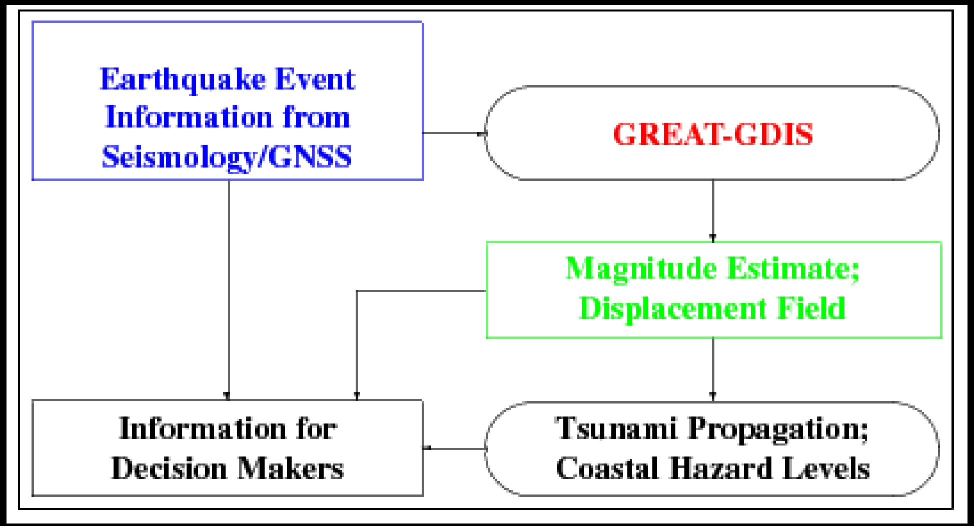
→

Geodetic source model
- Inversion
- Other algorithms

→

Computation of displacement field:
- Earth model & algorithm

The GPS-aided Real-Time Earthquake and Tsunami Alert System (GREAT): a distributed system with components at JPL and UNR



Problem: Inversion of geodetic source model not (yet) possible with low latency

Current solution: Regression with pre-computed fingerprints for a fault database

Requirements (Products)

Disaster Assessment for Response and Rescue Planning:
- In the U.S.: HAZUS, key inputs:
  - vulnerability and exposure database
  - shakemaps

Determination of shakemaps (peak acceleration, peak velocities, spectral response):
- interpolation of seismic data
- better: model computation from source geometry and rupture model

Contribution of geodetic data:
- improved source geometry through inversion of surface displacements

Aftershocks:
- changes in Coulomb Stress Field
- required: long-term strain rates, co-seismic strain field, time-variable post-seismic strain rates

Requirements (Latencies)

Tsunami Early Warning:

- Warning in near-field (impact within 10 to 20 minutes):
  - static displacements at a few near-field stations within less than 5 minutes
  - unbiased magnitude within 5 to 10 minutes;
  - displacement field within 5 to 10 minutes.
- Warning in far-field (oceanwide tsunami):
  - displacement field as input for tsunami propagation models within 15 minutes

Earthquake Damage Assessments:

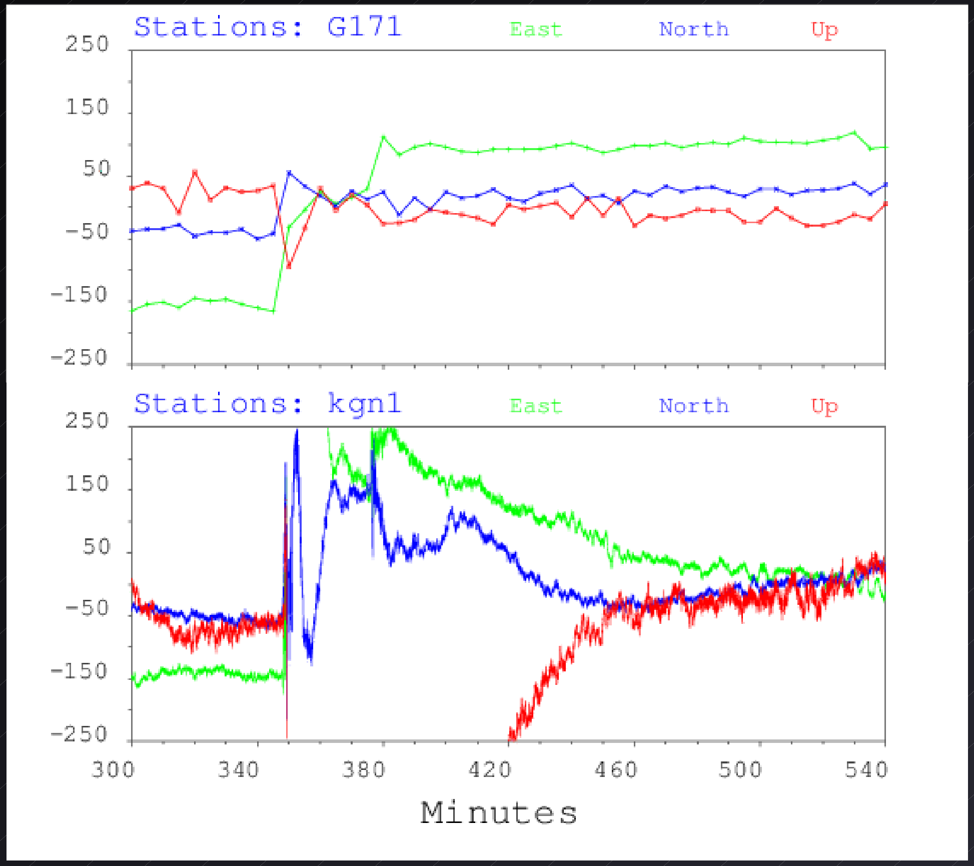
- source geometry with a latency of 15 minutes

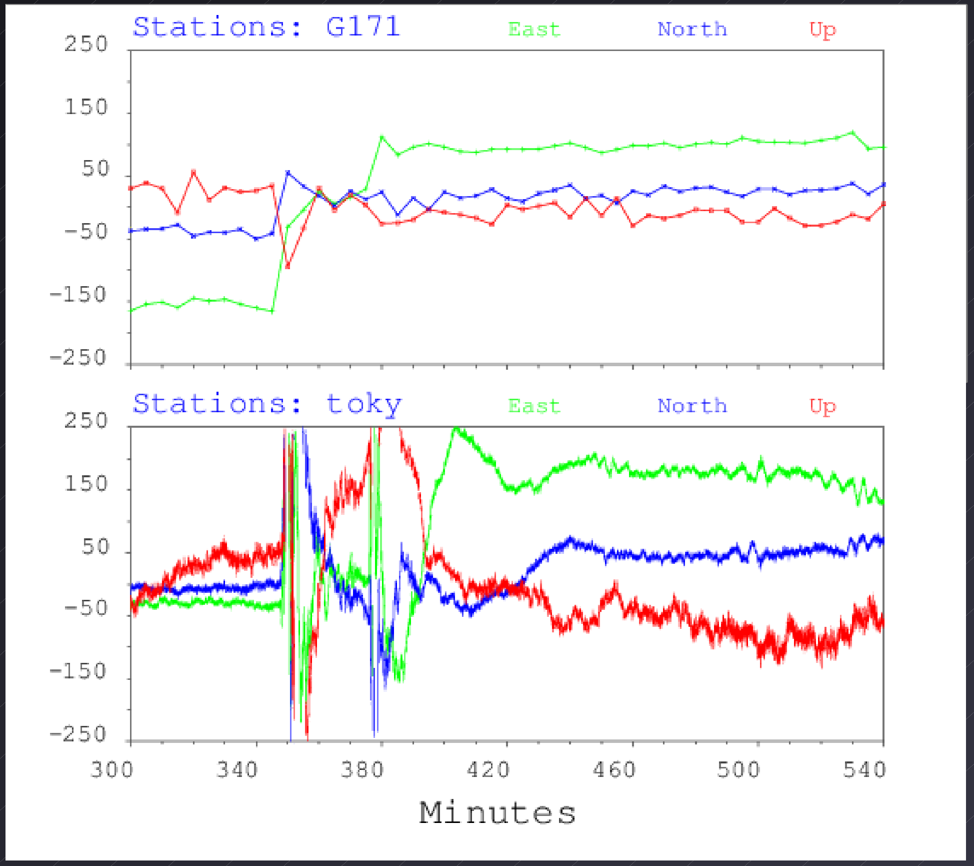
Aftershocks:

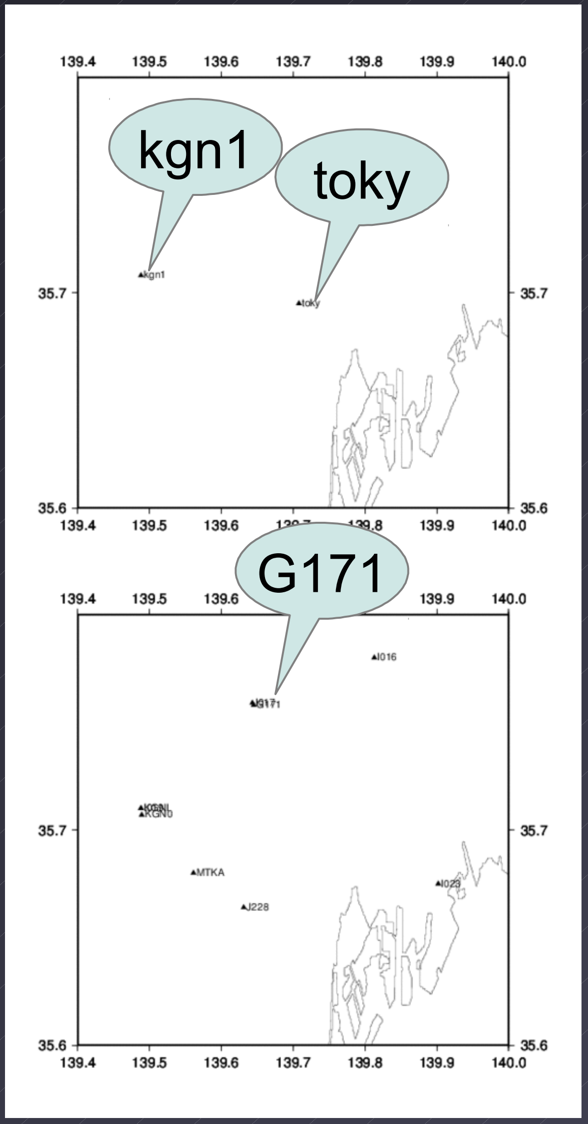
- secular strain rates
- co-seismic strain field with a latency of 1 hour
- post-seismic strain field frequently updates; latency of 1 hour

Status

In terms of accuracy and latency, two endpoints:
- highly accurate, daily coordinates, with latencies of a few days
- far less accurate, 1s data, with latencies of 10 s and less.

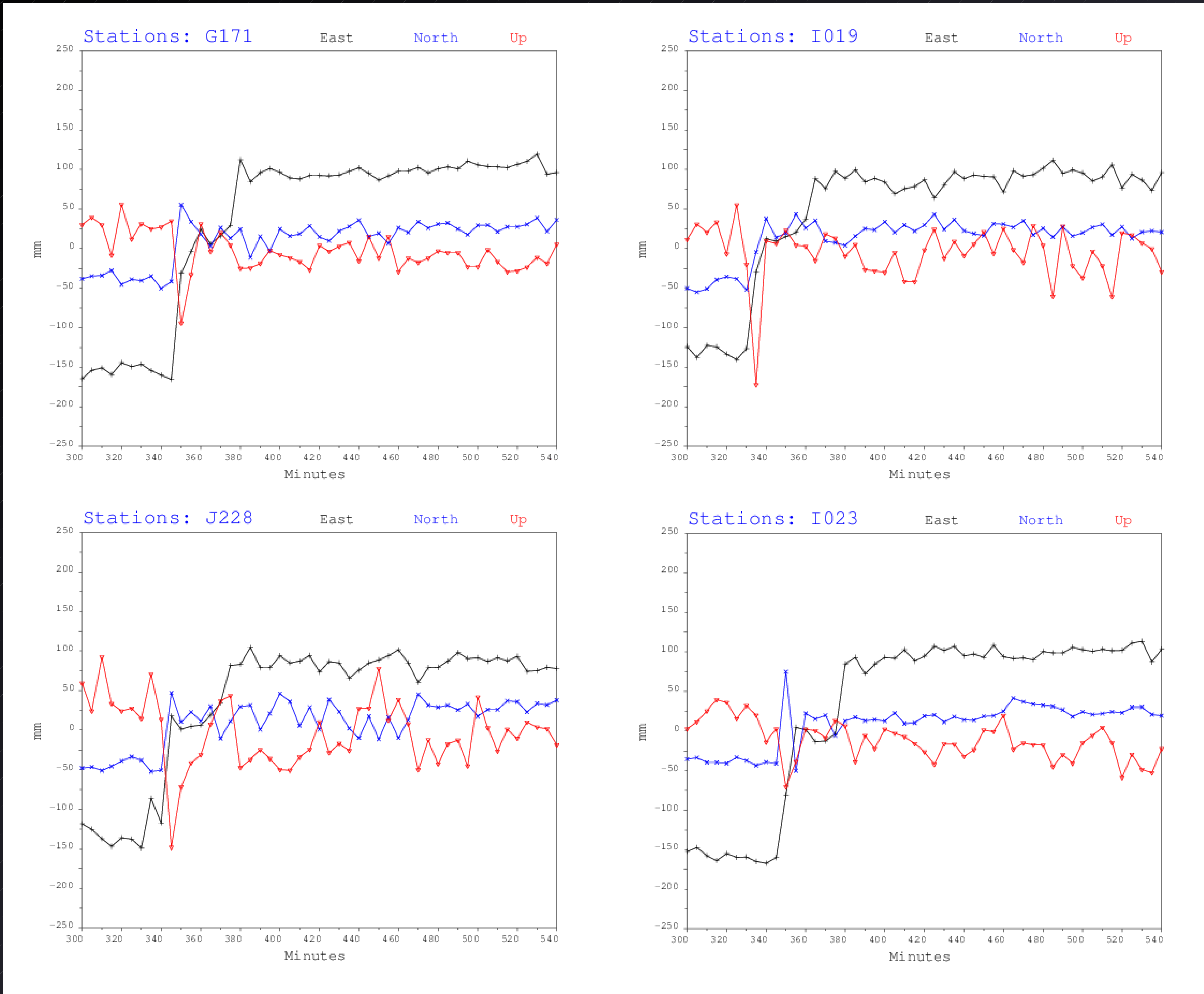






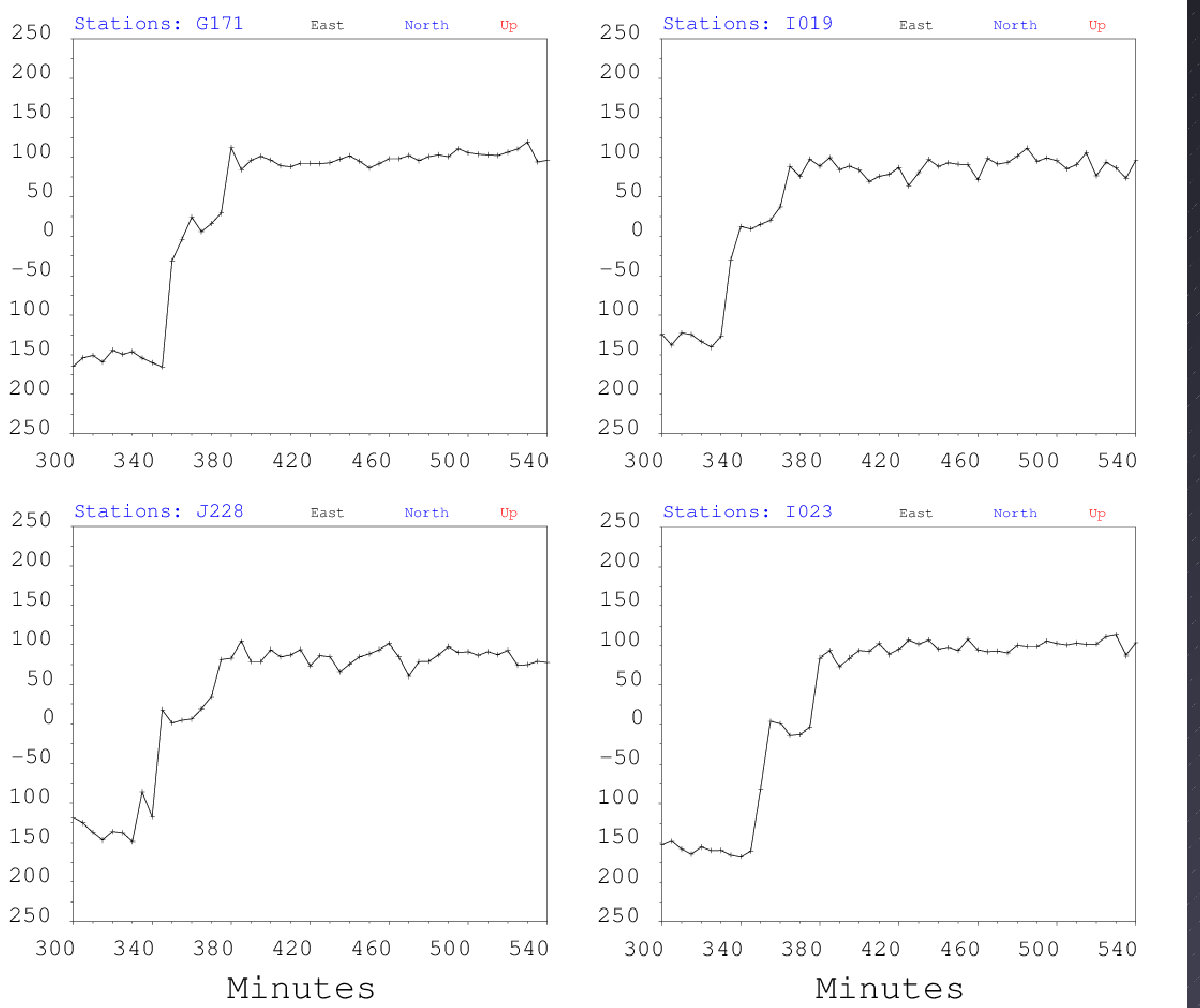
New development:
- 5 min data, latencies of up to 25 hours

Status



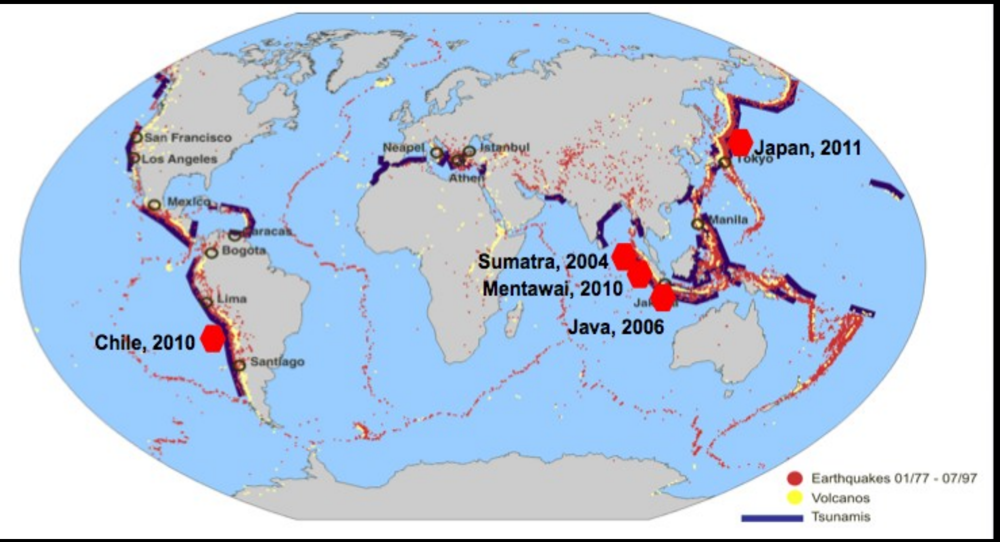
Stations: G171
East
North
Up
mm
Minutes
Stations: I019
East
North
Up
mm
Minutes
Stations: J228
East
North
Up
mm
Minutes
Stations: I023
East
North
Up
mm
Minutes

Status

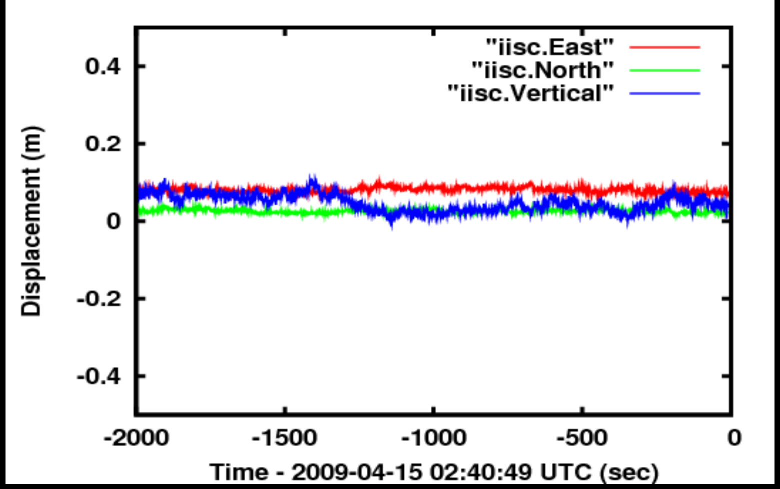

Stations: G171
East
North
Up
Stations: I019
East
North
Up
Stations: J228
East
North
Up
Stations: I023
East
North
Up
250
200
150
100
50
0
-50
100
150
200
250
300
340
380
420
460
500
540
Minutes
Minutes

Status: Tsunami Early Warning

Tsunami-Prone Areas



NASA DGPS:
- ~ 140 Stations globally;
- Level 2: Displacements,
  1 s data rate, <10 s latency;
- pushed data stream



NOAA's fault database (Gica et al., 2008):
- 573 100-km elements with upper and lower fault plane;
- “fingerprints” for unique strike-slip and dip-slip.

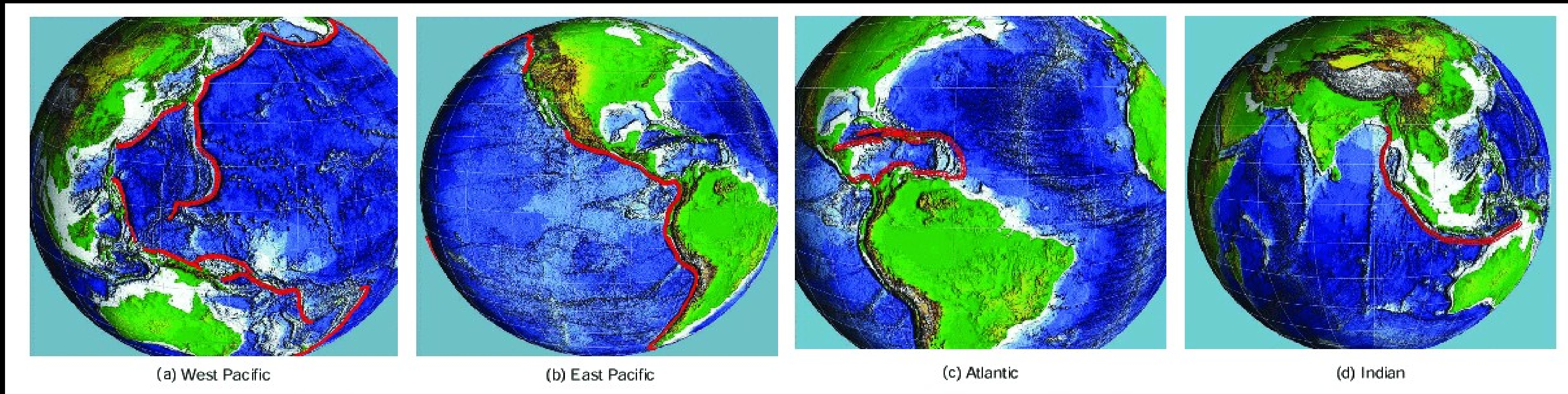
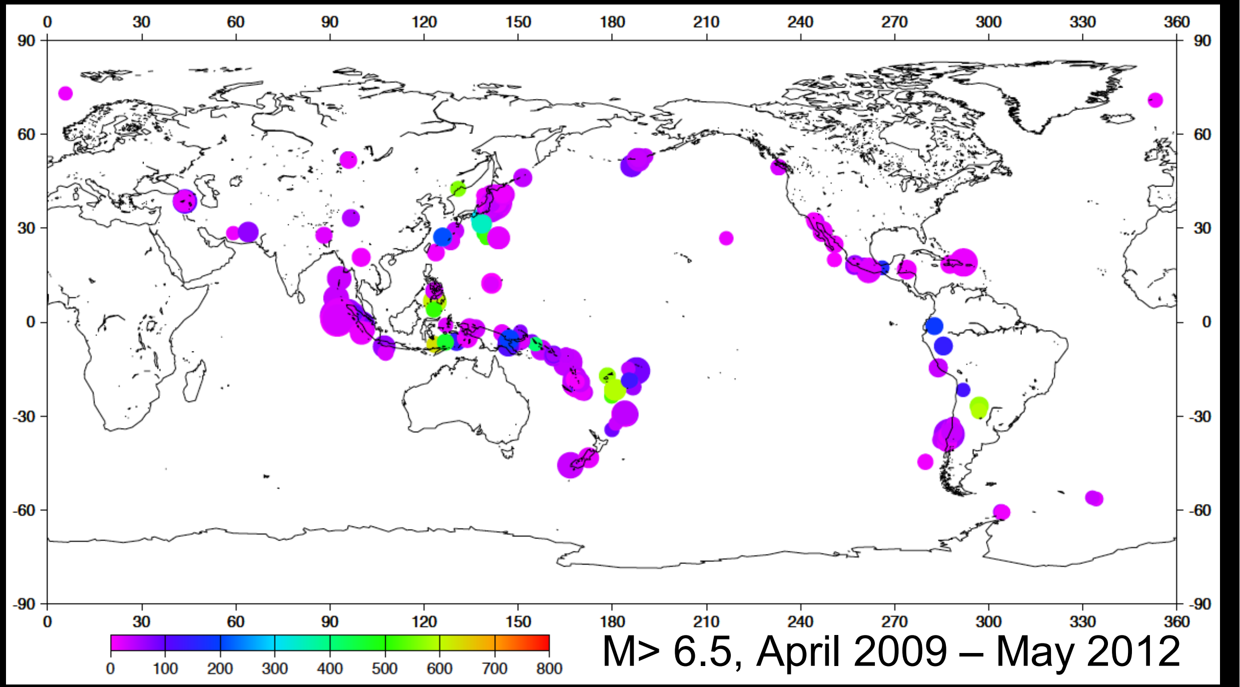


Figure A10a,b: 818 unit sources for the Pacific Ocean. Figure A10c,d: 184 unit sources for the Atlantic Ocean and 158 unit sources for the Indian Ocean (Makran sources not shown).

Status: Tsunami Early Warning: Experience Since April 2009

GPS station networks: station density highly variable; many relevant areas not covered; some dense networks provide testbeds.



Level 1: GPS real-time raw data stream: latency o.k., availability variable, robustness is an issue depending on infrastructure

USGS alerts, issues:
- False alarms;
- Multiple alarms;
- latency.

Level 2: Low-latency GPS-based displacements: 1 s sampling with latencies <10 s: low quality for PPP.

Level 3: Applications: EQ magnitude/moment & displacement field:
- rapid CMT determination possible;
- inversion for known finite faults geometry based on Green's function time consuming;
- land-based GPS alone may not be sufficient;
- regression ("fingerprint") method with low latency possible; depends on completeness of fault data base.

Level 4: Information for decision making: not at Technical Readiness Level (TRL)
- quality, reliability, and sufficiency of GPS displacements;
- determination of offshore displacement field;
- benchmarking.

Status

Earthquake Damage Assessment:

- Combined inversion of seismic and geodetic data for improved source geometry pending

Aftershocks:

- computation of co-seismic strain field possible if sufficient stations are available
- time-variable post-seismic strains require dense networks and high accuracy of displacements
- accuracy of strain field key for computation of Coulomb stress
- fault database required for determination of faults that might rupture

Outlook and IGS Contribution

Increased availability of low-latency surface displacements:
NASA: Results from the new Real-time Earthquake Analysis for Disaster (READI) Mitigation Network

IGS: More stations with low-latency data access

Increased accuracy:
NASA/UNR: Operational service for 5-min data:
- reduced latency
- global coverage

IGS: continuous data stream with accurate satellite orbits and clocks