Case study of Japan:
Reference Frames in Practice

Basara Miyahara and Koji Matsuo

Outline

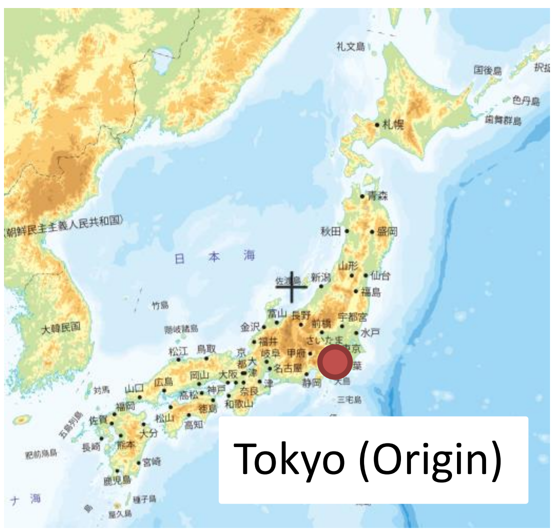
- Introduction
  - Geodetic reference frame of Japan
  - GEONET : continuous GNSS observation system
- Geometric reference frame
  - Tectonic background in Japan
  - Secular deformation by plate tectonics
  - Case study of the 2011 off-Tohoku EQ (M9.0)
  - Preliminary result of the 2016 Kumamoto EQ (M7.3)
- Gravimetric reference frame
  - JGSN75 and JGSN2013
- Summary

Introduction

- The Geospatial Information Authority of Japan (GSI) is responsible for providing the "reference" for the survey and mapping in Japan, including the geodetic reference frame for surveyors and other users of geodetic coordinates.
- GSI has been maintaining the geometric (horizontal and vertical) reference frame since 1892, the gravimetric reference frame since 1952.
- Because Japan is situated in the tectonically active region, its geodetic reference frame is continuously deforming, which requires the regular maintenance of reference frame.

Control network points in Japan

Survey Act (Japanese law for the survey and mapping) claims that all survey data should be referred to the origins of horizontal and vertical control networks.



Origin of horizontal control network for geographical latitude and longitude (Tokyo)

Origin of vertical control network for height (Tokyo)

Control network points in Japan

As of Apr. 2015

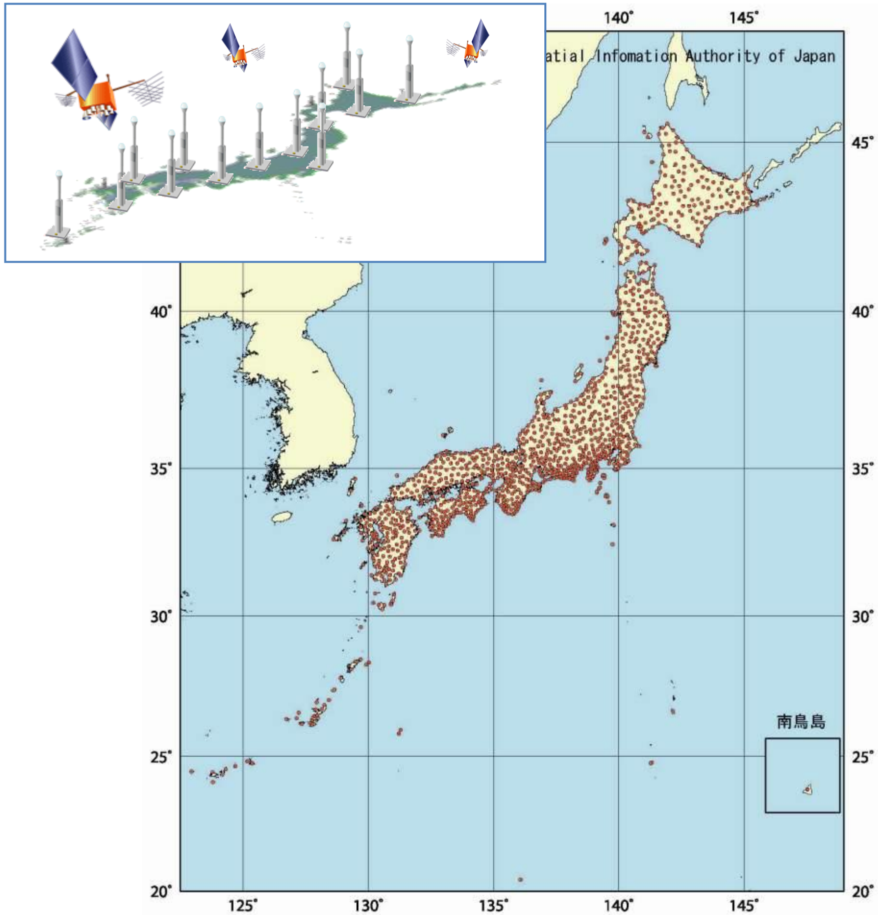
Category	Number	Sub-category	Average interval
VLBI	2	Tsukuba, Ishioka	
GNSS-based control stations (GEONET)	1318		20 km
Triangulation control points 	109,423	First order stations 975 Second order stations 5060 Third order stations 32,326 Fourth order stations 70,717	25 km 8 km 4 km 1.5 km
Vertical benchmarks 	17,081	Fundamental bench marks 86 First order bench marks 14,682 Second order bench marks 3471	150 km 2 km 2 km
Others		Gravity markers, Geomagnetic benchmarks, and son	
Total	128,824		

Shift to GNSS-based geodetic reference frame

- Horizontal positions can be determined more accurately and efficiently by GNSS than by triangulation surveys.
- GEONET can realize and maintain geodetic reference frame with a much smaller number of stations than triangulation control points.
- GSI decided to switch main geodetic control points from triangulation control points to GEONET stations and publicly announced a change at the end of June 2014.
- In the announcement, GSI stated;
  - GSI does not actively maintain triangulation control points and stop the maintenance of most of them within 10 years.
  - GSI makes the best of GEONET for realizing and maintaining geodetic reference frame in Japan.

GEONET (GNSS Earth Observation Network System)

- GNSS continuously operating reference stations (CORS) covering Japanese archipelago for surveying and crustal deformation monitoring.
- Founded in 1994.
- 1318 stations (As of Apr. 2015).
- Average spacing between stations about 20 km.



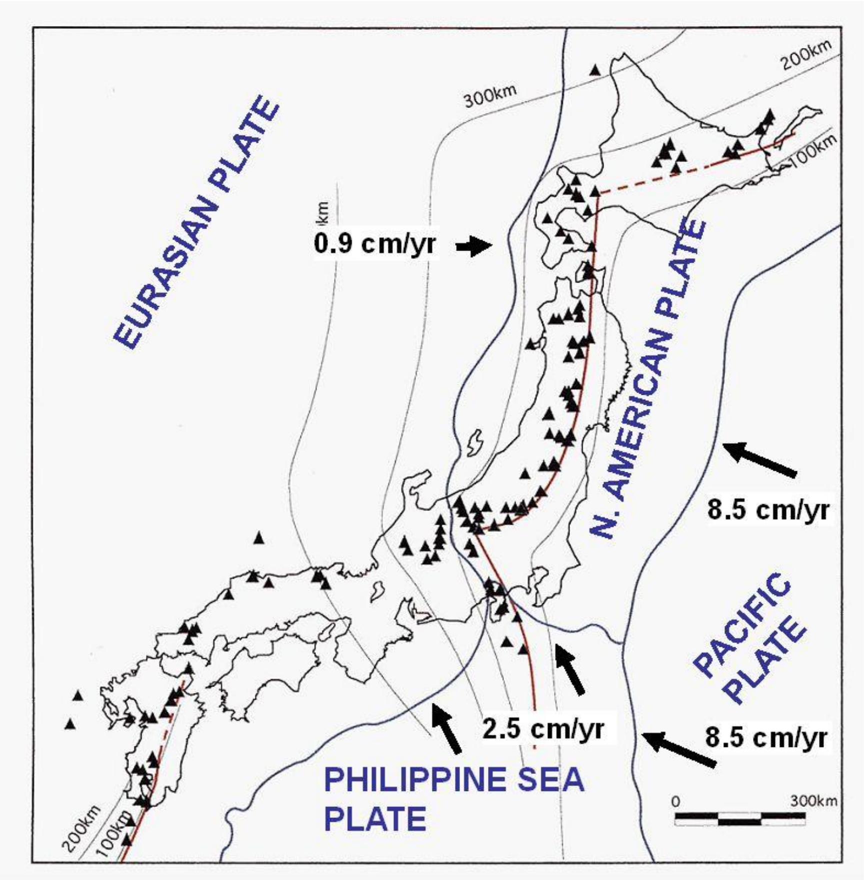
GEONET station

- Stainless steel pillar (5m tall)
- Chokering Antenna
- Clinometer and thermometer
- Dual frequency receiver (GPS, QZS, Galileo, Glonass)
- 24-hr observation
- 1-sec and 30-sec sampling
- Real-time data transfer

Geodetic reference frame

- Tectonic background in Japan
- Secular deformation by plate tectonics
- Case study of the 2011 off-Tohoku EQ (M9.0)
- Preliminary result of the 2016 Kumamoto EQ (M7.3)

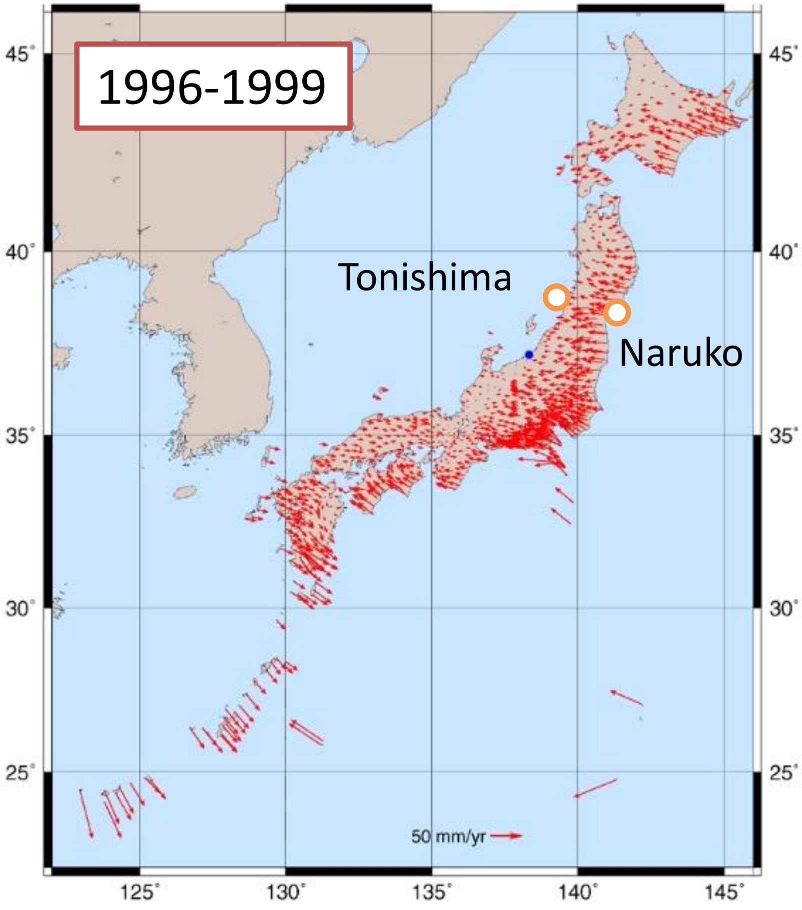
Tectonic background in Japan



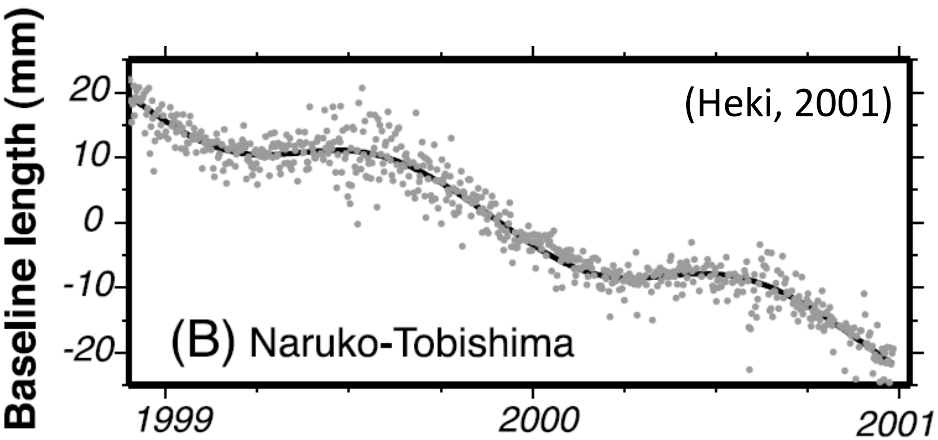
Martin et al. (2012)

- Japan is located on an area where four active plates are colliding.
- Subduction rates are 8.5 cm/yr for Pacific plate, 2.5 cm/yr for Philippine sea plates, and 0.9 cm/yr for Eurasian plate around main islands of Japan.
- Such active plane tectonics makes the country continuously deforming and prone to earthquakes and volcanic activities.

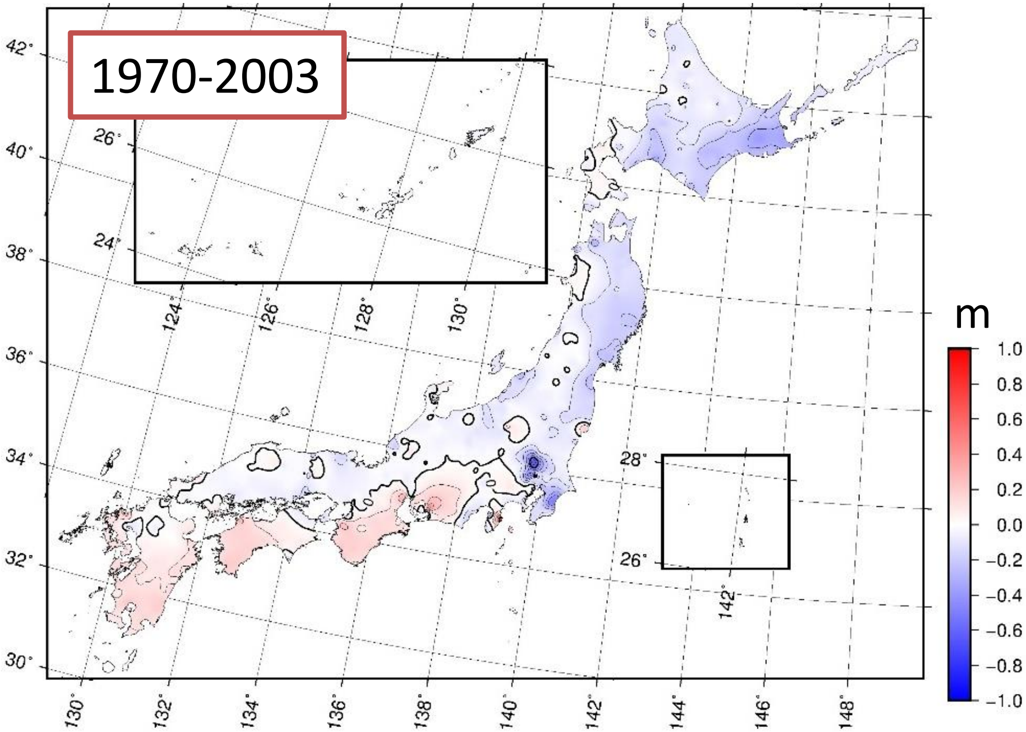
Secular deformation by plate tectonics



- Secular crustal deformations have been observed by GEONET.
- Baseline length between east coast and west coast region is shortening at the rate of about 10-20 mm/yr.



Secular vertical deformation



Cumulative vertical displacement measured by spirit leveling during 1970-2003

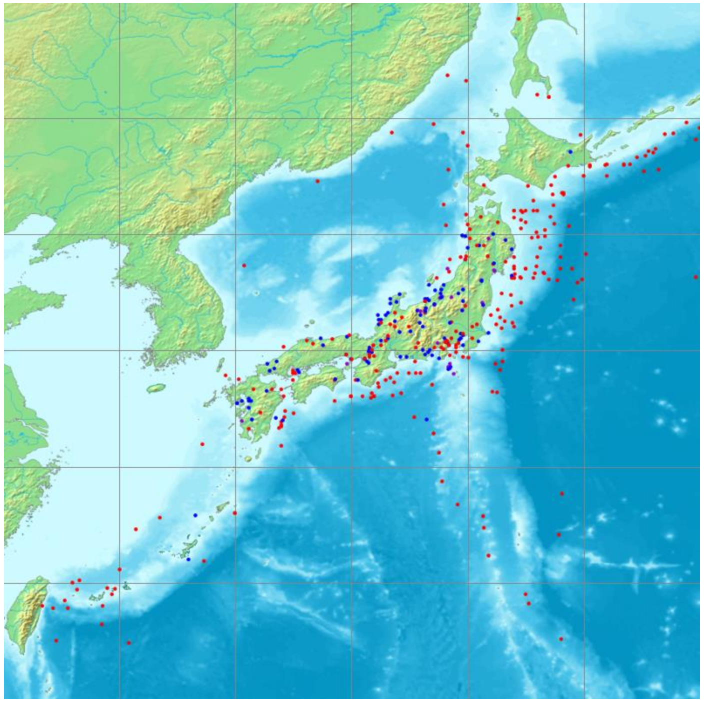
- GSI has conducted spirit leveling for Japan since 1883.
- All the first-order leveling route (about 18,000 km) are regularly measured every 10 years.
- Spirit leveling showed a depression trend of about 10 mm/yr in northeastern region and a uplift trend of 10 mm/yr in southwestern region

Recent seismic events with serious damages on society

1995.1.17	Kobe EQ (M7.2)
2000.10.6	Tottori EQ (M7.3)
2003.9.26	Off-Tokachi EQ (M8.0)
2004.10.12	Niigata-Chuetsu EQ (M6.8)
2007.3.25	Noto peninsula EQ (M6.8)
2007.7.16	Off-Chuetsu EQ (M6.8)
2008.6.14	Iwate-Miyagi EQ (M7.2)
2011.3.11	**Off-Tohoku EQ (M9.0)**
2014.11.22	Nagano EQ (M6.7)
2016.4.16	Kumamoto EQ (M7.3)

List of large earthquakes in Japan which caused large crustal deformation

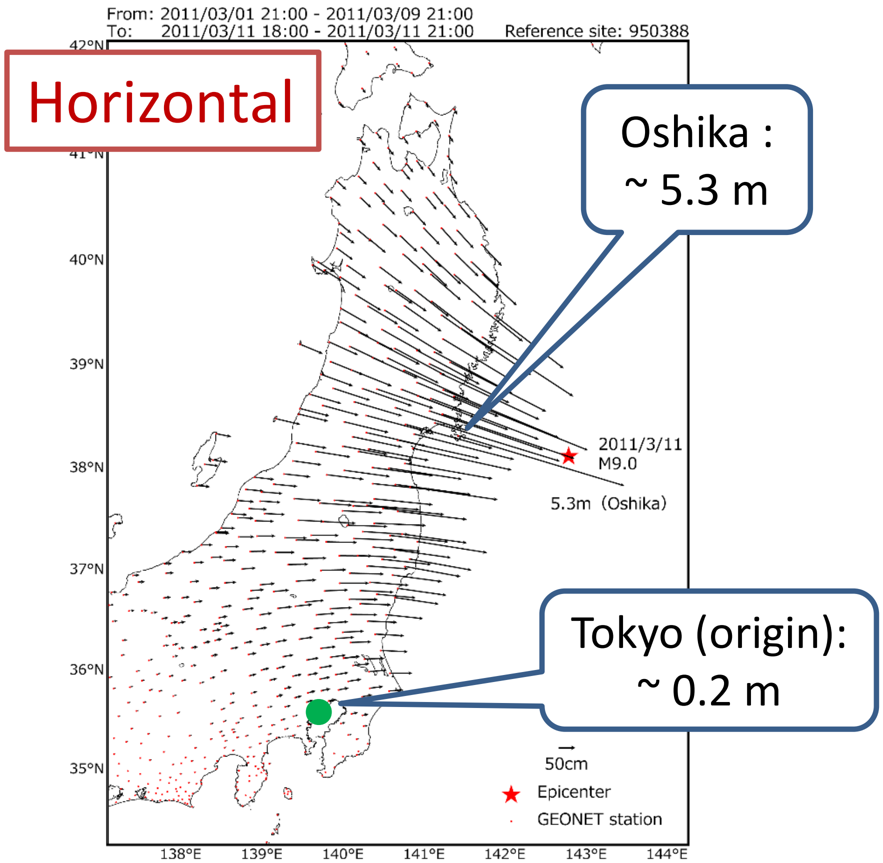
Map of the epicenters of the earthquakes larger than M7.0 during 1500-2000 (Utsu, 2000)

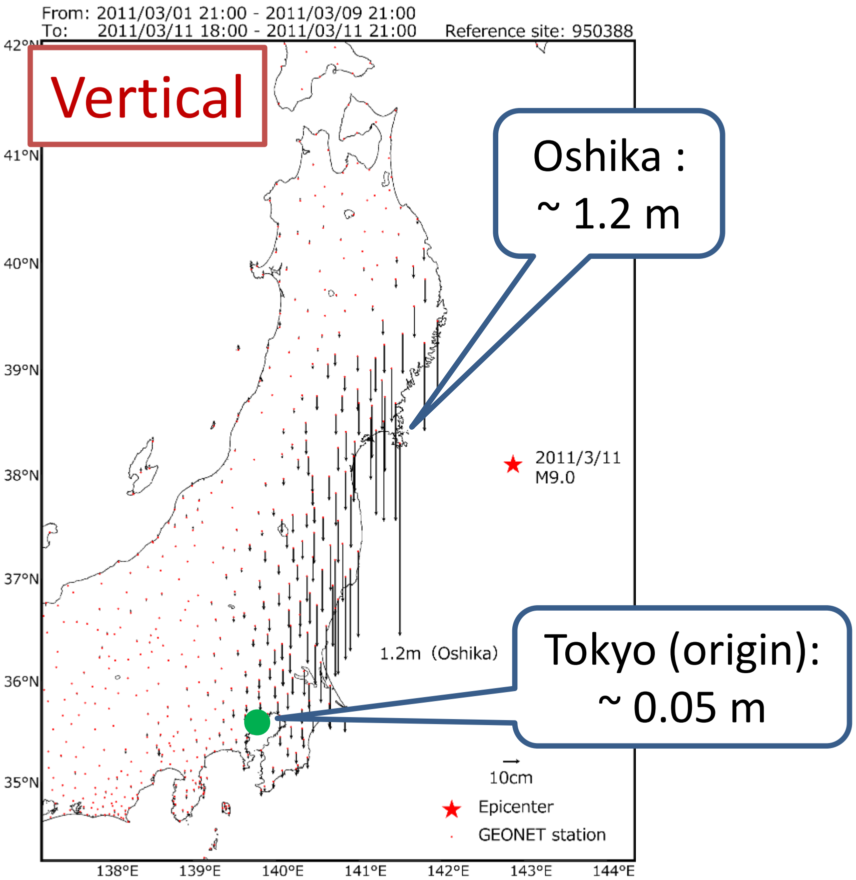


Red: Inland earthquake
Blue: Large Tsunami earthquake

Coseismic deformation by the 2011 off-Tohoku EQ (M9.0)

GEONET observation

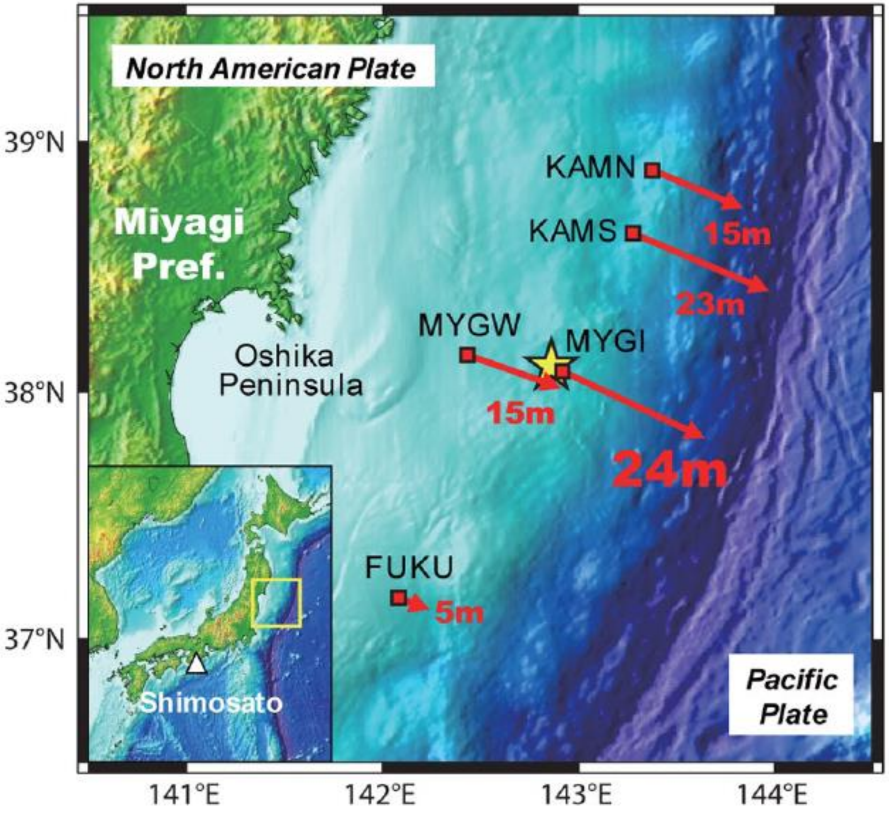




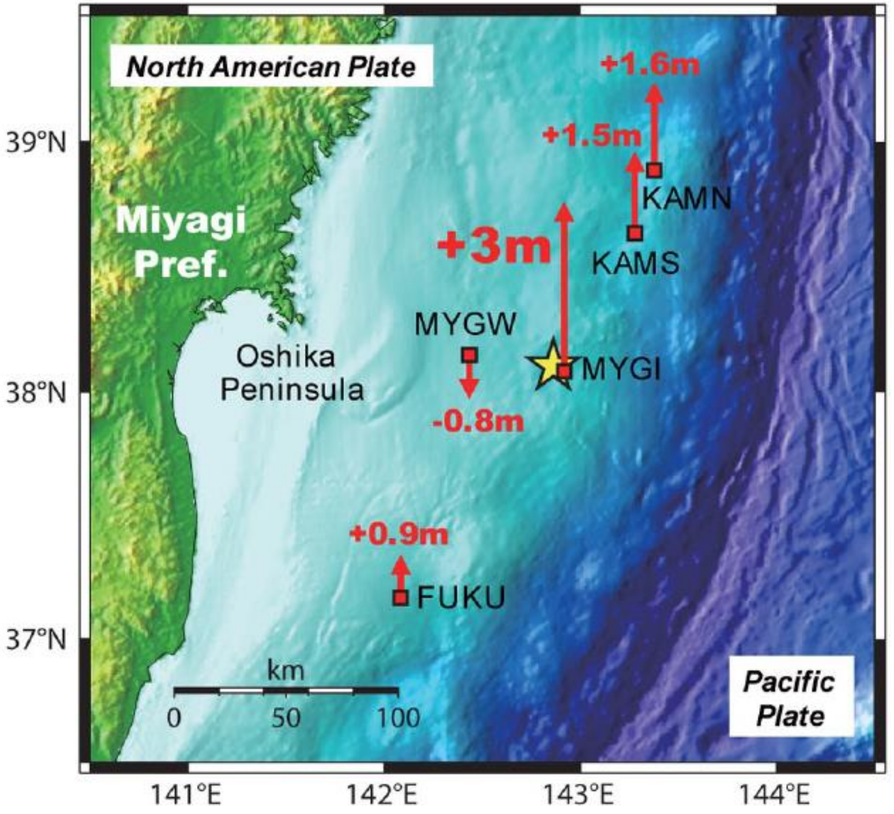
Coseismic deformation by the 2011 off-Tohoku EQ (M9.0)

Ocean-bottom GNSS/acoustic observation

(A) Horizontal displacements

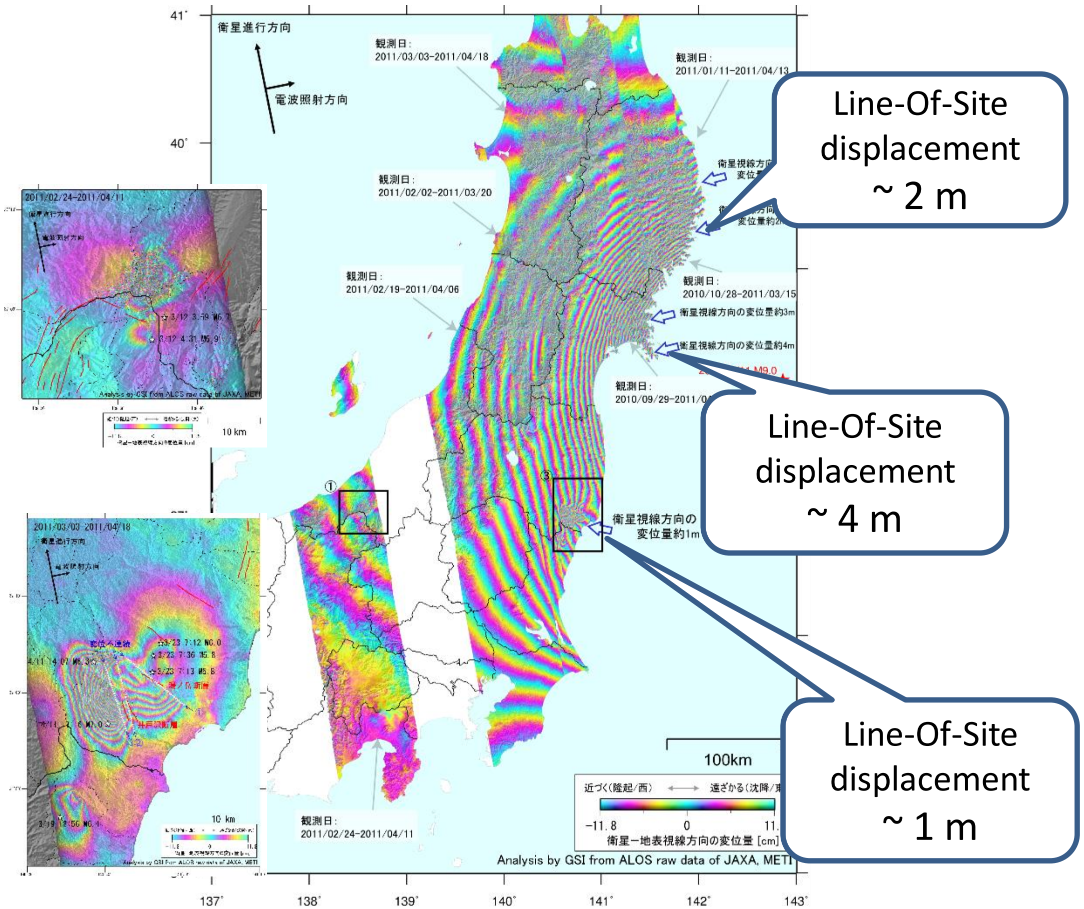


(B) Vertical displacements (Sato et al., 2011)

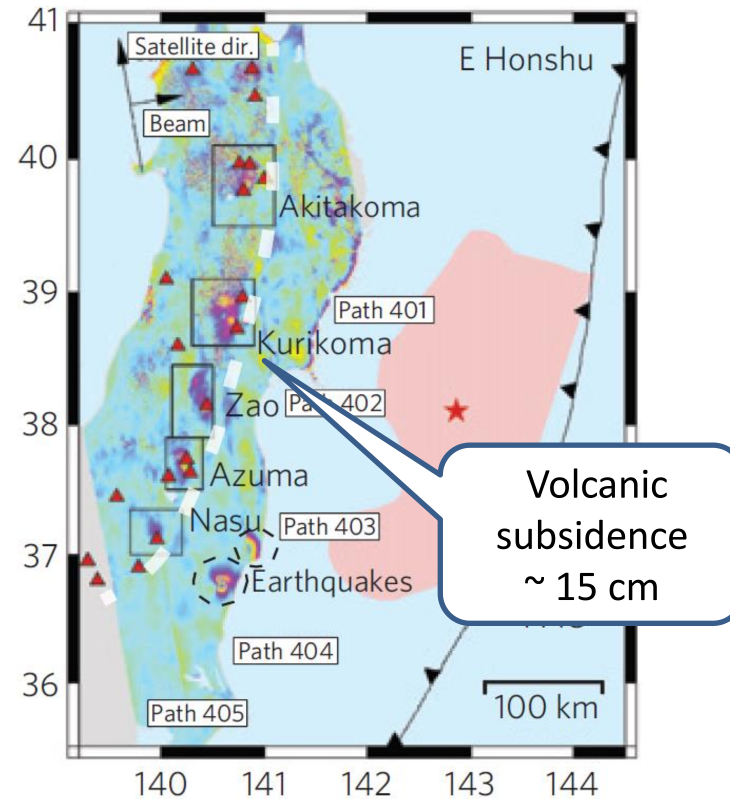


Coseismic deformation by the 2011 off-Tohoku EQ (M9.0)

ALOS/PALSAR observation



InSAR detected the deformation of magma chambers beneath volcanoes (Takada & Fukushima, 2013)

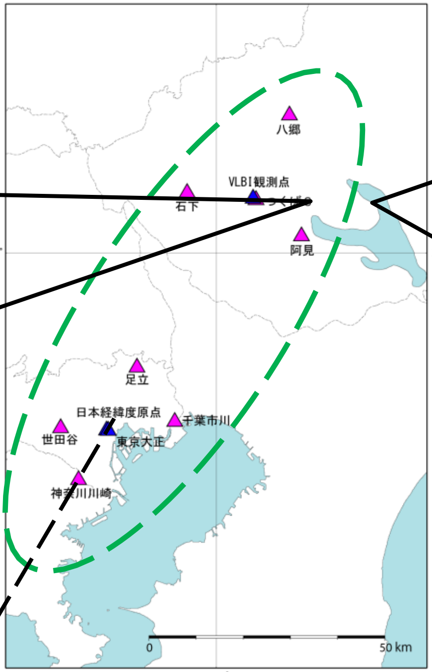


Sponsors: Land Information New Zealand Toitū te whenua, Leica Geosystems, Trimble

Revision of the datum

1. Determine the coordinate of VLBI station “Tsukuba” as of May 24, 2011.

VLBI station “Tsukuba” at GSI headquarters



2. GNSS observation was carried out at VLBI station “Tsukuba” and the origin, respectively.

GEONET stations are marked as ▲

3. Revise the horizontal and vertical origins

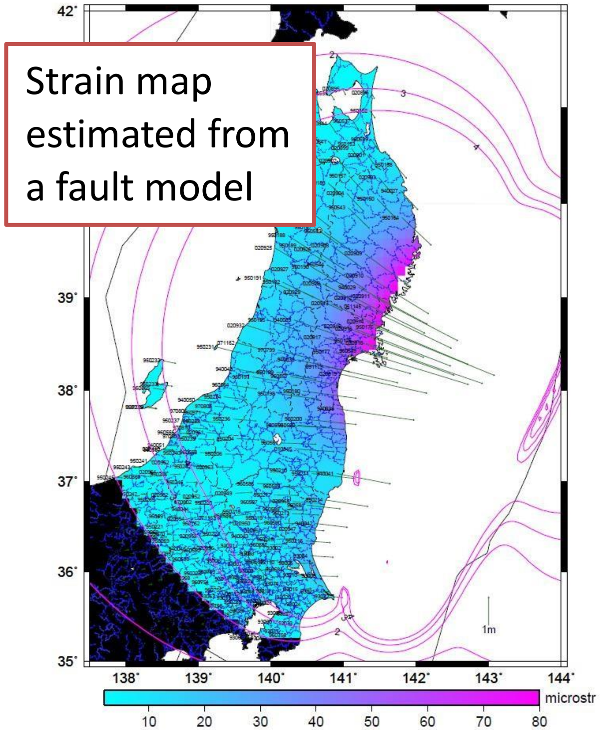
Moved eastward by 27 cm

Moved downward by 2.4 cm

4. Coordinates of GEONET stations were calculated by using a local tie at 2007 under the condition that the coordinate of VLBI station “Tsukuba” is fixed.

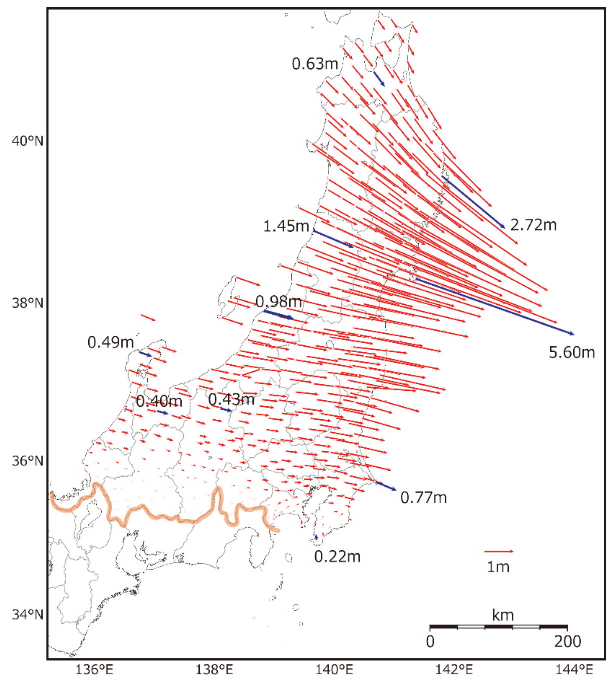
Revision of the datum

Determination of revision area
Criterion for revision



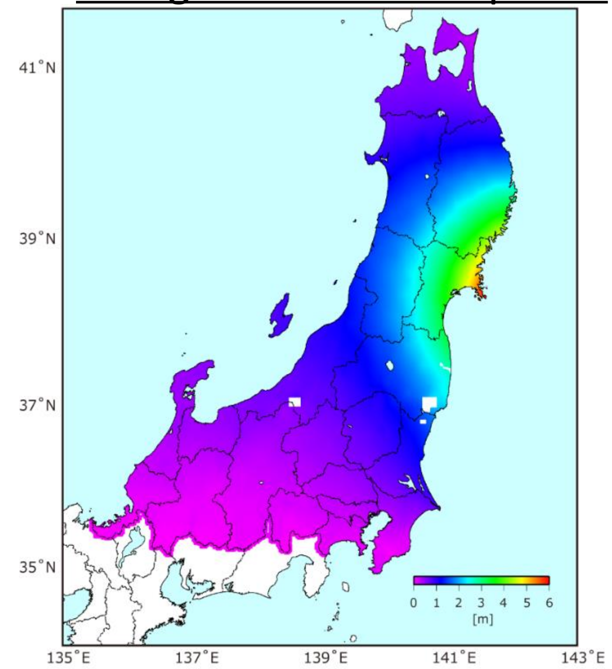
Prefecture including the area where estimated strain will be over 2 ppm.

Difference in GNSS positions between new and old datum



All data set is called "Geodetic Coordinates 2011"

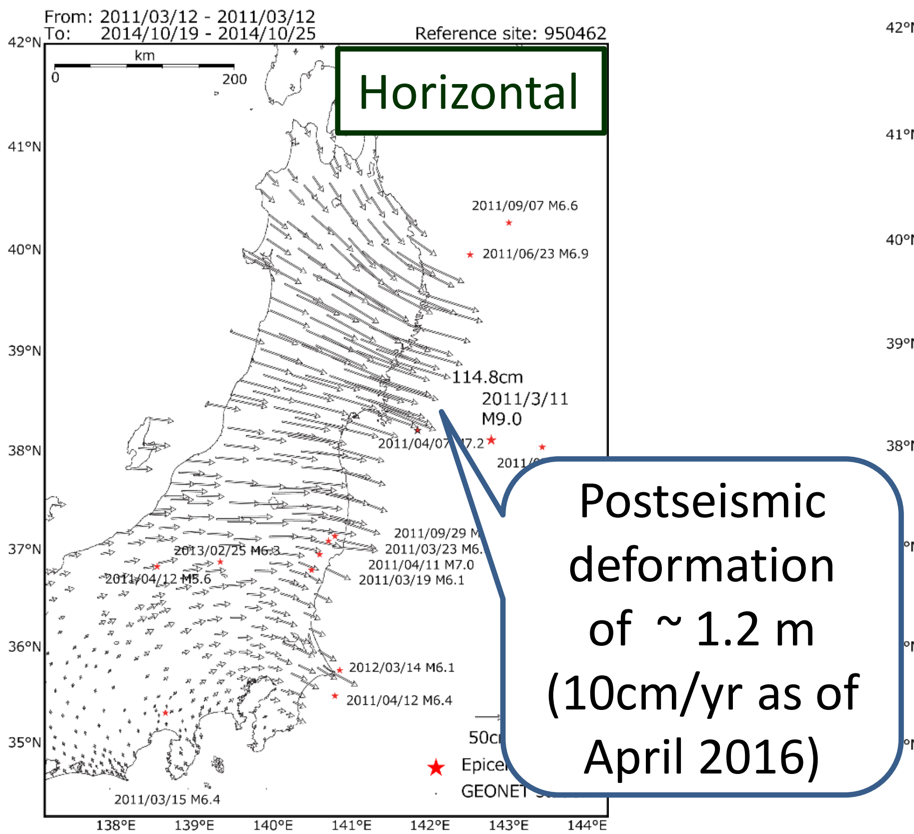
Correction parameters for triangulation control points

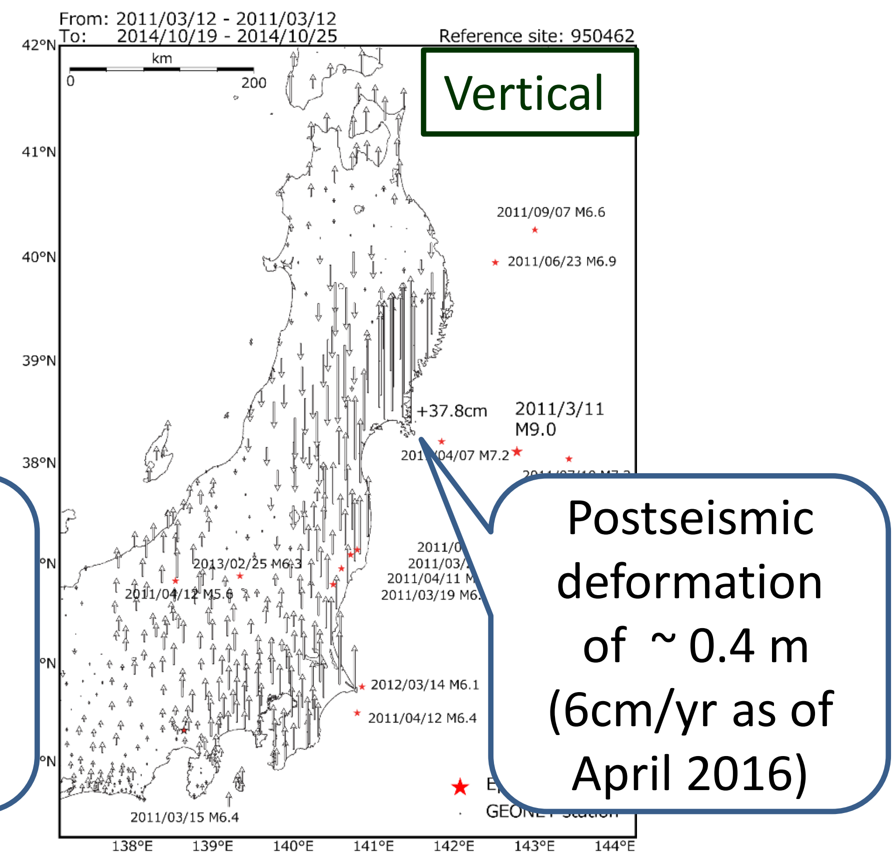


Correction parameters were calculated mainly from GEONET and applied for about 44,000 triangulation control points

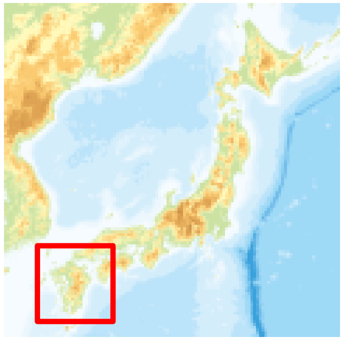
Future issues : postseismic crustal deformation

5 years cumulative deformation after the 2011 off-Tohoku EQ exceeds 1.2m in horizontal and 0.4m in vertical. The postseismic crustal deformation is still continuing.



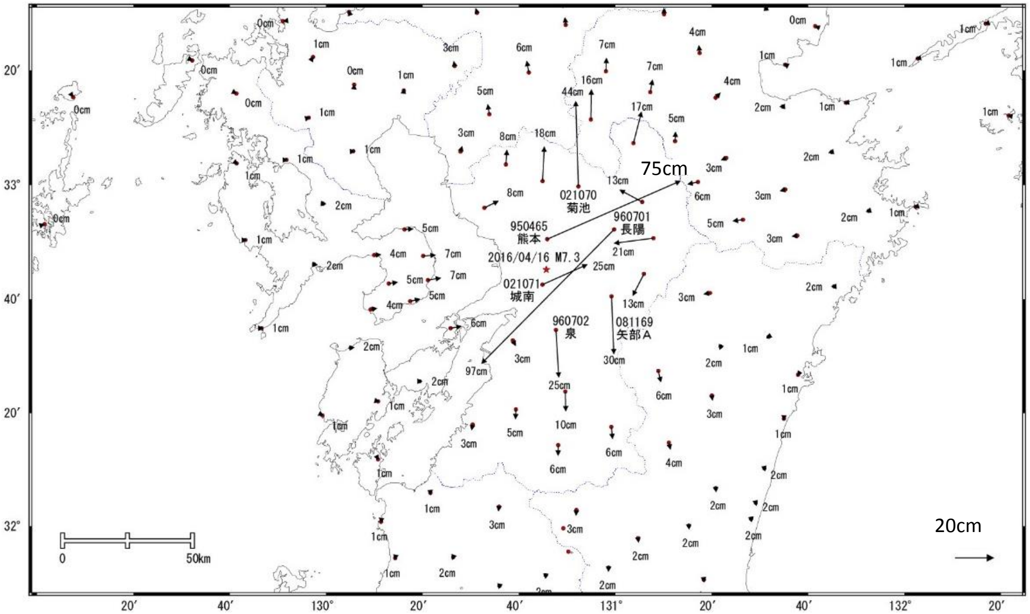


The 2016 Kumamoto EQ (M7.3)

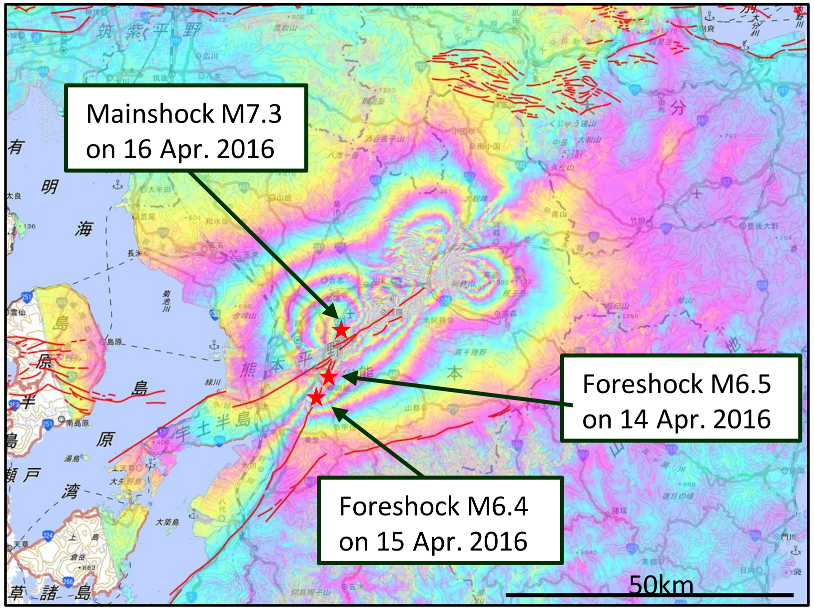


The sequence of strike-slip earthquakes occurred in Kumamoto prefecture, southwest of Japan, on 14-16 April 2016.

Japanese SAR satellite, ALOS-2, as same as GEONET, detected crustal deformation caused by the 2016 Kumamoto EQs.



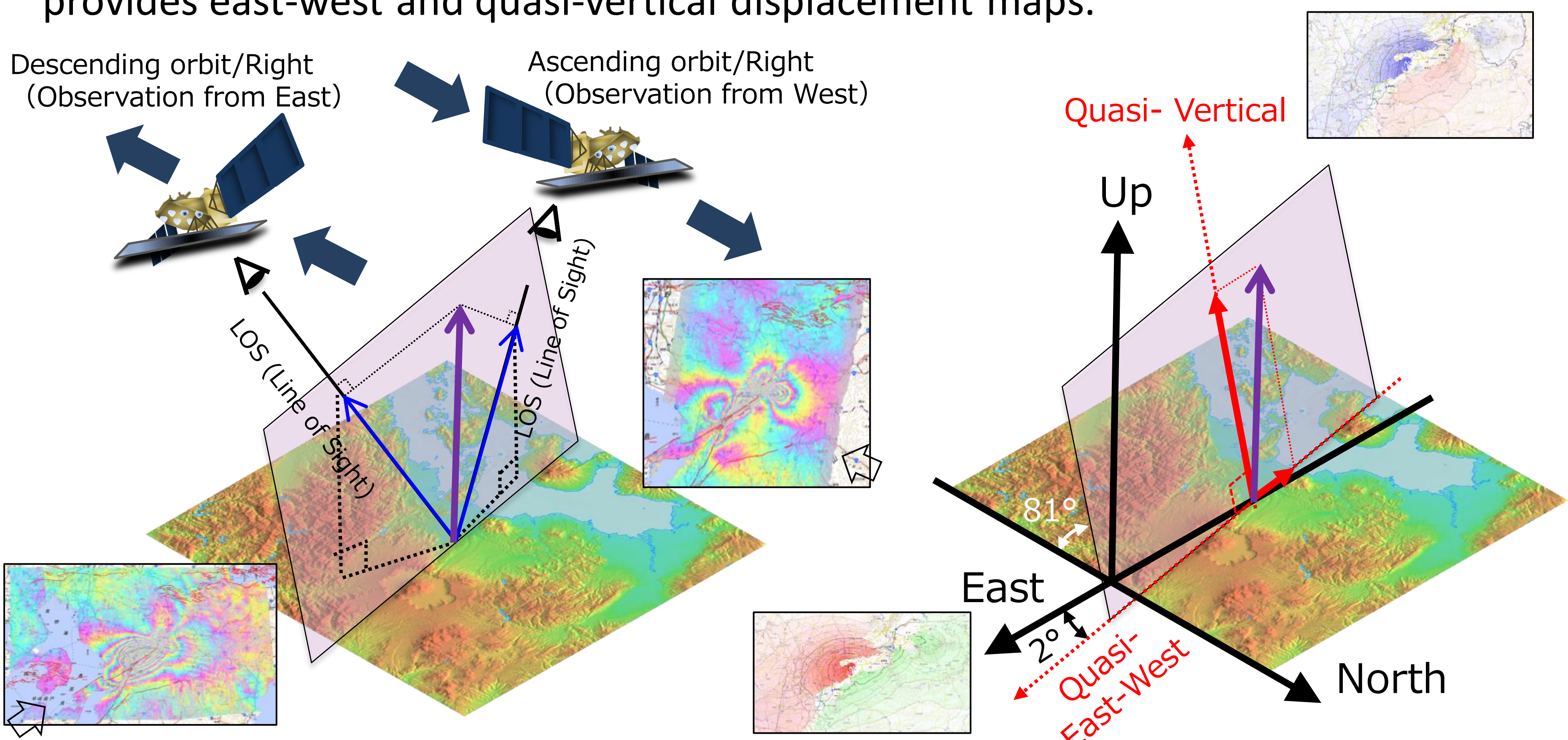
Horizontal displacement detected by GEONET



Displacement detected by ALOS-2 InSAR

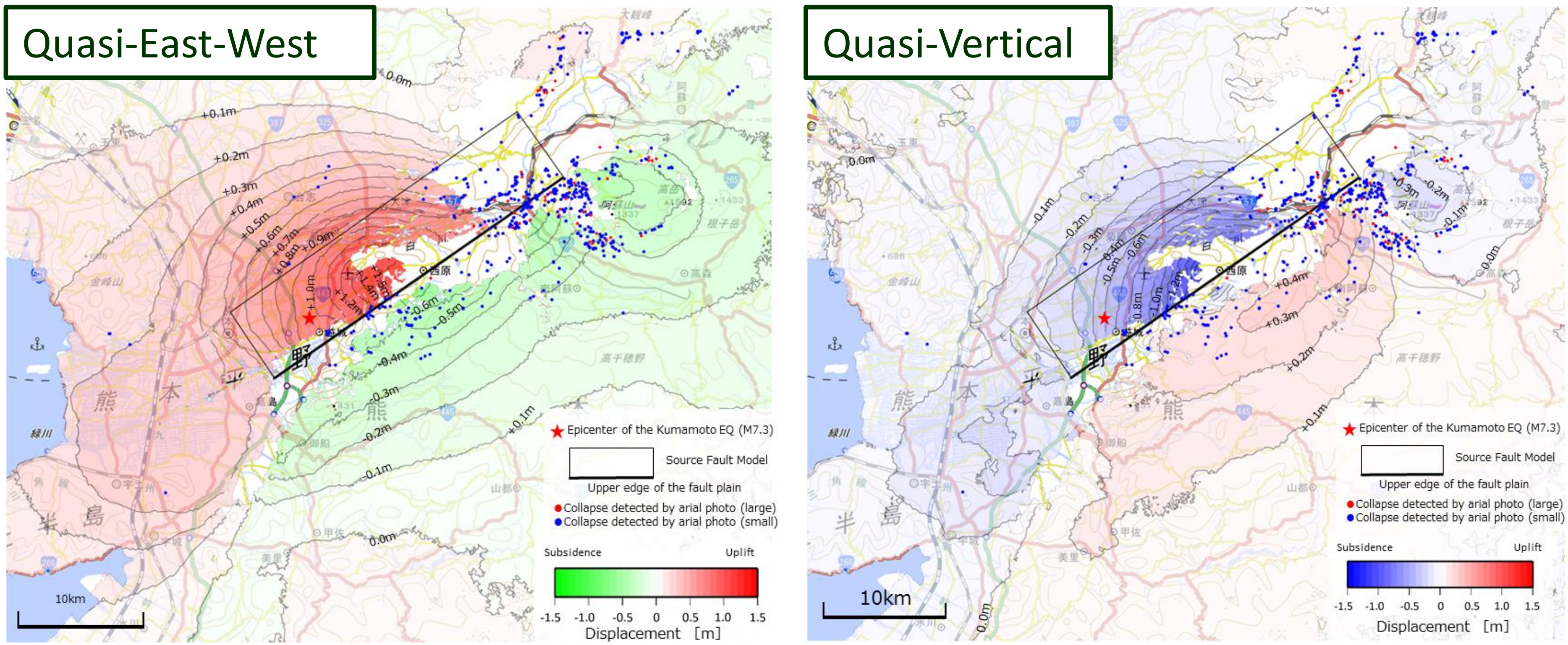
2.5D analysis of Interferometric SAR (InSAR) using ALOS-2

A combination of two InSAR images from ascending and descending orbits provides east-west and quasi-vertical displacement maps.



2.5D analysis of Interferometric SAR (InSAR) using ALOS-2

Japanese L-band SAR satellite, ALOS-2, launched in 2014, observed an area around the epicenter from both east and west side, and successfully delineates crustal deformation field of the 2016 Kumamoto EQ (M7.3).



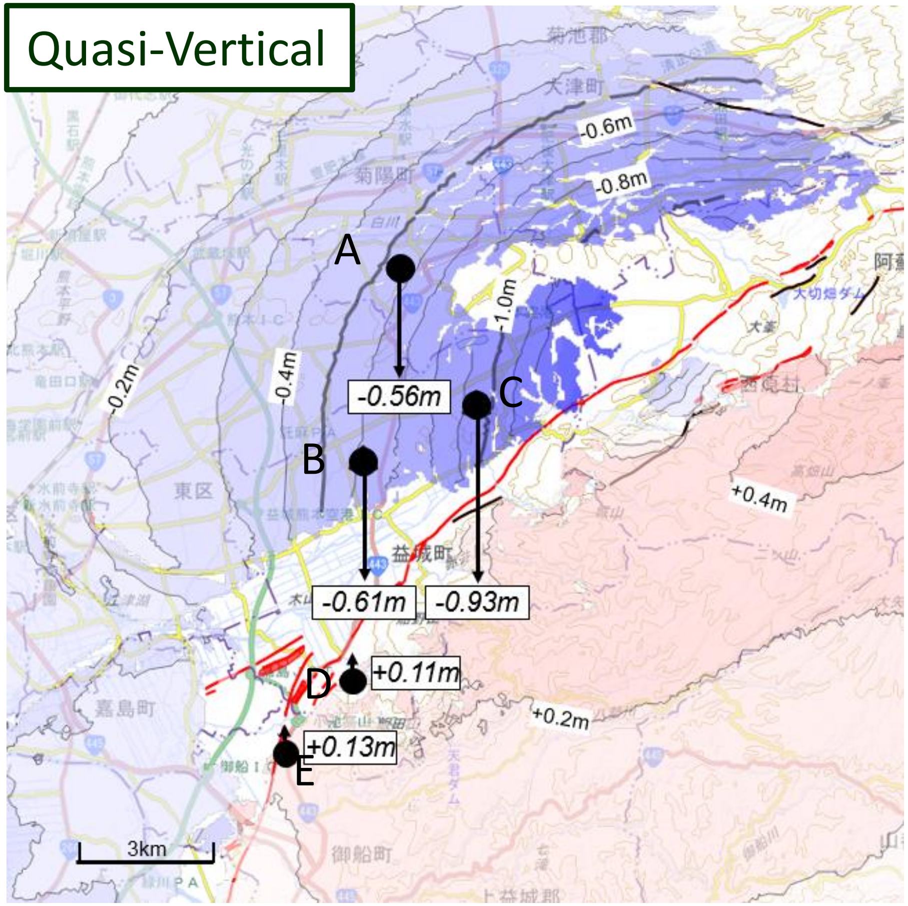
Application of InSAR data for revision of geodetic reference frame

Multi-direction InSAR analysis using ALOS-2 data provides the quasi-vertical crustal displacement field good agreement with GNSS observation within 3 cm except C.

Comparison of vertical displacement between GNSS and ALOS-2

Station	GNSS	ALOS-2
A (Touge)	-55 cm	-55.5 cm
B (kita-Okubo)	-59.6 cm	-61.1 cm
C (Osakozumi)	-103 cm	-93.4 cm
D (Koike)	14 cm	11.4 cm
E (Takagi)	15.2cm	12.5cm

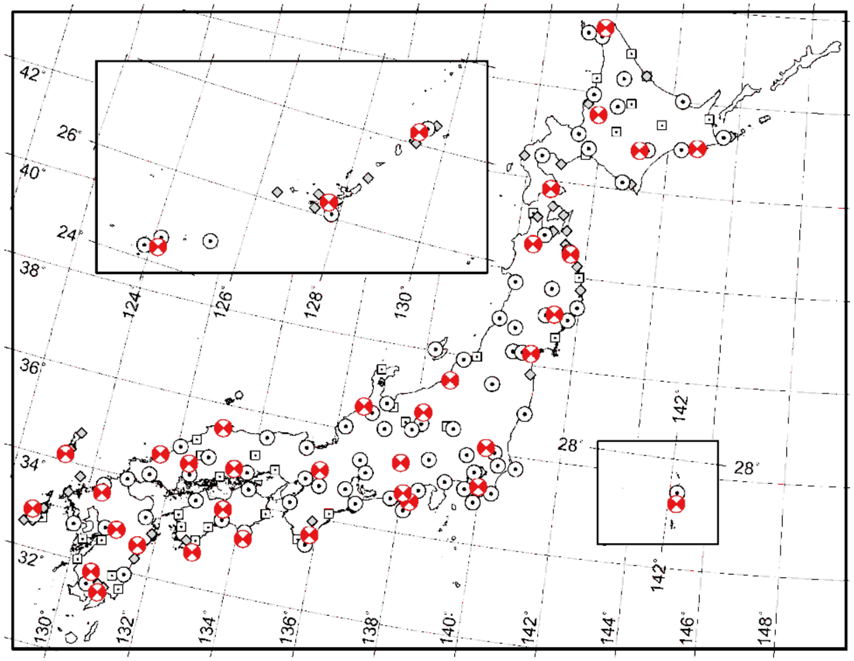
InSAR technique could be a powerful tool for revision of geodetic reference frame.



Gravimetric reference frame

JGSN75 and JGSN2013

Japan Gravity Standardization Net (JGSN)



Fundamental gravity station (35)
First-order gravity station (177)

JGSN75

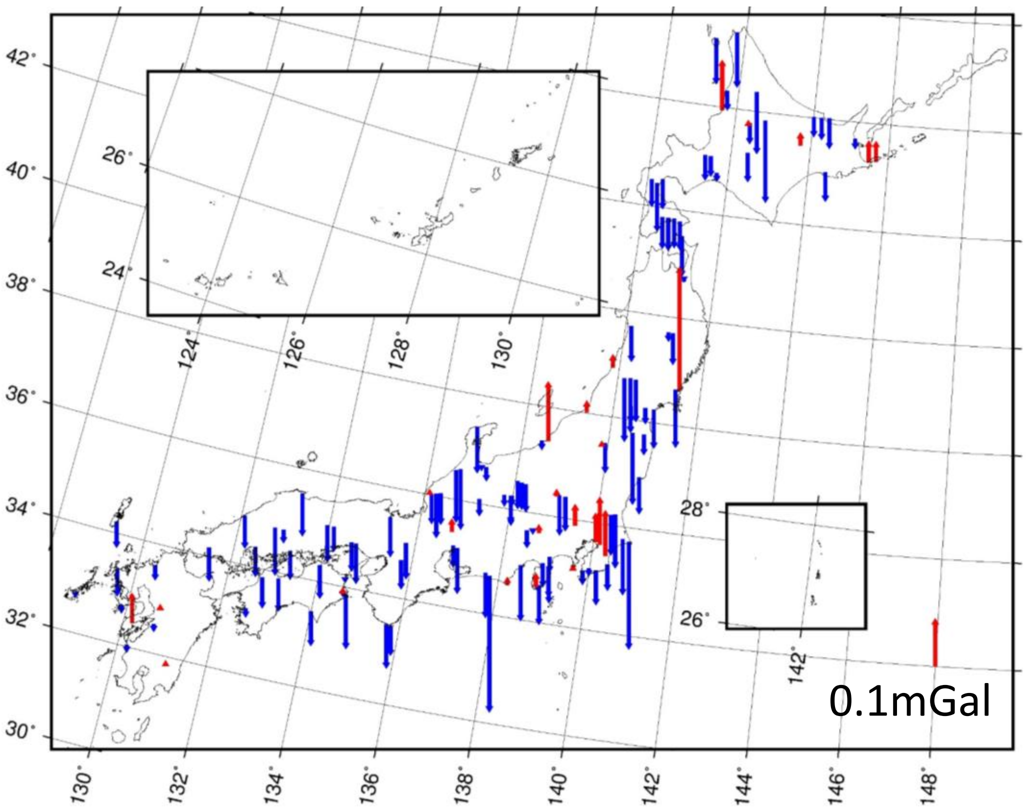
Establish in 1976
Consistent with IGSN71
Absolute accuracy : 100 μGal
Relative accuracy : 30 μGal
Instrument : GSI gravity pendulum
AG1 spring gravimeter

JGSN2013

Establish in 2013
Absolute accuracy : 20 μGal
Relative accuracy : 15 μGal
Instrument : FG5 absolute gravimeter
LaCoste spring gravimeter

Deference between JGSN2013 and JGSN75

JGSN2013 - JGSN75



Average difference of about 0.1mGal

As a whole, JGSN2013 is smaller than JGSN75

Instrumental measurement error? or gravity changes due to tectonic activities?

Estimation of gravity change due to tectonic activities

Gravity change =
Crustal uplift/depression + Coseismic mass change

Crustal uplift/depression :

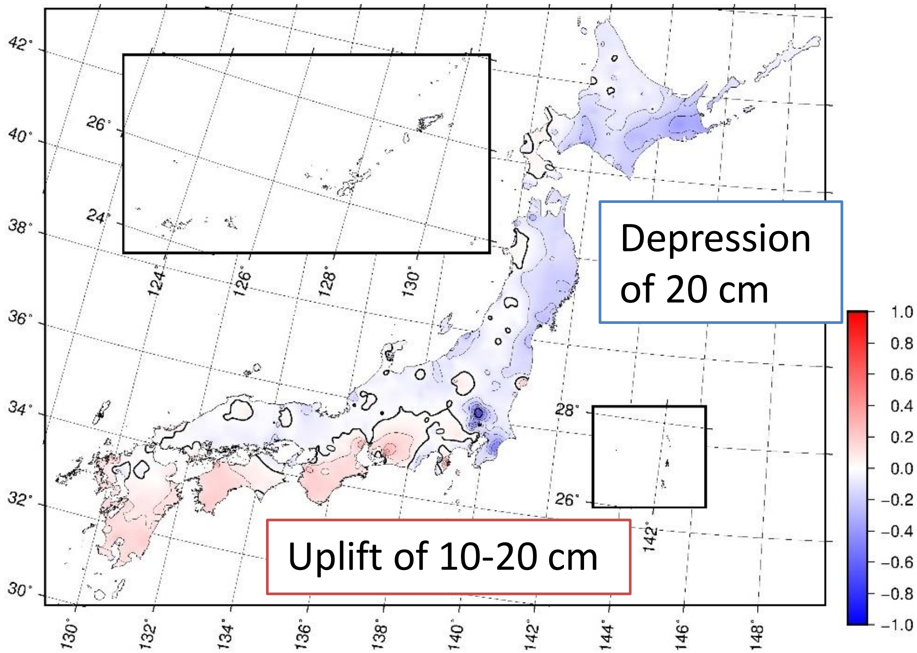
-> Geodetic observation data from spirit leveling and GNSS (GEONET)

Coseismic mass change :

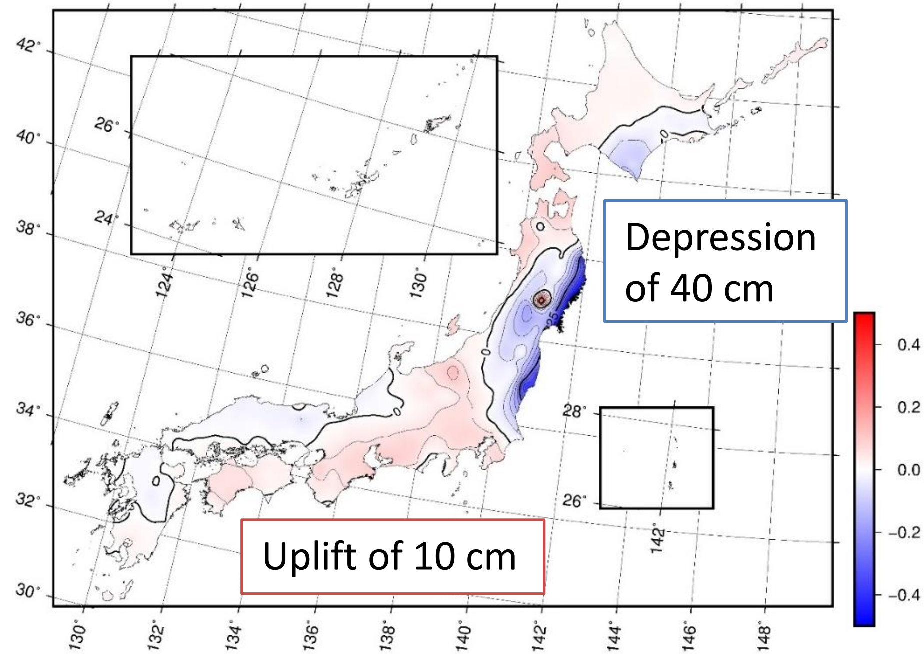
-> Calculation based on Okubo (1992)'s formula and fault models

Crustal uplift/depression

Free-air and bouguer gravity changes are computed from vertical displacements.

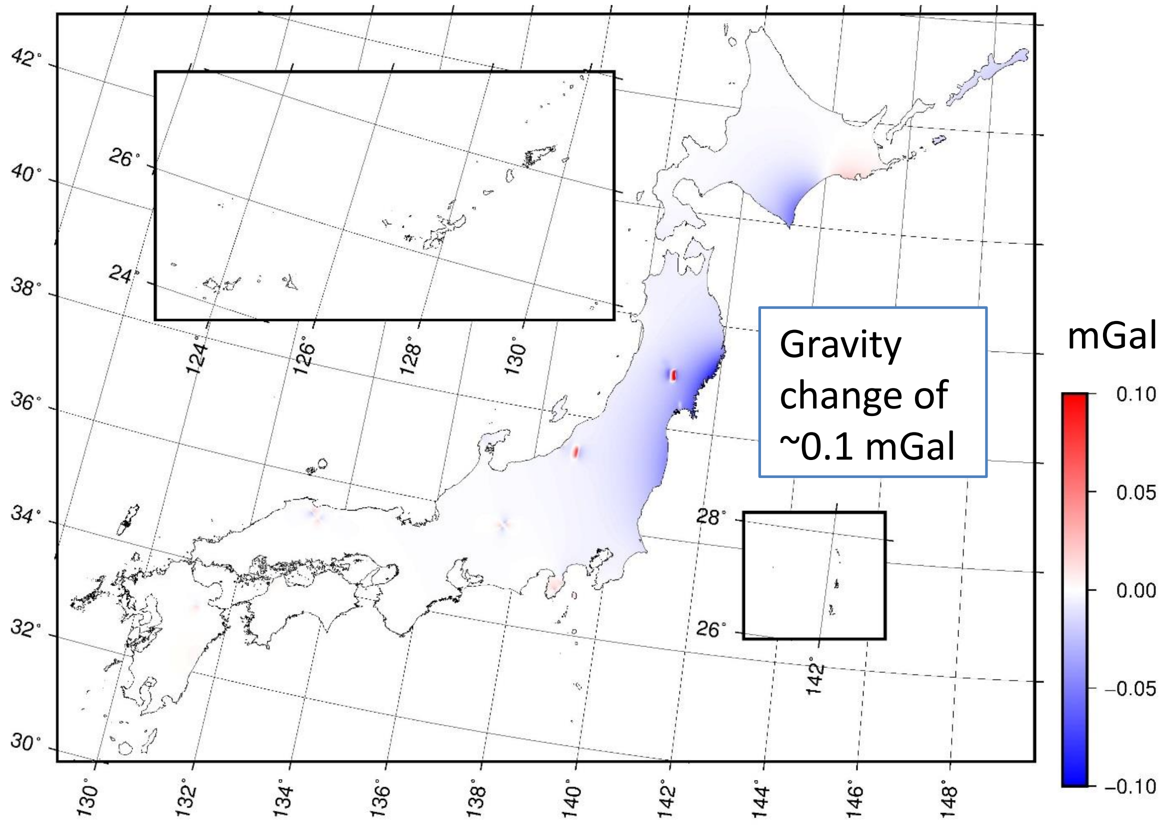


Spirit leveling during 1970-2003



GNSS observation during 2003-2015

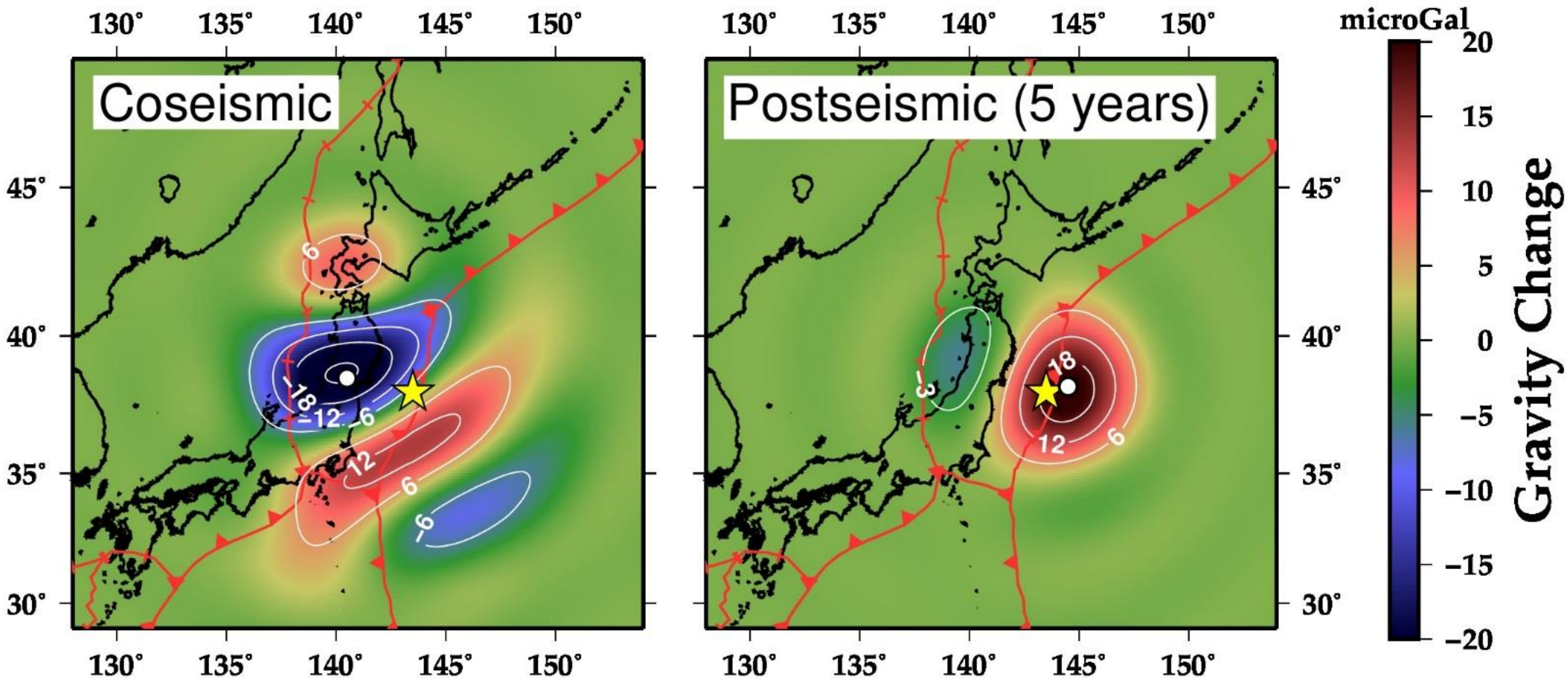
Coseismic mass change during 1976-2013



Okubo (1992)'s formula and fault parameter catalog are used.

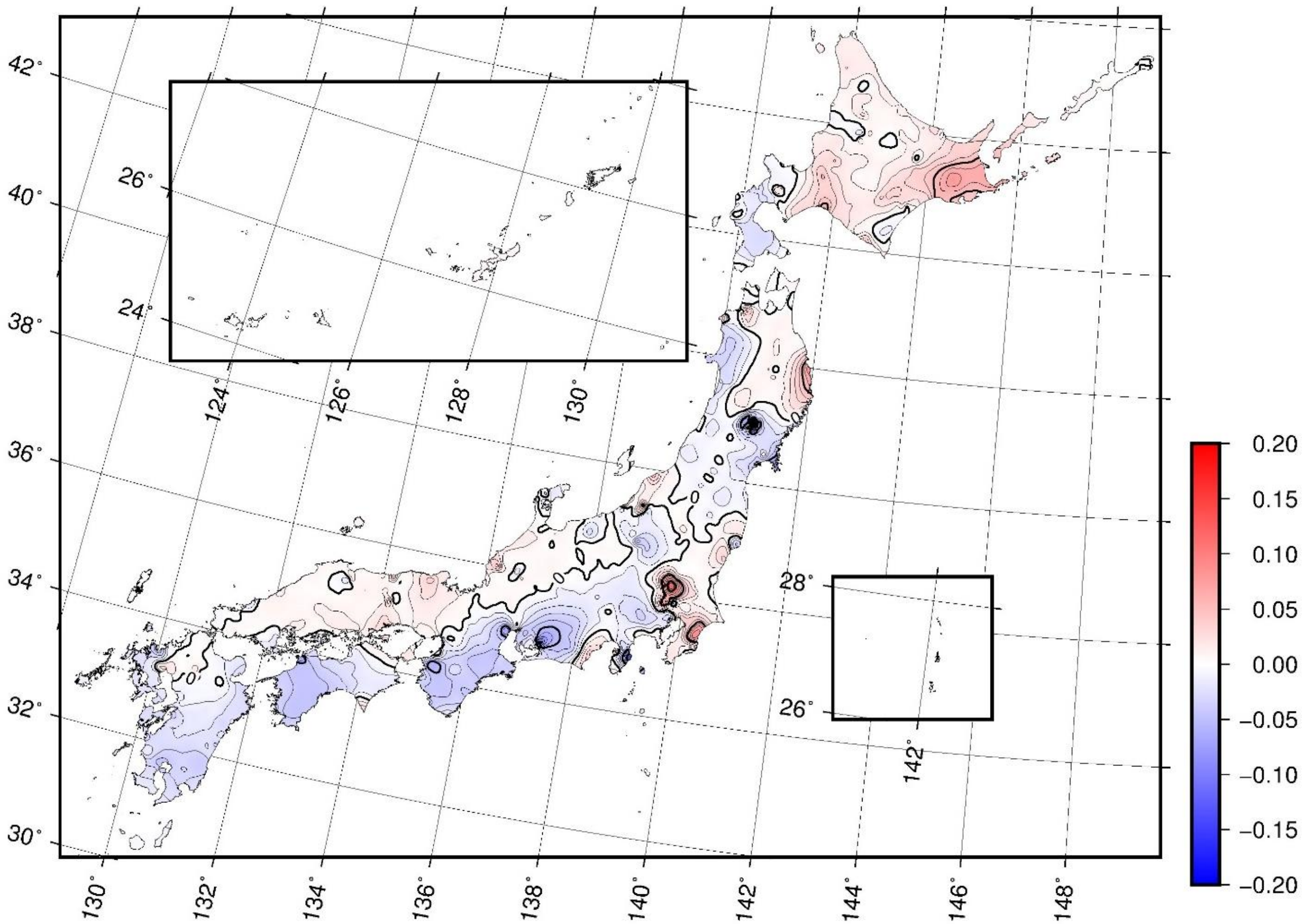
Large negative gravity change of about 0.1 mGal in Tohoku region, which is caused by the 2011 off-Tohoku EQ

GRACE observation of gravity change by Tohoku EQ

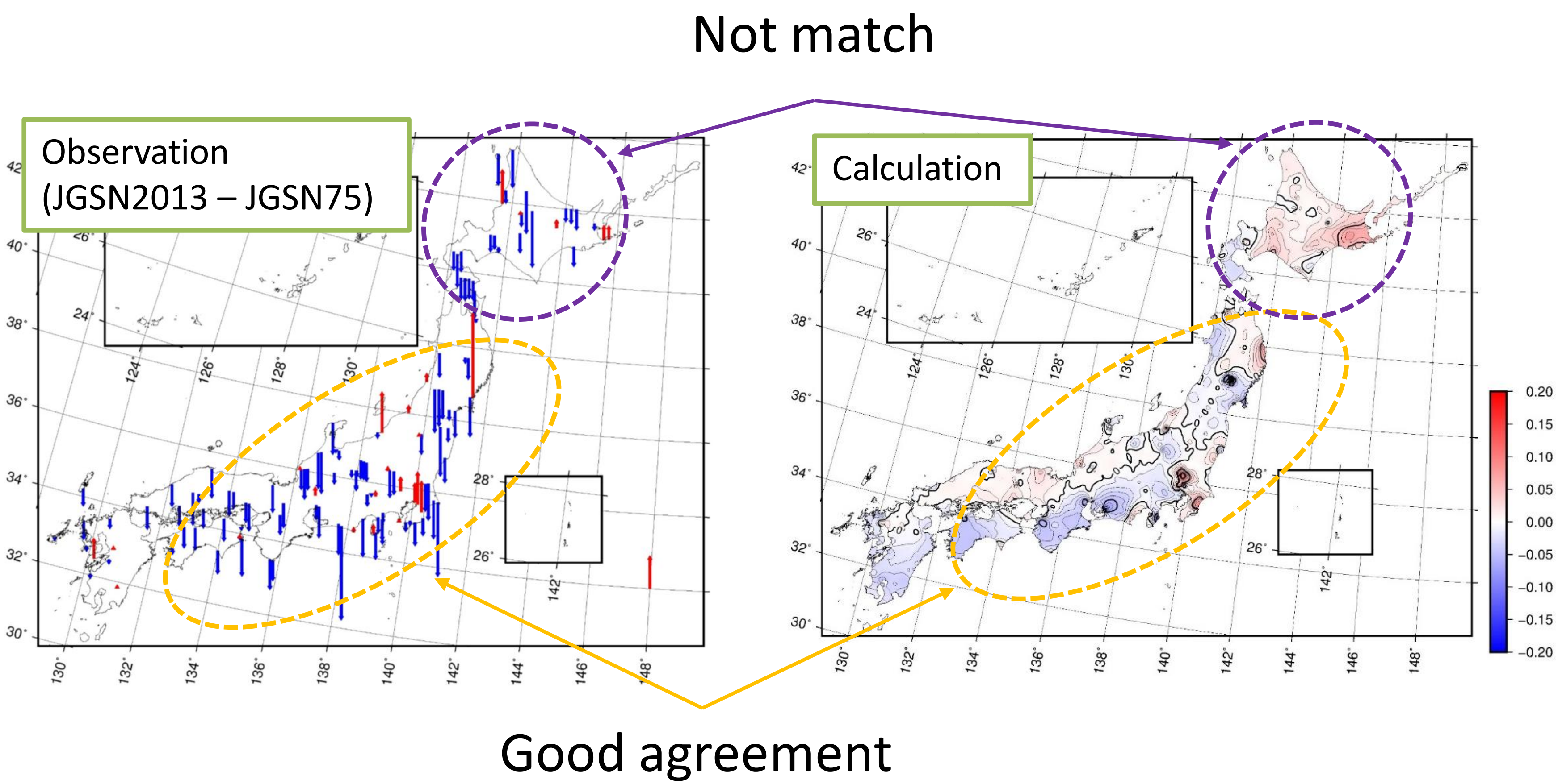


Large postseismic gravity changes continue to occur.

Gravity change by Tectonic activities during 1976-2013



Comparison between observation and calculation



Summary

- Dense GNSS array (GEONET) is essential infrastructure for Japan to maintain the geodetic reference frame as well as to monitor tectonic activities in Japan.
- GEONET analysis revealed the crustal deformation caused by the 2011 off-Tohoku EQ (M9.0), and contributed the quick revision of the geodetic reference frame after the earthquake.
- The gravimetric reference frame has been updated from JGSN75 to JGSN2013.
- The difference between JGSN2013 and JGSN75 can be partly explained by tectonic activities in Japan.

Thank you for your attention!