Reconstruction of geodetic reference frame after the 2011 off the Pacific coast of Tohoku Earthquake

3rd May 2016
FIG Working Week 2016

Basara Miyahara,
Toyofuku Takashi, Tomoaki Furuya,
Yohei Hiyama, Atsushi Yamagiwa
Geospatial Information Authority of Japan

Outline

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

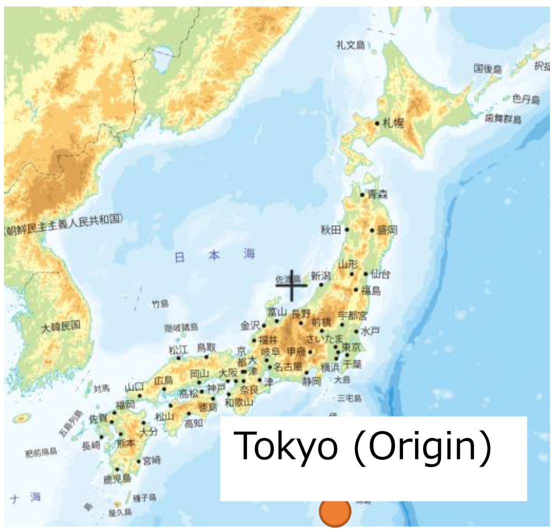
Introduction

国土地理院

- 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.
- Because Japan is situated in the tectonically active region, its geodetic reference frame is continuously deforming, which requires the regular maintenance of reference frame.
- The 2011 off-Tohoku EQ (M9.0) caused large crustal deformation along northeastern part of Japan. GSI reconstructed geodetic reference frame of Japan after the earthquake based on VLBI, GEONET and spirit leveling.

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

国土地理院

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 so on	
Total	128,824		

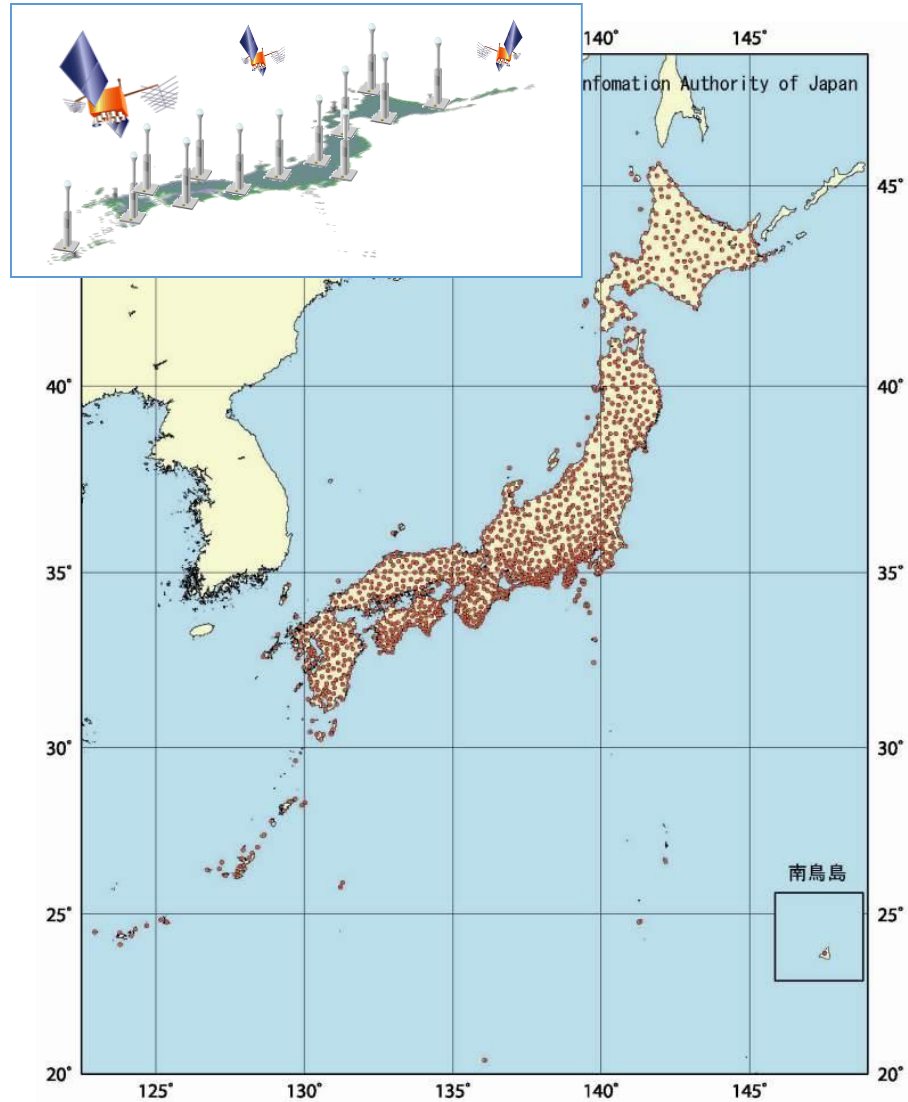
Shift to GNSS-based geodetic reference frame

- 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)

国土地理院

- 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

国土地理院

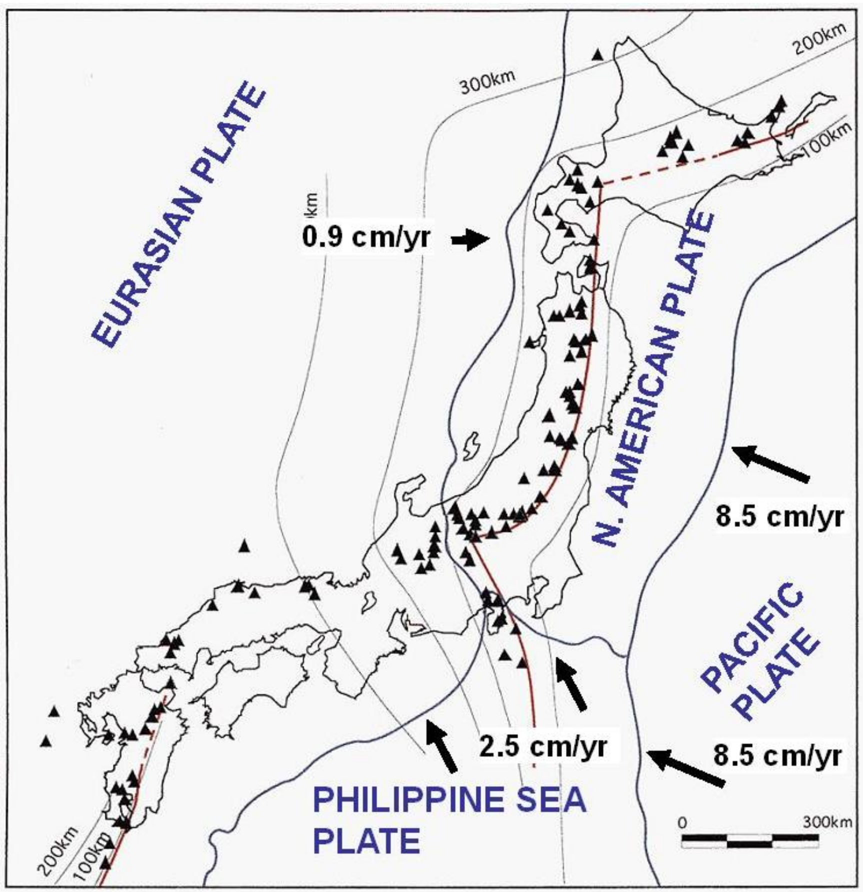
- Stainless steel pillar (5m tall)
- Chokering Antenna
- Clinometer and thermometer
- Dual frequency receiver (GPS, QZS, Galileo, Glonass)
- 24-hr observation
- 1-sec and 30-sec sampling
- Real-time data transfer (BINEX)
- Double tube structure (1/3)

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 EQs (M7.3)

Tectonic background in Japan

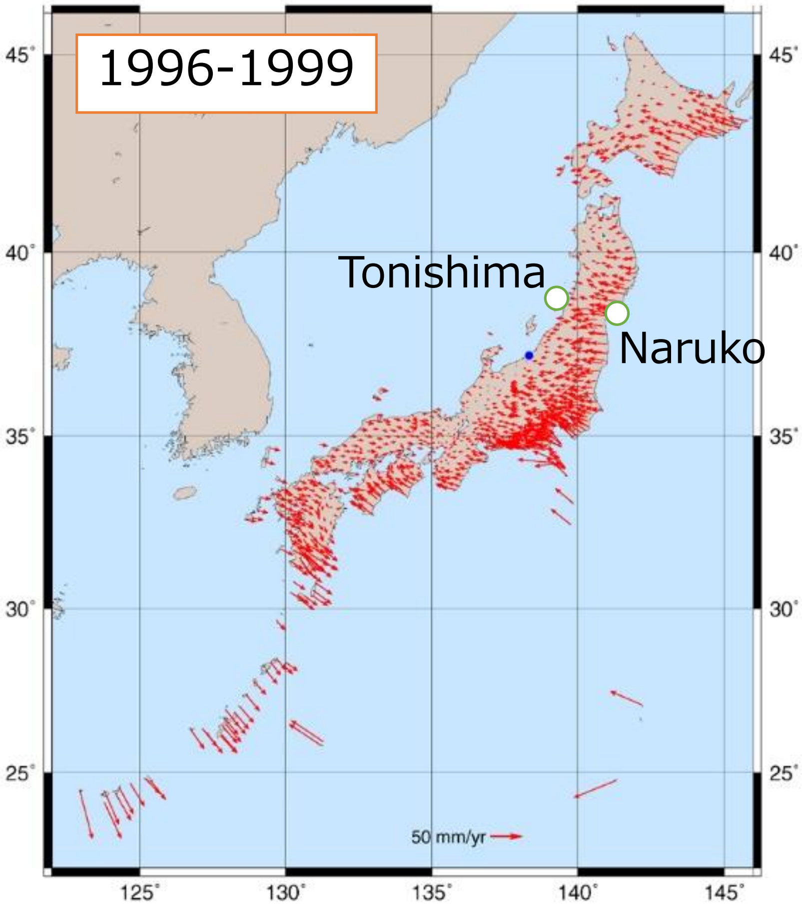
国土地理院



Martin et al. (2012)

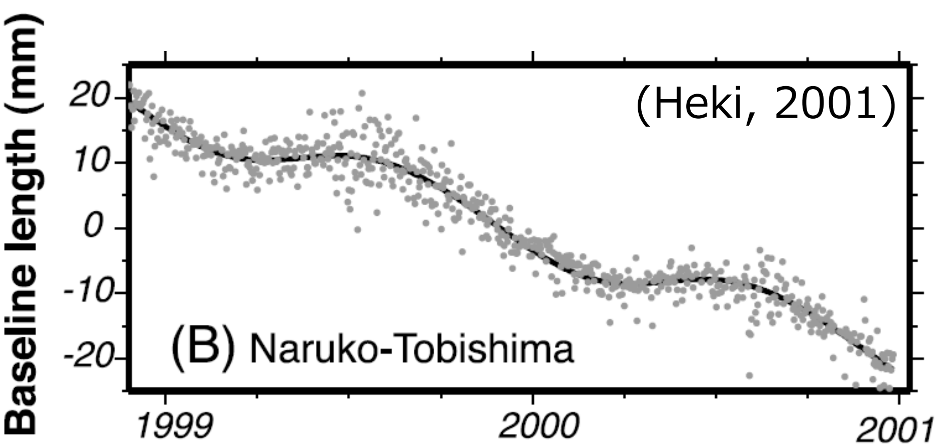
- Japan is located on an area where four active plates are colliding.
- Subduction rates are 8.5 cm/yr for Pacific plate, 2.5 cm/yr for Philippine sea plates, and 0.9 cm/yr for Eurasian plate around main islands of Japan.
- Such active plane tectonics makes the country continuously deforming and prone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

Secular deformation by plate tectonics



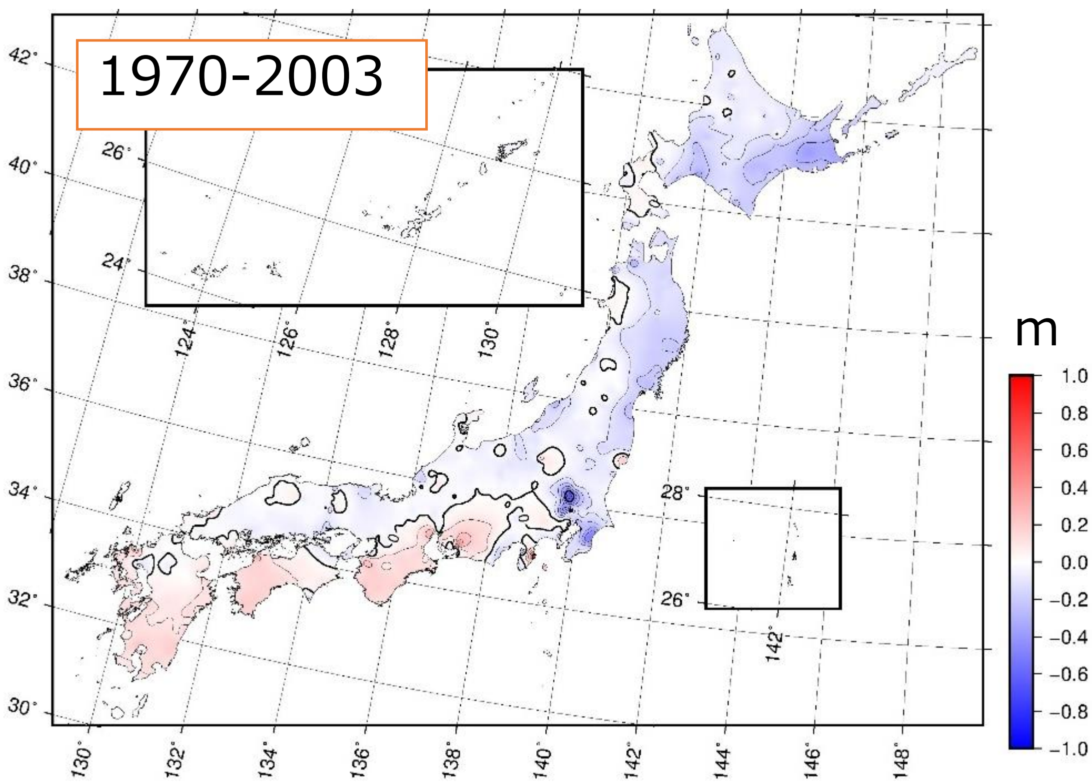
Horizontal crustal deformation filed of Japan from 1996-1999 detected by GEONET

- 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

国土地理院



Cumulative vertical displacement measured by spirit leveling during 1970-2003

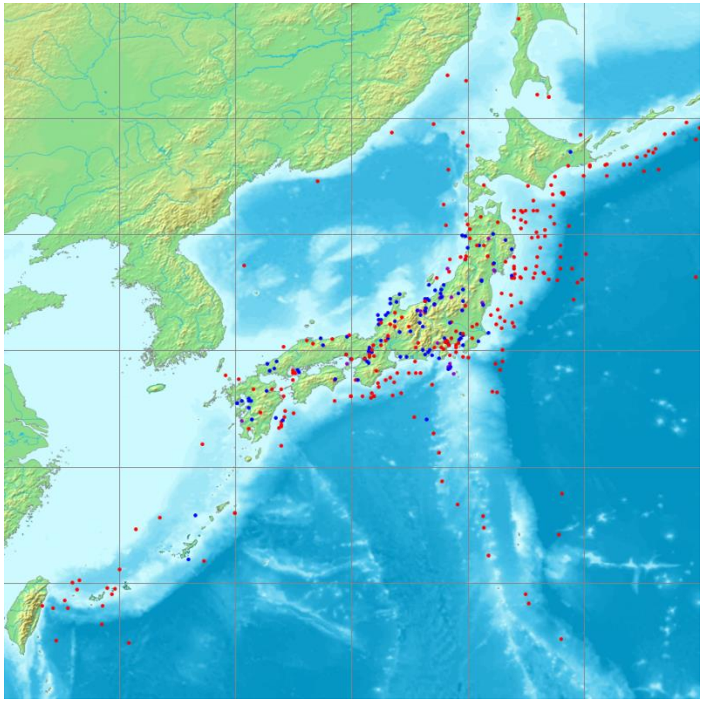
- GSI has conducted spirit leveling for Japan since 1883.
- All the first-order leveling route (about 18,000 km) are regularly measured every 10 years.
- Spirit leveling showed a depression trend of about 10 mm/yr in northeastern region and a uplift trend of 10 mm/yr in southwestern region

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)

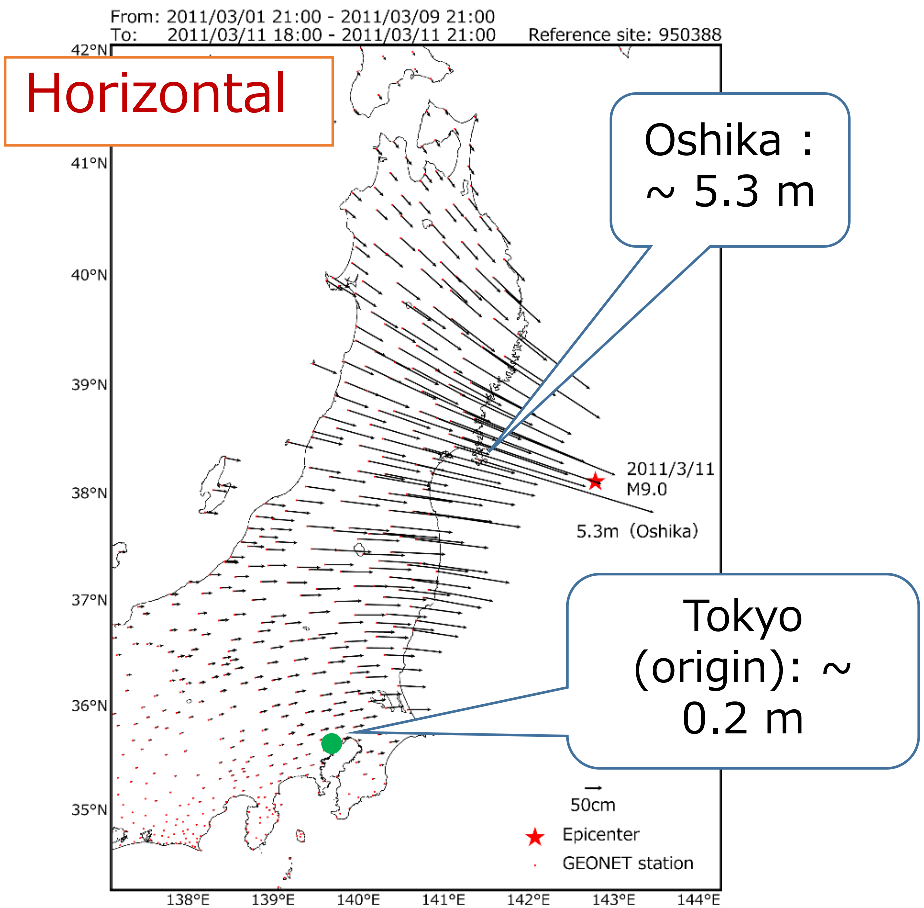
List of large earthquakes in Japan which caused large crustal deformation

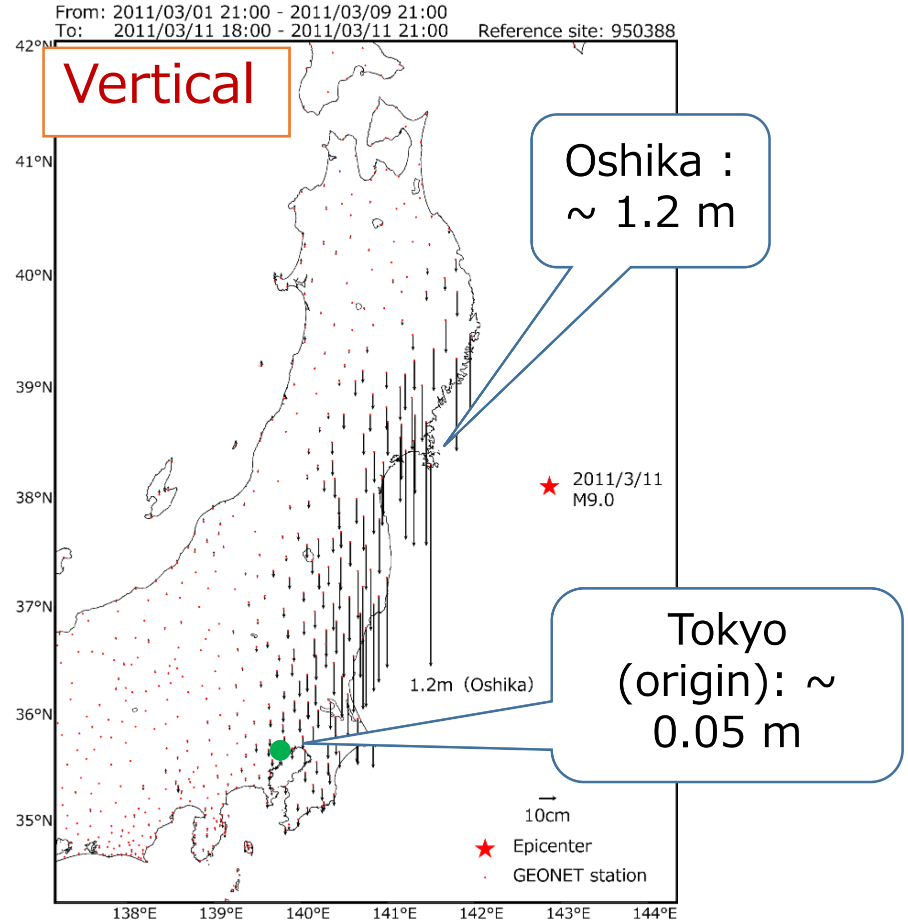
Map of the epicenters of the earthquakes larger than M7.0 during 1500-2000 (Utsu, 2000)



Red: Inland earthquake
Blue: Large Tsunami earthquake

GEONET observation



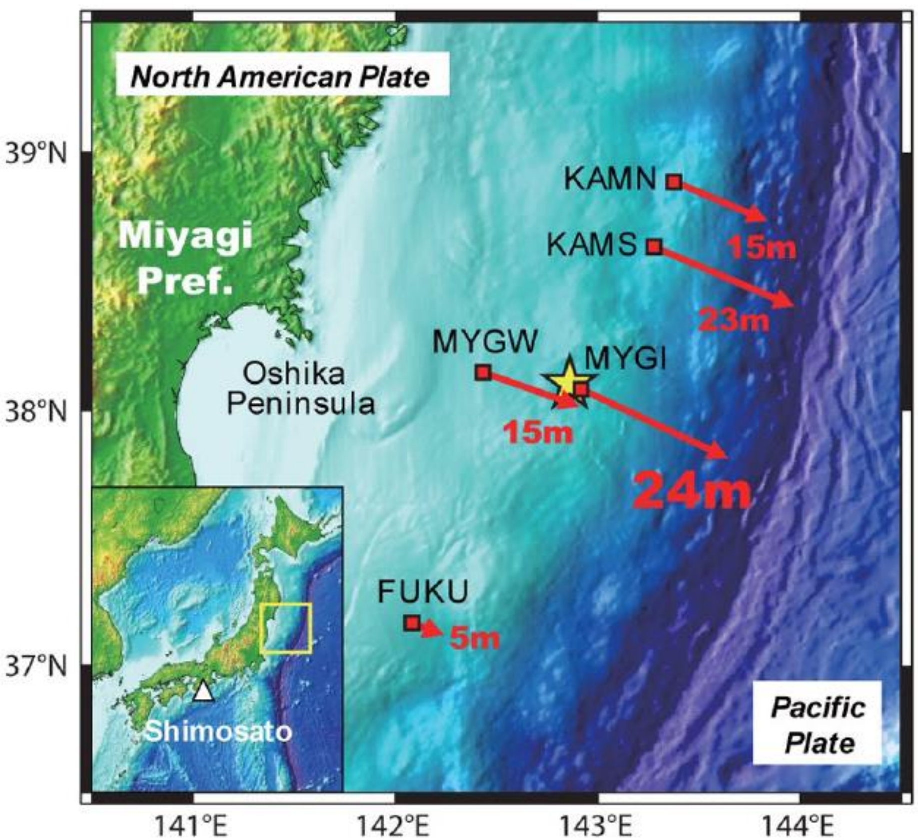


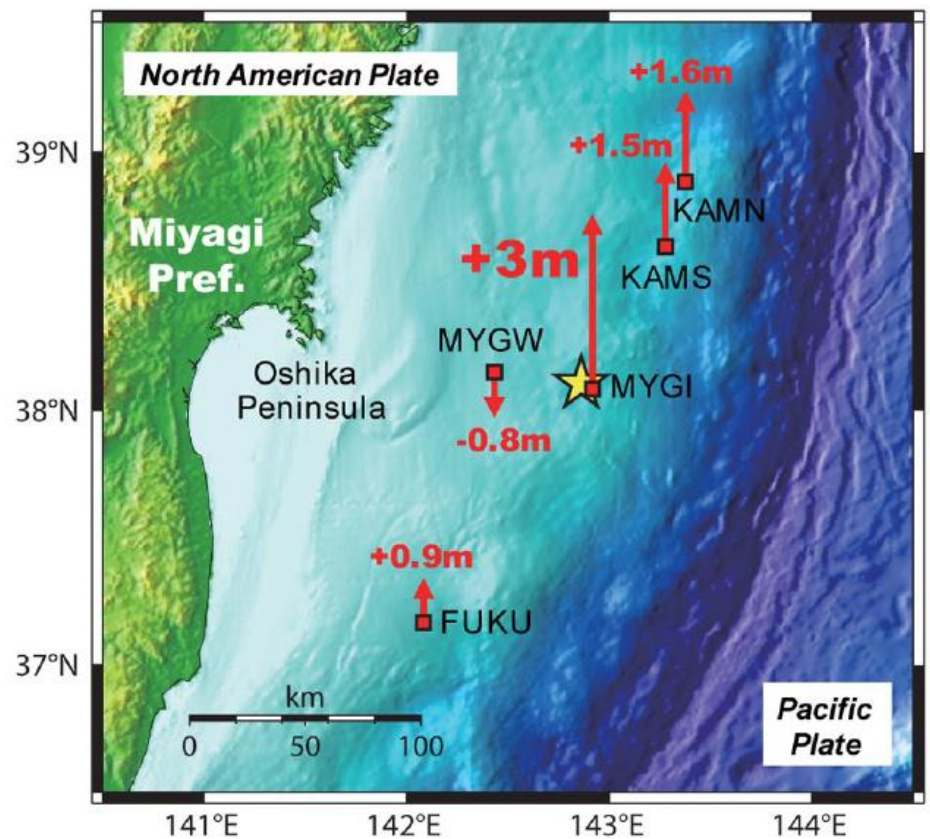
Ocean-bottom GNSS/acoustic observation

(A) Horizontal displacements

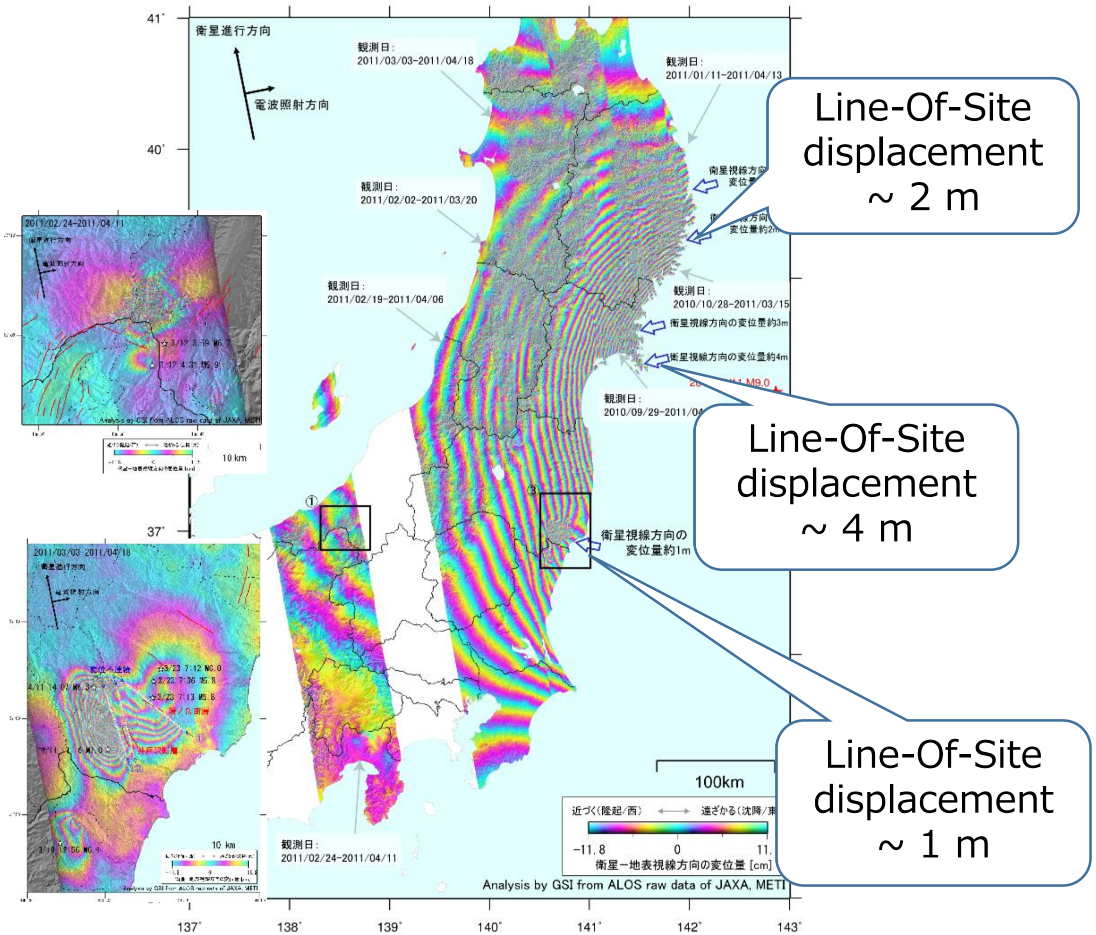
(B) Vertical displacements

(Sato et al., 2011)

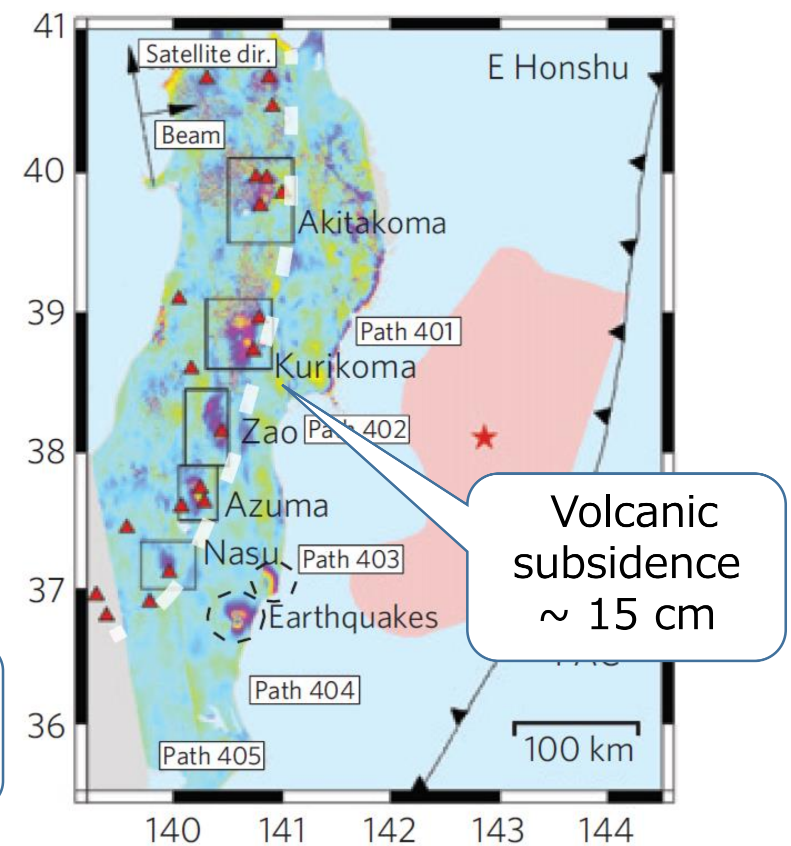




ALOS/PALSAR observation



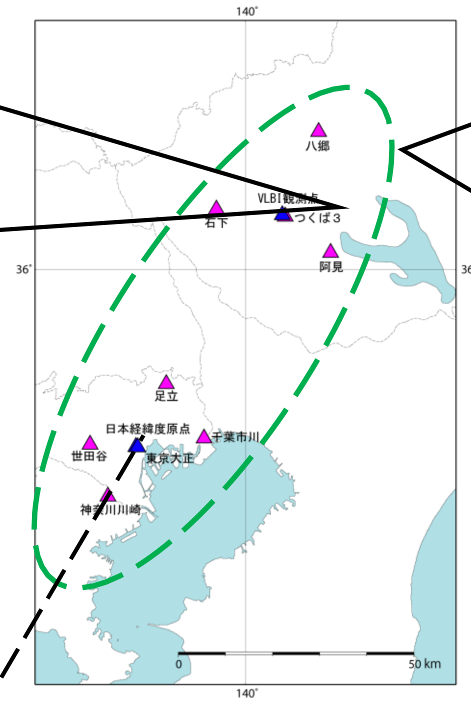
InSAR detected the deformation of magma chambers beneath volcanoes (Takada & Fukushima, 2013)



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

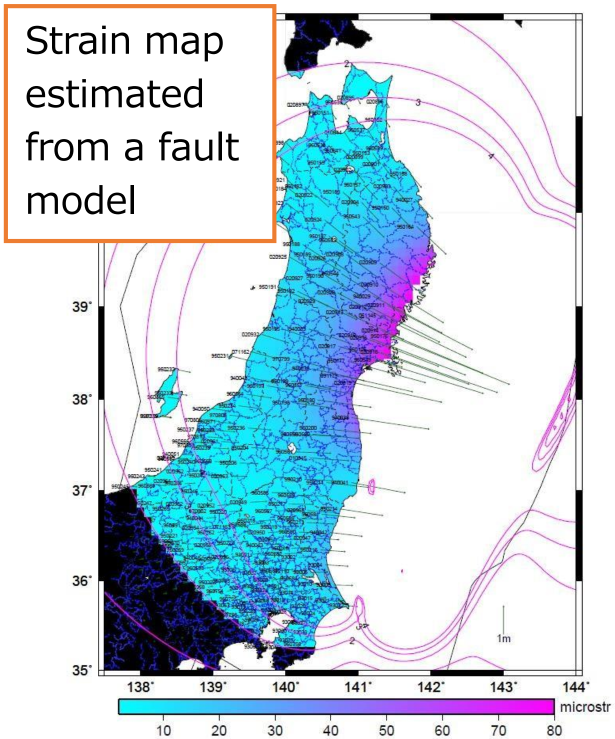
Moved downward by 2.4 cm

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

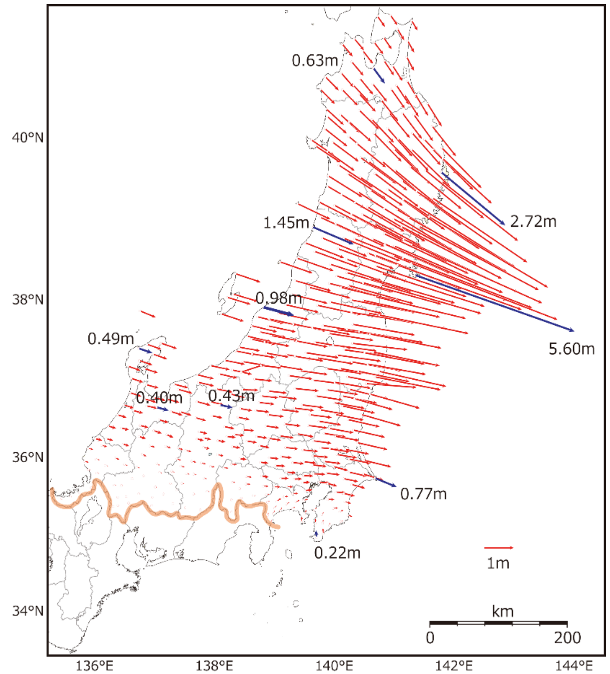
国土地理院

<u>Determination of revision area</u>
<u>Criterion for revision</u>



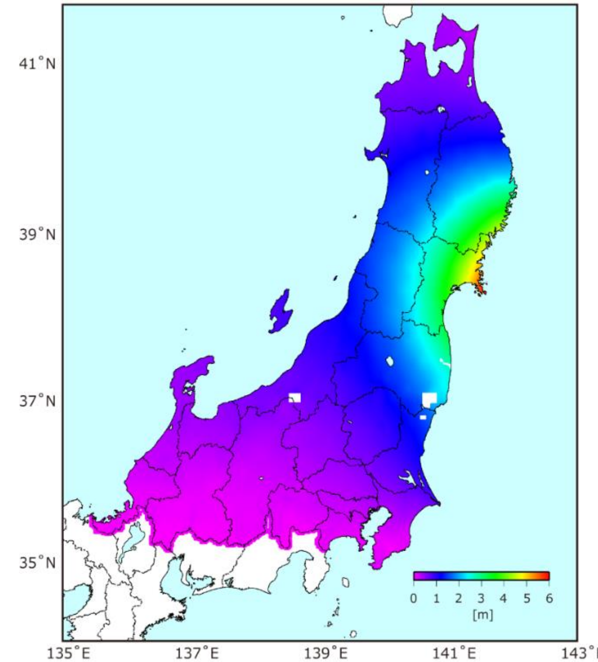
Prefectures including the area where estimated strain will be over 2 ppm.

<u>Difference in GNSS positions between new and old datum</u>



All data set is called "Geodetic Coordinates 2011"

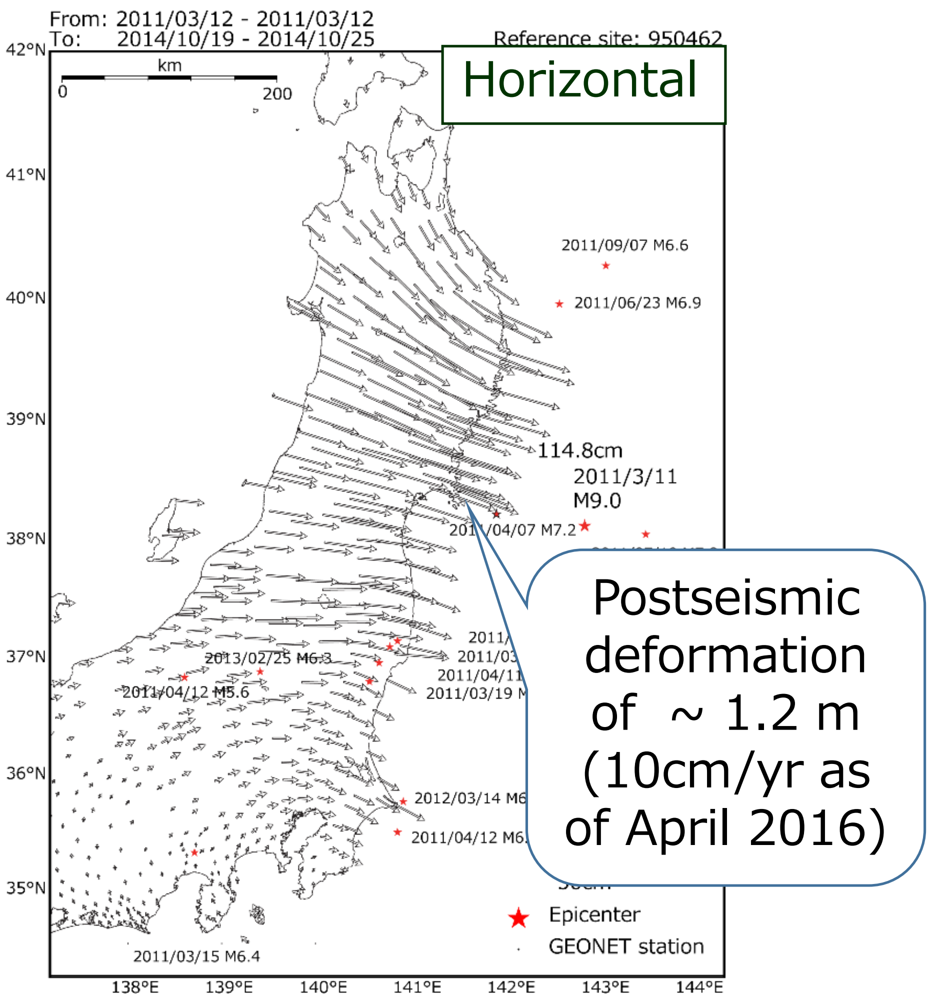
<u>Correction (transformation) parameters for triangulation control points</u>

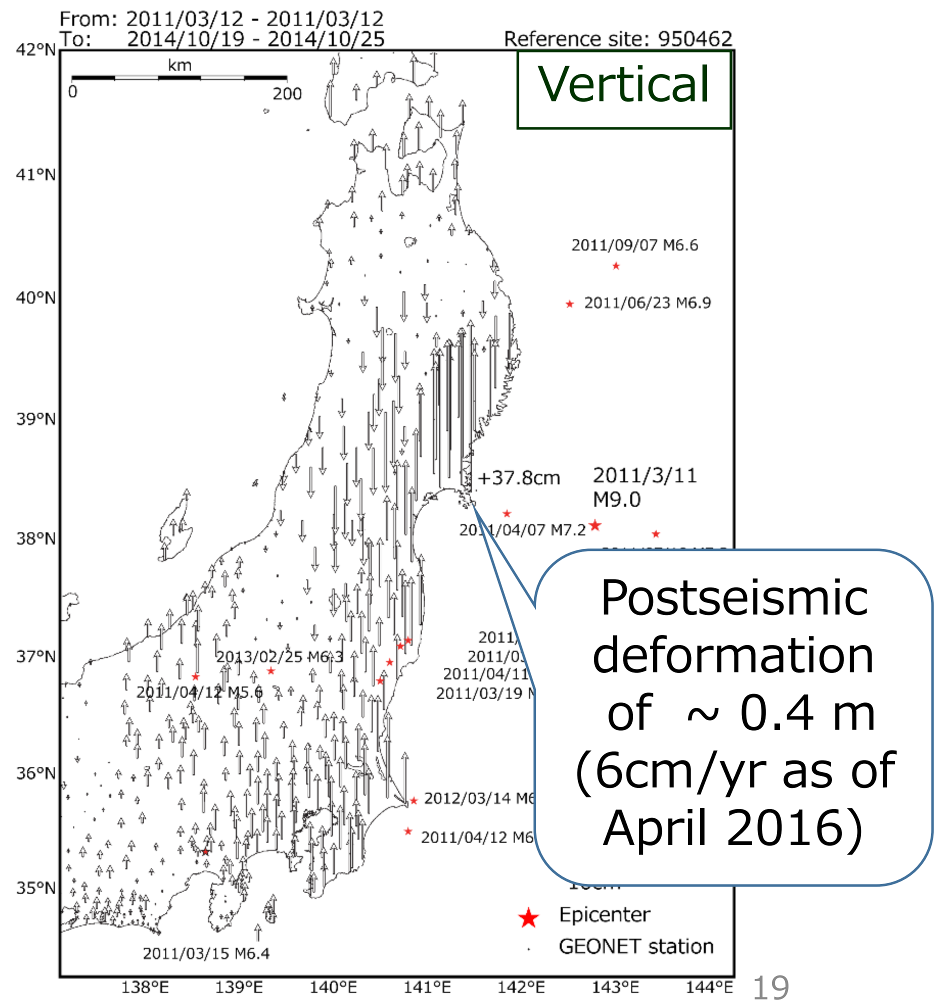


Correction parameters were calculated from GEONET and 600 GNSS campaign and applied for about 44,000 triangulation control points

Future issues : postseismic crustal deformation

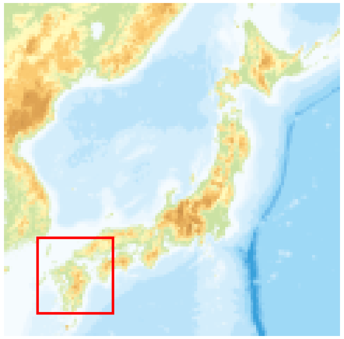
5 years cumulative deformation after the 2011 off-Tohoku EQ exceeds 1.2m in horizontal and 0.4m in vertical.
The postseismic crustal deformation is still continuing.





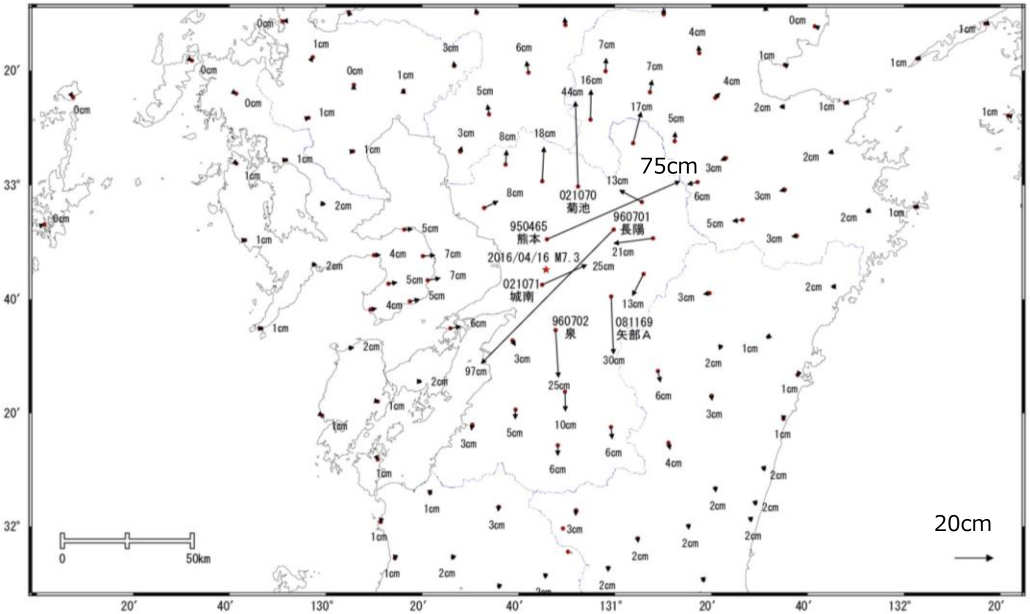
The 2016 Kumamoto EQ (M7.3)

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

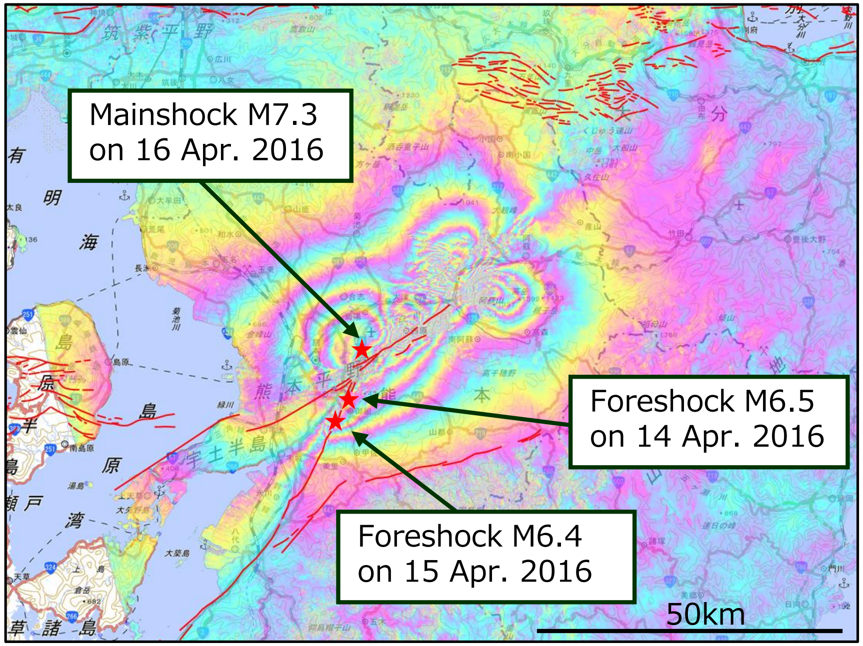


Japanese SAR satellite, ALOS-2, as same as GEONET, detected crustal deformation caused by the 2016 Kumamoto EQs.

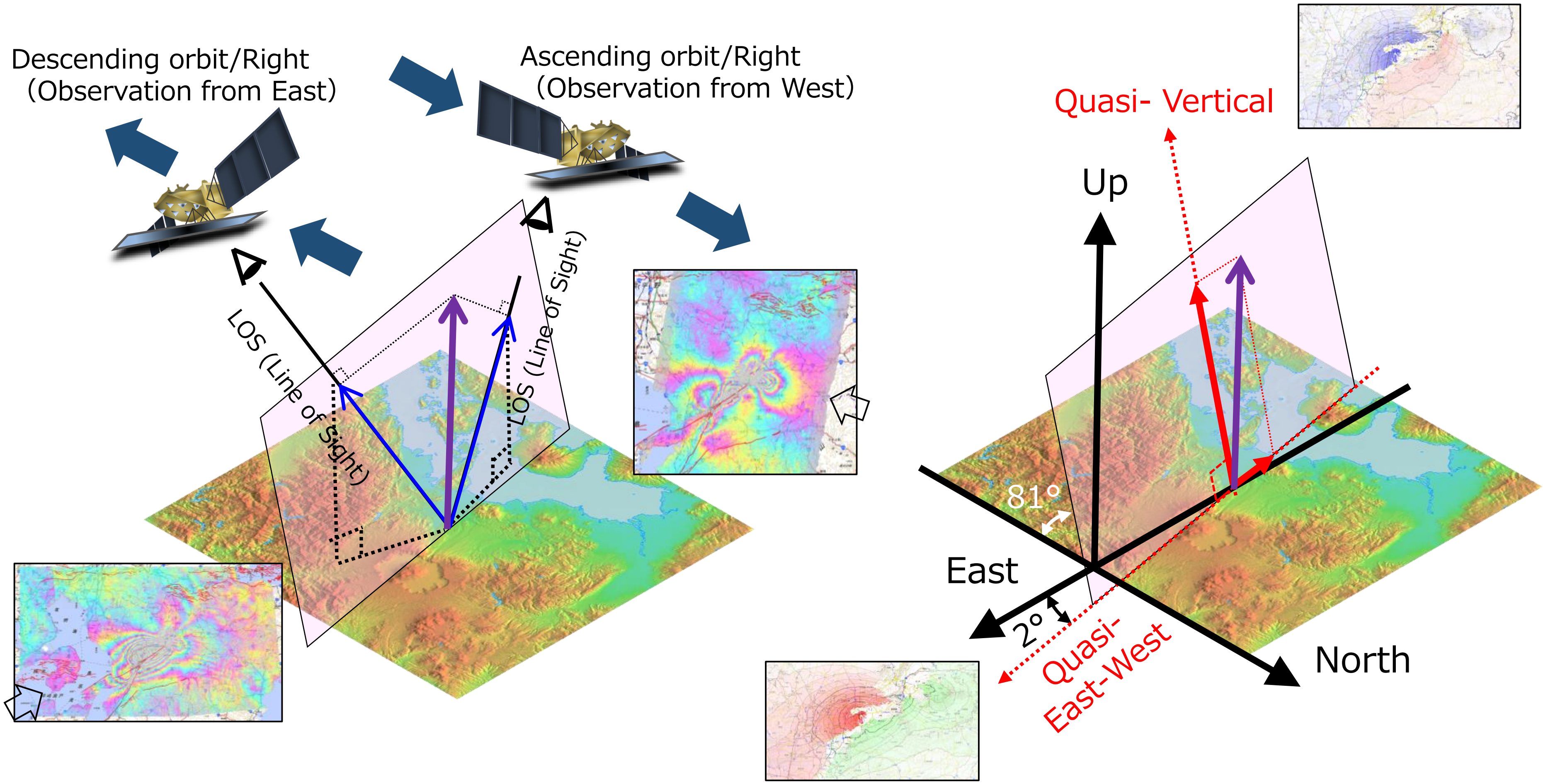
Horizontal displacement detected by GEONET



Displacement detected by ALOS-2 InSAR



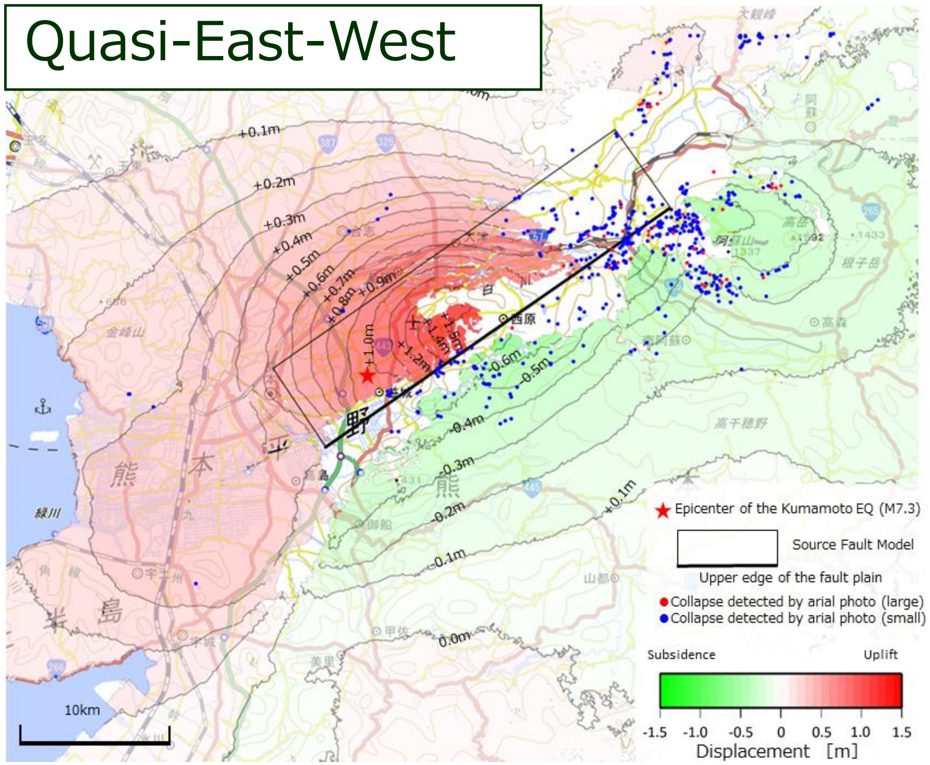
A combination of two InSAR images from ascending and descending orbits provides east-west and quasi-vertical displacement maps.

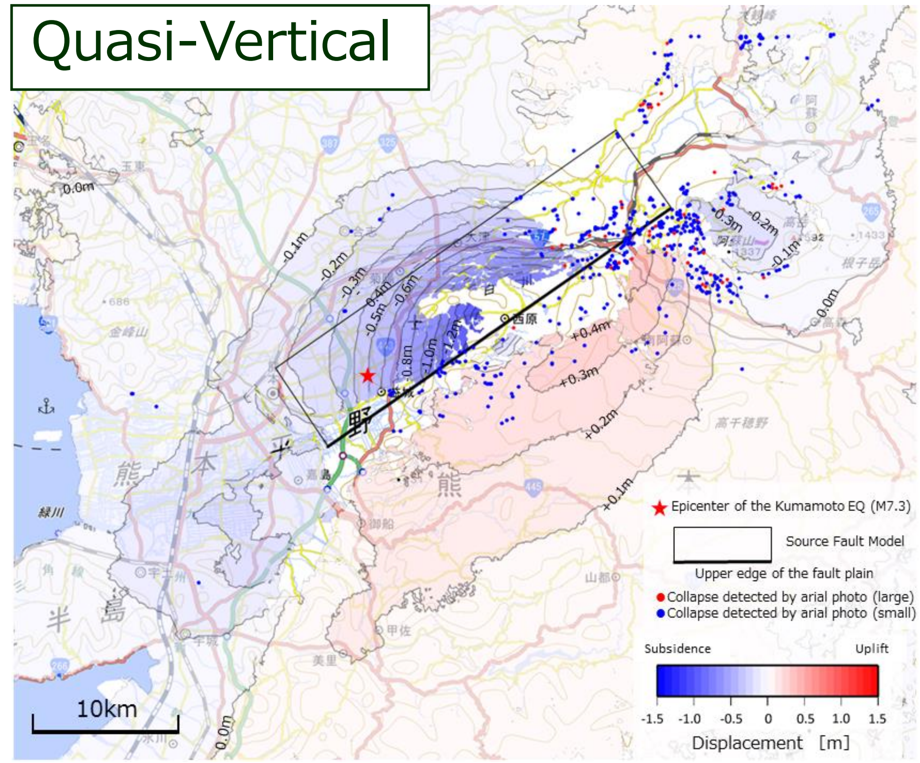


2.5D analysis of Interferometric SAR (InSAR) using ALOS-2

国土地理院

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).



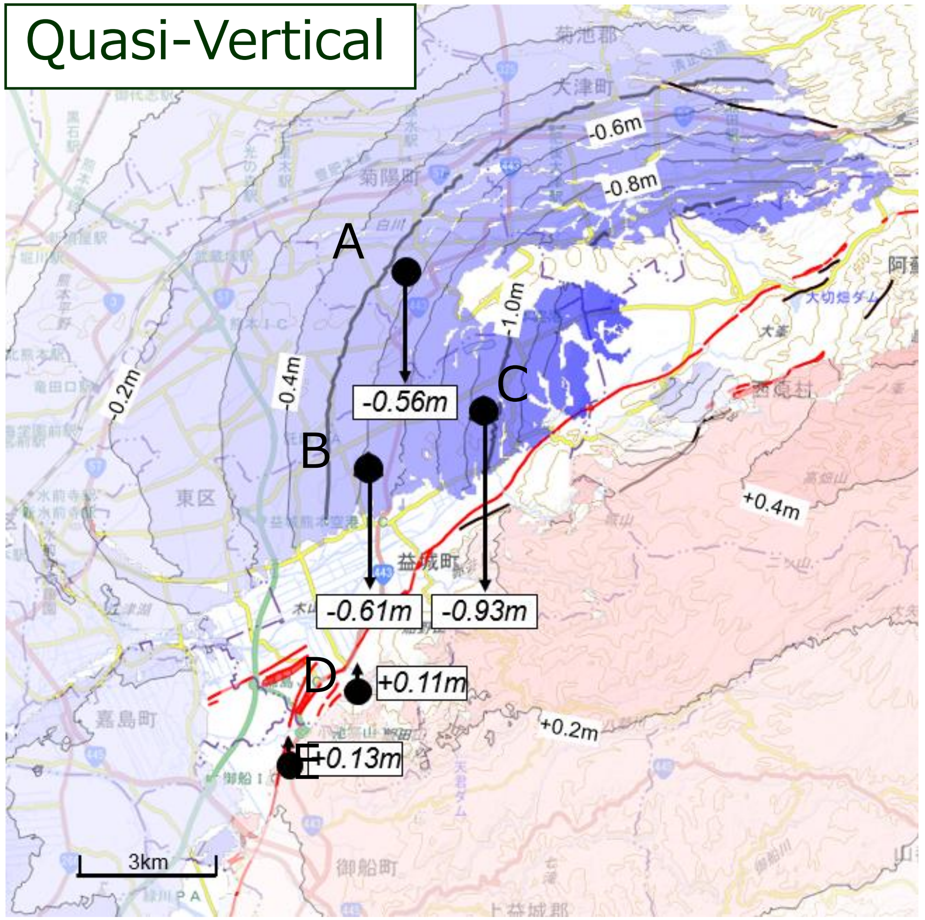


Multi-direction InSAR analysis using ALOS-2 data provides the Quasi-vertical crustal displacement field good agreement with GNSS observation within 3 cm except station C.

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.



Summary

国土地理院

- 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 was a key enabler of the quick revision of the geodetic reference frame after the earthquake.
- InSAR is also an effective tool for monitoring dense spatial distribution of crustal deformation and has a potential to be a powerful tool for revision of geodetic reference frame especially after large earthquakes.

Thank you for your attention!