Crustal deformation and fault model of the 2011 off the Pacific coast of Tohoku Earthquake

by

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ABSTRACT

This paper reports the overview of the crustal deformation caused by the 2011 off the Pacific coast of Tohoku Earthquake (hereafter referred as "the Tohoku Earthquake"), detected by GEONET, the GPS continuous observation system operated by GSI. We found very wide area of Japanese Islands was remarkably affected by the crustal deformation caused by the main shock of the Tohoku Earthquake, from Hokakido to Kinki district. We estimated the geometry of the seismogenic fault of the Tohoku Earthquake, as well as the slip model on the plate boundary between the Pacific plate and the North American plate, from the crustal deformation data. The length of the fault is estimated longer than 400 km from off Iwate prefecture in the north to off Ibaraki prefecture in the south. The largest slip estimate on the plate boundary is more than 56 m at the off Miyagi region near the Japan trench. The postseismic crustal deformation is also observed by GEONET. This means slow postseismic slip is ongoing along the plate boundary around the main fault zone.

KEYWORDS: Crustal Deformation, Fault Model, GEONET, Plate Boundary, Slip distribution, The 2011 off The Pacific Coast of Tohoku Earthquake

1. OVERVIEW OF THE EARTHQUAKE

The 2011 off the Pacific coast of Tohoku Earthquake (hereafter referred as "the Tohoku Earthquake") broke out on 14:46, March 11, 2011. It is the largest earthquake, of which magnitude is 9.0 (by JMA), among all earthquakes recorded in the history of seismic observation in Japan. The highest intensity, VII (JMA scale) was recorded at Kurihara City, Miyagi prefecture. The epicenter locates at off shore of Miyagi prefecture, where large plate boundary earthquakes, of which magnitude is 7 to 8 but not larger than 8.5, have occurred repeatedly. The Tohoku Earthquake generated a disastrous tsunami hitting the wide area of the Pacific coast from Hokkaido to Honshu causing great damages. Meiji-Sanriku Earthquake (M8_1/4), which occurred in 1896 at the neighboring area to the Tohoku Earthquake's source region, is known as "tsunami earthquake" and caused more than 22,000 casualties. The Tohoku Earthquake caused nearly the same number of dead and lost people.

2. COSEISMIC CRUSTAL DEFORMATION

Significant crustal deformation caused by the Tohoku Earthquake was detected by GEONET, the continuous GPS observation network operated by GSI. Figure 1 shows the horizontal movement, and Figure 2 shows the vertical movement of GEONET sites in the northeastern Japan. (GSI, 2011a)[1] The maximum movement is recorded at " Oshika" site in the Ishinomaki city, Miyagi prefecture. " Oshika" horizontally moved toward southeast by east about 5.3 meter, as much as vertically subsided about 1.2 meter.

Figure 3 shows the contour map of horizontal movements. (GSI, 2011b)[2] It is notable that a very wide area around the Tohoku and Kanto region is affected by the crustal deformation by the Tohoku earthquake. The GEONET sites in Iwate prefecture at the north, Yamagata

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prefecture at the west, and Ibaraki prefecture at the south, moved more than 1 meter. Even in Tokyo metropolitan area, about 0.2m horizontal movement is observed.

Figure 4 shows the contour map of vertical movement. (GSI, 2011b) It is remarkable that all places along the Pacific coast line in the Tohoku and Kanto region subsided coseismically. The Oshika peninsula, the nearest place to the epicentric area, subsided more than 1 meter. Several tens centimeter subsidence is recorded at many sites from Miyagi to Ibaraki prefecture coast line, where are affected by high tide after the earthquake..

3. FAULT MODELS

We constructed a fault model using coseismic surface displacement data observed by GEONET. A preliminary fault model which consists of two rectangular faults with a uniform slip in an elastic half-space is shown on Figure 5. The parameters of these faults are estimated, based on the formula introduced by Okada (1985). [3]. This figure shows that a total major rupture length reaches about 380 km with a fault width of 90-130 km. (Northern segment: about 180 km long/ Southern segment: about 180 km long). A reverse fault motion is inferred. Slip amounts of northern segment and southern one are estimated to be about 25 m and about 6 m, respectively. A total moment magnitude is 8.9. (Northern segment: M_w8.8 / Southern segment: M_w8.2)

Figure 6 shows a distributed slip model using coseismic surface displacement data observed by GEONET. (GSI, 2011b) We assumed that the coseismic slip occurred along the plate boundary between the Pacific Plate, which is subducting from east, and the North American plate, where the Tohoku region locates. The slip is estimated by the geodetic inversion based on the method of Yabuki and Matsu'ura (1992). [4]. The slip area, where the slip estimated larger than 4 m, extends more than 400 km from north to south, or nearly 450 km in the major axis along the Japan trench, as well as the width is about 200 km from west to east. The largest slip, estimated at near the epicenter, is about 27 m. (Ozawa et al., 2011)[5] Total amount of the energy coseismically released, or seismic moment based on this slip model, is 3.90 x 10^{22} Nm, equivalent to the moment magnitude (M_w) 9.0, assuming the rigidity as 40 GPa. This moment magnitude value is consistent to other results of the estimation based on seismic wave inversion or tsunami inversion analysis.

Figure 7 shows an advanced slip distribution model using GEONET data and seafloor crustal deformation data observed by Japan Coast Guard. (GSI, 2011b) The horizontal movement observed at "Miyagi-1" seafloor site is as large as 24m, and vertical movement there is about 3 m uplift. It is notable that the center of the slip area is estimated nearer to the Japan trench, or more eastward, compared with the previous model. Furthermore, the estimated maximum slip is more than 56 m, much larger than previous estimation. This extremely large slip means that the plate boundary around this area has been stuck very firmly before the earthquake, and has been accumulating strain energy for a long time.

4. POSTSEISMIC CRUSTAL DEFORMATION

GEONET reveals remarkable crustal deformation is ongoing around the Tohoku and Kanto region after the Tohoku Earthquake. Figure 8 shows the time series of the crustal deformation at the "Yamada" site, which locates on the coast of Iwate prefecture, after the Tohoku Earthquake. (GSI, 2011b) Horizontal movement toward southeast by east after the mainshock exceeds 50 cm on the time point at the end of June 2011.

Figure 9 shows postseismic horizontal (a) and vertical (b) movement vectors around northeastern Japan. (GSI, 2011b) The pattern of the horizontal movement vectors toward east to southeast means that crustal block on the North American plate, where Tohoku region locates, is moving eastward, overriding onto the Pacific plate, even after the Tohoku earthquake. However, when we look into the detail of the crustal movement pattern, we can note a slight difference between the coseismic one and postseismic one. Although all GEONET sites subsided coseismically, several sites in Miyagi prefecture and certain sites around Choshi have been uplifting after the earthquake.

Figure 10 shows the slip distribution model for the postseismic crustal deformation. (GSI, 2011b) Most significant feature of this slip model is that the center of slipping area is locating a little westward from the center of coseismic slip area. This means that postseismic slip along the plate boundary occurs mainly deeper zone compared with coseismic rapture zone. The geomorphological evidence, such as coastal terraces, shows that the coastal area of the Tohoku district has been uplifting for the long term. However, geodetic observation including leveling survey from one hundred years ago, tidal observation for several tens years, and GPS observation, shows that the Pacific coast of the Tohoku region has been subsiding before the Tohoku Earthquake. There was a hypothesis that a coseismic uplift caused by a great interplate earthquake would exceed the inter-seismic subsidence. However, the concerned area has been subsided by the Tohoku Earthquake. Another hypothesis explains that postseismic slip would widely spread into the deeper zone of plate boundary after a great earthquake, and that postseismic slip would be the main reason of inter-seismic uplift. We would be able to decide whether this explanation is appropriate or not, following the crustal deformation observation for several years. .

5. SUMMARY

The 2011 off the Pacific coast of Tohoku Earthquake is the largest earthquake in the history of seismic observation in Japan. Detected coseismic crustal deformation is remarkably large. Maximum horizontal movement, 5.3m, and subsidence of 1.2m is recorded at Ishinomaki. The slip distribution model derived from crustal deformation data shows extremely large slip, larger than 56 m, exists at the shallow plate boundary zone near the Japan trench. Remarkable postseismic crustal deformation has been ongoing since the mainshock. Even though slight uplift is observed at a part of subsided area, the rate of uplifting there is not as large as expected.

6. REFERENCES

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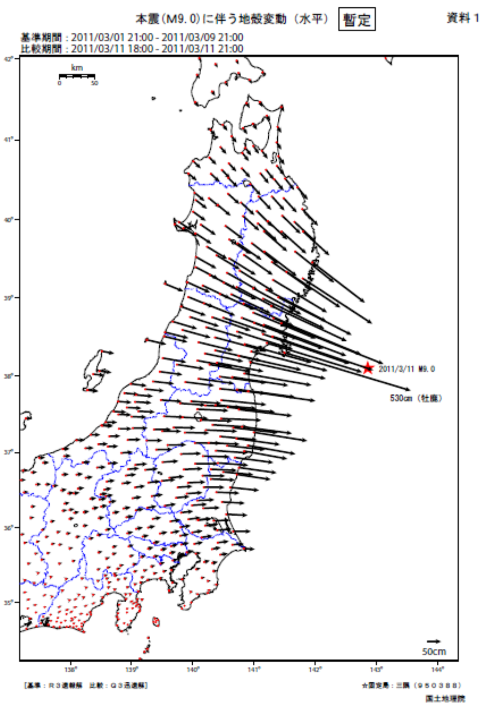


Fig. 1 Crustal deformation associated with the 2011 off the Pacific coast of Tohoku Earthquake on March 11, 2011 (horizontal)

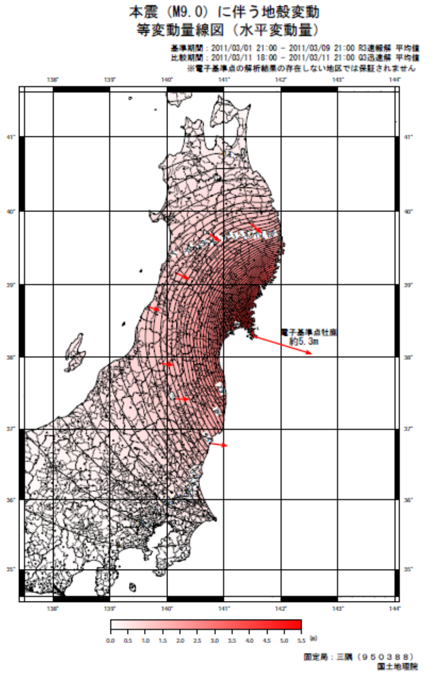


Fig. 3 Contour map of crustal deformation of the 2011 Tohoku Earthquake (horizontal).

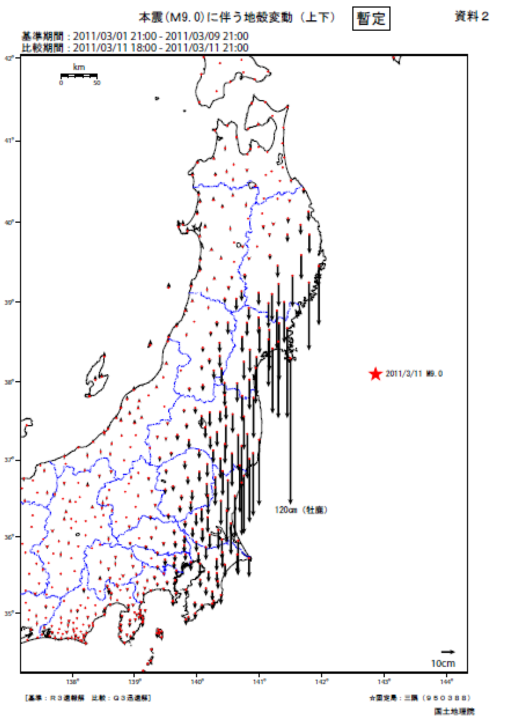


Fig. 2 Crustal deformation associated with the 2011 off the Pacific coast of Tohoku Earthquake on March 11, 2011 (vertical).

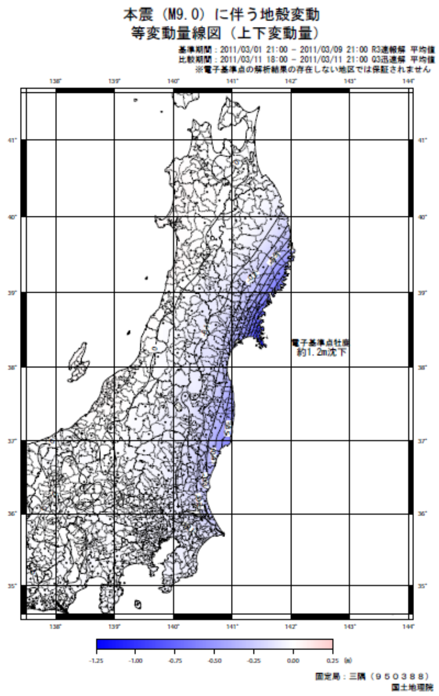
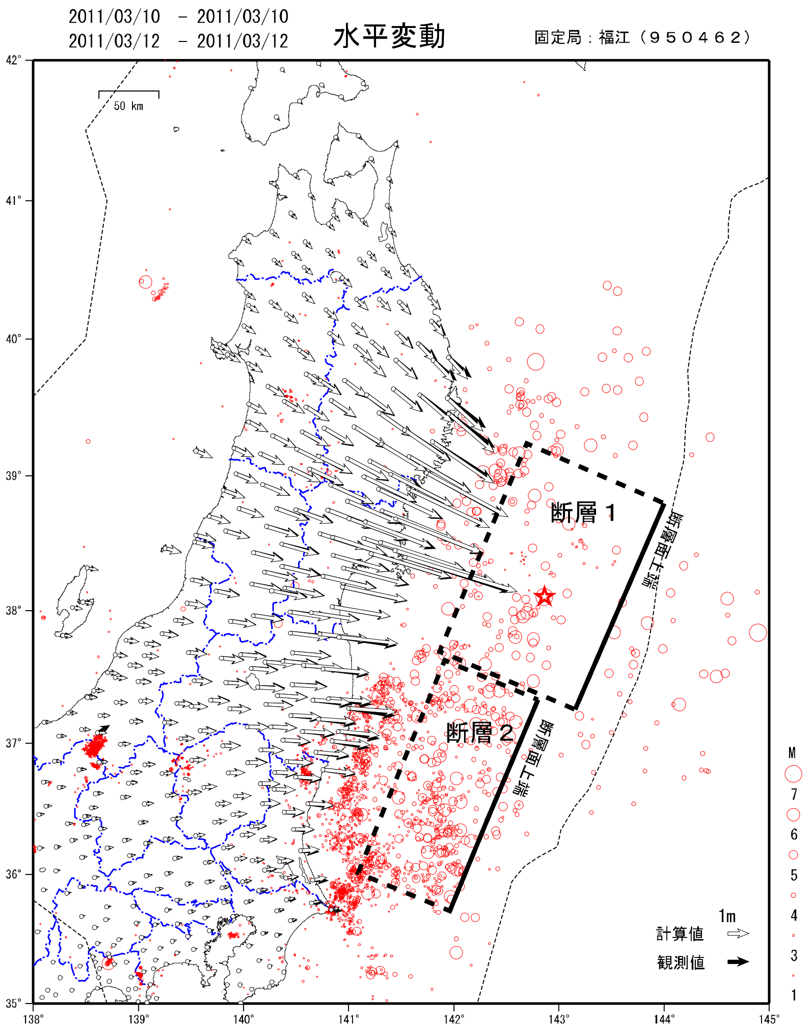


Fig. 4 Contour map of crustal deformation of the 2011 Tohoku Earthquake (vertical).

東北地方太平洋沖地震（2011年３月11日）の震源断層モデル

北側の矩形断層で２５ｍの大きなすべり．南側の断層で６ｍ程のすべりが推定された．
断層１の領域では．余震があまり発生していない．



星印は気象庁の震央（142.861°，38.104°）。
矩形断層二枚での推定結果。
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が8.8、南側が8.3。２つ合わせて8.9。
断層の長さは南北に約190kmの断層１と約190kmの断層２で合計約380km。
赤丸は気象庁一元化震源（3/11-3/15）。

	緯度	経度	上端深さ	長さ	幅	走向	傾斜角	すべり角	すべり量	Mw
			km	km	km				m	
断層１	38.80°	144.00°	5.1	186	129	203	16	101	24.7	8.8
断層２	37.33°	142.80°	17.0	194	88	203	15	83	6.1	8.3

Lat=38.80 Lon=144.00 D=5.1km L=186.2km W=128.5km Strike=203deg Dip=16deg Rake=101deg Slip=24.69m Open=0.0m Mw=8.8
Lat=37.33 Lon=142.80 D=17.0km L=193.9km W=87.9km Strike=203deg Dip=15deg Rake=83deg Slip=6.12m Open=0.0m Mw=8.3

Fig. 5 Earthquake source fault model of the 2011 off the Pacific coast of Tohoku Earthquake (rectangular fault model).
Northern segment: L=186km, W=129km, strike=203deg, dip=16deg, rake=101deg, slip=24.7m, Mw=8.8
Southern segment: L=194km, W= 88km, strike=203deg, dip=15deg, rake= 63deg, slip= 6.1m, Mw=8.3

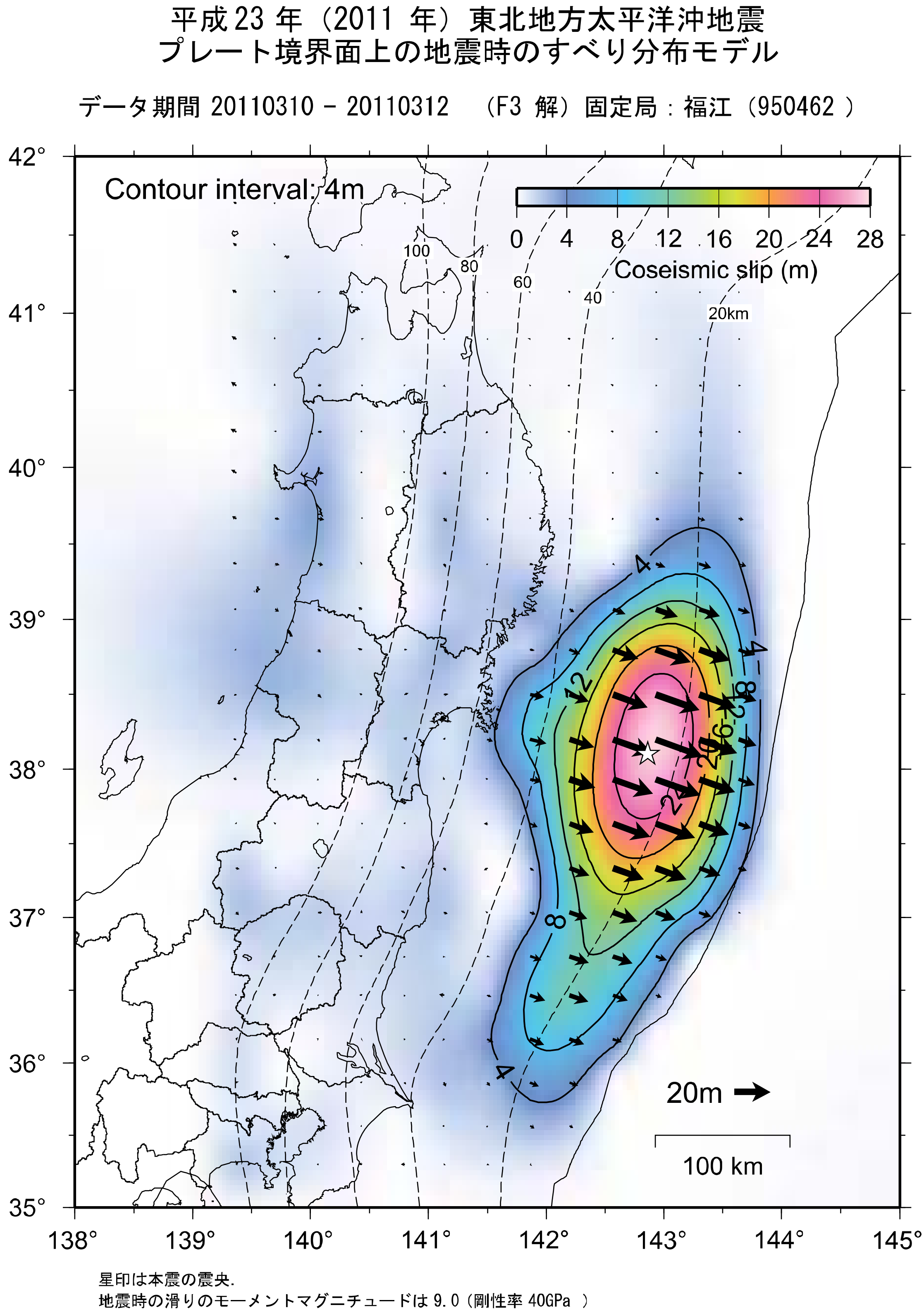
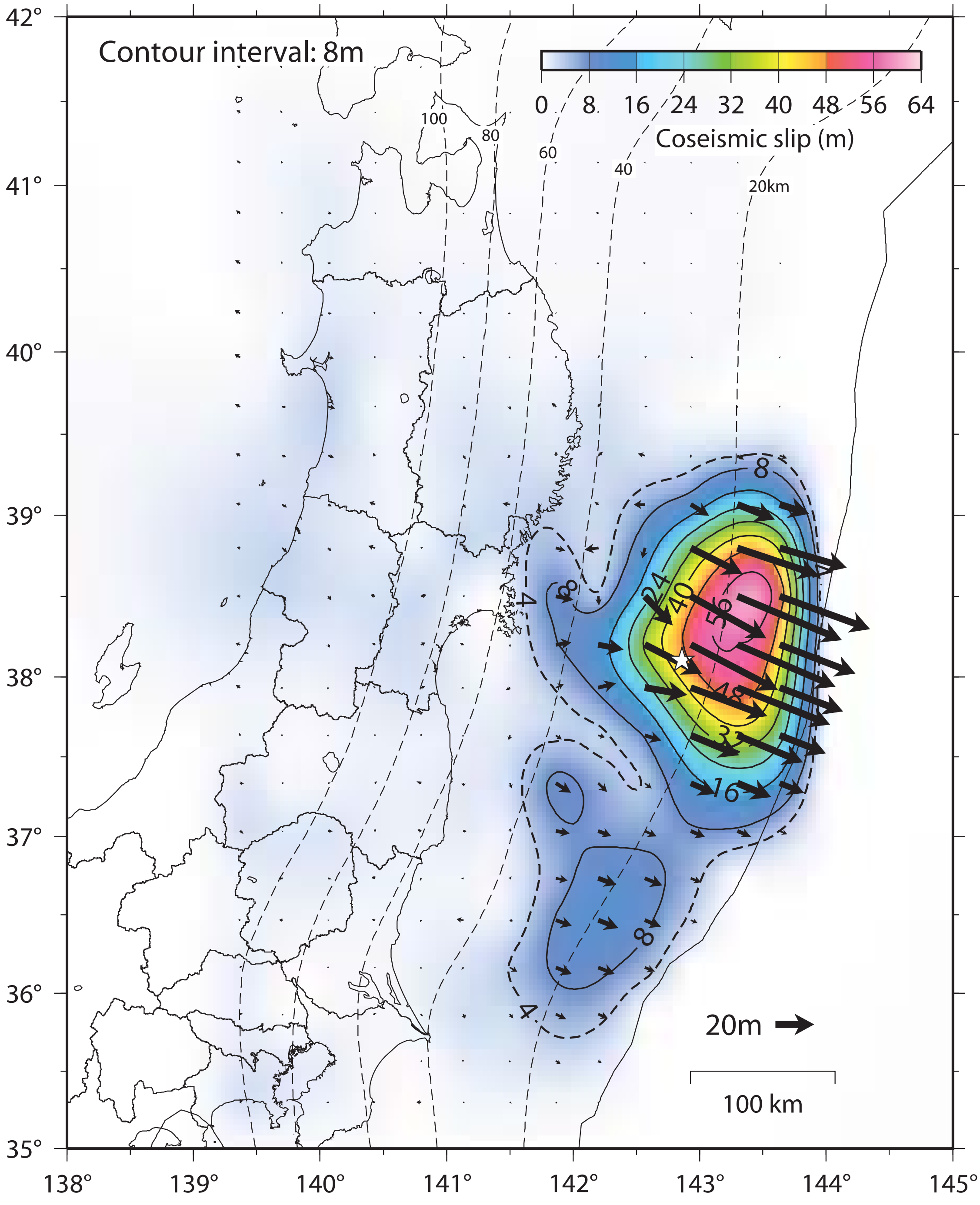


Fig. 6 Slip distribution model of the 2011 off the Pacific coast of Tohoku Earthquake, based on GEONET observation (slip distribution model on the plate interface)

データ期間 20110310-20110312 (F3解) 固定局：福江 (950462) ＋ SGO by JCG5



星印は本震の震央.
地震時の滑りのモーメントマグニチュードは 9.0 (剛性率 40GPa ）
点線はプレート境界面の深さを示す

Fig. 7 Slip distribution model of the 2011 off the Pacific coast of Tohoku Earthquake, based on GEONET observation on land and seafloor crustal deformation by GPS/acoustic observations(slip distribution model on the plate interface)

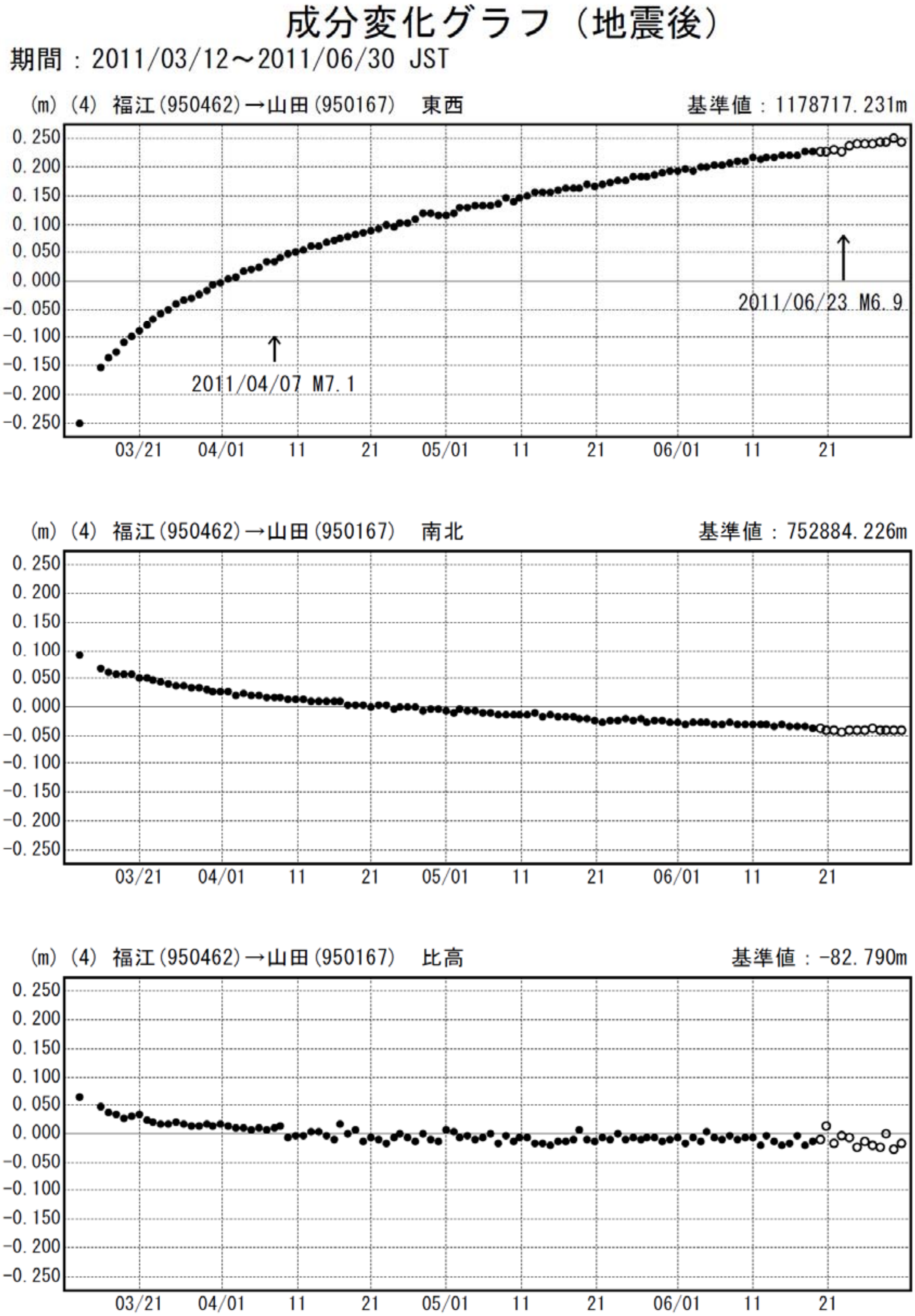


Fig. 8 Crustal deformation after the 2011 off the Pacific coast of Tohoku Earthquake, Time series at GEONET site "Yamada" in Iwate prefecture

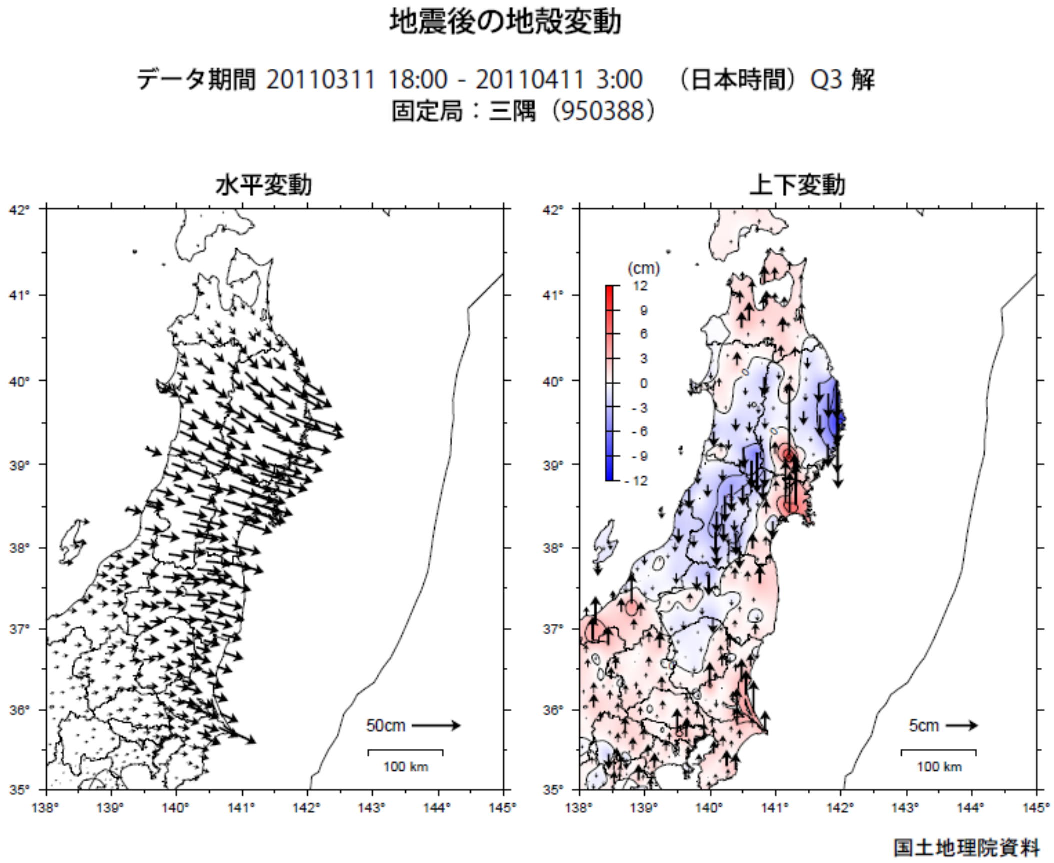


Fig. 9 (a)(left)Horizontal crustal deformation after the 2011 off the Pacific coast of Tohoku Earthquake as of April 11, 2011 (b)(right)Vertical crustal deformation after the 2011 off the Pacific coast of Tohoku Earthquake as of April 11, 2011.

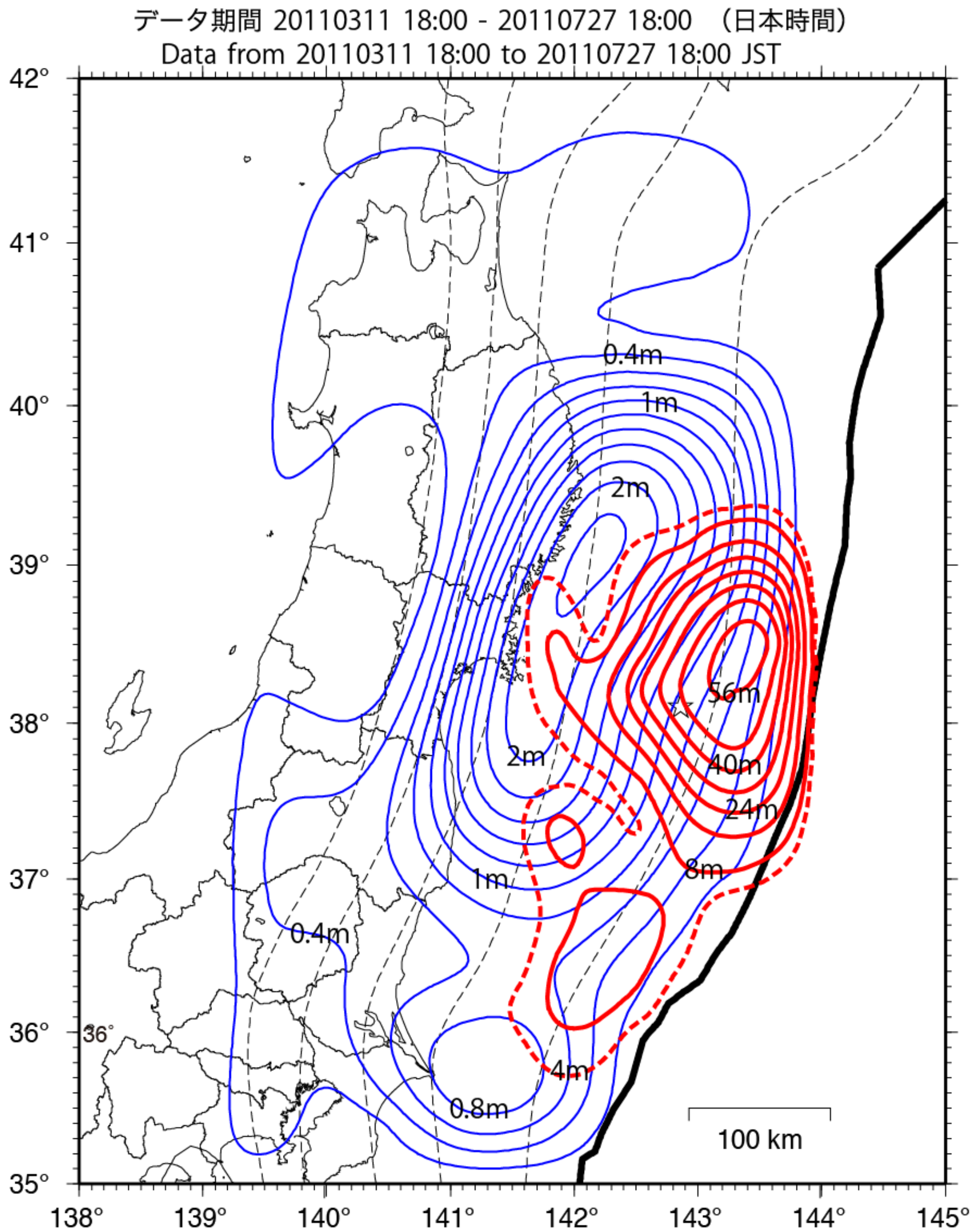


Fig. 10 Slip distribution model for postseismic crustal deformation of the 2011 off the Pacific coast of Tohoku Earthquake based on GEONET observations (blue lines), overlaying onto the coseismic slip distribution based on GEONET observation on land and seafloor crustal deformation by GPS/acoustic observations (red lines).