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Re-examination of GNSS Data Before the 2004 Chuetsu and the 2007 Chuetsu-oki Earthquakes

Angela MENESES-GUTIERREZ[(1,2)] and Takuya NISHIMURA

(1) Institute for Advanced Research, Nagoya University, Japan
(2) Disaster Mitigation Research Center, Nagoya University, Japan

Synopsis

We analyze GNSS data from GEONET data in the vicinity of the 2004 M6.6 Chuetsu and the 2007 M6.6 Chuetsu-oki earthquakes to assess the existence of crustal deformation anomalies before the events as reported by previous studies. Baseline estimation from different analysis strategies did not reveal systematic differences between the solutions. However, clear deformation patterns were not found from this analysis. On the other hand, evaluation of horizontal displacement rate distributions prior to the occurrence of each event, shows localized patterns: localized contraction is observed in the source region of the 2004 Chuetsu and the 2007 Chuetsu-oki earthquakes after the first event. Additionally, observations to the west suggest that the nucleation of the 2007 Chuetsu earthquake might have started before the 2004 event. Aseismic fault slip might play an important role of the deformation of this region.

Keywords: Crustal deformation, The 2004 Chuetsu earthquake, The 2007 Chuetsu-oki earthquake, aseismic slip

1. Introduction

The earthquake cycle consists of three main stages: interseismic strain accumulation, coseismic strain release and postseismic transient deformation following the earthquake. It has been recognized the existence of spatiotemporal variations in seismicity before the occurrence of major earthquakes (e.g. Kanamori, 1981). Analysis of such observations might reveal information about the physical mechanisms of earthquakes and in consequences, could be used towards the field of earthquake prediction.

The Japan island arc is located in a complex tectonic region where four tectonic plates converge: the Eurasian (or Amurian), the Pacific, the North American (or Okhotsk plate) and the Philippine Sea plate (e.g. Sagiya et al. 2000). This causes frequent earthquakes in the region. The island arc is covered with a dense seismic and GNSS network which have been extensively used for the analysis of earthquake related processes.

Several studies have focused on the existence of quiescence or activation of seismicity before a large earthquake (e.g. Ogata, 1992). In the case of Mid-Niigata, located within a zone of highly concentrated crustal contraction identified as the Niigata-Kobe Tectonic Zone (NKTZ) (Sagiya et al., 2000), Ogata (2007; 2011) studied seismic activity and crustal deformation before the occurrence of the 2004 M_w 6.6 Chuetsu (37.290N, 138.870 E, depth=5 km (NIED, 2004), Fig. 1) and the 2007 M_w 6.6 Chuetsu-oki (37.557 N, 138.610 E, depth=8 km (NIED, 2007), Fig. 1). Both events exhibit thrust-type focal mechanisms and a strike of around N35ºE, followed by a significant aftershock activity.

Ogata (2007; 2011) found seismic quiescence and activation near to the rupture zone, which he interpreted as evidence of slow aseismic slip events on the coseismic fault or its deeper extensions. He presented further evidence of crustal deformation by analyzing baseline changes from the data of the nationwide Global Navigation Satellite System (GNSS) Earth Observation Network System (GEONET) operated by the Geospatial Information Authority of Japan (GSI). In his analysis, he employed daily coordinates from the F2 solution of GEONET sites, provided by GSI. However, these results might contain systematic bias depending on the strategy of the coordinate calculation. For example, F2 solutions were calculated employing the Bernese 4.2 software (Hugentobler et al., 2001) and since its design, a new processing strategy has been implemented, where estimated atmospheric delay gradient and an absolute Phase Center Variation model has been included (Nakagawa, et al. 2009). Also, bias might occur associated with the network analysis within Bernese (Kawashima, 2019).

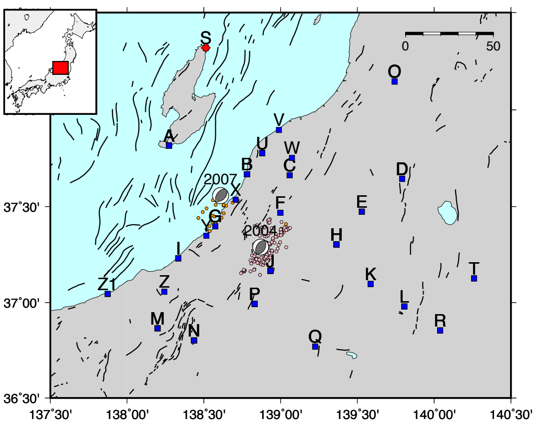

Fig. 1 Map view of the study area. Blue squares denote GEONET stations used in the baseline analysis. The red diamond represents the reference site used for velocity calculation. Stations are enumerated using letters, in correspondence with the nomenclature used in Ogata (2007). Focal mechanisms for the 2004 Chuetsu and the 2007 Chuetsu-oki earthquakes and aftershock distributions one month after each event are also shown (pink and orange circles). Thin black lines denote active Quaternary fault traces (Research Group for Active Faults of Japan, 1991). The inset figure shows the location of the study area with respect to the Japanese Islands.

In an effort to evaluate whether or not systematic crustal deformation anomalies before the 2004 Chuetsu and 2007 Chuetsu-oki earthquakes took place, we re-examine the GNSS data by using the new network analysis in place at GSI (F3 solutions, Nakagawa et al. 2009) and a Precise Point Positioning strategy (PPP). We also evaluate deformation using the F2 solutions in order to compare our results with those of Ogata (2007, 2011). We show that although a clear deformation pattern is not found from baseline analyses, horizontal displacement rate distributions before the 2004 and 2007 events show possible aseismic slips.

In the following, we introduce the data used for the analysis. We then present the methodology to inspect the static coordinates. Finally, we provide an interpretation of the results.

2. Data and methodology

We analyzed GNSS data from GEONET stations located in the vicinity of the 2004 M_w6.6 Chuetsu and the 2007 M_w6.6 Chuetsu-oki earthquakes (Fig. 1).

GSI estimates daily static coordinate solutions to monitor crustal movements utilizing the BERNESE software (e.g. Dach et al., 2007). The analysis strategy has been improved multiple times (Hatanaka, 2006). Ogata (2007, 2011) employees coordinates data from the third analysis strategy, “F2 solutions” (Hatanaka et al. 2003) for his study. Currently, a more advanced analysis strategy is employed routinely at the organization for the estimation of daily coordinates and the final solutions are commonly known as the “F3 solutions” (Nakagawa et al., 2009).

We analyze daily coordinates from both F2 and F3 solutions in order to evaluate if changes in the analysis strategy are responsible for the observed anomalies reported by previous studies. We also calculate precise daily coordinates for the GNSS data utilizing the Precise Point Positioning (PPP) processing strategy with ambiguity resolution and GIPSY 6.2 software (Bertiger et al., 2010; Zumberge et al., 1997). This was done, in order to assess any bias in the relative position method employed by GSI. Precise satellite orbits, Earth orientation parameters, and satellite clock corrections for the PPP processing were obtained from the final solutions provided by the Jet Propulsion Laboratory.

We analyze daily coordinates from January 1997 to the day before the occurrence of each earthquake, independently for each analysis strategy (F2, F3, and PPP). We calculate baseline time series in geocentric coordinates (*x, y, z*) by evaluating the Euclidian distance between the target GNSS stations (Figs. 2 and 6).

We use the least square method to estimate linear fits in the preseismic periods of the events: January 1997 to December 2000 in the case of the 2004 Chuetsu earthquake and January 1997 to September 2004 for the 2007 Chuetsu-oki earthquake (Figs. 2 and 6). These time periods were chosen following Ogata (2007; 2011). Offsets due to antenna changes for the total time series were estimated in the least squared sense a priori using a step function. In order to assess the presence of anomalous behaviors prior to each earthquake, we calculate residual time series after removing the linear trends in the corresponding case (Figs. 3 and 7). Then, we apply a moving average filter in a window of 365 days and evaluate the deviations of the trend with respect to the horizontal line to determine if accelerated contraction or extension occurred before the earthquake (Figs. 4 and 8), in the same way as in the studies by Ogata (Ogata 2007; Ogata 2011).

For further our understanding of the crustal deformation process in Mid-Niigata, we also estimate horizontal displacement rate patterns as follow. We consider interseismic velocities with respect to station 0232 (38.32ºN, 138.51ºE, stations S in Fig. 1) for two time periods before the occurrence of each seismic event in the Chuetsu region: one as a reference period (January 1998 to December 2000 for the 2004 Chuetsu earthquake and January 1998 January to September 2004 for the Chuetsu-oki earthquake) and the other just two years before the occurrence of each seismic event, considering that this period might contain the reported anomalies. Then, we calculated the residuals pattern between the two time periods in order to evaluate geodetic anomalies (Figs. 5 and 9). Horizontal displacement rate estimation includes fitting the time series by a combination of a linear trend and annual and semiannual sinusoidal variations.

In the case of the period prior to the 2007 Chuetsu-oki earthquake, we consciously do not use data from the first few months after the event, in order to avoid transient deformation associated with afterslip at the source fault.

3. Results ad Discussion

3.1 Crustal deformation prior to the 2004 Chuetsu earthquake

Fig. 2 shows the baseline change time series for selected stations in the time period prior to the 2004 Chuetsu earthquake for F2, F3, and PPP solutions. We identify linear trends with general contraction on the baselines in the East-West direction. Such deformation is in agreement with the presence of a high E-W contraction within the NKTZ. No major differences are observed between the solutions, the general trend is consistent in each strategy.

Detrended time series with respect to the time period from January 1997 to December 2000 are shown in Fig. 3 for the stations depicted in Fig. 2. A moving average filter with a 365 days window has been applied to evaluate the long-term deviation with respect to the linear trend, in agreement with Ogata (2007). We recognize deviations from the trend in several stations, with a maximum amplitude of 8 mm. A map view of the cumulative deviation from the trend is shown in Fig. 4. The sense of cumulative deviation is common to all the solutions, except for deformation the south of the source region of the 2004 Chuetsu earthquake (i.e., baseline NQ in Fig. 4), where accelerated contraction is observed from the F2 solutions, while deceleration is reported from both F3 and PPP solutions. In general, the amplitude of the deformation is slightly higher from PPP coordinates, especially at baselines associated with station 0563 (37.10ºN, 139.59ºE; K in Fig. 1), where large accelerated E-W contraction is recognized from the PPP solutions from February 2002 to the west (baseline JK in Fig. 4) and NS deceleration to the north (baseline DK in Fig. 4).

In most cases, accelerated motion is found to take place 2 years before the 2004 Chuetsu earthquake in agreement with Ogata (2007). However, residual values observed in this study are larger than the reported by Ogata (2007) and a clear pattern is not apparent, which make it difficult to derive a unique interpretation of the observed changes. Also, it is worth noticing, that many antenna changes in the Mid-Niigata region took place around this time.

Horizontal displacement distributions with respect to station 0232 (S in Fig. 1) for two time periods prior to the 2004 Chuetsu earthquake and a residual pattern are shown in Fig. 5. From this analysis, we recognize accelerated contraction between the source region of the 2004 and 2007 events and accelerated deformation in the sea side, near the source region of the 2007 Chuetsu-oki earthquake. This suggests that the nucleation of the 2007 Chuetsu-oki earthquake might have started prior to the 2004 event.

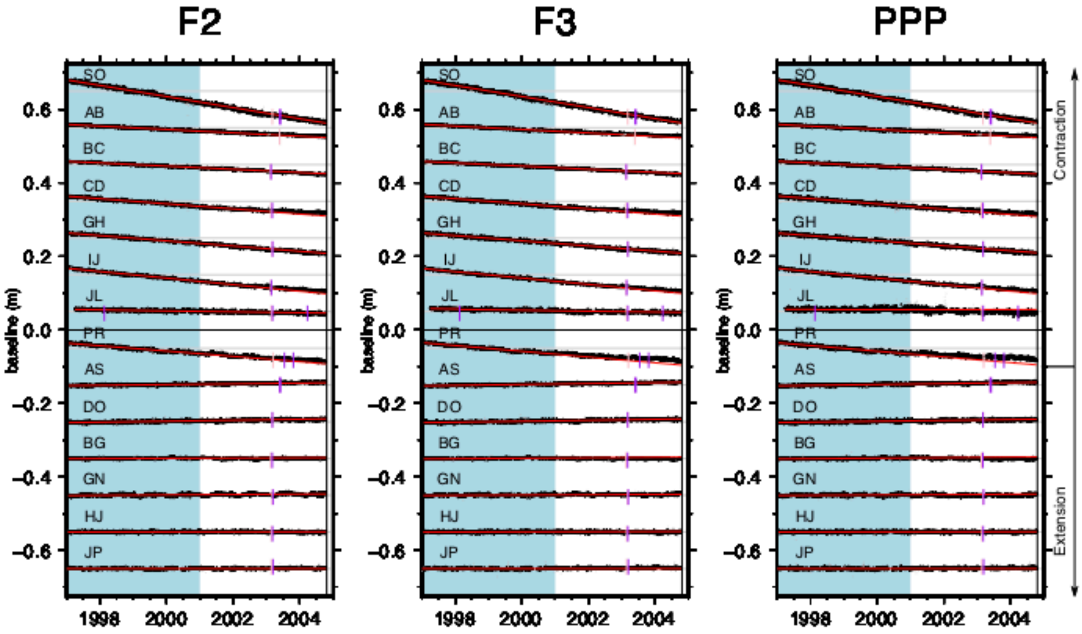

Fig. 2 Baseline change time series in the Mid-Niigata area prior to the 2004 Chuetsu earthquake. Shadow areas represent data used for a linear fit. Red line denotes the predicted linear trend from the fitting. Vertical lines on the time series denote the date of antenna changes. See Fig. 1 for stations location.

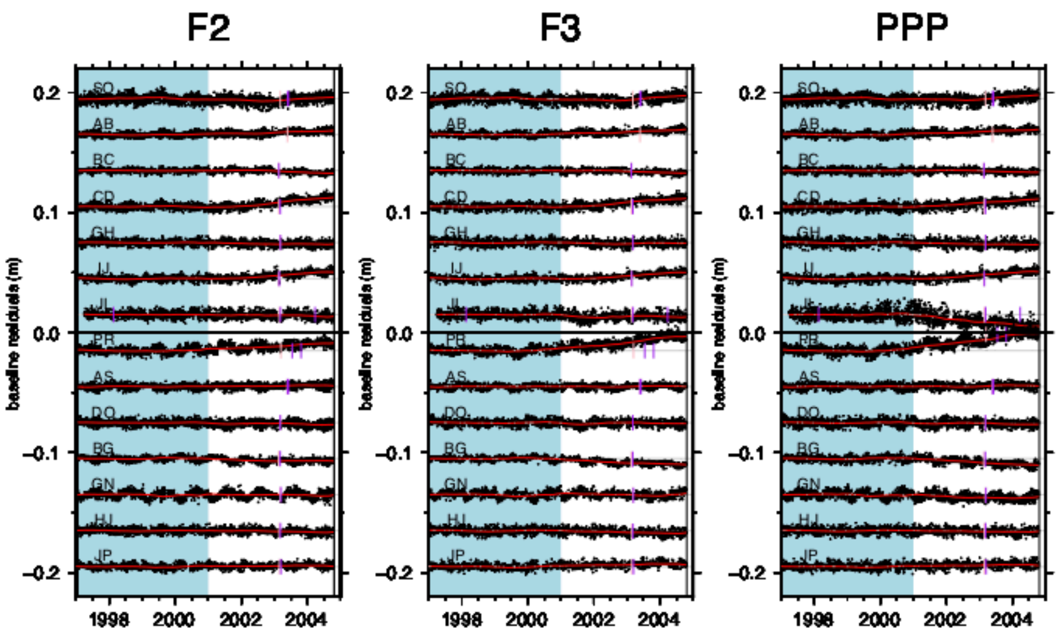

Fig. 3 Detrended baseline time series prior to the 2004 Chuetsu earthquake. Red line denotes moving average filter in 365 days window for each case. The other symbols are the same as in Fig. 2.

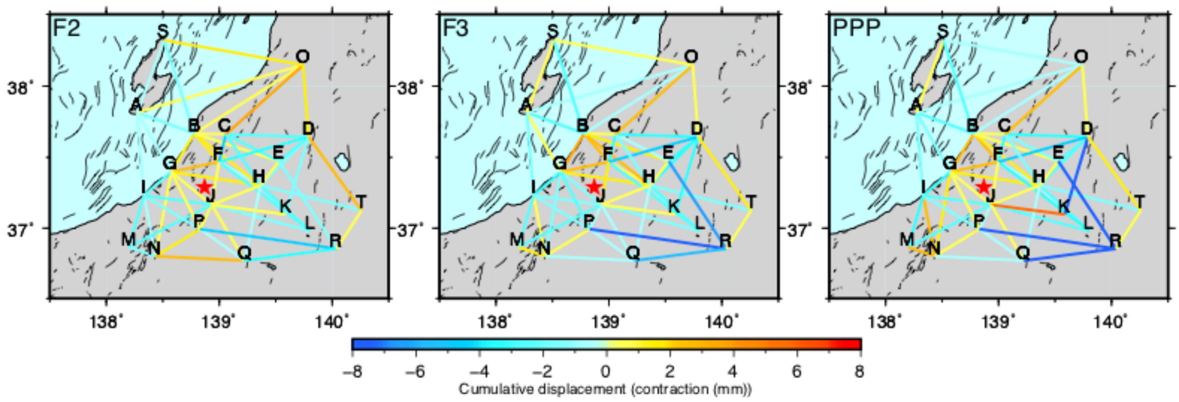

Fig. 4 Cumulative displacement (contraction) from GEONET estimated from the residuals baseline time series prior to the 2004 Chuetsu earthquake. Positive and negative values denote acceleration and deceleration of the contraction, respectively.

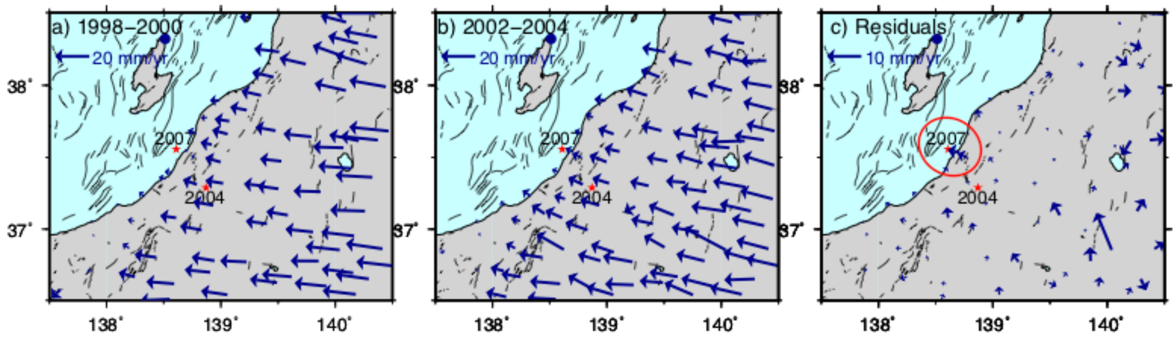

Fig. 5 Horizontal displacement rate patterns before the 2004 Chuetsu earthquake: (a) January 1998 to December 2000 and (b) January 2002 to September 2004. Residual velocity pattern (a) – (b) is shown on (c). Red stars represent hypocenter location of the 2004 and the 2007 events. Thin pink lines denote active Quaternary fault traces (Research Group for Active Faults of Japan, 1991).

3.2 Crustal deformation prior to the 2007 Chuetsu-oki earthquake

Fig. 6 shows the baseline change time series in the time period prior to the 2007 Chuetsu-oki earthquake for F2, F3 and PPP solutions at the stations included in the study by Ogata (2011). These baselines are oriented in the NE-SW direction, parallel to the trend of the NKTZ. We identify linear trends with constant contraction on all the baselines.

Detrended time series with respect to the time period of January 1997 to September 2004 are shown in Fig. 7 for each solution. We recognize deviations from the trend in all stations. Systematic differences are not found between the analysis strategies. Decelerating contraction is apparent across the source regions of the 2004 Chuetsu and the 2007 Chuetsu-oki events, except to the northernmost where contraction is reported (Figs. 7 and 8). These results are basically the same as those of Ogata (2011). However, interpretation of the results is not straightforward.

We analyze the horizontal displacement rate distributions prior to the 2007 Chuetsu-oki earthquake (Fig. 9), in the same manner as for the deformation of the 2004 event. We find localized contraction in the source region of the 2004 Chuetsu earthquake after the occurrence of this event. This is in agreement with results reported by Meneses Gutierrez (2014). This suggests possible aseismic slip on the mainshock fault of the 2004 Chuetsu earthquake after the event. We also find contraction in the vicinity of the 2007 Chuetsu-oki earthquake prior to the event. This contraction may also be interpreted by aseismic slip on the subsequent earthquake fault ruptured in 2007.

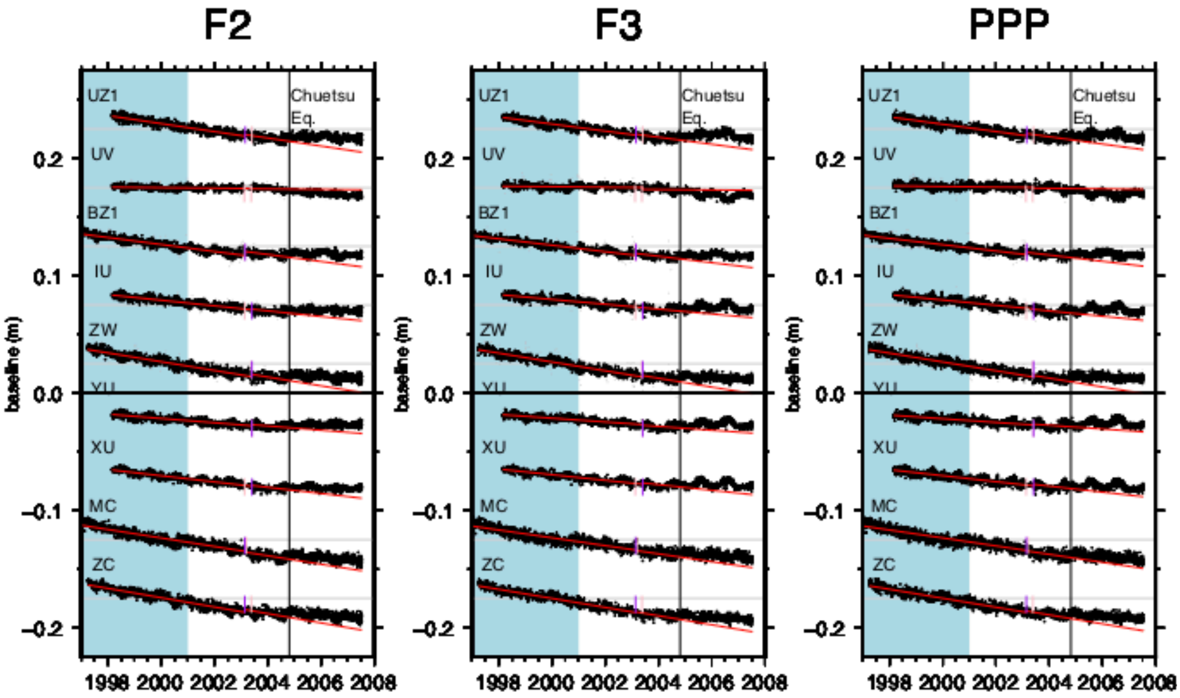

Fig. 6 Baseline change time series in the Mid-Niigata area prior to the 2007 Chuetsu-oki earthquake. Red line denotes the predicted linear trend from the fitting. The black vertical line denotes the 2004 Chuetsu earthquake. The other symbols are the same as in Fig. 2.

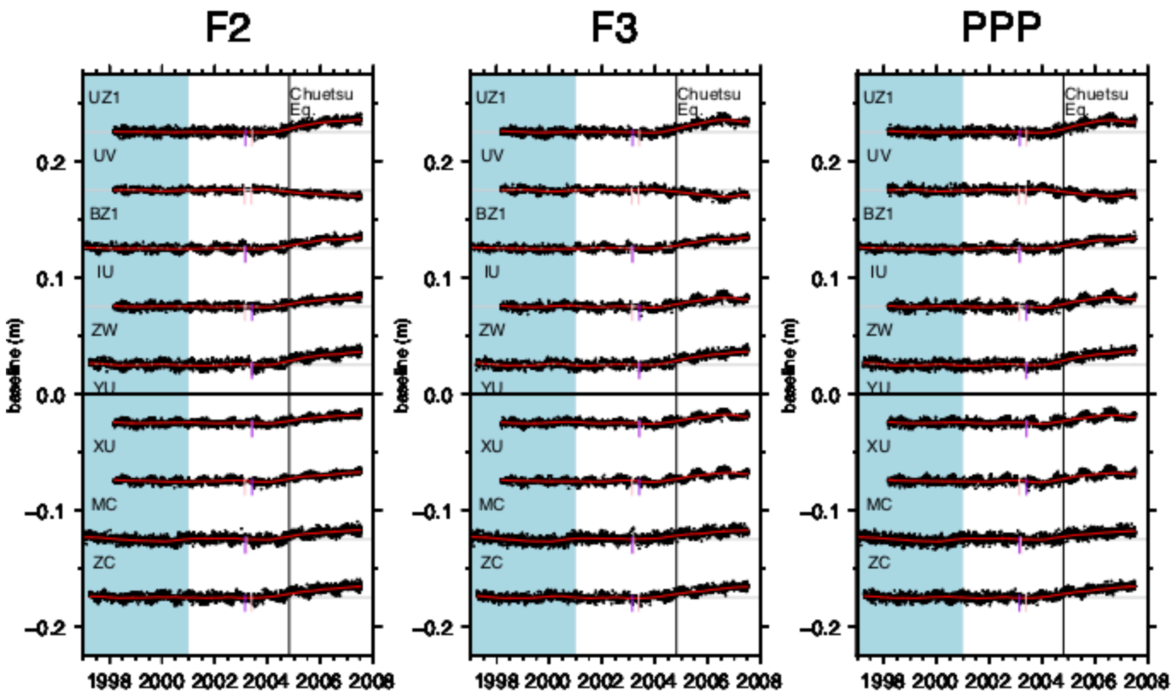

Fig. 7 Detrended baseline time series prior to the 2007 Chuetsu-oki earthquake. Red line denotes moving average filter in 365 days window for each case. The black vertical line denotes the 2004 Chuetsu earthquake. The other symbols are the same as in Fig. 2.

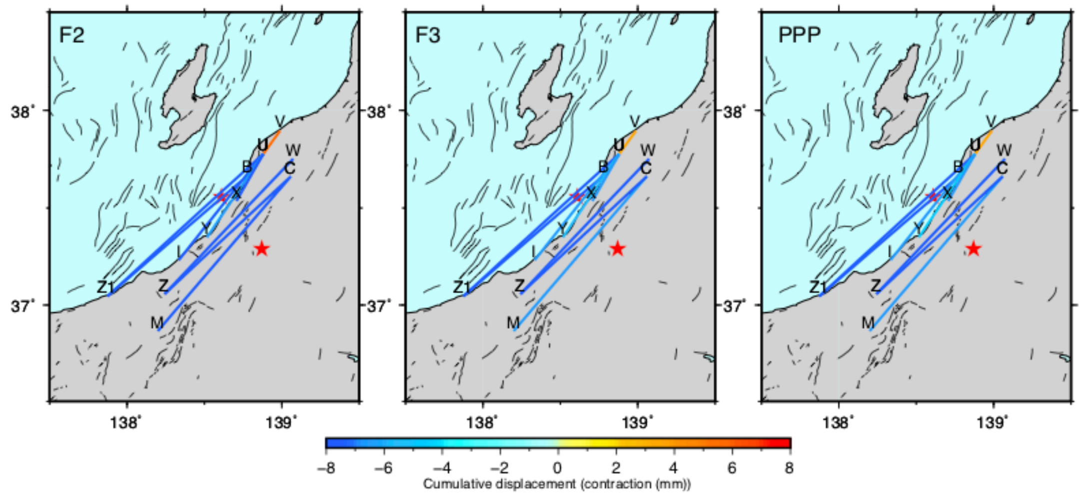

Fig. 8 Cumulative displacement changes (contraction) from GEONET estimated from the residuals baseline time series prior to the 2007 Chuetsu-oki earthquake. Positive and negative values denote acceleration and deceleration of the contraction, respectively.

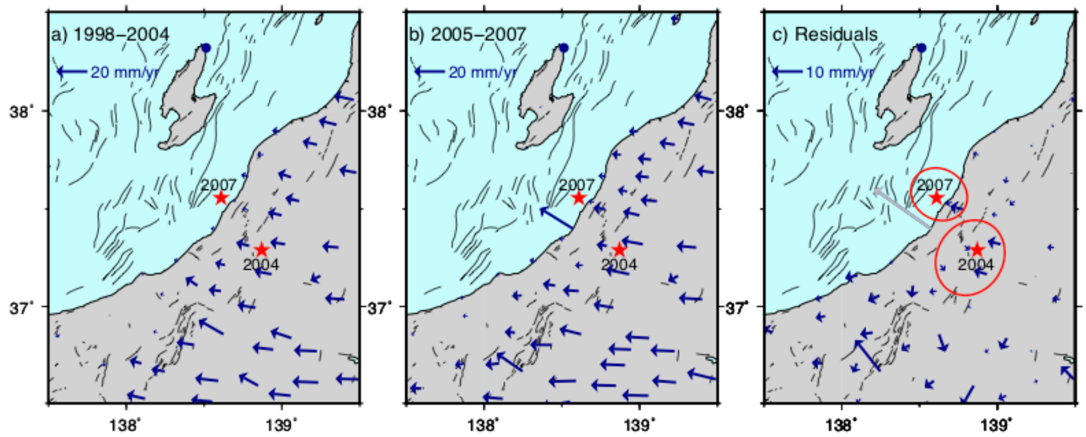

Fig. 9 Horizontal displacement rate patterns before the 2007 Chuetsu-oki earthquake: (a) January 1998 to September 2004 and (b) January 2005 to June 2007. Residual velocity pattern (a) – (b) is shown on (c). Red stars represent hypocenter location of the 2004 and the 2007 events. Thin pink lines denote active Quaternary fault traces (Research Group for Active Faults of Japan, 1991). Gray vectors denote outliers. Red ellipse enclosed localized deformation area.

4. Conclusions

We analyze GNSS data before the 2004 Chuetsu and the 2007 Chuetsu-oki earthquakes. Analysis of baseline changes for F2, F3 and PPP solutions recognize the existence of deviation from the linear trend prior to the occurrence of the events, in agreement with the results reported by Ogata (2007, 2011). However, residual values observed in this study are in general larger than those reported by previous studies and a clear pattern was not apparent. On the other hand, analysis of displacement rate distributions helped to clarify the deformation pattern. Our results show extension near to the source region of the 2007 Chuetsu-oki earthquake before the 2004 Chuetsu earthquake, suggesting that the nucleation of the 2007 event might have started prior to the 2004 event, On the other hand, localized contraction is observed in the source region of the 2004 Chuetsu and the 2007 Chuetsu-oki earthquakes after the first event. These observations suggest the presence of aseismic fault slip in the region. Quantitative models must be implemented to evaluate such possibility.

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References

Bertiger, W., Desai, S., Haines, B., Harvey, N., Moore, A. W., Owen, S., & Weiss, J. P. (2010): Single receiver phase ambiguity resolution with GPS data. Journal of Geodesy, Vol. 84, pp. 327–337. https://doi.org/10.1007/s00190-010-0371-9

Dach, R., Hugentbler, U., Fridez, P., and Meindl, M. (2007): Bernese GPS software Version 5.0. User Manual. Astronomical Institute, University of Bern, Bern.

Hatanaka, Y., Iizuka, T., Sawada, M., Yamagiwa, A., Kikuta, Y., Johnson, J.M., and Rocken, C. (2003): Improvement of the Analysis Strategy of GEONET, Bull. Geography. Surv. Instit., Vol. 9, pp. 11-34.

Hugentobler, U., Schaer, S., Fridez, P. (eds) (2001): Bernese GPS Software, Version 4.2. Astronomical Institute, University of Bern, Bern.

Kanamori, H. (1981): The nature of seismicity patterns before large earthquakes, Earthquake Prediction: AN international review, Maurice Ewing Ser., vol. 4, edited by D.W. Simpson and P.G. Richards, pp. 1-19, American Geophysical Union, Washington, D.C.

Kawashima, Y. (2019): Reanalysis of GEONET data with Precise Point Positioning: Stability of the F3 solution and accelerated crustal movement prior to the 2011 Tohoku-oki earthquake (Unpublished master's thesis), Nagoya University, Nagoya, Japan.

Meneses Gutierrez, A. (2014): Time dependent aseismic crustal deformation associated with the 2004 Chuetsu and the 2007 Chuetsu-oki earthquakes (Unpublished master's thesis), Nagoya University, Nagoya, Japan.

Nakagawa, H., Toyofuku, T., Kotani, K., Miyahara, B., Iwashita, C., Kawamoto, S., Hatanaka, Y., Munekane, H., Ishimoto, M., Yutsudo, T., Ishikura, N., Sugawara, Y. (2009): Development and validation of GEONET new analysis strategy (Version 4). J. Geogr. Surv. Inst. Vol. 118, pp. 1–8. (in Japanese).

National Research Institute for Earth Science and Disaster Resilience (2004): Broad Band Seismograph Network (F-net). http://www.fnet.bosai.go.jp/event/tdmt.php?_id=20041023085500&LANG=ja

National Research Institute for Earth Science and Disaster Resilience (2007): Broad Band Seismograph Network (F-net). http://www.fnet.bosai.go.jp/event/tdmt.php?_id=20070716011200&LANG=ja

Ogata, Y. (1992), Detection of precursory relative quiescence before great earthquakes through a statistical model, J. Geophys. Res., 97, pp. 19845–19871.

Ogata, Y. (2007): Seismicity and geodetic anomalies in a wide area preceding the Niigata-Ken-Chuetsu Earthquake of October 23, 2004, central Japan, J. geophys. Res., Vol. 112, B10301.

Ogata, Y. (2011): Pre-seismic anomalies in seismicity and crustal deformation: case studies of the 2007 Noto Hanto earthquake of M6.9 and the 2007 Chuetsu-oki earthquake of M6.8 after the 2004 Chuetsu earthquake of M6.8, Geophys. J. Int., Vol. 186, pp. 331-348

Research Group for Active Faults of Japan (1991): Active faults in Japan: Sheet maps and inventories. Revised Edition. Tokyo: University of Tokyo Press. [in Japanese]

Sagiya, T., Miyazaki, S. and Tada, T. (2000): Continuous GPS array and present day crustal deformation of Japan, Pure Appl. Geophys., Vol. 157, B07404, https://doi.org/10.1007/PL00022507

Wessel, P., and Smith, W. H. F. (1998): New, improved version of the Generic Mapping Tools released. Eos, Transactions American Geophysical Union, 79(47), 579. https://doi.org/10.1029/98EO00426

Zumberge, J. F., Heflin, M. B., Jefferson, D. C., & Watkins, M. M. (1997): Precise point positioning for the efficient and robust analysis of GPS data from large networks. Journal of Geophysical Research, 102(B3), pp. 5005–5017. https://doi.org/10.1029/96JB03860

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