Analysis of the tectonic deformations in the Japanese island arc following the 2011 Tohoku earthquake based on satellite geodetic data

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INTRODUCTION

- On March 11, 2011, the catastrophic Tohoku earthquake with Mw = 9.0 (according to JMA) occurred within the limits of a seismic gap stretched along the eastern coast of Honshu Island. This earthquake caused a destructive tsunami ranging in height from 3 to 15 m depending on the site (Lobkovsky et al., 2017).
- In the northeastern segment of the Japanese seismofocal zone (this segment extends in parallel to the Japanese trench), many interplate earthquakes with Mw ≈ 7 occur. However, beginning from the 17th century, Japanese historical documents contain no data on thrust earthquakes in the Japanese subduction zone the possible magnitudes of which could have exceeded 8.5 (Ozawa et al., 2011). In addition, the most destructive events, interplate M = 7.9 in 1968, M = 7.6 in 1994 and intraplate M = 8.6 1933 Showa–Sanriku, occured in the northernmost part of the seismofocal zone (Fig.1).

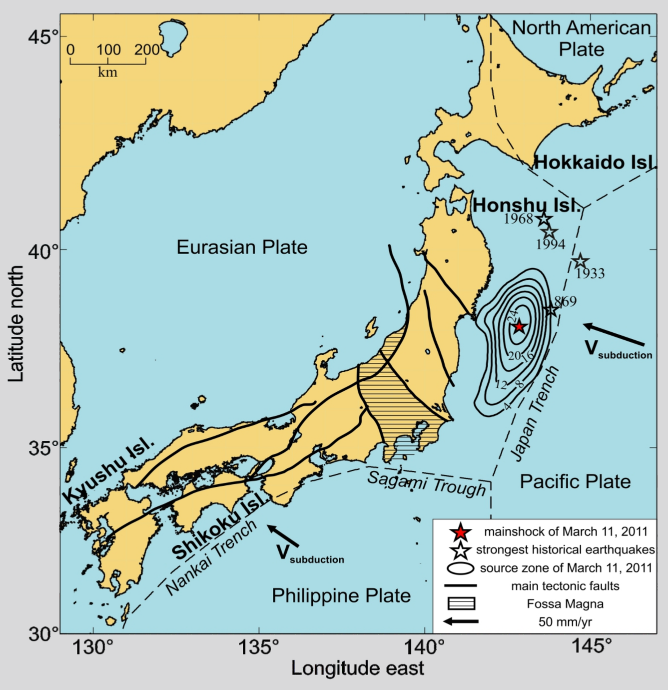

Figure 1. Source zone of Tohoku-oki earthquake and the historical seismic and tectonic background

- The previous catastrophic interplate earthquake that occurred in northeastern Japan was the 869 Sanriku. The estimates of its magnitude ranged from 8.4 to 9.0 and the average height of the triggered tsunami was about 8 m (Minoura et al., 2001). According to the results of recent geological studies, tsunamis similar to those generated by the 869 Sanriku earthquake have repeatedly struck the Pacific coast of northeastern Japan with a recurrence interval of about 800–1100 years (Minoura et al., 2001). Another study estimated that the elastic seismogenic potential, which is necessary for such an event to occur, could accumulate over a period as long as about 350–700 years (Ozawa et al., 2011).

KEYBOARD MODEL OF THE SEISMIC DEFORMATION CYCLE (SDC)

- According to the keyboard model (Lobkovsky et al., 1991) the frontal part of the island arc is divided on wedge-shaped blocks (keys - B), which are separated from each other by transcurrent vertical faults (C) that reach the surface of a subducting plate (D) (Fig. 2). The blocks are bounded from the ocean-side by deep-sea trench, and from the continental side by a longitudinal fracture zone, which separates them from the main arc massif (A).
- Due to interaction between the oceanic and continental lithospheric plates, the blocks accumulate elastic stresses, which are released during the thrust earthquakes. The stage of elastic energy accumulation within each block occupies the principal part of the periods between great earthquakes (Fig. 2).
- The block projection on the surface during the long-term energy-accumulated stage is identified with a seismic gap according to the given model. Release of the seismic energy of the whole seismogenic block occurs in the seismic stage, when a critical value of the tangential stress is achieved along the greater part of the contact surface between the block and the subducted plate. This leads to rupture of the contact surface accompanied by coseismic displacement and a great earthquake of the thrust type. As a result, unloading seismogenic blocks almost instantly shift towards the ocean.

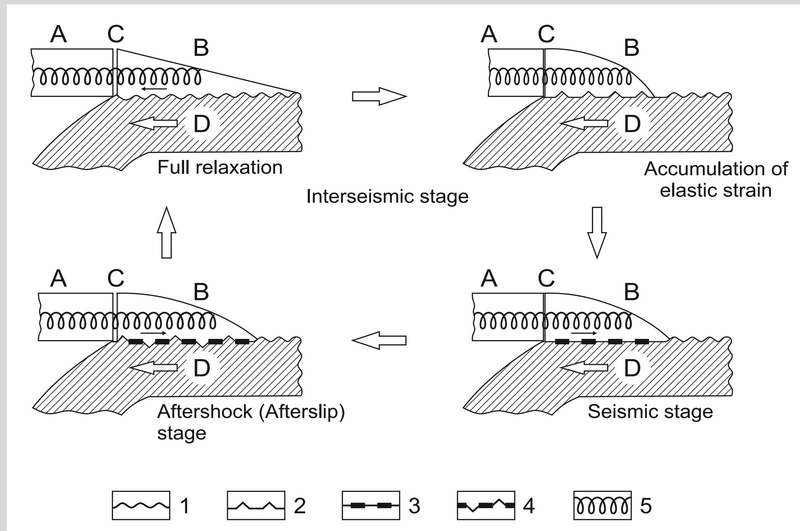

Figure 2. Scheme of successive stages of deformation (loading and relaxation) of the seismogenic blocks and the corresponding stages of the seismic cycle:
1 – Undisturbed "rough" contact zone structure (CZS) (stable stage of the cycle); 2 – elastic "smoothed" CZS (preseismic stage of the cycle); 3 – strongly fragmented and heterogeneous CZS (seismic stage of the cycle); 4 – partly restored CZS (aftershock stage of the cycle); 5 – spring imitating the elastic interaction between blocks [Lobkovsky et al., 1991].

- However, during a fast seismic stage, only a partial relaxation of accumulated stress occurs. The release of the remaining part of the elastic energy stored in the blocks takes place at the aftershock stage of the SDC during the final "straightening" of the system. The so-called aftershock stage can last several months or years and the end of it marks the beginning of a new SDC, when the seismogenic blocks are at a maximum distance from the islands.

PRESEISMIC STAGE OF THE SDC

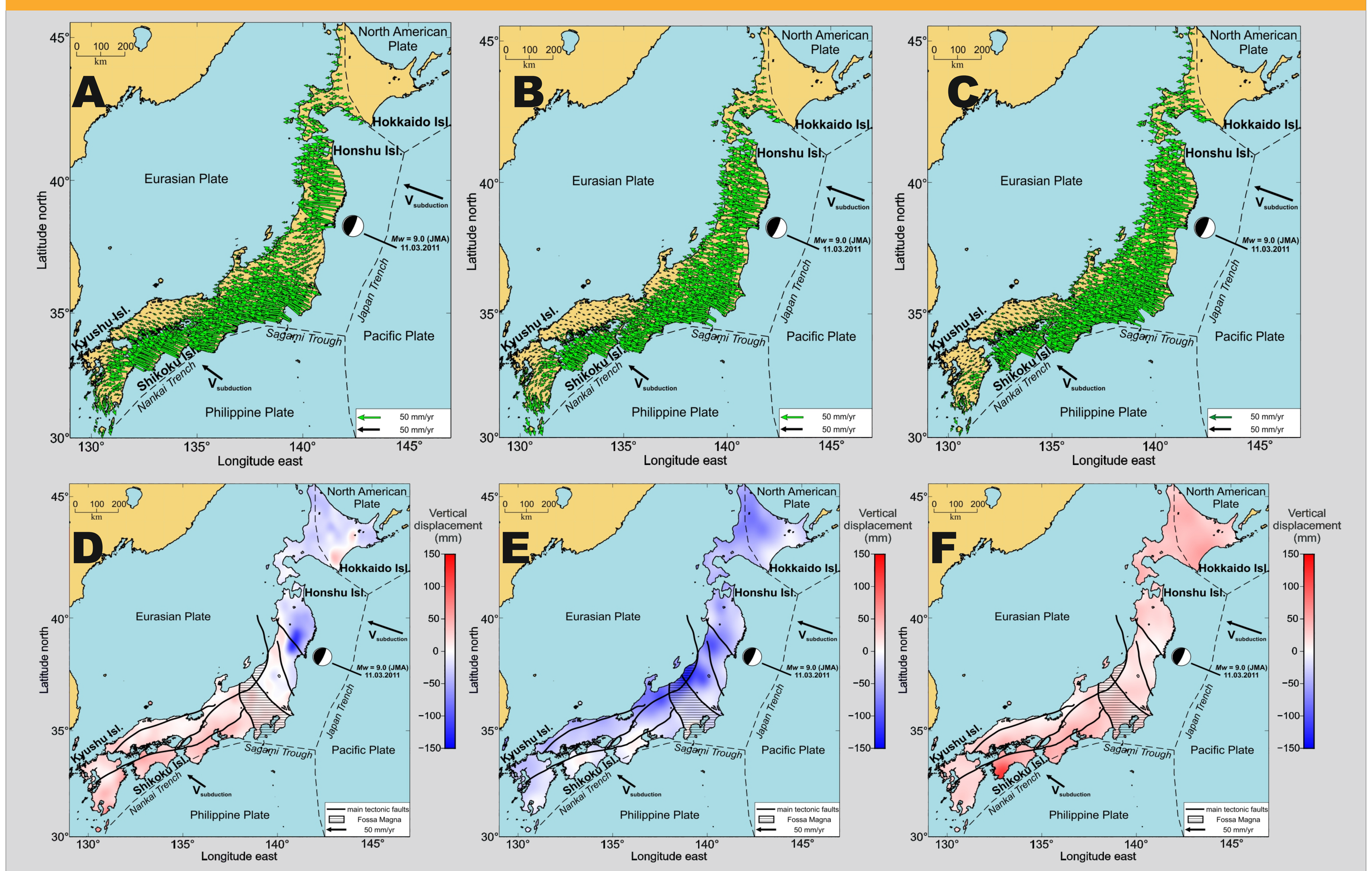

Figure 3. Horizontal (A-C) and vertical (D-F) displacement rates of GEONET stations estimated before the 2011 earthquake over 1-year intervals: 1) 11.03.2008–10.03.2009 (A and D); 2) 11.03.2009–10.03.2010 (B and E); 3) 11.03.2010–10.03.2011 (C and F). Displacements are given relative to stable Eurasian lithospheric plate.

- In terms of the keyboard model, the codirectional character for the vectors of horizontal displacement rates observed before the Tohoku earthquake and the vectors of plate convergence, as well as the decrease in values of horizontal displacement rate vectors toward the interior parts of the islands (Fig. 3), reflect the compression of seismogenic blocks and the rear massif at the interseismic stage of the seismic cycle.
- The characteristic pattern of vertical displacement rates field (coastal uplift along the trench and lowering deeper into the islands) also indicates the long-term compression of seismogenic blocks. However, there is a notable anomaly (Fig.3D) - lowering of coastal region just opposite the future source zone of 2011 earthquake, which is an evidence for an end of accumulation of stresses and a transition of SDC to a preseismic stage.
- At the same time, the represented displacement rates fields prominently and consistently differs year to year. One can see the decrease of magnitudes of displacement rates over the whole Japan Islands two years before the Tohoku earthquake (Fig.3B, E) and then its increase in the last year before the event (Fig.3C, F).

COSEISMIC STAGE OF THE SDC

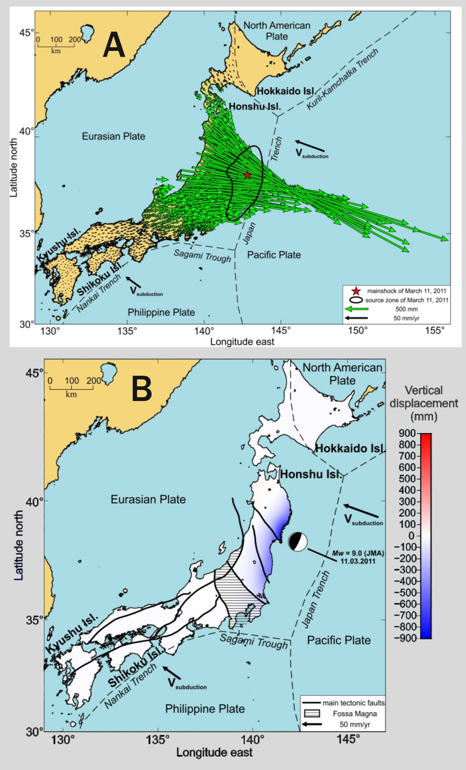

Figure 4. Horizontal (A) and vertical (B) coseismic offsets during the Tohoku earthquake.

- During the 2011 Tohoku earthquake, GEONET stations over the entire area of the Japanese Islands recorded rapid coseismic displacements, which were maximal (5 m) at the stations located on the coast of Honshu Island, nearest to the epicenter (Fig. 4). The obtained horizontal displacement vectors are oriented toward the earthquake epicenter, and their values decrease in the directions both into the Japanese Islands (down to 1.5–2 m) and abruptly after crossing the Fossa Magna graben (down to 3–5 cm). Vertical coseismic motion indicates significant subsidence of the coastal area opposite the source zone.
- Such a pattern of recorded displacements agrees well with the assumed shift of seismogenic blocks into the ocean during the coseismic stage. The observation data suggest that only blocks located to the northeast of the Fossa Magna suffered coseismic displacements.

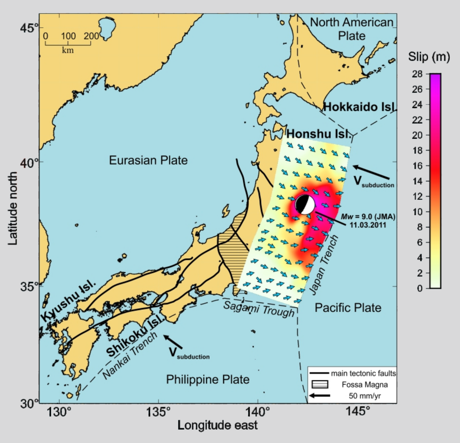

Figure 5. Model of slip distribution in the source zone of Tohoku earthquake based on inversion of GPS coseismic offsets.

- Horizontal coseismic displacements recorded by the GEONET stations during the Tohoku earthquake were used to construct a model of distributed slip in the source zone of this earthquake using code STATIC1D by F. Pollitz.
- The constructed model (Fig. 5) is in good agreement with the same models based on teleseismic and other geodetic data (Lay et al., 2011; Ozawa et al., 2011; Kyriakopoulos et al., 2013; Hashima et al., 2016).

POSTSEISMIC (AFTERSLIP) STAGE OF THE SDC

- In the first year after the 2011 Tohoku earthquake, the displacement vectors in the northeastern part of Honshu Island retain their direction toward the oceanic trench (Fig.7). In terms of the keyboard model, this is caused by continuing oceanward retreat of seismogenic blocks at the aftershock stage of the SDC. This process is accompanied by further release of accumulated stresses in the seismogenic zone. The values of postseismic displacements reached up to 50 cm/yr at the stations near the epicenter and gradually decreased down to 25 cm/yr in the direction into the island. The directions and values of displacement vectors to the southwest of the FMG remain unchanged relative to the interseismic stage of the SDC for Shikoku and Kyushu islands and for the southeastern coast of Honshu Island.

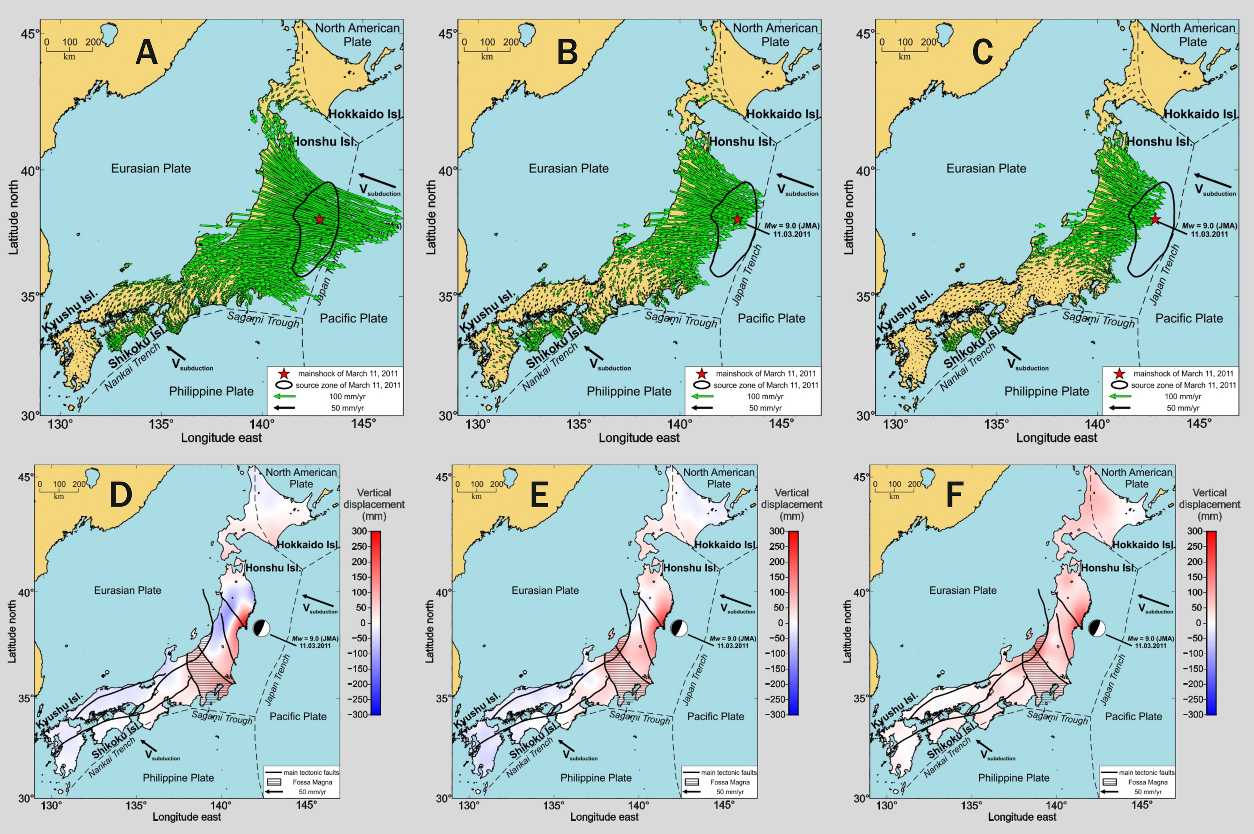

Figure 7. Horizontal (A-C) and vertical (D-F) displacement rates of GEONET stations estimated after the 2011 earthquake over 1-year intervals: 1) 12.03.2011–10.03.2012 (A and D); 2) 11.03.2012–10.03.2013 (B and E); 3) 11.03.2013–10.03.2014 (C and F).

- In the next two years, the values of the displacement rates (Fig.7) decreased systematically (to 10-15 cm/yr near the epicenter), while their directions remained the same over all the islands of Japan.
- Using STATIC1D by F. Pollitz, we model the development of afterslip in the source zone of Tohoku earthquake on the basis of postseismic GPS displacements in the first six months after the event. As one can see on Fig. 8, the afterslip in the source zone developed mostly downdip of the fault plane, which is consistent with a concept of ongoing retreat of seismogenic blocks towards the ocean on the afterslip stage of the SDC. The afterslip in the source zone significantly decreases to the end of the six months interval.

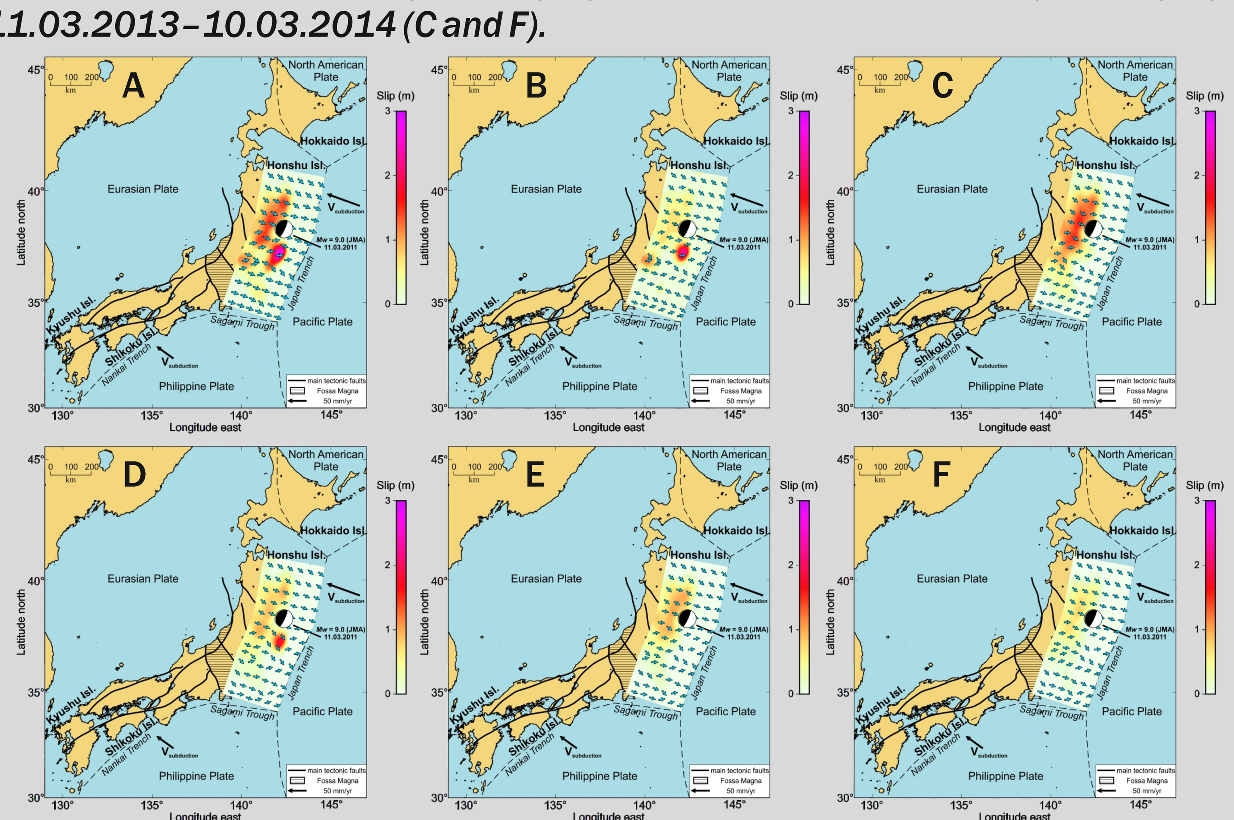

Figure 8. Modeling of afterslip process in the first 6 months after Tohoku earthquake based on 1-month data, from A - first month after earthquake to F - six month after earthquake.

CONCLUSIONS

- Application of the keyboard model allowed us to completely explain the displacements observed by satellite geodetic methods prior to, during, and after the 2011 Tohoku earthquake.
- Source zone of the Tohoku megathrust earthquake affected all possible seismogenic blocks, limited by geological bounds, such as Fossa Magna, which resulted in reestablishing of seismic cycle for the whole northeastern part of Japan subduction zone.
- A long–term postseismic stage, which can last after megathrust earthquakes up to several decades (Vladimirova and Steblov, 2015) can significantly affect the peculiarities of the passage of the seismic cycle in the northeastern part of the Japan subduction zone, providing an explanation for such a long duration of the entire cycle.

REFERENCES

Lobkovsky L.I., Baranov B.V., Pristavakina E.I. and Kerchman V.I (1991) Analysis of seismotectonic processes in subduction zones from the standpoint of a keyboard model of great eartquakes. Tectonophysics. V. 199. I. 2–4. P. 211–236.

Minoura K., Imamura F., Sugawara D., Kono Y. and Iwashita T. (2001) The 869 Jogan tsunami deposit and recurrence interval of large-scale tsunami on the Pacific coast of northeast Japan. J. Nat. Disaster Sci. V. 23. N. 2. P. 83–88.

Lay T., Ammon C.J., Kanamori H., Kim M.J. and Xue L. (2011) Outer trench-slope faulting and the 2011 Mw 9.0 off the Pacific coast of Tohoku Earthquake. Earth Planets Space. V. 63. P. 713–718.

Ozawa S., Nishimura T., Suito H., Kobayashi T., Tobita M. and Imakiire T. (2011) Coseismic and postseismic slip of the 2011 magnitude 9 Tohoku-Oki earthquake. Nature. V. 475. P. 373–377.

Kyriakopoulos C., Masterlark T., Stramondo S., Chini M. and Bignami C. (2013) Coseismic slip distribution for the Mw 9 2011 Tohoku-Oki earthquake derived from 3-D FE modeling. J. Geophys. Res., Solid Earth. V. 118. P. 3837–3847.

Vladimirova I.S. and Steblov G.M. (2015) Postseismic development of source zones of the strongest earthquakes. Geofiz. Issled. V. 16(2), P. 27–38.

Hashima A., Becker T. W., Freed A. M., Sato H. and Okaya D.A. (2016) Coseismic deformation due to the 2011 Tohoku-oki earthquake: influence of 3-D elastic structure around Japan. Earth, Planets and Space. V. 68. N. 159. P. 1–15.

Lobkovsky L., Garagash I., Baranov B., Mazova R. and Baranova N. (2017) Modeling features of both rupture process and the local tsunami wave field from the 2011 Tohoku earthquake. Pure Appl. Geophys. V. 174. N. 10. P. 3919–3938.

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