Crustal Deformation Model in Northeast Japan

Hisashi Suito[(1)], Mikio Iizuka[(2)] and Kazuro Hirahara[(3)]

(1) Research Center for Seismology and Volcanology, Graduate School of Environmental Studies, Nagoya University, Nagoya, 464-8602, Japan (e-mail: suito@eps.nagoya-u.ac.jp; phone: +81-52-789-3014). (2) Research Organization for Information Science and Technology, Tokyo, 153-0061, Japan (e-mail: Iizuka@tokyo.rist.or.jp; phone: +81-3-3712-5321). (3) Division of Earth and Environmental Sciences, Graduate Sc hool of Environmental Studies, Nagoya University, Nagoya, 464-8602, Japan (e-mail: hirahara@eps.nagoya-u.ac.jp; phone: +81-52-789-3651).

Abstract

We implement a 3-D viscoelastic finite element method (FEM) simulation based on the backslip model to understand the origin of geodetically observed crustal deformations in northeast Japan. The simulation results can explain the observed crustal deformation fairly well, assuming four tectonic sources: the subduction of the PAC and the AM, large interplate earthquakes that have occurred around northeast Japan since 1890 and the 1896 Riku-u earthquake. Considering the observed long-term horizontal strain rate, we found the possibility for a huge slow slip event with an inferred magnitude of 8.4 in the Japan Trench.

Introduction

Northeast Japan is considered to be subject to the interaction of three plates, the Pacific plate (PAC), the North American plate (NAM) and the Amurian plate (AM) (Finn et al., 1994[1]; Seno et al., 1996[16]). Among these plates, the crustal deformation in this region is dominated by the effect of the westward subduction of the PAC, which causes the E-W compression of the inland. In fact, observed crustal deformation in northeast Japan by a recent GPS survey shows the E-W or ENE-WSW compression field (Kato et al., 1998[7]; Sagiya et al., 2000[14]), and the field can be explained as the effect of the subduction of the PAC (Ito et al., 1999[6]). However, long-term deformation observed by triangulation and trilateration surveys since 1883 shows the tension field in the Tohoku district (Ishikawa and Hashimoto, 1999[5]). N-S tension dominates on the Pacific coast side (Fig. 1). The reason for this observed extension field is not yet understood. Moreover, the large interplate earthquakes have recurred irregularly both in time and space in this region. Hence, it has been very difficult to understand the observed long-term deformation.

To understand the origin of the geodetically observed crustal deformations in northeast Japan, we implemented numerical simulation using the 3-D viscoelastic finite element method (FEM) code “GeoFEM” (Iizuka et al., 2002[4]) based on the backslip model (Savage, 1983[15]). We assigned the slip on the fault plane using the split node technique

(Melosh and Raefsky, 1981[10]), and computed the elastic and the viscoelastic responses. Assumed tectonic sources are the subduction of the PAC, the AM, large interplate earthquakes (M>7.4) that have occurred around northeast Japan since 1890, and the 1896 Riku-u earthquake, which seriously affected the surface deformation in the Tohoku district (Thatcher et al., 1980[18]; Suito and Hirahara, 1999[17]).

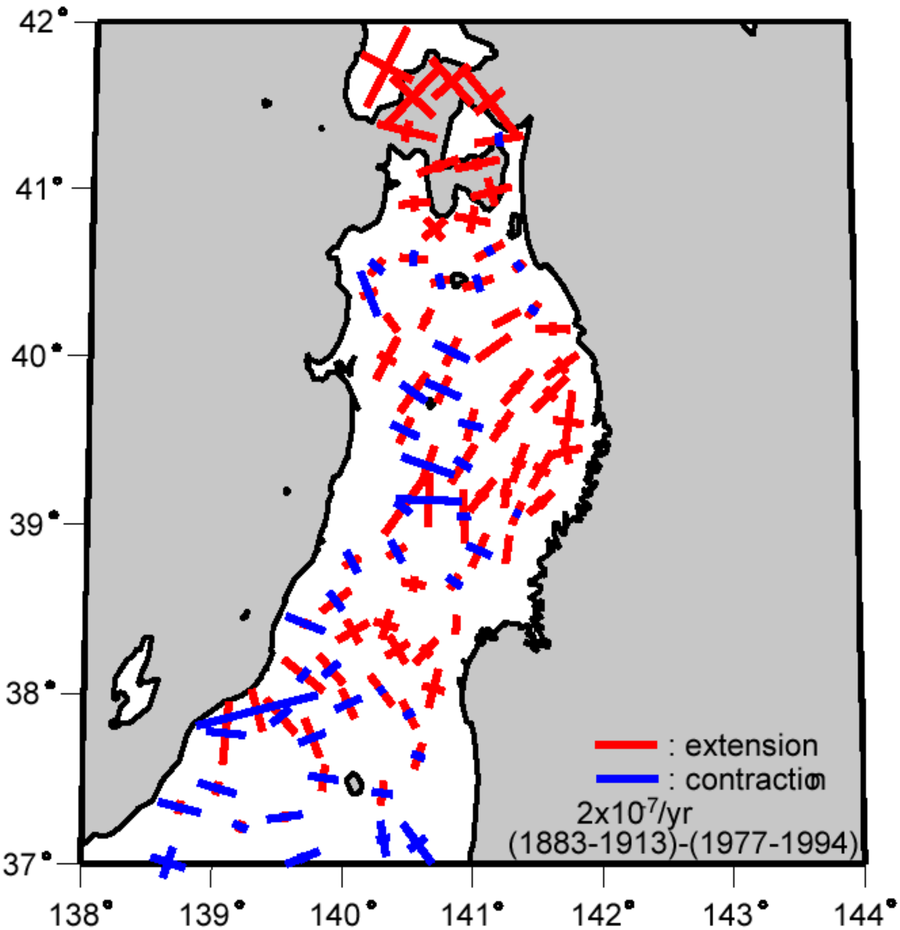

Figure 1: Observed horizontal strain rate by geodetic survey during the past 100 years in the Tohoku district (modified after Ishikawa and Hashimoto, 1999[5]). Red and blue bars indicate the axes of extension and contraction, respectively.

3-D viscoelastic FEM Model

The area modeled is 1150 × 1250 km in northeast Japan, to a depth of 200 km (Fig. 2). The total numbers of nodes and elements are 26,880 and 24,242, respectively. Our model is composed of the elastic crust and plate, and the viscoelastic upper mantle wedge with a Maxwell time of 5 years (Table 1). Based on the distribution of the micro-seismicity, we determined the plate boundary and the configuration of the subducting PAC (Hasegawa et al., 1983[2]; Ohtake, 1995[11]). Lateral variations in the crustal thickness are deduced from the seismic velocity structure determined by explosion and tomographic studies (RGES, 1977[13]; Zhao et al., 1992[21]). As a boundary condition, we assigned the model surface to be free, and the remaining five outer boundaries normal to the X, Y or Z axes are constrained to have slip components only in the Y-Z, X-Z or X-Y planes.

Table 1: Material Property

No.	Rigidity (Pa)	Poisson's Ratio	Viscosity (Pa·s)	Material Type
(1) Crust	3.30×10^{10}	0.226		Elastic
(2) Upper Mantle	5.89×10^{10}	0.274	9.3×10^{18}	Maxwell Body
(3) Plate	19.1×10^{10}	0.258		Elastic

Material properties for the viscoelastic structural models. These values are quoted from Suito and Hirahara (1999)[17]. The numerals in the firstcolumn correspond to the portions in Fig. 2b.

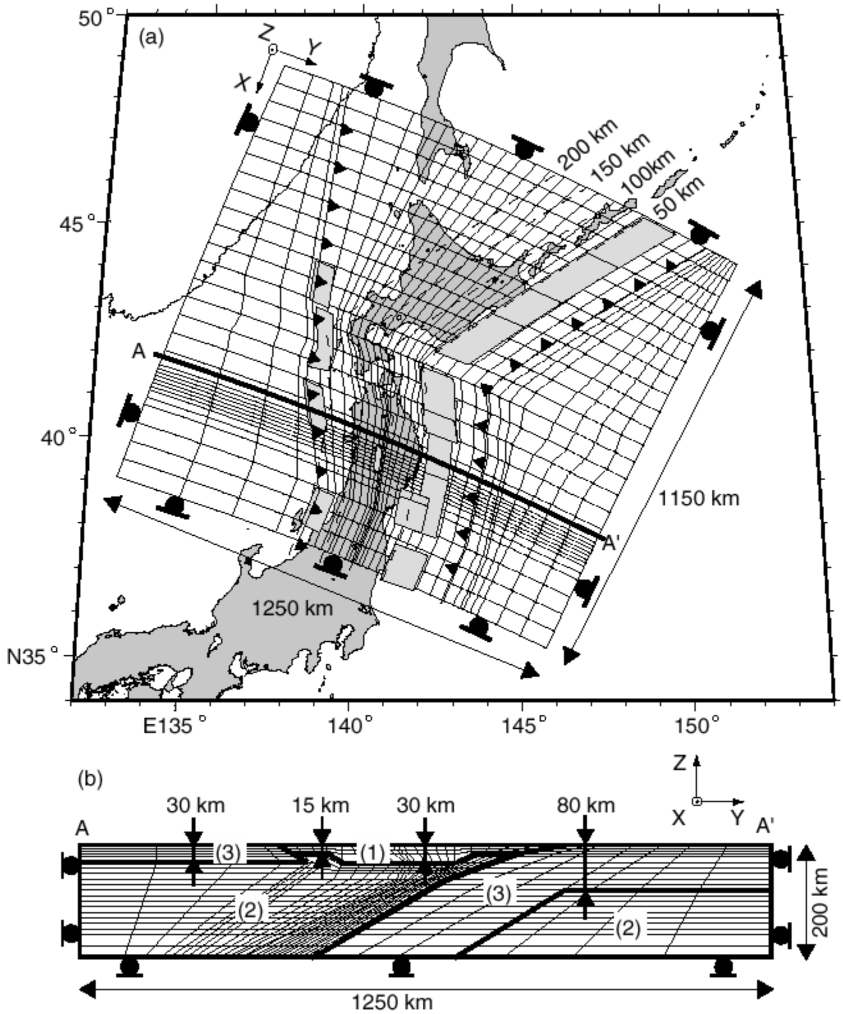

Figure 2: Finite element mesh constructed in this study. (a) Horizontal projection of the finite element mesh. The barbed lines mark the plate boundaries. Rectangles are the horizontal projections of the fault plane for the interplate earthquakes considered in this study. Thick-dashed lines indicate the isodepth contours of the upper boundary of the PAC subducting beneath the northeast Japan. For boundary conditions, see the text. (b) Vertical projection of the finite element mesh along the line A -A'. The portions (1), (2) and (3) represent the crust, the upper mantle and the plate, respectively. The acceleration recordings from large earthquake contain abundant information of the dynamic rupture process on the fault.

Results and Discussion

Modeling results of considering only the above-mentioned four tectonic sources could not explain the long-term observed tension field in the Tohoku district (Fig. 3a). E-W compression, which is the effect of the westward subduction of the PAC and the postseismic deformation due to the 1896 and the 1897 earthquakes, dominates on the Pacific coast side. To explain the observed extension field on the Pacific side requires a virtual earthquake at the Sanriku-Oki region (Fig. 3b). The fault size of this virtual earthquake is 200 × 73.1 km, with a depth ranging from 15 to 40 km and a dislocation of 5.7 m. The magnitude of this virtual earthquake is inferred to be Mw 8.4. If such a great earthquake had occurred, it would be detected by conventional seismograms, and the damage might be very significant. However such a large earthquake has not been recorded in the historical documents. Therefore this earthquake would be the slow slip event recently detected around this region (Kawasaki et al., 1995[8]; Heki et al., 1997[3]; Ueda et al., 2001[19]). It should be noted that our computed results are small compared with the observations. We discuss the trend of the deformation, not the quantitative comparisons.

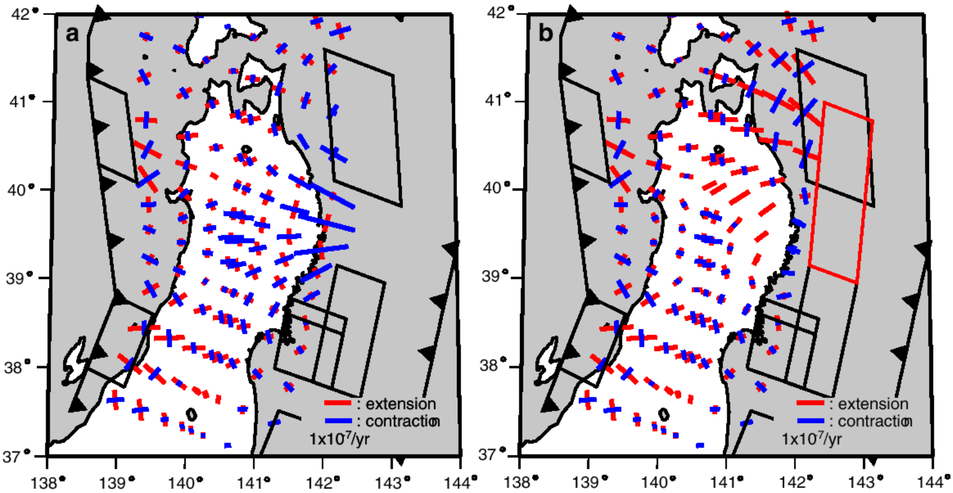

Figure 3: (a) Computed strain rate field in the Tohoku district during the period of 1897-1987. The barbed lines mark the plate boundaries. The rectangle regions correspond the horizontal projection of the faults for the interplate earthquakes, which occurred in analyzed period. (b) Including the effect of the virtual interplate earthquake. The red rectangle means the fault plane of the virtual earthquake.

We note again that westward subduction of the PAC has been considered to produce E-W compression in the inland Sanriku region, as is shown in recent GPS observations (Kato et al., 1998[7]; Sagiya et al., 2000[14]). Nevertheless the observed long-term deformation reveals the extension field (Fig.1). Our interpretations of this observed extension field are as follows. Large interplate earthquakes that occurred in the 1890s (1896 Sanriku-Oki and 1897 Miyagiken-Oki) ruptured the whole region along the Japan Trench. In the 1900s, however, large interplate earthquakes occurred only off Aomori Prefecture (1968 Tokachi-Oki) and off Miyagi Prefecture (1936 Kinkazan-Oki and 1978 Miyagiken-Oki), and did not occur off Iwate Prefecture (Fig.4a). The 1936 Kinkazan-Oki, the 1968 Tokachi-Oki and the 1978 Miyagiken-Oki earthquakes produce the observed N-S tension field around Iwate Prefecture. Off Iwate Prefecture, strain release by the virtual earthquake balances the strain accumulation due to westward subduction of the PAC during the period 1897-1987. Hence, the N-S tension field produced by the above three earthquakes (1936, 1968 and 1978 earthquakes) appears in this observed period.

Previous studies have estimated the seismic coupling ratio, which is the ratio of the earthquake slip amount to the product of the predicted relative plate motion and the recurrence time of the earthquakes, to be about 0.3 in the Japan Trench (Pacheo et al., 1993[12]). These studies have considered the interplate coupling to be about 30 %, which means that 30 % of the relative motion increases the strain at the plate interface, and the remaining 70 % does not increase the strain. Recently, Kawasaki et al. (2001)[9] estimated the ratio in this area to be 0.5-0.85 based on the moment release of the past 30 years, including the effect of slow events. Our estimation of this ratio during the past 100 years is 0.58 including the virtual event (Fig. 4). The interplate coupling that our modeling assumed is 100 %. Therefore, the interplate earthquakes release 58 % of the accumulated strain due to the subduction of PAC. The release of the rest of the accumulated strain is not clear. One interpretation is that the seismic coupling is underestimated, because there is a possibility that an undiscovered slow slip event exists. Another possibility is that the rest of the strain will be released by future earthquakes, or will cause the inland to deform and accumulate the strain necessary for the occurrence of inland earthquakes.

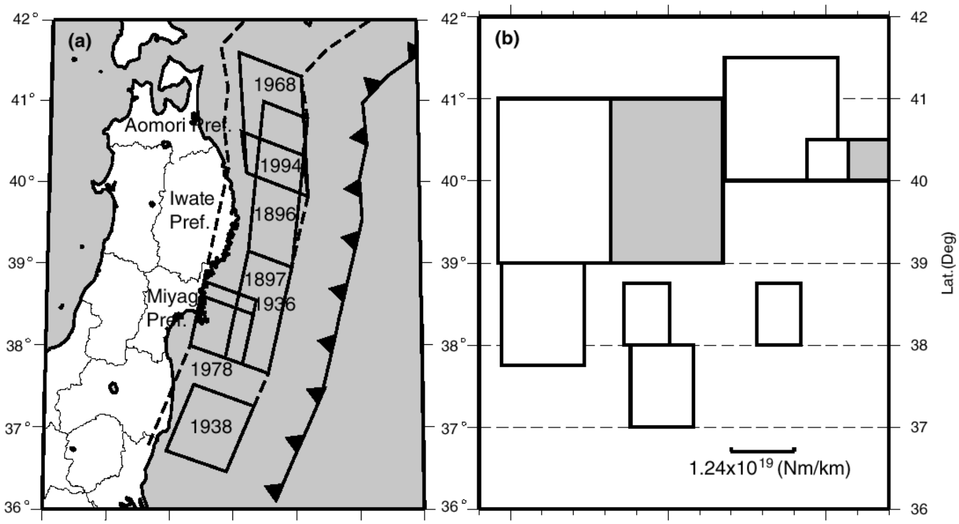

Figure 4: (a) Horizontal projection of the fault planes for interplate earthquakes considered in this study. Broken lines indicate the coupling region. (b) Space-time distribution of seismic moments released by seismic events for the period from 1890 to 2020. Shaded rectangles mean the virtual earthquake and afterslip of the 1994 Sanriku -Haruka -Oki earthquake. Horizontal axis indicates time in years. Vertical axis is latitude. The left side of each rectangle indicates the year of occurrence. Upper and lower sides are northern and southern boundaries of fault area. The width of the rectangle is normalized by 6.2×10^{17} Nm/km/year. Thus, if the seismic coupling ratio is 1.0, rectangles should fill all the space in panel.

Summary

We investigated the origin of geodetically observed crustal deformation in northeast Japan using 3-D viscoelastic FEM modeling, assuming four tectonic sources. We could adequately explain the observed crustal deformation. We also derived the possibility of a huge slow slip event in the Japan Trench based on comparison with the observed long-term horizontal strain rate field.

Acknowledgments

This research was supported by Research Fellowships of the Japan Society for the Promotion of Science for Young Scientists and by grants from "Earth Simulator Project" of the Science and Technology Agency. The authors used a software package, GMT (Wessel and Smith, 1991[20]) to draw most of the maps used in this paper.

References

[1] Finn, C., G. Kimura and K. Suyehiro, *Introduction to the special section Northeast Japan: A case history of subductio*n, J. Geophys. Res., **99**, 22,137-22,145, 1994.

[2] Hasegawa, A., N. Umino, A. Takagi, S. Suzuki, Y. Motoya, S. Kameya, K. Tanaka, and Y. Sawada, 1983, *Spatial distribution of earthquakes beneath Hokkaido and northern Honshu, Japa*n, J. Seismol. Soc. Jpn., Ser. 2, **36**, 129-150, (in Japanese with English abstract).

[3] Heki, K., S. Miyazaki and H. Tsuji, 1997, *Silent fault slip following an interplate thrust earthquake at the Japan Trenc*h, Nature, **386,** 595-598.

[4] Iizuka, M., D. Sekita, H. Suito, M. Hyodo, K. Hirahara, D. Place, P. Mora, O. Hazama and H. Okuda, 2002, *Parallel simulation system for earthquake generation: Fault analysis modules and parallel coupling analysi*s, Concurrency and Computat.: Pract. Exper., **14**, 499-519.

[5] Ishikawa, N. and Hashimoto, M., 1999, *Average Horizontal Crustal Strain Rates in Japan during Interseismic Period Deduced from Geodetic Surveys (Part 2*), J. Seismol. Soc. Jpn., Ser. 2, **52,** 299-315, (in Japanese with English abstract).

[6] Ito, T., S. Yoshioka and S. Miyazaki, 2000, *Interplate coupling in northeast Japan deduced from inversion analysis of GPS dat*a, Earth Planet. Sci. Lett., **176,** 117-130, 2000.

[7] Kato, T., G. S. El-fiky, E. N. Oware and S. Miyazaki, 1998, *Crustal strains in the Japanese islands as deduced from dense GPS arra*y, Geophys Res. Lett., **25**, 3445-3448.

[8] Kawasaki, I., Y. Asai, Y. Tamura, T. Sagiya, N. Mikami, Y. Okada, M. Sakata and M. Kasahara, 1995, *The 1992 Sanriku-Oki, Japan, ultra-slow earthquak*e, J. Phys. Earth, **43**, 105-116.

[9] Kawasaki, I., Y. Asai and Y. Tamura, 2001, *Space-time distribution of interplate moment release including slow earthquakes and the seismo-geodetic coupling in the Sanriku-oki region along the Japan trenc*h, Tectonophysics, **330,** 267-283.

[10] Melosh, H. J. and A. Raefsky, 1981, *A simple and efficient method for introducing faults into finite element computation*s, Bull. Seism. Soc. Am. **71**, 1391-1400.

[11] Ohtake, M., 1995, *A seismic gap in the eastern margin of the Sea of Japan as inferred from the time-space distribution of past seismicit*y, The Island Arc, 4, 156-165.

[12] Pacheo, L., L. R. Sykes and C. H. Scholz, 1993, *Nature of seismic coupling along plate boundaries of the subduction typ*e, J. Geophys. Res., **98,** 14,133-14,159.

[13] Research Group for Explosion Seismology, 1977, *Regionality of the upper mantle around northeastern Japan as derived from explosion seismic observations and its seismological implication*s, Tectonophysics, **37**, 117-130.

[14] Sagiya, T., S. Miyazaki and T. Tada, 2000, *Continuous GPS Array and Present-day Crustal Deformation of Japa*n, Pure Appl. geophys., **157,** 2303-2322.

[15] Savage, J. C., 1983, *A dislocation model of strain accumulation and release at a subduction zon*e, J. Geophys. Res., **88,** 4984-4996.

[16] Seno, T., T. Sakurai and S. Stein, 1996, *Can the Okhotsk plate be discriminated from the North American plate*?, J. Geophys. Res., **101**, 11,305-11,315.

[17]] Suito, H. and K. Hirahara, 1999, *Simulation of Postseismic Deformations caused by the 1896 Riku-u Earthquake, Northeast Japan: Re-evaluation of the viscosity in the upper mantl*e, Geophys. Res. Lett., **26,** 2561-2564.

[18] Thatcher, W., T. Matsuda, T. Kato and J. B. Rundle, 1980, *Lithospheric Loading by the 1896 Riku-u Earthquake, Northern Japan: Implications for Plate Flexure and Asthenospheric Rheolog*y, J. Geophys. Res., **85**, 6429-6435.

[19] Ueda, H., M. Ohtake and H. Sato, 2001, *Afterslip of the plate interface following the 1978 Miyagi-Oki, Japan, earthquake, as revealed from geodetic measurement dat*a, Tectonophysics, **338**, 45-57.

[20] Wessle, P. and W. H. F. Smith, 1991, *Free software helps map and display dat*a, Abstr. EOS Trans. Am. Geophys. Union, **72**, 445-446.

[21] Zhao, D., A. Hasegawa and S. Horiuchi, 1992, *Tomographic Imaging of P and S Wave Velocity Structure Beneath Northeastern Japa*n, J. Geophys. Res., **97**, 19,909-19,928.