Article

The cause of the east–west contraction of Northeast Japan

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Abstract: Northeast (NE) Japan, where the Pacific Plate is subducted to the west, frequently suffers large earthquakes not only along the Japan Trench but also along the Japan Sea side. Those occurred in the former area (subduction–zone earthquake) such as the 2011 off the Pacific coast of Tohoku Earthquake can easily be understood as a releasing process of accumulated stress along the boundary between the subducting Pacific Plate and the overlying plate. On the contrary, those in the latter area (inland earthquake), which occur at relatively shallow depth (<20 km), cannot be explained by such a simple dislocation model. Here I show, the cause of such inland earthquakes can be identified by considering the plate kinematics around the Japanese Islands on the basis of three dimensions, not conventional two dimensions, and the cause of the present E–W contractive tectonics of NE Japan is not the Pacific Plate motion itself but the northwestward–moving Philippine Sea Plate.

1. Introduction

It is well known that the Japanese Islands are currently situated under E–W compression stress field (Terakawa and Matsu'ura, 2010). The E–W contraction causes segmentation of the upper crust of NE Japan separated by a large number of N–S trending reverse faults, which results in its topography (Okamura *et al*., 1995; Sato, 1989; Sato, 1994; Sato *et al*., 2002). The Niigata Prefecture Chuetsu Earthquake (Mw = 6.6) in 2004 is a typical example of the inland earthquakes generated by such crustal deformation. Most of the Japanese earth scientists consider that a relatively rapid Pacific Plate motion of 9–10 cm/year to the west (Demets *et al*., 2010) is the cause of the E–W contractive tectonics (Ikeda, 2012). However, there is a fatal problem in the idea.

If we assume the contraction of NE Japan as an elastic deformation, the accumulated stress acting on the inland arc crust will be reset to the initial state once a large subduction–zone earthquake occurs. On the other hand, when we treat NE Japan as a viscoelastic body, its topographic growth would be reproduced as an inter–seismic plastic deformation. But the geological investigation revealed that the E–W contractive tectonics started at about 3 Ma after tectonically calm state of more than 10 million years (Sato, 1994) while the motion of the Pacific Plate has been almost constant for more than past

40 million years (Harada and Hamano, 2000). Therefore, suppose the E–W contraction of NE Japan is caused by the Pacific Plate motion itself, the Japanese Islands should have been contracted at least for 15 million years after the Japan Sea opening, a hypothesis which is promptly dismissed by the geological evidence. The mpeg-4 movie of the thought–experiment for the cause of the E–W contraction of NE Japan is also presented to make it easier to understand (Takahashi, 2017). Analog models are used for help the comprehension through this work.

The Japanese Islands except the eastern Hokkaido locate on the eastern margin of the Eurasian Plate, under which both the Pacific and Philippine Sea Plate are subducted (Fig. 1), and the relative motion of these three tectonic plates is considered to trigger large earthquakes in the region. The Philippine Sea Plate moves northwestward and is subducted beneath Southwest (SW) Japan along the Nankai Trough at a velocity of 4 cm/year (Seno *et al*., 1993), while the Pacific Plate moves to the west at a velocity of 9–10 cm/year (Demets *et al*., 2010) and is subducted underneath of NE Japan along the Japan Trench. The Pacific Plate is also subducted under the Philippine Sea Plate along the Izu–Ogasawara Trench. Three plates and three plate boundaries (trenches) meet at a point offshore central Japan, which is called a trench–trench–trench (T–T–T) triple junction. The geometric stability of the T–T–T triple junction is the key to solve the riddle.

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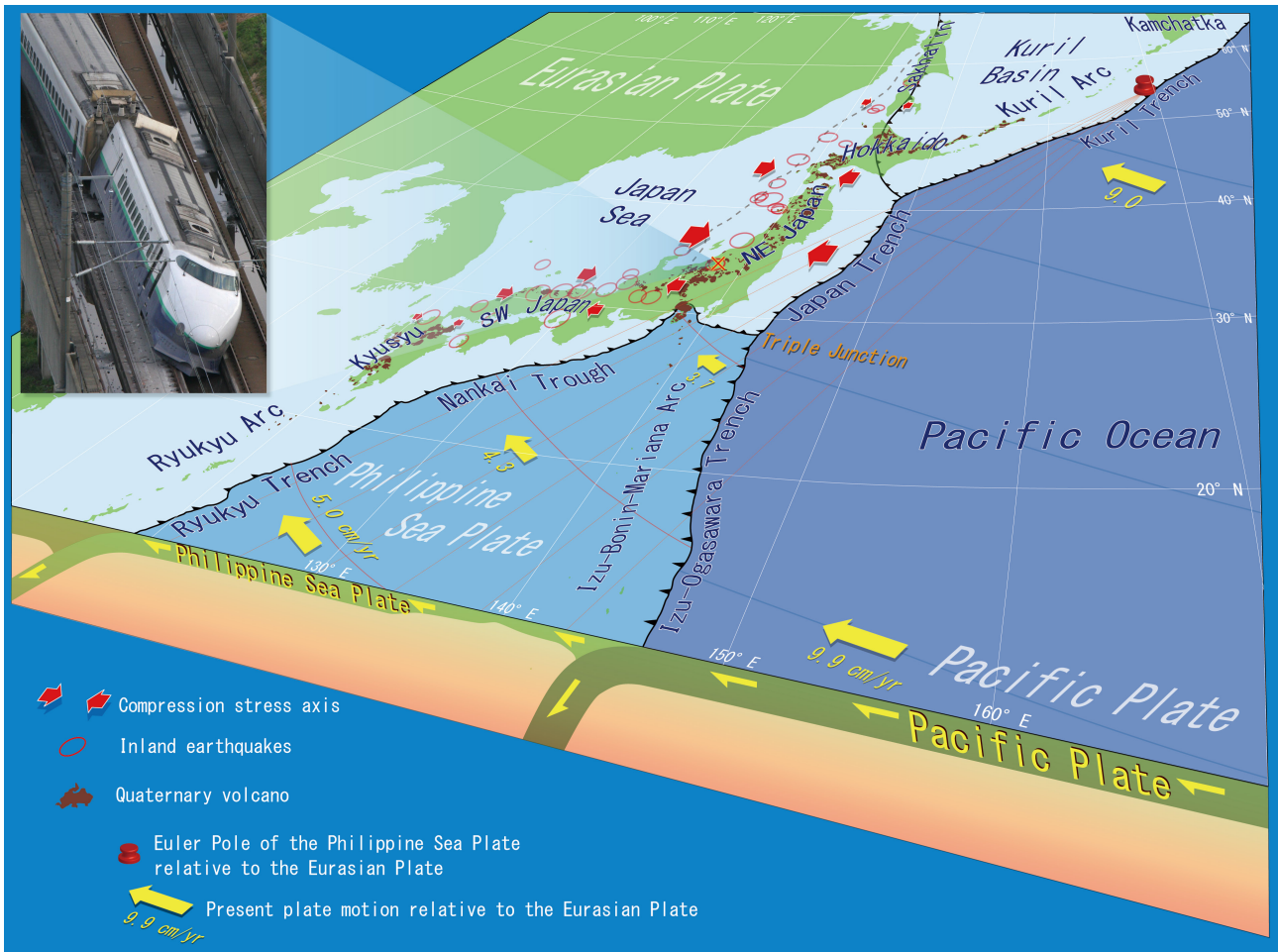
Fig. 1 Tectonic setting of the Japanese Islands. A number of large earthquakes occur particularly along the Japan Sea side of NE Japan. A high–speed train (Shinkansen) was derailed in the Niigata Prefecture Chuetu Earthquake occurred on Nov. 23, 2004 (Photo by the Yomiuri).

2. Analog model experiment

2. 1 Initial model

An analog model is very helpful in visual comprehension of the relationship between the three plates around Japan (Takahashi, 2017). At the beginning, two–dimensional plate kinematics is reproduced using the model (Fig. 2), which is composed of three parts: a wooden board (Base Board), and two transparent acrylic sheets which correspond to the Philippine Sea Plate (Sheet A) and the Eurasian Plate (Sheet B). The Sheet A is pinned at the present Euler Pole of the Philippine Sea Plate (a red pin in Fig. 2) located to the northeast of Hokkaido (Seno *et al.*, 1993), so that it can rotate around the pole. The Sheet B is laid over the Sheet A and fixed to the Base Board. This model, in which Japanese Islands are assumed as a part of stable Eurasian Plate and never be deformed, can simply reproduce the motion and subduction of the Philippine Sea Plate.

The geometric transition of the three plates from the present to 12 million years later is illustrated in Fig. 3.

The Japan Trench is fixed in place throughout the period, whereas the Izu–Ogasawara Trench migrates westward as the Philippine Sea Plate rotates. Thereby, the Japan Trench and the Izu–Ogasawara Trench are pulled apart from each other, generating a transform fault that connects these two separating trenches. The length of the transform fault increases with time. The moment the Izu–Ogasawara Trench moves away from the Japan Trench, the T–T–T triple junction becomes another type, a T–T–F (transform fault) triple junction. This is the reason why the present T–T–T triple junction offshore central Japan is regarded as a geometrically unstable condition (McKenzie and Morgan, 1969).

If the two trenches depart from each other, the Pacific Plate should be cut by a tear fault (Fig. 3), forming a right–lateral transform fault between them. Three million years later, the displacement between the two trenches will be 50–60 km based on the present Philippine Sea Plate motion, while the Pacific Plate will travel about 300 km, because it moves to the west at a rate of 10 cm/year. This means that the tear fault will have split the
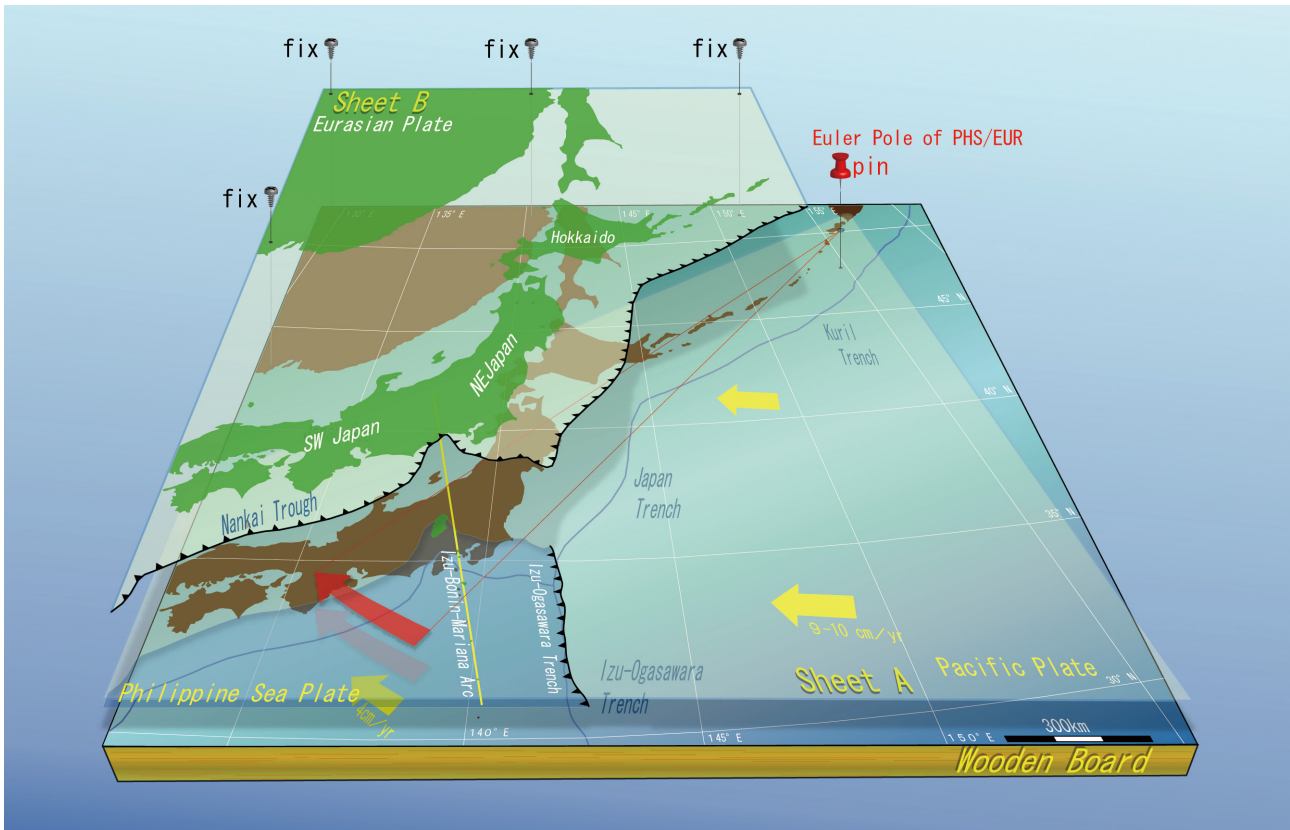
Fig. 2 Initial analog model of the Philippine Sea Plate motion. Overlaying Japanese Islands (NE and SW Japan) are not deformed in this case.
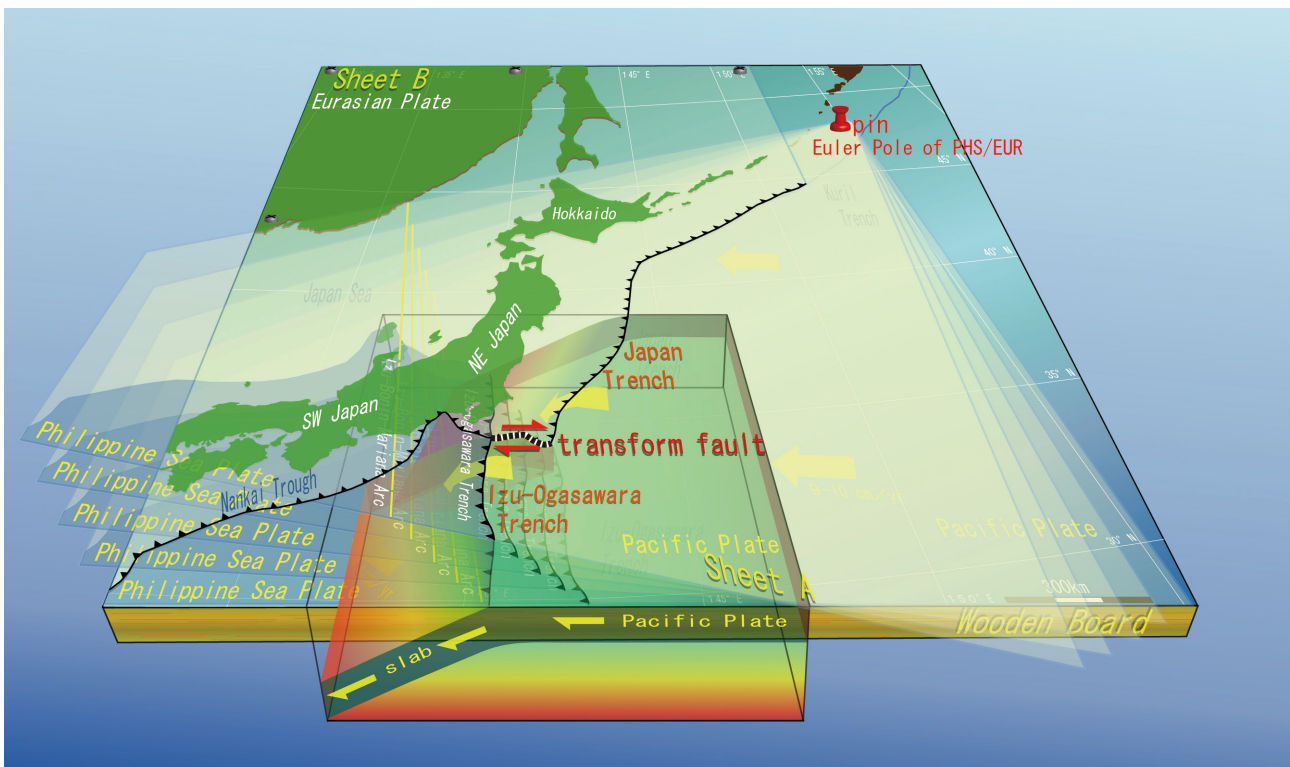

Fig. 3 Three–dimensional geometry of the three plates around the triple junction (present to 12 m.y. future). The subducting Pacific Plate (slab) should be cut by a tear fault, if NE Japan will never be deformed.
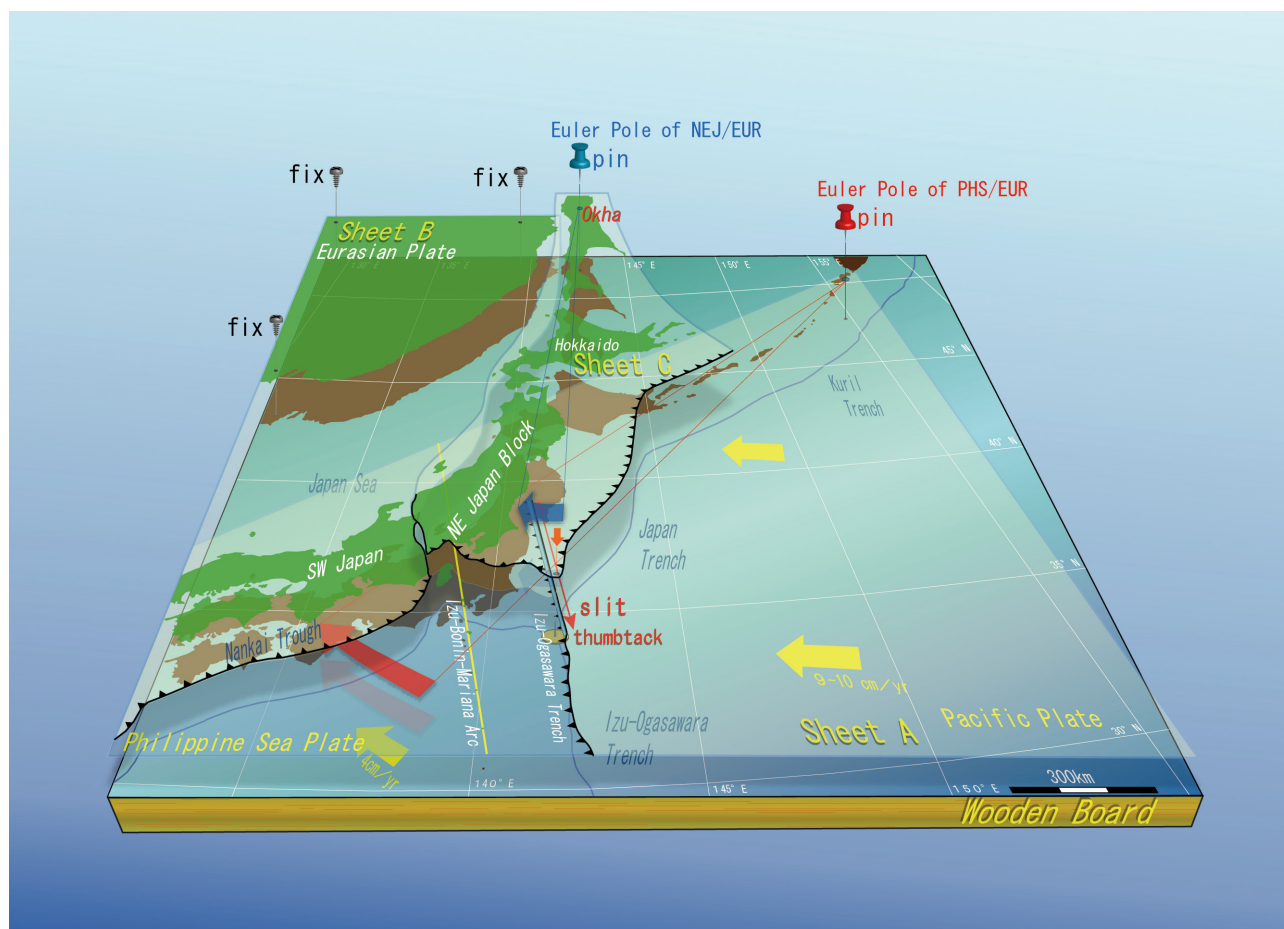
Fig. 4   The Pacific Plate will never be cut by tear fault in this improved model.

Pacific Plate for almost 300 km. However, the Pacific Plate, formed in Jurassic to Cretaceous Periods, is the thickest (about 90 km) and coldest plate on the Earth, so is too rigid to be sheared easily. In fact, the slab of the Pacific Plate is observed to be continuous around the triple junction based on the hypocenter distribution of subduction–zone earthquakes (Nakajima *et al*., 2009). Consequently, it is quite unlikely that the Pacific Plate is to be sheared at the triple junction, i.e., two trenches should be continuous. Therefore, the model should be revised so that the Japan Trench and Izu–Ogasawara Trench can always be continuous under all circumstances.

2. 2   Improved model

The model is taken apart first and a linear slit is cut in the Sheet A along the Izu–Ogasawara Trench (Fig. 4). This corresponds to the subducted part of the trench. Then the Sheet A is pinned at its Euler Pole (shown as a red pin) so that it can rotate about the pole. Second, NE Japan (Sheet C) is cut off from the Sheet B along the eastern margin of the Japan Sea, because it is considered to move independently from the Eurasian Continent. Third, a thumbtack is inserted into the slit from under the bottom of the Sheet A, on which the Sheet B is overlaid.

Only the Sheet B is screwed on the Base Board. Next, the Sheet C is overlaid on the Sheet B, being pierced by the thumbtack at the southern tip of the Japan Trench so that the Japan Trench and the Izu–Ogasawara Trench can move together. Finally, the Sheet C is stuck by a blue pin at northern Sakhalin, because the Euler Pole between NE Japan and stable Eurasian Plate is located near Okha in Sakhalin (Wei and Seno, 1998). The thumbtack moves along the slit as the Philippine Sea Plate rotates, which turns NE Japan clockwise. Now, an unsplit Pacific Plate model, in which two trenches move along with each other, has been completed.

3.   Discussion

In the improved analog model, both the Izu–Ogasawara Trench and triple junction move westward together with the Philippine Sea Plate motion. The Japan Trench, which was immovable in the previous model, also migrates westward because the southern end of the Japan Trench is pierced by the thumbtack of the Philippine Sea Plate sheet (Sheet A in Fig. 5). In this model, the eastern margin of NE Japan corresponds to the Japan Trench, so NE Japan on the Sheet C swings to the west around a pivot at Sakhalin
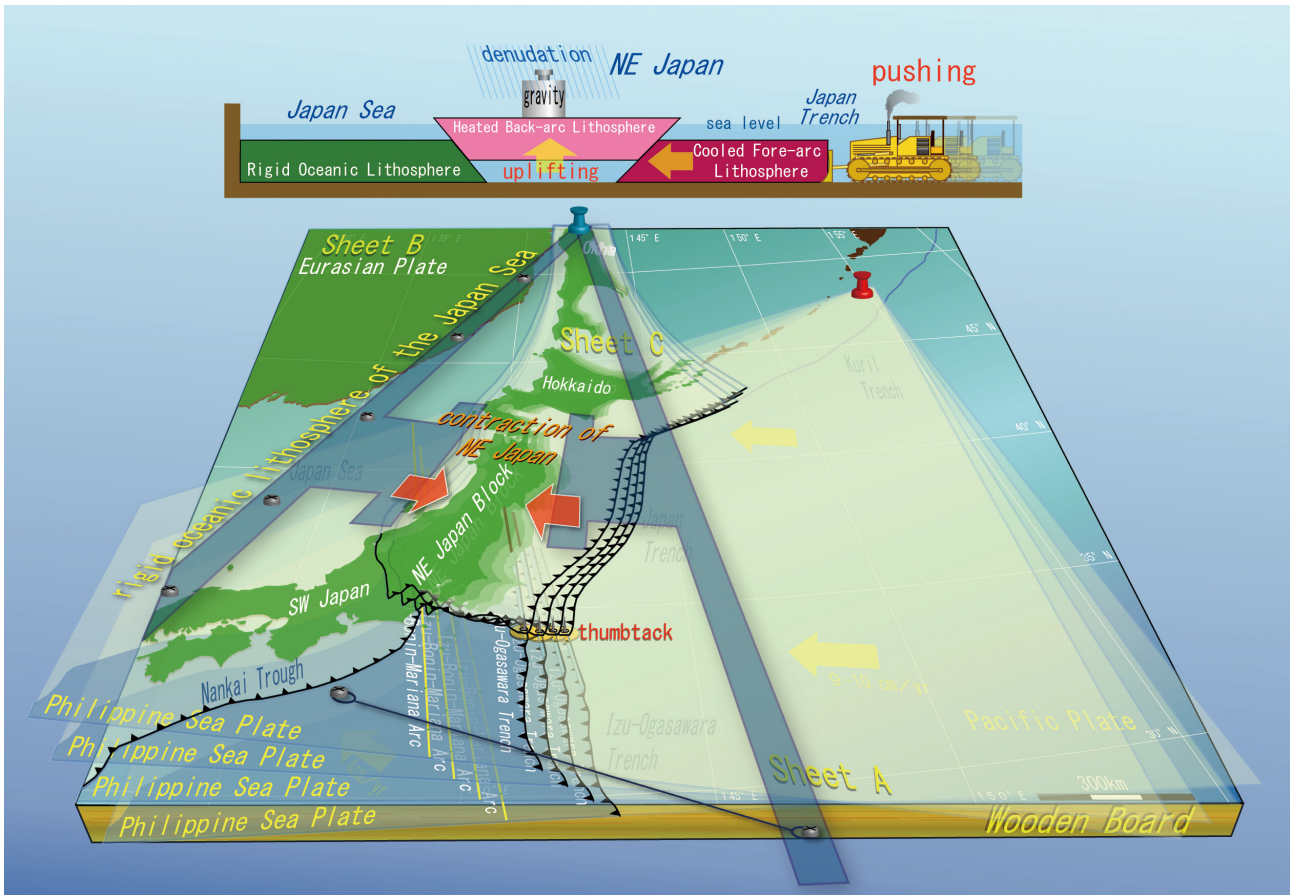
Fig. 5   Geodynamic flame work of the Japanese Islands. NE Japan is contracted like a walnut caught in a nutcracker.

(blue pin in Fig. 4).

The relative velocity of migrating triple junction to stable Eurasia is estimated as 2–3 cm/year based on the present Philippine Sea Plate motion. Therefore, the southern end of the Japan Trench also moves westward at the same speed. The westerly migrating Japan Trench will push the overriding NE Japan to the west, unless whole of its westward motion is cancelled out by tectonic erosion along the Japan Trench (Von Huene and Lallemand, 1990). The arc crust of NE Japan is thus sandwiched between the westerly moving Japan Trench and the rigid and stable oceanic lithosphere of the Japan Sea and then contracted (Fig. 5).

The western half of NE Japan arc crust (back-arc region) has been heated and weakened for a geologically long time by volcanic activity (Yoshida, 2001). In fact, possible deep-seated magmatic activity is imaged in the region by seismic tomography (Hasegawa *et al.*, 1991; Zhao *et al.*, 1992). By contrast, the fore–arc region (Japan Trench side), which has been cooled by the subducting old oceanic lithosphere of the Pacific Plate, is not so deformable. Thus the E–W contraction of NE Japan has been concentrated along the Japan Sea side due to thermo-rheological difference.

Thus, if the Pacific Plate is assumed not to be shorn by a tear fault at the triple junction, and actually it is not, the Philippine Sea Plate motion will cause the Izu–Ogasawara Trench to migrate westward, then T–T–T triple junction, Japan Trench, and NE Japan successively. Thereby, the arc crust of NE Japan has no choice but to shorten its width as it drifts westward. This E–W contraction tectonics causes a number of large inland earthquakes particularly along the back–arc region, far from the plate subduction boundary (Japan Trench). Therefore, the cause of inland earthquakes along the Japan Sea side of NE Japan is the Philippine Sea Plate, not the Pacific Plate. It is the imposed displacement arising from moving subduction boundary of the Pacific Plate (Japan Trench) that causes the E–W contraction of NE Japan, not the Pacific Plate motion itself.

4.   Conclusion

Considering the three dimensional kinematics of the Pacific and Philippine Sea Plates relative to the overlying Eurasian Plate, I propose that the present E–W contractive tectonics of NE Japan is brought about by the north–westward motion of the Philippine Sea Plate, not by the Pacific Plate motion itself.

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東北日本の東西短縮テクトニクスの原因

高橋雅紀

要　旨

　大部分がユーラシアプレートに属する日本列島には，南からフィリピン海プレートが，東から太平洋プレートが沈み込んでいる．日本列島のうち，本州(東北日本から西南日本)の広い範囲は東西圧縮応力場におかれ，内陸地震が頻発し，断層運動に伴って山地は隆起し内陸盆地は沈降している．この東西短縮テクトニクスの原因について，3つのプレートの運動と，3つの収束境界(海溝)が一点に集まる海溝型三重会合点の三次元幾何学を組み合わせた思考実験を行った．その結果，これまで，西に移動する太平洋プレートの運動そのものに起因すると考えられてきた東西短縮テクトニクスの原因が，北西に移動するフィリピン海プレートの運動によってコントロールされていることが判明した．すなわち，フィリピン海プレートの運動により三重会合点が西に移動し，追随するように日本海溝も西に移動する．その結果，東北日本も西に移動するが，日本海の海洋リソスフェアに阻まれるため，東北日本の島弧地殻は東西に短縮せざるを得ない．このことは，内陸地震の原因が，太平洋プレートの運動そのものではなく，沈み込み位置(日本海溝)の移動であることを意味している．