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Strike-slip tectonics within the northernmost Philippine Sea plate in an arc-continent collisional setting

Wei Gong[a,b,*], Xiaodian Jiang[a,b], Yufan Guo[a,b,c], Junhui Xing[a,b], Congying Li[a,b], Yang Sun[a,b]

[a] College of Marine Geosciences, Ocean University of China, Qingdao 266100, China
[b] Key Lab of Submarine Geosciences and Prospecting Techniques, Ministry of Education, Qingdao 266100, China
[c] Seismological Bureau of Jiangxi Province, Nanchang 330039, China

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ABSTRACT

The geological processes in the northernmost Philippine Sea plate, which is bounded by the Suruga and Sagami troughs, are a typical example of an active collision zone. We attempt to illustrate the stress field through seismic estimations and geodetic analysis and propose the kinematic mode of the northernmost tip of the Philippine Sea plate. Seven events ($M \geq 4.0$) are chosen for waveform inversion by the ISOLA software to distinguish the stress field. In particular, six of the chosen events, which exhibit strike-slip motion, are distributed in the eastern area, where few focal mechanisms have been reported by previous studies. According to the available focal mechanisms, strike-slip faults with similar P and T axes are widely distributed in the study area. The stress inversion suggests that the northern area is characterized by a NW-SE compression and a NE-SW extension stress regime, although some spatial differences exist. As indicated by an analysis of the geodesy, epicenters, focal mechanisms, gravity anomalies and velocity structure, the deformation in the northernmost tip is mainly accommodated by several conjugate strike-slip fault systems with steep dips that center on the Izu volcanic line. Generally, the maximum principal stress of the kinematics is derived from the collision between the Philippine Sea plate and Central Japan. Because of the different subduction angles, rates and directions of the down-going plate, diverging slab-pull forces along the Suruga and Sagami troughs may be causing the NE-NNE extension in most of the areas that are bounded by the two troughs. The extension propagates southwards along the Izu volcanic line and reaches the area adjacent to Miyake-jima.

1. Introduction

Subduction zones, which are one of the most complex geosystems, have attracted increasing attention from geologists (Stern et al., 2003). A complicated subduction pattern, namely, the subduction of the Izu-Bonin arc beneath Central Japan, exists in the northernmost tip of the Philippine Sea plate between the Suruga and Sagami troughs, which is adjacent to the triple junction of the Philippine Sea, Eurasian and North American plates (Ukawa, 1991). This environment provides an unusual opportunity to study the fundamental geological processes of the active collision between two island arcs (Mazzotti et al., 1999; Tani et al., 2011). Moreover, knowing the present-day kinematics of the northernmost tip of the Philippine Sea plate is important to understand the potential seismic hazards because of the occurrence of many earthquakes (e.g., 1923 Kanto earthquake).

However, obtaining a reasonable tectonic understanding of this region, including both the differential tectonic movement of the blocks within the Philippine Sea plate and the complexity of the collision between the Philippine Sea plate and Central Japan, is very difficult. In addition, this environment may be somewhat influenced by the downward subduction of the Pacific plate.

Various models have been proposed based on the focal mechanisms, geodetic data, etc. to understand the tectonics of the study area (Ukawa, 1991; Mazzotti et al., 1999, 2001; Henry et al., 2001; Nishimura et al., 2007; Loveless and Meade, 2010; Nishimura, 2011).

Seismicity is regarded as the partial release of tectonic stress by sudden brittle rupture. The focal mechanisms can provide the most reliable information (fault plane solutions, principal axes, rock rupture direction, etc.) on the crustal stress states (Terakawa and Matsu'ura, 2010). Thus, the focal mechanisms play a key role in the regional stress state of the northernmost Philippine Sea plate (Ukawa, 1991; Mazzotti et al., 1999).

Similarly, the GPS (Global Positioning System) can track spatial and temporal variations in surface motions. GPS has been shown to be an accurate and efficient tool for measuring complex deformation patterns, providing insight into the underlying tectonic forces (Shimada and

* Corresponding author at: College of Marine Geosciences, Ocean University of China, No. 238 Songling Road, Laoshan District, Qingdao City, Shandong Province, China.
E-mail address: 21120411040@ouc.edu.cn (W. Gong).

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Bock, 1992). Several space geodetic methods have confirmed the motion rates of the northernmost tip through direct measurements to understand the active plate boundary processes in recent periods (Henry et al., 2001; Mazzotti et al., 2001; Nishimura et al., 2007; Loveless and Meade, 2010; Nishimura, 2011).

Despite these extensive studies, several contentious or unresolved issues remain regarding the kinematics of the northernmost tip.

(1) Many scientists inverted the strain rate tensors that were derived from the GPS velocity field and estimated the elastic deformation field (Shimada and Bock, 1992; Hashimoto and Jackson, 1993; Henry et al., 2001; Nishimura et al., 2007; Loveless and Meade, 2010; Nishimura, 2011). Compared to the quantification of the complicated movement in the northernmost tip, the spatial anisotropic analysis of the current tectonic stress field is quite deficient, especially in terms of the focal mechanisms. In Ukawa's (1991) study, the compressional axes (P axis) remain horizontal throughout the region and show a fan-shaped pattern, which is interpreted to be the result of the collision between the Izu block and the Eurasian plate.

(2) Although previous studies may have clarified some of the regional kinematics, these models have not been uniformly applied to the northernmost tip of the Philippine Sea plate. Some scientists proposed that upper-middle crust that was delaminated from the subducting lower part was involved in the Izu arc's material accretion onto Honshu island, which was characterized by the low-angle thrusts; the same was true for the southern area between the Suruga and Sagami troughs (Taira et al., 1998; Yamamoto et al., 2009a, 2009b; Tamura et al., 2010; Arai et al., 2013; Arai and Iwasaki, 2014). Recently, Lallemand (2014) examined the strain modes in arc-continent collisional settings that led to arc material subduction and proposed that the stress conditions were characterized by compressional deformation in the upper crust at the northernmost tip. In contrast, Mazzotti et al. (1999) proposed a tectonic scheme for the Izu collision system that was closely related to an extensional tear of the Philippine Sea slab, which was propagating southwards along the volcanic arc because of diverging slab-pull forces on each side of the Izu peninsula.

The purpose of this study is to assess the tectonic processes, present a reasonable tectonic model, and provide key insights into the tectonic origin in the Izu collision zone based on well-distributed seismological observations and GPS data. In contrast to previous studies, newly available focal mechanisms that are inverted by ISOLA, combined with other available focal mechanisms, additional GEONET GPS data, gravity anomalies and seismic velocity from the study area, enable us better to understand the kinematics of the northernmost tip.

2. Geological setting

Along the northernmost boundary of the Philippine Sea plate, the eastern Nankai-Suruga trough and the Sagami trough, the Philippine Sea plate is subducting underneath the Eurasian and North American plates with a convergence rate of 3–5 cm/a in a NW (305–315°) direction (Ukawa, 1991; Shimada and Bock, 1992; Lin et al., 2013). The northern segment with the Izu-Bonin volcanic arc is colliding against the midsection of Honshu island in the vicinity of the Izu Peninsula (Fig. 1A and B). The volcanic arc is located approximately 110–120 km above the upper surface of the descending Pacific slab and consists of a chain of volcanoes, including Oh-shima, Nii-jima, Miyake-jima, etc. (Fig. 1C).

The northern section of the Izu-Bonin arc has been colliding with Central Japan since the middle Miocene (~15 Ma) and has gradually accreted onto the Honshu island (Mazzotti et al., 1999; Stern et al., 2003; Tani et al., 2011; Lallemand, 2014). Along with the collision and landward retreat of the trench, the Izu peninsula is now surrounded by the Suruga-Sagami troughs and the collision boundary to the north. The plate boundary has been significantly deformed into a wedge shape, with the Izu peninsula as a rigid indenter that is pushing the continental upper crustal layers forward (Ida, 2009; Lallemand, 2014).

As estimated from the hypocenter distribution and seismic tomography, the subducting slab extends to a depth of less than 200 km along the Suruga and Sagami troughs (Kamiya and Kobayashi, 2007; Nakajima et al., 2009). Henry et al. (2001) proposed that the subduction velocity in the northern Suruga trough might range between 20 and 32 mm/a according to geodetic data, and the best-fit subduction velocity was 26 mm/a towards the NNW (~335°) along the Sagami trough.

In addition, the Pacific plate is subducting beneath the Philippine Sea and North American plates along the Izu-Bonin trench and the Japan trench to the east of the Kanto district, respectively. Thus, the genesis of the Izu-Bonin arc that is subducting underneath Central Honshu and parallel to the strike of the descending Pacific slab is closely correlated with the subducting Pacific plate. Moreover, the Philippine Sea plate that is subducting along the Sagami trough even contacts the subducting Pacific plate at < 100 km depth beneath the Kanto district (Fig. 1B) (Henry et al., 2001; Wang and Zhao, 2006; Kamiya and Kobayashi, 2007; Wu et al., 2007; Nakajima et al., 2009; Uchida et al., 2009). In particular, Toda et al. (2008) suggested that a fragment of the Pacific plate, which was detached upon the collision of two subducting Pacific plate seamount chains around 2 Ma, was sandwiched among the Pacific, Philippine Sea plates and Central Japan and influenced the seismicity beneath greater Tokyo.

As shown in Fig. 1C, the Izu peninsula is the northernmost region of the Philippine Sea plate and has been separated from the rigid portion of the plate (Hashimoto and Jackson, 1993). According to Mazzotti et al. (1999, 2001) and Nishimura et al. (2007), this peninsula was a component of the plate 2 Ma ago as estimated from the history of the Ashigara Basin (at the northern edge of the Izu peninsula) and is now assumed to be an independent block called the Izu microplate (IMP).

The IMP rapidly rotates clockwise at 10°/Ma, with a rotation pole relative to the Central Japan block (Mazzotti et al., 1999, 2001; Nishimura et al., 2007). Yamasaki and Seno (2005) mentioned that the IMP might be reducing the convergence velocity between the plates.

Thus, complicated tectonic stress fields might be caused by such a special tectonic setting in the northernmost tip, which is adjacent to the triple junction of the Philippine Sea, Eurasian and North American plates (Ukawa, 1991; Nishimura, 2011). Within the northernmost tip, the fault systems accommodate the collision between the Philippine Sea plate and Central Japan. The major structures are N-S and NE-SW left-lateral faults, with the deformation that is limited by these faults accommodated by right-lateral en echelon faults (Fig. 1C) (Mazzotti et al., 1999). The extensional zone along the arc strike is bounded by N-NNW-trending normal faults and is distributed behind the volcanic front from 27.5° to 33.5°N, with the rifting having initiated 2.8 Ma ago (Taylor, 1992; Taylor and Nesbitt, 1998; Debari et al., 1999; Ishizuka et al., 2009; Nishimura, 2011) (Fig. 1C).

As shown in Fig. 2, not many epicenters are present within the area along the Suruga and Sagami troughs, which corresponds to the small convergence velocity across the troughs (Henry et al., 2001; Nishimura, 2011). The boundary of the Philippine Sea plate along the Suruga and Sagami troughs may contain strongly coupled faults (1854, M = 8.4, Tokai; 1923, M = 7.9, Kanto) compared to the plate boundary to the north of the Izu peninsula (Nishimura et al., 2007).

On the contrary, many epicenter clusters (≥4 clusters) are distributed in the area that is bounded by the troughs, the patterns of which are similar to the fault lines that are associated with the deformation. Three epicenter clusters of the swarm are elongated parallel to the Izu-Bonin arc (Fig. 2). Furthermore, these events have been recognized as tectonic earthquakes and may have been generated by changes in the tectonic stress field because of fault activity, plate collision and volcanic activity (Glasby and Kasahara, 2001).