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Cenozoic lithospheric deformation in Northeast Asia and the rapidly-aging Pacific Plate

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ABSTRACT

Northeast Asia underwent widespread rifting and magmatic events during the Cenozoic. The geodynamic origins of these tectonic events are often linked to Pacific plate subduction beneath Northeast Asia. However, the Japan Sea did not open until the late Oligocene, tens of millions of years after Pacific Plate subduction initiation in the Paleocene. Moreover, it is still not clear why the Baikal Rift Zone extension rate increased significantly after the late Miocene, while the Japan Sea opening ceased at the same time. Geodynamic models suggest these enigmatic events are related to the rapidly-aging Pacific Plate at the trench after Izanagi–Pacific spreading ridge subduction. Subduction of the young Pacific Plate delayed the Japan Sea opening during the Eocene while advection of the old Pacific Plate towards the trench increases seafloor age rapidly, allowing the Japan Sea to open after the early Miocene. The Japan Sea opening promotes fast trench retreat and slab stagnation, with subduction-induced wedge zone convection gradually increasing its extent during this process. The active rifting center associated with wedge zone convection upwelling also shifts inland-ward during slab stagnation, preventing further Japan Sea spreading while promoting the Baikal Rift Zone extension. Our geodynamic model provides a good explanation for the temporal-spatial patterns of the Cenozoic tectonic and magmatic events in Northeast Asia.

1. Introduction

Northeast China and surrounding areas lie at the continental margin of the northwest Pacific subduction zone (Fig. 1a). This region is comprised of three plates, including Eurasia, Amuria, and Okhotsk Plates from inland toward the trench (Bird, 2003). The continental lithosphere in this region has diverse rheological strength and deformation histories. The southeast part of the Eurasia Plate, the Siberian Craton, is strong with little Phanerozoic deformation, whereas the continental lithosphere of the Amuria and Okhotsk Plates is rheologically weak with significant Mesozoic and Cenozoic deformation (Ren et al., 2002; Yin, 2010).

Widespread magmatic and rifting events occurred in Northeast China and surrounding areas during the Cenozoic (Chen et al., 2007; Liu et al., 2001; Ren et al., 2002; Yin, 2010). Rifting in this region culminated in the opening of the Japan Sea and the rifting of the Baikal Lake (Ren et al., 2002; Yin, 2010). The Japan Sea lies at the margin between the Okhotsk and Amuria Plates (Fig. 1a). It opened from the early to middle Miocene (∼23 to ∼15 Ma) (Jolivet et al., 1994; Van Horne et al., 2017). Since the late Miocene (∼13 Ma), a neutral stress regime prevailed in the Japan Sea with both weak extension and compression (Sato, 1994). Since 4 Ma, this region has undergone strong compression and tectonic inversion, with most of the previous normal faults formed during the rifting period re-activated and strongly inverted (Sato, 1994). Today, the Japan arc is advancing toward the Amuria Plate (Jolivet et al., 1994; Van Horne et al., 2017). The Baikal Lake (or the Baikal Rift Zone) lies between the stable Eurasia Plate and the well deformed Amuria Plate (Fig. 1a). The Baikal rifting mainly occurred after the late Oligocene, with accompanying sedimentation and volcanism (Krivonogov and Safonova, 2017). Since the late Miocene, the Baikal Lake rifting rate has increased quickly (Krivonogov and Safonova, 2017), when the Japan sea ceased spreading.

Far-field effects of the Indian–Eurasia collision are often invoked to explain the widespread East Asia lithospheric deformations and marginal sea opening spanning from the South China Sea to the Bering Sea (Jolivet et al., 1994; Tapponnier et al., 1986; Xu et al., 2014). However, the contrary rotation of NE and SW Japan during the Japan Sea opening is not well explained by the

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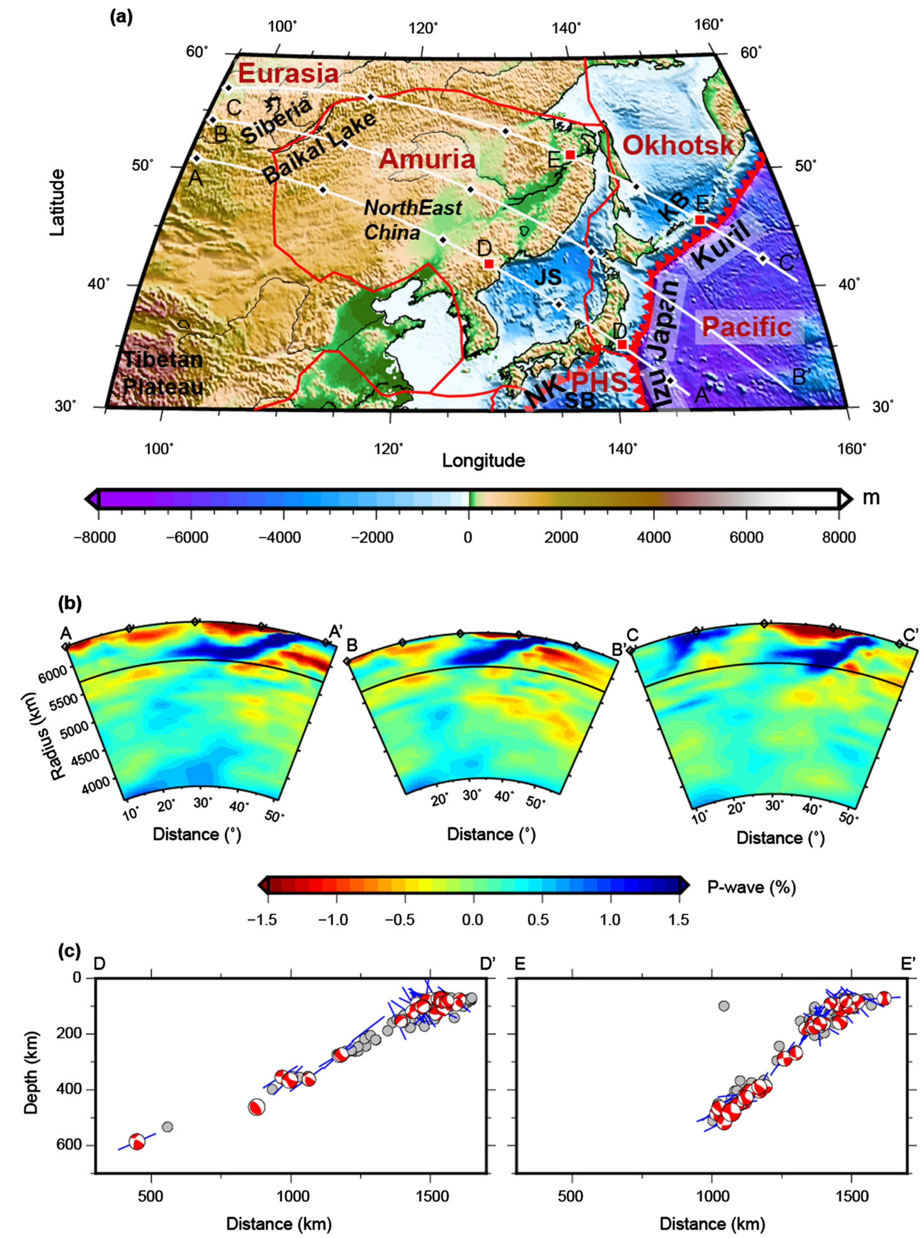

Fig. 1. (a) Topography and major plate boundaries in Northeast China and surrounding areas. Abbreviations: JS: Japan Sea, KB: Kuril Basin, NK: Nankai Trench, PHS: Philippine Sea Plate, SB: Shikoku Basin. Plate boundaries (Bird, 2003) are indicated by red lines. Triangles at the subduction zones point to the overriding plate. (b) Vertical cross-sections of P-wave velocity tomography (Obayashi et al., 2013) along three profiles. The 660 km discontinuity is indicated as a black line. (c) Focal-mechanism and projected P-axis orientations (blue bars, assumed to represent the principal compressional stress direction) of intermediate-depth and deep earthquakes. Focal mechanism solutions show that above 200 km depth, the slab is mainly under along-slab extension while beneath that, the slab is mainly under along-slab compression. Profile locations in (b) and (c) are shown in (a). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

pull-apart model suggested by the India–Eurasia collision (Van Horne et al., 2017). Although the sinistral strike-slip motion between Amuria and Eurasia along Stanovoy is often invoked to support that the Baikal Lake rifting is mainly induced by the India–Eurasia collision (Krivonogov and Safonova, 2017), the sinistral strike-slip motion does not necessarily preclude subduction-induced Baikal Lake extension if the three-dimensional effects with a finite-length trench are considered (Schellart and Lister, 2005). GPS measurements also indicate that the Baikal Rift extension rate (∼0.5 cm/yr) is at least two times larger than the 0–0.2 cm/yr extension rate predicted by the collision models (Calais et al., 1998). Besides, the SKS splitting fast direction across the Baikal Lake is perpendicular to the rift axis (Gao et al., 1994), inconsistent with the pull-apart model suggested by the India–Eurasia collision.

Plate subduction has long been found to play an important role in overriding plate deformations (Clark et al., 2008; Dal Zilio et al., 2017; Lallemand et al., 2005; Yang et al., 2016). Geological and geophysical investigations suggest that the Pacific Plate subduction beneath Eurasia plays an important role in East Asia lithospheric deformation and marginal sea opening, at least locally (Northrup et al., 1995; Schellart and Lister, 2005). Previous studies (Dal Zilio et al., 2017; Faccenna et al., 2010; Schellart and Lister, 2005; Yang et al., 2016) suggest that slab subduction can influence regions more than 3000 km away from the trench, suggestive of the potential influence of the Pacific Plate subduction on the extension of the Baikal Rift Zone that is 3000 km away from the Japan Trench. Seismic observations reveal a >1000 km long stagnant slab in the mantle transition zone beneath Northeast Asia (Fig. 1b) (Chen et al., 2017; Wei et al., 2012; Zhao et al., 2009). The stag-