Origin and time evolution of subduction polarity reversal from plate kinematics of Southeast Asia

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ABSTRACT

We present a regional model of plate geometry and kinematics of southeast Asia since the Late Cretaceous, embedded in a global plate model. The model involves subduction polarity reversals and sheds new light on the origin of the subduction polarity reversal presently observed in Taiwan. We show that this subduction zone reversal is inherited from subduction of the Proto South China Sea plate and owes its current location to triple junction migration and slab rollback. This analysis sheds new light on the plate tectonic context of the Taiwan orogeny and questions the hypothesis that northern Taiwan can be considered as an older, more mature equivalent, of southern Taiwan.

INTRODUCTION

Subduction zones are major drivers of plate motions (e.g. Conrad and Lithgow-Bertelloni, 2002; Stadler et al. 2010) and govern much of Earth's topography; they influence the architecture of mountain belts and location of volcanic arcs (Dewey et al., 1973). Seismic tomography and geologic evidence suggest that subduction zones change polarity as the overriding and subducting plates switch their roles either in time (at a given location) or space, along the strike of a convergent plate boundary (at a given time). Polarity reversals have been recognized in the geological record at a number of locations (Fig. 1) and may have happened in particular in response to collisions of volcanic arcs with ocean-continent subduction zones or with subducting ridges (Brown et al., 2011). It has been proposed that polarity reversals can be related to spontaneous flipping along a transform fault, propagating slab tear and break off, collision of two subduction zones, or propagating slab tear and roll-back (e.g., Brown et al., 2011; Clift et al., 2003). These concepts are mostly derived from reasoning based on 2D lithosphere-scale cross-sections or from present day plate configurations. Here we assess subduction zone reversal in the context of a time-evolving plate tectonic model, taking global plate movements into account, as regional reconstructions tend to push inconsistencies outside the area of interest in regional reconstructions, as noted by Hall (2002).

To understand better how subduction polarity reversals originate and evolve, we investigate the plate tectonic evolution of southeast Asia, focusing on the Taiwan orogeny, where two active subduction zones of opposite vergence meet (Fig. 1B). Subduction polarity is known to have reversed in time there as well: the eastern Eurasian margin was the upper plate to the westward subducting Pacific Plate in the Late Cretaceous, whereas it presently forms the lower plate and subducts eastward beneath the Philippine Sea Plate (e.g., Hall, 2002). The kinematics of this reversal raises the possibility of gaining insights in the mechanisms responsible for polarity reversals, and may provide an alternative hypothesis on structuring of the pre-collisional Eurasian passive margin. This is of particular interest in the light of a polarity reversal potentially occurring in Taiwan at present (Suppe, 1984; Ustaszewski et al., 2012) (Supplementary Material, SM). Here we present a plate tectonic reconstruction of the Taiwan area since the late Cretaceous embedded in a global plate model.

POLARITY REVERSALS IN TIME AND SPACE

We reconstruct the Philippine Sea Plate starting from previous models (Hall, 2002; Seton et al., 2012; Zahirovic et al., 2013), using GPlates (www.gplates.org). This software is based on data from spreading. It allows calculation and real-time visualization of global plate tectonic reconstructions (Boyden et al. 2011). Here we use rigid plate motions, which does introduce errors associated with plate deformation. However, it is an appropriate tool to trace polarity reversals through time. Our model can be seen as a locally refined version of the model of Seton et al. (2012) adjusted to fit geological constraints on the evolution of the Taiwan area (SM). We start our reconstructions at a time when the oceanic crust of the now extinct Izanagi Plate (a conjugate to the Pacific Plate) was subducted westwards beneath Eurasia, i.e., opposite to present day subduction polarity south of Taiwan.

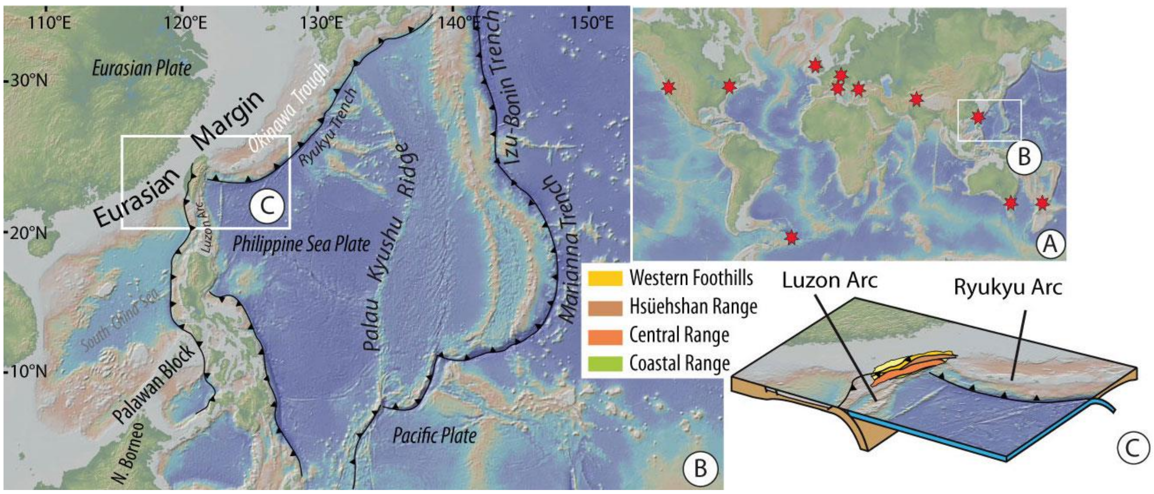


Figure 1. A: Compilation of areas where subduction polarity reversals have been conjectured in ancient orogens. B: Geodynamic map of SE Asia showing Taiwan standing at the junction of two oppositely dipping subduction zones. Taiwan is the result of collision between the Philippine Sea Plate and the Eurasian Plate. C: Structural map of Taiwan and plate configuration. Costal Ranges are the part of the Luzon Arc that has been accreted to Eurasia. Topographic maps from GeoMapApp (Ryan et al., 2009).

Westward subduction beneath Eurasia occurred during the entire Mesozoic, and during Late Mesozoic the Eurasian margin underwent widespread diffuse continental extension, putatively driven by eastward rollback of the Izanagi slab (Zhou and Li, 2000). Widespread tectonic subsidence reached as far east as the East China Sea at 65 Ma (Yang et al., 2004), while also affecting the Taiwan region (Lin et al., 2003).Extension in south and east China resulted in opening of the Proto South China Sea, and subsequent sea floor spreading (Zahirovic et al., 2013). The extend of this oceanic plate is unconstrained, which does however not influence the large-scale plate tectonic framework. During early Cenozoic, southeast Asia extruded eastwards, either due to collision of the Indian Plate and the Eurasian margin (e.g., Tapponnier et al., 1982), extension along the Eurasian margin (Houseman and England, 1993), or a combination of both (Hall, 2002; Morley, 2012). This eastward extrusion modified the kinematics of the eastern Eurasian margin, and coincided with widespread extension (Jolivet et al., 1994). At 48 Ma the Philippine Sea Plate located east of the Borneo subduction zone and south of the Proto South China Sea (Fig. 2A) started to rotate and moved northwards. Due to this northward movement, the young and buoyant Philippine Sea Plate reached the southern edge of the relatively old Proto South China Sea at ~48 Ma (Fig. 2A). The juxtaposition of relatively old crust of the Proto South China Sea against relatively young crust of the Philippine Sea (Fig. 2A) eventually resulted in subduction initiation, possibly at the location of a pre-existing strike-slip fault. The Proto South China Sea started to subduct eastwards (Fig. 2B). Such major tectonic events at regional scale related to changes in plate motions are well known candidates for subduction initiation or reversal (Gurnis et al., 2004).

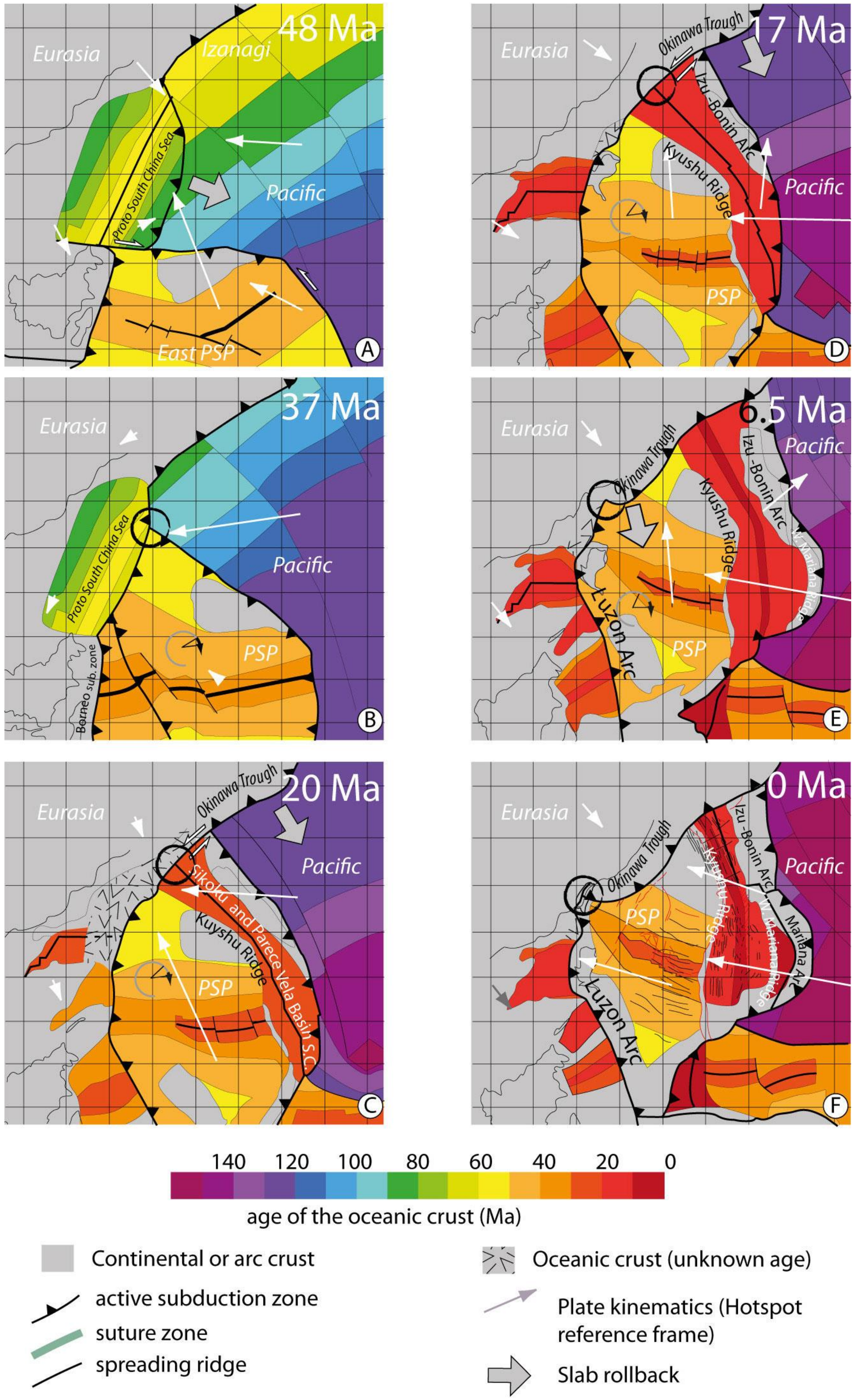
During consumption of the Proto South China Sea, the Philippine Sea Plate rotated clockwise, as suggested by the abandonment of the east-west oriented spreading ridge in favor of a NNE-SSW trending ridge (Deschamps and Lallemand, 2002). From 48 to 37 Ma, the Philippine Sea Plate continued moving northwards along the Eurasian margin propagating the polarity reversal and consuming the Proto South China Sea (Fig. 2A and B). At 37 Ma, the Proto South China Sea had been almost entirely consumed, and the subduction zone became jammed by the middle Miocene (Clift et al., 2008; Hinz et al., 1989). The Mindoro ophiolites and the basement of Sabah, as well as parts of the Lupar Line suture in western Sarawak or the Huatung Basin offshore Taiwan have been suggested to be remnants of this subduction zone (Deschamps et al., 2000; Hall, 2002; Hutchison, 2005; Zahirovic et al., 2013). Eastward consumption of the Proto South China Sea is consistent with previous reconstructions (e.g., Hall, 2002; Zahirovic et al., 2013). In tomographic images, flat lying high amplitude anomalies at a depth of 500 – 600 km under the South China Sea, NW Borneo, and the Luzon Arc have been interpreted as the Proto South China Sea slab (Zahirovic et al., 2013).

After consumption of the Proto South China Sea, the Eurasian margin is subducted in an eastward direction beneath the Philippine Sea Plate. Due to northward movement of the Philippine Sea Plate together with the Australian Plate and accompanying clockwise rotation of the Philippine Sea Plate, the polarity reversal continued moving northwards at the triple junction between Eurasia, Philippine Sea Plate, and Pacific Plate between 37 and 21 Ma (Fig. 2C). This northward movement coincides with extension affecting southeast Asia, and formation of the South China Sea (e.g., Lin et al., 2003; Seton et al., 2012). The South China Sea reached its maximum extent at 30 Ma, followed by a reorganization of plate boundaries in southeast Asia at ~25 Ma, which however mostly affects the plate boundaries north of Australia (Hall, 2002; Seton et al., 2012; Zahirovic et al., 2013).

North of the Philippine Sea Plate the Pacific Plate was subducting northwards below Eurasia. During the late Paleogene to early Miocene the Pacific Plate started rolling back, which may be related to spreading initiation between the Kyushu Ridge and the West Mariana Ridge and opening the Shikoku and Parece Vela Basins between 32 and 31 Ma (Mrozowski and Hayes, 1979), as well as to opening of the Okinawa Trough (Xu et al., 2014), Figure 2C. At 20 Ma, the Philippine Sea Plate continued its northward motion and clockwise rotation at a rate of 1.5°/Ma. The absence of displacement towards the east and spreading east of the Kyushu Ridge disabled propagation of the polarity reversal farther northeast. Due to ongoing rollback of the Pacific Plate and continuous opening of the Shikoku and Parece Vela Basins east of the Kyushu Ridge (Seno and Maruyama, 1984), a left-lateral fault developed at the northwestern tip of the Philippine Sea Plate (Mahony et al., 2011), Figure 2C and D. Spreading east of the Kyushu Ridge ceased at ~17 Ma (Mrozowski and Hayes, 1979), which roughly coincides with formation of the Luzon Arc as an intra-oceanic arc along the western boundary of the Philippine Sea Plate (Sibuet and Hsu, 2004).

During the Miocene, opening of the Okinawa Trough continued and reached its most extensive phase in the Pliocene (Yamaji, 2003), Fig. 2E. Possibly related to this increase in rollback velocities the Pacific trench propagated westwards, and subduction of the Philippine Sea Plate along the former strike-slip fault north of Shikoku Basin initiated (Fig. 2E; Fig. 3). Rollback of the Philippine Sea Plate and contemporaneous north-westward movement of the Luzon Arc resulted in the present day configuration: oblique collision of the Luzon Arc with Eurasia and consequently a mature steady-state orogeny in central Taiwan, and ongoing subduction of oceanic Eurasian crust in southern Taiwan (Malavieille et al., 2002), Fig. 2E and F.

Figure 2. Tectonic reconstructions of southeast Asia. Subduction polarity reversal induced by the motion (northward migration combined with rotation) of the Philippine Sea Plate in three stages. A) 48 Ma: the Philippine Sea Plate is the upper plate of the Borneo subduction zone. At its southern tip it gets juxtaposed against young, buoyant crust of the Philippine Sea Plate. Initially connected by a strike slip zone, subduction initiates in a NW-ward direction B) 37 Ma: the Proto South China Sea is consumed below the Philippine Sea Plate. This motion together with rotation of the plate causes migration of the polarity reversal. At 35 Ma the South China Sea starts spreading. C) 20 Ma: Rotation of the Philippine Sea Plate has stopped, and polarity reversal is not moving northwards anymore. Spreading between the Kyushu Ridge and the West Mariana Ridge is accommodated along a strike slip fault. D) 17 Ma: Subduction initiates along the strike slip zone, and the Okinawa Trough extends westwards; E) 6.5 Ma: Collision starts in Central Taiwan, the Pacific Plate rolls back rapidly; F) At present day, the rollback of the subduction has reached the Eurasian margin, and interacts with mountain building in Taiwan.


48 Ma
Eurasia
Izanagi
Proto South China Sea
Pacific
East PSP
A
37 Ma
Eurasia
Proto South China Sea
Pacific
PSP
Borneo sub. zone
B
20 Ma
Okinawa Trough
Eurasia
Pacific
Sikoku and Parece Vela Basin S.C.
Kuyshu Ridge
PSP
C
17 Ma
Okinawa Trough
Eurasia
Izu -Bonin Arc
Kyushu Ridge
Pacific
PSP
D
6.5 Ma
Eurasia
Okinawa Trough
Pacific
Izu -Bonin Arc
Kyushu Ridge
Luzon Arc
PSP
E
0 Ma
Eurasia
Okinawa Trough
Izu -Bonin Arc
Pacific
PSP
Mariana Arc
Luzon Arc
F
140 120 100 80 60 40 20 0
age of the oceanic crust (Ma)
Continental or arc crust
Oceanic crust (unknown age)
active subduction zone
suture zone
spreading ridge
Plate kinematics (Hotspot reference frame)
Slab rollback

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Previous plate tectonic reconstructions of the area differ from our model (see SM for compilation of models), due to uncertainties mentioned above, as well as lack of data in some areas. Opportunities for testing the model will be afforded through detailed imaging the Proto South China Sea slab at depth, as well as comprehensive mapping and dating of its proposed remnants.

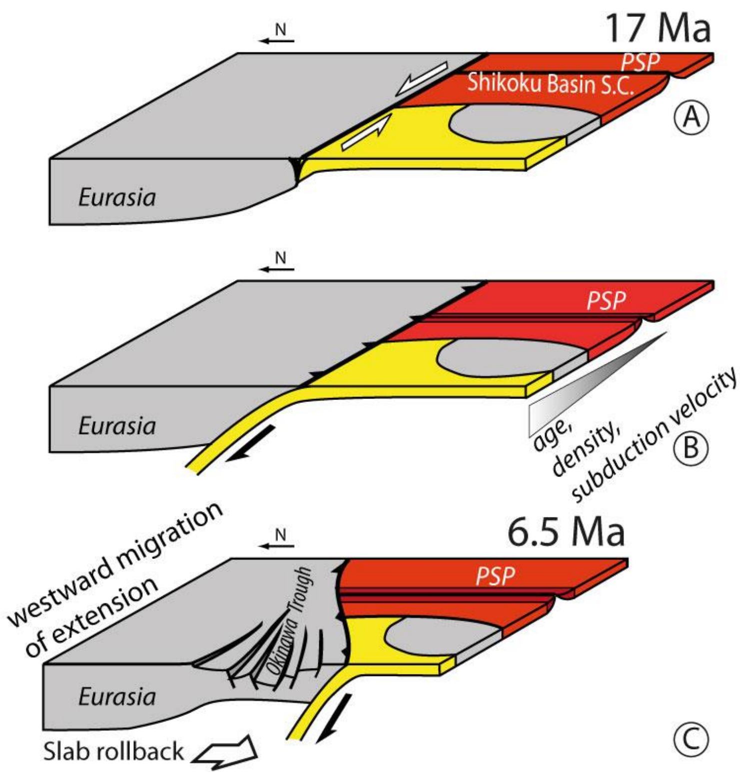

Figure 3. 3D Sketches showing the subduction initiation at the northern Philippine Sea Plate along a strike slip zone and its evolution due to slab rollback. (A) Initial situation at 17 Ma. S.C. denotes spreading center. (B) The Philippine Sea Plate starts to subduct below the Eurasian margin, where oceanic crust is opposed to continental Eurasian curst. (C) The Okinawa trough extends westwards due to rapid rollback of the Philippine Sea Plate.

REGIONAL AND GLOBAL IMPLICATIONS

Our reconstruction has major implications for southeast Asian geodynamics and Taiwan in particular. The reconstructions show that formation and consumption of the Proto South China Sea played a key role for southeast Asian geodynamics until the present day. First, this event of sea floor spreading modified the buoyancy of the passive margin. During this spreading, the Pacific Plate rolled back and subducted below the Proto South China Sea. Due to northward movement of the Philippine Sea Plate, young, buoyant oceanic crust was juxtaposed against older oceanic crust of the Proto South China Sea. This resulted in eastward subduction of the Proto South China Sea. This reversed subduction polarity was able to propagate northwards along the Eurasian margin until it reached the Taiwan area, where further propagation was inhibited. At a later stage, the Ryukyu trench along which the Philippine Sea Plate is subducted northwards below the Eurasian margin rolled back and reaches the Taiwan area. This interplay between the two diachronous but related movements resulted in the present day plate configuration of Taiwan.

This implies that northern Taiwan might not be an older equivalent of central and southern Taiwan, as commonly assumed (e.g. Malavieille et al., 2002; Suppe, 1984), but questioned by new thermochronological data (Lee et al., 2015). Only in central and southern Taiwan is the orogeny propagating southward due to the oblique collision of the Luzon Arc with Eurasia (e.g. Simoes and Avouac, 2006) as Suppe (1984) initially conjectured. The difference between northern and southern Taiwan results from the late interaction of the Ryukyu subduction zone with the pre-structured passive Eurasian margin rather than from a decreasing degree of maturity from north to south. The Ryukyu subduction zone does not play a major role during the orogeny (Clift et al., 2003).In contrast, it is the Mesozoic polarity reversal which controls recent mountain building in Taiwan.

At a larger scale, this study emphasizes the importance of global reconstructions for understanding subduction polarity reversal and their influence on present day mountain belts. Polarity reversal, triggered by plate reorganization and buoyancy contrasts (Gurnis et al., 2004) may migrate over large distances. 2D models such as spontaneous slab break off, or models only based on the present day plate configuration need to be tested against models of plate kinematic evolution through time, and against reconstructions that include lithosphere consumed previously. Our results may be applied to areas where similar detail is not possible because of later tectonic events, for instance in the European Alps or Caledonian orogenic belts of northern Europe and the Eastern U.S.

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REFERENCES CITED

Boyden, J. A., R. D. Müller, M. Gurnis, T. H. Torsvik, J. A. Clark, M. Turner, H. Ivey-Law, R. J. Watson, and J. S. Cannon, 2011, Next-generation plate-tectonic reconstructions using GPlates, in G. R. Keller and C. Baru, eds., Geoinformatics: Cyberinfrastructure for the Solid Earth Sciences, Cambridge University Press, 95-113

Brown, D., Ryan, P.D., Afonso, J.C., Boutelier, D., Burg, J.P., Byrne, T., Calvert, A., Cook, F., DeBari, S., Dewey, J.F., Gerya, T.V., Harris, R., Herrington, R., Konstantinovskaya, E., Reston, T., and Zagorevski, A., 2011, Arc–Continent Collision: The Making of an Orogen, *in* Brown, D., and Ryan, P., eds., Arc-Continent Collision: Springer Berlin Heidelberg, p. 477–493, doi:10.1007/978-3-540-88558-0_17.

Clift, P., Lee, G.H., Anh Duc, N., Barckhausen, U., Van Long, H., and Zhen, S., 2008, Seismic reflection evidence for a Dangerous Grounds miniplate: No extrusion origin for the South China Sea: Tectonics, v. 27, p. TC3008, doi:10.1029/2007TC002216.

Clift, P.D., Schouten, H., and Draut, A.E., 2003, A general model of arc-continent collision and subduction polarity reversal from Taiwan and the Irish Caledonides: Geological Society of London, Special Publications, v. 219, p. 81–98, doi:10.1144/GSL.SP.2003.219.01.04.

Conrad, C.P., and Lithgow-Bertelloni, C., 2002, How mantle slabs drive plate tectonics: Science, v. 298, p. 207–209, doi:10.1126/science.1074161.

Deschamps, A., and Lallemand, S., 2002, The West Philippine Basin: An Eocene to early Oligocene back arc basin opened between two opposed subduction zones: Journal of Geophysical Research: Solid Earth (1978–2012), v. 107, p. EPM 1–1-EPM 1–24.

Deschamps, A., Monié, P., Lallemand, S., Hsu, S.K., and Yeh, K.Y., 2000, Evidence for Early Cretaceous oceanic crust trapped in the Philippine Sea Plate: Earth and Planetary Science Letters, v. 179, p. 503–516, doi:10.1016/S0012-821X(00)00136-9.

Dewey, J.F., Pitman, W.C., Ryan, W.B.F., and Bonnin, J., 1973, Plate Tectonics and the Evolution of the Alpine System: Geological Society of America Bulletin, v. 84, p. 3137–3180, doi:10.1130/0016-7606(1973)84<3137:PTATEO>2.0.CO;2.

Gurnis, M., Hall, C., and Lavier, L., 2004, Evolving force balance during incipient subduction: Geochemistry Geophysics Geosystems, v. 5, p. Q07001, doi:10.1029/2003GC000681.

Hall, R., 2002, Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: Computer-based reconstructions, model and animations: Journal of Asian Earth Sciences, v. 20, p. 353–431, doi:10.1016/S1367-9120(01)00069-4.

Hinz, K., Fritsch, J., Kempter, E., Mohammad, M.A.M., Meyer, J., Mohamed, M.D., Vosberg, D.G.H., Weber, D.I.J., and Benavidez, M.J., 1989, Thrust tectonics along the north-western continental margin of Sabah/Borneo: Geologische Rundschau, v. 78, p. 705–730, doi:10.1007/BF01829317.

Houseman, G., and England, P., 1993, Crustal thickening versus lateral expulsion in the Indian-Asian continental collision: Journal of Geophysical Research. Solid Earth, v. 98, p. 12233–12249, doi:10.1029/93JB00443.

Hutchison, C.S., 2005, Geology of North-West Borneo: Elsevier, Sarawak, Brunei and Sabah.

Jolivet, L., Tamaki, K., and Fournier, M., 1994, Japan Sea, opening history and mechanism: A synthesis: Journal of Geophysical Research: Solid Earth (1978–2012), v. 99, p. 22237–22259.

Lee, Y.-H., Byrne, T., Wang, W.-H., Lo, W., Rau, R.-J., and Lu, H.-Y., 2015, Simultaneous mountain building in the Taiwan orogenic belt: Geology, v. 43, p. 451–454, doi:10.1130/G36373.1.

Lin, A.T., Watts, A.B., and Hesselbo, S.P., 2003, Cenozoic stratigraphy and subsidence history of the South China Sea margin in the Taiwan region: Basin Research, v. 15, p. 453–478, doi:10.1046/j.1365-2117.2003.00215.x.

Mahony, S., Wallace, L., Miyoshi, M., Villamor, P., Sparks, R., and Hasenaka, T., 2011, Volcano-tectonic interactions during rapid plate-boundary evolution in the Kyushu region, SW Japan: Geological Society of America Bulletin, v. 123, p. 2201–2223, doi:10.1130/B30408.1.

Malavieille, J., Lallemand, S.E., Dominguez, S., and Deschamps, A., 2002, Arc-Continent collision in Taiwan: New marine observations and tectonic evolution: Geological Society of America. Special Paper, v. 358, p. 189–213.

Morley, C.K., 2012, Late Cretaceous–Early Palaeogene tectonic development of SE Asia: Earth-Science Reviews, v. 115, p. 37–75, doi:10.1016/j.earscirev.2012.08.002.

Mrozowski, C.L., and Hayes, D.E., 1979, The evolution of the Parece Vela Basin, eastern Philippine Sea: Earth and Planetary Science Letters, v. 46, p. 49–67, doi:10.1016/0012-821X(79)90065-7.

Ryan, W.B., Carbotte, S.M., Coplan, J.O., O’Hara, S., Melkonian, A., Arko, R., Weissel, R.A., Ferrini, V., Goodwillie, A., and Nitsche, F., 2009, Global multi-resolution topography synthesis: Geochemistry Geophysics Geosystems, v. 10, p. Q03014.

Seno, T., and Maruyama, S., 1984, Paleogeographic reconstruction and origin of the Philippine Sea: Tectonophysics, v. 102, p. 53–84, doi:10.1016/0040-1951(84)90008-8.

Seton, M., Müller, R.D., Zahirovic, S., Gaina, C., Torsvik, T., Shephard, G., Talsma, A., Gurnis, M., Turner, M., Maus, S., and Chandler, M., 2012, Global continental and ocean basin reconstructions since 200 Ma: Earth-Science Reviews, v. 113, p. 212–270, doi:10.1016/j.earscirev.2012.03.002.

Sibuet, J.-C., and Hsu, S.-K., 2004, How was Taiwan created?: Tectonophysics, v. 379, p. 159–181, doi:10.1016/j.tecto.2003.10.022.

Simoes, M., and Avouac, J. P., 2006, Investigating the kinematics of mountain building in Taiwan from the spatiotemporal evolution of the foreland basin and western foothills: Journal of Geophysical Research, v. 111, no. B10, p. B10401

Stadler, G., M. Gurnis, C. Burstedde, L. C. Wilcox, L. Alisic, and O. Ghattas, 2010, The dynamics of plate tectonics and mantle flow: From local to global scales, Science, v. 329, p. 1033-1038, doi: 10.1126/science.1191223, 2010.

Suppe, J., 1984, Kinematics of arc-continent collision, flipping of subduction, and back-arc spreading near Taiwan: Memoir of the Geological Society of China, v. 6, p. 21–33.

Tapponnier, P., Peltzer, G., Le Dain, A.Y., Armijo, R., and Cobbold, P., 1982, Propagating extrusion tectonics in Asia: New insights from simple experiments with plasticine: Geology, v. 10, p. 611–616, doi:10.1130/0091-7613(1982)10<611:PETIAN>2.0.CO;2.

Ustaszewski, K., Wu, Y.-M., Suppe, J., Huang, H.-H., Chang, C.-H., and Carena, S., 2012, Crust–mantle boundaries in the Taiwan–Luzon arc-continent collision system determined from local earthquake tomography and 1D models: Implications for the mode of subduction polarity reversal: Tectonophysics, v. 578, p. 31–49, doi:10.1016/j.tecto.2011.12.029.

Xu, J., Ben-Avraham, Z., Kelty, T., and Yu, H.-S., 2014, Origin of marginal basins of the NW Pacific and their plate tectonic reconstructions: Earth-Science Reviews, v. 130, p. 154–196, doi:10.1016/j.earscirev.2013.10.002.

Yamaji, A., 2003, Slab rollback suggested by latest Miocene to Pliocene forearc stress and migration of volcanic front in southern Kyushu, northern Ryukyu Arc: Tectonophysics, v. 364, p. 9–24, doi:10.1016/S0040-1951(03)00047-7.

Yang, S., Hu, S., Cai, D., Feng, X., Chen, L., and Gao, L., 2004, Present-day heat flow, thermal history and tectonic subsidence of the East China Sea Basin: Marine and Petroleum Geology, v. 21, p. 1095–1105, doi:10.1016/j.marpetgeo.2004.05.007.

Zahirovic, S., Seton, M., and Mueller, R.D., 2013, The Cretaceous and Cenozoic tectonic evolution of Southeast Asia: Solid Earth Discussions, v. 5, p. 1335–1422, doi:10.5194/sed-5-1335-2013.

Zhou, X.M., and Li, W.X., 2000, Origin of Late Mesozoic igneous rocks in Southeastern China: implications for lithosphere subduction and underplating of mafic magmas: Tectonophysics, v. 326, p. 269–287, doi:10.1016/S0040-1951(00)00120-7.