

Geodynamic Context of the Taiwan Orogen

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Four independent arguments suggest that the Ryukyu subduction zone extended from Japan to southwest Taiwan (118°E) from the late Cretaceous to early Miocene (17–18 Ma): i) An analysis of the structure and timing of rifting in the basins of the East Asia continental shelf and west of Taiwan shows that they are located within four belts parallel to the mainland Chinese shoreline, which becomes younger oceanward since early Tertiary. Ridges with volcanic products are present between these belts. We interpret these basins and associated ridges as relict backarc basins and arcs of the Ryukyu subduction system. ii) Subsidence curves across west Taiwan Basins show that rifting ceased 17–18 Ma. iii) A new shear wave velocity model suggests that the Ryukyu slab extended in the past southwest of Taiwan, beneath the northern China Sea margin. iv) A deep seismic line shot across the northeastern South China Sea margin also suggests that this margin was active in the past. We conclude that about 15–20 Ma, the southwestern extremity of the Ryukyu subduction zone jumped from 118°E (southwest of the Tainan Basin) to 126°E (where the present-day trend of the Ryukyu subduction zone changes direction). Since that time, the southwestern extremity of the Ryukyu subduction zone continuously moved westwards to its present-day location at 122°E. Since the beginning of formation of proto-Taiwan during late Miocene (9 Ma), the subducting PH Sea plate moved continuously through time in a N307° direction at 5.6 cm/yr with respect to EU, tearing the EU plate.

1. INTRODUCTION

The collision of the Luzon volcanic arc with the South China Sea (SCS) margin is probably one of the best examples of modern arc-continent collision associated with the Taiwan uplift. The geology of the island as well as the mechanisms of deformation are quite well understood but in gen-

Continental–Ocean Interactions Within East Asian Marginal Seas
Geophysical Monograph Series 149

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10.1029/149GM08

eral, most of the geodynamic context in which this uplift occurs is largely unknown or at least oversimplified. For example, the continental margin before collision is widely considered as a typical passive margin and shelf basins are considered to be tensional basins formed during the rifting of the adjacent continental margin. In this paper, we define the geological and kinematic contexts of the formation of Taiwan not only during the collision of the Luzon arc with the Eurasian plate, which results in the formation of the proto- and present-day Taiwan, but also before the Taiwan uplift. This work is partly based on a series of papers published during recent years [Hsu

and Sibuet, 1995; Sibuet *et al.*, 1998; Sibuet and Hsu, 1997; Sibuet and Hsu, 2004; Sibuet *et al.*, 2002; Sibuet *et al.*, 1995]. We demonstrate that the Tertiary shelf basins, located between Japan and southwest Taiwan, were formed as backarc basins linked to the Ryukyu subduction zone. Backarc basins older than 15–20 Ma are linked to the subduction of the Philippine and Taiwan Seas, which are bounded to the south by the Luzon-Ryukyu transform plate boundary (LRTPB) now located in the northeastern part of the SCS. South of the LRTPB, the SCS was opening between 37 and 15 Ma. The Pearl River shelf basins were formed by extension during the rifting of the SCS continental margins [Clift and Lin, 2001]. A major issue in understanding the tectonics of Taiwan is the local plate kinematic configuration, which is partly hidden by extensive deformation. We here establish that the kinematic pattern controls the formation of proto- and present-day Taiwan, in particular where and how the newly formed Luzon Arc started to collide with the Eurasian margin. We also demonstrate that the upper portion of the Luzon Arc is accreted along the Eurasian margin while the lower crust is subducted with the Philippine (PH) Sea plate beneath Eurasia (EU). We define the location of the western boundary of the PH Sea plate (Point A) that bounds the western termination of the Ryukyu Benioff zone and triggers the occurrence and development of a tear fault within the EU plate. To the south, the PH Sea plate boundary extends along the Longitudinal Valley of Taiwan and then runs east of the Manila accretionary prism. The PH Sea plate has been moving westward through time with respect to the EU plate in the northwestern direction (*e.g.* Seno and Maruyama [1984]). We attempt to explain the process of Taiwan uplift within a simple plate tectonic context, which includes a comprehensive history of the westward migration of the collision. For that purpose, we clarify a series of points concerning the geometry of plate boundaries, as well as the nature of the deformation and the associated stress patterns.

2. PRE-COLLISIONAL GEOLOGY: RYUKYU SUBDUCTION ZONE AND ASSOCIATED BACKARC BASINS

The Tertiary basins of the Chinese continental shelf around Taiwan are roughly oriented NE-SW [Letouzey *et al.*, 1988], *i.e.* parallel to the East China shoreline and margin (Plate 1). The tectonic history of these basins shows that rifting generally occurred between early Paleocene and middle Miocene (65–15 Ma), except for the active Okinawa Trough (OT), which is mostly in the rifting stage [Sibuet *et al.*, 1987]. From the geological evolution of a continental shelf basin, it is impossible to decipher if its tensional environment is related to the rifting of the nearby continental margin or if it is a backarc basin linked to the presence of a subduction zone. This is true for the con-

tinental shelf basins of the East and South China Seas, which are traditionally considered as having formed during the rifting of the adjacent continental margins. For example, Teng and Lin [2004, *in press*] consider that the Ryukyu subduction zone, which extended at least from Japan to Indochina, ceased in late Cretaceous and resumed during early Miocene in order to explain the formation of the OT backarc basin. In this scenario the Ryukyu subduction zone was not active during most of the Tertiary, which is in opposition with all published kinematic works. For example, Teng and Lin [2004, *in press*] also suggest that the Paleogene rifting of all the other continental shelf basins of the East and South China Seas continental shelf occurred during the simultaneous Paleogene extensive crustal attenuation of the adjacent continental margin (rifting episode for us). However, such a hypothesis does not take into account any of the recent data acquired in the deep ocean. Here we describe these shelf basins, distinguish their rifting from post-rifting periods and identify what basins are backarc basins or rifted shelf basins on the basis of the geodynamic context established from the interpretation of marine data.

2.1. Taiwan and Surrounding Basins

2.1.1. Pearl River Basins. The Pearl River Basins are a continuous succession of connected basins (Zhujiangkou Basins), which extend from the island of Hainan to west of the Tainan Basin (west of the LRTPB, Plate 1a). Well data indicate that basement rocks comprise Paleozoic metasedimentary rocks and Jurassic and upper Cretaceous formations consisting mainly of non-marine sequences, granitic intrusions and volcanic rocks [Sun, 1981; Sun, 1985]. The basins are mostly Paleogene NE-SW trending half-grabens or grabens bounded by normal faults with some tilted fault blocks. Sediments are composed of non-marine sediments, mostly shallow lake mudstones overlain by synrift Eocene deep lake mudstones with some fluvial sandstones interbedded with shales [Ru, 1988]. Deposition of these sediments is controlled by the throw of normal faults, mostly striking NE-SW [Ru and Pigott, 1986]. A regional late Eocene-early Oligocene unconformity separates synrift from flat and undeformed postrift sediments, which display the late Oligocene-early Miocene thin layers of limestone indicative of the first marine transgressions [Zhao, 1988]. Continuous marine deposition was interrupted in the middle Miocene by a significant tensional event characterized by E-W trending normal faults, a major unconformity and widespread basaltic extrusions [Yu, 1994]. The principal rifting event seems to have occurred mostly during Eocene and early Oligocene (Plate 1b) perhaps during the rifting of the northeastern SCS margin, before the onset of seafloor spreading (*e.g.* [Briais *et al.*, 1993; Hayes *et al.*, 1995]) (Plate 1a).

2.1.2. West Taiwan Basins. The Tainan Basin is located at the northeastern end of the SCS continental margin and extends onshore into southwestern Taiwan (Plate 1a). Numerous seismic and well data obtained by the Chinese Petroleum Company show that, although the basin is ENE-WSW trending, roughly parallel to the continental slope, the main boundary of the northern side of the basin is composed of EW segments which either lie together in an en-échelon pattern or are connected by orthogonal transfer faults with strike-slip motion [Lee *et al.*, 1993; Tzeng *et al.*, 1996; Yang *et al.*, 1991]. These transfer faults do not seem to be related to pre-existing features. In the basin itself, normal faults are also discontinuous and EW-oriented, though the direction of opening of the basin is NNW-SSE [Yang *et al.*, 1991]. This structural pattern is similar to the one of the OT backarc basin where en-échelon normal faults do not trend in the direction of the trough itself [Sibuet *et al.*, 1995]. The reconstruction of the different evolutionary stages and seismic sequences developed in the Tainan Basin show that, although the basin was relatively symmetrical during its formation, the bounding horst limiting the basin to the south and whose southern flank corresponds to the continental slope, has continuously subsided since the early Pliocene [Lee *et al.*, 1993]. This explains the present-day asymmetrical shape of the basin and the relative depth of the horst (3 km, Figure 3), which limits the Tainan Basin on the shelf edge side. Rifting occurred from early Oligocene to early middle Miocene (Plate 1b). Fault-controlled subsidence is the dominant tectonic mechanism for the deposition of sedimentary sequences [Lee *et al.*, 1993]. The rifting phase was followed by a thermal subsidence phase followed by a rapid flexural subsidence phase linked to the uplift of Taiwan since the Pliocene (6.5 Ma) [Lin *et al.*, 2003].

The Taishi Basin located northwest of Taiwan (Plate 1a) seems to differ from the NE-SW trend of most of the other basins. A series of horsts and grabens are trending N080° [Huang *et al.*, 1993]. Two rifting phases seem to occur in the Taishi Basin (Figure 1). The first one started during late Paleocene (58 Ma) and seems to terminate during middle Eocene (37 Ma). The second one started in early Oligocene (30 Ma) and seems to terminate during late early Miocene (17–18 Ma) (Plate 1b and Figure 1). Since this period, several compressional or transpressional regimes have caused the tectonic inversion of the basin.

The Nanjihtao Basin is separated from the Taishi Basin by the Nanjihtao Ridge (Plate 1a), which is a NE-SW trending half-graben limited in the southeast by a major boundary fault with more than 3-km normal displacement. Stratigraphic correlations indicate that rifting occurred between the early Paleocene and late Eocene (Plate 1b), after which time a major unconformity characterized by erosional truncation represents the late Eocene to late Oligocene [Chow *et al.*, 1991].

The Penghu Basin, located between the Nanjihtao and Pearl River Basins (Plate 1a), is also NE-SW trending, with bounding faults approximately oriented in the same direction [Letouzey *et al.*, 1988]. Though poorly described in the published literature, the main rifting period in the Penghu Basin seems to have occurred from Paleocene to middle Eocene times and possibly during late Eocene [Hsiao *et al.*, 1991] (Plate 1b).

2.1.3. North and northeast Taiwan Basins. The Tugyintao and Tahchentao Basins, located close to Mainland China, are half-grabens (Plate 1a). From seismic and well data, the basement is known to be late Cretaceous, with rifting mostly dated as Paleocene (3.5 km of synrift sediments) (Plate 1b), after which subsidence slowed considerably during the Eocene and early Oligocene [Huang *et al.*, 1992].

The north and south Pengchiahsu Basins, located southeast of the basins already mentioned, are characterized by NE-SW trending normal faults (Plate 1a). Prerift sequences are Paleocene or slightly older, and the synrift sequences are Eocene or slightly younger [Huang *et al.*, 1992] (Plate 1b). The Eocene synrift sequence is more than 3-km thick, with a lower section showing chaotic reflections suggestive of deposition in a semi-enclosed environment overlain by an upper section deposited in a more marine environment [Huang *et al.*, 1992].

The NE-SW trending Taipei Basin is located between the Pengchiahsu Basins and the Taiwan-Sinzi Ridge (Plate 1a). The prerift sequences are dated as Eocene, and the synrift sequences as Oligocene [Huang *et al.*, 1992] (Plate 1b), although middle Miocene and late Miocene to Pliocene/Pleistocene tensional phases, post-dating the main rifting phase, are also observed [Huang *et al.*, 1992]. The Oligocene synrift sequence is more than 4-km thick and composed of a prograding lower Oligocene deltaic sequence overlain by strongly stratified sandstone and shale alternations, and an extensive late Oligocene deep marine mudstone sequence [Huang *et al.*, 1992].

The OT backarc basin extends from Taiwan to Kyushu Island and is separated from the Taipei Basin by the Taiwan-Sinzi Ridge (Plate 1a). Rifting of the OT started during late middle Miocene times [Letouzey and Kimura, 1986; Sun, 1981] and is still active today [Sibuet *et al.*, 1987] (Plate 1b). However, the beginning of extension could be much more recent (6 Ma) as suggested by Kimura [1996]. Three main phases of opening have been identified, and poles and angles of rotation have been determined [Sibuet *et al.*, 1998; Sibuet *et al.*, 1995]. The first phase of rifting is the most important one with 50 to 75 km of extension from the southern to the northern OT [Sibuet *et al.*, 1995]. This extension started in the middle Miocene (12 Ma) or late Miocene (6 Ma). The two most recent phases of rifting are dated as late Pliocene-Pleistocene and late Pleistocene to Recent, with only a total of a few tens of kilometers of extension [Sibuet *et al.*, 1998].