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Is Taiwan the result of arc–continent or arc–arc collision?

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Abstract

Conventionally, it has been accepted that the formation of Taiwan results from the collision of the Luzon arc with the Eurasian continental margin. We suggest that Taiwan results from the collision of the Luzon arc with the former Ryukyu subduction zone. Before the collision, the latter extended a few hundred kilometres southwest of its present-day termination. In the early to middle Miocene, the subduction became inactive in its southwest portion and the Manila trench migrated northeastward, giving rise to the formation of the Luzon arc. The collision started in the late Miocene by closing the oceanic domain located between the Luzon arc and the former Ryukyu arc. Because the Luzon arc moved northwestward with respect to the former NE–SW trending Ryukyu arc, the oblique collision first resulted in the indentation on the south Ryukyu arc, west of 123.5°E, and the narrowing of the corresponding portion of the Okinawa trough prior to the uplift of Taiwan. Today, the Hsüehshan and Backbone Ranges represent the uplifted portion of the backarc basin and the Longitudinal valley corresponds to the suture zone between the former Ryukyu and the Luzon arcs.

In this model, we propose to link, although they are not of the same age, two truncated backarc basins: the active Okinawa trough to the northeast and the former active Tainan backarc basin to the southwest. The former backarc basin extended from southwest of Taiwan to southern Japan and could have been initiated near the paleo-location of Taiwan as early as the Eocene–Oligocene. The result of the collision is the truncation of the ancient backarc basin associated with the shortening, deformation and uplift of the ancient outer arc and related backarc region, which provides the fundamental mechanism of the Taiwan mountain building. This model is in agreement with a counterclockwise rotation of the portion of Taiwan located west of the Coastal Range (belonging to the Luzon arc) and a clockwise rotation of the south Ryukyu arc. Earthquake focal mechanisms, geodetic observations and the distribution of the petrologic and structural features are also consistent with the proposed arc–arc collision model.

1. Introduction

Taiwan is located near the junction of the East China, the South China and the Philippine seas (Fig. 1a). The Taiwan mountain belt is usually believed to be the result of the collision between the Luzon volcanic arc and the Eurasian continental margin (arc–continent collision model) (e.g. [1–6]). For most of the authors, the initial opening of the Okinawa trough is linked to this collision and due to some lateral extrusion or block rotation at the western end of the Ryukyu arc (e.g. [4–8]). Nevertheless, an overview of the satellite-derived marine gravity anomalies [9] shows that the Okinawa trough is

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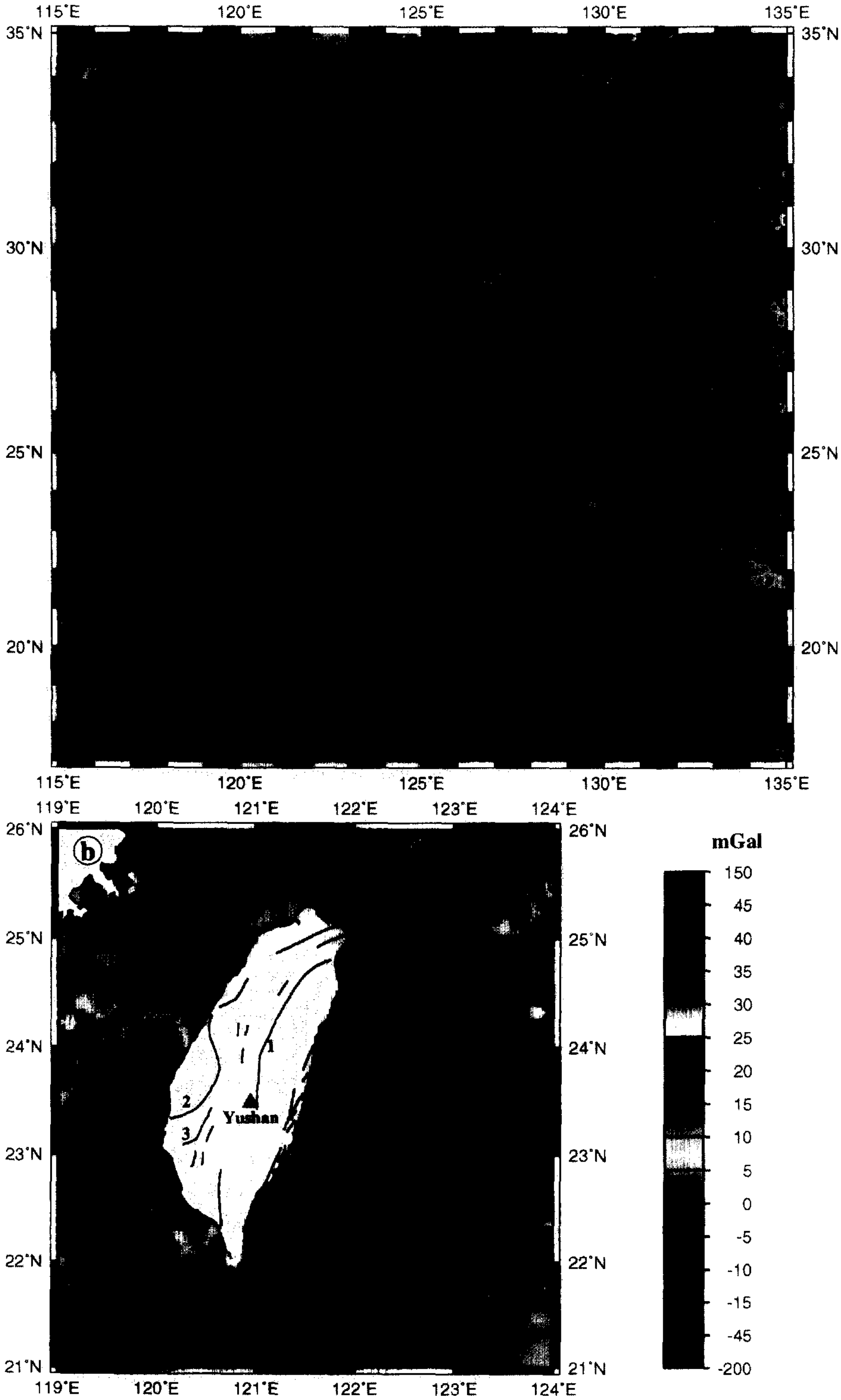
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probably linked to the Tainan basin, on the basis of the similar amplitudes and general features of gravity anomalies (Fig. 1a). If this hypothesis is correct, a corresponding subduction zone should have existed before the uplift of Taiwan. The main consequence of this assumption is that Taiwan results from the collision of the Luzon arc with the former Ryukyu subduction zone, extending at that time at least a few hundred kilometres southwest of its present-day termination. In that case, instead of an arc-continent collision, the origin of Taiwan should be better described as a result of an arc-arc collision. In this paper, we will present geophysical and geological considerations which support this hypothesis.

2. Configuration of the former subduction zone (backarc basin, arc and trench)

The Chinese continental margin generally displays extensional features with predominant NE-SW trending basins [10,11]. However, only the Tainan basin and the Okinawa trough exhibit similar positive gravity signatures with relative lows along their elongated axes (Fig. 1a). Except for the striking northward shortening and the clockwise rotation of the southwestern portion of the Ryukyu subduction zone, located between northeastern Taiwan and 123.5°E [12,13], the curvature of the Ryukyu subduction zone could be extended to the area surrounding the Tainan basin (Fig. 1a). The two roughly parallel NE-SW trending borders of the Tainan basin (black dashed lines in Fig. 1b) could be connected with the Yichu and Hsinhua-Chuko active faults located in southwestern Taiwan (2 and 3, Fig. 1b). These two faults bound an onshore sedimentary basin located in the prolongation of the Tainan basin which disappears toward the northeast. The axis of this basin can be identified on the pre-Miocene basement relief map established from drilling data but disappears just south of Fault D (Fig. 2) [14]. The ancient arc associated with the ancient backarc basin in southwest Taiwan is poorly expressed; however, its position is revealed on the Bouguer anomaly map [15], which shows a NE-SW oriented local maximum in the northeastern prolongation of the suggested outer arc of the Tainan basin (red area located south of the black dashed lines in Fig. 1b).

In its southwestern portion, the Okinawa trough becomes narrow and disappears in the Ilan plain, considered to be the westward termination of the present-day active backarc basin. The Lishan fault lies in the direct continuation of the backarc basin, as shown by the presence of a deep valley located in the prolongation of the Ilan plain (Fig. 3). The Lishan fault, generally dipping southeastward for most of the authors (e.g. [2]), separates similar argillite-slate facies of the Hsüehshan and Backbone Ranges (Fig. 2) [2]. These argillaceous sediments were deposited in an outer neritic to upper bathyal environment. We assume that they represent uplifted and metamorphosed sediments deposited in a former backarc basin. In this interpretation, the Lishan fault is the trace of a major normal fault of the backarc basin, re-mobilised as a crustal thrust fault during later compression, and the Hsüehshan and Backbone Ranges are the two margins of the former backarc basin.

Considered as the suture zone of the ancient backarc basin, the Lishan fault can be traced from the Ilan plain to the Yushan mountain (Figs. 1b and 2) [2,16-20]. However, its connection with the onshore Tainan basin shows a right-lateral offset of over 40 km (Fig. 2). This offset is underlined in the Bouguer anomaly map [15] and by geodetic observations [21], which show that the region located on the northern side of the Yushan mountain is stable; whereas, on the southern side, the horizontal velocity

Fig. 1. (a) Satellite-derived marine gravity anomaly around Taiwan [9]. Note that, except for the bent region west of 123.5°E, the general curvature of the Ryukyu subduction zone (including the Ryukyu arc, the Okinawa trough and the Taiwan-Sinzi folded belt) can be extended to the Tainan basin and its continental margin. The two white arrows indicate a probable fossil transform fault. The white dashed line indicates a segment of the former Ryukyu trench. (b) Close-up of the region surrounding Taiwan. Active faults in Taiwan are plotted as red lines [18]. *GR* = Gagua ridge; *KS* = Kyushu Island (south Japan); *LVA* = Luzon volcanic arc; *LZ* = Luzon; *MT* = Manila trench; *NB* = Nanao basin; *OT* = Okinawa trough; *PGI* = Penghu islands; *RI* = Ryukyu islands; *RT* = Ryukyu trench; *TB* = Tainan basin; *TSF* = Taiwan-Sinzi folded belt; *TW* = Taiwan; *1* = Lishan fault; *2* = Yichu fault; *3* = Hsinhua-Chuko fault. Yushan is the highest mountain in Taiwan (about 4 km). The white dashed line indicates a segment of the former Ryukyu trench.

field of the crust increases southward and eastward with respect to Eurasia. In other words, the present-day convergence linked to the collision of the Luzon arc is absorbed in southern Taiwan by thrusts and strike-slip faults; whereas, in the eastern portion of northern Taiwan, it should be accommodated by the subduction of the northern portion of the Luzon arc. Right-lateral strike-slip faults located on the western side of the Yushan mountain may be related to this offset (Fig. 2). By what mechanism this offset is produced remains a question. However, it might be related to heterogeneities in the arcs or backarc regions. For example, the inner arc seems to be absent along segment HH' (Fig. 1b).

The Longitudinal valley is the convergent boundary between the Philippine Sea and Eurasian plates

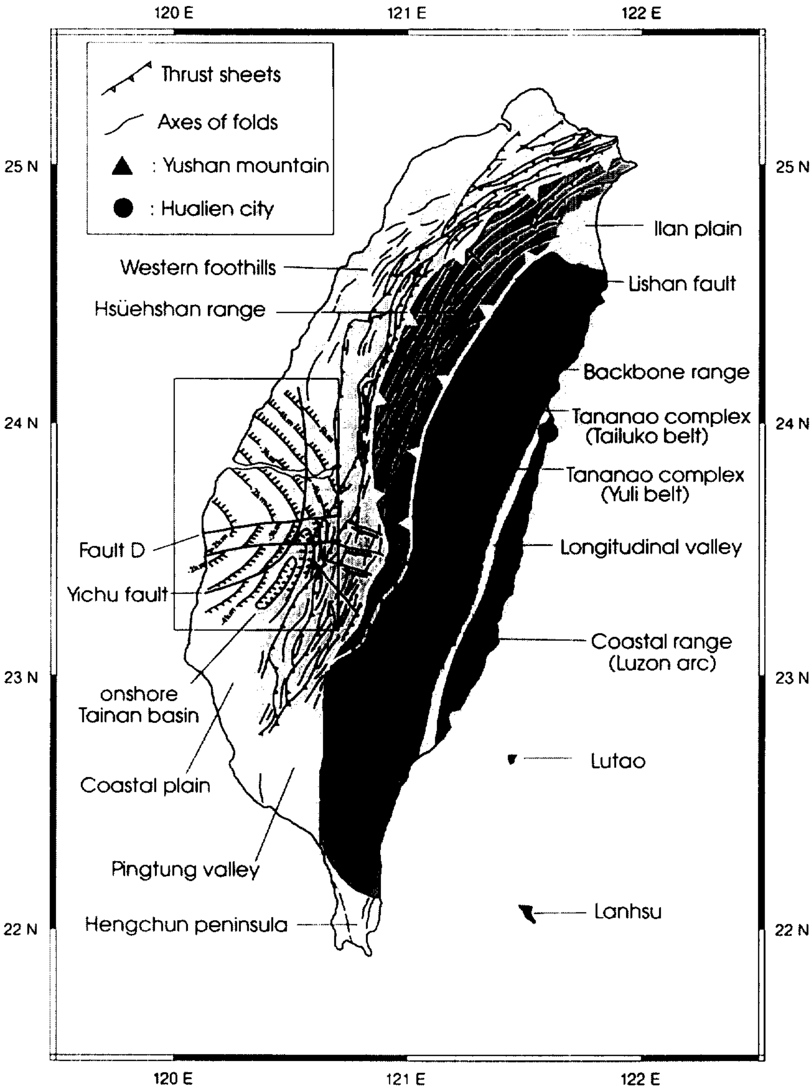

Fig. 2. General structural map of Taiwan modified from [2,14]. The pre-Miocene basement relief beneath the Coastal Plain is shown in the box. Note that the onshore Tainan basin disappears south of Fault D. Right-lateral strike-slip fault zones on the western side of the Yushan mountain correspond to a right-lateral offset zone between the Lishan fault and the onshore Tainan basin.

[2]. In our model it corresponds to the suture zone between the former Ryukyu trench, becoming inactive in the early–middle Miocene, and the former Manila trench, active at the time of collision. To the east, the Coastal Range comprises volcanic and siliciclastic sequences and belongs to the Luzon arc [2]. To the west, the Tananao complex comprises metamorphic and sedimentary sequences above a Paleozoic/Mesozoic basement and belongs, in our hypothesis, to the Ryukyu arc and forearc system (Fig. 2) [22]. Because the Tananao complex consists of a metamorphic belt pair [23] — the high *T* low *P* Tailuko belt to the west and the low *T* high *P* Yuli belt to the east (Fig. 2) — it indicates that the Philippine Sea plate subducted westward beneath the former Ryukyu arc.

South of the Tainan basin, in the northern South China Sea, a relatively low gravity anomaly, roughly parallel to 21.3°N (white dashed line in Figs. 1a and b), suggests that a subduction zone could have existed there. This subduction zone was probably bounded to the west by a NW–SE trending feature, which probably represents a former transform fault (indicated by two white arrows in Fig. 1a). The existence of this feature is also clearly evidenced in the magnetic anomaly map [24] and the ETOPO5 bathymetry.

In summary, prior to the formation of Taiwan, a continuous subduction zone existed from Japan to the southwest Taiwan. Today, the trace of the former Ryukyu trench follows the present-day Ryukyu trench, the Nanao basin, the Longitudinal valley and the base of the continental slope located south of the Tainan basin; the trace of the former backarc basin follows the Okinawa trough, which ends in the Ilan Plain and the uplifted Hsüehshan and Backbone Ranges located on each side of the Lishan fault and the onshore and offshore Tainan basin (Fig. 1).

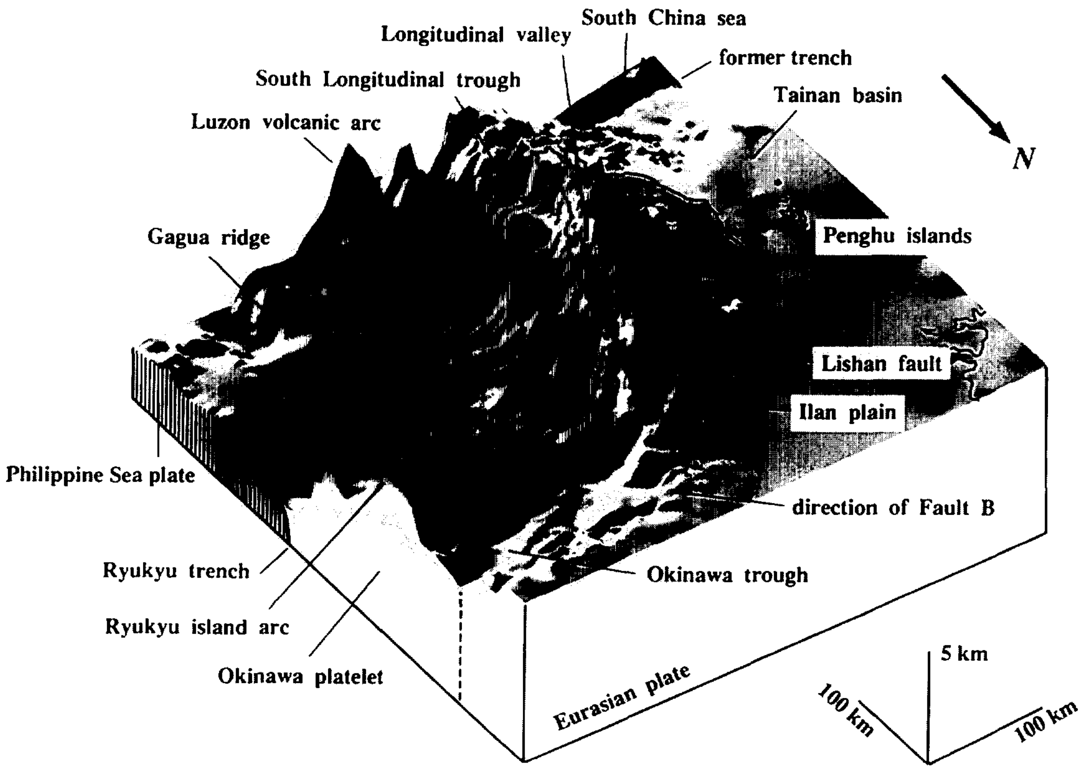

Fig. 3. 3-D topographic diagram of the area shown in Fig. 1b. Note that the southeastern Okinawa trough ends in the Ilan Plain. In its southward prolongation, the Lishan fault is considered to be the suture of the former Okinawa trough backarc basin. The Longitudinal valley is the suture zone between the former Ryukyu arc and the Luzon arc.

3. Earthquake relationship

Fig. 4a shows the location of earthquakes and areas with similar type of focal mechanisms [19]. A large number of shallow earthquakes with compressional mechanism occur in zone D (Fig. 4a), which suggests that the Nanao basin is a weak zone. In contrast, a large number of earthquakes with extensional mechanism occur in the corresponding backarc region (zone E). This phenomenon could be ascribed to various factors, such as the pressure release due to faulting and/or the input of cold material [12]. In zone C, numerous earthquakes with mostly compressional mechanisms are directly linked to the collision between the Luzon arc and the former Ryukyu arc. These earthquakes, especially those occurring along the Longitudinal valley with a sinistral motion, are linked to the oblique convergence of the Luzon arc with respect to the Tananao complex. In addition, a shallow Wadati–Benioff zone dipping eastward is observed in zone C [25], which suggests that the Longitudinal valley marks the trace of the former Manila trench, which was active during the collision. The present-day Manila trench is, however, separated from this former segment of the Manila trench by a right-lateral strike-slip fault located south of Taiwan (Fig. 1). Along the Lishan fault backarc basin suture zone (zone F), earthquakes also exhibit compressional mechanisms. In zone B, earthquakes show mostly compressional mechanisms and could be related to the right-lateral offset, located between the onshore Tainan basin and the Lishan fault. In zone A, earthquakes with mainly extensional mecha-

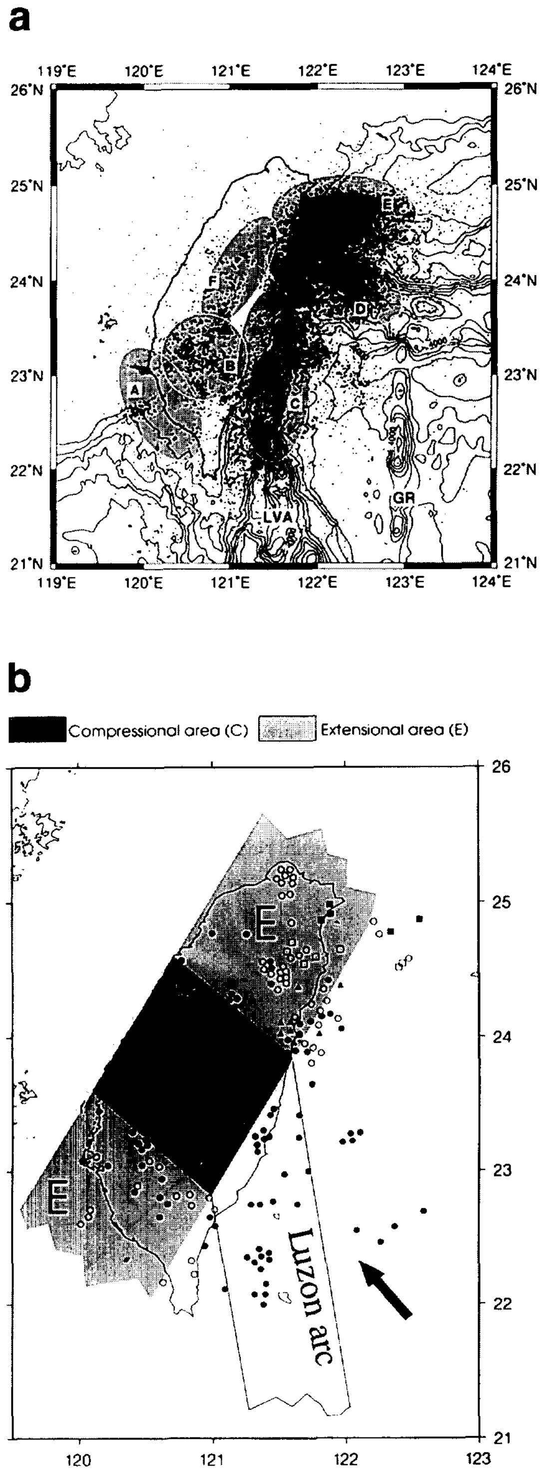

Fig. 4. (a) Distribution of earthquakes of the magnitude greater than 4 and areas with similar focal mechanisms near Taiwan [19]. In general, zones A and E are extensional areas linked to backarc extension. Other zones are compressional areas linked to the arc–arc collision. *LVA* = Luzon volcanic arc; *GR* = Gagua ridge. (b) Schematic diagram showing areas under compressional regime (region C), due to the collision of the Luzon arc, and under extensional regime (regions E), related to backarc extension. The extensional region E in northern Taiwan probably resumed its extension after the collision of the Luzon arc migrated southward. ● and ▲ = thrusts or strike-slip mechanisms; ○ = normal fault mechanisms; squares = earthquakes associated with the subducted slab of the Philippine Sea plate [19].

nisms characterise a still active, though weak, extensional domain, including the former Tainan backarc basin and associated forearc region.

Accordingly, earthquakes occurring in the area of Taiwan could be ascribed to two principal factors: the extension of the backarc basin and the collision of the Luzon arc. Because the Luzon arc, considered to be part of the Philippine Sea plate [26], moves northwestward with respect to the Eurasian plate [27], the region located on the northwest side of the Luzon arc is under a compressional regime, while outside the region is mostly under an extensional regime (Fig. 4b). Because the Luzon arc collision migrates southward [6], the southwesternmost Oki-

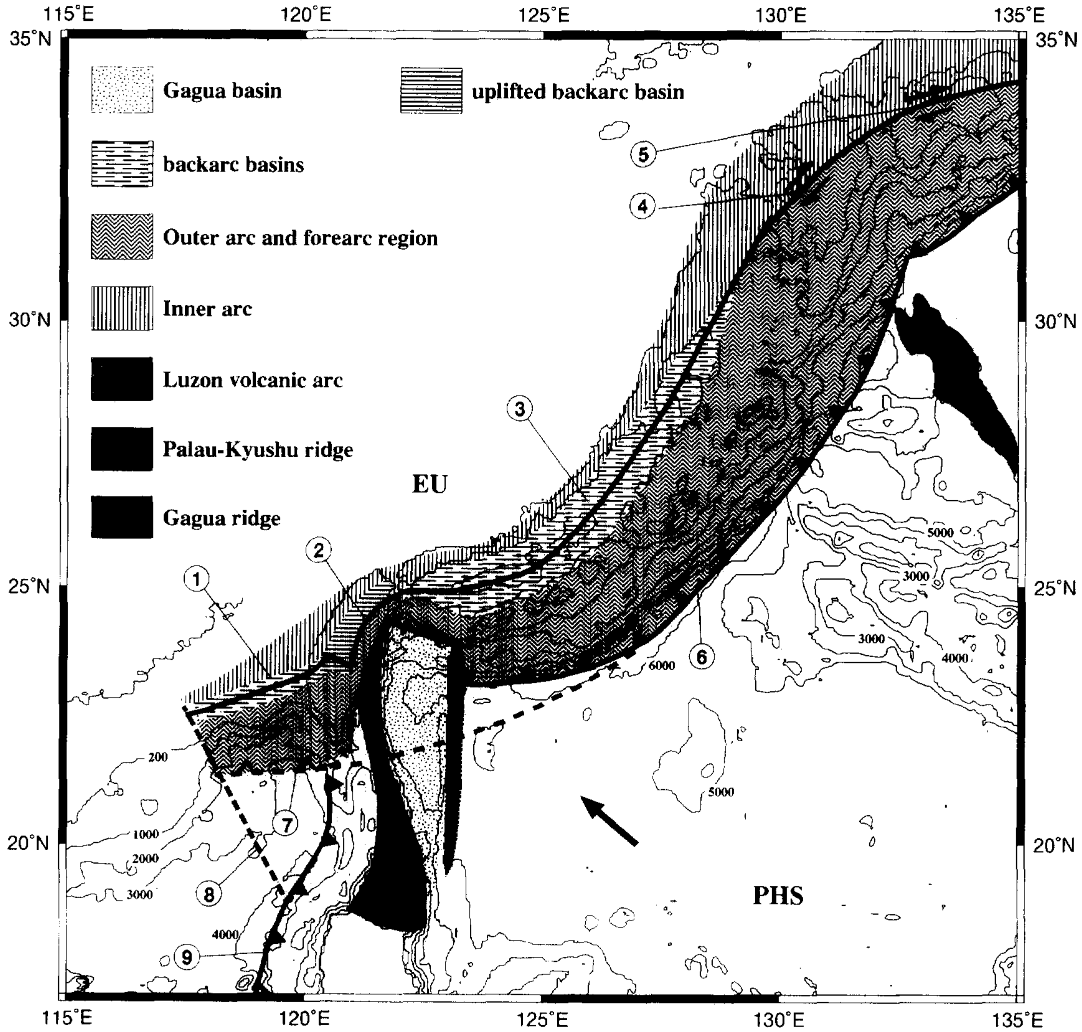

Fig. 5. Simplified geological sketch showing the present-day position of the trench and backarc basin axis of the former Ryukyu subduction zone. *1* = Tainan basin (former backarc basin); *2* = Lishan fault (suture of the backarc basin); *3* = Okinawa trough; *4* = Oita–Kumamoto Tectonic Line; *5* = Median Tectonic Line; *6* = Ryukyu trench; *7* = former extension of the Ryukyu trench; *8* = fossil transform fault; *9* = Manila trench; *EU* = Eurasian plate; *PHS* = Philippine Sea plate. The arrow indicates the direction of convergence of PHS with respect to EU. The dashed line between 6 and 7 corresponds to the position of the trench before the collision of the Luzon arc.

nawa trough probably resumed its extension after the northern tip of the Luzon arc swept passed it [12], while southwestern Taiwan is still a region to be compressed and uplifted.

4. Tectonic evolution

From drilling data in the northern Okinawa trough, it is assumed that the present-day backarc extension began in the middle Miocene [28]. However, the sedimentary units located on each side of the Lishan fault (Backbone and Hsüehshan Ranges, Fig. 2) were deposited under extensional regime in the Eocene–Oligocene and have been under compression since the late Miocene/Pliocene (e.g., [16]). Simultaneously, the Tainan basin started to subside in the late Oligocene with ENE–WSW trending grabens formed during rifting [29]. Basaltic tuffs, tuff breccias and some lava flows are found in most of the Miocene sediments in Taiwan; however, in southern Taiwan, only sparse, small tuffaceous lenses are scattered in the late Miocene sediments [2]. Consequently, the opening of the former backarc basin(s) should have started near Taiwan in the Paleogene. In addition, submarine volcanism occurred in several local centres of the former backarc basin [2] with basalts similar to those recovered in other backarc basins [30].

During the Paleogene the former transform fault (Fig. 1a) probably connected the southern end of the former Ryukyu trench with the northern end of the Manila trench. This transform fault became inactive in the early–middle Miocene and the former Manila trench migrated northeastward, giving rise to the formation of the Luzon arc. Simultaneously, the previous transform fault jumped further northeast, connecting the northern end of the Luzon arc with the southwestern end of the active Ryukyu arc located near 123.5°E. However, because of the relatively northwestward motion of the Luzon arc, this transform fault progressively diminished in length and disappeared when the collision between the two arcs began. The northeastward jump in the activity of the transform fault induced the cessation of the subduction between the southwest of Taiwan and the south Ryukyu subduction zone. This jump in the location of the subduction coincides with the end of the South China Sea opening and with a major plate kinematic reorganization.

Assuming that the shape of the former Ryukyu arc was regular and NE–SW oriented before the collision (Fig. 5), and that the SSE–NNW trending Luzon arc moved northwestward [27], the initial collision between the two arcs was oblique. The indentation of the former Ryukyu arc and the narrowing of the Okinawa trough backarc basin occurred before the uplift of Taiwan. Because west of 123.5°E the Okinawa trough displays striking NW–SE structural trends and is quite different from the rest of the Okinawa trough, which generally shows NE–SW trends, the arc–arc collision could have first occurred near 123.5°E, following the direction of convergence of the Philippine Sea plate relative to the Eurasian plate [12]. This implies that the convergent boundary between northern Taiwan and the bent Ryukyu arc became a transform boundary after the Luzon arc collision. This hypothesis could explain the pronounced bending of the Ryukyu arc and the triangular shape of the Okinawa trough west of 123.5°E. During the process of indentation of the former Ryukyu arc the portion of arc and backarc region located west of the Luzon arc should have rotated counterclockwise and the eastern portion clockwise. This is in agreement with the counterclockwise motion in western Taiwan, deduced from the paleostress study [31], and the clockwise rotation of the south Ryukyu arc, deduced from the paleomagnetic study [8], occurring during the last 10 My [8]. Thus, we interpret the clockwise rotation of the south Ryukyu arc as a consequence of the Luzon arc collision, rather than a consequence of the wedge-shaped opening of the Okinawa trough [8]. Several NW–SE trending dextral strike-slip faults across the entire subduction zone, including Fault B, were active during the indentation of the Ryukyu arc west of 123.5°E (Figs. 1 and 2) [12].

In addition, the collision and the consecutive accretion of the Coastal Range, a portion of the Luzon arc composed of Miocene–Pleistocene volcanic rocks [1,2], occurred in northern Taiwan and propagated southwestward, as suggested by Suppe [6]. As a consequence, an extensional regime was still able to exist in southern Taiwan with continuous subsidence and sedimentation, although collision occurred in northern Taiwan. This phenomenon accounts for the increased sedimentary thickness toward the south [4].

5. Conclusions

The axis of the Tainan basin, the area between the Yichu and the Hsinhua–Chuko faults, the Lishan fault, the axis of the Okinawa trough, the Oita–Kumamoto and the Median Tectonic lines constitute a continuous feature which corresponds to the axis of a former system of backarc basins evolving into a shear zone in southern Japan (Fig. 5). The initial opening of the backarc basin probably occurred as early as the Eocene–Oligocene near the paleo-location of Taiwan. The former Ryukyu arc–trench system was active from south of the Tainan basin to Japan. In the early–middle Miocene, the subduction became inactive in its southwest portion and the former Manila trench migrated northeastward, giving rise to the formation of the Luzon arc. In the late Miocene, because of the similar buoyancy, the southwestern portion of the former Ryukyu arc and the Luzon arc collided. The uplift of Taiwan started after the indentation of the south Ryukyu arc and the narrowing of the corresponding portion of the Okinawa trough and was followed by the closure of the oceanic lithosphere located between the Tananao complex (belonging to the former Ryukyu arc) and the Coastal Range (belonging to the Luzon arc). As a result, the former Ryukyu arc and associated backarc basin were partly squeezed, deformed and uplifted (Taiwan mountain building), leaving two independent backarc basins: the still active Okinawa trough and the almost inactive Tainan basin. The Longitudinal valley marks the suture zone between the former Ryukyu arc and the Luzon arc. The Ryukyu arc–trench system was collided and indented not only by the Luzon arc but also by the Palau–Kyushu ridge (Fig. 5). This provides a simple mechanism, as suggested by Vogt [32], to explain the entire arcuated form of the Ryukyu arc.

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