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Geodynamics of the Taiwan arc–arc collision

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Abstract

Hsu and Sibuet (1995), on the basis of an overview of the satellite-derived marine gravity anomalies, postulated that the Ryukyu subduction zone extended before the formation of Taiwan a few hundreds kilometres south of its present-day termination, and that Taiwan resulted from an arc–arc collision rather than from an arc–continent collision.

An analysis of the structure and timing of rifting in the basins of the Southeast Asia continental shelf offshore and onshore Taiwan shows that they are located within four belts parallel to the main China shoreline. Rifting occurred at the same time within basins belonging to each of these four belts and becomes younger oceanward for each belt. As a first approximation, the four rifting phases occurred during Paleocene, Eocene, Oligocene to Early Miocene and early Middle Miocene times to Present. Ridges with volcanic products are present between these belts. They seem to be the same age as basins located immediately northwest. We interpret these basins and associated ridges as relict backarc basins and arcs of the Ryukyu subduction system which were successively active since the early Tertiary. The geographic distribution of basins and ridges suggests that the Ryukyu subduction zone extended from Japan to southwest Taiwan from early Tertiary to Early Miocene times. During the early Middle Miocene, the southeast portion of the subduction zone facing the Tainan basin and the future island Taiwan became inactive. Southwest of the Tainan basin, the Pearl River basins are tensional basins formed during the rifting of the northern South China Sea margin. Consequently, the geology of the Southeast Asia continental shelf supports the existence of a former subduction zone with which the Luzon arc entered into collision in the Late Miocene. The kinematic evolution of the Southeast Asia region is compatible with such constraints. Such a detailed kinematic evolution of the collision between the Luzon arc and the former Ryukyu subduction zone is proposed both in plan views and in cross-sections. Collision started with the compression and uplift of the Hsüehshan trough backarc basins, where the continental crust and lithosphere were thin and weak, followed by the compression and uplift of the Luzon and Ryukyu arcs. The Lichi and Kenting melanges are explained in the framework of the arc–arc collision model.

Keywords: geodynamics; Taiwan; arc–arc model; rifting continental shelf basins; plate kinematics

1. Introduction

The Taiwan mountain belt is one of the youngest in the world. Three main hypotheses have been proposed regarding this collision zone: (1) the thin-skin tectonic model of Suppe (1981) in which the Luzon arc collided with the Eurasian continental margin; (2) the Lu and Hsü (1992) model which implies a first collision of an exotic block with the Eurasian continental margin followed by a second collision of the Luzon arc with the already accreted exotic block; (3) the arc–arc collision model (Hsu and Sibuet, 1995)

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which suggests that, before the Taiwan orogeny, the Ryukyu subduction system extended west of the present-day position of Taiwan. In this hypothesis, Taiwan mountain building resulted from the collision of the Luzon arc with a former arc and backarc basin system. The purpose of the present paper is to discuss previous hypotheses, to explore the new hypothesis of Hsu and Sibuet (1995) in the light of geological constraints onshore and offshore Taiwan and to propose a new geodynamic comprehensive sketch for the formation of Taiwan.

2. Tectonic framework of Taiwan

The following four major tectono-stratigraphic units, from east to west, characterise the geology of Taiwan (Fig. 1).

(1) The Coastal Range is the onshore portion of the Luzon arc and results from the oblique collision of this part of the Philippine Sea plate with the Eurasian plate. The thrust belt is composed of a thick arc volcanic sequence belonging to the Luzon arc in the lower part, and syn-collisional volcaniclastic and clastic rocks in the upper part. The oblique accretion of the subduction complex (Lichi melange), forearc basin and volcanic islands resulted in a southward propagation of the collision at a rate of about 85–90 km/Ma (Davis et al., 1983; Suppe, 1984). Collision is still going on south of 23.6°N latitude (Yu et al., 1995) which means that most of the Coastal Range is still in the process of accretion, but the northern portion of the Coastal Range and the northern submarine portion of the Luzon arc could have started to subduct beneath northeastern Taiwan or beneath the southwestern Ryukyu arc and forearc. The subduction of the northern portion of the Luzon arc could be also suggested by the triangular shape of the Luzon arc which decreases in width northwards and which disappears near 24°N (Fig. 2; Hsu et al., 1996a). Laboratory modelling of Chemenda (1994, 1995) also postulate the onset of subduction of the northern Coastal Range but beneath eastern Taiwan.

(2) The Tananao Metamorphic Complex (Tailuko and Yuli belts) exposed along the eastern flank of the Central Range, is composed of deformed and metamorphosed basement rocks. The basement is composed of three lithologic units metamorphosed under greenschist to amphibolite facies conditions (Yen, 1962). The first unit, of at least Late Permian age, consists of quartz–mica schists, phyllite, metasandstone and metaconglomerate with exotic blocks of marble, quartzite, metabasite, amphibolite and ultramafic rocks. The second unit consists only of Palaeozoic massive marble (Jahn, 1988) and the third unit includes Mesozoic granites (Lu and Hsü, 1992). Though numerous isotopic ages have been published for the Tananao Complex, Lo and Onstott (1995) have demonstrated that most of the uplifted Mesozoic amphibolites and granitic rocks have been overprinted by the late Tertiary metamorphism (1.6–1.7 Ma) giving ages on partially reset minerals ranging from Mesozoic to late Tertiary. The Tananao Metamorphic Complex is interpreted as a melange formed in an ancient accretionary wedge or suture zone (Hsü, 1988; Yui et al., 1988) or as an ancient portion of the Ryukyu arc, forearc and accretionary prism which extended southwest of Taiwan until early Middle Miocene (Hsu and Sibuet, 1995; Cheng et al., 1996) and was uplifted during Plio–Pleistocene.

(3) The Slate Range (Backbone and Hsüehshan ranges) consists of a typical thick flysch sequence severely sheared and uplifted. The Hsüehshan Range is a curved range only exposed in middle and north Taiwan. It is composed of Eocene to Oligocene shallow marine sequences. The section is dominated by a thick sequence of Oligocene sediments (up to 15 km in northern Taiwan) that are not present in the Backbone Range (Lu and Hsü, 1992). Like the Hsüehshan Range, the Backbone Range consists primarily of slate and sandstone exposed all along the Taiwan island, although thick sandstones units are absent, and limy to marly nodules or lenses and volcanic/volcaniclastic rocks are more common (Ho, 1984; Tillman and Byrne, 1995). Eocene strata are unconformably overlain by latest Oligocene to Miocene strata. Teng et al. (1991) propose that the Backbone Range lacks Oligocene strata because the Hsüehshan trough was subsiding during the Oligocene and acted as a sedimentary sink preventing sediment from reaching outer portions of the margin. Teng et al. (1991) proposed that the sediments exposed in the Slate Range were initially deposited in a NE-trending half-graben (the Hsüehshan trough) which contains as much as 15 km of sediment. The Lishan fault, which limits the Backbone and Hsüehshan ranges, is a major feature of a contro-

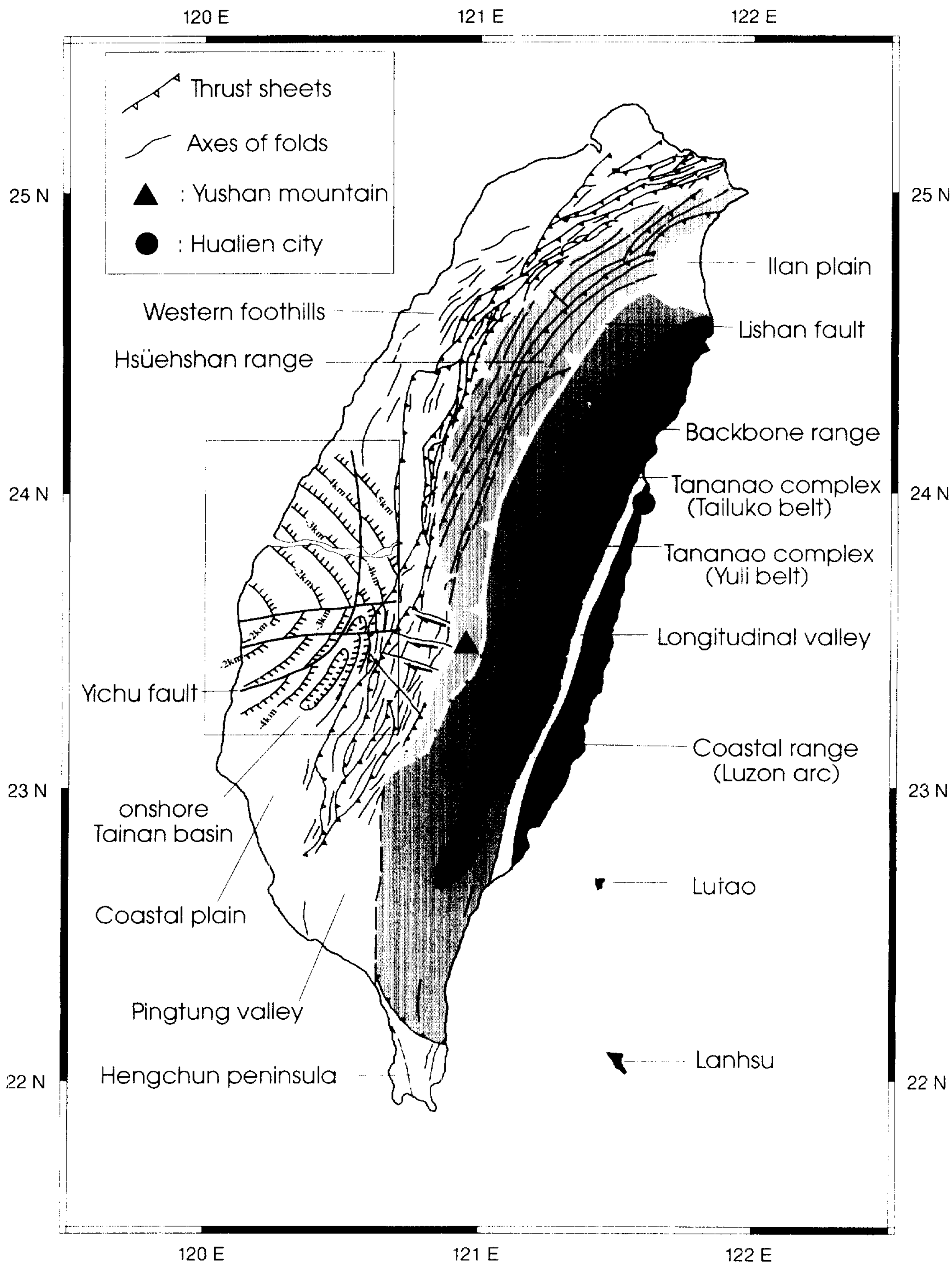


Fig. 1. General structural map of Taiwan from Tang (1977), Ho (1984) and Hsu and Sibuet (1995).

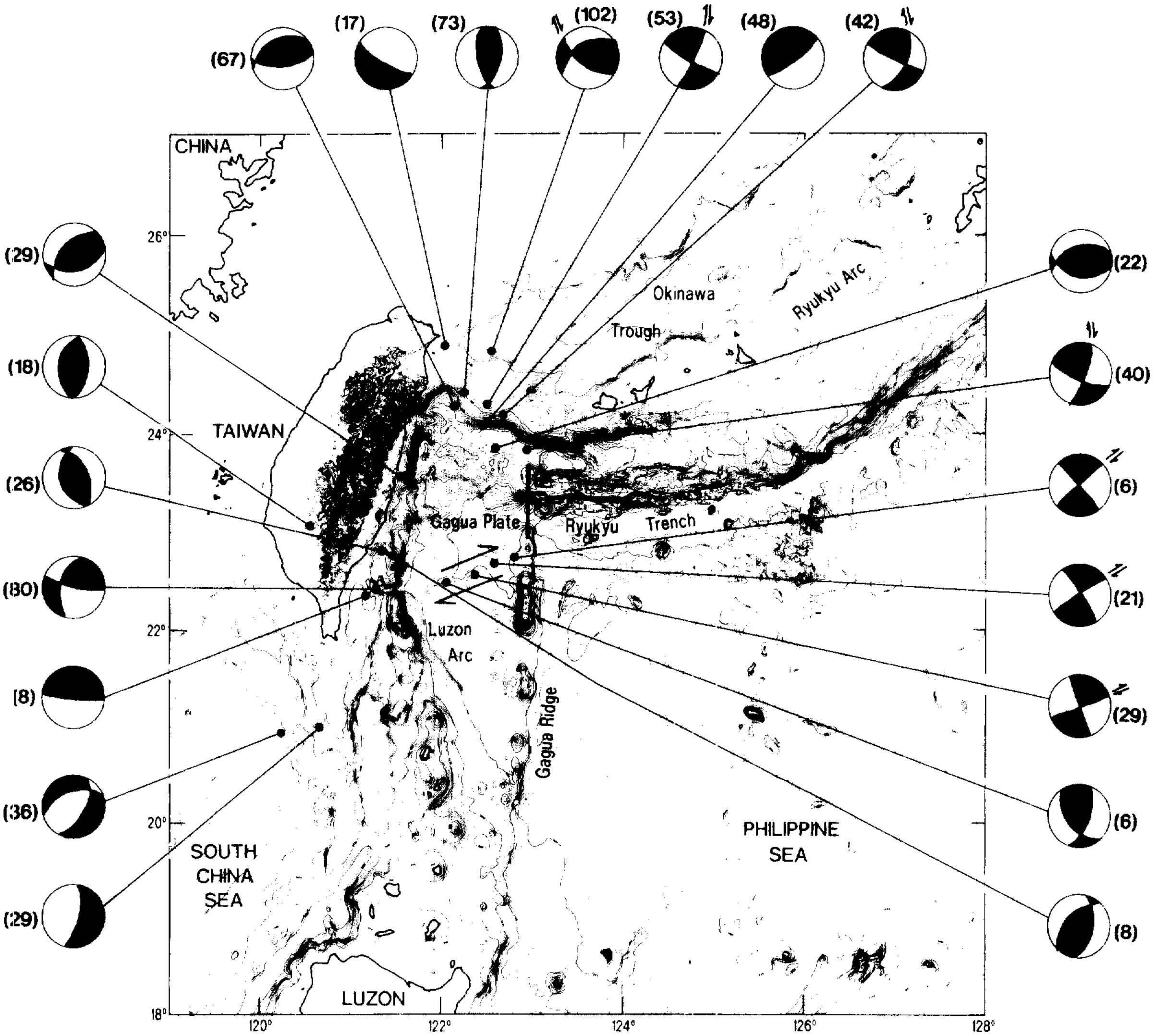


Fig. 2. Bathymetric map around Taiwan with the topography of Taiwan after Hsu et al. (1996a). Mercator projection. Contour interval 200 m. Focal mechanisms of large earthquakes ($M > 6$) recorded between 1963 and 1975 superposed onto the bathymetric map suggest the existence of a right-lateral strike-slip fault located in the Gagua basin (Hsu et al., 1996a). Numbers in brackets indicate the earthquake depths in km. Note the present-day decoupling of the northern portion of the Philippine Sea plate which represents a nascent plate (the Gagua plate) bounded by the Gagua ridge, the right-lateral fault which offsets the Luzon arc at 22.4°N, the Luzon arc and the eastern Ryukyu trench. Contours of the Gagua plate are underlined by the location of these large earthquakes.

versial structural nature. It is interpreted as a normal fault during the Oligocene (Teng et al., 1991), an oblique left-lateral shear zone with west-vergent reverse component (Biq, 1971), an east-vergent backthrust (Clark et al., 1993b), or the boundary between the Philippine Sea plate and the Eurasian plate (Lu and Hsü, 1992).

Based on fission track (Liu, 1982, 1988; Hsieh, 1990) and illite crystallinity data (Chen, 1979, 1984; Chen et al., 1983), the metamorphic grade generally increases across the Hsüehshan Range from prehnite–pumpellyite facies in the west to lower greenschist facies in the east although a higher metamorphic grade in the core of the Hsüehshan Range is suggested by the presence of metamorphic biotite. There is an abrupt drop in metamorphic grade across the Lishan Fault, from low greenschist facies in the eastern Hsüehshan Range to prehnite–pumpellyite facies in the western Backbone Range.

The Hsüehshan Range is characterised by upright and symmetric folds with a coaxial strain history and a gradual increase in strain magnitude toward the hinterland which is consistent with pure shear deformation. In contrast, the Backbone Range is characterised by a multiphase folding, a moderately dipping SI foliation associated with asymmetric folds and extremely large non-coaxial strains and fold axis parallel extension (Clark et al., 1993a,b; Tillman and Byrne, 1995).

These observations show that two different styles of compressive deformation occurred in the Hsüehshan Range, where shortening was important due to the large thickness of sediment and the reduced thickness of the crust, and in the Backbone Range, where the basin was not so deep and the lithosphere thicker than beneath the Hsüehshan Range.

(4) The Western Foothills and the Coastal Plain expose two superimposed basins which correspond to the tectono-sedimentary record of two collisions occurring between 8 and 3 Ma in the Slate Range and between 3 Ma and Present in the Coastal Range (Déramond et al., 1996). For these authors, each basin consists of: (a) a foreland platform retrograding on the Eurasian margin and divided into deepening infilling cycles, and (b) mobile foreland basins with synorogenic terrigenous deposits which evolve in time and space towards the foreland from turbidites and/or subduction melanges to fluvial deposits. Déramond et al. (1996) link these tectono-sedimentary records to the two successive collisions of the Gutaiwan block (Tananao Complex) and of the Luzon arc in the the hypothesis of Lu and Hsü (1992). We interpret these units as belonging to the Eurasian continental shelf and upper western slope of the ancient extension of the Ryukyu backarc basin.

3. Previous models

3.1. Arc–continent model (Suppe, 1981)

The first comprehensive model for the formation of Taiwan was proposed by Suppe (1981). The collision of Taiwan results from the northwestward motion of the Luzon arc, roughly NS-oriented, with the stable continental shelf of China oriented NE–SW. Basically, he assumed a morphotectonic continuity between Taiwan and the Luzon volcanic arc to the south. The Luzon arc continues northwards into the Coastal Range while the associated submerged non-volcanic arc (accretionary wedge) expands continuously toward the north, rising above sea level to merge morphologically with the Slate Range of Taiwan which is composed of west-vergent thrust sheets. Thus, the collision is oblique and Suppe considered in his model that the Luzon arc and the continental margin have a cylindrical symmetry. The major topographic effect of the arc–continent collision is the expansion of the accretionary wedge in width and height as the Luzon arc encountered and incorporated the thick sediments of the Chinese continental margin. The mechanics of the process are similar to the deformation of a wedge of soil in front of a bulldozer. The soil deforms until a critical taper is attained. The critical taper is the shape for which the strength of the material within the wedge is balanced by the friction along the basal decollement. In his model, for continuity of displacement, Suppe (1981) inferred two decollements which coincide beneath the Slate Range (Fig. 3), tentatively concluding that a double-sided wedge exists in Taiwan.

Using data of the telemetric seismic network in Taiwan, the velocity distributions in the crust and upper mantle under Taiwan have been obtained (Rau and Wu, 1995). Thickening of the crust and up-arching of the lower crustal materials forming a root under the Central Range are observed, showing that a significant portion of the lithosphere is involved in the Taiwan orogeny. This calls into question the appropriateness of the modelling of the Taiwan orogeny in terms of thin-skin tectonics (Rau and Wu, 1995).

3.2. Double collision model (Lu and Hsü, 1992)

Lu and Hsü (1992) consider that two main collision events occurred during the Cenozoic Taiwan orogeny. The first collision occurred about 12 m.y. ago, between the Gutaiwan block and the Eurasian continent (Fig. 4). The Gutaiwan block includes the Tananao Complex and an accretionary prism located

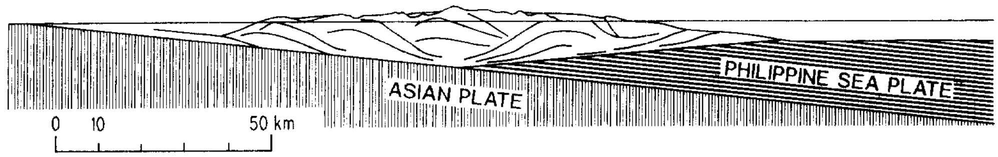


Fig. 3. Arc–continent collision model of Taiwan from Suppe (1981) involving two decollements which merge below the Slate Range.

on its western side which gives rise to the Backbone Range and to the Kenting melange. The Gutaiwan block is supposed to belong to the Philippine Sea plate and to have collided with the Chinese margin. In this hypothesis, the Lishan fault represents the plate boundary between the Eurasian and Philippine Sea plates. Subsequently, the Luzon arc began to grow. The second collision occurred around 3 m.y. ago between the Luzon arc and the Gutaiwan block and gave rise to the Lichi melange located on the western flank of the Coastal Range (Fig. 4).

3.3. Arc–arc collision model (Hsu and Sibuet, 1995)

The satellite-derived gravity anomaly map (Sandwell and Smith, 1994) shows that the Okinawa trough is probably linked to the Tainan basin (Fig. 5), in spite of different ages for their formation, on the basis of similar amplitudes and shapes of gravity anomalies features (Hsu and Sibuet, 1995). Hsu and Sibuet suggested that Taiwan resulted from the collision of the Luzon arc with an extinct portion of the Ryukyu subduction zone extending at that time southwest of the present-day position of Taiwan. After the closure of the oceanic domain located between the Luzon arc and the former Ryukyu subduction zone, Taiwan mountain building started with the closure and uplift of the ancient Ryukyu backarc basins (Fig. 5). The closure between the inactive portion of the Ryukyu arc and the Luzon arc occurred mostly after the deformation and uplift of the sediments infilling the backarc basins. In this model, the Eurasia/Philippine Sea plate boundary is the Longitudinal Valley.

4. Taiwan basins and surrounding basins: a hypothesis concerning their formation and evolution

In this section, we propose to summarise the geometry, structure and timing of formation of the Tertiary basins created on the Chinese continental shelf around Taiwan, including the portion of the shelf where Taiwan developed, and then to propose a comprehensive scheme of formation and evolution of these basins (Fig. 6). All these basins are roughly NE–SW-oriented (Letouzey et al., 1988), i.e., parallel to the East China shoreline and continental margin. The tectonic history of these basins shows that rifting generally occurred between Early Paleocene and Middle Miocene, except for the Okinawa trough which is still in the rifting stage (Sibuet et al., 1987). No satisfactory mechanism has been proposed to explain both the large number of these continental basins and why continental extension occurs over a so long period of time. Though the exact duration of the rifting period for each basin is sometimes poorly known, we propose to discuss their relative evolution in order to understand their mechanism of rifting.

4.1. Pearl River basins

The Pearl River basins are a continuous succession of connected basins (Zhujiangkou basins) which extend from the island of Hainan to the west-northwest of the Tainan basin (Fig. 6). Well data indicate that basement rocks comprise Palaeozoic metasedimentary rocks and Jurassic and Upper Cretaceous formations consisting mainly of non-marine sequences, granitic intrusions and volcanic rocks (Sun, 1981, 1985). The basins are mostly Palaeogene NE–SW-trending half-grabens or grabens bounded by normal faults with some tilted fault blocks. Sediments are composed of non marine sediments, mostly Paleocene shallow lake mudstones overlain by synrift Eocene deep lake mudstones with some fluvial sandstones interbedded with shales (Ru, 1988). The deposition of these sediments is controlled by the vertical motion of the normal faults mostly striking NE–SW (Ru and Pigott, 1986) and the associated subsidence. A regional Late Eocene–Early Oligocene unconformity separates synrift from

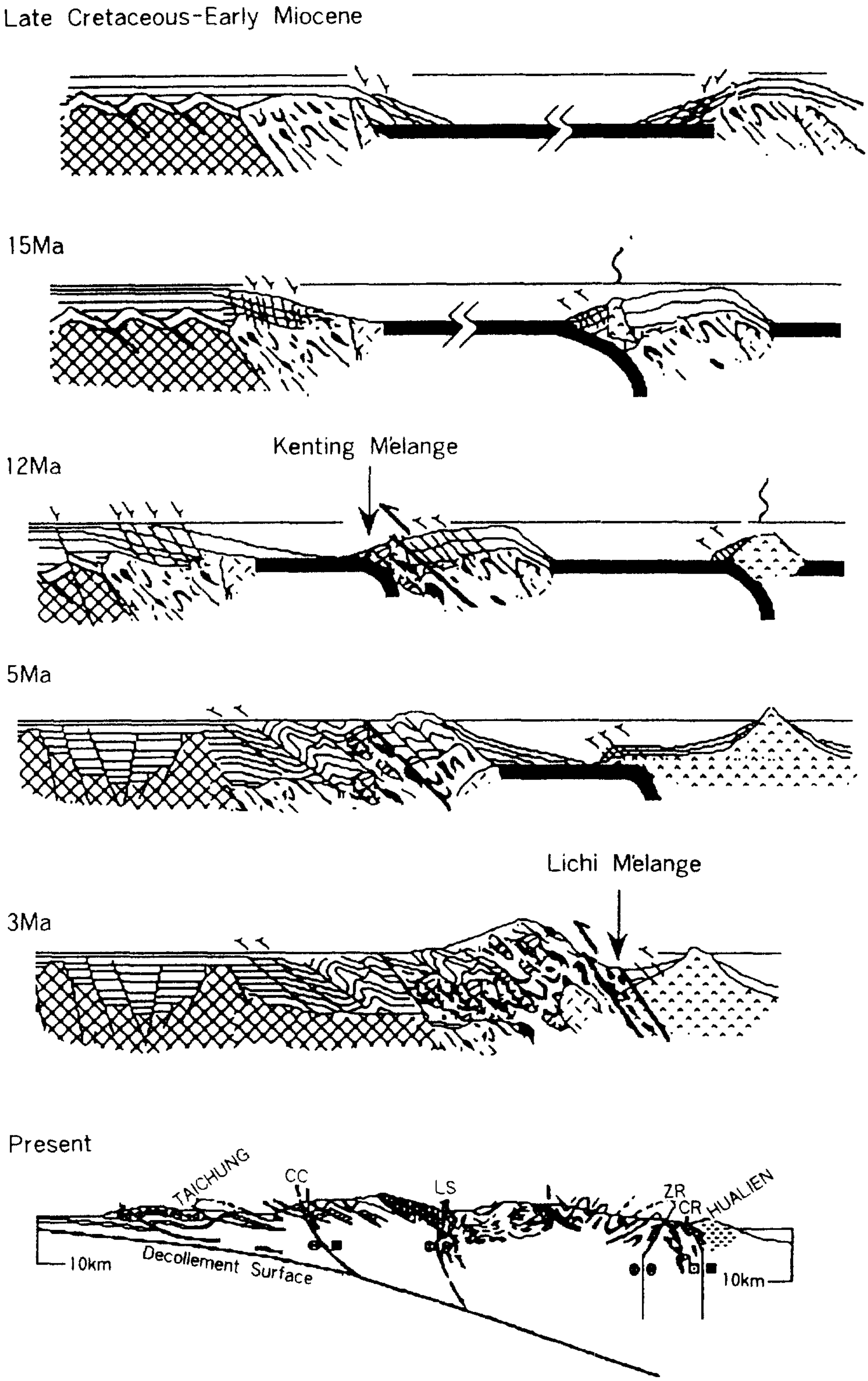


Fig. 4. Tectonic evolution of Taiwan from Lu and Hsü (1992).

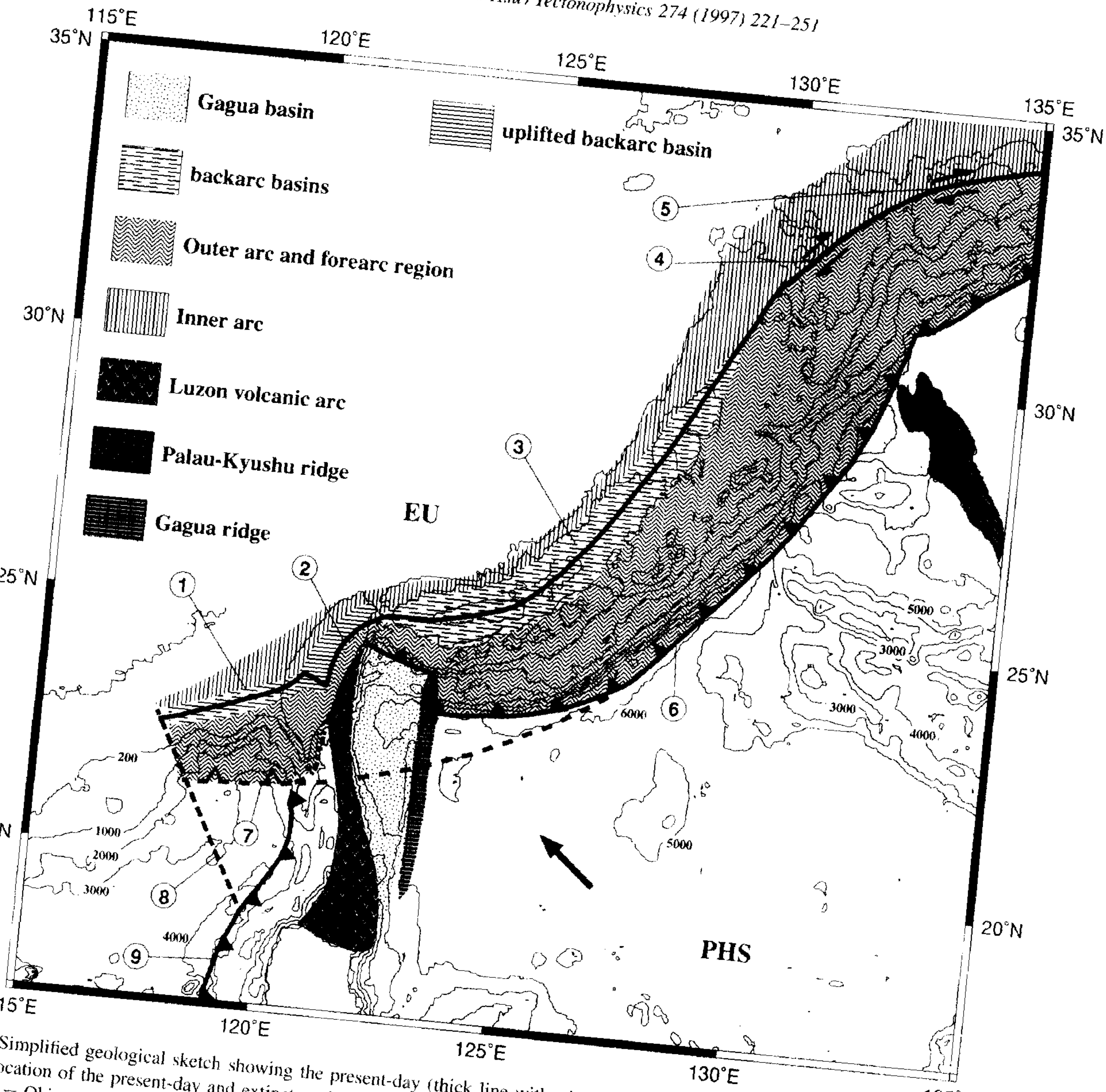


Fig. 5. Simplified geological sketch showing the present-day (thick line with triangles) and former (dashed line) Ryukyu trench as well as the location of the present-day and extinct positions of the backarc basin axis (Hsu and Sibuet, 1995): *1* = Tainan basin; *2* = Lishan Fault; *3* = Okinawa trough; *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.

flat and undeformed postrift sediments which display the first Late Oligocene–Early Miocene thin layers of limestones indicative of the first marine transgressions (Zhao, 1988). Continuous marine deposition was interrupted in the Middle Miocene by a significant tensional event characterised 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 time.

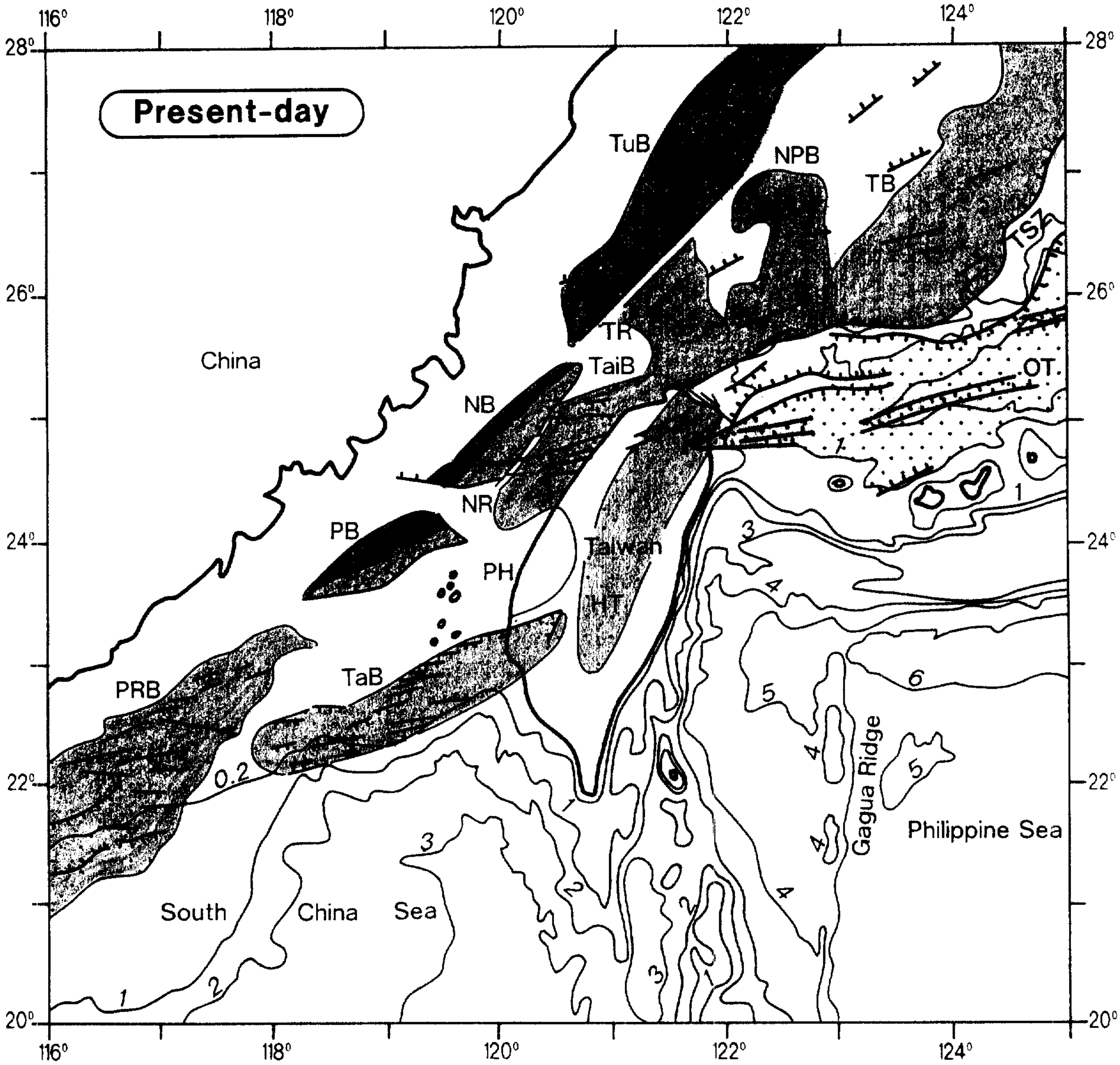


Fig. 6. Chinese continental shelf basins (dotted areas) with their main controlling normal faults: *HT* = Hsüehshan trough; *NB* = Nanjihto basin; *NPB* = north Pengchiahsu basin; *NR* = Nanjihtao ridge; *OT* = Okinawa trough; *PB* = Penghu basin; *PH* = Penghu high; *PRB* = Pearl River basins; *SPB* = south Pengchiahsu basin; *TB* = Taipei basin; *TaiB* = Taishi basin; *TaB* = Tainan basin; *TR* = Tungyintao ridge; *TSZ* = Taiwan–Sinzi Zone; *TuB* = Tungyintao and Tahchentao basins.

4.2. West Taiwan basins

The Tainan basin is located at the northeastern end of the South China Sea continental margin and extends onshore southwestern Taiwan (Fig. 6). Numerous seismic and well data obtained by the Chinese Petroleum Company (CPC) show that, although the basin is trending ENE–WSW, roughly parallel to the continental slope, the main boundary of the northern side of the basin is composed of E–W segments (Fig. 6) which either lie together in an en-échelon pattern or are connected by orthogonal transfer faults with strike-slip motion (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 E–W-oriented though the direction of opening of the basin is NNW–SSE. This structural pattern is similar to the one of the Okinawa trough backarc basin where en-échelon normal faults do not trend in the direction of the trough itself (Sibuet et al., 1995). 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 which limits the Tainan basin on the shelf edge side. Rifting occurred from Early Oligocene to early Middle Miocene. The 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 subsidence phase linked to the uplift of Taiwan since the Pliocene.

The Taishi basin located northwest of Taiwan seems to differ from the NE–SW trend of most of the other basins. A series of horsts and grabens also trending N080 indicate that the basin was subjected to extension during the Eocene rifting phase with weak tensional activity during the Oligocene. However, the presence of deep synrift sediments of unknown age below the Eocene may mean that the rifting period could have started during the Paleocene. In addition, a weak rejuvenation of normal faults occurred during the Early and early Middle Miocene which suggests that the extension could have extended to early Middle Miocene (Huang et al., 1993). Since this period, several compressional or transpressional regimes produced the tectonic inversion of the basin.

The Nanjihto basin is separated from the Taishi basin by the Nanjihtao ridge. It is a NE–SW-trending half-graben limited in the southeast by a major boundary fault with more than 3 km normal displacement. Although there is no commercial well drilled in this basin, stratigraphic correlations indicate rifting occurred between the Early Paleocene and Late Eocene. Then, a major unconformity characterised by an erosional truncation exists from the Late Eocene to Late Oligocene (Chow et al., 1991).

The Penghu basin located between the Nanjihto and Pearl River basins is also trending NE–SW with bounding faults approximately oriented in the same direction (Letouzey et al., 1988). Though poorly described in the published literature, the main rifting period seems to occur from Paleocene to Middle Eocene time (S.-T. Huang, pers. commun., 1995).

4.3. *Northern and northeastern Taiwan basins*

The Tungyintao and Tahchentao basins located close to mainland China are typically half-graben basins (Fig. 6). From seismic and well data, the basement is Late Cretaceous and rifting mostly occurred during the Paleocene (3.5 km of synrift sediments), and slowed down considerably during the Eocene and Early Oligocene (Huang et al., 1992).

The northern and southern Pengchiahsu basins located southeast of the preceding basins are characterised by NE–SW-trending normal faults (Fig. 6). The prerift sequences are Paleocene or slightly older and the synrift sequences Eocene or slightly younger (Huang et al., 1992). The Eocene synrift sequence is more than 3 km thick with a lower section showing chaotic reflections suggesting deposition in a semi-closed 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 zone (Fig. 6). The prerift sequences are dated as Eocene and the synrift sequences Oligocene (Huang et al., 1992) though Middle Miocene and Late Miocene to Pliocene/Pleistocene tensional phases, post-dating the main rifting phase, are observed. The Oligocene synrift sequence is more than 4 km thick and composed of a prograding Late 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 Okinawa trough backarc basin extends from Taiwan to Kyushu Island and is separated from the Taipei basin by the Taiwan–Sinzi zone (Fig. 6).

Rifting started in late Middle Miocene (Letouzey and Kimura, 1986; Sun, 1981) and is still active today (Sibuet et al., 1987). However, the beginning of the 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., 1995). The first phase of rifting is the most important one with 50 to 75 km of extension from the southern to northern Okinawa trough (Sibuet et al., 1995). It started in Middle Miocene (12 Ma) or Late Miocene (6 Ma) times. The two recent phases of rifting are dated Late Pliocene–Pleistocene and Late Pleistocene to Recent, with only a total of a few tens of kilometres of extension.

4.4. Taiwan onshore basins (Hsüehshan trough)

Several authors have already suggested the existence of a large basin in the area of Taiwan before its uplift (Ho, 1984; Teng, 1992). Located on the outer continental shelf before the collision, it was named Hsüehshan trough by Teng et al. (1991). This basin corresponds to the present-day Western Foothills and the Slate belt (Hsüehshan and Backbone ranges). In the Hsüehshan Range, Eocene and Oligocene shallow-marine sediments are estimated to be up to 15 km thick and Early to Middle Miocene sediments about 1 km thick. Syn-sedimentary growth faults or normal faults trend nearly in the east–west direction (Lu et al., 1991) as in the offshore Tainan and Taishi basins. However, no such tensional features were found in the Backbone Range. There, Oligocene sediments seem to be absent, suggesting to Teng (1992) that the Mesozoic basement was there closer to the surface. Before collision, the Hsüehshan trough, floored with a Mesozoic basement, was at least 250 km long, as shown by the north–south extension of the Hsüehshan and Backbone ranges, and about 200 km wide taking into account compressional features in the Western Foothills and the Hsüehshan and Backbone ranges (Suppe, 1980; Teng et al., 1991). The main rifting episode occurs during middle Eocene to Oligocene and perhaps during lower Miocene (Lu and Hsü, 1992).

There is already two main interpretations of the Slate Range: for Teng (1992), the Lishan fault represents a major listric fault with at least 3 km of vertical offset which affects the Mesozoic basement creating a major depression west of the Lishan fault; Lu and Hsü (1992) postulated that the rocks which belong to the Eocene unit were exotic blocks in the Miocene unit of the Backbone Range and interpreted the Backbone Range as a Miocene accretionary wedge. For them, the Backbone Range is a huge mass of slate, phyllite and greywacke constituting a sedimentary sequence comparable to the schistes lustrés of the Pennine Alps, which belongs to the Philippine Sea plate. Syn-sedimentary volcanic rocks (Chen, 1991) of the Backbone Range are interpreted as ophiolites derived from the disruption of the former Philippine Sea oceanic crust.

In our interpretation, the Hsüehshan trough corresponds to two parallel backarc basins: the northwestern one, very deep, filled with more than 15 km of sediment and corresponding to the Hsüehshan Range and the eastern part of the Western Foothills; and the southeastern one, a few kilometres deep corresponding to the Backbone Range. They were probably separated by a linear topographic feature which forces Oligocene turbidites coming from the Chinese platform first to fill the western depression. Sediment in the southeastern depression either bypassed the western basin since the Late Oligocene and/or are derived from the adjacent Ryukyu arc. Igneous rocks such as pillow lavas, diorite and gabbros are common in the Hsüehshan trough. Subordinate andesites and dolerites are present within the Backbone Range sediments but apparently not in the Hsüehshan Range (Chen, 1991). We suggest that these rocks could be backarc basin volcanism and exotic arc volcanic rocks coming from the former Ryukyu arc (presently the Tananao complex). The Lishan fault, which limits the Hsüehshan and Backbone ranges, was a normal or listric fault located between the northwestern and southeastern depressions and bounding the linear topographic feature to the west. It was reactivated as a reverse fault later on.

4.5. Structure of basins and timing of rifting

Fig. 6 shows that basins of the continental shelf around Taiwan are oriented NE–SW and are parallel to the main China shoreline, except for the Tainan basin and the southern Okinawa trough which are trending ENE–WSW and E–W, respectively. However, when clearly established, the trend of normal faults is significantly different from the mean direction of basins and generally oriented E–W. This is true for the Tainan and Taishi basins, the Okinawa trough, and also for the Pearl River basins where two families of normal faults are present, one active during almost the entire rifting phase and parallel to the northern border of the basins and the other E–W-oriented dating from the end of the rifting phase (Sun, 1981, 1985; Ru and Pigott, 1986; Ru, 1988). Except for the Pearl River basins created during the rifting of the northern South China Sea margin (Ru and Pigott, 1986), before the onset of spreading of the South China Sea, we suggest that the discrepancy between the direction of normal faults and the basin trends occurs in a backarc basin environment. Generally, backarc basins lie roughly parallel to the directions of trenches and continent shorelines, but normal faults are not systematically parallel to the basin trend. In fact, the poles of rotation of the arc platelet with respect to the mainland appear to be approximately in the direction of normal faults for each tectonic phase as demonstrated by Sibuet et al. (1995) in the Okinawa trough. Slight changes in the subduction parameters such as convergence rate, angle of convergence and dipping angle of the Benioff zone, induced major changes in the tectonic regime and in the position of poles of rotation (Sibuet et al., 1987). Based on the structural analysis we suggest that, as for the Okinawa trough, the Tainan and Taishi basins are backarc basins and that the other continental basins, except the Pearl River basins, could be also considered as backarc basins.

Fig. 7 shows the timing of rifting for continental basins around Taiwan. Some uncertainty exists about the exact beginning and end of their main rifting phase, mostly because the shutdown tensional rifting activity could be interpreted as part of the postrift thermal subsidence phase or subsequent slightly less important tectonic phases with later tensional faulting which could complicate the interpretation. However, we identify four main rifting phases: (1) the Late Cretaceous–Palaeogene phase during which basins subsided along and close to the main China shoreline (Penghu, Nanjihtao, Tungyintao and Tahchentao basins); (2) the Eocene phase during which extension decreased and ceased in the older basins but started further southeast in the south and north Pengchiahsu and Taishi basins and later on in the Hsüehshan trough (Fig. 6); (3) the Oligocene–early Middle Miocene phase during which rifting was active in the Tainan basin, the Hsüehshan trough and the Taipei basin, i.e. in three new basins located southeast of the previous ones; (4) rifting ceased in all basins but started in the Okinawa trough during the late Middle Miocene (12 Ma) or later during the Late Miocene (6 Ma).

4.6. Proposed mechanism of formation of the East China continental shelf basins

As demonstrated in the previous section, basins around and in Taiwan progressively developed from the main China shoreline in the southeast direction. During each of the main four phases of extension, active basins appear to be en échelon or more generally distributed continuously along the continental shelf (Fig. 6). Fig. 6 suggests three main observations. (1) On the continental shelf, there is no basin younger than late Early Oligocene southeast of the Pearl River basins. (2) There is no basin younger than Middle Miocene southeast of the Tainan basin and the Hsüehshan trough. (3) The Okinawa trough is still in the rifting stage.

Based on these observations, four belts of basins appear on the continental margin. The oldest (belt 1) formed mostly during the Paleocene and Early Eocene and consists of the Penghu, Nanjihto, Tungyintao and Tahchentao basins. Belt 2 formed mostly during the Eocene and includes the Taishi, and the north and south Pengchiahsu basins. Belt 3 formed mostly during the Oligocene and Early Miocene and consists of the Tainan basin, the Hsüehshan trough and the Taipei basin. Belt 4 only consists of the Okinawa trough which has been active since the Miocene.

Belts 1, 2 and 3 are continuous and parallel except that belt 3 does not extend between the Penghu and Tainan basins. This could be due to the badly defined Penghu basin rifting phase which could extend during the Eocene or, because the Penghu high is so large, to an excess of arc magmatism during the Eocene (though the oldest ages measured on the Penghu islands basalts are Early Miocene (Chen et al., 1996)) which would have accommodated the whole extension associated with the formation of

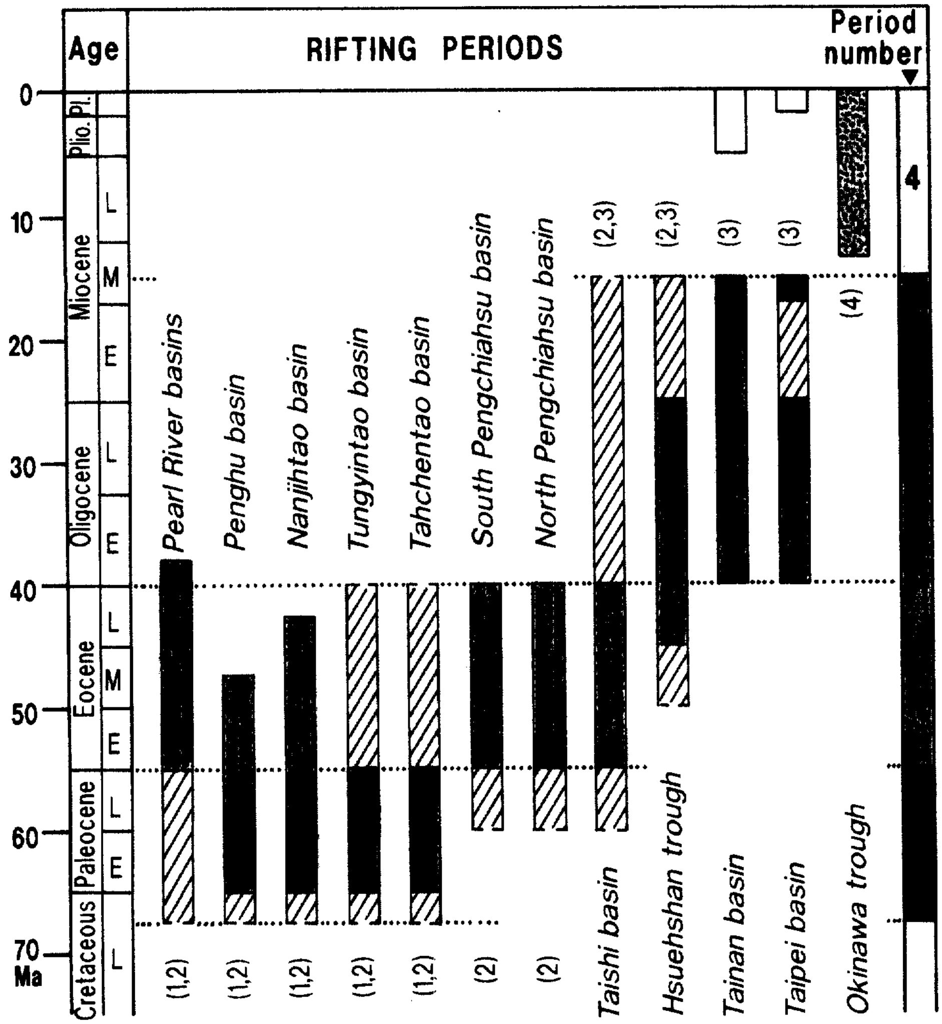


Fig. 7. Main rifting phase of each continental basin around Taiwan including the Hsüehshan trough, the basin lying before the uplift of Taiwan. Detailed explanations and references in the text. Hatchured areas, main rifting phase; dotted areas, decreased rifting activity; white areas, posterior tensional activity. Four main rifting periods have been identified. Periods during which rifting occurs appear for each basin.

backarc basins of belt 2. If valid, this hypothesis could explain why a large basaltic body within the continental lithosphere induced and still induces different strain and stress patterns in north and south Taiwan (Hu, 1995; Yu et al., 1995).

The structure and stratigraphy of the Pearl River basins are related to the Palaeogene rifting of the northern South China Sea margin (Holloway, 1982) followed by the South China Sea opening starting in early Late Oligocene time. In addition, southwest of the Tainan basin, west of the 118°E longitude, no major positive free-air anomalies exist on the continental shelf in the direction of Indochina (Fig. 8), except the slight positive free-air anomaly located on the shelf edge and which corresponds to the edge effect. The large negative anomalies correspond to the Pearl River basins. Therefore, the very large contrast between free-air anomaly values northeast and southwest of the southwestern termination of the Tainan basin also suggests that, at least during the Palaeogene, the former Ryukyu subduction zone did not extend southwest of the Tainan basin and that the

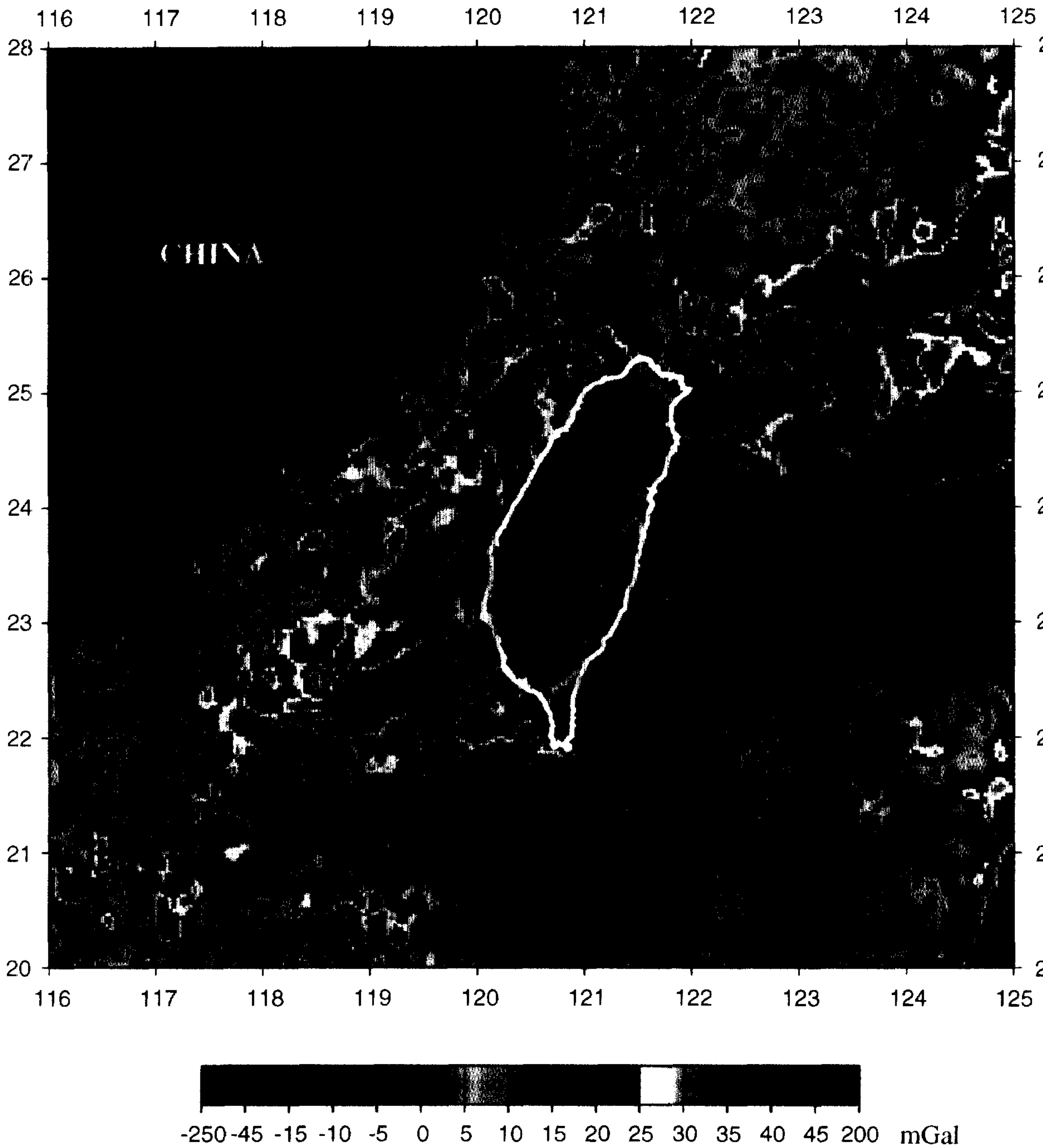


Fig. 8. Satellite-derived marine free-air gravity anomalies around Taiwan (Sandwell and Smith, 1994) and Bouguer anomalies in Taiwan (Yeh and Yen, 1991).

Pearl River basins are rifted basins of the continental shelf linked to the rifting of the northern South China Sea margin.

As the four belts of continental shelf basins become younger towards the southeast, such a chronology is difficult to explain in a passive continental margin environment. We consequently interpret each basin as the relic backarc basin of the basin located immediately southeastward and propose that all these basins belonging to the four belts formed as backarc basins associated with the Ryukyu subduction zone. In this hypothesis, from Late Cretaceous/Early Paleocene to early Middle Miocene, the Ryukyu subduction zone extended from Japan to the western end of the Tainan basin where the continental margin changes direction (118°E, Fig. 6). In the early Middle Miocene, the portion of subduction zone corresponding to the Tainan basin and the Hsüehshan trough became inactive and the southwestern limit of the subduction zone at 118°E jumped north of Taiwan at 123.5°E. Such an interpretation in terms of backarc basins has already been proposed at a reduced scale for the northern Taiwan basins by Huang et al. (1992) and Chi (1996).

4.7. Relic arcs in the East China continental margin

Fig. 8 represents the satellite-derived marine free-air gravity anomaly map around Taiwan (Sandwell and Smith, 1994). Bouguer anomalies in Taiwan (Yeh and Yen, 1991) have been added but do not match by definition marine free-air anomaly data at the shoreline. All continental shelf basins identified around Taiwan (Fig. 6) correspond to relative gravity lows but there is more information on the gravity map than on the structural map. The limits of basins slightly differ in the two maps because information on the nature of basins, their internal subdivisions, local irregularities and changes in sedimentary thicknesses are contained in the gravity data. From Japan to the southwestern extremity of the Tainan basin, the outer continental shelf is characterised by high free-air anomaly values. Northeast of Taiwan, the present-day active Ryukyu arc is associated with a very high anomaly which underlines its lateral extension. Southwest of Taiwan, an ENE–WSW-trending feature of similar positive amplitude is located on the upper continental slope, just south of the Tainan basin and corresponds to the ridge which limits the southern border of the Tainan basin. By analogy with the present-day Ryukyu arc, we interpret this ridge as the southwestern end of the former Ryukyu arc and we name it the Tainan arc. Between the Penghu high and the Tainan arc and between the Taiwan–Sinzi zone and the Ryukyu arc, the relative free-air anomaly minima correspond to the Tainan basin and the Okinawa trough, respectively.

The Taiwan–Sinzi zone, located between the Taipei basin and the Okinawa trough, is also associated with a large positive free-air anomaly. It is composed of palaeohighs of deformed metamorphic rocks of Cretaceous age or older, intruded by Miocene volcanic rocks which crop out in the Sinkoku, Danjyo and northwest Kyushu islands. Strong positive magnetic anomalies (Magnetic Anomaly Map of East Asia, 1994) over the Taiwan–Sinzi zone confirms the existence and extension of a continuous remnant volcanic arc. The Penghu high is also underlined by strong positive anomalies larger than 40 mGal and a belt of positive magnetic anomalies which lies just north of the Tainan basin and is adjacent to it. By similarity with the Taiwan–Sinzi zone, we interpret the Penghu high as a remnant arc. A few radiometric ages have been obtained in the basaltic flows of Penghu Islands (Juang, 1988; Chen et al., 1996). Dates from these alkali–tholeiitic basalts range from 8.0 to 17.8 Ma.

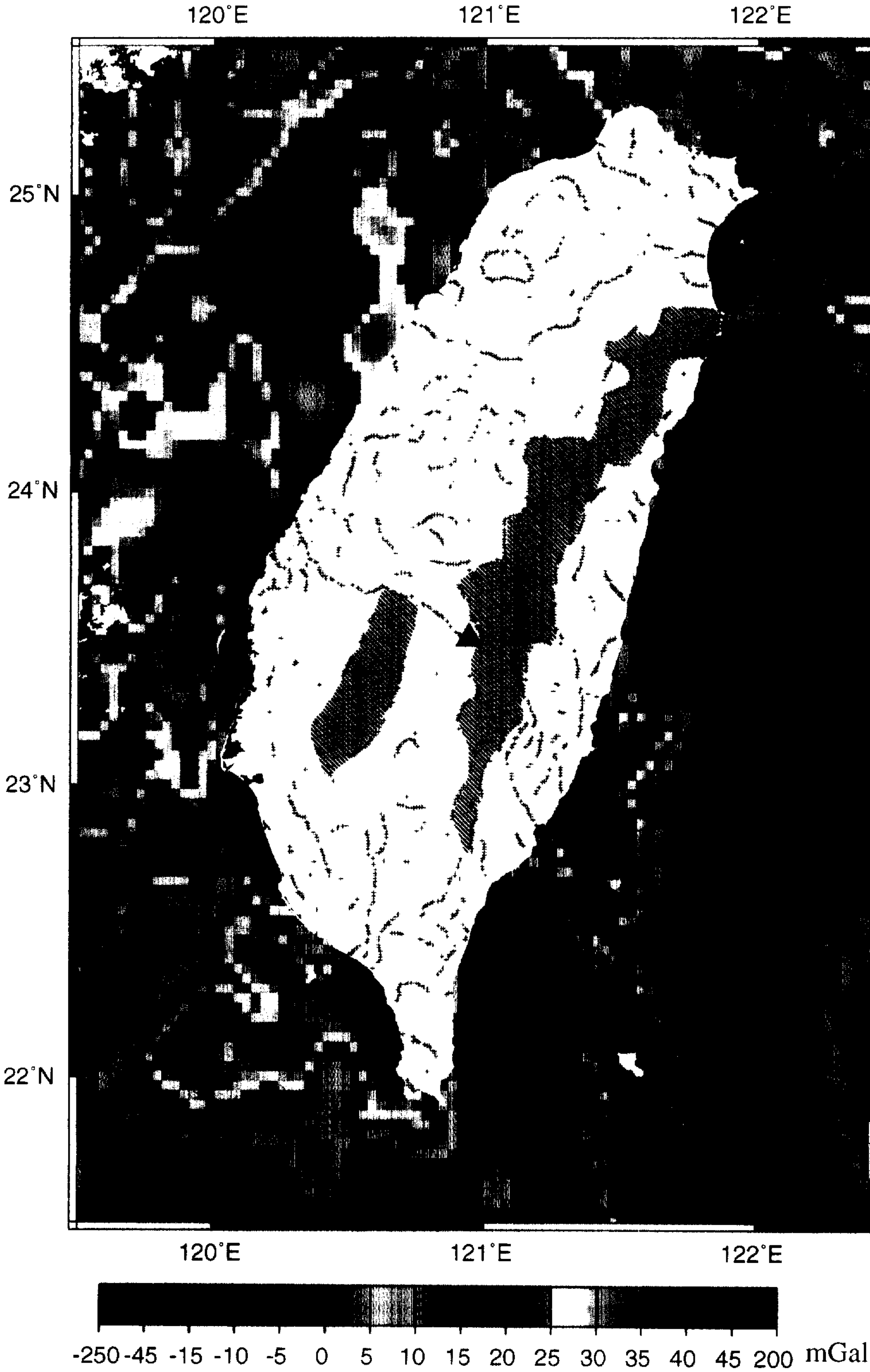
Other ridges have been identified between basins and could be interpreted as remnants of a volcanic or non-volcanic island arc (Fig. 6). For example, between the Tungyintao and Pengchiahsu basins, arc volcanism of probable Palaeogene age exists on the Tungyintao ridge and is associated with significant magnetic anomalies on the Magnetic Anomaly Map of East Asia (1994). A relative positive gravity anomaly is associated with this ridge. However, this gravity anomaly extends in the southwest direction down to 24.5°N and is located just on the northwestern border of the Nanjihtao basin. This observation suggests that the Tungyintao ridge could be a remnant arc which continued west of the Nanjihtao basin. Similarly, the Nanjihtao ridge located between the Nanjihtao and Taishi basins could be a remnant arc, though no relative positive gravity anomaly is associated with it. However, because the backarc volcanic rocks are rare in the Okinawa trough and because the southern Ryukyu islands south of Okinawa Island do not show any arc volcanic rocks, it is not anticipated to systematically find backarc or arc volcanic material in all remnant backarc basins and island arcs. In particular, no significant magnetic anomalies are associated with the Tainan arc or some other remnant arcs identified on the continental shelf.

We consequently interpret ridges generally associated with positive or relative positive gravity anomalies and sometimes with positive magnetic anomalies as remnant arcs linked to the Ryukyu subduction zone. The width of the broad positive anomaly increases northeast of Taiwan probably because the subduction zone died southwest of Taiwan during Middle Miocene time and was consequently less developed. Based on these observations, four belts of remnant arcs could be identified on the continental margin, though less well defined than the four belts of basins. The oldest one (belt A) formed mostly during the Palaeogene consists of the Tungyintao ridge. Belt B possibly formed later during the Palaeogene and includes the Nanjihtao ridge and the Penghu high although the oldest volcanism dated there is Early Miocene. Belt C formed mostly during the Oligocene and Early Miocene and consists of the Tainan arc, the Tananao Complex and the Taiwan–Sinzi zone. Belt D is the Ryukyu arc active since the Middle Miocene with a present-day activity located on the southern border of the southern Okinawa trough (Sibuet et al., 1995). Though still provisional and speculative, the following belts of backarc basins and volcanic (or non-volcanic) arcs could have been formed within the Ryukyu subduction system at different periods: Belts 1 and A during the Paleocene, Belts 2 and B during the Eocene, Belts 3 and C during the Oligocene and Early Miocene, Belts 4 and D since the Miocene.

5. Tananao complex and eastern Backbone Range: the former arc of the Ryukyu subduction system

In our interpretation the Tananao complex and eastern Backbone Range correspond to the arc and forearc system of the former Ryukyu subduction zone. On the Bouguer anomaly map of Taiwan (Yeh and Yen, 1991), a 30-km wide positive stripe appears south of 24°N, on the eastern side of the island (Fig. 8). This area corresponds to the continuation of the Luzon arc but comprises not only the Coastal Range but also part of the Tananao Complex. Geological boundaries have been automatically determined by the method of the high-resolution enhanced analytic signal technique (Fig. 9) developed by Hsu et al. (1996b). The geological boundaries (crosses on Fig. 9) underline the locations of faults or density contrasts. This technique helps to identify the possible location of the former arc beneath Taiwan which is globally associated with a positive or relative positive anomaly. Surprisingly, the eastern hachured area corresponds mostly to the Tananao Complex but includes the eastern portion of the Backbone Range. Fig. 9 shows that the Tananao Complex and eastern Backbone Range lie in the direct continuation of the present-day Ryukyu arc. This correspondence has also been noticed by Cheng et al. (1996) on the basis of onshore and offshore seismic refraction experiments conducted in northeastern Taiwan. The velocity structure from the surface to 10–15 km depth beneath the eastern Central Range (Tananao Complex and eastern Backbone Range) is similar to the one of the Ryukyu arc but differs completely from the velocity of the Coastal Range (Luzon arc). Thus, Cheng et al. (1996) suggests that the eastern Central Range probably belongs to the southwestern Ryukyu arc. In fact, this correspondence existed before the opening of the Okinawa trough. At that time, the Ryukyu arc was adjacent to the Taiwan–Sinzi zone. Consequently, before the Okinawa opening and the Taiwan uplift, the eastern Central Range corresponded to the southwestward extension of the Ryukyu arc including at that time both the Taiwan–Sinzi zone and the present-day Ryukyu arc as already suggested by Wageman et al. (1970).

Fig. 9. Geological boundaries have been automatically determined by the method of the high-resolution enhanced analytic signal technique developed by Hsu et al. (1996b) applied to the Bouguer anomaly map of Taiwan (Yeh and Yen, 1991). The geological boundaries (crosses) underline the locations of faults or density contrasts. Hachured areas could correspond to fossil portions of the Ryukyu arc. Outside of Taiwan, satellite-derived marine free-air gravity anomalies are from Sandwell and Smith (1994). The eastern hachured area mostly corresponds to the Tananao Complex and the eastern Backbone Range. The western hachured area corresponds to the prolongation of the Tainan arc located just south of the onshore extension of the Tainan basin.


120°E
121°E
122°E
25°N
24°N
23°N
22°N
-250 -45 -15 -10 -5 0 5 10 15 20 25 30 35 40 45 200 mGal

Southwest of Taiwan, the offshore location of the former arc is suggested only by gravity data. The western hachured area near 23.3°N, 120.5°E corresponds to a relative positive anomaly (Fig. 8) and could be the onshore prolongation of the Tainan arc because it lies in the continuation of the Tainan arc (Fig. 9) and just south of the onshore prolongation of the Tainan basin (Figs. 1 and 6). However, due to the presence of thick sediments, geological data cannot help to identify the eastern hachured area (Fig. 9) as a portion of arc. As the two hachured areas in Taiwan are not connected but overlap, these portions of possible arcs could be related to two distinct backarc basins: one linked to the Tainan basin and the other one to the Hsüehshan trough (Fig. 6).

6. Plate kinematic evolution of Southeast Asia since the Early Miocene

How can the extension of the Ryukyu subduction zone southwest of Taiwan from Late Cretaceous to early Middle Miocene fit the plate kinematic evolution of the region? After subduction ceased along the South China Sea margin in the Late Cretaceous, rifting of the northern South China Sea margin started in Early Paleocene and the onset of spreading in early Late Oligocene (chron 11, 32 Ma; (Briais et al., 1993)). According to Ludwig et al. (1979) and Holloway (1982) the Reef and Macclesfield banks rifted away in the Paleocene from the northern South China Sea margin. Rifting of Pearl River basins (Fig. 7) located on the adjacent continental shelf occurred during the rifting episode of the margin and seems linked to it. Spreading stopped in the South China Sea in the Middle Miocene (chron 5c, 16 Ma; Taylor and Hayes, 1980; Pautot et al., 1986).

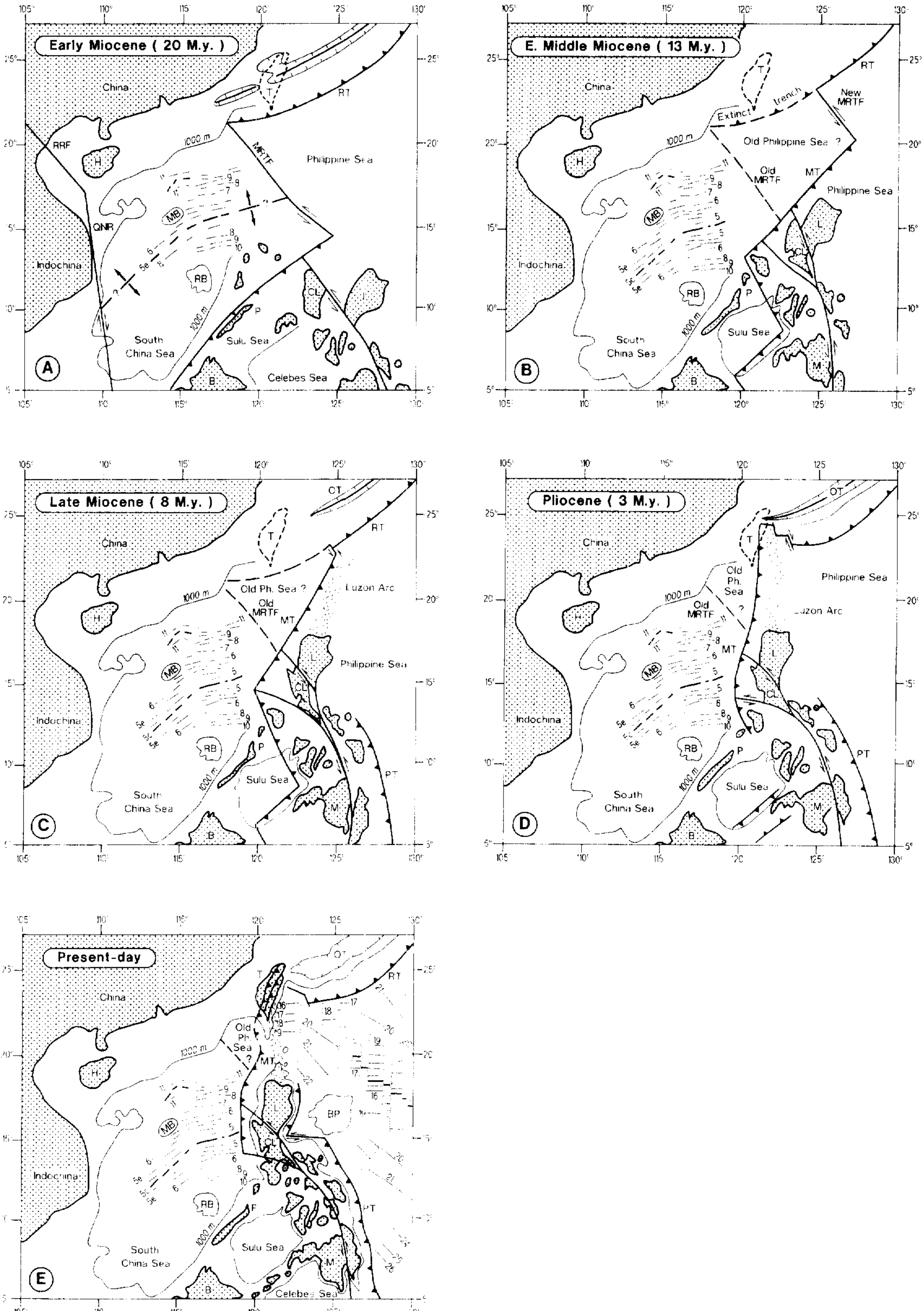
Because the Philippine Sea plate is bounded by active margins, its motion with respect to Eurasia is poorly constrained (Seno, 1977; Seno and Maruyama, 1984) though numerous palaeomagnetic data were obtained in and around the Philippine Sea plate (Fuller et al., 1991; Hall et al., 1995a,b) and constrain the latitudinal position of microplates. However, some authors postulate a late Cenozoic movement similar to the present-day one, and others assume a change in the Philippine Sea plate motion from NNW to WNW with respect to Eurasia in the Late Neogene based on deformations in the surrounding areas and palaeomagnetic data (Barrier and Angelier, 1986; Hall et al., 1995b). In addition, the Philippine mobile belt, which comprises all the islands located south of Taiwan, has a complex tectonic history, including subduction with polarity inversions, collision of allochthonous Eurasian terranes and major transcurrent faulting during the Tertiary (Rangin, 1991).

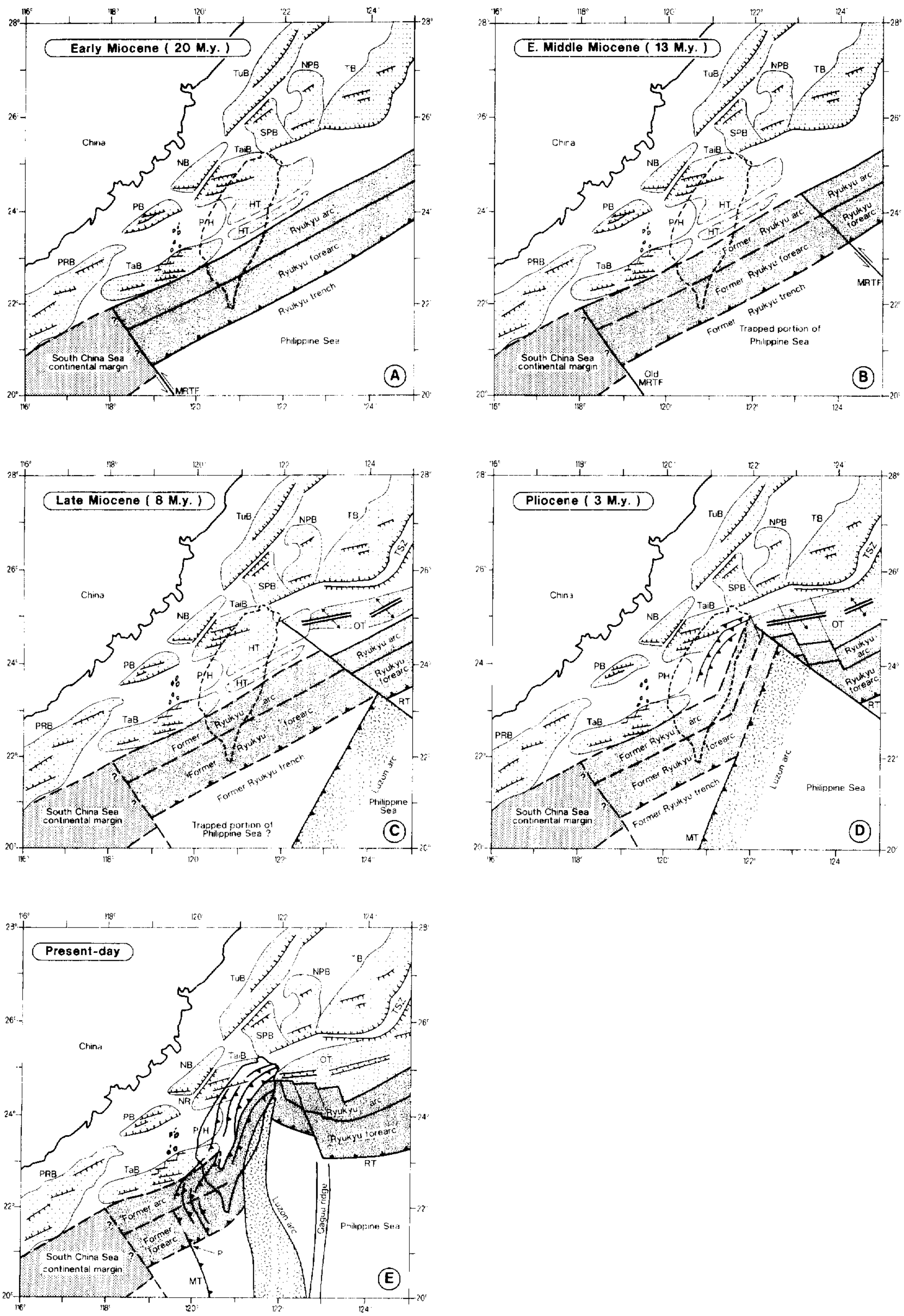
In the following sections we will present a series of five kinematic reconstructions, ranging from Early Miocene (20 Ma) to the present day, taking into account the geological constraints previously established. It is not in the scope of this paper to discuss the global kinematic framework of Southeast Asia but to start from the latest Cenozoic plate kinematic reconstructions (Rangin et al., 1990,b; Rangin, 1991; Lee and Lawver, 1994; Hall et al., 1995a,b; Lee and Lawver, 1995) and to show how the new geological constraints fit the modified kinematic reconstructions (Fig. 10). Though the Taiwan uplift started much more recently than at 20 Ma, the first discussed reconstruction concerns the Early Miocene in order to show how the Luzon arc formed before its collision with the former Ryukyu arc. Simultaneously, we will present a simplified sketch of the geodynamic evolution of the Taiwan region (Fig. 11).

6.1. Early Miocene (20 Ma) reconstruction of Southeast Asia (Figs. 10A and 11A)

The South China Sea was opening but at that time there was a significant change in the direction of opening from N–S to NW–SE and in the spreading rates (Pautot et al., 1986; Briais et al., 1993).

Fig. 10. Proposed kinematic reconstructions of the Southeast Asia region: (A) Early Miocene (20 Ma); (B) early Middle Miocene (13 Ma); (C) Late Miocene (8 Ma); (D) Pliocene (3 Ma); (E) Present-day. Magnetic lineations in the South China Sea from Briais et al. (1993) and in the west Philippine Sea basin from Hilde and Lee (1984). Abbreviations: *B* = Borneo; *BP* = Benham Plateau; *CL* = central Luzon; *H* = Hainan; *L* = Luzon; *M* = Mindanao; *MB* = Macclesfield bank; *MRTF* = Manila–Ryukyu transform fault; *MT* = Manila trench; *OT* = Okinawa trough; *P* = Palawan; *PT* = Philippine trench; *QNR* = Qui Nhon ridge; *RB* = Reed bank; *RRF* = Red River fault; *RT* = Ryukyu trench; *T* = Taiwan.


Early Miocene (20 M.y.)
China
RRF
QNR
Indochina
MRTF
Philippine Sea
RT
T
MB
RB
P
South China Sea
Sulu Sea
Celebes Sea
CL
B
1000 m
A
E. Middle Miocene (13 M.y.)
Extinct trench
New MRTF
Old Philippine Sea ?
Old MRTF
MT
L
M
B
Late Miocene (8 M.y.)
CT
Old Ph. Sea ?
Luzon Arc
PT
C
Pliocene (3 M.y.)
OT
Old Ph. Sea
Luzon Arc
D
Present-day
BP
E


Early Miocene (20 M.y.)
E. Middle Miocene (13 M.y.)
Late Miocene (8 M.y.)
Pliocene (3 M.y.)
Present-day
China
TuB
NPB
TB
SPB
TaiB
NB
PB
P/H
HT
PRB
TaB
OT
TSZ
NR
Ryukyu arc
Ryukyu forearc
Ryukyu trench
Former Ryukyu arc
Former Ryukyu forearc
Former Ryukyu trench
Former arc
Former forearc
Philippine Sea
Trapped portion of Philippine Sea
Trapped portion of Philippine Sea ?
South China Sea continental margin
MRTF
Old MRTF
RT
MT
Luzon arc
Gagua ridge
A
B
C
D
E

From 28 to 20 Ma and perhaps to Middle Miocene time, a large shear fault (the Qui Nhon ridge) was active along the Vietnam margin with a minimum right-lateral offset of 160 km (Rangin et al., 1995a; Roques et al., 1995). This ridge was the transform plate boundary which limited the South China Sea opening to the west. It was in the prolongation of the Red River fault, which was, before 16 Ma, a transtensional strike-slip system linked to the extrusion of the Indochina peninsula (Tapponnier et al., 1982; Huchon et al., 1993; Rangin et al., 1995a). A northwestward-verging trench was probably active north of Borneo and south Palawan. The southeastward-verging palaeo-Ryukyu trench was active from Japan to the west of the Tainan basin. A major transform fault, the Manila–Ryukyu transform fault (MRTF) connected the two trenches with opposite vergences and was the plate boundary between the Philippine Sea and South China Sea plates. The main difference with other plate reconstructions is that the MRTF either does not exist, which is not compatible with the simultaneous opening of the South China Sea (Taylor and Hayes, 1983; Lee and Lawver, 1994) or ends at the location of the future Taiwan island (Hilde et al., 1977; Letouzey et al., 1988; Angelier, 1990). On the continental margin, in the northwestward continuation of the MRTF, a transfer fault separated the Ryukyu subduction zone from the northern South China Sea passive continental margin. Luzon Island started to be built from 32 to 16 Ma as part of a volcanic arc. However, some authors linked the initial construction of Luzon Island to a subduction zone verging eastwards (Wolfe, 1981; Maleterre, 1989).

6.2. Early Middle Miocene (13 Ma) reconstruction of Southeast Asia (Figs. 10B and 11B)

A major plate reorganisation occurred in early Middle Miocene. The end of seafloor spreading at 16 Ma in the South China Sea, with the cessation of Qui Nhon transform fault activity to the west, was probably due to the collision of the north Palawan microplate with Borneo/south Palawan and the subsequent disappearance of the southern portion of the palaeo-Manila subduction zone. The end of the rifting phase in the continental shelf basins located around Taiwan (Taishi, Tainan and Taipei basins and the Hsüeshan trough) occurred about 13 m.y. ago, which means that the southwestern portion of the Ryukyu trench became inactive at that time and that consequently the Manila trench extended northeastwards, incorporating a portion of the old Philippine Sea plate in the South China Sea plate. The location of the former transform fault, which connected the Ryukyu and Manila trenches, has been identified on the satellite-derived marine gravity anomaly (Hsu and Sibuet, 1995) (NW–SE trend crossing 22°N, 118°E in Fig. 8).

Since 15 Ma, the left-lateral movement of the Philippine fault brought the northern Luzon close to its final position with respect to central Luzon (Barrier et al., 1991). The second well-constrained period of magmatism in the central cordillera of Luzon is dated 13–0 Ma after about 3 m.y. cessation of magmatic activity (Maleterre, 1989) and is linked to the eastward subduction along the Manila trench (Stéphan et al., 1986). Located north of Luzon Island, the Luzon arc started to form at that time as

Fig. 11. Detailed reconstructions around Taiwan. Abbreviations as in Fig. 6. Dark dotted areas, active backarc basins at the time of the reconstruction. (A) Early Miocene (20 Ma); the Tainan basin, the Hsüehshan trough and the Taipei basin were active backarc basins associated with the Ryukyu arc, forearc and trench. The Manila–Ryukyu transform fault (*MRTF*) separated the Philippine Sea and South China Sea (Eurasia) plates and was prolonged on the continental margin by a transfer fault which separated the Ryukyu subduction zone and the northern South China Sea passive continental margin. (B) Early Middle Miocene (13 Ma); the MRTF jumped northeastwards, leaving inactive a portion of the Ryukyu subduction zone located southeast of the Tainan basin and the Hsüehshan trough. (C) Late Miocene (8 Ma); the Taipei backarc basin became inactive but a new backarc basin, the Okinawa trough, started to open southeastwards since 12 Ma (Letouzey and Kimura, 1986) or 6 Ma (Kimura, 1996). (D) Pliocene (3 Ma); the Okinawa trough continued to open. The Luzon arc already collided with the former Ryukyu subduction zone, resulting in a northwestward bending of the former Ryukyu arc and forearc (Hsu et al., 1996a) and the shortening and uplift of the Hsüehshan trough. (E) Present-day; since 3 Ma, the Okinawa trough continued to open and collisional processes mostly occurring in the Hsüehshan trough before 3 Ma, mostly resumed in the shortening and uplift of the former Ryukyu arc and forearc (Tananao Complex and eastern part of the Backbone Range). Point *P*, the present-day contact between the Eurasia and Philippine Sea plates, is at the intersection of the Manila trench and the base of the northern South China Sea continental slope (southwestern extremity of the former Ryukyu trench).

an arc volcanic formation linked to the northeastern extension of the Manila trench. In the Lichi melange (Coastal Range), the oldest fragments of rhyolite and rhyodacite thought to belong to the Luzon arc have been dated 15 Ma (H. Bellon, pers. commun., 1996) which supports the relatively young age of the Luzon arc.

In early Middle Miocene (13 Ma), all continental shelf basins were already formed and at least partly filled with sediments except the Okinawa trough which did not exist at that time. The Hsüehshan trough, composed of the northwestern and southeastern depressions, was quite large (Teng, 1992) and probably did not extend southwest of the present-day Taipei basin. The Ryukyu arc and forearc were N60°-oriented and supposed to be linear as suggested by its present-day regular shape, at least between Japan and Okinawa Island.

6.3. Late Miocene (8 Ma) reconstruction of Southeast Asia (Figs. 10C and 11C)

After 13 Ma, the Luzon arc formed and a 20° counter-clockwise rotation of Luzon Island and the Luzon arc occurred in Middle to Late Miocene times (Stéphan et al., 1986). The new Manila–Ryukyu transform fault connecting the Ryukyu and Manila opposite-verging trenches was consumed, which initiated the collision between the Luzon arc and the Ryukyu subduction zone. Note that the counter-clockwise rotation of the Luzon arc is in contradiction with the proposed clockwise rotation of the Philippine Sea plate based on palaeomagnetic reconstructions (Hall et al., 1995a; Rangin et al., 1990). This discrepancy could be due to the former existence of a Luzon plate distinct of the Philippine Sea plate but similar in shape and position to the present-day Gagua plate (Fig. 2). In this hypothesis, the Luzon plate would have experienced a 20° counter-clockwise rotation with respect to the Philippine Sea plate.

8 m.y. ago, the Tainan basin, the Hsüehshan trough and the Taipei basin were inactive backarc basins as was the portion of the Ryukyu arc, forearc and trench located southeast of the Tainan basin and the Hsüehshan trough. A new backarc basin, the Okinawa trough, started to open at 12 Ma (Sibuet et al., 1987) or possibly 6 Ma (Kimura, 1996).

6.4. Pliocene (3 Ma) reconstruction of Southeast Asia (Figs. 10D and 11D)

The Philippine Sea plate continued to move in a northwestward direction and was consumed by subduction in the Ryukyu and Philippine trenches. Simultaneously, the South China Sea and the trapped portion of the old Philippine Sea subducted beneath the Philippine Sea plate.

Since 8 Ma, when the new Manila–Ryukyu transform plate boundary disappeared, the collision of the Luzon arc, considered as an indenter, with the former Ryukyu subduction zone has resulted in a 20° counter-clockwise rotation of the former Ryukyu arc and forearc (Fuller et al., 1991) which became roughly parallel to the Luzon arc (Hsu et al., 1996a) and could be due to the possible existence of a former Luzon plate. Thus, the westward component of the compressive stress from the collision of the Luzon arc should have become predominant in the collisional system resulting mostly, at the beginning of the collision, in the shortening and uplift of the Hsüehshan trough.

6.5. Present-day tectonic map of Southeast Asia (Figs. 10E and 11E)

Fig. 10E shows the present-day location of plates and microplates in the vicinity of Taiwan, and magnetic anomalies in the South China Sea and Philippine Sea (Hilde and Lee, 1984; Briais et al., 1993). Since the time of the collision of the Luzon arc with the Ryukyu subduction system, there is no major change in the Southeast Asian plate kinematic motions except that: (1) the rate of motion along the Philippine fault could have changed from 40 mm/y. (Lee and Lawver, 1994) to 20 mm/y. (Barrier et al., 1991); (2) the consequence of Taiwan uplift and of the relative locking north of the Manila trench was a counter-clockwise rotation of the trend of the Manila subduction zone; (3) the northeastern portion of the South China Sea progressively disappeared and the surface of the old trapped portion of the Philippine Sea plate was considerably reduced.

The Okinawa trough continued to open and collisional processes occurring in the Hsüehshan trough before 3 Ma mostly resumed, resulting in the shortening and uplift of the former Ryukyu arc and forearc (Tananao Complex and eastern part of the Backbone range). The shape of the Luzon arc deduced from the new bathymetric map (Fig. 2) decreased in width in a northern direction probably because of shortening during the collision with the former Ryukyu arc and forearc and because of the onset of subduction beneath northern Taiwan (Chemenda, 1994, 1995) and beneath the southwestern Ryukyu arc and forearc. Simultaneously, southwest of the Okinawa trough, the width of the former Ryukyu arc and forearc has decreased because compression and shortening mostly occurred in this region since at 3 Ma (Déramond et al., 1996). For clarity, the former Ryukyu arc and forearc have been drawn continuously although the analysis of the Bouguer anomaly in Taiwan (Fig. 9) has shown that the arc was probably cut into two distinct units in the same manner that the backarc basin was not continuous with the existence of the two independent basins, the Tainan basin and the Hsüehshan trough.

7. The arc–arc model

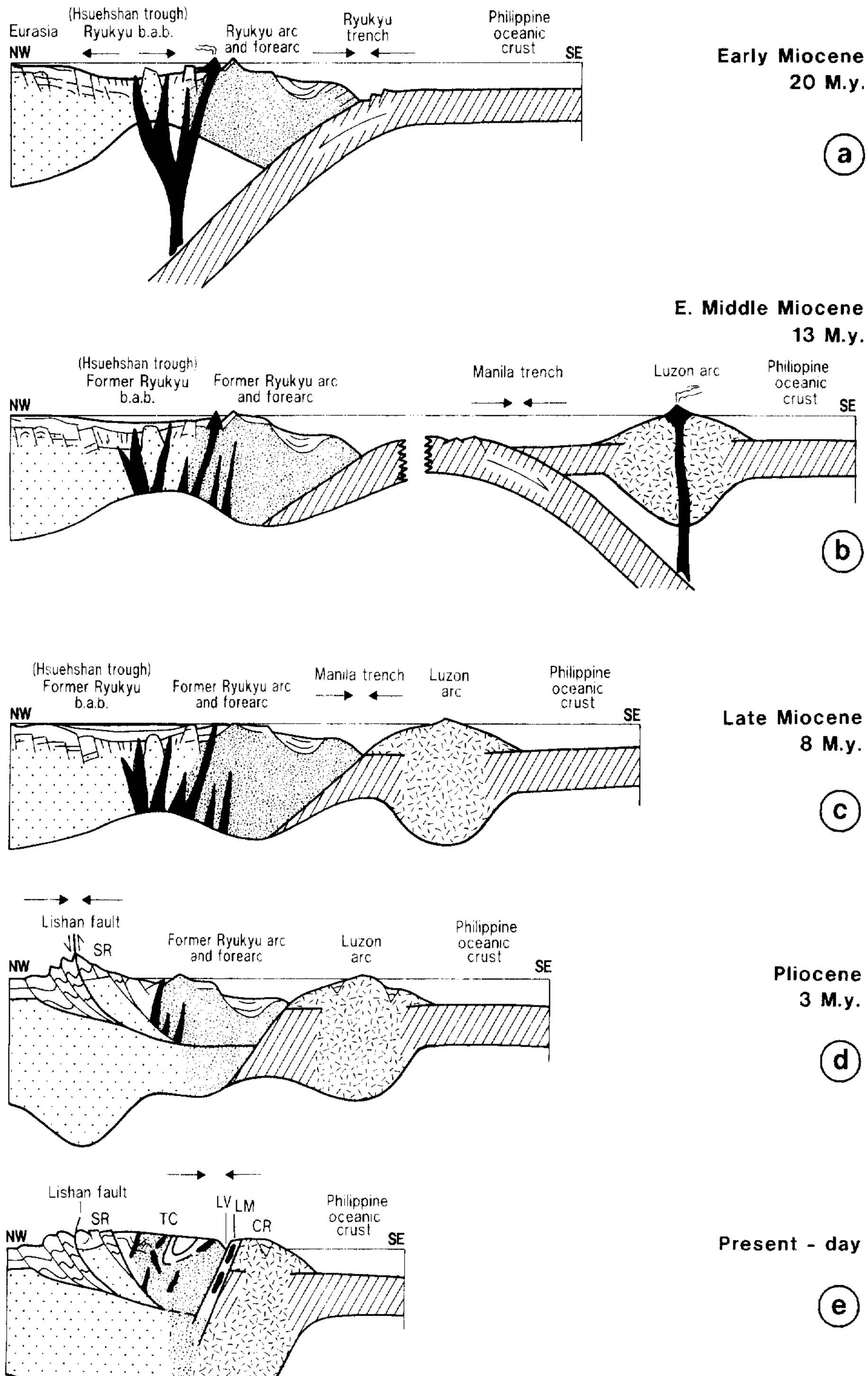
Fig. 12 shows the geodynamic evolution of the Taiwan area along a profile perpendicular to the Longitudinal Valley. In the Early Miocene (20 Ma), the Ryukyu subduction zone was active and extended southward of the present-day position of Taiwan (Fig. 12A). The Ryukyu backarc basin there was the 200-km wide Hsüehshan trough (Teng et al., 1991) with its double basins separated by a ridge. Slight backarc magmatic rocks intruded the Hsüehshan trough (Chen, 1991) and the continental crust was extremely thinned (about 15 km as today in the southern Okinawa trough (Hirata et al., 1991; Sibuet et al., 1995). A limited amount of arc volcanism appeared in the Ryukyu arc (Tananao Complex and eastern Backbone Range). On the Chinese continental shelf, the thickness of the crust was about 30 km. The Ryukyu arc and forearc developed with minor arc volcanism south of Okinawa Island as evidenced in the southern Ryukyu Islands. In a sense, this NW–SE cross-section located near 23.5°N is quite similar to the present-day cross-section of the Ryukyu subduction zone across the Okinawa trough (Letouzey et al., 1988), although not at the right scale because the slab does not dip enough and partial melting occurred at a depth of about 120 km in the continental lithosphere or in the downgoing oceanic crust.

In the early Middle Miocene (13 Ma), subduction ceased east of the present-day position of Taiwan and started further west with the intra-oceanic formation of the Luzon arc in the prolongation of Luzon Island (Fig. 12B).

In the Late Miocene (8 Ma), the already formed Luzon arc collided with the former Ryukyu subduction zone (Fig. 12C), filling first the gap between the Luzon arc and the former Ryukyu arc and forearc system until both features became almost parallel. At this stage, the two Ryukyu and Luzon arc crusts, about 25 to 30 km thick, were closely linked. In the constant compressive regime created by the northwest motion of the Philippine Sea plate with respect to Eurasia, the Luzon arc would not subduct beneath Eurasia mostly because it was a newly created buoyant feature which resisted to subduction. Behind, the Hsüehshan trough with a reduced crustal thickness of about 15 km in its deepest portion, was a peculiar zone of weakness.

Thus, between 8 and 3 Ma, compression was focused in the Hsüehshan trough, where the continental crust and lithosphere were the thinnest. As demonstrated on passive continental margins subject to subsequent compression, normal faults are reactivated as reverse faults (Whitmarsh et al., 1993). This probably happened in the Hsüehshan trough in particular along the Lishan fault, the southeastern main boundary fault of the northwestern depression whose vertical offset was very large. As a consequence, the whole lithosphere was deformed and the thickness of the crust increased beneath the Slate Range (previously the Hsüehshan trough) by a factor of 2 to 3.

About 3 m.y. ago, during the Pliocene, the former Hsüehshan trough was largely uplifted (Fig. 12D) and the crust was so thick that further compressive motion became almost impossible there, explaining why the compressive deformation jumped elsewhere and probably to the east, in the area of the two Ryukyu and Luzon arcs as suggested by Déramond et al. (1996). The compressive deformation localised there gave rise to the uplift, shortening and crustal thickening of the two colliding arcs. In fact, this scenario with compression, occurring first in the Hsüehshan trough and then in the region of the two arcs is oversimplified and is more complex, with


(Hsuehshan trough)
Eurasia
Ryukyu b.a.b.
Ryukyu arc and forearc
Ryukyu trench
Philippine oceanic crust
NW
SE
Early Miocene 20 M.y.
a
E. Middle Miocene 13 M.y.
(Hsuehshan trough) Former Ryukyu b.a.b.
Former Ryukyu arc and forearc
Manila trench
Luzon arc
Philippine oceanic crust
b
(Hsuehshan trough) Former Ryukyu b.a.b.
Former Ryukyu arc and forearc
Manila trench
Luzon arc
Philippine oceanic crust
Late Miocene 8 M.y.
c
Lishan fault
SR
Former Ryukyu arc and forearc
Luzon arc
Philippine oceanic crust
Pliocene 3 M.y.
d
Lishan fault
SR
TC
LV
LM
CR
Philippine oceanic crust
Present - day
e

compressive motions occurring in the two arcs region during the main shortening of the Hsüehshan trough and vice versa. In addition, the whole process is complicated by the propagation of the collision of the two arcs from north to south (Huang et al., 1995b). Beneath the Tananao Complex and the Slate Range, the Moho is presently at a constant depth (Fig. 12E) of about 40 km (Rau and Wu, 1995; Wu et al., 1995) which indicates that most of the deformation has already occurred in northern and central Taiwan and why the northern portion of the Luzon arc started to subduct beneath northeastern Taiwan (Chemenda, 1994, 1995) or beneath the southwestern Ryukyu arc and forearc to accommodate the convergent motion of the Philippine Sea plate with respect to Eurasia.

Our arc–arc model emphasises the physical processes involved during the compression. In particular, we have shown that the compressive deformation was not restricted only to the sedimentary cover as proposed by Suppe (1981), or the upper crust as proposed by Lu and Hsü (1992), but affected the whole crust and lithosphere (Rau and Wu, 1995; Wu et al., 1995). In fact, compressive deformation preferentially occurred within the weak portion of the lithosphere where basins are located. This constraint must be imperatively taken into account in all realistic schemes of the Taiwan formation at the expense, for example, of the extensive use of large superficial upper crustal thrust faults.

8. Consequences of the arc–arc model

8.1. Tectonic significance of the Longitudinal Valley

The Longitudinal Valley (Figs. 1 and 12) is the contact between the Coastal Range and the Tananao Complex. In the arc–arc model, the Longitudinal Valley is the initial plate contact between the former Ryukyu and Luzon arcs and forearcs. At the onset of the collision, the two features which come into contact were the Manila trench and the former Ryukyu trench located at the base of the northern South China Sea continental slope. Now, the contact is still at the intersection between the former Ryukyu trench and the Manila trench (point P in Fig. 11E). Consequently, point P moved through time from the northern part of the Longitudinal Valley to its present-day position (Fig. 11E). Since the beginning of the collision, the loci of points P are consequently the suture between the Eurasia and Philippine Sea plates. Since 8 Ma, sediments filled up the Tainan basin, and both the Tainan basin and the Tainan arc subsided because of the high accumulation rate and thermal cooling of the lithosphere. Simultaneously, the Manila sedimentary prism grew during the subduction of the South China Sea, with the accretion of sediments offscraped from the South China Sea, and the north Luzon trough (forearc basin) was closed by backthrusting of the accretionary prism (Lundberg et al., 1995). Due to the presence of so much sediments on both margins, the transfer of simple plate convergence from the Manila trench to the collision in Taiwan implies a complex lithospheric strain partitioning starting south of point P with most of the plate convergence transferred across the upper plate from near the Manila trench to near the forearc basin and Luzon arc. At the latitude of southern Taiwan, GPS data show that 60% of the plate convergence is now accommodated east of the Coastal Range and the rest west of the Coastal Range (Yu et al., 1995). The net result is a continuous change along strike in the direction of both the Manila trench and Luzon arc. Consequently, both the large accumulation of sediments on the two margins and the resulting complexity of the lithospheric strain partitioning along strike from subduction to collision partly hides the initial fundamental mechanism of the arc–arc collision model.

8.2. Significance of the Lichi and Kenting melanges in the arc–arc model

The Lichi and Kenting melanges are the two youngest Cenozoic melanges identified in Taiwan, respectively in the Coastal Range, south of the Longitudinal Valley, and in the Hengchun penin-

Fig. 12. Five-stage simplified scheme of the arc–arc model explaining the Taiwan collision since 20 Ma along a NW–SE cross-section located near 23.5°N. Arc and backarc volcanism in black; hachured areas, oceanic crust; largely spaced dotted areas, continental crust; closely spaced dotted areas, Ryukyu arc and forearc crust; areas with thin short lines, Luzon arc; *CR* = Coastal Range; *LM* = Lichi melange; *LV* = Longitudinal Valley; *SR* = Slate Range; *TC* = Tananao Complex. See text for explanations of the model.

sula at the southern tip of Taiwan. Without entering into the numerous detailed works done on the two melanges and into their controversial interpretations, their modes of emplacement can be easily integrated in the framework of the arc–arc model.

The Lichi melange is located west of the forearc sequences of the Luzon arc and east of the Philippine Sea–Eurasia plate suture. It is of Pliocene age with a mixture of Miocene and Pliocene sediments and contains millimetre- to kilometre-size sedimentary blocks and ophiolitic blocks derived from the South China crust according to Liou et al. (1977), but from the old Philippine Sea in our interpretation (Fig. 10). The melange extends southward to the offshore Huatung ridge (Huang et al., 1995b).

Modified from Pelletier and Stéphan (1986) and Huang et al. (1995b), we suggest that the emplacement of the Lichi melange could be the following:

(1) In the Late Miocene, the continent-derived turbidites were deposited on the continental slope of the Ryukyu subduction system and in the deep ocean (old Philippine Sea).

(2) In the Pliocene, part of the Philippine Sea oceanic crust, continent-derived slope and deep-sea sediments were offscraped during the Luzon arc and former Ryukyu arc collision (Fig. 12D, E) to form the Huatang accretionary wedge. This wedge was further sheared along the plate boundary.

The NW–SE-trending Kenting melange contains sheared blocks of basalts, volcanics, with intercalation of Miocene cherts and sedimentary blocks identical to the Miocene deep-water turbidites of the Mutan formation deposited on the continental slope of the Ryukyu subduction system (Pelletier et al., 1985). Mixing of Pleistocene microfossils with the Miocene fauna has been described by Huang (1984). The Kenting melange is intensively sheared and faulted as well as its contact with the Mutan formation. It is interpreted as a thick Pleistocene mega-shear zone developed on the continental margin after the formation of the Lichi melange (Huang et al., 1995a).

Modified from Pelletier and Stéphan (1986) and Huang et al. (1995a), we suggest that the emplacement of the Kenting melange could be the following.

(1) In the Late Miocene, turbidites were deposited in canyons of the continental slope of the Ryukyu subduction system. These canyons were oriented NW–SE, more or less perpendicular to the N60° direction of the subduction zone (Fig. 11B). Conglomerates and pebbles probably come from the Ryukyu arc which could include rocks initially belonging to the Asian continent.

(2) In the Pliocene, the Luzon arc and the former Ryukyu arc, forearc and accretionary prism collided at the latitude of the Hengchun peninsula (Fig. 11C). The first moderate deformation of these sediments formed the incipient Hengchun prism.

(3) About 2 m.y. ago, the Manila trench was closed east of central Taiwan but extended southward along the partly closed Southern Longitudinal trough.

(4) In the Pleistocene, thrusts faults parallel to the N60° Ryukyu margin were active and a mega-shear zone developed within the Hengchun prism, in a direction perpendicular to the former Ryuku subduction system (Fig. 11D, E). Pieces of the Philippine Sea oceanic crust could have been brought up either by thrust faulting or more probably within the mega-shear zone. The occurrence of Pleistocene fauna in the Kenting melange indicates that the thrusting took place in the Pleistocene at approximately 1 Ma.

In this scheme, both the Lichi and Kenting melanges have been emplaced in the same tectonic context but at different periods due to the progressive contact and collision, from north to south, of the Luzon arc and the former Ryukyu subduction system. From a mechanical point of view, the Luzon arc could be viewed as an indenter belonging to the Philippine Sea plate which is pushed in the northwest direction with respect to Eurasia. The collision is oblique (about 30° between trends of the Luzon arc and the Ryukyu margin, Fig. 11C) and consequently progressed from north to south. However, because the Luzon arc is a moderate-size feature with respect to large indenters as the Indian plate for example, this explains why subduction of the Luzon arc could have started recently in the north and why the arc could have been broken and could have progressively changed direction in the south (Fig. 2 and Fig. 11E). A series of 4 large earthquakes located in the Philippine Sea west of the Gagua ridge (Wu, 1978) (Fig. 2) suggests that a N75°-oriented right-lateral strike-slip fault could presently have started to broke the Luzon arc at 22.4°N. Other large earthquake ($M > 6$) focal mechanisms show that the northern part of the Philippine Sea plate bounded by the Luzon arc, the eastern Ryukyu trench, the Gagua ridge and this dextral strike-slip fault could correspond to the initiation of a new plate that we name the Gagua plate, characterised by a smaller northwest motion than the Philippine Sea plate with respect to Eurasia. This observation suggests that friction increases between the Coastal Range and the former Ryukyu subduction zone and, from a kinematic point of view, that a decoupling zone might exist in the southwest prolongation of the dextral shear fault up to the Manila trench. Several lines of evidence suggest that this transform plate boundary exists today: (1) the seismicity associated with the Manila Wadati–Benioff zone disappears north of 21.5°N (Tsai, 1986; Cheng and Yeh, 1991); (2) a dextral shear motion has been suggested south of Taiwan (Lin and Tsai, 1981) from focal determinations of shallow earthquakes located south of Taiwan (F. Wu, pers. commun., 1995); (3) the satellite free-air anomaly map (Fig. 8) shows an E–W discontinuity at 21.5°N with high gravity values to the north and low gravity values to the south. Consequently, it seems that the arc–arc collision model which explains the formation of Taiwan is now evolving in a more complex stage in which the Luzon arc does not react as an undeformable body.

9. Conclusions

The arc–arc collision model was initially proposed by Hsu and Sibuet (1995) on the basis of an overview of the satellite-derived marine gravity anomalies (Sandwell and Smith, 1994) which shows that the Okinawa trough has the same gravity signature as the Tainan basin. Therefore, Hsu and Sibuet suggested that the Ryukyu subduction zone extended before the formation of Taiwan a few hundreds of kilometres south of its present-day termination and that Taiwan resulted from an arc–arc collision model rather than from an arc–continent collision model. In this paper we have examined this hypothesis in detail and outlined the following points.

(1) The numerous basins of the continental shelf are located within four belts which are parallel to the main China shoreline.

(2) Rifting occurred at the same time within the basins belonging to each of these four belts and these basins become younger oceanward. The four rifting phases occurred during Paleocene, Eocene, Oligocene–Early Miocene and early Middle Miocene–Present times.

(3) The basins are separated by ridges where volcanic material generally exists. These ridges seem to be of the same age as basins located immediately northwest.

(4) We interpret these basins and associated ridges as backarc basins and portions of relict arcs linked to the Ryukyu subduction zone which have been successively active from the early Tertiary to today in the Okinawa trough.

(5) The Pearl River basins are tensional basins formed during the rifting of the northern South China Sea margin.

(6) The Ryukyu subduction zone extended from southwest Taiwan to Japan until the early Middle Miocene where the southeast portion of the subduction zone facing the Tainan basin and the future Taiwan island became inactive.

(7) The geology of the Southeast Asian continental shelf supports the existence of a former subduction zone with which the Luzon arc entered into contact in the Late Miocene.

(8) The kinematic evolution of the Southeast Asian region is compatible with such constraints.

(9) Collision between the Luzon arc and the former Ryukyu subduction zone started with the deformation and uplift of the Hsüehshan trough backarc basin, where the continental crust and lithosphere were thin and weak, followed by the major compression and uplift of the Luzon and former Ryukyu arcs.

The main difference between the model of Lu and Hsü (1992) and the arc–arc model is that in the first model the Tananao Complex is considered as an exotic block which first collided with the Eurasian margin in the Middle Miocene, the Backbone Range being the associated deformed accretionary wedge, and that in our model, the Tananao complex and eastern Backbone Range are a portion of the former Ryukyu arc. These two models are fundamentally different and should be tested. In particular in the Lu and Hsü (1992) model, the origin of the exotic block travelling with the Philippine Sea plate, as well as the origin of the accretionary wedge must be established. In our model, initially based on geophysical considerations, the origin of the arc and backarc magmatism must be better established by looking in more detail at the geochemistry of the few magmatic occurrences.

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