East Asia plate tectonics since 15 Ma: constraints from the Taiwan region

Jean-Claude Sibuet^{a,*}, Shu-Kun Hsu^b, Xavier Le Pichon^c, Jean-Pierre Le Formal^a,
Donald Reed^d, Greg Moore^e, Char-Shine Liu^f

^a*Ifremer Centre de Brest, DROIGM, B.P. 70, F-29280 Plouzané Cedex, France*

^b*Institute of Geophysics, National Central University, Chung-Li, Taiwan*

^c*Collège de France and Ecole Normale Supérieure, 24 rue Lhomond, 75231 Paris Cedex 05, France*

^d*Department of Geology, San Jose State University, San Jose, CA 95192-0102, USA*

^e*Department of Geology and Geophysics, University of Hawaii, 2525 Correa Road, Honolulu, HI 96822, USA*

^f*Institute of Oceanography, National Taiwan University, P.O. Box 23-13, Taipei 106, Taiwan*

Received 17 January 2001; accepted 10 September 2001

Abstract

15 Ma ago, a major plate reorganization occurred in East Asia. Seafloor spreading ceased in the South China Sea, Japan Sea, Taiwan Sea, Sulu Sea, and Shikoku and Parece Vela basins. Simultaneously, shear motions also ceased along the Taiwan–Sinzi zone, the Gagua ridge and the Luzon–Ryukyu transform plate boundary. The complex system of thirteen plates suddenly evolved in a simple three-plate system (EU, PH and PA). Beneath the Manila accretionary prism and in the Huatung basin, we have determined magnetic lineation patterns as well as spreading rates deduced from the identification of magnetic lineations. These two patterns are rotated by 15°. They were formed by seafloor spreading before 15 Ma and belonged to the same ocean named the Taiwan Sea. Half-spreading rate in the Taiwan Sea was 2 cm/year from chron 23 to 20 (51 to 43 Ma) and 1 cm/year from chron 20 (43 Ma) to 5b (15 Ma). Five-plate kinematic reconstructions spanning from 15 Ma to Present show implications concerning the geodynamic evolution of East Asia. Amongst them, the 1000-km-long linear Gagua ridge was a major plate boundary which accommodated the northwestward shear motion of the PH Sea plate; the formation of Taiwan was driven by two simple lithospheric motions: (i) the subduction of the PH Sea plate beneath Eurasia with a relative westward motion of the western end (A) of the Ryukyu subduction zone; (ii) the subduction of Eurasia beneath the Philippine Sea plate with a relative southwestward motion of the northern end (B) of the Manila subduction zone. The Luzon arc only formed south of B. The collision of the Luzon arc with Eurasia occurred between A and B. East of A, the Luzon arc probably accreted against the Ryukyu forearc. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Plate tectonics; East Asia; Taiwan; 15 Ma

1. Introduction

The Taiwan mountain belt is one of the youngest in the world and is still in construction. Regarding this collision zone, three main hypotheses have been proposed: (1) the thin-skin tectonic model of Suppe

* Corresponding author. Fax: +33-2-98-22-45-49.

E-mail addresses: jcsibuet@ifremer.fr (J.-C. Sibuet),
hsu@oc.gep.ncu.edu.tw (S.-K. Hsu), lepichon@sphene.ens.fr
(X. Le Pichon), leformal@ifremer.fr (J.-P. Le Formal),
dreed@geosun1.sjsu.edu (D. Reed), moore@soest.hawaii.edu
(G. Moore), csliu@ccms.ntu.edu.tw (C.-S. Liu).

(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; Sibuet and Hsu, 1997) in which, 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 this paper is to improve the kinematic context in which the island of Taiwan was formed, and to identify the origin of the oceanic crust adjacent to Taiwan (relationship to the Philippine Sea (PH), South China Sea (SCS) or other oceanic domain?) in order to constrain geodynamical models of Taiwan formation. Three sets of data will be used: (1) magnetic anomaly and gravity maps compiled around Taiwan by some of us (Hsu et al., 1998) and updated for the magnetic map with newly acquired data south of Taiwan; (2) a specific geophysical survey (R/V *l'Atalante* ACT survey) designed to identify the southwestern extension of the former Ryukyu subduction zone; and (3) deep seismic lines (R/V *Maurice Ewing* EW9509 survey) acquired on the northeast SCS margin.

2. Late Tertiary motion of the Philippine Sea plate with respect to Eurasia

The Sloan and Patriat (1992) geomagnetic polarity timescale has been used throughout this paper. The west Philippine Sea plate (WPH) formed during two distinct spreading phases, before and after subduction initiated along the Palau Kyushu trend, 54 Ma ago (boninites, commonly attributed to the initiation of subduction, were found along the Izu–Bonin–Mariana trend at the eastern edge of the PH (Cosca et al., 1998)). From chrons 26 to 20 (57–43 Ma), spreading was NE–SW oriented with respect to the present-day position of the Philippine Sea plate (PH) and from chrons 20 to 13 (43–36 Ma), spreading changed to N–S (Hilde and Lee, 1984). In the Shikoku and Parece Vela basins (east Philippine Sea plate, EPH), rifting started 29 Ma ago and spreading resumed in an E–W direction from

chrons 7 to 6A (27–21 Ma) and then in a NE–SW direction from chrons 6A to 5B (21–15 Ma) (Chamot-Rooke et al., 1987; Okino et al., 1998, 1994).

Because the PH is bounded by active margins, its motion through time with respect to the Eurasia plate (EU) is poorly defined (Seno, 1977; Seno and Maruyama, 1984). The inversion of earthquake slip vector data along the PH boundaries constrains reasonably well the present-day motion (Seno et al., 1993); however, the absence of an accreting plate boundary precludes use of magnetic anomaly information or transform strike data to determine the PH motion through time with respect to adjacent plates. However, we can use two types of information to constrain the PH/EU motion: (i) the paleomagnetic data obtained in and around the PH (Fuller et al., 1991; Hall et al., 1995a,b), which help to define the latitudinal position of microplates; (ii) PH boundary geological constraints as the orientation of the Gagua ridge, which is a former transform plate boundary (this paper and Deschamps et al., 1998) or the observation that the contact point of the Izu–Bonin ridge with Eurasia remained in its present-day position since late Miocene (Seno and Maruyama, 1984) or more probably since early Miocene (15 Ma) (Aoike, personal communication, 1997). Thus, the PH late Tertiary motion could be summarized as follows.

(1) 8 Ma ago, the Izu–Bonin collision started vigorously with the accretion of Tanzawa, the uplift of northern Japan, and a weak compression in the Japan Sea. These tectonic events continued until Present. Consequently, since 8 Ma, the PH/EU pole of rotation has been located northeast of Japan. The PH motion was the same for the last 8 Ma and we have adopted for this period (8 Ma to Present) the present-day PH/EU motion determined by Seno et al. (1993) from seismic slip vectors. This pole position was recently confirmed by using GPS observations on the PH (Kotake and Kato, 1998) (Table 1).

(2) About 15 Ma ago, a major plate kinematic rearrangement occurred in East Asia with: (a) the end of opening of the SCS (Briais et al., 1993), Japan Sea (Jolivet et al., 1994), and Shikoku and Parece Vela basins (Okino et al., 1994, 1998); (b) the first contact between the Izu–Bonin arc with Honshu (Aoike, personal communication, 1997); (c) the Ryukyu subduction retreat from west to east of Taiwan and the end of the rifting phase for the east China Sea and

Table 1

Tertiary motion of the Philippine Sea plate with respect to Eurasia

Epoch	Latitude	Longitude	Angular rotation (°/Ma)	References
Before 15 Ma	15°N	160°E	– 3	(Hall et al., 1995b)
Before 15 Ma	30°N	180°E		(this study)
8–15 Ma	35°N	140°E	– 2	(Taira et al., 2000, submitted), (adopted in this study)
0–8 Ma	48.2°N	152°E	– 1.09	(Seno et al., 1993), (adopted in this study)
0–8 Ma	41.55°N	152.46°E	– 1.50	(Kotake and Kato, 1998)

northeastern SCS continental shelf basins (Sibuet and Hsu, 1997); (d) the eastward to westward change in the subduction vergence beneath Luzon (Wolfe, 1981; Maletierre, 1989); and (e) the end of opening of the Sulu Sea (Rangin and Silver, 1991) and the beginning of the western convergence in the Molucca Sea (Sangihe arc) (Moore and Silver, 1982). Judging from the weak collision of the Izu–Bonin arc with Honshu, the transgression on the northern Honshu and southwest Japan margins and the presence of widely dispersed granitic and andesitic (magnetite) volcanic occurrences over the whole Japan (A. Taira, personal communication, 1998), subduction ceased at that time, suggesting a location of the PH/EU pole of rotation close to Honshu (Table 1). Thus, from 15 to 8 Ma, the PH/EU clockwise motion was considerably reduced near Japan, but with almost the same amplitude as previously for the southern portion of the PH. We consequently suggest that the pole of rotation was located near Honshu for the 15 to 8 Ma period (Table 1 and Fig. 1).

Though different from the location of poles proposed from paleomagnetic data alone (Hall et al., 1995b), the computed latitudes of paleomagnetic sites in and around the PH by using our poles of rotation for the past 15 Ma are within the bounds of paleolatitudes deduced from paleomagnetic measurements (Hall et al., 1995a and R. Hall, personal communication, 2001).

(3) Before 15 Ma, the PH/EU motion was significantly different. Hall et al. (1995b) (Table 1 and Fig. 1) proposed a clockwise motion with an $\sim 5^\circ$ error in the latitude for their early Neogene pole of rotation. Such a northward motion and a clockwise rotation of the PH/EU seem to be now widely accepted. Nevertheless, a 010°N direction of convergence is predicted

in the Taiwan area. A northward shift of the Hall et al. (1995b) pole of rotation is thus required to match the N–S trend of the Gagua ridge. This northward shift of the Hall et al. pole must be still increased to take into account the following 15 Ma to Present PH/EU rotation. Though it is not the purpose of this paper, the combination of geological and paleomagnetic constraints suggest that the pole might be located close to 30°N ; 180°E , a location still belonging to the path within which rotation poles must lie to satisfy the paleomagnetic data alone (Hall et al., 1995a).

3. Morphology and structure of the northeastern South China Sea

3.1. *R/V Maurice Ewing EW9509 and l'Atalante ACT surveys*

During the EW9509 cruise (July 1995) of the *R/V Maurice Ewing*, multichannel seismic (MCS) lines were shot in the northeastern SCS (Fig. 2) as part of an ongoing cooperative project between USA and Taiwan. The source was an array of 20 airguns with a volume of 8425 c.i. (135 l), recorded on a 4.2-km-long 160-channel streamer at 2 ms in SEG-Y. The following processing sequence was applied: alias filter and resample to 4 ms, true amplitude recovery, velocity analysis every 100 common middle points, 3–6; 64–72-Hz bandpass filter, predictive deconvolution, normal moveout, dip moveout, velocity analysis, Radon velocity filter for multiple attenuation, top mute, inside mute for additional multiple attenuation, stack, F–K migration and scale (500 ms AGC). Only MCS lines 34, 35 and 45 are shown in this paper. Magnetic and 3.5 kHz data were

Fig. 1. Satellite-derived marine gravity map of Sandwell and Smith (1994) showing the main physiographic features of East Asia. J, Japan; L, Luzon; OT, Okinawa Trough; Ph, Philippine Sea; PV, Parece Vela basin; S, Shikoku basin; SCS, south China Sea; T, Taiwan. The white arrow shows the Taiwan–Sinzi folded zone. Large black dots are the locations of rotation poles of Table 1.

collected simultaneously at a mean ship's speed of 5 knots.

During the active collision in Taiwan (ACT) cruise (June 1996) of the R/V *l'Atalante* (Lallemand et al., 1997) and the following transit between Taiwan and

New Caledonia, an integrated geophysical survey of the northeastern SCS and Manila accretionary prism was conducted as part of an ongoing cooperative project between France and Taiwan (Fig. 2). Eight EM12 swath-bathymetric profiles trending ENE–

Fig. 2. General bathymetric map and topography of Taiwan every 200 m from Liu et al. (1998) completed by ETOPO5 data (west of 118°E and south of 20°N). 99 to 101 are locations of seismic reflection profiles acquired during the ACT cruise of the R/V *l'Atalante* (June 1996, continuous lines) and shown on Fig. 3. 34, 35 and 45 are locations of seismic profiles acquired during the EW9509 cruise of the R/V *Maurice Ewing* (July 1995, dashed lines) and shown on Fig. 6. The deformation front corresponds to the Manila trench in the south and to the western limit of compressional features in the north (Liu et al., 1997). Fracture zones FZ1, FZ2 and FZ3 were identified on the ACT seismic profiles and Ewing profile 45. Gray lines are plate boundaries, which limit to the south both the northeastern south China Sea (proto-SCS) and the Huatung basin sensu stricto. The third gray line is the boundary between the Luzon island arc and the Luzon arc. HP, Hengchun peninsula.

WSW and each about 100 km long were acquired in the oceanic domain, west of the northern part of the Manila trench, in order to determine the location of a

possible former plate boundary. In addition, six-channel high-speed (10 knots) seismic data using two GI (generator/injector) guns operated in harmonic mode

(Pascouet, 1991) were collected simultaneously with gravity, magnetic and 3.5 kHz data. The following processing sequence was applied to all seismic profiles: F–K filter, 4–12; 35–45 Hz bandpass filter, threefold stack with a constant velocity of 1480 m/s, Kirchhoff migration with a constant velocity of 1420 m/s. The swath-bathymetric coverage was almost complete. Fig. 2 shows the survey track lines with a line spacing of 10 nautical miles (18.5 km).

3.2. Morphology of the northeast South China Sea

Swath-bathymetric data were used to produce a digital terrane model bathymetric grid with a 125-m spacing. The gridded raw digital terrane model, illuminated from 290°N with a low elevation viewpoint (Plate 1A), outlines the following main topographic features.

(1) The deformation front corresponds to the Manila trench in the south and to the western limit of compressive features located southwest and west of Taiwan (western Foothills).

(2) A major canyon, named the Formosa canyon (Liu et al., 1998), begins on the upper part of the Chinese continental slope, where the margin changes direction from E–W to N–S (Fig. 2 and Plate 1A). Then, the canyon abruptly changes direction from 135°N to 090°N just north of a large oceanic seamount and further southeast merges with the 155°N-trending Penghu channel, which roughly follows the northern portion of the deformation front (Liu et al., 1997).

(3) Seismic sections acquired in this area (Fig. 3) display sediment waves in the uppermost parts of the sections, the rest of the sedimentary pile being unaffected. For some of the eight seismic sections, the morphological expression of surface sedimentary fea-

Plate 1. (A) Bathymetric map in Mercator projection of the northeast south China Sea and its northern margin established from the ACT swath-bathymetric EM12D and EM950 data. The 290°N simulated hill-shading of the swath-bathymetric data established from the gridded data set every 125 m is superposed over the bathymetric background established by Liu et al. (1998). The two elongated areas correspond to fracture zone identifications FZ1 and FZ2 and the gray line to the plate boundary between south China Sea and northeastern south China Sea based on morphology, gravity and magnetic data. Note the presence of large sediment waves corresponding to turbidite overflows on the external sides of canyons after each abrupt change in canyon trends, both for the Penghu canyon at lat 21°45'N and the Formosa canyon at lat 21°20'N. (B) Seismicity map of Taiwan with earthquakes recorded during the 1991–1997 period and determined by the Central Weather Bureau of Taiwan. A and B are vertical planes which bound the Ryukyu and Manila subduction zones. Isobaths of the Wadati–Benioff zones are every 50 km. South of B, the Luzon arc is forming; between A and B, the Luzon arc is colliding with the Eurasia margin; east of A, the Luzon arc is probably accreted to the Ryukyu forearc.

Plate 2. (A) Basement depth in seconds two-way traveltime (s.t.w.t.) of a portion of the northeast south China Sea (southern portion of the box in Fig. 2). Open dots are basement depth control points (ACT and EW9509 profiles). Contours every 0.2 s. Fracture zones (FZ1, FZ2 and FZ3) and the plate boundary between south China Sea and northeastern south China Sea (proto-SCS) have been identified on seismic profiles of Fig. 3 and correspond to gradients on the seismic profiles and in the basement map. (B) Detailed magnetic grid established by using available data already included in the grid of Hsu et al. (1998) and data systematically collected since 1998 during six cruises (N–S-oriented profiles with a 10-km spacing). In the northeastern south China Sea (proto-SCS), fractures zones FZ1, FZ2 and FZ3 are parallel to magnetic lineations. Beneath the Manila accretionary prism, magnetic lineations are weak and 253°N–256°N-oriented. The Manila trench and its northern prolongation, the deformation front, abruptly separate two distinct oceanic domains.

Plate 3. (A) Free-air anomaly map of the Taiwan area (Hsu et al., 1998). Black areas corresponds to gravity values < -45 mgal. The deformation front corresponds to the Manila trench in the south and to the western limit of compressional features in the north (Liu et al., 1997). The two elongated areas correspond to fracture zone identifications (FZ1 and FZ2) based on the ACT seismic data. Two gray lines are plate boundaries between south China Sea and northeastern south China Sea (proto-SCS) and in the Huatung basin. The third gray line is the limit between the Luzon island arc and the Luzon arc formed since 15 Ma. (B) Magnetic anomaly map of the Taiwan area (Hsu et al., 1998). The square box located south of Taiwan corresponds to the new magnetic grid established with already available data (Hsu et al., 1998) and magnetic data systematically collected south of Taiwan by one of us (S.-K. Hsu). See legend of Plate 3A for the definition of the deformation front and plate boundaries. P1 to P5 are profiles along which magnetic data were extracted.

Plate 4. Plate kinematic reconstructions of East Asia: (a) Early middle Miocene (15 Ma⁺); (b) Early middle Miocene (15 Ma[−]); (c) Late Miocene (8 Ma); (d) Pliocene (3 Ma); (e) Present-day. Yellow, continental domain; white, oceanic domain; ochre, intraoceanic arcs; thick red lines, active plate boundaries; large red arrows, WPH/EU or PH/EU motions; large black dot, pole of rotation (Table 1). Fracture zones and main magnetic lineations with their identifications are shown. Spreading ceased at the same time (15 Ma) in the Taiwan Sea, SCS, Sulu Sea, Japan Sea, and Shikoku and Parece Vela basins.

tures corresponds to the underlying basement topographic highs. However, where recent sediment waves do not hide this topographic expression, most of the associated bathymetric features are laterally shifted with respect to the location of basement features. On the two northern profiles (110 and 111), though the sediment thickness is larger than 2 s (t.w.t.), the 315°N portion of the Formosa canyon seems to have been controlled since its formation by the basement morphology. Southeast of the large volcanic seamount located at lat 21°08'N, a 315°N-trending topographic limit, which corresponds to the western limit of recent sedimentary waves, lies in the extension of the northern portion of the channel. Consequently, the morphology established from swath-bathymetric data underlines a 315°N-oriented feature located between lat 20°40'N and lat 21°30'N which corresponds, as shown later, to a former plate boundary.

3.3. Basement features of the northeast South China Sea

Fig. 3 shows the eight seismic profiles and their interpretations aligned on their right-hand side on the deformation front. Two basement topographic gradients are underlined by double arrows and thick gray lines. On the two northern profiles (110 and 111), the basement depth is greater than 2 s (t.w.t.), the maximum depth of penetration which can be reached with the high-speed (10 knots) seismic system used during the ACT cruise. The acoustic basement is thus poorly defined and the northwestern basement extension cannot be clearly followed. However, in this area, several sedimentary features affecting the whole sedimentary column are observed beneath the Formosa canyon and are linked to the role of dam through time of these two closely spaced parallel features (Fig. 3). These features are characterized by a basement high located on their western side, except on Profile 108, where a seamount culminates about 3 km above the mean basement depth. West of the basement highs and because of the eastward basement deepening linked to the subduction zone, the mean basement depth is significantly shallower. Despite the large 20-km seismic line spacing of the ACT survey, a general eastward deepening of the basement is observed: the two features make a significant angle with the direction of the trench and are not associated with the subduction system.

The basement map (Plate 2A) has been established from the eight ACT profiles acquired perpendicularly to the deformation front and the southern portions of EW9509 profiles 34, 35 and 45. The ACT profiles end in the deeper part of the Manila accretionary prism. Basement depths were digitized and gridded every one-arc minute. Despite the 20-km spacing of ACT seismic lines and the poor spatial resolution giving rise to peaks and depressions along survey lines, the resulting 0.2 s (t.w.t.) contoured map shows two significant 290°N-oriented basement gradients underlined by polygonal areas which correspond to the two closely spaced features already identified on seismic profiles (Fig. 3). We interpret these two features as oceanic fracture zones that we name FZ1 and FZ2. In the northern part of the basement map, another 290°N-oriented feature corresponds to a third fracture zone (FZ3) also characterized by a basement depth larger on its northeastern side.

Though a general basement deepening is observed west of the deformation front and the Manila trench, the mean direction of basement deepening is not perpendicular to the deformation front, but oriented 040°N, in the direction roughly perpendicular to the 315°N-oriented plate boundary that we name the Luzon–Ryukyu transform plate boundary (LRTPB). The mean basement depth, corrected for the sedimentary load, is about 0.8 km shallower southwest of the LRTPB than northeast in the area away from the deformation front near 21°30'N; 119°20'E. The oceanic domain is consequently older northeast of the LRTPB than southwest. Such an observation raises the question of the origin and significance of this old portion of oceanic crust located between the deformation front and the LRTPB.

4. Gravity and magnetic data in the northeast South China Sea and Huatung basin

Gravity and magnetic data have been compiled around Taiwan (Hsu et al., 1998). Additional magnetic data collected south of Taiwan since 1998 have been included. Plates 3A and B are gravity and magnetic anomaly maps of the northeast SCS and the Huatung basin extracted and contoured from these one-arc minute gridded data sets.

4.1. Gravity data in the northeast South China Sea and Huatung basin

South of lat 20°N, the Manila subduction zone is associated with a double negative free-air anomaly oriented 035°N (Plate 3A). The smaller negative anomaly coincides with the bathymetric depression of the Manila trench and the larger negative anomaly (black area), located beneath the accretionary prism and parallel to the Luzon island volcanic arc, corresponds to the main gravimetric expression of the subduction zone. North of lat 20°N, the smaller negative anomaly, oriented 340°N, still roughly follows the bathymetric depression associated with the deformation front; however, the largest negative anomaly, oriented 005°N, follows the western border of the Luzon arc. An angular discrepancy exists between the smaller negative anomaly associated with the deformation front and the larger anomaly which corresponds to the main expression of the subduction zone. Thus, gravity data help to define a domain which extends beneath most of the area located beneath the Manila accretionary prism, i.e. as far as the western border of the Luzon arc to the east and beneath the Hengchun peninsula, the southern tip of Taiwan, to the north. The eastward subduction of a 10-km-thick crust beneath the Hengchun peninsula is shown by the interpretation of an E–W wide-angle seismic reflection and refraction profile shot on each side of the Hengchun peninsula (22°12'N) (Nakamura et al., 1998), but also south of 22°40'N, by the extension of the present-day active eastward dipping Benioff zone which extends down to 150 km (Plate 1B) (e.g. Tsai, 1986). Nevertheless, the nature of the overriding plate beneath the Manila accretionary prism has never been established.

The northwestern extension of the LRTPB, in the 315°N direction, coincides with the Formosa canyon (Fig. 2), which underlines the large change in trend direction of the northeast SCS margin. This canyon is also marked by gravimetric contours up to the point where the Chinese continental margin changes direction (Plate 3A); the southeastern extension of the LRTPB intersects the deformation front at lat 20°N,

where a change in trend of both the Manila trench and the Luzon volcanic arc occurs.

The southern boundary of the Huatung basin is underlined by a linear negative anomaly oriented 331°N. This feature is parallel to the southwestern termination of the deep Huatung basin against the eastern side of the Luzon arc and makes a 15° angle with the LRTPB (Fig. 2).

4.2. Magnetic data in the northeast South China Sea and northern Huatung basin

Since 1998, magnetic data were systematically collected by one of us (S.-K. Hsu) during six cruises run in the northeastern SCS and over the Manila accretionary prism. The updated contours appear in Plates 2B and 3B. Magnetic data show that the deformation front corresponds to the boundary between two magnetic domains. To the southwest, the oceanic domain of the SCS is characterized by broad, generally positive magnetic anomalies, roughly 085°N-oriented. The portion of oceanic domain located between the deformation front and the 315°N plate boundary already identified on bathymetric, basement depth and gravity maps (Fig. 2, Plates 1A, 2A and 3A) displays strong negative magnetic lineations whose directions are parallel to FZ1, FZ2 and FZ3 (Plate 2B). The FZ trends are too close to resolve the rift pattern directions.

Beneath the Manila accretionary prism, sediments are thick (Lundberg et al., 1995) and the amplitude of magnetic anomalies is weak. Numerous parallel magnetic lineations oriented 253°N–256°N, with a mean spacing of 20 km, terminate at the Manila trench to the west and abut against the western border of the Luzon arc to the east, suggesting that the crust is of oceanic nature beneath the Manila accretionary prism. North of 21°30'N, the decreasing amplitude of magnetic anomalies is due to the increasing depth of magnetic sources beneath the accretionary wedge. Magnetic lineations are oriented differently on each side of the Manila trench because the oceanic crust of the northern South China Sea subducts beneath another piece of oceanic crust and the magnetic effect

Fig. 3. ACT migrated seismic reflection profiles aligned on their right-hand side on the deformation front and their interpretation. Locations of profiles in Fig. 2. Vertical exaggeration: 13. Fracture zones, FZ1 and FZ2, are identified by double arrows on each profile and from profile to profile by thick gray lines.

of the subducting plate is not recorded in surface magnetic data. Thus, the portion of overlying oceanic domain located beneath the Manila accretionary prism (Plate 2) and imaged on magnetic data corresponds to a portion of oceanic domain located between a trench and an intraoceanic arc and above a Wadati–Benioff zone (Plate 1B).

In the Huatung basin, where numerous crossing lines have been used in the magnetic compilation (Hsu et al., 1998), we have identified six main magnetic lineations oriented E–W (268°N – 270°N), the amplitude of the northern ones decreasing beneath the Ryukyu accretionary wedge. On their eastern side, they abut against the Gagua ridge (Hilde and Lee, 1984), an N–S feature marked on Plate 3B by a series of discontinuous magnetic anomalies. On their western side, the E–W magnetic lineations disappear at the base of the Taiwan continental margin (eastern border of the Luzon arc). The southward extension of E–W magnetic lineations is limited by a 331°N -oriented feature, which corresponds to a narrow linear feature on the gravity map (Plate 3A). This feature is parallel to a 200-km-long bathymetric gradient, but 30 km offset northeast (Plate 3 and Fig. 2) associated itself with a small linear gravity low. South of this boundary, the pattern of magnetic anomalies is different, suggesting that the 331°N feature is a major plate boundary between the Huatung basin *sensu stricto* to the north and the southern Huatung basin.

In conclusion, two different oceanic domains are juxtaposed in the SCS, the SCS *sensu stricto* and an older oceanic domain whose geographical extension is weak. Both domains are subducting beneath the Philippine Sea crust *sensu lato*. The overlying portion of oceanic crust located beneath the Manila accretionary prism belongs to another oceanic domain. The purpose of the following sections is to show that this last piece of oceanic domain could belong to the same oceanic domain than the Huatung basin *sensu stricto*.

4.3. Ages of oceanic crusts beneath the Manila accretionary prism and the northern Huatung basin

Profiles P1 and P2 are perpendicular to the trend of magnetic lineations beneath the Manila accretionary prism and profiles P3, P4 and P5 are perpendicular to the trend of magnetic lineations in the northern Huatung basin (Plate 3B). The location of these

profiles has been chosen away from the fracture zones trends or discontinuities identified in the two areas. Magnetic anomalies have been extracted from the one-arc minute spacing magnetic grid of Hsu et al. (1998) implemented with new data collected over the Manila accretionary prism and northeastern South China Sea (Fig. 4). Synthetic magnetic anomalies have been computed by using Sloan and Patriat (1992) code. Magnetic basement depth have been assumed at 9 and 5 km from seismic data and the latitude of emplacement of the oceanic crust at 18°N and 23°N beneath the Manila accretionary prism and Huatung basin, respectively. However, the identification of magnetic lineations is not unique because there are only a few magnetic reversals, which could be identified both in the Huatung basin and beneath the Manila accretionary prism.

With a 1 cm/year half-spreading rate in the 345°N direction, a fairly good correspondence between synthetic and observed magnetic anomalies exists between chrons 7 and 16 (27 to 39 Ma) beneath the Manila accretionary prism. Fig. 5 shows the geographic distribution of the identified magnetic lineations. West of the deformation front, magnetic lineations have not been identified. In the SCS, chrons 5c to 11 (16 to 33 Ma) have been identified by Biais et al. (1993) assuming a 2 cm/year half-spreading rate in the N–S direction. Though there is a 6-Ma period of common spreading (chrons 7 to 11) in the SCS and beneath the Manila accretionary prism, spreading rate in the SCS was double that beneath the Manila accretionary prism, suggesting that these two oceanic domains were not formed as parts of the same ocean.

With a 2 cm/year half-spreading rate in the N–S direction, a fairly good correspondence between synthetic and observed magnetic anomalies exists between chrons 20 (possibly 18) and 23 (44 possibly 43 to 51 Ma) in the northern Huatung basin. Fig. 5 shows the geographic distribution of the identified magnetic lineations. Chron 18 has not been formally retained, as its amplitude is weak, due to the large depth of the oceanic basement (10 km) beneath the Ryukyu accretionary prism. Though we were unable to find chrons 16 to 18 identified by Hilde and Lee (1984) in the Huatung basin, our proposed identification is very close. Recently, an N–S deep-tow magnetic profile was collected in the Huatung basin (Lee et al., 1999), 1–2 km above the seafloor. Using our

Fig. 4. Observed and synthetic magnetic profiles beneath the Manila accretionary prism and in the Huatung basin. Locations of profiles in Plate 3B. Synthetics are computed with the code and geomagnetic polarity timescale developed by Sloan and Patriat (1992).

model, computed magnetic anomalies at the depth of recording fits with these data. However, Deschamps et al. (2000) have determined accurate lower Cretaceous ages at three locations in and around the Huatung basin (Fig. 5). They suggest that the opening of the Huatung basin occurred during early Cretaceous with a spreading rate of 6 cm/year if a sequence of magnetic lineations corresponding to chrons M1 to M10. We disagree with this interpretation because none of the samples belong to the Huatung basin *sensu stricto*. (i) At site RD19 (Fig. 5), gabbros were collected in what we interpret as a portion of the proto-SCS (see Section 7.3). (ii) Site RD20 (Fig. 5) seems to be located in the Huatung basin *sensu stricto*. Gabbros were collected there on a seamount which belongs to a volcanic chain

of seamounts whose axis is parallel to the Gagua ridge and located 25 km to the west (Liu et al., 1998). This ridge is part of the Gagua ridge system composed of two parallel ridges that we interpret as the plate boundary bounding the PH to the west. Rafted material from an other oceanic domain located 100 km to the south could be expected if we refer to the same mechanism involved to explain the presence of continental fragments dredged in the Equatorial Atlantic. There, lateral jumps within active transform faults could displace exotic terranes. (iii) The lower Cretaceous cherts discovered in northern Lanyu Island (Fig. 5) are interpreted as deposited in a deep old oceanic basin, before the surrection of the Luzon arc, possibly in the proto-SCS (Deschamps et al., 2000). We suggest

Fig. 5. Geodynamic interpretation of the south China Sea, Huatung basin and surrounding areas in terms of pieces of ocean belonging to different plates. The south China Sea ocean-continent boundary (OCB) has been approximately drawn from bathymetric, gravity and magnetic data. Magnetic lineations, fracture zones (FZ1, FZ2 and FZ3) and plate boundaries are identified in the northeastern south China Sea (proto-SCS), beneath the Manila accretionary prism (old Taiwan Sea plate) and in the Huatung basin sensu stricto as well as in the south China Sea (SCS) (Biais et al., 1993). The southern part of the Huatung basin probably belongs to the proto-SCS. The three black circles correspond to locations where early Cretaceous rocks have been discovered (Deschamps et al., 2000). B, vertical plane which limits the Manila subduction zone to the north; CR, Coastal Range; LRTPB, Luzon–Ryukyu transform plate boundary; LV, Longitudinal Valley.

that all the three locations belong to the same piece of oceanic domain, the proto-SCS as suggested by several authors (Hall et al., 1995a; Deschamps et al., 1998; Rangin et al., 1999) (Fig. 5).

East of the Gagua ridge, chrons 22 to 20 (49 to 43 Ma) (Hilde and Lee, 1984) belong to the oldest phase of spreading identified in the west Philippine Sea basin. The direction of spreading is a NE–SW and

the half-spreading rate is 4.4 cm/year. Consequently, from chrons 23 to 20, both the amplitudes and directions of spreading rates are different in the northern Huatung basin and in the Philippine Sea, showing that the Gagua ridge system is a former plate boundary and the Huatung basin *sensu stricto* belongs to a different plate than PH.

4.4. Oceanic crusts beneath the Manila accretionary prism and northern Huatung basin: did they belong to the same ocean?

We have established that oceanic crusts located beneath the Manila accretionary prism and the SCS belong to different plates and that the Huatung basin *sensu stricto* and the rest of the Philippine Sea also belong to different plates. Now the question is: Were oceanic crusts beneath the Manila accretionary prism and the Huatung basin parts of the same ocean? The directions of magnetic anomalies are 253°N–256°N beneath the Manila accretionary prism and 268°N–270°N in the northern Huatung basin. As the directions of magnetic lineations beneath the Manila accretionary prism and northern Huatung basin make an angle of 15°, let us assume that, during their formation, these two pieces of oceanic crust were parts of the same ocean that we name the Taiwan Sea and lately moved apart and 15° rotated. In this hypothesis, the Taiwan Sea was formed between chrons 23 (51 Ma) and 7 (27 Ma) or possibly 5b (15 Ma). In the later hypothesis, the Taiwan Sea would cease to open at the same time than all the surrounding oceans (Japan Sea, Shikoku and Parece Vela basins, SCS, Sulu Sea). The plate boundaries of the former Taiwan Sea were the Gagua ridge, the deformation front and the Eurasian margin. The old southern Huatung basin (*proto-SCS*) did not belong to the Taiwan Sea.

In the following sections, we will try to demonstrate that about 15 Ma ago, the Luzon arc started to form as an intraoceanic island arc located within the Taiwan Sea by subduction of SCS beneath PH. Let us consider that the Taiwan Sea existed with the following constraints. (1) half-spreading rates were 2 cm/year from chron 23 to 20 (51 to 43 Ma) and 1 cm/year from chron 16 to 7 (39 to 27 Ma). As a major change in spreading rates and spreading directions occurred at chron 20 in the west Philippine basin (Hilde and Lee, 1984), we assume that a similar change in spreading rate also

occurred at chron 20 in the Taiwan Sea. (2) Spreading ceased in the Taiwan Sea 15 Ma ago, at the same time that in the SCS (Briais et al., 1993), Sulu Sea (Rangin and Silver, 1991), Japan Sea (Jolivet et al., 1994), and Shikoku and Parece Vela basins (Chamot-Rooke et al., 1987; Okino et al., 1994, 1998). Because the sequence polarities of magnetic lineations are in opposite direction, oceanic crusts beneath the Manila accretionary prism and Huatung basin were formed on opposite side of the spreading center. In the following sections, we will examine the types of motions occurring along the Taiwan plate boundaries prior to 15 Ma and how the Luzon arc formed within the Taiwan Sea.

5. Constraints at plate boundaries

5.1. Age of formation of the Luzon Island and Luzon arcs

Cretaceous rocks and arc related ophiolitic rocks outcrop in Luzon Island, but the construction of the intraoceanic Luzon arc, located north of the Philippine islands, is linked to the SCS subduction at the Manila trench and is younger than 15 Ma. There is a large debate about the sense of vergence of the subduction zone before 15 Ma. Stéphan et al. (1986) suggested that the Manila subduction zone already existed west of Luzon island. Other authors linked the construction of Luzon Island to a subduction zone verging eastwards (Wolfe, 1981; Maletierre, 1989). However, recent tomographic inversions clearly show a deep westward dipping subduction zone named the Sangihe subduction zone (Rangin et al., 1999), which died to the north, near Luzon Island, suggesting prior to 15 Ma a convergent motion evolving northwards to a transform motion. The internal consistency of the kinematic reconstructions presented later supports such a change of vergence.

North of Luzon Island, the 15 dates available on volcanic rocks collected on the islands of the Luzon arc are younger than 9.4 Ma (Lo et al., 1994; Yang et al., 1996; Maury et al., 1998). In the Coastal Range of Taiwan, the onshore portion of the Luzon arc, fission track age determinations give ages younger than 16 Ma. K–Ar dates on outcropping andesites give some ages between 15 and 29 Ma (Richard et al., 1986); however, the effects of various alteration reactions as delineated by Lo et al. (1994) have not been taken into

account. Samples analyzed by Richard et al. (1986) are characterized by very low K_2O content which could artificially raise radiometric ages by loss of potassium. In conclusion, we think that the change of vergence could have occurred 15 Ma ago simultaneously with the onset of the northward extension of the Manila trench connecting the Ryukyu trench through the Taiwan Sea. However, because the younger identified magnetic lineation is chron 7 (27 Ma) in the Taiwan Sea, we cannot exclude an earlier change of vergence in the Philippine islands from east to west, sometime between 15 and 27 Ma.

5.2. Subduction of the Taiwan Sea and northeastern South China Sea beneath Eurasia

Before 15 Ma, three types of arguments show that the Taiwan Sea and the northeastern South China Sea were subducting beneath Eurasia. However, the amount of subduction cannot be quantified.

(1) Sibuet and Hsu (1997) have proposed that the east China Sea continental shelf basins could be interpreted as backarc basins linked to the Ryukyu subduction zone system. In particular, the Tainan basin, located southwest of Taiwan, and the adjacent ridge, parallel and close to the shelf edge, are the southwesternmost expression of the Ryukyu arc and backarc system. Rifting ceased in the Tainan basin and at the emplacement of Taiwan (Hsüehshan trough) in early Middle Miocene (Teng, 1992). The Ryukyu subduction zone extended from southwest Taiwan to Japan until the early Middle Miocene (15 Ma). Since 15 Ma, the portion of the Ryukyu subduction zone facing the Tainan basin and the future Taiwan island became inactive. From a kinematic point of view, this change is associated with a plate reorganization.

(2) Tomographic results show that the Ryukyu subduction zone extends down to a depth of 400 to 500 km beneath Eurasia (Obayashi et al., 1997). However, Tajima et al. (1997) tomography results with a grid spacing of 25 km, show that the southwestward limit of the Ryukyu subduction zone extends west of Taiwan. Assuming that the direction of the PH/EU motion is $307^\circ N$ in the area of Taiwan for the last 15 Ma, the portion of the Wadati–Benioff zone located S–W of the present-day Ryukyu subduction zone could be considered as a relict of the extinct portion of the Ryukyu subduction zone facing

until 15 Ma both the Tainan basin and the backarc basin located at the emplacement of Taiwan.

(3) Seismic profiles EW9509 45 and 34 (Fig. 6) are perpendicular to the northern margin of the northeastern South China Sea (Fig. 2). Profile 45 cuts across FZ2 at CDP 16,600 and confirms that FZ2 is a major crustal feature. The large igneous body associated with a magnetic anomaly at $21^\circ 15' N$; $119^\circ 45' E$ (Plate 3B) was emplaced (possibly during the Miocene) above undeformed sediments overlying the oceanic crust. Northwest of the igneous body (CDP 15,000 on profile 45), the layering of the undeformed sedimentary layer completely disappears (CDP 11,500) and the deformed sedimentary layer thickens toward the margin. We interpret the layer of deformed sediments as an old accretionary prism linked to the subduction of the proto-SCS beneath Eurasia. Above the accretionary prism, about 4 s (t.w.t.) of undeformed turbiditic sediments have been deposited. N–W of CDP 10,000, the shape of seismic reflections on top of oceanic crust and the velocity structure defined there from an OBS refraction survey (Chen and Jaw, 1996) indicate that the underlying crust is oceanic and dips northwestward, suggesting an old subduction of oceanic crust. Beneath the continental shelf, the Tainan basin, whose rifting period occurs from 30 to 21 Ma (Lin et al., 1999), shows a complex tectonic evolution. We still interpret the Tainan basin as a backarc basin (Sibuet and Hsu, 1997). Beneath the upper part of the margin, the deep body devoid of seismic reflections would be the former arc and forearc body, now buried beneath the sediments coming from the east China Sea continental platform. Because most of the seismic profiles previously shot by the Chinese Petroleum Company (CPC) did not extend over the continental slope (Tzeng et al., 1996), the relationship between the Tainan backarc basin and the arc/forearc body, the sedimentary prism and the subducting oceanic crust was not previously expected. In conclusion, we interpret profile 45 as a seismic section across a portion of an extinct northwestward dipping subduction zone located beneath the Tainan basin and the former basin situated at the emplacement of Taiwan (Sibuet and Hsu, 1997) which both ceased to open 15–21 Ma ago.

Seismic profile EW9509 34 (Fig. 6) is parallel to profile EW9509 45, but located 30 km west of it (Fig. 2). The sedimentary layer corresponding to the deformed sediments (accretionary prism) of profile

45 is folded, but less deformed than on profile 45, demonstrating that the amount of subducted crust decreased when approaching the LRTPB. Folds cannot be considered there as tilted fault blocks linked to the formation of a passive margin because no faults are observed between undulations.

Seismic profile EW9509 35 (Fig. 6) cuts across profile 45 (Fig. 2). Its southwestern extremity corresponds to the southeastern extremity of profile 34. Dipping reflectors are clearly identified within the igneous body. Below, folded sediments similar to those of profile 34 are observed.

In conclusion, the interpretation of deep seismic profiles shot by the R/V *Maurice Ewing* shows the existence of a former subduction zone imaged by the subduction of the oceanic crust, the existence of a thick accretionary prism located in the lateral continuity of undeformed oceanic sediments, an arc and forearc feature, and a backarc basin (Tainan basin). Between the LRTPB and the deformation front, the amount of subduction beneath EU is unknown. However, if subduction occurred west of the deformation front as previously shown, and east of the Gagua ridge, it might also have occurred between these two features, i.e. north of the Taiwan Sea plate. Though unknown, the amount of subduction of the Taiwan Sea plate beneath EU cannot exceed 150 km if we consider that magnetic lineations 17 to 23 of the Huatung basin have not been identified beneath the Manila accretionary prism.

5.3. Transform motion between the Taiwan Sea and the Philippine Sea

During the ACT cruise, the Gagua ridge and the Ryukyu arc-trench system were both surveyed. The 350-km-long linear Gagua aseismic ridge (Fig. 2) is N–S trending, 30 km wide, culminates about 3–4 km above the seafloor, 4–5 km above the oceanic basement and is flanked on its western side by a smaller chain of seamounts. The juxtaposition of a large gravity high below the ridge and a large gravity low to the west (Hsu et al., 1998) suggests the existence of a former compressive component on the Gagua ridge which would explain part of the abnormal elevation of the Gagua ridge above the adjacent oceanic basement. Sibuet et al. (1998) have already demonstrated that the Gagua ridge was a transform plate boundary at the

time of formation of adjacent oceanic domains. This was confirmed in a previous section of this paper by the identification of similar magnetic lineations created at different spreading rates on each side of the Gagua ridge. Sibuet et al. (1998) have also demonstrated that the Gagua ridge subducted beneath Eurasia and extended at least beneath the Okinawa Trough as shown by seafloor features as the large reentrant located at the base of the Ryukyu prism, the uplift of part of the Nanao forearc basin, the deformation of the sedimentary arc, and the cross-backarc volcanism identified in the southwestern Okinawa Trough. NNW–SSE crests and troughs identified on the swath bathymetric survey of the Gagua Ridge have been interpreted as Riedel shears, strongly suggesting the existence of a N–S strike–slip zone (Deschamps et al., 1998) localized near the ridge axis. As previously shown, the Gagua ridge was a transform plate boundary which displays transpressional strike–slip features. Its northward prolongation extended in direction of the Ryukyu subduction zone during early Tertiary and since then, continuously subducted beneath Eurasia. In the southward direction, the west dipping Sangihe subduction zone (beneath Philippines) was probably in continuity with the Gagua ridge. Modern analogues of this system are the Puysegur ridge, a transpressional strike–slip system evolving to a nascent subduction zone (Collot et al., 1995) or the Shackleton ridge, a shear plate boundary in the southward prolongation of the Chile trench which disappears beneath the South Shetland trench (Maldonado et al., 2000).

By using the directions and values of spreading rates deduced from the identification of magnetic lineations beneath the Manila accretionary prism and in the Huatung basin and the types of motions previously described along its boundaries, we conclude that the Taiwan Sea existed as a single ocean and was formed by seafloor spreading between 51 and 15 Ma.

6. Plate kinematic evolution of East Asia since early middle Miocene

In the preceding sections, we have identified a series of distinct oceanic domains with some age determinations. All these oceanic pieces are located in a transitional domain located between the Philippine Sea and Sundaland. Within the simple PH/EU

Fig. 6. Migrated seismic profiles EW9509 34, 35 and 45 (a) located in Fig. 2 and interpretation (b). The two parallel profiles (34 and 45) are perpendicular to the northern margin of the northeastern south China Sea (proto-SCS) and aligned on the southeastern limit of what we interpret as an arc and forearc feature. On profile 45, the large igneous body is associated with a large magnetic anomaly (located at $21^{\circ}15'N$; $119^{\circ}45'E$ on Plate 3B) and was probably emplaced above undeformed sediments overlying the oceanic crust. Northwest of the igneous body, the layering of this undeformed sedimentary layer completely disappears, leaving place to a completely deformed sedimentary layer which thickens in direction of the margin and that we interpret as an old sedimentary accretionary wedge. The underlying oceanic crust dips northeastward, even if the sedimentary load is removed.

proposed motion since 15 Ma (Table 1), is it possible to find a kinematic solution which takes into account the shape and ages of these microplates or portions of them? We present a set of five-plate kinematic reconstructions starting in early middle Miocene (15 Ma⁺). There are always large uncertainties in these reconstructions. Amongst them, the location of the Luzon plate is crucial. Spreading in the Taiwan Sea ceased 15 Ma ago though the youngest identified magnetic lineation is chron 7 (27 Ma) and the oldest age of the recent Luzon arc is 15 Ma or could be a bit older. To summarize, the following assumptions have been made in the kinematic reconstructions.

(1) Spreading in the Taiwan Sea was 2 cm/year from chron 23 to 20 (51 to 43 Ma) and 1 cm/year from chron 20 (43 Ma) to 5b (15 Ma). Spreading ceased at the same time (15 Ma) in the Taiwan Sea, SCS, Sulu Sea, Japan Sea, and Shikoku and Parece Vela basins.

(2) From 15 Ma to Present, the PH/EU motion occurred along 307°N. The direction of flow lines with respect to PH/EU poles of rotation was similar from 15 to 8 Ma and from 8 Ma to Present (Table 1) because the poles of rotation are located on a great circle cutting through the Taiwan area (Fig. 1). Near Taiwan, for the past 15 Ma, the mean PH/EU velocity is assumed to be 5.6 cm/year in the 307°N direction (Seno et al., 1993) in order to match magnetic lineations belonging to the Huatung basin and beneath the Manila accretionary prism.

6.1. Luzon arc rotation since 15 Ma

Though the age of various magnetizations is not good enough to preclude local rotations at different times, the interpretation of Luzon Island paleomagnetic data was quite contradictory (Vacquier and Uyeda, 1967; Karig, 1983; Sarewitz and Karig, 1986; Jolivet et al., 1989; Fuller et al., 1991; Hall, 1996). However, given the likely errors and assumptions in these studies, Hall et al. (1995b) suggest in their synthesis a 20° clockwise rotation since 20 Ma. If, during the last 15 Ma, the PH/EU motion (and consequently the motion of Luzon Island, which belonged to the PH) occurred around poles of rotation of Table 1 at a 5.6 cm/year mean rate of convergence, a 15° clockwise rotation is expected since 15 Ma (i.e. 1°/Ma). This simple relative PH/EU motion since 15 Ma is consequently in agreement with both paleo-

magnetic results and the 15° clockwise rotation of the Huatung basin required to fit the direction of magnetic lineations beneath the Manila accretionary prism.

6.2. Early middle Miocene reconstruction (15 Ma⁺, Plate 4a)

Assuming previously defined kinematic hypotheses and a symmetric spreading in the Taiwan Sea, we have restored the positions and contours of plates and magnetic lineations 15 Ma ago. Consequences of such reconstructions are as follows.

(1) The north Taiwan Sea (NTA) and south Taiwan Sea (STA) plates are oceanic plates formed during early Tertiary (since chron 23, 51 Ma), west of the west Philippine Sea (WPH). A shear motion, perhaps with some limited compressive component, must have occurred along the Gagua ridge, the plate boundary between the NTA and STA plates and the WPH plate. The pole position before 15 Ma (Table 1) accommodates both such a shear motion along the Gagua Ridge and the northern portion of the Sangihe subduction system and a significant convergent motion further south, east of the Luzon plate (LU). Simultaneously, a shear motion occurred along the LRTPB to accommodate different spreading velocities on each side of this feature. The shape of the northeastern South China Sea plate (proto-SCS) is inferred from constraints along its boundaries: subduction along its northern side and shear motion along the LRTPB. However, the location, direction and type of motion along its eastern boundary with the Taiwan Sea (NTA and STA plates) is unknown because of its subsequent disappearance by subduction in the Manila trench.

(2) The opening of the Japan Sea occurred from 30 to 15 Ma by a 30° rotation of Kyushyu Island (Chamot-Rooke et al., 1989; Jolivet et al., 1994) with respect to Eurasia. This motion has to be transferred southward. Le Pichon (1997) proposed that the southwestward extension of the Tsushima fault, located between Korea and Kyushyu Island, would be such a feature recognized on the satellite-derived marine gravity anomaly map (Fig. 1) (Sandwell and Smith, 1994) and extending to the northern margin of the Okinawa Trough. This feature is called the Taiwan–Sinzi folded zone (Wageman et al., 1970) [or the Diaoyudao folded uplift belt (Zhou et al., 1989)]. It was strongly faulted and folded during Miocene (Wang et al., 1995) and is characterized

by a chaotic seismic facies for the lower Miocene and older sediments (Kong et al., 2000). Overlying sediments are not deformed. West of the junction of the Taiwan–Sinzi folded zone with the northern Okinawa margin, the feature changes direction, follows the northern Okinawa Trough edge, but corresponds there to a different origin as it results from the Luzon arc collision with the Eurasian continent (Hsiao et al., 1999) during late Miocene. The opening of the Okinawa Trough is much more recent than 15 Ma. By closing it (parameters of rotation given in Sibuet et al., 1995), the northern portion of the Taiwan–Sinzi folded zone appears to be in the extension of a major Ryukyu arc crustal discontinuity (Miyako depression) already identified by Kodaira et al. (1996) and Park et al. (1998). Le Pichon (1997) have calculated the motion of the Okinawa–Japan plate (OJ) during the opening of the Japan Sea and find 230 km of right-lateral motion with some tensional component along the Taiwan–Sinzi zone and Miyako depression.

(3) The SCS was opening at the expenses of the proto-SCS which subducted in the south along the Palawan trench, beneath the Cagayan Ridge (Plate 4a). The Sulu Sea opened as a backarc basin associated with this subduction system. West of the SCS, a large shear fault (the Qui Nhon ridge) located in the prolongation of the Red River Fault system (Plate 4a) was active along the Vietnam margin with a minimum right-lateral offset of 160 km (Rangin et al., 1995; Roques et al., 1995).

(4) The WPH plate was already formed. Opening occurred since chron 7 (27 Ma) in the Shikoku and Parece Vela basins. In Plate 4, oceanic features and intraoceanic arcs of the WPH, EPH and PA plates are extended up to the Ryukyu trench.

6.3. Early middle Miocene reconstruction (15 Ma⁺, Plate 4b)

15 Ma ago, the PH/EU motion changed direction to 307°N. A major plate reorganization occurred at the end of seafloor spreading activity in the SCS, Japan Sea, Taiwan Sea, Sulu Sea, and Shikoku and Parece Vela basins. Simultaneously, shear motions ceased along the Taiwan–Sinzi zone, the Gagua ridge and along the LRTPB; the southwestern portion of the Ryukyu trench became inactive with a cessation of activity along the LRTPB. Plate contours changed

drastically. The complex system of thirteen plates (Eurasia (EU), Okinawa–Japan (OJ), Luzon (LU), north Taiwan Sea (NTA), Pacific (PA), northern proto-SCS (PSCS), southern South China Sea (SSCS), south Taiwan Sea (STA), Cagayan (CA), Celebes (CE), Indochina (IC), west Philippine Sea (WPH) and east Philippine Sea (EPH)) suddenly changed to a simple three-plate system (EU, PH and PA). The EU plate now includes the former OJ, SSCS, NSCS, PSCS, SSCS, CA, CE and IC plates and the western parts of NTA and STA plates; the PH plate includes the WPH, EPH, LU plates, the eastern parts of NTA and STA plates and a smaller part of the proto-SCS located south of the SCS.

The subduction vergence changed beneath the Luzon island arc from east to west, leaving the former active Gagua ridge in its present-day northeastern prolongation. As shown in Plate 4b, when subduction flipped, no existing plate boundaries or features existed within the proto-SCS and the SCS immediately north of Luzon. The newly active Manila Trench has been simply drawn along a trend parallel to the Gagua ridge. In previous reconstructions (Angelier, 1990) and following kinematic works, e.g. (Lee and Lawver, 1994; Sibuet and Hsu, 1997)), a transform plate boundary was assumed to join the Manila and Ryukyu subduction zones. In the Angelier (1990) model, due to the opposite vergence of the Manila and Ryukyu subduction zones, the collision started in Taiwan when the length of the transform boundary was reduced to zero, i.e. when the Luzon arc began to collide with Eurasia. In Plate 4b, north of the Luzon island arc, such a complication disappears and EU started to subduct 15 Ma ago beneath PH. The construction of the intraoceanic Luzon arc began when the Wadati–Benioff zone reached a depth of 100–150 km. Due to its minor initial relief at the beginning of the subduction process, the Luzon arc started to subduct with the entire PH. It is only 6–9 Ma ago that the newly created Luzon arc resisted subduction and collided with EU.

6.4. Late Miocene reconstruction (8 Ma, Plate 4c)

Since 15 Ma, the PH Sea plate rotated clockwise (Table 1). Near Taiwan, the former LU plate moved 400 km in the northwest direction (5.6 cm/year in the 307°N direction). The Luzon arc already started to collide EU, creating a large mountain belt (Hsiao et al., 1999), east

of the present-day position of Taiwan, in the southwestern prolongation of the Taiwan–Sinzi zone. The eastern ancestor of Taiwan Island was then completely eroded and/or partly subsided simultaneously with the formation, since 2 Ma, of the southwestern tip of the Okinawa Trough (Sibuet et al., 1998).

The Taiwan Sea progressively disappeared by subduction, partly in the northern Manila trench for its western part and partly in the Ryukyu trench for its eastern part. Thus, the eastern part of the NTA and STA plates progressively shifted northwards and clockwise rotated with respect to the former western part of the same plates.

6.5. Pliocene reconstruction (3 Ma, Plate 4d)

8 Ma ago, the PH/EU pole of rotation slightly changed position (Table 1, Fig. 1), but the direction and velocity of convergence did not change in the Taiwan area where the motion of the former LU plate was still in the 307°N direction. The former Taiwan Sea spreading center (chron 5b) was almost completely subducted west of the Manila trench and east of the Luzon arc, with the subduction of its eastern portion in the Ryukyu subduction zone and its western portion in the Manila subduction zone. The Luzon arc was still colliding with Eurasia, creating now the northern portion of Taiwan Island. The Gagua ridge continued to subduct beneath Eurasia.

6.6. Present day (Plate 4e)

The surface of the remaining SCS is reduced to approximately a third of the surface occupied 15 Ma ago. During Pleistocene, collision of the Luzon arc with Eurasia rotated 30° clockwise the northern portion of the arc located north of lat 22°N (Fig. 2) as shown by numerous paleomagnetic measurements performed on early Pliocene to Pleistocene sediments deposited in the Coastal Range (Lee et al., 1990).

7. Discussion

Geological constraints near Taiwan have been integrated in a set of kinematic reconstructions restricted to the period spanning from 15 Ma to Present and only concerning East Asia. Though not extended to the

whole S–E Asia, the proposed reconstructions do not violate paleomagnetic data acquired in and around S–E Asia. For the past 15 Ma, paleolatitudes of paleomagnetic sites computed with poles of Table 1 fall within the error bars of paleolatitudes computed from paleomagnetic data (Hall et al., 1995a and R. Hall, personal communication, 2001). Thus, we are allowed to examine the implications of the presented kinematic reconstructions concerning the geodynamic evolution of East Asia. For example, the beginning of mountain building in Taiwan is not coeval with a major change of motion of the PH as suggested by several authors (e.g. Barrier and Angelier, 1986), but is linked to the growth of the Luzon arc and its subsequent collision with Eurasia. We will discuss the formation of Taiwan in the light of the new set of kinematic reconstructions as well as several questions concerning the eastern extension of the SCS and proto-SCS.

7.1. South China Sea extension

Before chron 5b (15 Ma), both the SCS and the Taiwan Sea opened. One can suggest that they formed a single ocean, progressively opening in the south-westward direction. Magnetic lineations are roughly E–W oriented and their age decreases from chron 16 (39 Ma) at the contact with the Eurasia margin near Taiwan, to chron 11 (33 Ma) southeast of Pearl River basins and to chron 5b (15 Ma) at the southwestern tip of the SCS. However, because the spreading rate was double in the SCS than in the Taiwan Sea and the Taiwan Sea subducted beneath Eurasia during its accretion, the hypothesis of a single ocean must be disregarded. The existence of several oceanic basins opening at different spreading rates is probably linked to the juxtaposition of two groups of oceanic plates and features evolving differently: the SCS, proto-SCS, Sulu Sea and Celebes Sea system on one side and of the Taiwan Sea and Luzon Island arc system on the other side. In other words, the Taiwan Sea and Luzon Island arc acted as an adjusting stripe between PH and Sundaland.

7.2. Northeastward extension of the proto-South China Sea

The existence of a proto-SCS was discussed for decades (e.g. Rangin et al., 1990) and suggested to

explain the Palawan trough, the arc volcanic nature of the Cagayan ridge and the opening of the Sulu Sea as a backarc basin. According to Rangin et al. (1990), the N–S initial width of the proto-SCS was probably around 500 km and its eastern extension was the transform plate boundary bounding the Philippine Sea plate (Rangin et al., 1990). Our reconstructions also suggest that the proto-SCS extended not only south of the SCS, but also south of the Taiwan Sea, as far as the Gagau ridge (Plate 4a). Another piece of proto-SCS existed in the northeastern SCS, but we have no indication on its former eastern extension.

7.3. Kinematic constraints on the formation of Taiwan

In the kinematic reconstructions of Plate 4, the Luzon arc started to form progressively since 15 Ma. Since that time, the Luzon arc subducted beneath Eurasia as part of the PH Sea plate. It is only 6–9 Ma ago that the Luzon arc resisted subduction and collided with the EU plate border composed of the extinct portion of the Ryukyu forearc, arc and backarc system (Sibuet and Hsu, 1997), uplifting the ancestor of Taiwan located at the present-day position of the southwestern Okinawa Trough (Sibuet et al., 1998; Hsiao et al., 1999). Since 15 Ma, the vertical plane (A) which bounds to the west the subducting PH plate was moving westwards. On Plate 1B, this boundary is presently located west of the deep earthquakes associated with the Ryukyu subduction zone. The oldest portion of Luzon arc which initially collided EU is now possibly accreted to the Ryukyu forearc and associated with the large negative free-air anomaly observed beneath the Nanao basin (Hsu et al., 1998).

South of Taiwan, a second vertical plane (B) limits to the northwest the deep earthquakes associated with the subduction of the SCS beneath the PH plate (Plate 1B). The kinematic reconstructions (Plate 4) show that B existed since 15 Ma and was located at the base of the Eurasian margin. B presently divides the Luzon arc into two segments making a significant angle (Plate 1B and Fig. 5). South of B, the subduction of the SCS is still active and the Luzon arc is still growing as attested by the emplacement of present-day intraoceanic arc rocks on the islands (Yang et al., 1996; Maury et al., 1998). North of B, collision between the Luzon arc and Eurasia plate is still going on.

The formation of Taiwan is consequently driven by two simple lithospheric motions, which are active since 15 Ma, as follows.

- The subduction of the PH Sea plate beneath Eurasia with a relative westward component of about 4.5 cm/year. As a consequence, A is also moving westward at the same velocity.

- The subduction of EU beneath PH and the relative northwestward motion of the Luzon arc with respect to EU. Whilst the northern portion of the Luzon arc is colliding with EU, the portion of the Luzon arc located south of B is moving above the Eurasian Wadati–Benioff zone, which underlies itself the portion of oceanic crust located beneath the Manila accretionary prism. As a consequence, B is always located at the base of the Eurasian margin, but migrates southwestward along its own trend, simultaneously with the westward retreat of the Manila trench (Plate 1B) as confirmed by a rapid frontal offscraping (Nguyen et al., 1998).

8. Conclusions

The main conclusions of this study are as follows.

(1) Maps of basement depth, gravity and magnetic anomalies show that the crust immediately beneath the Manila accretionary prism was formed by seafloor spreading. Magnetic lineations are oriented 253°N–256°N. At 1 cm/year half-spreading rate in the 345°N direction, a fairly good correspondence between synthetic and observed magnetic anomalies exists between chrons 7 and 16 (27 to 39 Ma) beneath the Manila accretionary prism. Spreading rates are different beneath the Manila accretionary prism and the rest of the South China Sea, showing that these two pieces of ocean were parts of different plates.

(2) In the Huatung basin, an oceanic domain exists with magnetic lineations 15° clockwise rotated with respect to those located beneath the Manila accretionary prism. At 2 cm/year half-spreading rate in the N–S direction, a fairly good correspondence between synthetic and observed magnetic anomalies exists between chrons 20 (possibly 18) and 23 (43 possibly 42 to 51 Ma). From chrons 23 to 20, both values and directions of spreading rates are different in the Huatung basin and in the Philippine Sea, showing that the Gagau ridge was a former plate boundary and

the Huatung basin belongs to a different plate than the Philippine Sea plate.

(3) These two pieces of oceanic domains (Manila accretionary prism and northern Huatung basin) belonged to the same ocean named the Taiwan Sea. 15 Ma ago, seafloor spreading ceased in the Taiwan Sea, which was cut into two parts by the Manila trench. The eastern part of the Taiwan Sea was incorporated in the Philippine Sea plate and the western part of Taiwan Sea is the oceanic domain located between the Manila trench and the intraoceanic arc of Luzon. Since 15 Ma, the Philippine Sea plate rotated 15° clockwise.

(4) The southern portion of the Huatung basin whose formation is dated lower Cretaceous and the northern part of the SCS comprised between the Manila trench and the LRTPB and which is older than the rest of the SCS could be relicts of the proto-SCS.

(5) For the set of five plate kinematic reconstructions of East Asia, we assume the following.

- Spreading in the Taiwan Sea was 2 cm/year from chron 23 to 20 (51 to 43 Ma) and 1 cm/year from chron 20 (43 Ma) to 5b (15 Ma).

- Spreading ceased at the same time (15 Ma) in the Taiwan Sea, South China Sea, northeastern South China Sea, Sulu Sea, Japan Sea, and Shikoku and Parece Vela basins.

- For the last 15 Ma, the mean PH/EU velocity was 5.6 cm/year in the 307°N direction in order to match magnetic lineations belonging to the Huatung basin and beneath the Manila accretionary prism. However, large uncertainties remain in these reconstructions. Amongst them, the location of the Luzon plate is crucial as well as the age of emplacement of the Luzon arc, assumed here to follow the seafloor spreading extinction in the Taiwan Sea (15 Ma). Alterations of this model are possible with a cessation of seafloor spreading and emplacement of the Luzon arc as earlier as An. 7 (27 Ma).

(6) Amongst the implications of such plate kinematic reconstructions.

- The Gagua ridge was a major transform plate boundary during the opening of the Taiwan and South China Seas. It was an about 1000-km-long linear feature which accommodated the northwestward shear motion of the west Philippine Sea plate with respect to Eurasia.

- The formation of Taiwan was driven by two simple lithospheric motions: (i) the subduction of the PH Sea plate beneath Eurasia with a relative westward component of 4.5 cm/year. The western boundary of the Ryukyu subduction zone (A), was also moving westward at the same velocity; (ii) the subduction of Eurasia beneath the Philippine Sea plate with a relative northwestward motion of the Luzon arc with respect to Eurasia. The northern boundary of the Manila subduction zone (B), located at the base of the Eurasian margin, divides the Luzon arc in a southern portion created above the corresponding portion of Eurasia and a northern portion colliding with Eurasia.

The collision of the Luzon arc with Eurasia always occurred between A and B. Though the morphology of the Taiwan belt seems to be continuous across B, collisional processes were different on both sides. South of B, mountain building results from the deformation of the huge accretionary wedge recently deposited south of Taiwan. North of B, compression results in the collision of the Luzon arc with the Eurasian margin.

Acknowledgements

Data presented in this paper were acquired during the ACT cruise (1996) and the following transit onboard the Ifremer R/V *l'Atalante* as part of an ongoing cooperative project between France and Taiwan and during the EW9509 cruise (1995) of the R/V *Maurice Ewing* as part of an ongoing cooperative project between US and Taiwan. Many ideas were improved during discussions with Jacques Angelier, Benoît Deffontaines, Jo Déramond, Serge Lallemant and Claude Rangin. Constructive comments from T.-Y. Lee, Y. Nakamura, K. Okino and especially R. Hall greatly helped to improve the manuscript. The GMT software package was used to display some of the figures (Wessel and Smith, 1991) and Alban Crussion for drawing Plate 4.

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