JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. B7, PAGES 13,751–13,768, JULY 10, 2001

Regional seismicity and on-land deformation in the Ryukyu arc: Implications for the kinematics of opening of the Okinawa Trough

Marc Fournier
Laboratoire de Tectonique, CNRS ESA 7072, Université Pierre et Marie Curie, Paris, France

Olivier Fabbri
Département de Géosciences, EA 2642, Université de Franche-Comté, Besançon, France

Jacques Angelier and Jean-Paul Cadet
Laboratoire de Tectonique, CNRS ESA 7072, Université Pierre et Marie Curie, Paris, France

Abstract. The stress field evolution and the kinematics of opening of the Okinawa Trough are investigated on the basis of earthquake focal mechanisms and structural data in the Ryukyu arc and the Okinawa Trough. Focal mechanisms show that the crust underlying the arc and the trough undergoes extension along two suborthogonal directions: a regional arc-perpendicular extension and a local arc-parallel extension. Both extensions are concurrent and related to the same regional stress field characterized by permutating horizontal σ_2 and σ_3 axes. Earthquake slip vectors reveal a southward motion of the Ryukyu arc with respect to the south China block. The current pole of opening of the Okinawa Trough is located around 16°N and 50°E. Fracture analysis in Okinawa island allows identification of three episodes of extension: a late Miocene N40°W to N20°E extension (episode I), a late Pliocene to early Pleistocene N20°E extension (episode II), and a latest Pleistocene to present-day N20°W extension (episode III). Episodes II and III are characterized by permutations between the two horizontal σ_2 and σ_3 axes. By synthesizing regional deformation data and by comparing the geometry of the deformation with analogue models of oblique rifting we reconstruct the kinematics of opening of the Okinawa Trough since the late Miocene. The direction of divergence of the Ryukyu arc has rotated clockwise from ~N150°E in the late Miocene to nearly N-S today.

1. Introduction

Within the framework of plate tectonics the formation of a back arc basin typically implies a strip of continental crust that moves away from a continent, thus becoming an island arc [*Karig*, 1971]. It is often difficult to study the deformation of the oceanward migrating arc because numerous marginal basins are presently in closing stages [*Cardwell et al.*, 1980; *Nakamura*, 1983; *Tamaki et al.*, 1992] and what can be observed is the result of a long and complex history of deformation. Together with the Bonin-Mariana Trough [*Taylor et al.*, 1991; *Martinez et al.*, 1995] and the Lau Basin-Havre Trough [*Wright*, 1993; *Taylor et al.*, 1996], which represent early stages of simple back arc basin opening above a retreating subduction zone, the Okinawa Trough and the associated Ryukyu arc [*Letouzey and Kimura*, 1985; *Kimura*, 1985; *Sibuet et al.*, 1987, 1998] (Figure 1) are ideal laboratories to study the deformation of arcs migrating away from continents.

In order to understand the deformation of the Ryukyu arc since the inception of back arc basin formation in the Miocene we analyzed two kinds of data: shallow seismicity (events with focal depths < 50 km) in the Eurasia plate lithosphere of the Ryukyu arc-back arc region and deformation recorded by Neogene and Quaternary series exposed on Okinawa Island. These series offer valuable constraints on the temporal evolution of the stress field in the Ryukyu arc-Okinawa Trough region since their deposition is synchronous of the opening of the Okinawa Trough. The first part of this paper is devoted to the analysis of the shallow seismicity. Focal mechanisms of major earthquakes allow the reconstruction of the present-day regional strain field and the proposal of a new kinematic model for the opening of the Okinawa Trough. The second part of this paper aims at reconstructing the paleostress trajectories along the arc by means of fracture analysis in Neogene and Quaternary strata of Okinawa Island. Three episodes of extension can be defined, which are afterward compared with the active deformation and with the extension stages determined offshore in the Okinawa Trough [*Sibuet et al.*, 1998] and onshore in the southern and northern parts of the Ryukyu arc [*Fabbri and Fournier*, 1999; *Fabbri*, 2000]. It appears that since the late Miocene, the Ryukyu arc has been undergoing both an arc-perpendicular extensional deformation due to back arc crustal stretching and an arc-parallel extension caused by the increase of the total length

Paper number 2001JB900010.
0148-0227/01/2001JB900010$09.00

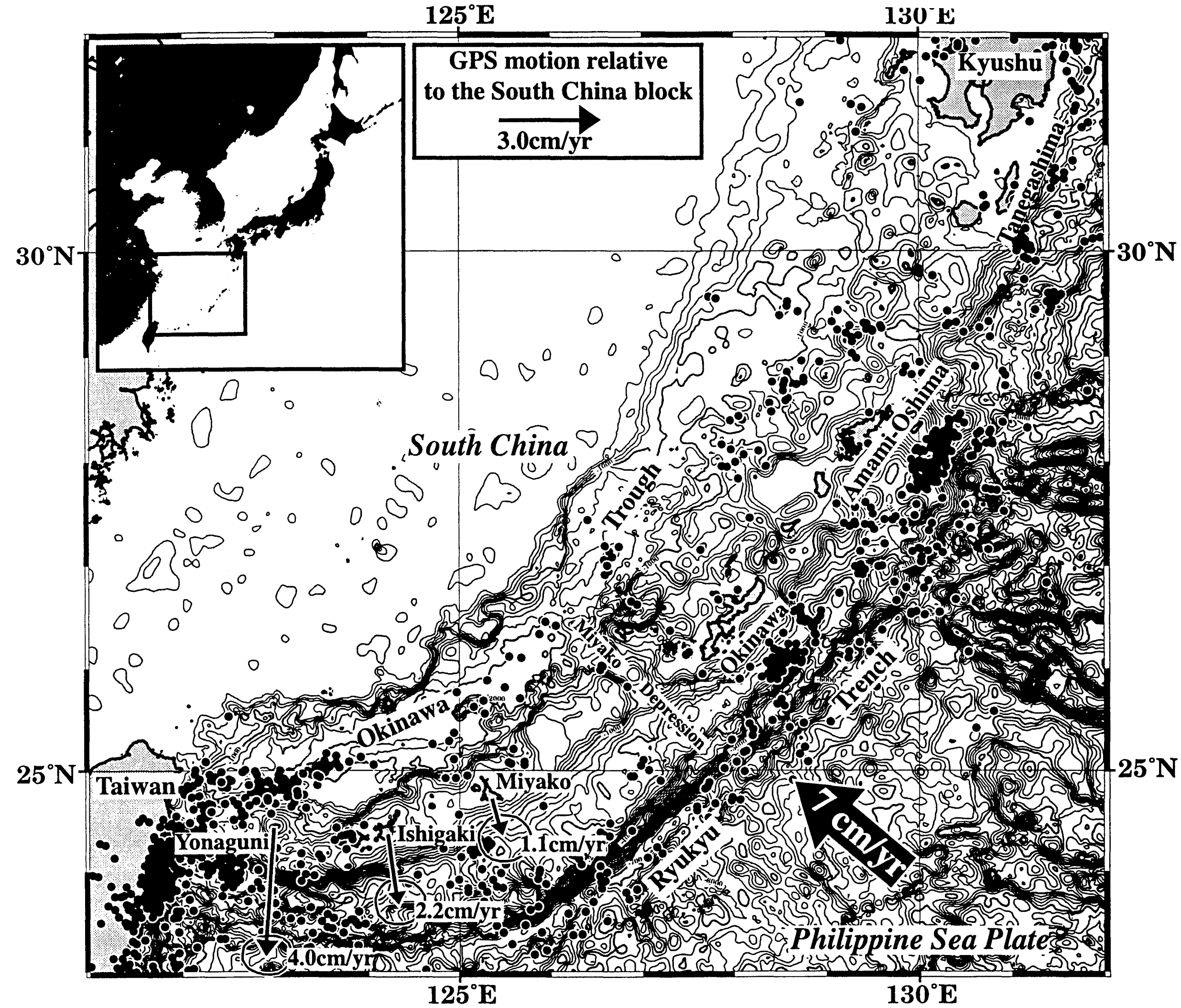

Figure 1. Bathymetric map of the Okinawa Trough-Ryukyu Trench region and shallow seismicity since 1964 (focal depth < 50 km) [*Engdahl et al.*, 1998]. The horizontal displacements, measured by GPS, of the southwestern Ryukyu arc with respect to south China (Shanghai VLBI station) are shown with thin solid arrows [*Imanishi et al.*, 1996; *Heki*, 1996]. The 1 σ error ellipse is shown at the tip of each velocity vector. The motion of the Philippine Sea plate relative to Eurasia (thick arrow) is from *Seno et al.* [1993]. The back arc opening is active mainly in the southwestern part of the basin, near the Taiwan collision zone. Bathymetric contour interval is 200 m.

of the arc. We conclude by proposing a kinematic evolution for the Okinawa Trough since the late Miocene.

2. Geodynamical and Geological Setting

The Okinawa Trough is a back arc basin currently opening behind the Ryukyu arc-trench system where the Philippine Sea plate subducts beneath the south China margin (Figure 1). It has been the site of crustal stretching and thinning since the Miocene [*Aiba and Sekiya*, 1979; *Lee et al.*, 1980; *Letouzey and Kimura*, 1985, and references therein]. Rifting in the northern Okinawa Trough occurs within a series of N60°E subgrabens aligned obliquely to the N30°-N45°E structural trend of the arc and trench (Figure 2) [*Sibuet et al.*, 1987]. Conversely, in the southern Okinawa Trough, the N80°-90°E trending subgrabens strike parallel to the E-W regional trend. The crustal thickness along the trough axis decreases from 27-30 km in the northern part near Kyushu to 15-18 km in the southern part near Taiwan [*Lee et al.*, 1980; *Iwasaki et al.*, 1990; *Hirata et al.*, 1991; *Sibuet et al.*, 1995]. Such crustal thicknesses indicate that the Okinawa Trough is still in a rifting stage. Subparallel, east to ENE trending linear magnetic anomalies were mapped in the axial part of the southern Okinawa Trough. Given their irregular traces, these anomalies are not indicative of seafloor spreading but rather of the presence of basaltic dykes [*Sibuet et al.*, 1987] or of crests of tilted basement blocks beneath the sedimentary cover [*Oshida et al.*, 1992].

GPS measurements in the southwestern part of the Ryukyu arc during the period 1994-1995 [*Imanishi et al.*, 1996] show that the Ryukyu arc is migrating southward with respect to the Shanghai VLBI station in South China

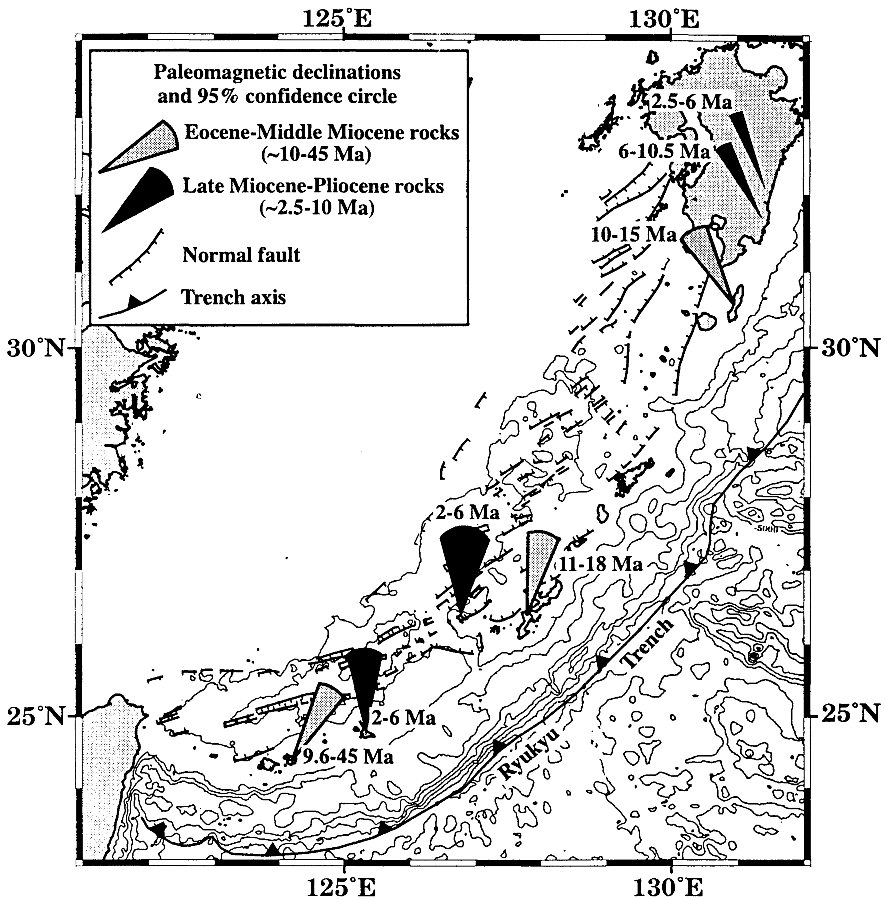

Figure 2. Structural map of the Okinawa Trough [*Sibuet et al.,* 1987] and paleomagnetic declinations of Tertiary rocks from the Ryukyu arc and southern Kyushu (sources of data are given in Table 1). Reported ages are for the rocks which recorded the paleomagnetic declinations. Bathymetric contour interval is 1000 m.

[*Heki,* 1996] (Figure 1). These preliminary data suggest that the present-day rate of motion progressively increases from east (1.1 cm/yr at Miyako) to west (4.0 cm/yr at Yonaguni).

The paleomagnetic declinations recorded by Tertiary rocks of the Ryukyu arc and southern Kyushu Island provide information about the rotation history of the arc during the last 10 m.y. (Table 1 and Figure 2). Since ~6 Ma, the southern and central Ryukyu arc has not undergone any rotation [*Miki,* 1995], while the northern Ryukyu arc and southern Kyushu Island have rotated ~30° counterclockwise [*Kodama and Nakayama,* 1993]. *Kodama et al.* [1995] showed that the major part of the rotation (~20°) occurred during the last 3 m.y. Between 6 and 10 Ma, the northern Ryukyu arc did not rotate [*Kodama et al.,* 1991; *Kodama and Nakayama,* 1993] and the central part did not experience any significant rotation [*Miki,* 1995]. For the same 10-6 Ma period the southern Ryukyu arc rotated 25° clockwise [*Miki et al.,* 1990; *Miki,* 1995]. The rotations of the northern arc since 6 Ma and of the southern arc between 6 Ma and 10 Ma appear to be recorded only at the extremities of the arc. Two categories of models have been proposed to account for the counterclockwise and clockwise rotations of the northern and southern extremities of the Ryukyu arc, respectively. In the first category of models (tapered extension) the rotations are considered as passive phenomena linked with the termination of the opening process toward both extremities of the basin [*Kodama and Nakayama,* 1993; *Kodama et al.,* 1995]. In these models the Ryukyu arc behaves as a rigid or quasi-rigid platelet. In the second category of models (collision-induced lateral rotations) the rotations would reflect indentation of the continental margin and subsequent rotation of the insular arc by subducting ridges or arcs [*Vogt et al.,* 1976], namely, the Luzon arc at Taiwan and the Palau-Kyushu ridge at Kyushu [*Letouzey and Kimura,* 1985; *Viallon et al.,* 1986]. As we will see in section 3.2, active kinematics favor the first category of models.

3. Active Deformation in the Okinawa Trough and Ryukyu Arc

3.1. Focal Mechanisms of Shallow Earthquakes

The shallow seismicity (focal depths < 50 km) is concentrated mainly in the southwestern part of the Okinawa Trough, in the vicinity of Taiwan (Figure 1). The back arc opening process appears to be more active in the southwestern end of the basin near the collision zone of Taiwan than in its northeastern part near Kyushu.

Table 1. Paleomagnetic Results From the Ryukyu Arc and Southern Kyushu[a]

Age, Ma	Locality	Formation or Rock Type	D, deg	α_{95}, deg	References
		Southern Ryukyu Arc			
43-45	Ishigaki	Nokoso	29.6	9.8	1, 2
9.6	Ishigaki	Andesitic Dike	36		1
2-6	Miyako	Shimajiri	358.5	12.5	2
		Central Ryukyu Arc			
11-18	Okinawa-Kume	Aradake	12.0	11.1	2
2-6	Kume-Omu	Uegusuku-dake	3.3	18.0	2
		Northern Ryukyu Arc			
10-15	Tanegashima	Kukinaga	331.2	9.9	3
		Southern Kyushu			
6-10.5	Kyushu	Uchiumigawa	331.8	6.0	4
2.5-6	Kyushu	Miyazaki	338.6	5.2	5

[a] D is declination, and α_{95} is the radius of 95% confidence circle. References: 1, Miki et al. [1990]; 2, Miki [1995]; 3, Kodama et al. [1991]; 4, Kodama and Nakayama [1993]; 5, Kodama et al. [1995].

We selected in the Harvard centroid moment tensor (CMT) catalog all focal mechanisms of earthquakes shallower than 50 km which occurred between 1976 and 1997 in the Okinawa Trough [*Dziewonski et al.*, 1981, 1998a, 1998b, and references therein] (Table 2). Forty mechanisms have been obtained, which are all of extensional or strike-slip type. We also included one extensional mechanism (May 17, 1974) from *Kao and Chen* [1991]. The 41 mechanisms are plotted in Figure 3. Three zones of homogenous deformation (similar style of faulting and similar orientations of seismic axes) can be defined: the southern Okinawa Trough where all mechanisms are extensional, the central northern Okinawa Trough (also including the southern part of Kyushu Island) where strike-slip faulting prevails, and the region centered on Miyako Island with two extensional mechanisms with different orientation of nodal planes compared to the surrounding areas.

In the southern Okinawa Trough the nodal planes of the extensional mechanisms commonly strike within 30° of the E-W direction (Figure 3). The distribution of the seismic axes highlights the homogeneity of the seismogenic regime: all tension *T* axes are nearly horizontal and trend between N350°E and N20°E with a mean trend of N05°E, while all compression *P* axes are nearly vertical (stereoplot in Figure 3, top left insert). This deformation pattern is consistent with a tensional regional stress field with σ_3 (minimum principal stress; $\sigma_1 > \sigma_2 > \sigma_3$) trending N-S.

Earthquakes in the central northern Okinawa Trough and southern Kyushu region are of two types: extensional (five events) and strike slip (19 events). The five predominantly extensional earthquakes (events 18, 22, 23, 25, and 36) display mechanisms similar to those in the southern Okinawa Trough. With three exceptions (events 21, 29, and 35), the strike-slip mechanisms have nodal planes between N-S and N20°E and between N90°E and N110°E. The *T* axes of both extensional and strike-slip mechanisms are nearly horizontal, scattered between N135°E and N180°E, with a mean trend of N153°E (stereoplot in Figure 3, top insert). This deformation pattern is consistent with an intermediate-type (σ_2 vertical) regional stress field with σ_3 and σ_1 trending N150°E and N60°E, respectively.

Between the southern and the central northern Okinawa Trough the Miyako area corresponds to a bend in the Ryukyu arc (Figure 3). It is affected by arc-parallel extension evidenced by two extensional focal mechanisms with NE-SW *T* axes. This extension is also expressed in Miyako Island by kilometer-scale NW-SE normal faults which offset the upper Pleistocene Ryukyu Limestone [*Research Group for Active Faults in Japan*, 1991; *Fabbri and Fournier*, 1999] (Figure 3, bottom left insert).

The overall deformation pattern illustrates the mechanism of opening of the back arc basin and deformation of the arc (Figure 3, bottom right insert). As already noted by *Eguchi and Uyeda* [1983], the extension does not show a perfectly radial pattern: in the southern Okinawa Trough the opening is accommodated by a N-S extension perpendicular to the N90°E trending trough (perpendicular rifting), whereas in the central and northern Okinawa Trough it is accommodated by a N150°E extension oblique to the ~N45°E trending trough (oblique rifting). As the basin opens, the curvature of the oceanward migrating arc slightly increases, and the arc is stretched. It undergoes both across-strike extension and along-strike extension, the latter accommodating stretching. The along-strike extension results from the local permutation of the horizontal principal stresses σ_2 and σ_3. As discussed in section 4, this permutation is recorded also by surface faults that account for the extensional deformation pertaining to the back arc basin formation.

Table 2. Source Parameters of Earthquake Focal Mechanisms

Event	Date	Origin Times, UT	Latitude, °N	Longitude, °E	Depth, km	Moment,[a] dyn cm	Plane 1 Strike, Dip, Rake, deg	Plane 2 Strike, Dip, Rake, deg
				Southern Okinawa Trough				
1	April 19, 1984	1729:04	24.89	122.42	36	8.1E23	92, 38, -68	245, 56, -106
2	Sept. 20, 1985	1501:25	24.60	122.31	10	1.8E24	96, 27, -79	264, 63, -95
3	Jan. 16, 1986	1304:34	24.74	122.10	15	10.7E24	53, 28, -96	240, 62, -87
4	March 22, 1986	1031:07	24.73	122.91	15	2.9E24	72, 45, -141	313, 64, -52
5	March 22, 1986	1206:33	24.71	122.92	15	5.4E24	317, 40, -39	79, 66, -123
6	March 22, 1986	1427:17	24.58	122.95	15	12.6E23	82, 20, -94	266, 70, -88
7	March 22, 1986	1845:32	24.76	123.24	15	8.6E23	248, 52, -131	123, 54, -50
8	March 25, 1986	1213:47	24.80	123.23	15	6.3E23	270, 30, -93	94, 60, -88
9	July 31, 1986	1136:35	24.86	122.71	21	9.3E23	125, 41, -83	296, 49, -96
10	Oct. 20, 1992	0718:51	24.44	123.66	30	8.6E23	81, 31, -95	266, 59, -87
11	Oct. 28, 1994	2351:12	24.75	122.18	33	3.3E24	294, 41, -63	81, 54, -111
12	June 9, 1996	0833:55	24.95	123.45	18	8.4E23	73, 36, -100	265, 55, -83
13	June 9, 1996	0853:48	24.97	123.30	17	2.5E24	91, 31, -80	260, 60, -96
14	Sept. 24, 1996	0027:51	24.94	123.48	15	3.3E24	98, 40, -74	258, 52, -103
15	Jan. 5, 1997	1034:19	24.68	122.46	27	7.4E23	275, 35, -98	104, 55, -85
				Miyako Area				
16	May 17, 1974	1711:53	25.1	125.5	25	1.1E25	340, 49, -75	137, 43, 74
17	Sept. 11, 1978	0740:52	24.93	124.85	15	1.2E25	142, 42, -80	308, 49, -99
				Central and Northern Okinawa Trough				
18	Dec. 22, 1977	0445:14	29.55	127.81	15	11.1E24	92, 33, -55	233, 64, -110
19	March 2, 1980	2328:57	26.99	126.62	15	3.4E25	97, 57, -11	193, 81, -147[b]
20	March 9, 1980	0841:07	27.18	126.59	15	1.2E24	93, 71, -1	183, 89, -161[b]
21	Dec. 31, 1982	0958:00	28.68	128.54	28	1.6E24	318, 68, 11	223, 80, 157
22	May 27, 1984	0339:30	28.77	128.55	13	2.9E24	80, 36, -100	272, 55, -83
23	Jan. 15, 1985	0956:47	25.68	125.27	23	11.2E23	36, 27, -134	264, 71, -70
24	July 25, 1986	2341:10	26.45	125.95	15	1.8E25	11, 83, 179[b]	101, 89, 7
25	Sept. 2, 1989	2229:22	25.62	125.16	15	9.4E23	99, 54, -46	221, 54, -133[b]
26	Sept. 3, 1989	0019:37	25.55	125.28	15	1.8E24	191, 59, 177[b]	282, 87, 31
27	Sept. 5, 1989	1125:57	29.43	128.70	15	2.4E24	294, 64, -14	30, 77, -153
28	Nov. 6, 1989	1512:54	25.81	125.50	15	1.9E24	271, 60, -35	20, 60, -145[b]
29	Aug. 3, 1991	0833:16	29.33	129.06	24	3.8E24	339, 86, 1	249, 89, 176
30	June 3, 1992	0328:53	28.11	128.27	26	1.4E24	10, 79, 174[b]	101, 84, 11
31	June 4, 1992	0404:06	27.96	128.35	21	1.3E25	100, 79, 11	7, 79, 168[b]
32	June 6, 1992	0441:14	28.12	127.97	27	1.3E24	104, 82, -3	195, 87, -172[b]
33	July 7, 1993	1110:53	27.84	128.05	32	2.0E24	278, 72, -12	12, 79, -162[b]
34	Aug. 16, 1995	2058:52	28.44	128.06	34	4.5E24	109, 85, 4	19, 86, 175[b]
35	Aug. 26, 1995	1606:14	28.48	128.41	34	9.9E23	33, 80, 176	124, 86, 10
36	April 5, 1997	2037:43	28.73	128.54	15	1.9E24	72, 34, -96	259, 57, -86
				Kyushu Area				
37	Aug. 14, 1984	1830:12	31.60	130.02	16	10.3E23	96, 82, 1	6, 89, 172[b]
38	March 26, 1997	0831:47	31.92	130.43	30	1.8E25	8, 89, 179[b]	98, 89, 1
39	April 2, 1997	1933:22	31.82	130.09	15	1.8E24	2, 70, 166[b]	97, 77, 20
40	April 5, 1997	0424:51	31.95	130.43	33	5.1E23	194, 69, -168[b]	99, 78, -21
41	May 13, 1997	0538:30	31.82	130.28	16	1.4E25	280, 75, -14	14, 77, -164[b]

[a] Read 8.1E23 as 8.1×10^{23}.

[b] Fault planes and slip vectors used for the determination of the South China-Ryukyu arc euler pole.

3.2. Current Kinematics of the Okinawa Trough Opening

3.2.1. Previous kinematic studies. On the basis of paleomagnetic data or offshore structural data, several authors determined opening poles for the Okinawa basin. The poles based on paleomagnetic data account for rotations of the northern and southern parts of the arc by assuming a wedge-shaped opening at both tips of the basin. *Vander Zouwen* [1984] and *Kamata and Kodama* [1994] located an opening pole at Kyushu to account for the counterclockwise rotation of the northern arc, whereas *Miki* [1995] located a pole in northern Taiwan to account for the clockwise rotation of the southern arc (Figure 4a). As noticed by *Sibuet et al.* [1995], these poles imply an amount of extension which would be unrealistic if extrapolated to the entire trough.

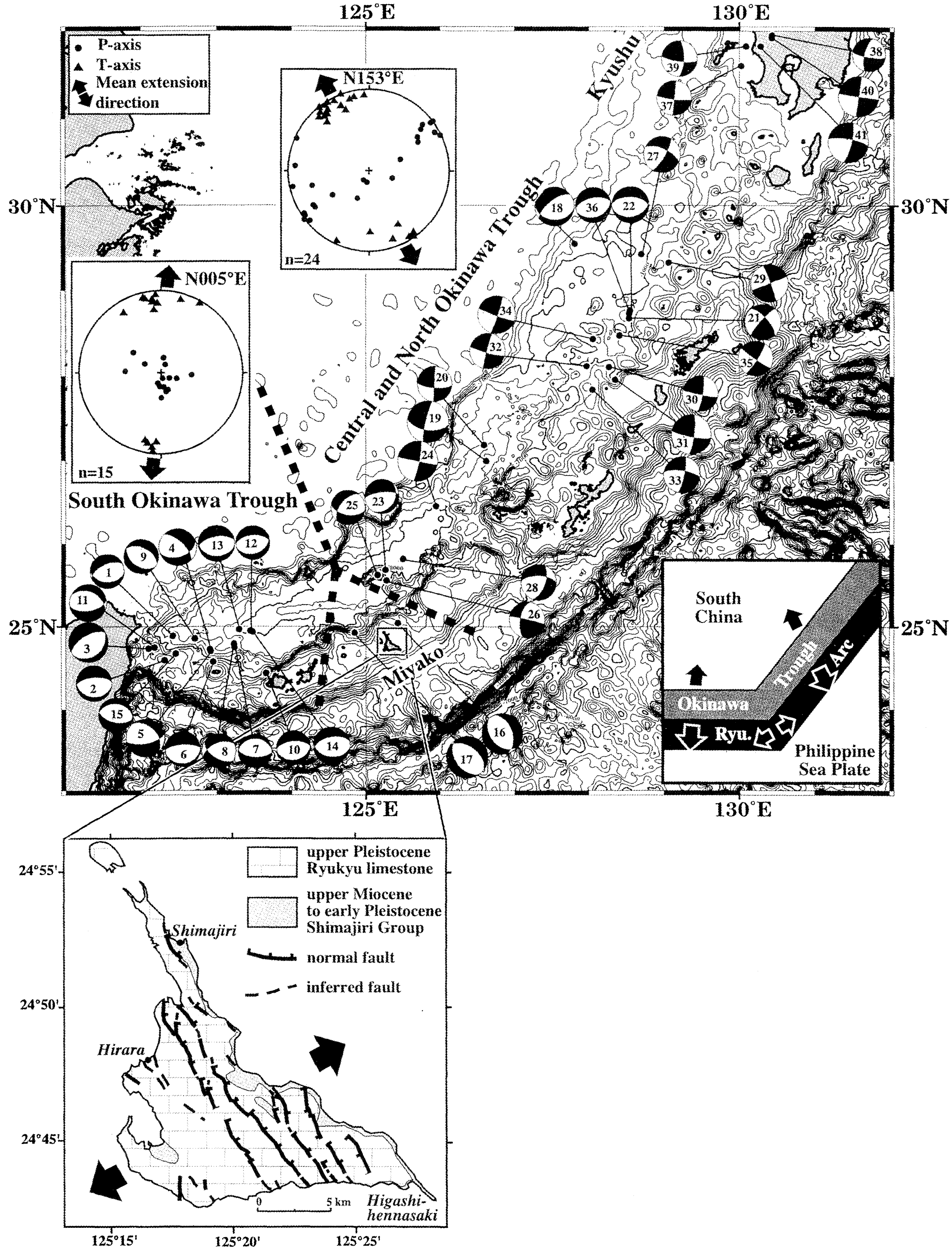

Figure 3. Focal mechanisms of 41 earthquakes that occurred in the Okinawa Trough region since 1974 [*Dziewonski et al.*, 1981, 1998a, 1998b; *Kao and Chen*, 1991]. Numbers inside the focal spheres refer to the chronological list of events given in Table 2. Top left inserts show equal-area projections of compression *P* and tension *T* axes for the south Okinawa Trough and for the central north Okinawa Trough and Kyushu Island. Bottom right insert shows an illustration of the arc response (arc-parallel stretching in the hinge area) to arc-perpendicular extension in the Okinawa Trough. Bottom left insert shows Holocene normal faults in Miyako Island (hinge area) after *Research Group for Active Faults in Japan* [1991]. Bathymetric contour interval is 200 m.

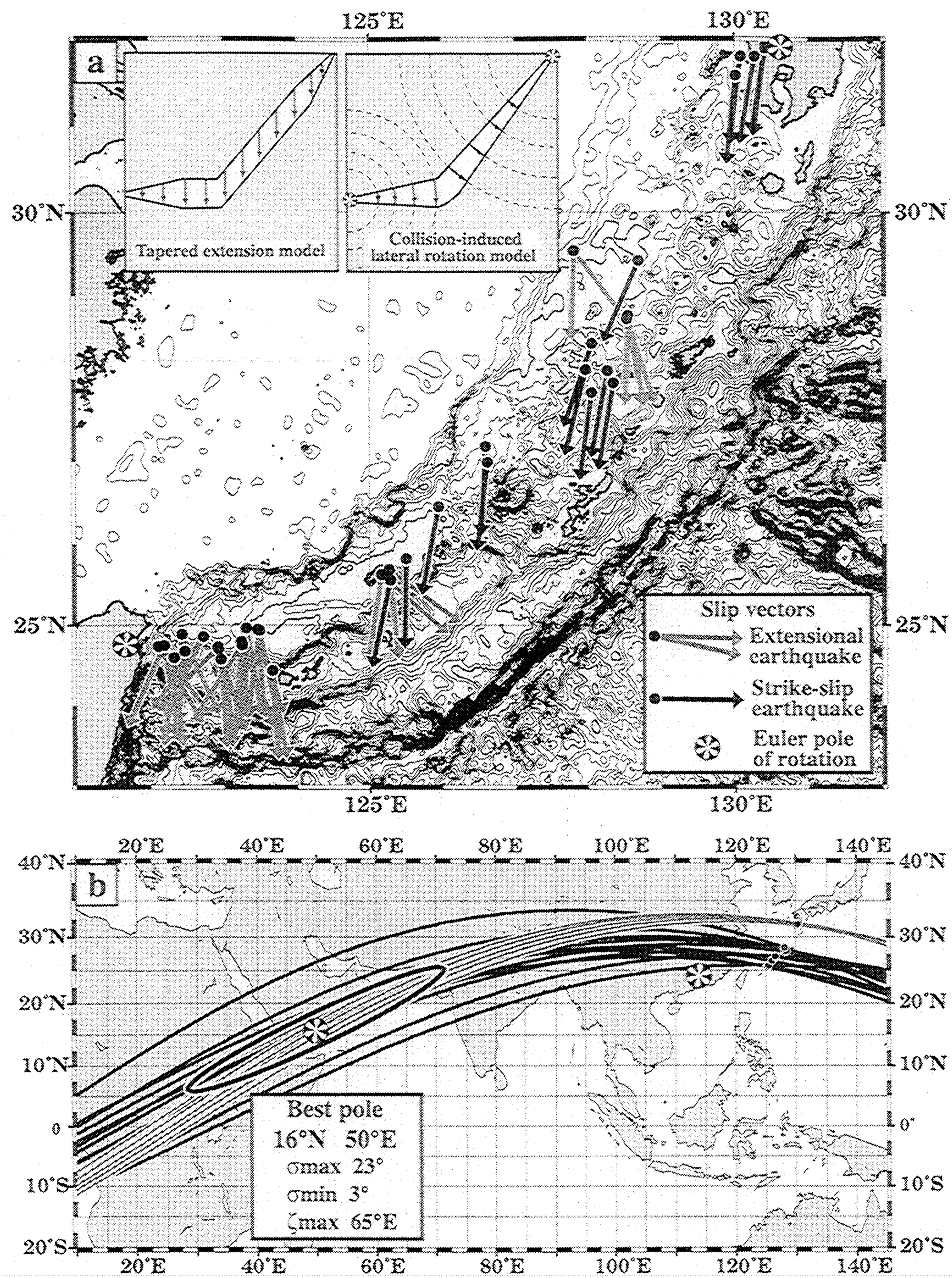

Figure 4. (a) Slip vectors of the extensional (shaded arrows) and strike-slip (solid arrows) mechanisms in the Okinawa Trough and southern Kyushu (relative to the stable south China block). Concerning the extensional mechanisms, the two possible slip vectors are plotted. Concerning the strike-slip mechanisms, only the vectors close to N-S are plotted. The poles of rotation of *Vander Zouwen* [1984] and *Kamata and Kodama* [1994] in Kyushu, *Miki* [1995] in northern Taiwan, and *Sibuet et al.* [1995] in south China are plotted. Bathymetric contour interval is 200 m. (b) Pole of rotation of the Ryukyu arc relative to the south China block with its error ellipse obtained from the slip vectors of strike-slip earthquakes in the Okinawa Trough and in southern Kyushu (inversion by the Monte Carlo method [*Jestin et al.,* 1994]). The great circles perpendicular to the slip vectors of strike-slip earthquakes in the central and northern Okinawa Trough (solid curves) and in southern Kyushu (shaded curves) intersect around the pole.

On the basis of the strikes of kilometer-scale normal faults mapped offshore in the Okinawa Trough and assumed to be purely normal, *Sibuet et al.* [1995] determined a Holocene rotation pole for the Ryukyu arc with respect to the south China block, which is located in south China (24.6°N, 113.6°E; Figure 4b). Using the same method with the recent and more accurate data of the ACT (Active Collision in Taiwan) cruise in the southern Okinawa Trough, *Sibuet et al.* [1998] determined a pole located near Hawaii (157°W, 22°N). The difficulty of obtaining a stable pole of rotation lies in the extreme sensitivity to variations in the distribution of mapped faults: small changes in the data set can result in a dramatic change in the location of the pole of rotation.

3.2.2. Kinematics based on earthquake slip vectors. The slip vectors of the earthquake focal mechanisms in the Okinawa Trough are plotted on Figure 4a. For the tensional mechanisms it is not possible to determine which of the two nodal planes is the fault plane. This is the reason why the two possible slip vectors are plotted (shaded arrows). Despite this uncertainty, there is always a slip vector close to N-S for all the extensional mechanisms scattered in the basin. Consequently, we selected as fault plane for each strike-slip mechanism the nodal plane closest to the N-S direction. Figure 4a shows that the azimuths of the slip vectors of 16 strike-slip earthquakes (solid arrows) are well clustered between N-S and N20°E (three mechanisms, events 21, 29, and 35, were discarded because their slip vectors significantly depart from the average N-S direction). The homogeneity of the directions of motion in the trough suggests that the Ryukyu arc moves southward (~N190°E) with respect to the south China block in a rigid or quasi-rigid way. As discussed above, the Ryukyu arc is not totally devoid of seismic deformation. However, the seismic activity is considerably lower in the Ryukyu arc than in the Okinawa Trough, so that the arc can be regarded in first approximation as a rigid platelet.

The slip vectors of the strike-slip earthquakes can then be used to estimate the location of the pole of rotation of the Ryukyu arc with respect to the south China block. The intersections of the great circles perpendicular to the trend of the slip vectors define the euler pole of rotation [*Morgan*, 1968]. The strike-slip earthquake data set was inverted with the Monte Carlo method [*Jestin et al.*, 1994] and yielded a south China-Ryukyu arc euler pole around 16°N and 50°E (Figure 4b): the great circles corresponding to earthquakes of the central and northern Okinawa Trough (solid curves) and those corresponding to earthquakes of southern Kyushu (shaded curves) intersect around this pole.

The pole is located at ~70° from the study area. This implies that the opening rate is nearly constant along the Okinawa Trough. This result is consistent with estimates of the total amount of extension (75-80 km) which do not vary significantly along the trough axis [*Sibuet et al.*, 1995]. The lack of precise information about the opening rate of the Okinawa Trough does not allow the calculation of a precise angular velocity. However, considering a mean opening velocity between 1 and 2.5 cm yr^{-1}, as suggested by the GPS data (Figure 1), the estimated angular velocity lies between 0.10 and 0.24° $m.y.^{-1}$.

3.2.3. Implications for the opening models. Active kinematics allows us to choose between the two categories of opening model. Indeed, the directions of motion given by the earthquake slip vectors are not arranged in the same way in the two cases. In the tapered extension model the directions of motion are homogeneous in the basin and show that the arc is translated southward with respect to the south China block in a rigid or quasi-rigid way (Figure 4a, insert). In the second category of models the directions of motion in the northern and southern parts of the trough are different and arranged concentrically around two opening poles located to the northeastern and southwestern ends of the trough, respectively. Our study, which shows that the motion directions are regionally homogeneous, favors the tapered extension model.

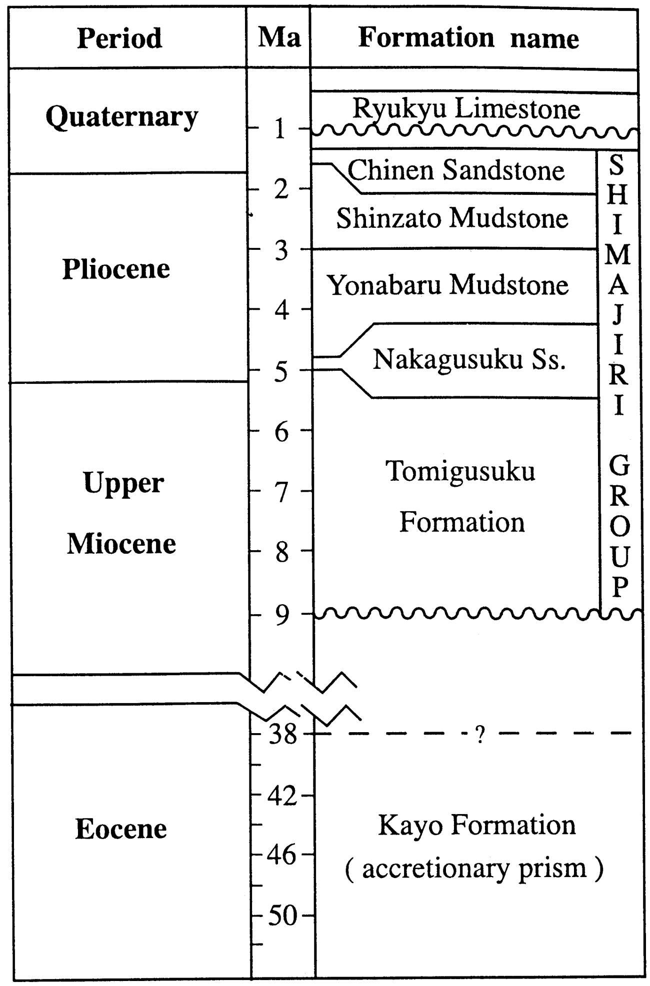

Figure 5. Stratigraphic synthesis of the Neogene strata exposed on Okinawa Island and surroundings islets. Sources of data are *Kano et al.* [1991] and *Ujiie* [1994].

4. Directions of Extension Deduced From Fault-Slip Data

The geology of the Ryukyu arc is summarized by *Kizaki* [1986] and *Miki* [1995]. Neogene and Quaternary strata are distributed in the southwestern part of the Okinawa Island and on nearby islands. They unconformably cover Cretaceous and Paleogene deposits of the Shimanto accretionary wedge and middle Miocene igneous intrusions. They consist of upper Miocene to upper Pliocene marine deposits, lower Pleistocene fluviatile deposits, upper Pleistocene reefal limestone, and Holocene marine and alluvial terrace deposits (Figure 5).

4.1. Record of Three Stages of Extension in Okinawa Island

About 450 tectonic joints and striated fault planes were examined in 20 localities scattered over the southern part of Okinawa Island (Figures 6-8). Most fault planes show

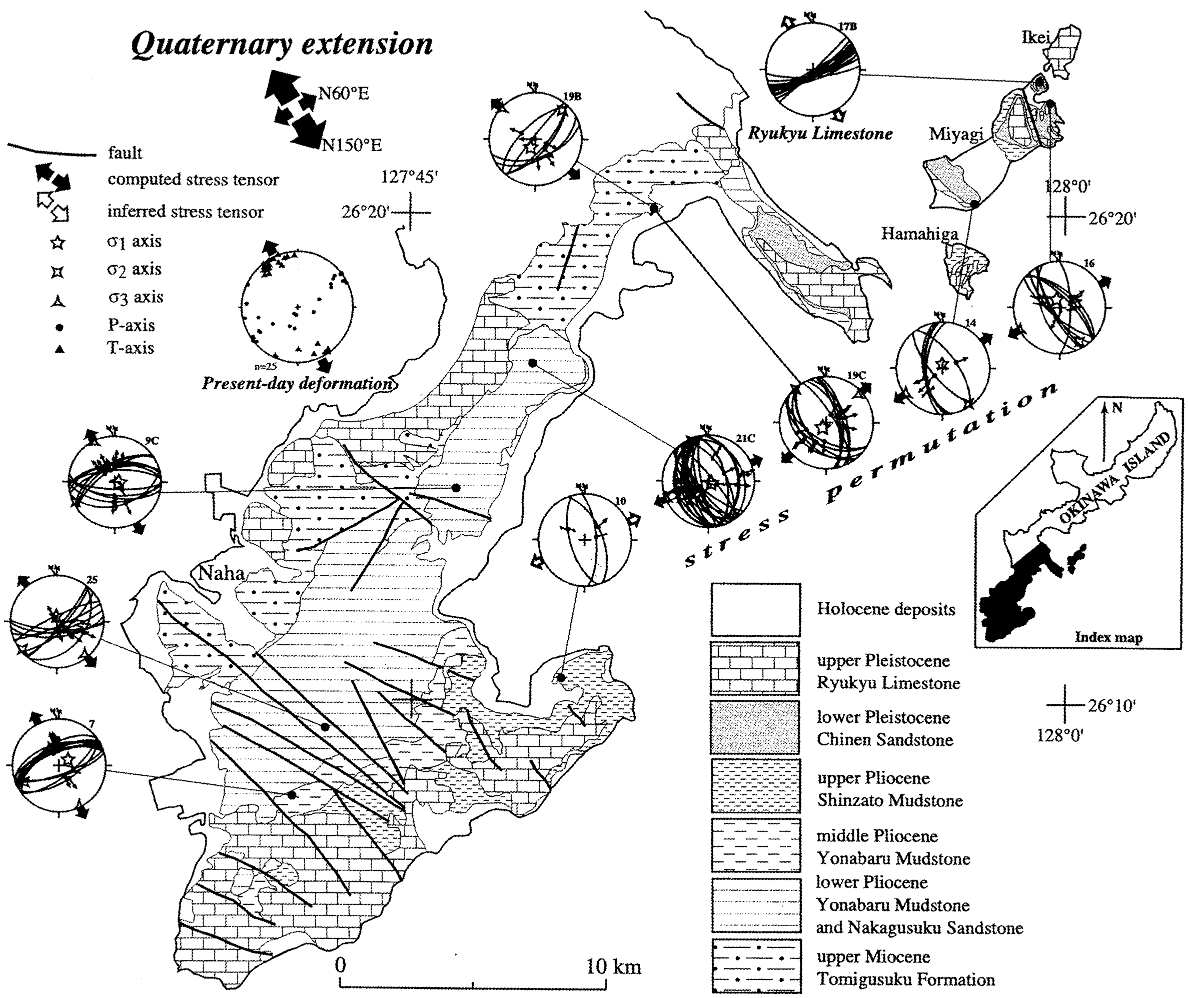

Figure 6. Quaternary extension recorded in upper Miocene to upper Pleistocene strata. *P* and *T* axes of nearby earthquakes (central and north Okinawa Trough earthquakes of Figure 2) are also shown. Two highly oblique directions of extensions can be inferred from tectonic joint and fault slip data. The N150°E direction, parallel to the trend of the mean *T* axis of earthquakes, is considered to be representative of the regional deformation. The N60°E direction reflects local permutations between the σ_2 and σ_3 stress axes.

normal displacements. Tectonic joints belong to the extensional joint type [*Hancock*, 1985]. On the basis of collection and inversion of fault slip data sets the orientations of the principal stress axes were determined using computer-aided methods developed by *Angelier* [1984, 1990, 1994]. In some localities the observed fault slip data sets, too complicated to be explained by a single stress tensor, obviously result from superimposed distinct tectonic events. For such data sets, it is necessary to separate homogeneous subsets identified with A, B, or C suffixes (localities 3, 9, 17, 19, 21, and 22 in Figures 6-8). The sorting was done in three ways. (1) At some sites, syndepositional faults were observed and could be distinguished from post depositional faults (e.g., Figures 6 and 8, locality 19). (2) At sites where all fault planes were similar (e.g., dip-slip normal faults) they could be classified according to their strikes (e.g., Figures 6 and 7, locality 21). (3) In some exposures, two different types of fractures affect two diachronous strata: this is the case at locality 17 (Figures 6 and 7) where Chinen-type sandstones are cut by syndepositional normal faults, whereas the unconformably overlying Ryukyu-type limestone is cut by post depositional extensional joints.

After inversion, all data sets or subsets provide vertical σ_1 axes (Table 3 and Figures 6-8). This means that all stress fields are tensional. All data sets, however, do not pertain to a unique stress field. The following observations help in distinguishing three diachronous episodes. Synsedimentary faulting affecting the Tomigusuku Formation, on one hand, and the Shinzato Mudstone and Chinen Sandstone, on the other hand, indicates two extensional episodes (Figure 9): a late Miocene one (Tomigusuku Formation) and a late Pliocene-early Pleistocene one (Chinen Sandstone). The definition of a third Holocene episode is based on kilometer-scale normal faults and on extensional joints affecting the upper Pleistocene Ryukyu limestone, as discussed in section 4.1.1. These three episodes are not only diachronous but also indicate different directions of extension, as summarized on Figure 9.

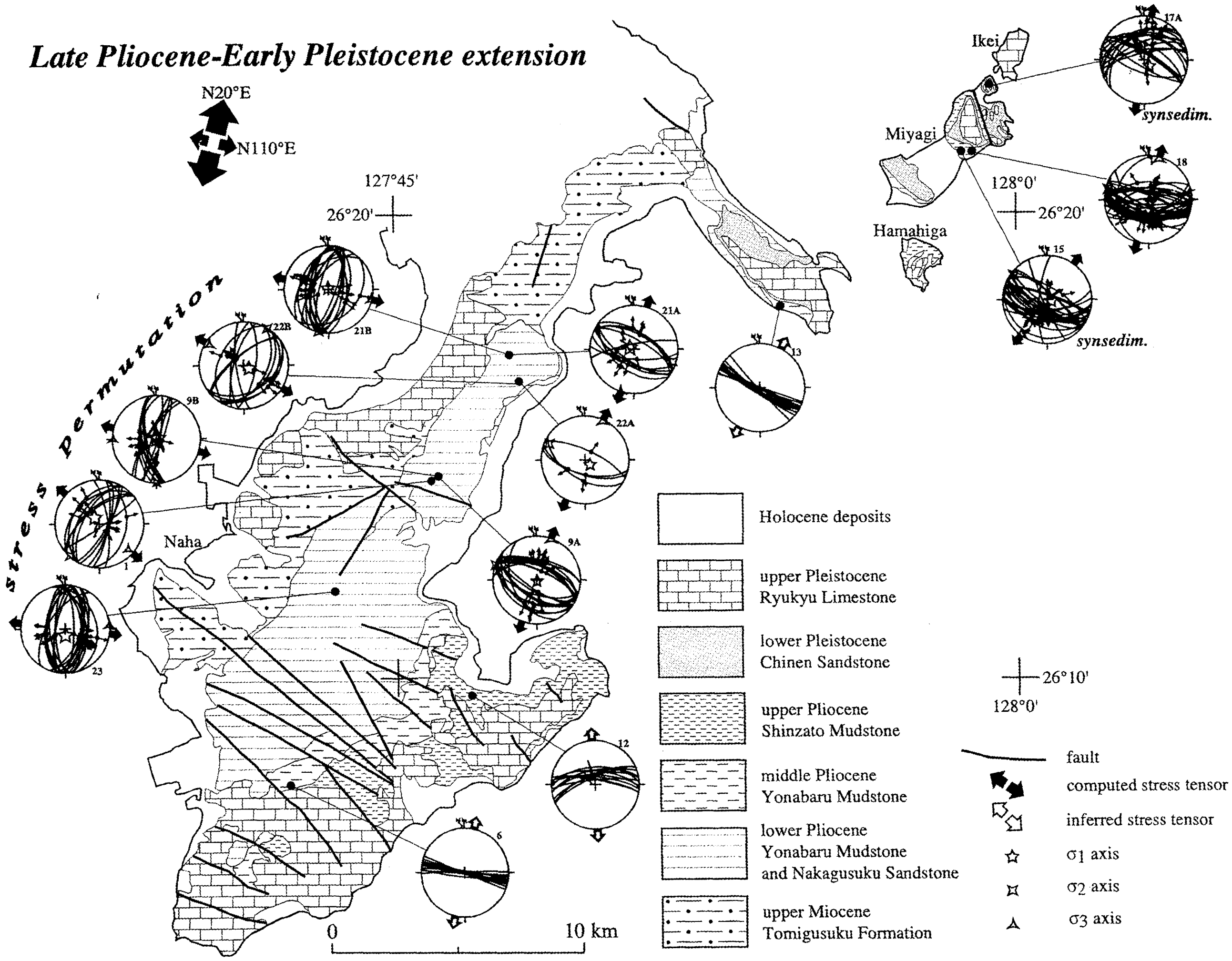

Figure 7. Late Pliocene to early Pleistocene extension recorded in Pliocene strata. Two nearly perpendicular directions of extension can be deduced from tectonic joint and fault slip data: a N20°E direction and a N100°-N120°E direction. Both directions are considered to pertain to a same and unique stress field. The direction of the main extension is thought to be around N20°E, which is the direction suggested by synsedimentary faults observed in the upper Pliocene Shinzato Mudstone.

4.1.1. Episode III: Quaternary to present-day extension. At the southern tip of Okinawa Island, a network of kilometer-scale, steeply dipping normal faults cut the Ryukyu limestone and, locally, Holocene marine terrace deposits, along two main directions: NW-SE and NE-SW [*Research Group for Active Faults in Japan*, 1991]. Most planes dip NW or NE. The limestone layers are also slightly tilted southeastward or southwestward. Estimates of vertical offsets for individual faults range from 5 to 60 m, with most values around 10-20 m. Assuming that all the normal faults are dip slip in type, two perpendicular directions of extension can be inferred from this fault pattern: N50°E and N150°E.

One set of vertical extensional joints affecting the Ryukyu Limestone suggests a NNW-SSE extension (Figure 6, Miyagi islet, locality 17B). This observation, taken together with the mean NNW-SSE trend of T axes of the nearby earthquakes (Figures 3 and 6) and the N150°E extension inferred from regional faulting, defines a N150°E, post-Ryukyu Limestone (Holocene) extension. Four sets of conjugate normal faults striking between N45° and N90°E in the lower to middle Pliocene strata of the Shimajiri Group also indicate a NNW-SSE extension (Figure 6, localities 7, 9C, 19B, and 25). Though the exact age of faulting is unknown, we consider this deformation as being synchronous with the Holocene extension evidenced above.

A WSW-ENE extension affects the upper part of the Shimajiri Group (Figure 6, localities 10, 14, 16, 19C, and 21C). The exact faulting age is unknown, but observations at sites 14 and 16 indicate that the WSW-ENE extension is post-Chinen sandstone deposition (post 1 Ma). In the absence of field evidence in younger formations, this extension may have predated the deposition of the Ryukyu limestone, but we rather consider that it is posterior, in agreement with the NW-SE regional faulting affecting the Ryukyu limestone. The post-Ryukyu Limestone extensions, which are nearly orthogonal (N150°E and N50°-N60°E), may be attributed to two different stress fields, but we interpret them in terms of permutations

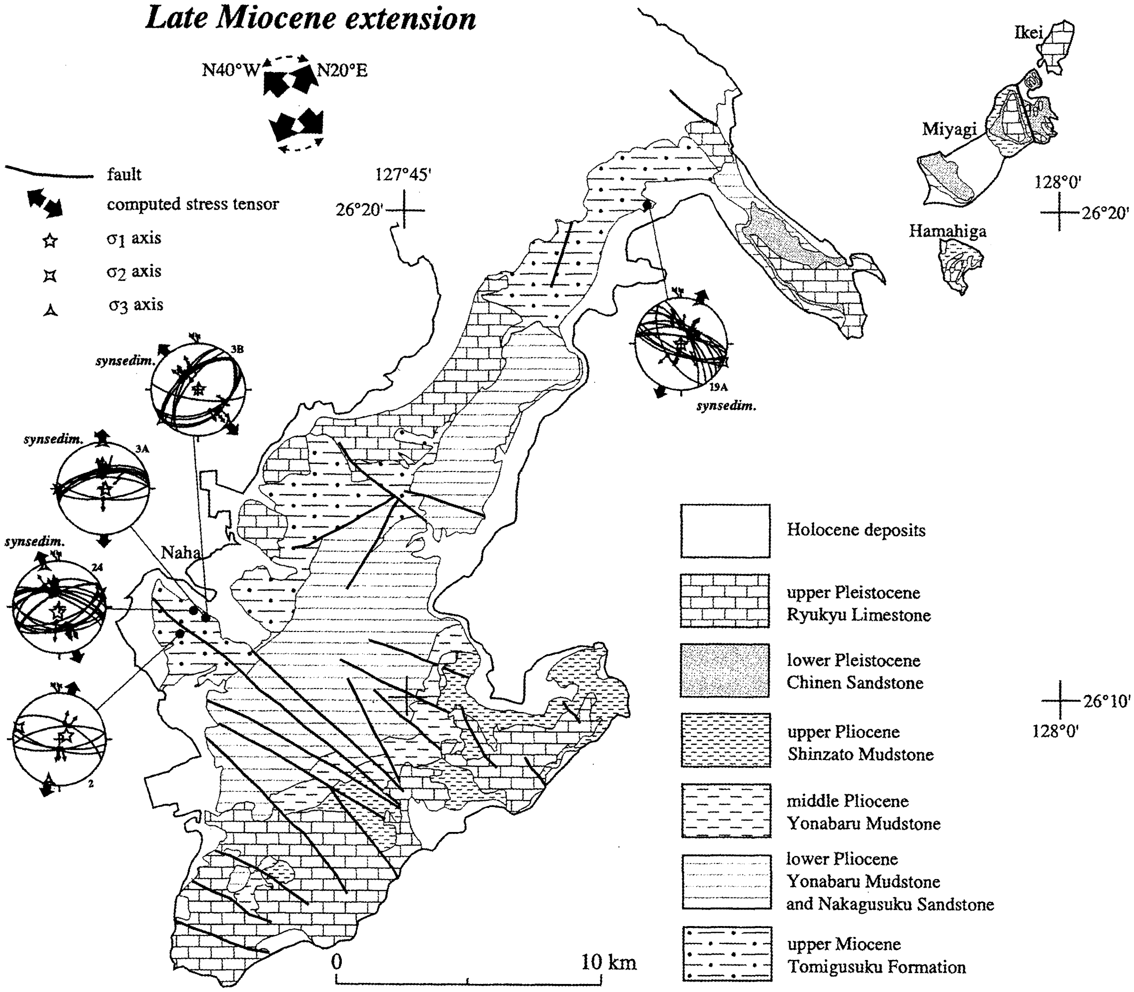

Figure 8. Late Miocene extension recorded in the upper Miocene Tomigusuku Formation. Directions of extension deduced from fault slip data (including synsedimentary faults) are scattered between N40°W and N20°E.

between the two principal horizontal σ_2 and σ_3 axes within a unique Holocene to present-day tensional stress field.

4.1.2. Episode II: late Pliocene to early Pleistocene extension. Synsedimentary normal faults observed in the upper Pliocene Shinzato Mudstone and the lower Pleistocene Chinen sandstone (Figure 7, Miyagi islet, data sets 17A and 15) document a late Pliocene-early Pleistocene N10°E to N35°E extension. Similar directions of extension can be inferred from post sedimentary fractures in the Shimajiri Group (Figure 7, data sets 6, 9A, 12, 13, 18, 21A, and 22A). The mean direction of extension is N20°E. Another series of data indicates a perpendicular (N100°E to N130°E) direction of extension (Figure 7, data sets 1, 9B, 21B, 22B, and 23), which should be considered again in terms of stress permutations within a single late Pliocene to early Pleistocene tectonic regime.

4.1.3. Episode I: Late Miocene extension. Synsedimentary normal faults cutting the upper Miocene Tomigusuku Formation document a late Miocene extensional episode (Figure 8, sets 3A, 3B, 19A, and 24). The directions of extension are scattered between N40°W and N20°E. Conjugate normal faults of locality 2 (Figure 8) can be related to this episode, although their activity cannot be accurately dated. As a whole, there is evidence for a late Miocene extension, but the relevant data are too scarce to precisely define the trends of the minimum principal stress, which remain scattered between N40°W and N20°E.

4.2. Regional Synthesis: A Succession of Three Episodes of Extension

4.2.1. Data from adjacent areas. Figures 10 and 11 provide a synthetic picture of the extensional deformation and kinematics of the Ryukyu arc region since the late Miocene. From the analysis of swath bathymetry and seismic reflection profiles in the Okinawa Trough, *Sibuet et al.* [1995, 1998] and *Thareau et al.* [1997] identified and dated three main phases of extension, which are, from the youngest to the oldest, (1) a latest Pleistocene to Holocene extension trending N175°-190°E in the ~N90°E trending southern Okinawa Trough (at longitude 123°E), N160°-180°E in the ~N60°E trending central Okinawa Trough (at longitude 125.5°E), and N150°-170°E in the ~N40°E trending northern Okinawa Trough (at longitude 128°E);

Table 3. Trend and Dip of Principal Stress Axes Computed From Fault Slip Data[a]

Site	Number of Faults	Formation	Age	σ_1 Strike, Dip, deg	σ_2 Strike, Dip, deg	σ_3 Strike, Dip, deg	Φ	Direction of Extension
1	13	Yonabaru Mudstone	lower Pliocene	321, 76	222, 02	132, 14	0.24	132°E
2	5	Tomigusuku	upper Miocene	62, 76	286, 10	185, 10	0.38	5°E
3A	10	Tomigusuku	upper Miocene	110, 86	269, 4	359, 2	0.42	179°E
3B	12	Tomigusuku	upper Miocene	45, 89	230, 1	140, 0	0.54	140°E
6	19	Yonabaru Mudstone	middle Pliocene					10°E
7	14	Yonabaru Mudstone	middle Pliocene	57, 72	244, 18	154, 2	0.52	154°E
9A	20	Yonabaru Mudstone	lower Pliocene	159, 88	290, 1	20, 2	0.57	20°E
9B	14	Yonabaru Mudstone	lower Pliocene	180, 83	16, 7	286, 2	0.16	106°E
9C	11	Yonabaru Mudstone	lower Pliocene	104, 83	242, 5	333, 4	0.20	153°E
10	3 joints	Shinzato Mudstone	upper Pliocene					65°E
12	13 joints	Shinzato Mudstone	upper Pliocene					175°E
13	12 joints	Shinzato Mudstone	upper Pliocene					35°E
14	6	Yonabaru Mudstone	lower Pliocene	352, 82	144, 7	235, 3	0.57	55°E
15	28	Shinzato Mudstone	upper Pliocene	108, 83	307, 7	217, 2	0.40	37°E
16	9	Shinzato Mudstone and Chinen Sandstone	upper Pliocene to lower Pleistocene	338, 75	150, 15	240, 2	0.36	60°E
17A	19	Chinen Sandstone	lower Pleistocene	139, 76	278, 11	10, 9	0.51	10°E
17B	18 joints	Ryukyu Limestone	upper Pleistocene					150°E
18	39	Shinzato Mudstone	upper Pliocene	142, 83	285, 6	15, 4	0.59	15°E
19A	14	Tomigusuku	upper Miocene	270, 90	114, 0	24, 0	0.42	24°E
19B	6	Tomigusuku	upper Miocene	210, 73	43, 16	312, 4	0.39	132°E
19C	12	Tomigusuku	upper Miocene	216 79	318, 2	48, 11	0.28	48°E
21A	11	Nakagusuku Sandstone	lower Pliocene	291, 82	108, 8	198, 0	0.19	18°E
21B	15	Nakagusuku Sandstone	lower Pliocene	345, 88	194, 2	104, 1	0.40	104°E
21C	29	Nakagusuku Sandstone	lower Pliocene	129, 84	337, 5	247, 3	0.28	67°E
22A	4	Nakagusuku Sandstone	lower Pliocene	134, 77	294, 12	25, 4	0.54	25°E
22B	12	Nakagusuku Sandstone	lower Pliocene	123, 79	32, 0	302, 11	0.32	122°E
23	20	Nakagusuku Sandstone	lower Pliocene	175, 74	8, 16	277, 3	0.37	97°E
24	18	Tomigusuku	upper Miocene	196, 80	71, 5	340, 8	0.30	160°E
25	10	Yonabaru Mudstone	lower Pliocene	351, 80	231, 5	140, 8	0.48	140°E

[a] Here σ_1, σ_2, and σ_3 are maximum, intermediate, and minimum principal stress axes. Φ is the ratio $(\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$.

(2) a latest Pliocene to Pleistocene extension along N150°-170°E in the southern Okinawa Trough, along N145°-160°E in the central Okinawa Trough, and along N135°-155°E in the northern Okinawa Trough; and (3) a middle to late Miocene N155°E extension in the southern Okinawa Trough.

Only two episodes of extension were identified from fracture analysis in the southern Ryukyu arc [*Fabbri and Fournier*, 1999]: a N-S Holocene extension and a N135°E Miocene to earliest Pleistocene extension. This last episode is well dated only at Miyako, where it is recorded in the upper Shimajiri Group of late Pliocene age and sealed by the upper Pleistocene Ryukyu Limestone. A Holocene arc-parallel extension (N60°E) was also identified at Miyako (Figure 3, bottom).

Fracture analysis in the Tanegashima Island in the northernmost part of the arc (Figure 1) shows that middle Miocene (16-10 Ma) strata recorded two extensional events, one along N45°E and another along N135°E [*Fabbri*, 2000]. These two extensions, which are considered to pertain to the same tensional stress field with σ_1 vertical and permutating σ_2 and σ_3 axes, were completed before the deposition of undeformed Pliocene (5-2 Ma) strata and thus before the completion of most of the 30° counterclockwise rotation which is recorded in the island [*Kodama et al.*, 1991, 1995]. This explains that in Figure 11 (top) the extension axes obtained at Tanegashima are rotated clockwise 30° in order to cancel the subsequent tectonic rotation.

4.2.2. Correlation between Okinawa and adjacent areas. Figures 10 and 11 allow a comparison between the offshore and onshore directions of extension. On-land data were obtained from areas much smaller than those for offshore data, but the directions of extension are determined much more accurately than for the offshore domain where the slip vectors could never be observed directly. Moreover, the on-land data described here reveal an arc-parallel extension that could not be evidenced offshore.

Despite the contrast in accuracy and domain size the

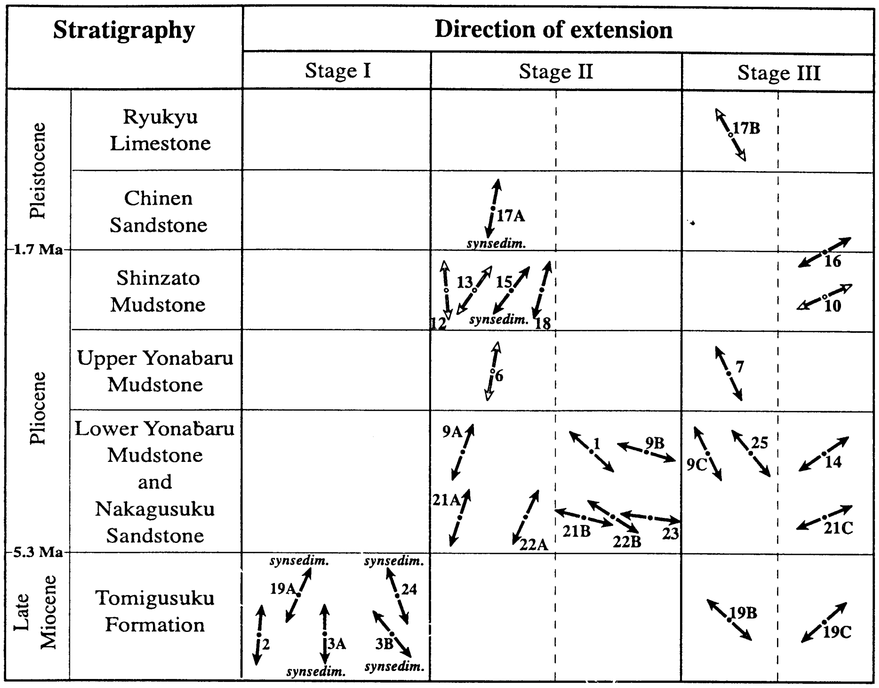

Figure 9. Synthesis of onland deformation in Okinawa Island. The directions of extension are taken identical to the trends of the σ_3 axes when these can be computed (solid arrows) or inferred from fracture geometry when computation is not possible (open arrows).

onshore directions of extension are in general agreement with the offshore directions of extension. There is a good parallelism between extension axes for present-day episode III and an acceptable parallelism for episode I (late Miocene) extension directions in the southern part of the arc where both types of data are available. The main difference concerns episode II (late Pliocene to early Pleistocene): offshore studies in the central Okinawa Trough indicate a N145°E extension, whereas our investigations in Okinawa Island give a N20°E direction. This difference could possibly reflect a local perturbation of the stress field in Okinawa Island.

5. Kinematics and Deformation

5.1. Results of Analogue Modeling of Oblique Rifting

The process of oblique rifting, for which the relative direction of displacement is not perpendicular but oblique to the rift trend, has been investigated by means of analytical modeling [*Withjack and Jamison*, 1986] or analogue modeling carried out on clay [*Withjack and Jamison*, 1986], sand-silicone [*Tron and Brun*, 1991; *Dauteuil and Brun*, 1993], or sand models [*McClay and White, 1995*]. These models show that oblique rifting is accommodated by both normal and strike-slip faults whose relative proportion depends on the rifting obliquity, which is the angle between the normal to the rift trend and the direction of displacement. For an obliquity comprised between 0° and 60°, normal faults are predominant. Strike-slip faults start to appear for an obliquity exceeding 45° and will predominate for obliquities exceeding 60°. The models also show that three structural directions are linked: the rift trend (or its perpendicular), the direction of relative displacement between the two sides of the rift, and the greatest principal strain axis ε_1 of the finite strain ellipsoid, taken horizontal and perpendicular to the mean strike of the normal faults. *Withjack and Jamison* [1986] showed that the ε_1 axis lies approximately halfway between the direction of relative displacement and the normal to the rift trend. This rule of thumb, which allows one direction to be deduced when the two others are known, has already been applied to determine the direction of opening of the northern Okinawa Trough and the southern Okinawa Trough by *Thareau et al.* [1997] and *Sibuet et al.* [1998], respectively (see hereafter section 5.3).

5.2. Current Opening

The present-day extension in the Okinawa Trough is the result of the southward displacement of the Ryukyu arc with respect to the south China block (Figures 4 and 10). The principal strain directions depend on the direction of relative motion with respect to the mean trend of the trough. In the southern part the direction of relative motion (~N-S) is nearly perpendicular to the local trend of the trough (E-W). The formation of the trough involves pure extension without any shear component: the greatest axis ε_1 of the strain ellipsoid is horizontal and parallel to the direction of movement (Figure 10b). The deformation is accommodated by E-W striking normal faults perpendicular to ε_1. In the central and northern parts the relative motion (N-S) is oblique to the local trend of the trough (~N40°E): rifting is oblique, and the obliquity is ~50°. The formation of the trough involves a combination of extension and simple shear. The greatest horizontal axis ε_1 of the strain ellipsoid trends halfway between the

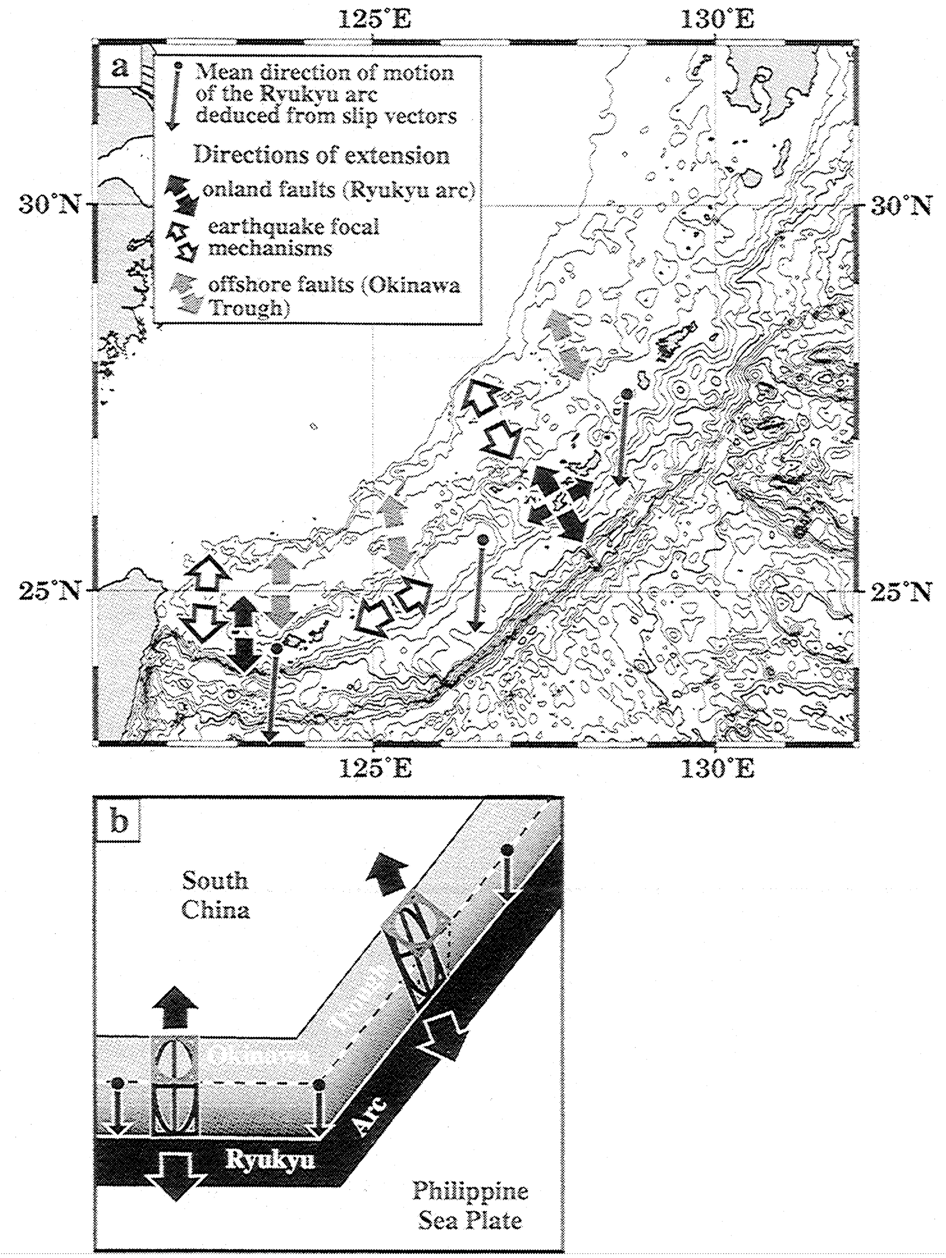

Figure 10. (a) Synthesis of the directions of present-day extensions in the Ryukyu arc region. The direction of motion of the Ryukyu arc relative to south China is given by the mean direction of slip vectors of strike-slip earthquakes (N190°E). Sources of data are *Sibuet et al.* [1995, 1998] and *Thareau et al.* [1997] for the Okinawa Trough and *Fabbri and Fournier* [1999] for the southern Ryukyu arc. Bathymetric contour interval is 500 m. (b) Interpretation of present-day extensional deformation. In the southern Okinawa Trough the relative displacement is perpendicular to the rift trend: the deformation is purely extensional, and the greatest axis of the ellipse is parallel to the direction of relative displacement. In the central and northern Okinawa Trough the relative displacement is oblique to the rift trend: the deformation is transtensional, and the greatest axis of the ellipse trends halfway between the perpendicular to the rift and the direction of relative displacement, as shown by *Withjack and Jamison* [1986] and *Tron and Brun* [1991]. Note that the longitudinal stretching of the arc is not taken into account in this simplified model.

direction of relative motion and the normal to the rift trend (Figure 10b). An estimate of the trend of ε_1 is given by the mean direction of the *T* axes of earthquakes in this area (N153°E; Figure 3). The extension is accommodated by a combination of normal faults striking perpendicularly to the direction of ε_1 and by right-lateral faults roughly parallel to the N-S direction of relative displacement as evidenced by the focal mechanisms of earthquakes.

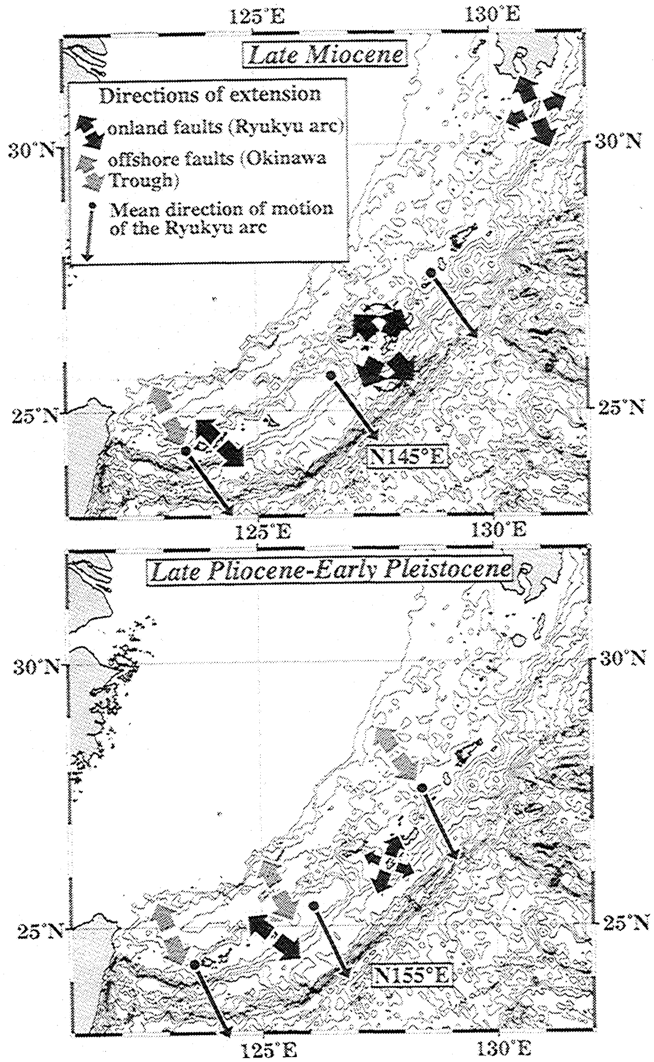

Figure 11. Synthesis of the directions of Neogene extensions obtained in the Ryukyu arc region. Sources of data are *Thareau et al.* [1997] and *Sibuet et al.* [1998] for offshore directions, *Fabbri and Fournier* [1999] for the southern Ryukyu arc, and *Fabbri* [2000] for the northern Ryukyu arc. Bathymetric contour interval is 500 m.

5.3. Past Kinematics

The directions of extension obtained onshore for episodes I and II (Figure 11) are not precise enough to improve the results obtained by *Thareau et al.* [1997] and *Sibuet et al.* [1998] from offshore data. The directions of relative motion proposed by these authors are N145°E for the late Miocene (episode I) and N155°E for the late Pliocene-early Pleistocene (episode II). The 10° difference between these two directions of opening may not be significant given the error margin (±15°) of the method based on analogue models. Extension episodes I and II could as well correspond to a unique N150°E direction of opening. To the contrary, the accuracy of the method is sufficient to allow a distinction between the present-day opening whose direction is N-S to N190°E, and the late Miocene to early Pleistocene opening whose direction is N145-155°E. This clockwise rotation of ~30° of the direction of opening was achieved during the last 5 m.y., and is independant from the paleomagnetic rotations which have been taken into account in the correction of the directions of extension.

6. Geodynamic Implications

From the geometric point of view the opening of the southern Okinawa Trough roughly resembles that of a tension fracture: it takes place at the southern end of the central and northern Okinawa Trough, which can be regarded as a dextral transtensional zone accommodating N-S displacement. This geometry is similar to that of the Japan Sea at 25 Ma, before the onset of sea floor spreading in the Japan Basin [*Tamaki et al.*, 1992]. The Japan Sea opened as a pull-apart basin between two N-S right-lateral strike-slip zones: to the east the eastern Japan Sea shear zone [*Jolivet et al.*, 1991, 1995; *Fournier et al.*, 1994, 1995] and the Tsushima fault system to the west [*Fabbri et al.*, 1996]. In the present case, the dextral strike-slip zone that extends from the central Okinawa Trough to Kyushu would be the equivalent of the east Japan Sea shear zone, and the southern Okinawa Trough would represent the Japan Sea in the rifting stage. However, unlike the Tsushima fault system in the Japan Sea case, no dextral strike-slip zone is observed along the westernmost margin of the Okinawa Trough: this absence can be explained by the collision in Taiwan between the Luzon arc and the south China margin.

The existence of dextral shear zones along the eastern margin of Asia is a general feature of the whole Asian margin, from the northernmost Okhotsk Sea [*Worral et al.*, 1996] through Sakhalin [*Fournier et al.*, 1994], the north China grabens [*Chen and Nabelek*, 1988] and the Ryukyu region, to the western margin of the South China Sea [*Roques*, 1996]. This dextral deformation accommodates the northward relative motion of Asia with respect to the western Pacific subduction zone. It can be regarded as resulting from the India-Eurasia collision [*Kimura and Tamaki*, 1986; *Davy and Cobbold*, 1988; *Jolivet et al.*, 1990; *Worral et al.*, 1996] or from the southward retreat of the subduction trenches due to the roll back of the downgoing slabs [*Uyeda and Kanamori*, 1979].

7. Conclusions

The combined analysis of the shallow seismicity and of the onshore and offshore faulting in the Ryukyu arc region gives a coherent picture of the extensional deformation associated with the opening of the Okinawa Trough since the late Miocene. The deformation is characterized by a predominant rift-perpendicular to rift-oblique extension observed in the arc and in the trough and a less widespread rift-parallel extension observed only in the Ryukyu arc. The direction of the predominant extension is perpendicular to the trough in its southern part, and it becomes more and more oblique when going northeastward.

Three successive episodes of extension can be recognized and dated in the Neogene and Quaternary strata of the southwestern Okinawa Island. This succession completes that found onland in the southern and northern Ryukyu arc. The three episodes of extension appear as distinct events, but they might as well constitute a continuous process with progressive reorientation of the directions of extension through time. Given the discontinuous stratigraphic succession, it is difficult to choose between the two possibilities.

The present-day kinematics derived from the earthquake slip vectors reveals a southward motion of the Ryukyu arc with respect to the south China margin. This N-S motion is confirmed by the comparison of the geometry of the Holocene to recent deformation in the trough with analogue models of oblique rifting. Late Miocene and late Pliocene directions of motion of the Ryukyu arc can be inferred from offshore data [*Thareau et al.*, 1997; *Sibuet et al.*, 1998]. The direction of divergence of the Ryukyu arc has rotated clockwise from ~N150°E in the late Miocene to the early Pleistocene (extension episodes I and II) to nearly N-S today (extension episode III). The Ryukyu trench, which is kinematically bound to the Ryukyu arc, has undergone the same displacement with respect to the south China margin.

Two main driving forces can be invoked to explain the formation of the Okinawa Trough. If the slab of the Philippine Sea plate is stable with respect to the asthenosphere, the Ryukyu trench does not retreat, and the relative motion between the Ryukyu arc and the south China margin is the result of the northward motion of south China following the India-Eurasia collision. According to this hypothesis, the clockwise rotation of the direction of relative motion since 5 Ma would reflect an increase of the eastward extrusion rate of south China relative to the western Pacific subduction zones. On the other hand, if the slab of the Philippine Sea plate undergoes a southeastward rollback process with respect to the asthenosphere, the opening of the Okinawa Trough is a consequence of the retreat of the Ryukyu trench. In this hypothesis, the clockwise rotation of the direction of relative motion since the late Miocene may be related to the collision of the Luzon arc with the south China margin in Taiwan which started at 5 Ma [*Ho*, 1986]. The later stage of opening of the Okinawa Trough could be a consequence of the collision, a scenario already advocated by *Letouzey and Kimura* [1985] and *Viallon et al.* [1986].

Acknowledgments. We thank the Associate Editor, C. Ebinger, and the reviewers, M.-A. Gutscher, P. Huchon, and G. Kimura, for constructive suggestions that helped improve the original manuscript. We also thank H. Ujiie for assistance and discussion in the field, the ACT cruise Scientific Party for discussions, L. Jolivet for a critical reading of the manuscript, and C. Cardenas for improving the English version. Figures were drafted using GMT software [*Wessel and Smith,* 1991].

References

Aiba, J., and E. Sekiya, Distribution and characteristics of the Neogene sedimentary basins around the Nansei-shoto (Ryukyu Islands), *J. Jpn. Assoc. Petr. Technol., 44*, 229-340, 1979.

Angelier, J., Tectonic analysis of fault slip data sets, *J. Geophys. Res., 89*, 5835-5848, 1984.

Angelier, J., Inversion of field data in fault tectonics to obtain the regional stress, III, A new rapid direct inversion method by analytical means, *Geophys. J. Int., 103*, 363-376, 1990.

Angelier, J., Fault slip analysis and palaeostress reconstruction, in *Continental Deformation*, edited by P.L. Hancock, pp. 53-100, Pergamon, Tarrytown, N.Y., 1994.

Cardwell, R. K., B. L. Isacks, and D. E. Karig, The spatial distribution of earthquakes, focal mechanism solutions, and subducted lithosphere in the Philippine and northeastern Indonesian Islands, in *The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands*, edited by D. E. Hayes, *Geophys. Monogr. Ser.,* vol. 23, pp. 1-35, AGU, Washington, D. C., 1980.

Chen, W. P., and J. Nabelek, Seismogenic strike-slip faulting and the development of the North China basin, *Tectonics, 7,* 975-989, 1988.

Dauteuil, O., and J. P. Brun, Oblique rifting in a slow-spreading ridge, *Nature, 361*, 145-148, 1993.

Davy, P., and P. R. Cobbold, Indentation tectonics in nature and experiment, 1, Experiments scaled for gravity, *Bull. Geol. Inst. Univ. Uppsala, 14*, 129-141, 1988.

Dziewonski, A. M., T. A. Chou, and J. H. Woodhouse, Determination of earthquake source parameters from waveform data for studies of global and regional seismicity, *J. Geophys. Res., 86*, 2825-2852, 1981.

Dziewonski, A. M., G. Ekström, and N.N. Maternovskaya, Centroid-moment tensor solutions for October-December, 1996, *Phys. Earth Planet. Inter., 105*, 95-108, 1998a.

Dziewonski, A. M., G. Ekström, and N.N. Maternovskaya, Centroid-moment tensor solutions for January-March, 1997, *Phys. Earth Planet. Inter., 106*, 171-179, 1998b.

Eguchi, T., and S. Uyeda, Seismotectonics of the Okinawa trough and Ryukyu arc, *Mem. Geol. Soc. China, 5,* 189-210, 1983.

Engdahl, E.R., R. van der Hilst, and R. Buland, Global teleseismic earthquake relocation with improved travel times and procedures for depth determination, *Bull. Seismol. Soc. Am., 88*, 722-743, 1998.

Fabbri, O., Extensional deformation in the northern Ryukyu arc indicated by mesoscale fractures in the middle Miocene deposits of Tanegashima Island, Japan, *J. Geol. Soc. Jpn., 106*, 234-243, 2000.

Fabbri, O., and M. Fournier, Extension in the southern Ryukyu arc (Japan): Link with oblique subduction and backarc rifting, *Tectonics, 18*, 486-497, 1999.

Fabbri, O., J. Charvet, and M. Fournier, Alternate senses of displacement along the Tsushima fault system during the Neogene based on fracture analyses near the western margin of the Japan Sea, *Tectonophysics, 257*, 275-295, 1996.

Fournier, M., L. Jolivet, P. Huchon, K. F. Sergeyev, and L. S. Oscorbin, Neogene strike-slip faulting in Sakhalin and the Japan Sea opening, *J. Geophys. Res., 99,* 2701-2725, 1994.

Fournier, M., L. Jolivet, and O. Fabbri, Neogene stress field in SW Japan and mechanism of deformation during the Japan Sea opening, *J. Geophys. Res., 100,* 24,295-24,314, 1995.

Hancock, P.L., Brittle tectonics: Principles and practice, *J. Struct. Geol., 7*, 437-457, 1985.

Heki, K., Horizontal and vertical crustal movements from three-dimensional very long baseline interferometry kinematic reference frame: Implications for the reversal time scale revision, *J. Geophys. Res., 101*, 3187-3198, 1996.

Hirata, N., H. Kinoshita, H. Katao, H. Baba, Y. Kaiho, S. Koresawa, Y. Ono, and K. Hayashi, Report on DELP 1988 cruises in the Okinawa Trough, part III, Crustal structure of the southern Okinawa Trough, *Bull. Earthquake Res. Inst. Univ. Tokyo, 66*, 37-70, 1991.

Ho, C. S., A synthesis of the geologic evolution of Taiwan, *Tectonophysics, 125*, 1-16, 1986.

Imanishi, M., F. Kimata, N. Inamori, R. Miyajima, T. Okuda, K. Takai, K. Hirahara, and T. Kato, Horizontal displacements by GPS measurements at the Okinawa-Sakishima Islands (1994-1995), *J. Seismol. Soc. Jpn., 49 (3),* 417-421, 1996.

Iwasaki T., N. Hirata, T. Kanazawa, J. Melles, K. Suyehiro, T. Urabe, L. Möller, J. Makris, and H. Shimamura, Crustal and upper mantle structure in the Ryukyu Island Arc deduced from deep seismic sounding, *Geophys. J. Int., 102*, 631-651, 1990.

Jestin, F., P. Huchon, J.M. Gaulier, The Somalia plate and the East African rift system: Present-day kinematics, *Geophys. J. Int., 116,* 637-654, 1994.

Jolivet, L., P. Davy, and P. Cobbold, Right-lateral shear along the northwest Pacific margin and the India-Eurasia collision, *Tectonics, 9,* 1409-1419, 1990.

Jolivet, L., P. Huchon, J.P. Brun, N. Chamot-Rooke, X. Le Pichon, and J.C. Thomas, Arc deformation and marginal basin opening, Japan Sea as a case study, *J. Geophys. Res., 96,* 4367-4384, 1991.

Jolivet, L., H. Shibuya, and M. Fournier, Paleomagnetic rotations and the Japan Sea opening, in *Active Margins and Marginal Basins of the Western Pacific, Geophys. Monogr. Ser.*, vol. 88, edited by B. Taylor and J. Natland, pp. 355-369, AGU, Washington, D. C., 1995.

Kamata, H., and K. Kodama, Tectonics of an arc-arc junction: An example from the Kyushu Island at the junction of the Southwest Japan Arc and the Ryukyu arc, *Tectonophysics, 233*, 69-81, 1994.

Kao, H., and W.-P. Chen, Earthquakes along the Kyushu-Ryukyu arc: Strain segmentation, lateral compression, and the thermomechanical state of the plate interface, *J. Geophys. Res., 96*, 21,443-21,485, 1991.

Kano, K., H. Kato, Y. Yanagisawa, and F. Yoshida, Stratigraphy and geologic history of the Cenozoic of Japan, *Rep. Geol. Surv. Jpn. 274,* 114 pp., 1991.

Karig, D., Origin and development of marginal basins in the western Pacific, *J. Geophys. Res, 76*, 2542-2561, 1971.

Kimura, G., and K. Tamaki, Collision, rotation and back arc spreading: The case of the Okhotsk and Japan Seas, *Tectonics, 5,* 389-401, 1986.

Kimura, M., Back-arc rifting in the Okinawa Trough, *Mar. Pet. Geol., 2*, 222-240, 1985.

Kizaki, K., Geology and tectonics of the Ryukyu Islands, *Tectonophysics, 125*, 193-207, 1986.

Kodama, K., and K. Nakayama, Paleomagnetic evidence for post-late Miocene intra-arc rotation of south Kyushu, Japan, *Tectonics, 12,* 35-47, 1993.

Kodama, K., T. Ozawa, K. Inoue, Y. Maeda, and T. Takeuchi, Paleomagnetism and post-Middle Miocene counter-clockwise rotation of Tanegashima Island off Kyushu, Japan, *J. Geomagn. Geoelectr., 43,* 721-740, 1991.

Kodama, K., H. Tashiro, and T. Takeuchi, Quaternary counterclockwise rotation of south Kyushu, southwest Japan, *Geology, 23*, 823-826, 1995.

Lee, C.S., G.G. Shor Jr., L.D. Bibee, R.S. Lu, and T. Hilde, Okinawa Trough: Genesis of a back-arc basin, *Mar. Geol., 35*, 219-241, 1980.

Letouzey, J., and M. Kimura, Okinawa Trough genesis: Structure and evolution of a back-arc basin developed in a continent, *Mar. Pet. Geol., 2,* 11-130, 1985.

Martinez, F., P. Fryer, N. Baker, and T. Yamazaki, Evolution of backarc rifting: Mariana Trough, 20°-24°N, *J. Geophys. Res., 100*, 3807-3827, 1995.

McClay, K. R., and M. J. White, Analogue modelling of orthogonal and oblique rifting, *Mar. Pet. Geol., 12,* 137-151, 1995.

Miki, M., Two-phase opening model for the Okinawa Trough inferred from paleomagnetic study of the Ryukyu arc, *J. Geophys. Res., 100*, 8169-8184, 1995.

Miki, M., T. Matsuda, and Y. Otofuji, Opening mode of the Okinawa Trough: Paleomagnetic evidence from the southern Ryukyu arc, *Tectonophysics, 175*, 335-347, 1990.

Morgan, J.W, Rises, trenches, great faults, and crustal blocks, *J. Geophys. Res., 73,* 1959-1982, 1968.

Nakamura, K., Possible nascent trench along the eastern Japan Sea as the convergent boundary between Eurasian and North American plates (in Japanese), *Bull. Earthquake. Res. Inst. Univ. Tokyo, 58,* 711-722, 1983.

Oshida, A., K. Tamaki, and M. Kimura, Origin of the magnetic anomalies in the southern Okinawa Trough, *J. Geomagn. Geoelectr., 44,* 345-359, 1992.

Research Group for Active Faults in Japan, *Active Faults in Japan: Sheet maps and inventories,* 437 pp., Tokyo Univ. Press, Tokyo, 1991.

Roques, D., Tectonique cénozoïque de la marge centre Vietnam: Implications pour l'ouverture de la mer de Chine méridionale, Ph.D. thesis, 323 pp., Univ. Pierre et Marie Curie, Paris, 1996.

Seno, T., S. Stein, and A. E. Gripp, A model for the motion of the Philippine Sea plate consistent with NUVEL-1 and geological data, *J. Geophys. Res., 98*, 17,941-17,948, 1993.

Sibuet, J.C., et al., Back-arc extension in the Okinawa Trough, *J. Geophys. Res., 92*, 14,041-14,063, 1987.

Sibuet, J.C., S.-K. Hsu, C.T. Shyu, and C.S. Liu, Structural and kinematic evolutions of the Okinawa Trough backarc basin, in *Backarc Basins: Tectonics and Magmatism*, edited by B. Taylor, pp. 343-379, Plenum, New York, 1995.

Sibuet, J.C., B. Deffontaines, S.-K. Hsu, N. Thareau, J.P. Le Formal, C.S. Liu, and ACT party, Okinawa trough backarc basin: Early tectonic and magmatic evolution, *J. Geophys. Res., 103*, 30,245-30,267, 1998.

Tamaki, K., et al., Tectonic synthesis and implication of Japan Sea ODP drilling, *Proc. Ocean Drill. Program Sci. Results, 127/128*, 1333-1348, 1992.

Taylor, B., A. Klaus, G.R. Brown, G. F. Moore, Y. Okamura, and F. Murakami, Structural development of Sumisu rift, Izu-Bonin arc, *J. Geophys. Res., 96*, 16,113-16,129, 1991.

Taylor, B., K. Zellmer, F. Martinez, and A. Goodliffe, Sea-floor spreading in the Lau back-arc basin, *Earth Planet. Sci. Lett., 144*, 35-40, 1996.

Thareau, N., J.C. Sibuet, H. Nouzé, S. Berné, K. Wang, and J. B. Li, Mécanisme d'extension dans la partie centrale du bassin d'Okinawa (Pacifique occidental), *C. R. Acad. Sci., Ser. 1, 325,* 683-688, 1997.

Tron, V., and J.-P. Brun, Experiments on oblique rifting in brittle-ductile systems, *Tectonophysics, 188*, 71-84, 1991.

Ujiie, H., Early Pleistocene birth of the Okinawa Trough and Ryukyu island arc at the northwestern margin of the Pacific: Evidence from Late Cenozoic planktonic foraminiferal zonation, *Paleogeogr., Paleoclimatol., Paleoecol., 108*, 457-474, 1994.

Uyeda, S., and H. Kanamori, Back arc opening and the mode of subduction, *J. Geophys. Res., 84,* 1049-1061, 1979.

Vander Zouwen, D.E., Structure and evolution of the southern Okinawa Trough, M.S. thesis, Tex. A&M Univ., College Station, 1984.

Viallon, C., P. Huchon, and E. Barrier, Opening of the Okinawa basin and collision in Taiwan: A retreating trench model with lateral anchoring, *Earth Planet. Sci. Lett., 80*, 145-155, 1986.

Vogt, P. R., A. Lowrie, D. R. Bracey, and R. N. Hey, Subduction of aseismic ridges: Effects on shape, seismicity, and other characteristics of consumming plate boundaries, *Spec. Pap. Geol. Soc. Am., 172*, 59 pp., 1976.

Wessel, P., and W. M. F. Smith, Free software helps map and display data, *Eos Trans. AGU, 72 (41)*, 441-446, 1991.

Withjack, M., and W. Jamison, Deformation produced by oblique rifting, *Tectonophysics, 126*, 99-124, 1986.

Worrall, D.M., V. Kruglyak, F. Kunts, and V. Kuznetsov, Tertiary tectonics of the Sea of Okhotsk, Russia: Far-field effects of the India-Eurasia collision, *Tectonics, 15*, 813-826, 1996.

Wright, I.C., Pre-spread rifting and heterogeneous volcanism in the southern Havre Trough back-arc basin, *Mar. Geol., 113*, 179-200, 1993.

J. Angelier, J. P. Cadet, and M. Fournier, Laboratoire de Tectonique, CNRS ESA 7072, Université Pierre et Marie Curie, Case 129, 4 place Jussieu, 75252 Paris cedex 05, France. (marc.fournier@lgs.jussieu.fr)

O. Fabbri, Département de Géosciences, EA 2642, Université de Franche-Comté, 16 route du Gray, 25030 Besançon cedex, France.

(Received July 12, 2000; revised November 21, 2000; accepted December 21, 2000.)