Okinawa trough backarc basin: Early tectonic and magmatic evolution

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Abstract. The Okinawa Trough, lying between Japan and Taiwan, is a backarc basin formed by extension within the continental lithosphere behind the Ryukyu trench-arc system. Stress directions associated with the two last extensional phases in the southwestern Okinawa Trough have been deduced from a comparison with analog modeling: the direction of extension is N150° for the Pleistocene phase of extension (2-0.1 Ma) and N170° for the late Pleistocene-Holocene phase of extension (0.1-0 Ma). The present-day Ryukyu volcanic arc, a narrow continuous feature extending from Japan to Taiwan, is located on the eastern side of the Okinawa Trough, 80-100 km above the Wadati-Benioff zone, the minimum depth for emplacement of arc magmatism. Scarce present-day backarc volcanism appears in the middle and southern Okinawa Trough within linear en echelon bathymetric depressions. A N045° oriented seamount volcanic chain cuts across obliquely the southwestern Okinawa Trough and lies in the direct line of extension of the Gagua ridge, a N-S linear volcanic feature of the Philippine Sea plate. Associated with this extension of the Gagua ridge, a large reentrant located at the base of the Ryukyu prism, the uplift of part of the Nanao forearc basin and the deformation of the sedimentary arc suggest that the voluminous cross-backarc volcanism could be tied to the subduction of the Gagua ridge located there at a depth of 80-100 km beneath the backarc basin. A second area of anomalous volcanism has been identified in the middle Okinawa Trough in the ENE extension of the Daito ridge, a WNW-ESE 400-km-long volcanic feature of the Philippine Sea plate. We suggest that the Gagua and Daito ridges initially induced stress at the base of the arc which is still brittle and cracks propagated through the overlying brittle lithosphere, allowing magmas with arc affinities to erupt at the seafloor. This excessive magmatism reaches the seafloor through conduits which preferentially follow in their shallowest portion the crustal normal faults of the backarc rifts. The Okinawa Trough is consequently still in an early stage of evolving from arc type to backarc activity.

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1. Introduction

The Okinawa Trough (OT) is a curved backarc basin located northwest of the Ryukyu trench and Ryukyu islands (Figure 1). Active volcanoes in the Ryukyu arc have been identified only north of Okinawa Island. The OT extends from southwest Kyushu Island (Japan) in the northeast to the Ilan Plain (Taiwan) in the southwest. The OT is 60-100 km wide in the south and reaches up to 230 km wide in the north. Its maximum water depth approaches 2300 m in the southern OT and progressively decreases to 200 m in the north.

The purpose of this paper is to describe the detailed tectonic, volcanic, and magmatic features of the southwesternmost extremity of the OT (Figure 1) and to understand the origin of the different types of volcanism emplaced within the whole backarc basin. For that, we characterize the two last phases of extension which control the OT opening since 2 Ma and identify the different types of volcanism in the OT. In particular, the two cross-backarc volcanic chains of seamounts observed in OT will be linked to the subduction of linear ridges of the Philippine Sea plate, and their directions will be explained by the OT kinematics
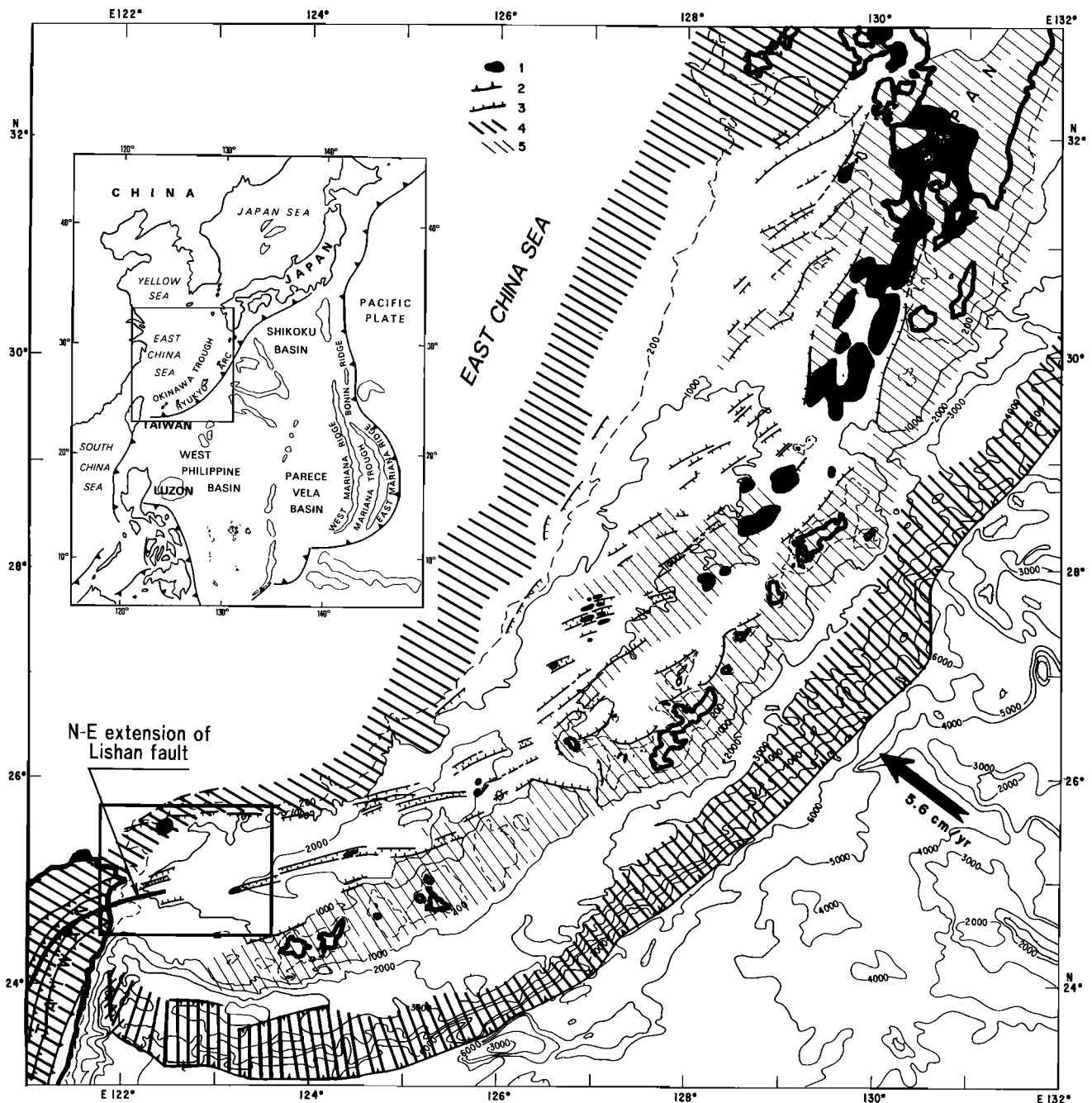
Figure 1. Geological and structural map of the Okinawa Trough [*Sibuet et al.*, 1987]: 1, Present-day and Recent volcanism; 2, trench axis; 3, normal faults; 4, trench slopes and accretionary complex; Taiwan-Sinzi folded belt; and 5, structural highs. Location of the active collision in Taiwan (ACT) survey close to Taiwan. Note the decreasing size of arc volcanoes from Japan to north of Okinawa Island and the overlapping en echelon normal faults in the northern Okinawa Trough and depressions in the southern Okinawa Trough.

deduced from the structural characteristics of the two last phases of extension.

2. Tectonic Setting of the Okinawa Trough

The OT formed by extension within the continental lithosphere as suggested by *Uyeda* [1977] or within continental lithosphere already intruded by arc volcanism [*Sibuet and Hsu*, 1997]. As the Ryukyu subduction zone was active since late Cretaceous [*Lee and Lawver*, 1994 and 1995], *Sibuet and Hsu*

[1997] interpret the series of continental shelf basins located parallel to the mainland China shoreline as several belts of backarc basins separated by volcanic or nonvolcanic relict arcs, suggesting a progressive eastward migration of the backarc basin system. The OT is the present-day active backarc basin. However, if there is a consensus about the two last phases of extension which occurred in the OT since 2 Ma, there is a large controversy about the age of the early rifting phase. The increasing northeastward width of the OT was generally explained by the rotation of the Okinawa platelet (Ryukyu arc

and OT portion located east of the trough axis) with respect to Eurasia around a pole located in northern Taiwan. However, the total amount of extension has been estimated from crustal refraction and gravity data along two transects located in the southern and northern OT. It slightly decreases from 80 km in the southern OT to 74 km in the northern OT [*Sibuet et al*, 1995], which demonstrates that the pole of rotation for the whole extension cannot be located in northern Taiwan as suggested by several authors but is rather far from this area, in the extension of OT.

The Recent phase of extension has been identified in late Pleistocene times [*Furukawa et al.*, 1991] on the basis of seismic correlations with drilling stratigraphy [*Tsuburaya and Sato*, 1985]. It is characterized by normal faults with vertical offsets of a few meters, changing progressively in direction along the OT. The amount of extension which occurred during this phase was estimated to about 5 km in the middle OT. The pole of rotation is located near Hawaii [*Sibuet et al.*, 1995; *Thareau*, 1996].

The second rifting phase started about 2 Ma at the Plio-Pleistocene boundary. Correlations with sedimentary basins between the OT and Kyushu regions [*Kimura*, 1985] and the uplift of the Ryukyu arc at the Plio-Pleistocene boundary [*Ujiie*, 1980] show that the initiation of the subsidence and block faulting in the central axial part of the OT occurred at about 2 Ma. It is characterized by tilted blocks. The faults displace the late Pliocene/early Pleistocene sediments and progressively change direction along the OT. The amount of extension for this phase was estimated to be 25 km in the northern OT. The pole of rotation is located east of Tokyo, in the northeast extension of OT [*Sibuet et al.*, 1995; *Thareau*, 1996].

The early rifting phase was dated late Miocene (9-6 Ma) [*Letouzey and Kimura*, 1985] as suggested by the presence of late Miocene marine sediments drilled in the northern OT [*Sun*, 1981]. However, the beginning of the OT extension and its duration are still debated. According to *Kimura* [1996], extension could have begun between 6 and 4 Ma, corresponding to the lower part of the Shimanjiri group, because late Miocene to early Pliocene strata belonging to this formation show specific sedimentary features which have been observed in the central part of the trough and are considered as synrift sediments. This observation would support the existence of a first extensional phase occurring during the latest Miocene to early Pliocene (6-4 Ma) with associated subsidence and sediment deposition. Alternatively, *Park* [1996] considers the period of deposition of the Shimanjiri group as a period of uplift, erosion, and nondeposition in the southern OT. In this hypothesis, it is assumed that no extension occurred within the southern OT from 6 to 2 Ma, which does not exclude a previous Tertiary phase of extension. Thus the early phase of extension is poorly constrained from geological data. However, if considered as a single homogeneous phase occurring in the whole OT, this phase is a major tectonic phase with about 60 km of extension in the northern OT and 50 km in the southwestern OT, the corresponding pole of rotation being located in Sumatra, in the southwestward extension of OT [*Sibuet et al.*, 1995; *Thareau*, 1996].

3. R/V *l'Atalante* Active Collision in Taiwan Survey

During the active collision in Taiwan (ACT) cruise (May-June 1996) and the preceding transit between Okinawa Island and Taiwan, an integrated geophysical survey of the southwestern

extremity of the OT was conducted as part of an ongoing cooperative project between France and Taiwan (Figure 2). Eighteen EM12/EM950 swath-bathymetric profiles trending NE-SW were acquired obliquely to the general E-W direction of the trough in order to establish the possible existence of three major NW-SE trends already inferred from gravity, magnetic, and earthquake data [*Hsu et al.*, 1996a]. In addition, six-channel high-speed seismic data using two GIs (generator/injector) guns operated in harmonic mode [*Pascouet*, 1991] were collected simultaneously with gravity, magnetic, and 3.5 kHz data at a mean ship's speed of 10 knots. The following processing sequence was applied to all seismic profiles: FK filter, 4-12; 35-45 Hz band-pass filter, three-fold stack with a constant velocity of 1480 m/s, and Kirchoff migration with a constant velocity of 1420 m/s. The swath-bathymetric coverage was almost complete except in the shallowest portions of the survey where the width of the surveyed area became too narrow. Figure 2 shows the survey track lines with a line spacing varying from 2.5 km on the upper slope and continental shelf to 7.5 km in the deepest portion of the trough (2000 m).

4. Morphology of the Southwestern Okinawa Trough

A digital terrain model (DTM) bathymetric grid with a 75-m grid spacing was produced without smoothing. Depending on the final scale of bathymetric maps, the appropriate smoothing was applied. However, most of the morphological content of the complete set of swath-bathymetric data appears in two types of documents: the conventional smoothed bathymetric maps (e.g., Figure 3 contoured with a 50-m spacing though working documents at a 1/200,000 and 1/100,000 scales with 5- and 2-m contouring intervals, respectively, were also produced) and the gridded raw DTM illuminated from different azimuths with low elevation view points (e.g., Plate 1). The main topographic features outlined in Figure 3 and Plates 1 and 2 are as follows:

1. Between 24°40'N and 25°12'N, the western part of the northern OT slope is a 7° southeast dipping slope with numerous minor gravity canyons interrupted in the north by the N135° trending major submarine canyon C (Figure 3) with several tributaries.

2. To the east, between 25°12'N and 25°30'N, the northern slope of the OT, though largely cut by two major canyons (B and C, Figure 3), presents a 2° gentle slope which shows the effect of the large sedimentary input coming from the east China continental shelf.

3. Three major canyons developed along the gently dipping northern boundary of the southwestern OT. Canyon C slightly buried the Eurasian continental margin, while canyon B (much bigger and larger) strongly erodes it. The latter is characterized by three main tributaries showing locally ENE-WSW to E-W offset tracks corresponding to already known structural directions. Furthermore it is locally affected by small landslides. Canyon A, surveyed in its lower portion, seems to be the largest one, if we only take into account its downstream width.

4. To the west, the northern OT continental margin ends abruptly on a N065° trending canyon that we name the Lishan trough, and which is the northeast extension of the Lishan fault (Figure 3) recently identified below the Ilan Plain [*Hsu et al.*, 1996b]. The Lishan trough separates the Eurasian continental margin to the north from the Ryukyu arc to the south. Along its length, several en echelon small antiforms were observed and are associated with kilometer-scale rectilinear scarplets and facets
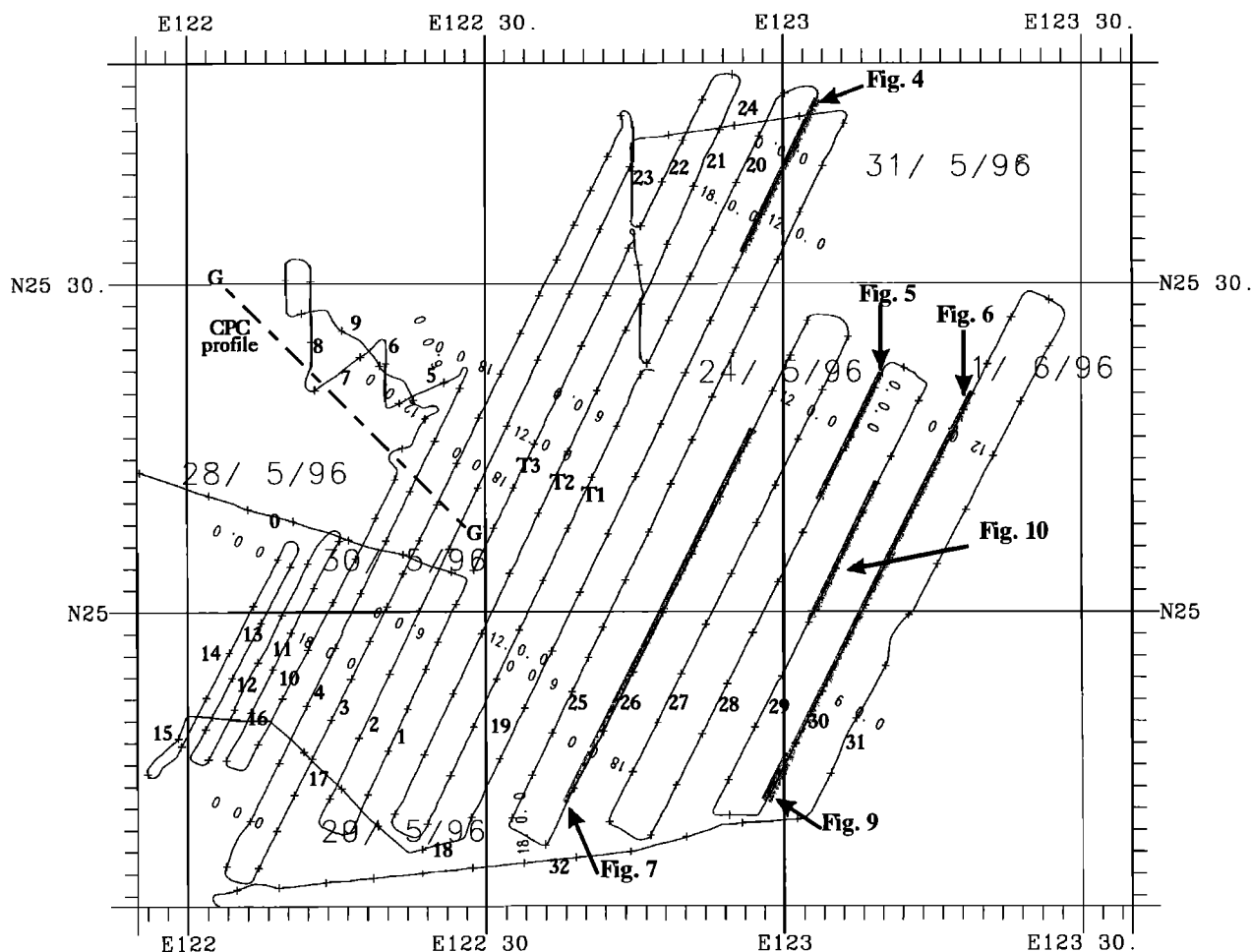
Figure 2. Track lines of the ACT cruise and the preceding transit of the R/V *l'Atalante* (May-June 1996) in the southwestern Okinawa Trough with locations of portions of profiles displayed in the following figures. GG', Chinese Petroleum Company seismic profile [*Huang et al.*, 1992].

(Plate 1). In its buried portion, the Lishan fault also presents a similar geometry [*Hsu et al.*, 1996b]. However, from morphological data, the nature and extent of motion remain unclear.

5. The southern flank of the southwestern OT corresponds to the northern slope of the Ryukyu arc. This margin is strongly differentiated and eroded by ENE-WSW trending minor canyons which are parallel to the Lishan trough. However, the eastern surveyed portion of the margin is gently dipping northward, little dissected, and affected by numerous E-W trending normal faults.

6. From a combined analysis of bathymetric, magnetic, gravity, and earthquake data, *Hsu et al.* [1996a] identified three main NW-SE trending discontinuities in the southwestern OT, approximately along B, C, and D directions (Figure 3). They interpreted these features as right-lateral strike-slip faults which were active at the beginning of the Luzon arc collision with the Eurasian margin, before the onset of rifting. These discontinuities are evidenced in the bathymetry (Figure 3) where B corresponds to a canyon trend, C to the trend of another canyon on the northern OT margin and to an offset of the southern OT margin and D to a minor change in direction of the northern OT margin but also to a significant offset of the southern OT margin.

7. In the deep part of the Trough (Figure 3, and Plates 1 and 2), the major morphological trend is a subtle N085° depression

about 13 km wide. Normal faults with vertical offsets of a few meters to few tens meters dip toward the axis of the depression. Numerous volcanic cones, sometimes locally aligned along these N085° normal faults, are in fact concentrated along a prominent broad band roughly oriented N045° (Figure 3). Surprisingly, this depression is not located in the OT axial part but mostly in the southern portion of the backarc basin, trending roughly parallel to the mean direction of the Ryukyu arc. In its western portion, the depression is bevelled and terminates against the Lishan fault extension. This could indicate that the plate boundary between Eurasia and the Okinawa platelet follows the axis of the depression and then the Lishan fault.

8. The present major sedimentation flow of the canyons of the northern margin and of the Lishan trough lies north of the N085° depression. Several dead channels with large meanders appear in different places of the deep backarc basin (Plates 1 and 2). The major one, which is possibly the most recently inactivated one, is located north of the N085° depression, mostly on the edge of a structural high with some meanders lying at deeper depths (Plate 2). This channel abruptly disappears west of 122°45'E, but when it was active, it was characteristic of a low-energy environment with muddy deposits and probably connected to the Lishan trough. Southward 10 km, the traces of an older channel are almost parallel to the preceding one and were perhaps connected
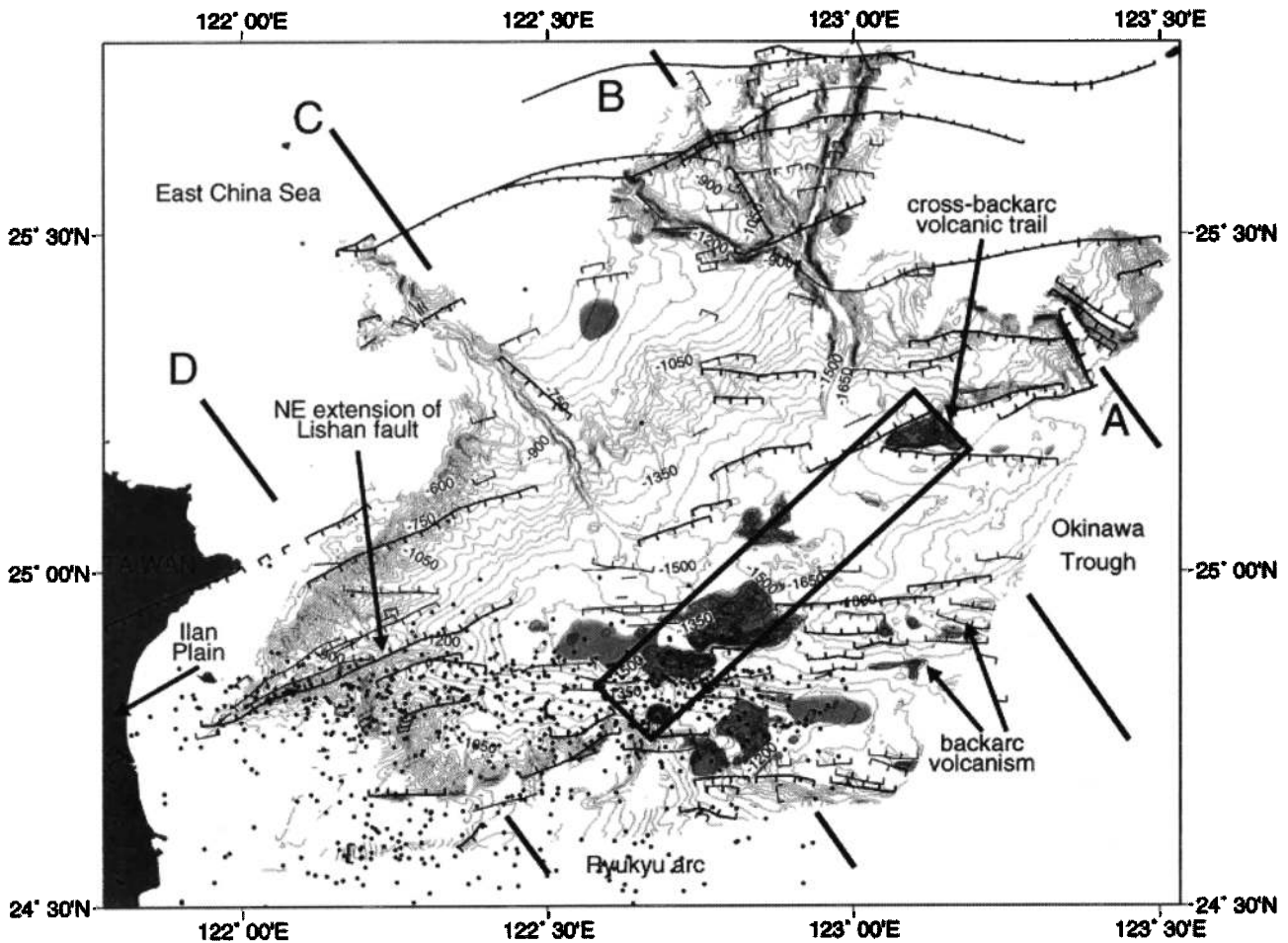
Figure 3. Bathymetric map of the southwestern Okinawa Trough established from the swath-bathymetric EM12D and EM950 data. Mercator projection; isobath spacing, 50 m. Dots are locations of earthquakes from the Taiwan Telemetered Seismograph Network (S.-N. Cheng, personal communication, 1996). Lines A, B, C, and D locate major geological discontinuities across the region. Structural context is indicated by thick or thin lines with large thick marks for normal faults with large or small vertical offsets identified from the ACT survey; thick or thin lines with small thick marks for normal faults with large or small vertical offsets identified by Huang et al. [1992] on the northern margin; dark areas for volcanic outcrops or slightly buried volcanism.

to the Lishan trough. Southeast of the N085° depression, a NW-SE old channel could be followed over 30 km and could correspond to canyon C but disappears on the southern border of the N085° depression. A few meanders are intersected by the N085° normal faults which postdates the normal faulting.

5. Structural and Tectonic Analysis

The structural interpretation (Figure 3) was undertaken using both the seismic data and the detailed seafloor morphology which gives additional constraints on the direction of the tectonic features. As already known, tectonic control is often maintained through time in the morphology, even if there is a lateral drift of the superficial bathymetric features due to peculiar conditions of sedimentation.

5.1. Late Miocene-Pliocene Sedimentary and Tectonic Features

On the East China Sea continental shelf, north of the studied area, Huang et al. [1992] have revealed the presence of N065°

deep-seated left-lateral strike-slip faults with a compressive component. They have interpreted these features as an extension of the northern Taiwan thrusts. Using newly reprocessed seismic profiles and correlations with stratigraphic wells, Hsiao et al. [1998] have established that in the southeastern parts of the north and south Pengchiahsu basins adjacent to the East China Sea shelf edge, the Miocene basins were inverted during late Miocene times (6-7 Ma), coinciding with the onset of uplift in Taiwan which initially occurred east of the present-day position of Taiwan. The associated anticlinal structure, sometimes intruded with more recent volcanics, is parallel to the shelf edge and corresponds to the southwestern portion of the Taiwan-Sinzi zone. Above the inverted features, Pliocene sediments are often absent, preventing to unambiguously determine the beginning of the early rifting phase in the southwestern OT.

5.2. Pleistocene Phase of Opening (N065° Trends)

The N065° thrust fault system was reactivated as normal faults (Figure 3) on the northern OT continental border (Sinzi-Taiwan zone) at the Plio-Pleistocene time boundary [Hsiao et al., 1998].
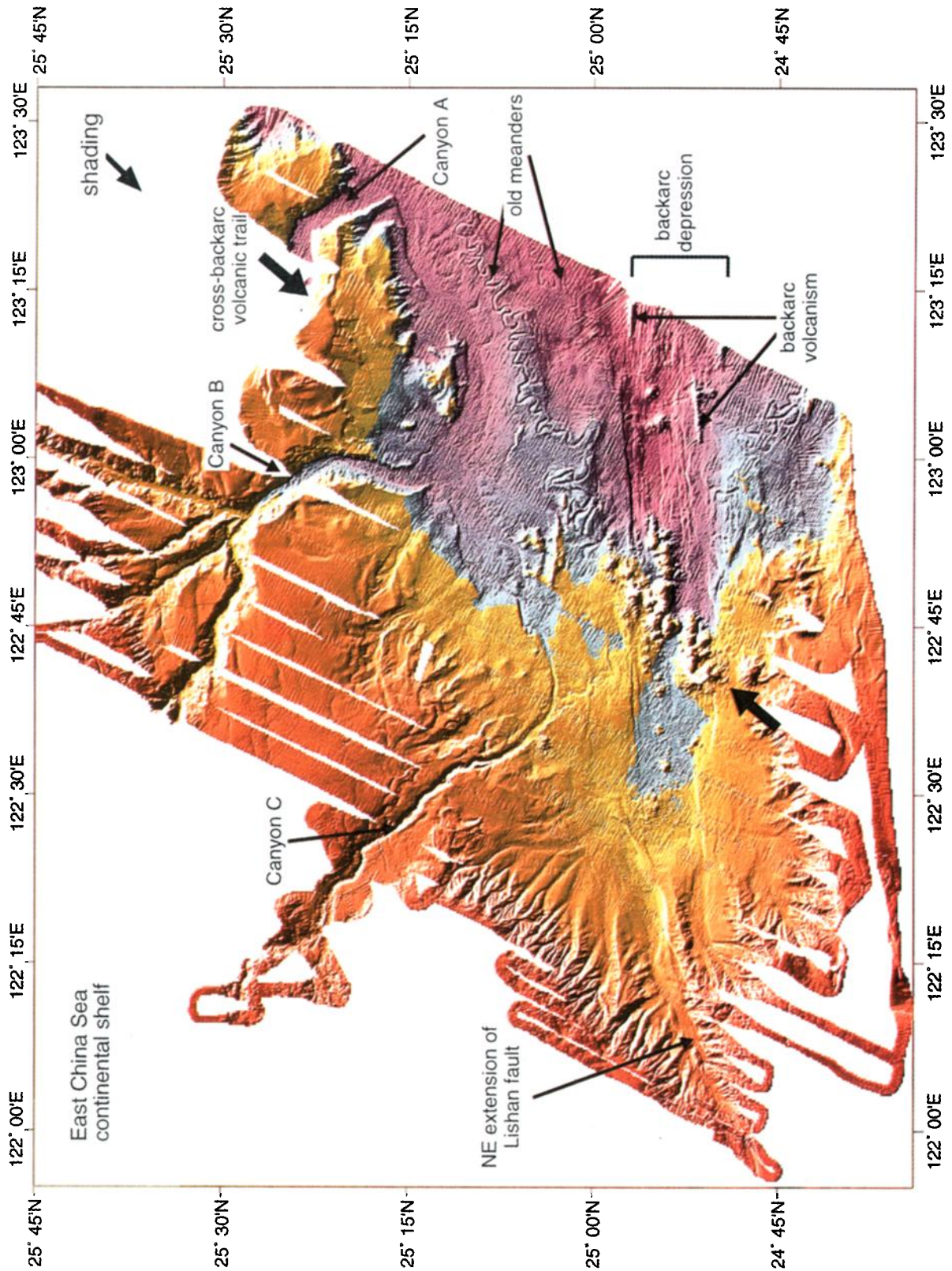
Plate 1. NE simulated hillshading of the southwestern Okinawa Trough established from raw data gridded every 75 m. The 1500-m isobath (blue to yellow boundary) underlines contours of the N085° backarc depression.
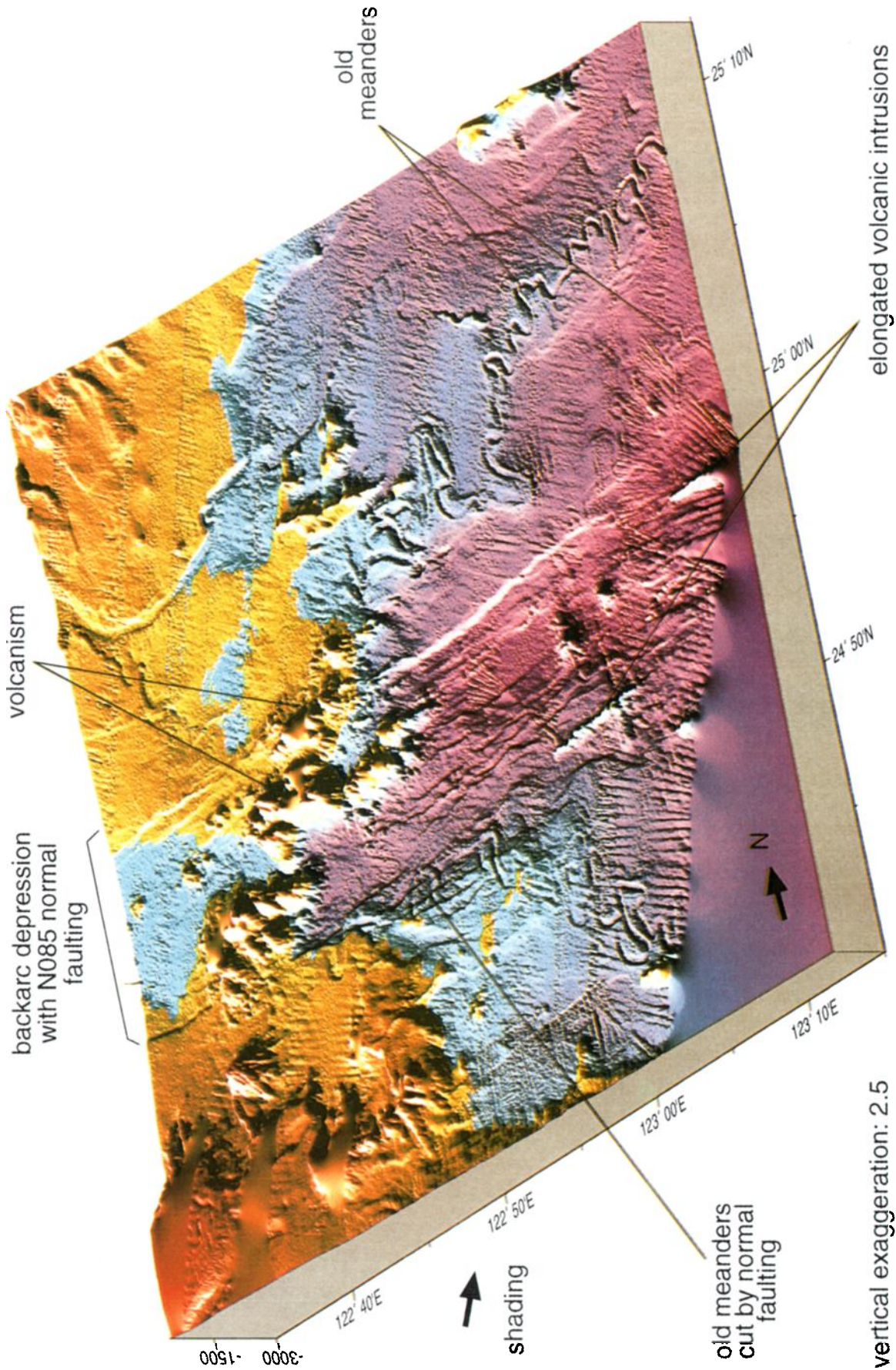
Plate 2. Three-dimensional view of the eastern portion of the southern Okinawa Trough bathymetric map (SW simulated hillshading). Note the presence of extinct channel meanders cut across by the N085° normal faults. Two types of volcanism are present in the backarc basin depression: elongated volcanic intrusions along N085° normal faults (backarc basin volcanism) and seamounts aligned along a NE-SW trend (cross-backarc volcanism).

Simultaneously, new parallel normal or listric faults, also N065° trending, developed in the Pengchiahsu and South Taipei basins located on the continental shelf, northeast of Taiwan [*Huang et al.*, 1992] giving rise to spectacular tilted faulted blocks. Figure 4 also shows similar southward dipping normal faults and the associated tilted faults blocks located on the northern OT

continental slope with vertical offsets ranging from a few hundreds meters to about 1 km. Profile to profile correlations and crosscorrelations with Chinese Petroleum Company (CPC) seismic profiles confirm the general N065° trend of these features (Figure 3) and that they were active at the Plio-Pleistocene boundary. The prerift deformation observed within
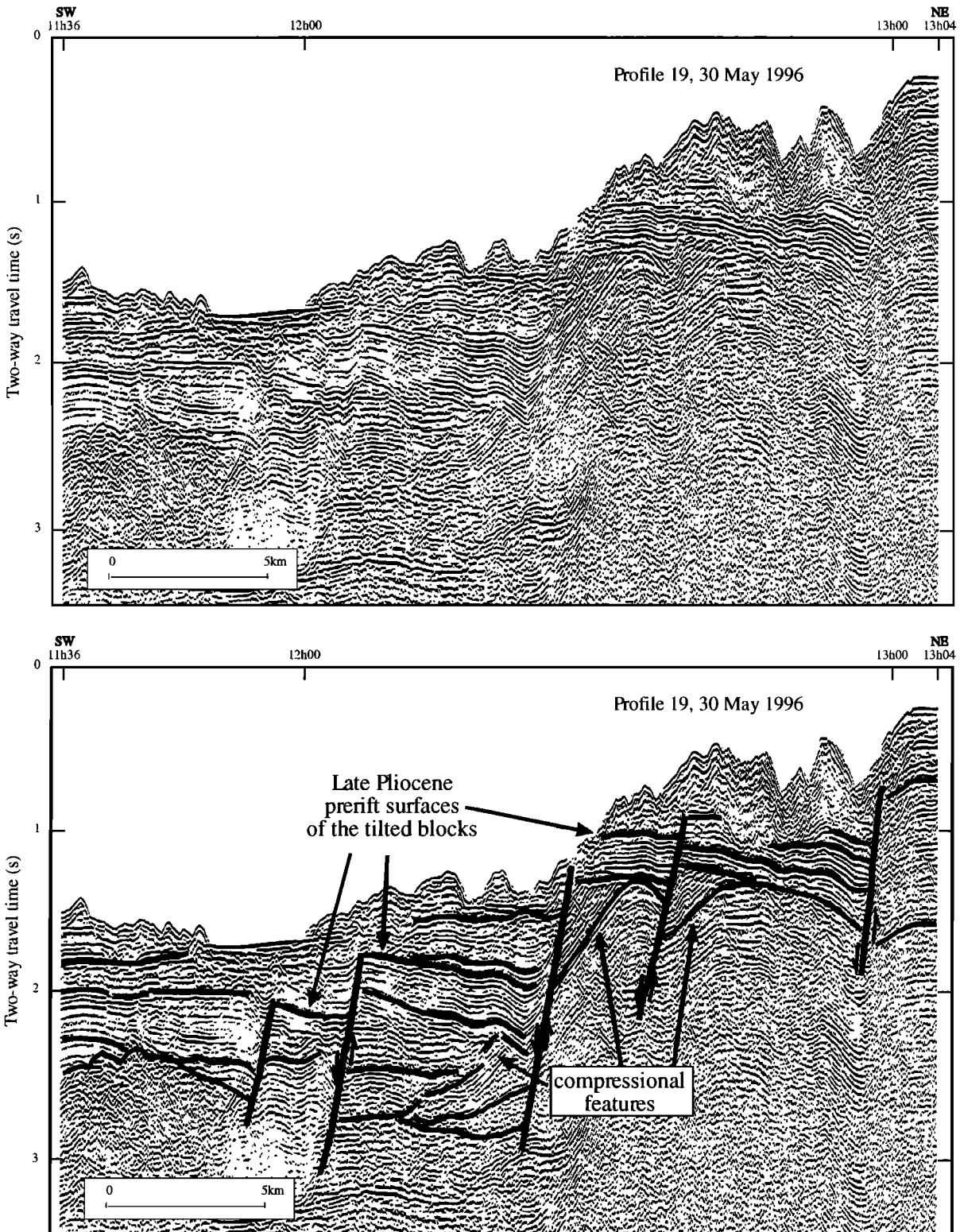

Figure 4. Migrated six-channel high-speed seismic profile 19 (location in Figure 2) across the northern OT margin. Example of tilted fault blocks formed at the Plio-Pleistocene boundary but showing internal deformations linked to late Miocene (6-7 Ma) tectonic compressive motions.

the tilted fault blocks (Figure 4) is late Miocene (6-7 Ma) and affects both early and late Miocene sediments. Consequently, the major phase in formation of the present-day southern OT is quite recent, beginning at the Plio-Pleistocene boundary as extrapolated from CPC continental shelf stratigraphic data [*Hsiao et al.*, 1998] and from the timing of tilted fault block rotations in the middle and northern OT [*Letouzey and Kimura*, 1985; *Sibuet et al.*, 1987]. Since that time, the East China Sea sediments were prograding on the northern margin, smoothing the continental slope, and contributing to a reduction in the present-day width of the OT.

A volcanic massif (Figure 5) was emplaced on the southern border of this N065° feature at 25°12'N; 123°07'E. Previously deposited sediments located on the southern flank were uplifted by the intrusion of volcanic material. In addition, onlapping sediments show that the intrusion could be as old as 2 Ma (Figure 5). Similar volcanic intrusions were emplaced along the N065° features (Figure 3) of the East China Sea continental shelf [*Huang et al.*, 1992]. We suggest that these intrusions were emplaced during Pleistocene along the active N065° deep-seated normal faults.

In conclusion, normal faults trending N065° were active probably since 2 Ma (Plio-Pleistocene boundary), as suggested by seismic profiling and drilling data obtained on the adjacent continental slope and shelf [*Hsiao et al.*, 1998; *Huang et al.*, 1992] and by Plio-Pleistocene block faulting identified in the northern and middle OT [*Letouzey and Kimura*, 1985; *Sibuet et al.*, 1987]. This major phase of opening corresponds to the reactivation of the N065° Taiwan thrust faults. It is associated with some volcanism generally intruded along these normal faults and now buried beneath sediments.

5.3. Late Pleistocene-Holocene Phase of Opening (N085° Trends)

The recent phase of extension is characterized by N085° normal faults which appear on the detailed illuminated bathymetric map (Plate 1) and on the 3.5 kHz and seismic profiles. Most of the normal faults are oriented N085° and are located in the southern portion of OT. However, normal faults roughly oriented E-W with offset up to 150 m are present in the whole surveyed area (Figure 5). Such normal faults are also observed at the base of the northern OT margin near 25°15'N; 122°45'E (Figure 3) where slumps recently occurred and were probably released by the vertical motion along E-W normal faults identified just above the slumps.

Based on swath-bathymetric data, the geographic distribution of normal faults in the southwestern OT is mostly restricted between 24°50'N and 25°N, where a N085° closely spaced system of normal faults exists from 122°15'W to 123°15'W longitude at least (Figure 3 and Plates 1 and 2) within a 13-km-wide band which terminates to the west against the Lishan fault extension. Normal faults could be as closed as 2 km apart, and their vertical offsets are a few tens meters. Volcanic intrusions are associated with this set of normal faults as narrow elongated volcanic features in the eastern part of the survey area (Figure 6) or well-developed volcanic intrusions controlled by the N085° normal fault pattern but lying preferentially along the N045° narrow band of volcanic seamounts (Figure 7).

Surprisingly, the 0- to 30-km-deep earthquakes are almost exclusively located in an E-W band located just south of the presently mapped system of closely-spaced normal faults (Figures 3 and 8). The present-day backarc activity has consequently just moved southward of the N085° backarc

depression, on the southern OT margin (Figure 8). Figure 9 shows a 3.5 kHz profile located in this area of crustal earthquakes. Normal faults with vertical offsets of a few meters and with a mean spacing of 600 m are observed but do not appear on the illuminated swath-bathymetric map of Plates 1 and 2 due to the smoothing and the compulsory generalization at this scale. The first signs of extension are consequently observed within this narrow area of seismicity.

Several extinct submarine channels with numerous meanders appear in OT (Plate 1). Their connections with slope canyons are unclear because of the presence of the N085° backarc depression and/or the recent major slump located east of canyon C. The rapidly rising mountains in Taiwan have shed large volume of sediments in the Huatung Basin and a smaller volume on the East China Sea continental shelf and in the OT through the Lishan trough and canyon C. In the deepest portion of OT, channel overspill has formed levees in low energy environment (Figure 10) possibly deposited during glacial lowstands when the shelf was emerged and rivers emptied directly into OT [*Carter et al.*, 1996]. Such conditions caused turbidity currents to sweep along channels and feed the 150-m-thick fan on top of Pleistocene monotonous sedimentary sequence (Figure 10). The observed extinct submarine channels could be as young as 20,000 years, the period of the last glaciation associated with a low sea level stand but not older than 300,000 years, if we assume a constant sedimentation rate since early Pleistocene. As meanders of the partly buried NW-SE extinct channel are several times offset by the N085° normal faults near 24°50'N; 122°55'W (Plate 2), the onset of the Recent phase of extension giving rise to the N085° depression could be very young (only a few tens thousands years). Thus the southward jump of backarc activity could have occurred as recently as a few thousands to a few tens of thousands of years ago. The associated present-day seismic activity is located within an E-W band (Figures 3 and 8), suggesting that normal faults (Figure 9) are roughly E-W trending. If no clear indication on the direction of extension is given from the trend of normal faults and focal mechanisms, Global Positioning System (GPS) measurements both in the Ilan Plain (H.-T. Chu, personal communication, 1996) and between Miyako Island and mainland China [*Kato et al.*, 1995] suggest that the present-day extension is still north-south.

6. Strain and Stress Orientations During Pleistocene and Pleistocene-Holocene

A systematic analysis of the orientations of the two families of faults has been performed. For each linear fault or segment of sigmoïdal fault, the latitude, longitude, vertical offset, azimuth, and dipping direction have been determined. In the southwestern OT, normal faults associated with the Pleistocene phase of extension are oriented N060° to N080°, and normal faults related to the late Pleistocene-Holocene phase are oriented N085° to N105° (Figure 11).

Knowing the strain directions, we propose to determine the paleostress directions (in fact, the direction of extension) by using the *Tron and Brun* [1991] results of analog modeling. They report several scale experiments of oblique rifting on a brittle/ductile system (sand and silicone). Uniaxial stretching has been applied obliquely to the external boundaries for α=0° (pure shear), 15°, 30°, 45°, 60°, and 90° (pure extension). The resulting fault patterns show that oblique rifting is characterized by en echelon fault patterns, mean fault trends not exactly perpendicular to the direction of extension, and mean initial fault
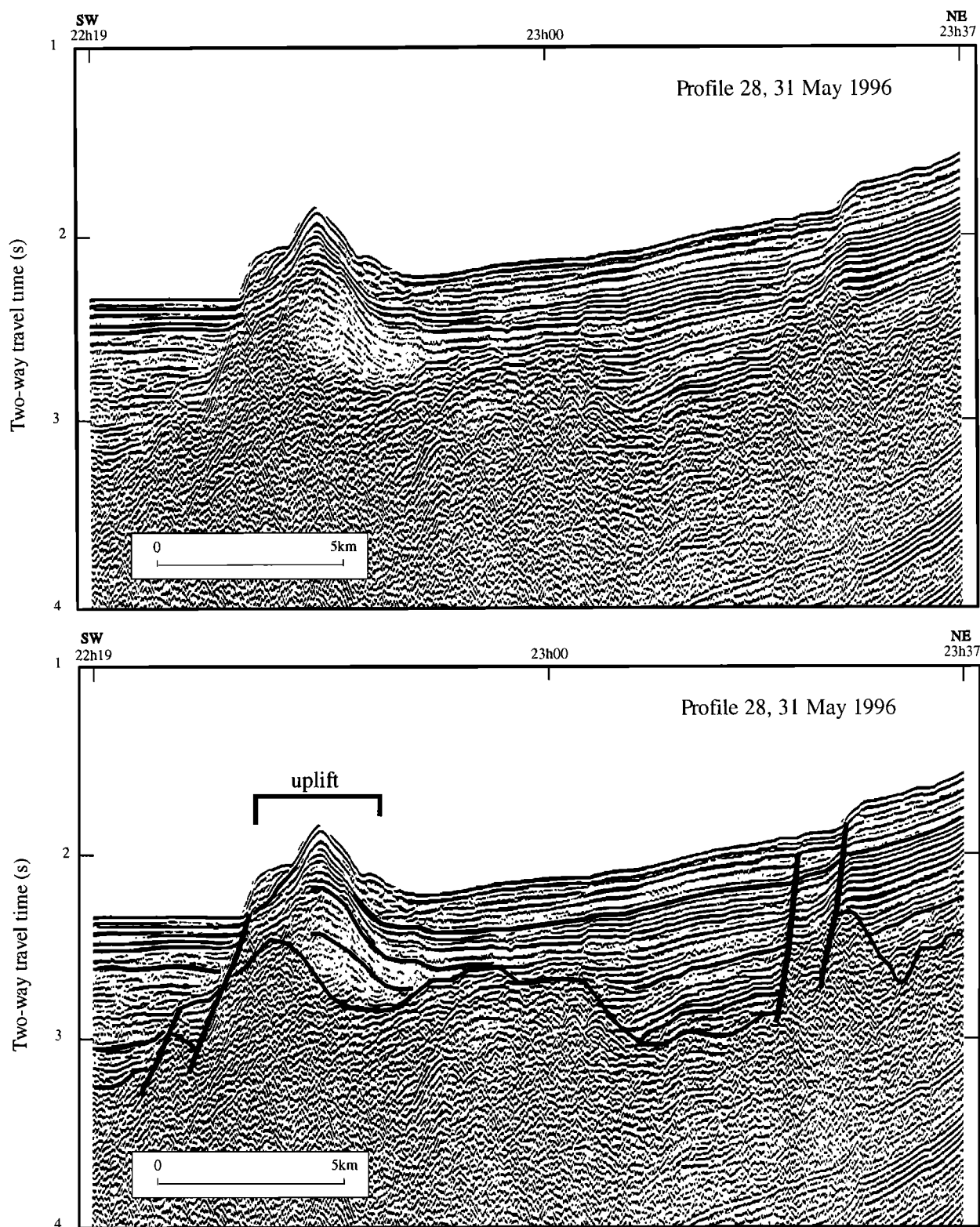
Figure 5. Migrated six-channel high-speed seismic profile 28 (location in Figure 2) across a major volcanic feature capped by undeformed uplifted sediments and bounded to the north by an ENE-WSW trend located at the base of the northern slope of the Okinawa Trough and to the south by a E-W normal fault (Figure 3).

dips higher than for dip-slip normal faults. For low-obliquity rifting ($\alpha \geq 45°$), curved faults are frequent, displacement along them varying from dip-slip to dominantly strike-slip. For high-obliquity rifting ($\alpha < 45°$), the motion is partitioned amongst distinct families of oblique-slip faults and strike-slip faults.

In the southwestern OT, the presence of curved faults (Figures

11a and b) shows that the obliquity α is approximately between 30° and 60° [*Tron and Brun*, 1991]. The histogram (Figures 11c and d) represents the frequency of fault number as a function of the azimuth of faults. The rift direction corresponds to the mean direction of the OT oriented N095°. If we substitute our measured orientations into the model of *Tron and Brun* [1991],
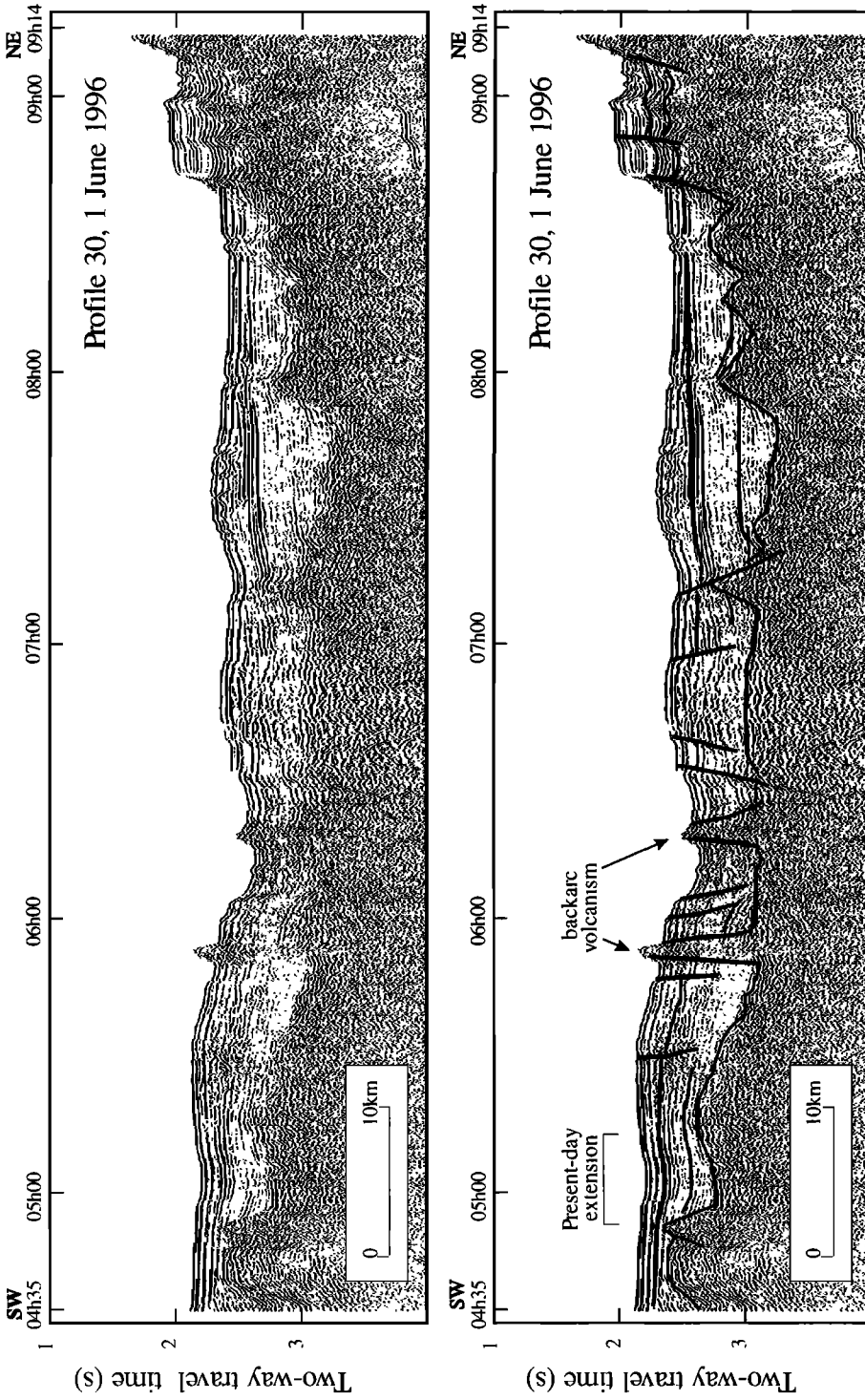
Figure 6. Migrated six-channel high-speed seismic profile 30 (location in Figure 2) across the OT showing the backarc volcanic elongated features near 0600 hours within the N085° backarc depression and the present-day extension near 0500 hours in the area of present-day seismicity. Normal faults and basement are underlined in the bottom panel.
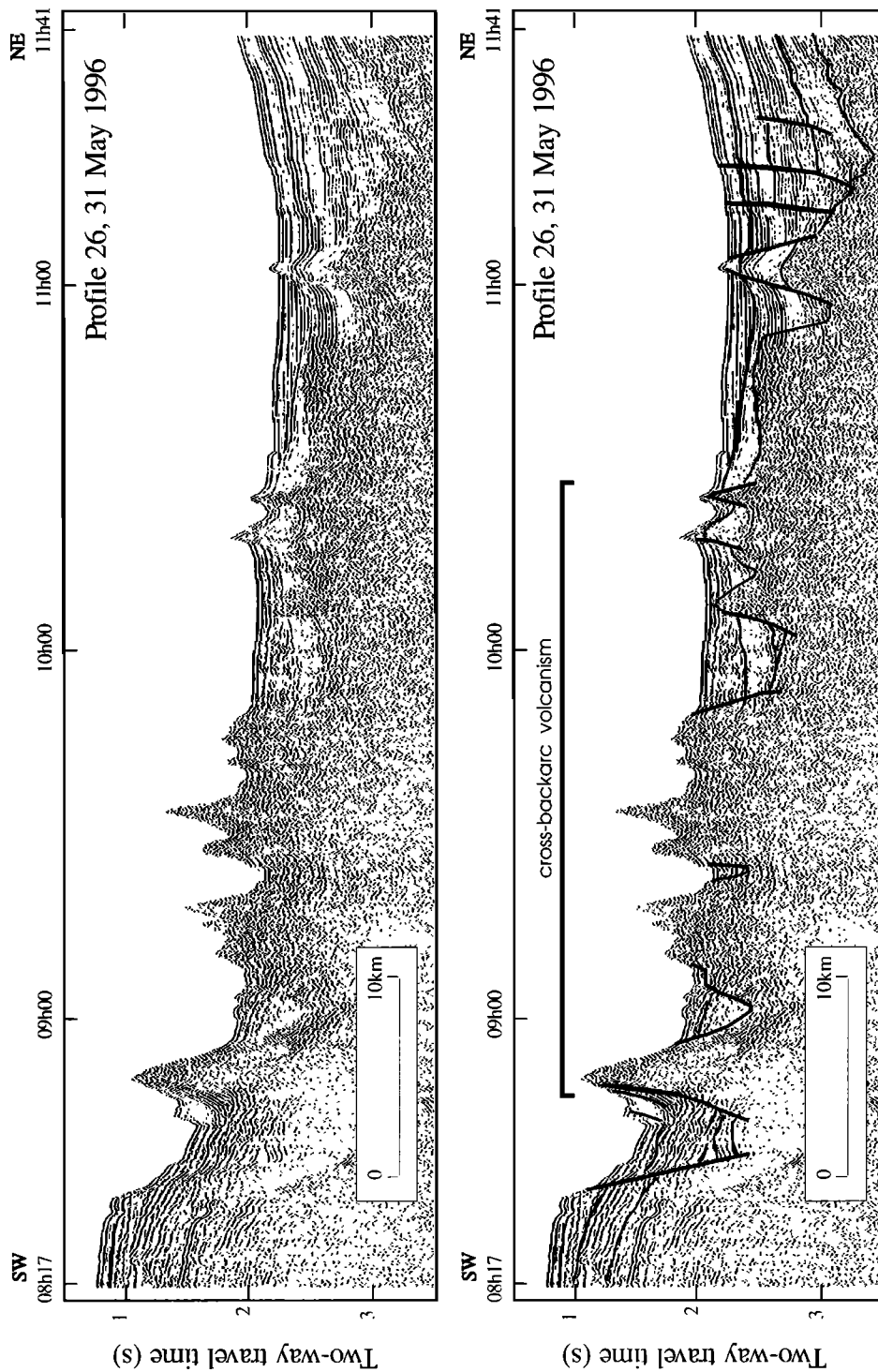
Figure 7. Migrated six-channel high-speed seismic profile 26 (location in Figure 2) across the OT, with the intense volcanism emplaced along the N045° cross-backarc trail. Normal faults and basement are underlined in the bottom panel.
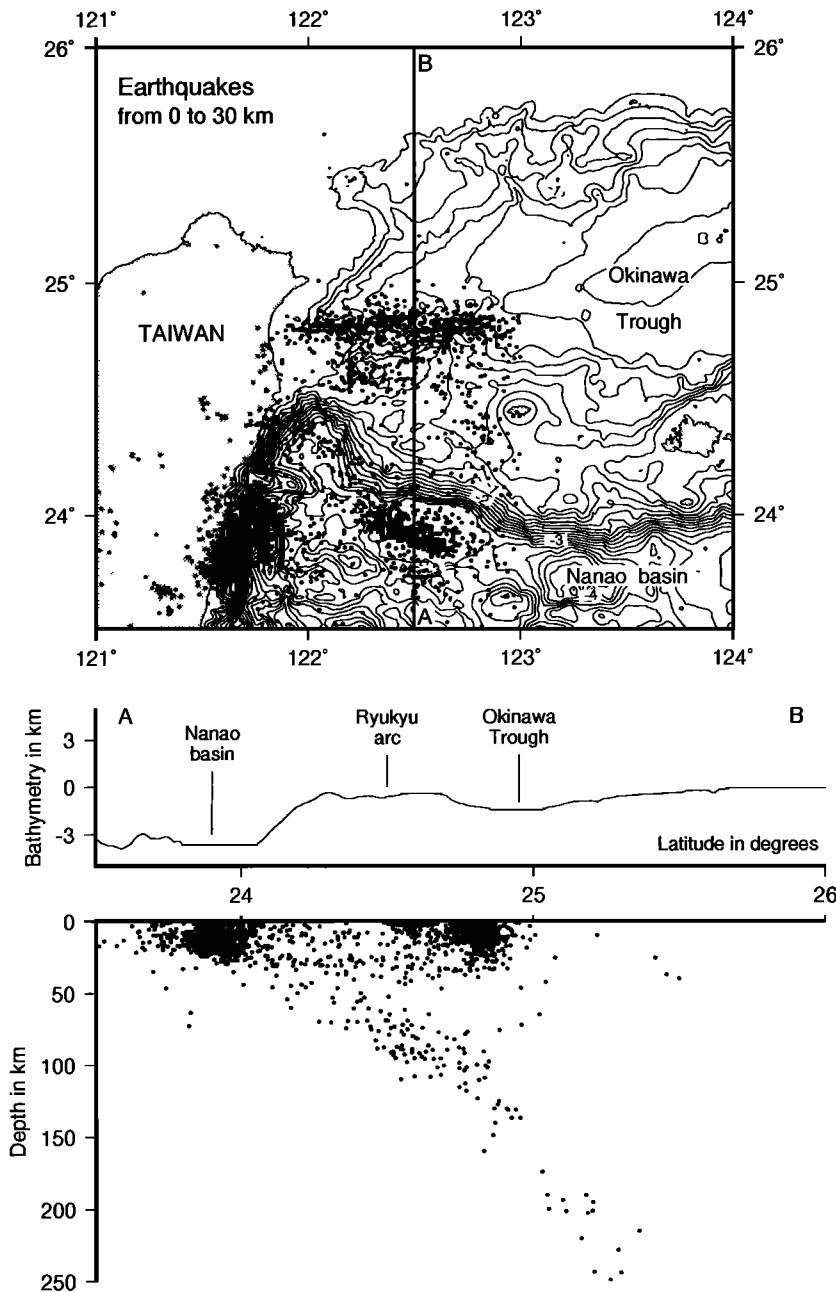
Figure 8. (top) Location of 0- to 30-km-deep earthquakes west of 123°W longitude (Telemetered Seismograph Network (S.-N. Chen, personal communication, 1996)) on the bathymetric map contoured every 250 m. (middle) and (bottom) N-S cross-section at 122°30'W (AB). Crustal earthquakes are mostly located on the southern margin of the Okinawa Trough where small offset normal faults are observed (Figure 9).

the directions of extension are N150° for the second phase of rifting and N170° for the third phase of extension. In the stress ellipsoid, σ_3 is N150° oriented, σ_2 is N060°, and σ_1 is vertical for the second phase of rifting; σ_3 is N170° oriented, σ_2 is N080°, and σ_1 is vertical for the third phase of rifting. These directions differ from the previous estimations of *Sibuet et al.* [1995], who assumed that normal fault directions of both phases were similar (N080°-N090°) in the southwestern OT and that the strain and stress directions were the same in the OT (Figure 12). However, the existence of several tectonic phases with such large

stress differences is probably linked to changes in the parameters of plate convergence, as already noted by Sibuet et al. [1987].

7. A Continuous Volcanic Arc From Japan to Taiwan

On the Magnetic Anomaly Map of East Asia produced by the *Geological Survey of Japan and Committee for co-ordination of Joint prospecting for Mineral Resources in Asian Offhore Areas (GSJ and CCOP)* [1994], numerous high-amplitude magnetic
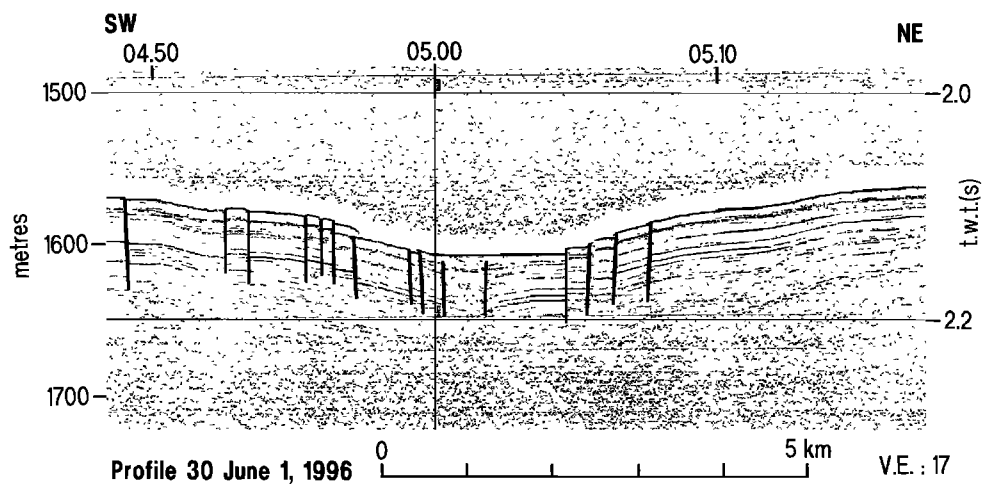
Figure 9. Portion of the 3.5 kHz profile 30 (location in Figure 2) located across the seismic area with the presence of a slight depression (also displayed on the seismic profile 30, Figure 6). Normal faults with a mean spacing of about 600 m present offsets of a few meters.

anomalies of limited extension and generally associated with seamounts are aligned along a narrow belt located just northwest of the Ryukyu arc and extending from Japan to Taiwan (Figure 13). In the northern OT, from Kyushu to Okinawa Island, most of these magnetic anomalies coincide with small subaerial active volcanoes located about 25 km west of the axis of the nonvolcanic arc. These magnetic anomalies of circular shape are different from the elongated linear magnetic anomalies identified as typical of backarc basin volcanism and located in the axial portion of the trough [Sibuet et al., 1987]. Features underlined by a thick grey line on Figure 13 correspond to the present-day Ryukyu volcanic arc which is continuous from Japan to Taiwan and is located in the OT portion immediately adjacent to the island arc. In November 1997, during the RN97 cruise of the T/S Nagasaki Maru in the southwestern OT [Shinjo et al., 1998b], dredged samples on several seamounts recovered fresh pumices and dacitic lavas interpreted as Quaternary eruptives belonging to the volcanic arc. However, arc volcanoes of the southwestern OT are probably much younger than volcanoes of rest of the arc (6 Ma (R. Shinjo, personal communication, 1998)).

In addition, Figure 13 shows the depth of the Wadati-Benioff zone beneath the Ryukyu arc and OT. This surface was assumed to be at the top of the seismogenic zone (Figure 8). The locations and depths of earthquakes were provided by Cheng and Yeh [1991] and the International Seismological Centre (ISC) except west of 123°W where identifications of the Taiwan Telemetered Seismograph Network (S.-N. Cheng, personal communication, 1996) were used and from which isobaths of the Wadati-Benioff zone were determined by Font et al. [1998]. East of 123°E, earthquake locations have been stacked along the axis of 100-km-wide stripes defined perpendicularly to the subduction zone trend. Contour depths of the Wadati-Benioff zone do not significantly differ from early determinations of Eguchi and Uyeda [1983] and are in close agreement with the picture of the Ryukyu slab given by Kao and Chen [1991].

The volcanic front overlies the dipping seismic zone with a constant depth of 110 ± 20 km [Tatsumi, 1986] in most of the subduction zones. Beneath the Ryukyu islands, the depth of the Wadati-Benioff zone is between 20 and 60 km which explains

why no present-day arc magmatism is observed in most of the Ryukyu islands. In contrast, the present-day active Ryukyu volcanic arc is located 80-100 km above the Wadati-Benioff zone over its entire length (Figure 13), 80 km being the minimum depth of the Wadati-Benioff zone required for the emplacement of arc magmatism [Gill, 1981; Tatsumi, 1986]. In addition, the volcanic front is located above a kink in the dip of the downgoing slab (Figure 13) as already shown by Kao and Chen [1991]. This depth of 80 km above the subducted oceanic crust only occurs beneath the OT portion immediately adjacent to the Ryukyu arc. Until now, the present-day volcanic arc was only identified north of Okinawa Island. Here, we establish the continuity of the present-day volcanic arc from Japan to Taiwan but note that the amount of arc magmatism is significantly reduced between Okinawa Island and Taiwan.

8. Magmatism in the Southwestern Okinawa Trough

The present-day Ryukyu volcanic arc is some distance from the areas of backarc volcanism emplaced along depressions located in the axial portion of the OT [Sibuet et al., 1987] (Figure 1). It is only within the southwestern OT that the volcanic front is very close to the N085° backarc depression. What is the origin of the southwestern OT volcanism: Arc or backarc volcanism? Oshida et al. [1992] modeled associated magnetic anomalies with a normally magnetized crust (2.5 A/m), suggesting a present-day emplacement, but this tells nothing about the arc or backarc origin of the magmatism. Geochemical analyses performed on basaltic samples collected on seamounts located eastward of the ACT survey, but in the same geodynamical context show a clear arc volcanic affinity [Sibuet et al., 1987]. However, the arc or backarc origin of the magmatism cannot be assessed because of the plausible arc contamination in the hypothesis of a backarc volcanism.

Based on the morphology of volcanic features, two types of magmatism have been identified within the southwestern OT:

1. A recent volcanism emplaced as elongated narrow volcanic features along the N085° normal faults of the backarc depression
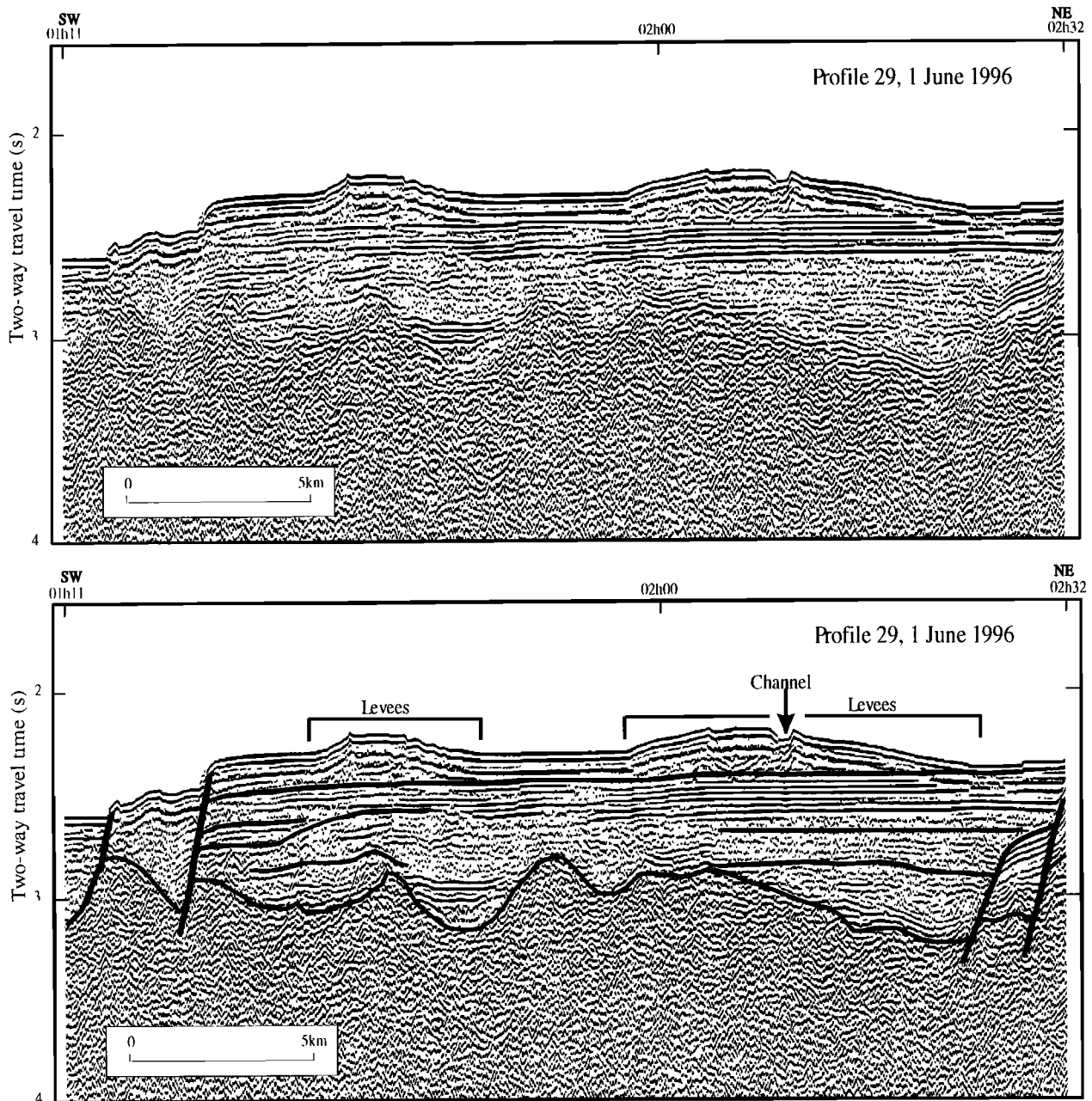
Figure 10. Migrated six-channel high-speed seismic profile 29 (location in Figure 2) across the extinct channel meanders located north of the backarc depression. Due to meandering, the seismic profile twice crosses the same submarine channel (Figure 2 and Plate 1). Note the presence of sedimentary levees about 150 m thick above the Pleistocene horizontal sedimentary sequence.

(Plates 1 and 2 and Figure 6) that we name backarc rift volcanism by comparison with the already identified backarc volcanism in the southern OT [*Sibuet et al.*, 1987]. Its age of emplacement could be less than a few tens of thousands of years.

2. A volcanic chain of seamounts, cutting across obliquely the southwestern OT, occurs along a N045° oriented, 20 km wide and 70 km long zone (Figure 3 and Plate 1, between 24°45'N and 25°13'N). In the central portion of the chain, between 25°N and 25°10'N, the volcanic basement is buried beneath sediments, but its volcanic nature could be clearly assessed from the interpretation of seismic profiles and associated magnetic anomalies. The age of the volcanic seamounts decreases

southwestward since early Pleistocene but perhaps irregularly along its trend. By comparison with the southern Havre Trough example [*Wright et al.*, 1996], we interpret this N045° trending anomalous volcanic feature as a cross-backarc volcanic chain formed within the active part of the backarc basin and progressively removed away from the axis as for the construction of oceanic crust.

In the Havre backarc basin example, *Wright et al.* [1996] and *Gamble and Wright* [1995] favor the formation of a major cross-arc ridge located between the remnant arc and the present-day arc by a monotonic age progression. The constructional process of the ridge would progressively occur within the active backarc rift
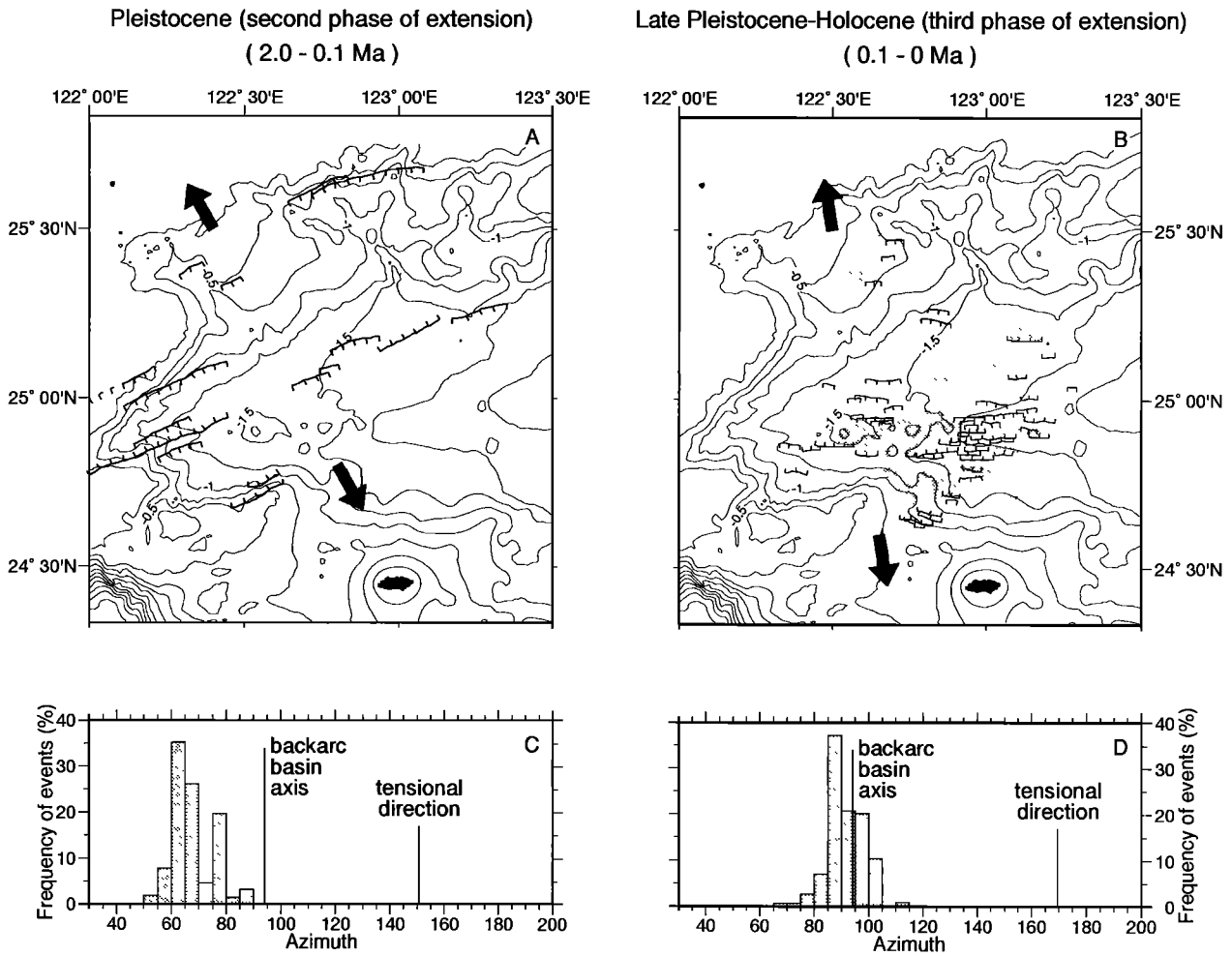
Pleistocene (second phase of extension)   Late Pleistocene-Holocene (third phase of extension)
(2.0 - 0.1 Ma)   (0.1 - 0 Ma)

Figure 11. (top) Distributions of the two simplified normal faults systems associated with the two last phases of extension in the southwestern Okinawa Trough as well as the inferred direction of extension (large arrows). (bottom) Frequency of normal faults segments in function of their azimuths and deduced tensional directions from comparison with analog modeling results.

Period	Main tensional phase	Mean direction of extension and amount of extension		Rate of extension
		Previous studies	This paper	
Holocene Recent	3rd phase 0.1 Ma	N180 +/-10° 3 km (1)	N170 +/-5° 5 km (2, 3)	3 (3) - 5 (2) cm/yr 4 cm/yr (4)
Upper Pleistocene	2nd phase 2 Ma	N170 +/-10° 3 km (1)	N150 +/-10° 30 km (2, 3)	0.9 (3) - 1.5 (2) cm/yr 1 - 2 cm/yr (5)
Lower Pleistocene				
Pliocene	1st phase 6-7 Ma	N141 80 km (1)	N145 50 km (2)	1 cm/yr (?) (2)
Upper Miocene	▼ ?		▼ ?	
Middle Miocene				

Figure 12. Main phases of extension in the southwestern Okinawa Trough. 1, S*ibuet et al.* [1995]; 2, T*hareau* [1996]; 3, this paper; 4, *Kato et al.* [1995]; 5, *Park* [1996].
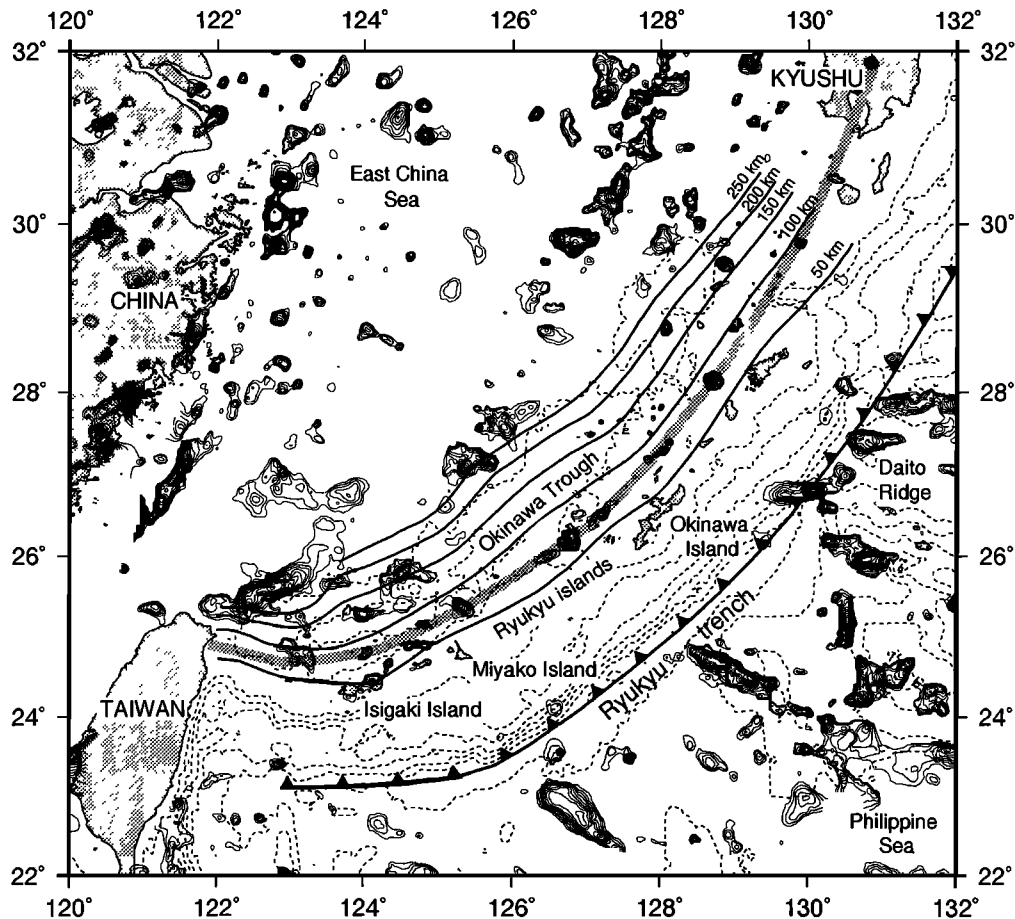
Figure 13. Isobaths of the Wadati-Benioff zone beneath the Okinawa Trough determined from locations and depths of earthquakes provided by *Cheng and Yeh* [1991], the International Seismological Centre (ISC) and the Taiwan Telemetered Seismograph Network (S.-N. Cheng, personal communication, 1996) and established by *Font et al.* [1998] west of 123°E. Bathymetric contours in dashed lines every kilometer. Magnetic anomalies [*Geological Survey of Japan and Committee for Co-ordination of Joint Prospecting for Mineral Resources in Asian Offshore areas (GSJ and CCOP)*, 1994] larger than +60 nT contoured every 20 nT to underline volcanic seamounts. The grey line corresponds to the present-day Ryukyu volcanic arc which extends from Japan to Taiwan and is located at a constant height of 80-100 km above the Wadati-Benioff zone.

by excess volcanism emplaced during the progressive basin widening propagating perpendicularly to the cross-arc line of constructional arc magmatism. If extension always occurs within the same rift, the cross-arc ridge would be younger in the central part of the backarc basin and older on the backarc basin sides. In the southwestern OT, this mechanism was probably involved though the active continental rift axis could have progressively migrated through recent time in the southward direction. However, along the cross-backarc magmatic trail, from northeast to southwest, the following supporting observations are: (1) At 25°12'N, the volcanic feature (Figure 5) is capped with uplifted undeformed sediments probably of lower Pleistocene age. (2) Between 25°05'N and 25°10'N, the volcanic basement is buried beneath sediments deposited during the Pleistocene phase of extension. (3) The N085° backarc depression corresponding to the late Pleistocene-Holocene phase of extension is located between 24°50'N and 24°58'N. (4) Crustal earthquakes with tensional mechanisms occur now south of 24°50'N. The large volcano (08h50 on Profile 26, Figure 7) belongs to this seismic zone and could be one of the most recent volcanoes of the N045° cross-backarc volcanic trail

During the ACT cruise, the Gagua ridge and the Ryukyu arc-trench system were both surveyed (Figure 14). The 350-km-long linear Gagua aseismic ridge trends north-south. The direction of magnetic lineations is roughly E-W in the Huatung Basin located west of the ridge [*Hsu et al.*, 1998] and ESE-WNW in the Philippine basin, east of the ridge, where chron 20 (45 Ma) has been identified [*Hilde and Lee*, 1984; *Hsu et al.*, 1996a]. The mean basement depth, corrected for the sedimentary load, is about 0.4 km shallower in the Philippine Sea basin compared with the Huatung Basin. Using the age versus depth of oceanic basement curve for slow spreading ridges [*Le Pichon et al.*, 1973; *Sclater et al.*, 1971], the oceanic crust of the Huatung Basin could be 8-16 M.y. older than in the Philippine Sea basin. The large linear relief of the Gagua ridge could be compared with two similar structures: either the Romanche fracture zone (equatorial Atlantic) [*Sibuet and Veyrat-Peinet*, 1980], a large offset fracture zone or the Ninetyeast Ridge, a 4000-km-long late Cretaceous-early Tertiary transform plate boundary which was a former fracture zone parallel to the Wharton basin fracture zones. A compressive component on Gagua ridge is suggested by gravity data [*Hsu et al.*, 1996a]. In addition, *Sibuet and Hsu*
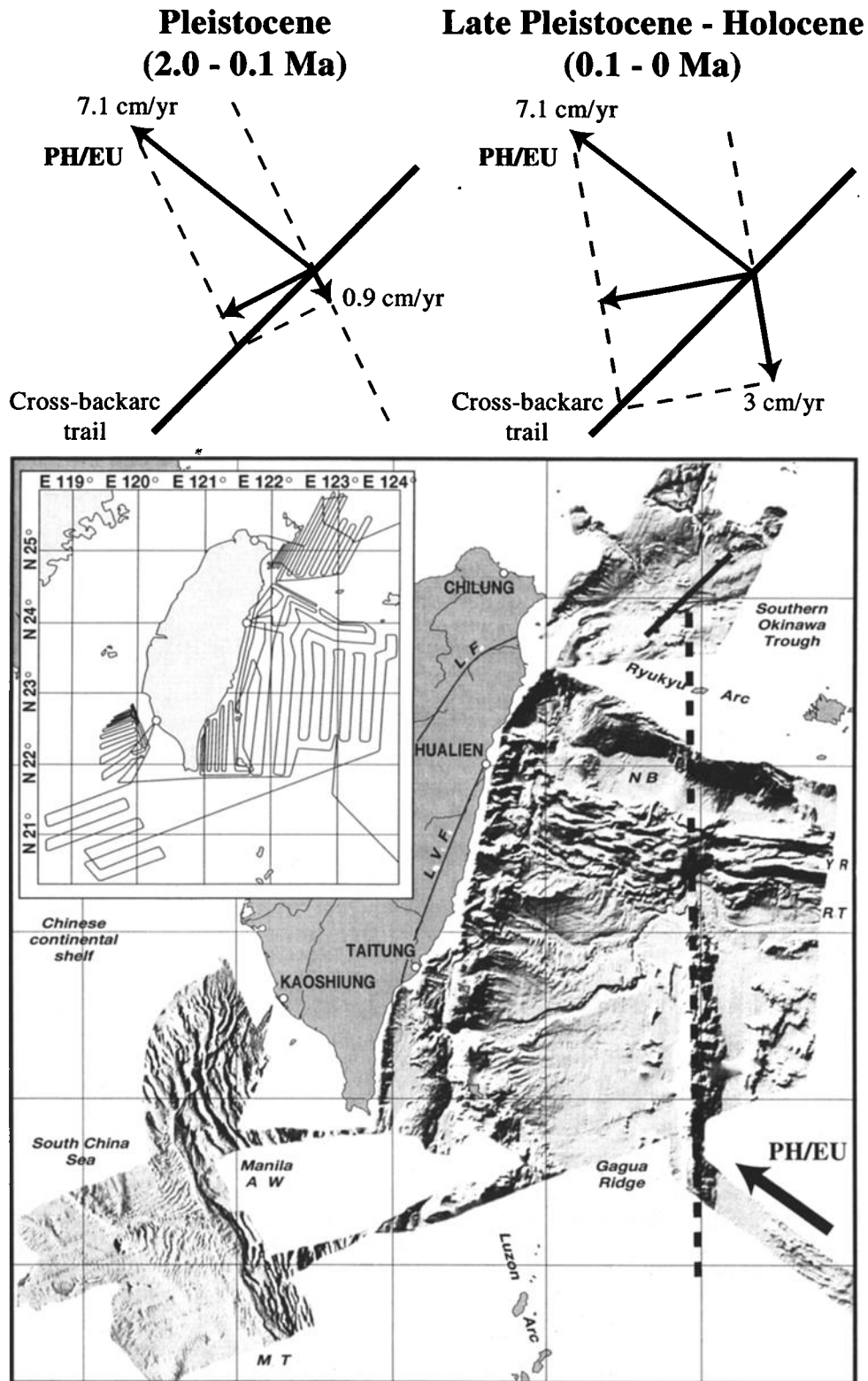
Figure 14. Shaded bathymetric map of ACT (as well as preceding and following transits) data [*Lallemand et al.*, 1997] showing the N358° trending Gagua ridge which subducts beneath the Ryukyu arc and forearc [*Dominguez et al.*, 1996]. Associated surface manifestations in its northern prolongation are the large reentrant located at the base of the Ryukyu prism (Yaeyama ridge (YR), the uplifted part of the Nanao forearc basin (NB), the deformation of the sedimentary arc and the Okinawa Trough voluminous arc volcanism which is located in the direct prolongation. The two diagrams show the velocity vectors needed to create the N045° cross-backarc trail for both the Pleistocene and late Pleistocene-Holocene phases of extension.

[1997] have shown that north of 23°N, the Gagua ridge could be a present-day plate boundary between the Philippine Sea and the Gagua (now Huatung) plates, the latter one being bounded by the eastern Ryukyu trench, the Luzon arc, and a N075° oriented right-lateral strike-slip fault joining the Gagua ridge at 23°N.

Consequently, the Gagua ridge is a large offset fracture zone or, more probably, a plate bounday which extended to the Ryukyu subduction zone during early Tertiary times and since then, subducts obliquely beneath the Ryukyu arc. At its northern extremity (Figure 14), the large reentrant located at the base of the Ryukyu prism (Yaeyama ridge), the uplift of part of the Nanao forearc basin, and the deformation of the sedimentary arc [*Dominguez et al.*, 1996], are consequences of the subduction of this linear feature whose upper surface lies 2-4 km above the Philippine Sea oceanic basement. Recently, *McIntosh and Nakamura* [1998] using wide-angle and refraction data acquired along an E-W profile in the Nanao basin suggested that a low velocity body at a depth of 15-20 km would be the northern prolongation of the Gagua ridge. As the southwestern OT seamount volcanic chain lies in the direct extension of the Gagua ridge, we suggest that this voluminous cross-backarc volcanism is linked to the presence of the Gagua ridge located there at a depth of 80-100 km (Figure 1).

The consequences of such an hypothesis are the following: during the Pleistocene phase of rifting (2-0.1 Ma), σ_3 is N150° oriented, σ_2 is N060° with 30 km of extension in the southern OT deduced from the kinematic motion of the Ryukyu plate [*Thareau*, 1996] (Figure 12). During the late Pleistocene-Holocene phase of extension (since 0.1 Ma), σ_3 is N170° oriented, σ_2 is N080°, with 5 km of extension in the southern OT also deduced from the kinematic motion of the Ryukyu plate [*Thareau*, 1996] (Figure 12). If the relative motion of the Philippine Sea plate with respect to Eurasia is constant through time (7.1 cm/yr in the N308° direction [*Seno et al.*, 1993]), the westward component of the Gagua ridge motion is 2.8 cm/yr along the N060° rift direction during the Pleistocene phase and 4.6 cm/yr along the N080° rift direction during the late Pleistocene-Holocene phase (Figure 14). The needed rate of extension to create a N045° cross-backarc trail within the southwestern OT is 0.9 cm/yr during the Pleistocene phase and 3.0 cm/yr during the late Pleistocene-Holocene phase (Figure 14).

Are the consequences of such an hypothesis reasonable? The obtained rate of extension for the Pleistocene phase (0.9 cm/yr) could be compared to the estimated annual average extension velocity of 1.5 cm/yr [*Thareau*, 1996] (Table 1) or 1-2 cm/yr calculated by Park [1996] from the basement fault geometry across an OT transect near Miyako island (Figure 15). The 3 cm/yr mean velocity during late Pleistocene-Holocene could be compared to the 5 cm/yr [*Thareau*, 1996] (Figure 12) or to GPS observations on Isigaki Island which indicate that this island is separating from mainland China at a velocity of 4 cm/yr [*Kato et al.*, 1995]. In our hypothesis, the amount of extension is 18 km during the Pleistocene and 3 km during late Pleistocene-Holocene. These values are consistent with the 30 and 5 km of extension deduced independently from the kinematic motion of the Ryukyu plate in the southern OT [*Thareau*, 1996] (Figure 12).

Thus the Pleistocene and late Pleistocene-Holocene extension rates, the corresponding amounts of extension and the length of the cross-backarc trail are in close agreement with observations. We conclude that the hypothesis of abnormal voluminous

magmatism emplaced along a cross-backarc trail whose formation is linked to the oblique subduction of the Gagua ridge beneath the OT is plausible. If such an hypothesis is valid, the geometry of the ridge at such a depth beneath the OT is probably still a linear feature culminating a few km above the subducting plate as for its present-day morphology. We suggest that the Gagua ridge initially induced stress at the base of the arc which is still brittle and cracks propagated through the overlying brittle lithosphere allowing magmas with arc affinities to erupt at the seafloor within the backarc basin because the volcanic arc is located in OT. The origin of this anomalous volcanism could be also partly due to an increase of friction of the Gagua ridge with the overlying brittle lithosphere near the volcanic front due to the oblique motion of the Gagua ridge with respect to the overlying lithosphere. A temperature increase of only ten or a few tens degrees would significantly increase the rate of partial melting in the overlying lithosphere and would also explain a relative excess of magmatism.

9. Origin of Magmatism in the Okinawa Trough

A second area where a significant amount of magmatism has been emplaced is located in the middle OT (VAMP area, Figures 1 and 15). The VAMP area is located in the exact prolongation of the Daito ridge, a linear volcanic feature of the Philippine Sea plate, about 400 km long, 100 km wide, and culminating at a depth less than 2000 m. As for the Gagua ridge, the Daito ridge disappears near the Ryukyu trench (Figure 15). In the northwest prolongation of the Daito ridge, a large reentrant exists at the base of the Ryukyu prism as well as in the upper part of the forearc [*Marine Safety Agency*, 1993]. We suggest that the Daito ridge extends beneath the VAMP area and that the origin of the volcanism is similar to the one of the southwestern OT cross-backarc volcanic trail.

We interpret both the southwestern OT trail and the VAMP area as localized volcanic features emplaced within active portions of backarc rifts which are linked to the subduction of major Philippine Sea topographic volcanic features beneath Eurasia. We suggest that the preferential way for magmatism to reach the seafloor is to follow conduits along crustal normal fault traces in the active backarc rifts. These zones act as preferential planes of weakness at least within the upper lithosphere.

Outside these two anomalous volcanic areas and the present-day volcanic arc, only five small elongated volcanic ridges were mapped in the deepest part of the backarc depressions (Figure 1 and stars in Figure 15 [*Sibuet et al.*, 1987]) and interpreted as the onset of backarc activity, with the emplacement of magmas along backarc depressions. Several lines of evidence indicate that the three types of volcanism observed in OT (backarc, arc, and anomalous volcanism) have arc affinity. Except for geochemical analyses concerning the arc volcanic front [*Shinjo et al.*, 1998a], all geochemical analyses performed on basaltic samples dredged in the VAMP area or along the backarc volcanic ridges [*Oshima et al.*, 1988; *Sibuet et al.*, 1987] show mixing compositions between mid-ocean ridge basalt (MORB) source and arc-like melts similar to other backarc basins (e.g., *Hawkins* [1994] for the Lau Basin).

Three types of volcanism have been identified in the OT (Figures 15, 16 and 17):

1. The present-day arc volcanism corresponds to a series of small submarine volcanoes or volcanic islands. The active arc is continuous from Japan to Taiwan and is located east of the
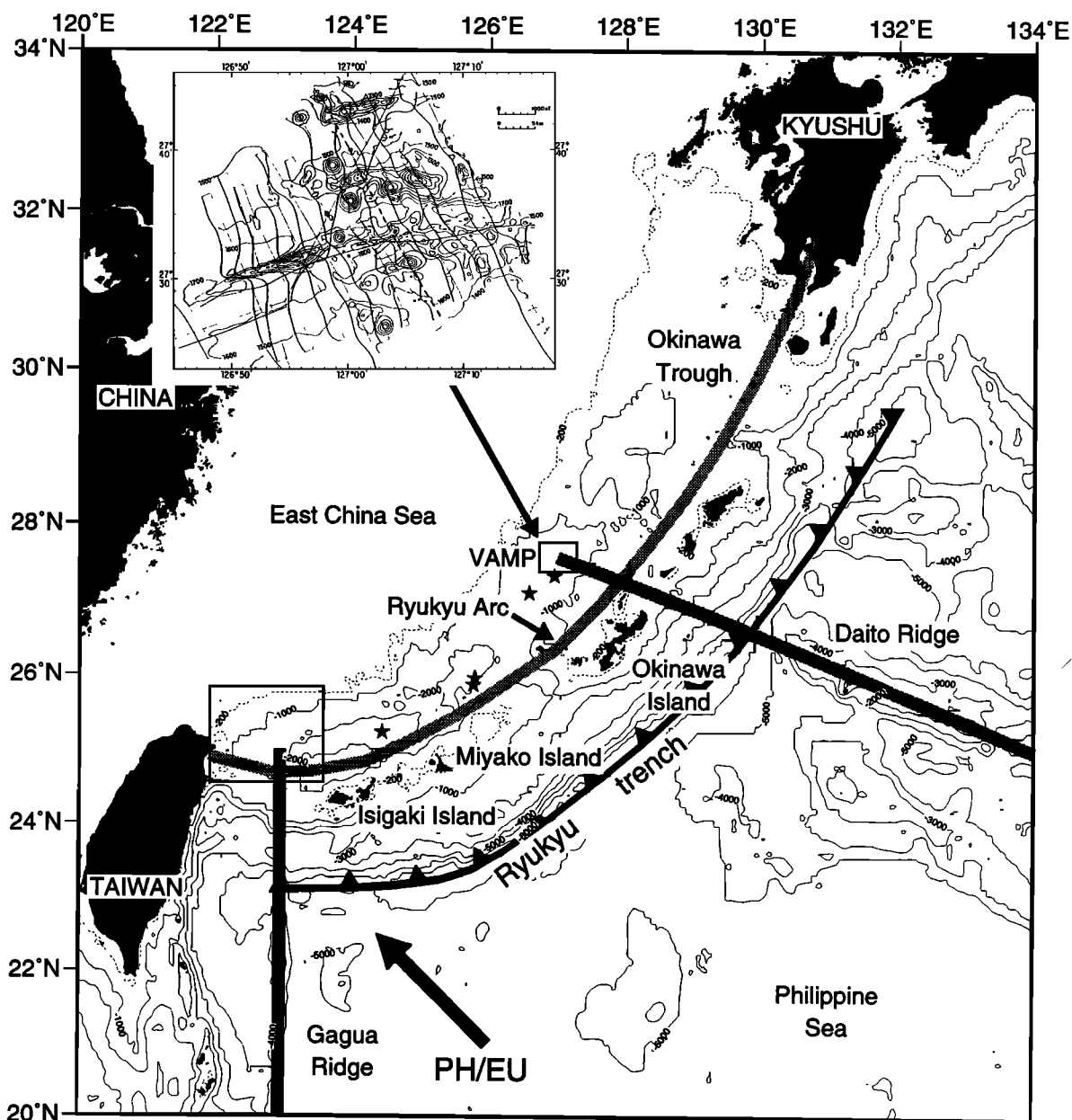
Figure 15. Location of the two OT areas of large anomalous volcanism in the prolongation of the Gagua ridge (southwestern OT) and of the Daito ridge (VAMP area, middle OT). Detailed bathymetry of the VAMP area and projected magnetic anomalies [*Sibuet et al.*, 1987] in the top left corner. Outside these two areas, there are only a few volcanic outcrops in the middle and southern OT interpreted as backarc volcanism (stars, from *Sibuet et al.* [1987]) and the Ryukyu volcanic arc shown as a continuous grey line between Japan and Taiwan.

Ryukyu islands, on the western OT margin, 80-100 km above the Wadati-Benioff zone.

2. The present-day backarc volcanism appears from middle to southern OT within en echelon elongated linear bathymetric depressions considered as central grabens. Only five of these depressions are intruded by elongated volcanic ridges of young fresh backarc basalt though their geochemical composition shows island arc affinity.

3. The cross-backarc volcanism considered as a voluminous backarc magmatism emplaced within the backarc active continental rifts. It forms two cross-backarc trails in the

southwestern and middle OT which are linked to the subduction of the Gagua and Daito ridges.

Such observations contradict earlier ideas suggesting that where bathymetric ridges interact with active trenches, the largest shallow earthquakes are generally smaller and less frequent and that gaps appear in the line of arc volcanoes [*Kelleher and McCann*, 1976]. *McGeary et al.* [1985] identified at least 24 such areas where >200 km spatial gaps in volcanic arcs coincide with collision or subduction of oceanic plateaus or ridges. However, exceptions were already noted for the portion of the Ryukyu arc north of Okinawa Island which is facing a zone of ridges
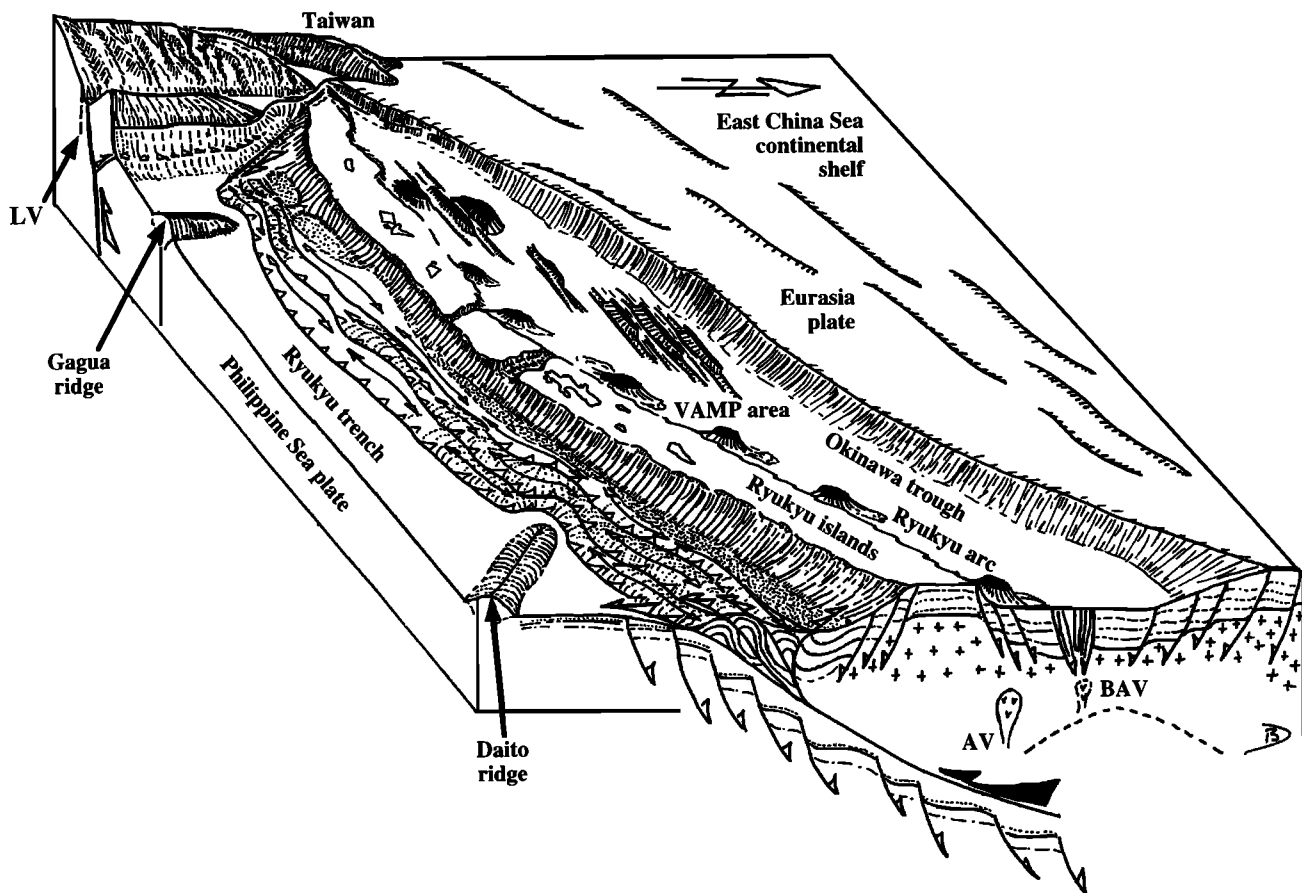
Figure 16. Three-dimensional artist view (B. Deffontaines) of the Ryukyu subduction system looking southwest with the three different types of volcanism (arc, backarc, and cross-backarc volcanisms) which appear in the Okinawa Trough. BAV, backarc volcanism; AV, arc volcanism; LV, Longitudinal Valley.

[*Kelleher and McCann*, 1976]. We have demonstrated the continuity of the Ryukyu volcanic arc from Japan to Taiwan. The size of arc volcanoes constantly decreases from Kyushu Island to Okinawa Island (Figure 1) and then from Okinawa Island to Taiwan where submarine arc volcanoes are only a few kilometers in diameter. Thus, small arc volcanoes are facing smooth deep oceanic features and large arc volcanic islands are facing deep-seated ridges (Figure 15) which is not in agreement with general ideas developed in the past [*Kelleher and McCann*, 1976; *McGeary et al.*, 1985]. In addition, shallow seismicity along the Ryukyu plate interface is systematic [*Kao and Chen*, 1991], and we have shown that backarc anomalous volcanism is present in the extension of the Gagua and Daito ridges. Our observations in the OT are difficult to reconcile with these general concepts, even if these authors noted that the Ryukyu subduction zone was an exception in their models.

10. Conclusions

The main conclusions of this study are as follows:

1. The two last tensional phases have been identified in the southwestern OT and paleostress directions have been deduced from a comparison with analog modeling: The direction of extension is N150° for the Pleistocene phase of extension (2-0.1

Ma) and N170° for the late Pleistocene-Holocene phase of extension (0.1-0 Ma).

2. The present-day Ryukyu volcanic arc comprises a series of submarine volcanoes and small volcanic islands distributed along a narrow band which is continuous from Japan to Taiwan. The volcanic arc is located on the OT eastern margin, the western flank of the Ryukyu islands, and appears at a constant height of 80-100 km above the Wadati-Benioff zone.

3. A N045° oriented volcanic chain cuts across obliquely the southwestern OT and lies in the direct prolongation of the Gagua ridge. In the northern prolongation of the Gagua ridge, a large reentrant located at the base of the Ryukyu prism, the uplift of part of the Nanao forearc basin and the deformation of the sedimentary arc show that the Gagua ridge is a continuous ridge which subducts beneath the forearc. We suggest that the Gagua ridge is still present beneath the OT and that the voluminous cross-backarc volcanism is linked to the subduction of the Gagua ridge located there at a depth of 80-100 km. We suggest that the Gagua ridge initially induced stress at the base of the arc (located beneath the OT itself) which is still brittle and cracks propagated through the overlying brittle lithosphere allowing magmas with arc affinities to erupt at the seafloor. An increase of friction of the Gagua ridge with the overlying brittle lithosphere near the arc volcanic front, due to the oblique motion of the Gagua ridge with
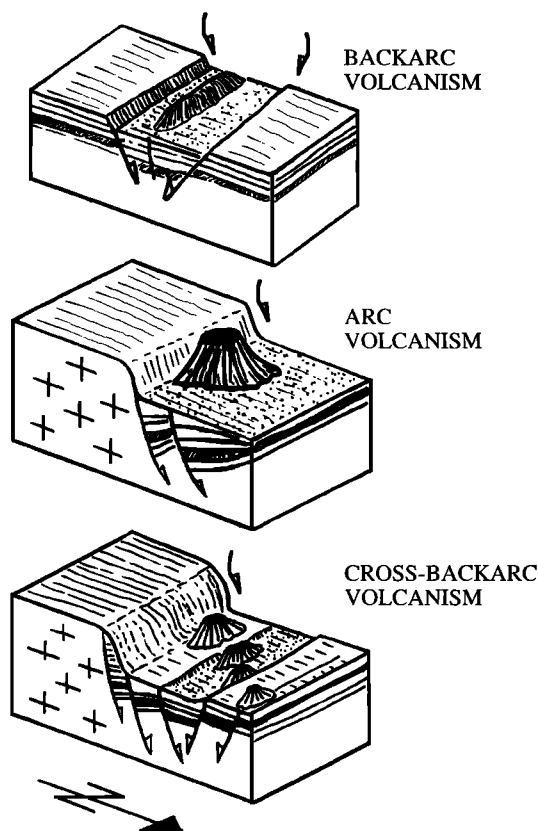
BACKARC VOLCANISM

ARC VOLCANISM

CROSS-BACKARC VOLCANISM

Figure 17. Sketches of the three different types of volcanism (arc, backarc, and cross-backarc volcanisms) which appear in the Okinawa Trough.

respect to the overlying lithosphere, could also locally increase temperature and would explain, at least partially, the relative excess of magmatism.

4. An other significant zone of OT anomalous volcanism (VAMP area) is located in the exact prolongation of the Daito ridge, a linear volcanic feature of the Philippine Sea plate. We suggest that the origin of the volcanism is similar to the one of the southwestern OT cross-backarc volcanic trail.

5. The excessive magmatism located in the southwestern OT and in the VAMP area reaches the seafloor through conduits which preferentially join crustal normal faults of the active backarc continental rifts.

References

Carter, L., R. M Carter, I. N. McCave, and J. Gamble, Regional sediment recycling in the abyssal southwest Pacific Ocean, *Geology*, 24, 735-738, 1996.

Cheng, S.-N., and Y. T. Yeh, Seismotectonics of the Taiwan-Luzon region as evidenced from seismicity and focal mechanism of earthquakes, in *Taicrust Workshop Proceedings, June 10-12, 1991*, pp. 219-226, Nat. Taiwan Univ., Taipei, 1991.

Dominguez, S., S. Lallemand, C.-S Liu, and ACT party, The southern Ryukyu arc-trench system and the Gagua ridge subduction: preliminary results of the ACT cruise, *Supplement to EOS, Trans. AGU, 77*, 731, 1996.

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

Font, Y, S. Lallemand, and J. Angelier, Etude de la transition entre l'orogène actif de Taiwan et la subduction des Ryukyu - Apport de la sismicité, *Bull Soc. Géol France*, in press, 1998.

Furukawa, M., H. Tokuyama, S. Abe, A. Nishizawa, and H. Kinoshita, Report on DELP 1988 cruises in the Okinawa trough, 2, Seismic reflection studies in the southwestern part of the Okinawa trough, *Bull Earthquake Res. Inst., Univ. Tokyo, 66*, 17-36, 1991

Gamble, J. A., and I. C. Wright, The southern Havre Trough: Geological structure and magma petrogenesis of an active backarc rift complex, in *Backarc Basins: Tectonics and Magmatism*, edited by B. Taylor, pp. 29-62, Plenum, New York, 1995.

Geological Survey of Japan and Committee for Co-ordination of Joint Prospecting for Mineral Resources in Asian Offshore Areas (GSJ and CCOP), Magnetic Anomaly Map of East Asia, Miscellaneous Map Series 32, Tokyo, 1994.

Gill, J., *Orogenic Andesite and Plate Tectonics*, 390 pp., Springer-Verlag, Berlin, 1981.

Hawkins, J W, Petrologic synthesis Lau Basin transect (Leg 135), *Proc Ocean Drilling Program, Scientific Results, 135*, 879-905, 1994.

Hilde, T. W. C., and C.-S. Lee, Origin and evolution of the west Philippine basin: A new interpretation, *Tectonophysics, 102*, 85-104, 1984

Hsiao, L.-Y., K.-A. Lin, S. T. Huang, and L. S Teng, Structural characteristics of the southern Taiwan-Sinzi folded zone, *Petrol. Geol Taiwan, 32*, in press, 1998.

Hsu, S.-K., C.-S. Liu, C.-T. Shyu, S.-Y. Liu, J.-C. Sibuet, S. Lallemand, C. Wang, D. Reed, and B Karp, New gravity and magnetic anomaly maps in the Taiwan-Luzon region and their preliminary interpretation, *TAO*, in press, 1998

Hsu, S.-K, J.-C. Sibuet, S. Monti, C.-T. Shyu, and C.-S. Liu, Transition between the Okinawa trough backarc extension and the Taiwan collision: new insights on the southernmost Ryukyu subduction zone, *Mar Geophys. Res, 18*, 163-187, 1996a

Hsu, S.-K., J.-C Sibuet, and C.-T. Shyu, High-resolution detection of geologic boundaries from potential field anomalies An enhanced analytic signal technique, *Geophysics, 61*, 373-386, 1996b.

Huang, S.-T., H.-H. Ting, R.-C. Chen, W.-R. Chi, C -C Hu, and H.-C. Shen, Basinal framework and tectonic evolution of offshore northern Taiwan, *Pet. Geol. Taiwan, 27*, 47-72, 1992.

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

Kato, T., M. Shinohara, Y Aoki, and F. Kimata, Opening of the Okinawa Trough: Evidence from GPS observation, *Seismol. Soc. of Jpn, 2*, 27, 1995

Kelleher, J., and W. McCann, Buoyant zones, great earthquakes, and unstable boundaries of subduction, *J. Geophys. Res., 81*, 4885-4896, 1976

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

Kimura, M, Active rift system in the Okinawa Trough and its northern continuation, *Bull Disaster Prev. Res. Inst., Kyoto Univ, 45*, 27-38, 1996.

Lallemand, S, C.-S. Liu, J. Angelier, J.-Y. Collot, B. Deffontaines, S Dominguez, M. Fournier, S.-K. Hsu, J.-P. Le Formal, S -Y. Liu, C.-Y. Lu, J. Malavieille, P. Schnürle, J.-C. Sibuet, N. Thareau, and F. Wang, Swath bathymetry reveals active arc-continent collision near Taiwan, *EOS Trans. AGU, 78*, 173-175, 1997.

Le Pichon, X., J. Francheteau, and J. Bonnin, *Plate Tectonics*, 300 pp., Developments in Geotectonics, Elsevier Sci., New York, 1973.

Lee, T.-Y., and L. A. Lawver, Cenozoic plate reconstruction of the South China Sea region, *Tectonophysics, 235*, 149-180, 1994.

Lee, T.-Y., and L. A Lawver, Cenozoic plate reconstruction of Southeast Asia, *Tectonophysics, 251*, 85-138, 1995.

Letouzey, J., and M. Kimura, Okinawa Trough genesis. Structure and

evolution of a back-arc basin developed in a continent, *Mar Pet Geol., 2*, 111-130, 1985.

Marine Safety Agency, Nippon Nansei-Syoto bathymetric chart, *Tokyo*, 1993.

McGeary, S., A Nur, and Z. Ben-Avraham, Spatial gaps in arc volcanism. The effect of collision or subduction of oceanic plateaus, *Tectonophysics, 119*, 195-221, 1985.

McIntosh, K. D., and Y. Nakamura, Crustal structure beneath the Nanao Forearc Basin from TAICRUST MCS/OBS line 14, *TAO*, in press, 1998.

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

Oshima, S., M. Takanashi, S. Kato, M. Uchida, I. Okazaki, S. Kasuga, C. Kawashiri, Y. Kaneko, M. Ogawa, K. Kawai, H Seta, and Y. Kato, Geological and geophysical survey in the Okinawa trough and the adjoining seas of Nansei Syoto, Rep. 24 Hydrogr. Res., Tokyo, 1988.

Park, J.-O., Seismic stratigraphy and tectonic evolution of the southern Ryukyu island arc, Ph. D. thesis, 145 pp., Ocean Res. Inst., Univ. of Tokyo, Tokyo, 1996.

Pascouet, A. P., Something new under the water, the bubbleless air gun, *Leading Edge, 10*, 79-81, 1991.

Sclater, J. G., R. N. Anderson, and M. N. Bell, Elevation of ridges and evolution of the central eastern Pacific, *J. Geophys. Res., 76*, 7888-7915, 1971.

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

Shinjo, R., S.-L. Chung, Y. Kato, and M. Kimura, Geochemical and Sr-Nd isotopic characteristics of volcanic rocks from central-south Okinawa Trough and Ryukyu arc: Implications for the evolution of a young, intra-continental backarc basin, *J. Geophys. Res.*, in press, 1998a.

Shinjo, R., I. Motuyama, M. Nakamura, Y. Takaki, H. Nishida, Y. Morii, and H. Tanaka, Report on RN97 cruise by T/S *Nagasaki Maru* in the southern Okinawa Trough, *Bull. Coll. of Sci, Univ. of Ryukyus*, Naha, Japan, in press, 1998b.

Sibuet, J.-C., and S.-K. Hsu, Geodynamics of the Taiwan arc-arc collision, *Tectonophysics, 274*, 221-251, 1997.

Sibuet, J.-C., and B. Veyrat-Peinet, Gravimetric model of the Atlantic Equatorial fracture zones, *J. Geophys. Res., 85*, 943-954, 1980.

Sibuet, J.-C., S.-K. Hsu, C -T. Shyu, and C.-S. Liu, Structural and kinematic evolution of the Okinawa trough backarc basin, in *Backarc Basins: Tectonics and Magmatism*, edited by B. Taylor, pp. 343-378, Plenum, New York, 1995.

Sibuet, J.-C., J. Letouzey, F. Barbier, J. Charvet, J.-P. Foucher, T. W. C. Hilde, M. Kimura, L.-Y. Chiao, B. Marsset, C. Muller, and J.-F. Stéphan, Backarc extension in the Okinawa Trough, *J. Geophys. Res., 92*, 14,041-14,063, 1987.

Sun, S. C., The Tertiary basins of off-shore Taiwan, *Proc. 2nd ASCOPE Conference*, Manila, 125-135, 1981.

Tatsumi, Y., Formation of the volcanic front in subduction zones, *Geophys. Res. Lett., 13*, 717-720, 1986

Thareau, N., Détermination des mécanismes d'extension et des contraintes en milieu continental aminci: L'exemple du bassin arrière-arc d'Okinawa, mémoire, 72 pp, Ecole et Observ. de Phys. du Globe, Strasbourg, France, 1996.

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

Tsuburaya, H., and T. Sato, Petroleum exploration well Miyakojima-Oki, *J. Jpn. Assoc Pet. Technol., 50*, 25-53, 1985.

Ujiie, H, Significance of "500 m deep island shelf" surrounding the southern Ryukyu island arc for its Quaternary geological history, *Quat. Res., 18*, 209-219, 1980.

Uyeda, S., Some basic problems in trench-arc-back-arc-system, in *Island Arcs, Deep Sea Trenches and Back-Arc Basins, Maurice Ewing Ser*, edited by Talwani, M. and W C. Pitman, vol. 1, pp. 1-14, AGU, Washington D.C., 1977

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

Wright, I. C., L. M. Parson, and J. A. Gamble, Evolution and interaction of migrating cross-arc volcanism and backarc rifting: An example from the southern Havre Trough (35°20'-37°S), *J. Geophys. Res., 101*, 22,071-22,086, 1996.

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