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MIDDLE MIOCENE OBDUCTION AND LATE MIOCENE BEGINNING OF COLLISION REGISTERED IN THE HENGCHUN PENINSULA: GEODYNAMIC IMPLICATIONS FOR THE EVOLUTION OF TAIWAN

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ABSTRACT

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Taiwan is located in the axis of the Manila Trench. It results from an oblique collision between the northernmost part of the Luzon arc and the Chinese passive margin. This active collision follows the subduction of the Oligocene–Miocene oceanic crust of the South China Sea along the Manila Trench. The tectonized Chinese margin emerged in the Hengchun peninsula (South Taiwan). Gentle folds which are delineated by the Quaternary reefal limestones demonstrate Recent deformations. These folds deformed a thick detrital sequence of Miocene age (Ssuchung Chi series) which was previously strongly folded and thrust westward (axis NS–N20) upon the Kenting mélange of Latest Miocene age. These main deformations, sealed by the Middle Pliocene, are the evidence for the onset of collision in this part of Taiwan at the end of the Miocene. Because of its obliquity, the collision started already in the northern part of Taiwan during the Late Miocene (6–7–8 Ma ?).

The Ssuchung Chi series, a sequence of proximal turbidites, has contained, since the Middle Miocene (NN 6 ~ 13 Ma), fragments of an Oligocene to Lower Miocene oceanic crust. This ophiolitic material is very similar to the East Taiwan Ophiolite of the Coastal Range. It originated most probably from a slice of South China Sea crust obducted in Middle Miocene times (13–14 Ma) upon the Chinese margin (North of the Hengchun peninsula). This obduction occurred 7 to 8 Ma before the beginning of collision. These results make it possible to propose an evolutionary model for Taiwan from the Oligocene to the Recent, with the different phases of a collision between a volcanic arc and a passive margin.

THE GEOLOGICAL AND GEODYNAMIC FRAMEWORK

Taiwan is located at the boundary between the Philippine Sea plate and the Eurasian plate (Fig. 1). The rate of the NW–SE convergence between the two plates is about 7 cm/year (Seno, 1977) in the area of Taiwan. This convergence has a different geological expression from one part of Taiwan to another:

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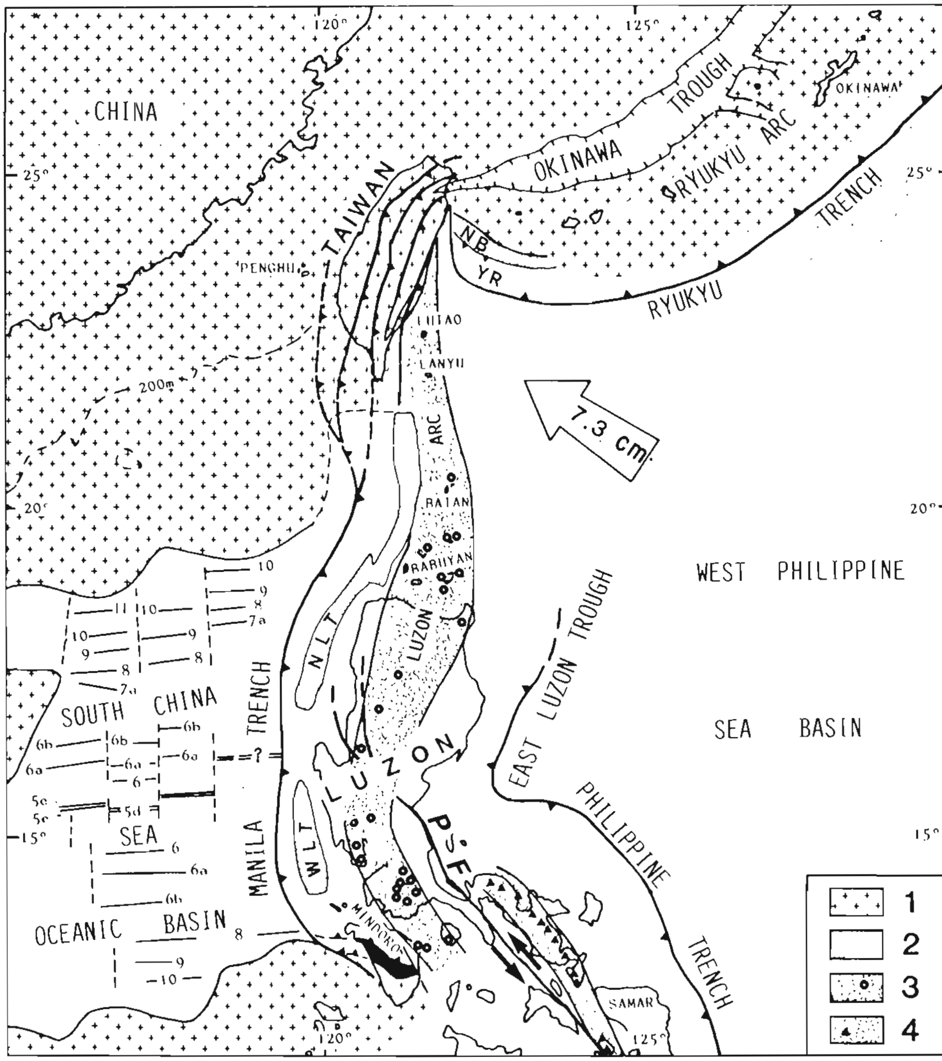


Fig. 1. Schematic map of the present-day tectonic features surrounding Taiwan, with indications of the instantaneous convergence vector of the Philippine Sea plate relative to the Eurasian plate, about 7 cm/yr (from Seno, 1977) and the magnetic anomalies of the South China Sea (from Taylor and Hayes, 1983). *1* = Eurasian continental margin; *2* = fore-arc basins; *3* = Luzon volcanic arc with its active volcanos related to the subduction of the South China Sea along the Manila Trench; *4* = Bicol volcanic arc and the active volcanos related to the subduction of the Philippine Sea plate along the Philippine Trench. *PF*—Philippine fault; *NLT*—North Luzon trough; *WLT*—West Luzon through; *NB*—Nanao basin; *YR*—Yaeyama ridge.

(1) In the northeast, the Paleogene oceanic crust of the West Philippine Sea basin is subducting below the Eurasia plate along the Ryukyu Trench. A submarine volcanic are located on a continental basement and a young marginal basin (Okinawa basin) are associated with this subduction.

(2) In the south, the Oligocene–Miocene oceanic crust of the South China Sea, belonging to the Eurasian plate, is subducting below the Philippine Sea plate along the Manila Trench. The associated volcanic arc lies on the continental basement of Luzon (Philippines). It can be followed northward along the archipelago of Babuyan and Batan where volcanism was recently active (Van Padang, 1953). Further north, on Lanyu and Lutao islands, as well as in the Coastal Range of Taiwan, the volcanism of the arc is essentially of Miocene–Pliocene age (Ho, 1975; Chi et al., 1981; Richard et al., 1986). However, in this area, the geodynamic context is not the same. The northern part of the Luzon micro-block, trending N–S, collided obliquely with the Chinese passive margin (SW–NE) creating Taiwan (Biq, 1972; Chai, 1972; Jahn, 1972; Yen, 1973; Bowin et al., 1978; Tsai, 1978; Wu, 1978; Ho, 1979; Suppe, 1981; Chi et al., 1981; Chang and Chi, 1983; Barrier, 1985; Pelletier et al., 1985). The Chinese margin is characterized by a thick series of terrigenous sediments deriving from the Asian continent. It was created by the opening of the South China Sea during Oligocene (32 Ma) and early Miocene (17 Ma) time (Taylor and Hayes, 1983). The transition from subduction to collision is located north of the latitude 21°30′N (Stephan, Rangin et al., 1984). Further north, westward overthrusts affect the Chinese margin as revealed by their prolongations in Taiwan.

In Taiwan two zones are juxtaposed (Fig. 2) separated by a major fault with seismicity oriented parallel to the Longitudinal Valley. It dips 50°–55° to the east and can be recognized down to a depth of 50 km (Tsai et al., 1977). In the field, the eastern zone overthrusts the Longitudinal Valley with a slight sinistral component (20%: Barrier et al., 1982; Barrier, 1985a).

The eastern part corresponds to the Coastal Range culminating at about 1500 meters. This range is characterized by an extensive andesitic arc volcanism of Middle to Late Miocene age (Hsu, 1956; Ho, 1975; Chi et al., 1981). The volcanic rocks are covered by a Pliocene-Early Pleistocene sequence of clastic sediments several thousand meters thick (Chi et al., 1981). The Lichi mélange is intercalated in its lower part. It includes, besides other blocks, fragments of the early Middle Miocene ophiolites (East Taiwan Ophiolite: Liou et al., 1977; Huang et al., 1979). The Coastal Range was folded less than 500,000 years ago (Chi et al., 1981).

The part west of the Longitudinal Valley belongs to the imbricated and overthrust Chinese continental margin. It represents the major part of the island and culminates at about 4000 m in the Central Range. The present deformation front (= front of collision) is located in the Taiwan strait between the western coast and the Penghu archipelago (Fig. 1). Between this front and the Longitudinal Valley, there are from west to east (Ho, 1975, 1979, 1982; Fig. 2):

(1) The Coastal Plain with hills of Pleistocene molasse related to recent tectonics.

(2) The Foothills consisting of imbrications including the Late Oligocene to Early Pleistocene cover. The tectonic is essentially of Pleistocene age.

(3) The Central Range composed, from west to east, of a large thrust consisting mainly of Eocene to Early Miocene folded and sub-metamorphosed argillaceous

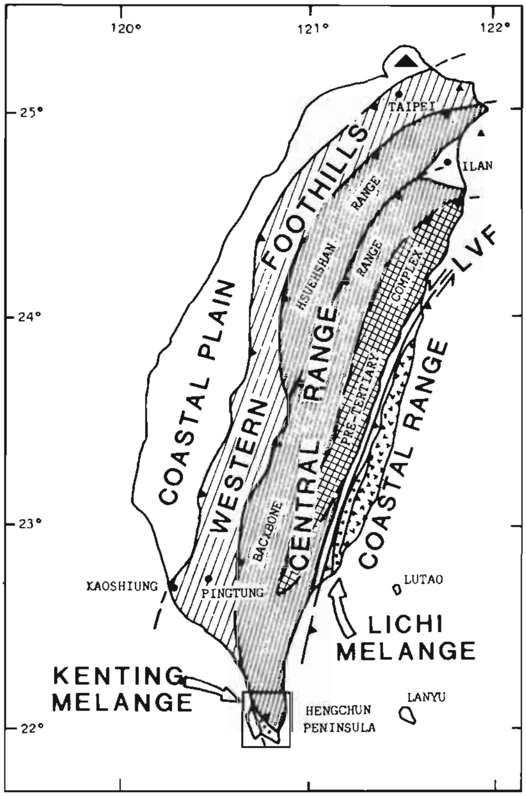


Fig. 2. Structural framework of Taiwan (after Ho, 1975; 1982). Locations of the Hengchun peninsula and the two mélanges of Taiwan. *LVF*—Longitudinal Valley fault.

sediments with a subordinate amount of sandstones (= zone of Hsuehshan) and a complex pre-Tertiary unit (= Tananao Schist Complex: Yen, 1954, 1963) forming the backbone of the range, which consists of a Paleozoic and Mesozoic polymetamorphosed basement (= Tailuko Belt: Permian marbles, amphibolites, micaschistes, orthogneiss, migmatites) and a unit of metaophiolites (Yuli Belt). The whole complex is unconformably covered by Eocene quartzites and phyllites (Hsinkao Formation) and followed by a thick phyllitic sequence (Lushan Formation) of Early to early Middle Miocene age.

The Tananao Schist Complex and its Tertiary cover form a broad anticline which is overturned to the west and reversed toward the east near the Longitudinal Valley (Stanley et al., 1981). The anticline axis plunges in the direction of the Hengchun peninsula, the southern point of Taiwan. From north to south, with decreasing altitude, the cover becomes progressively more complete, reaching the Upper Miocene in the Hengchun peninsula. In this area, a complex with blocks, the Kenting mélange, appears in front of the unit. Therefore, the position of the Hengchun peninsula is especially interesting regarding the uplift of the collision zone. The structure is still rather complete which makes it possible to describe the pre- to syn-collision history.

New results presented in this paper allow us to revise the model given by Suppe (1981) and adopted by other authors (Chi et al., 1981; Page and Lan, 1983; Barrier, 1985b; Barrier et Angelier, 1986). According to this model, the onset of collision in Taiwan is dated at 4 Ma (Chi et al., 1981). Taking into account the obliquity of the interaction arc/margin and the rate of convergence calculated by Seno (1977), Suppe (1981) argued that the collision started in northern Taiwan, propagating southward at a rate of 90 km/Ma. This means that collision is just beginning in the area of the Hengchun peninsula (Suppe, 1981, p. 71; Chi et al., 1981, p. 156). However, we have recognized in this region that the main deformations associated with schistosity began as early as the Late Miocene (around 5 Ma), which means that the beginning of collision is older than inferred in Suppe's model. We will also argue that a part of the Oligocene–Miocene South China Sea oceanic crust was obducted upon the Chinese margin in Middle Miocene times, prior to the collision.

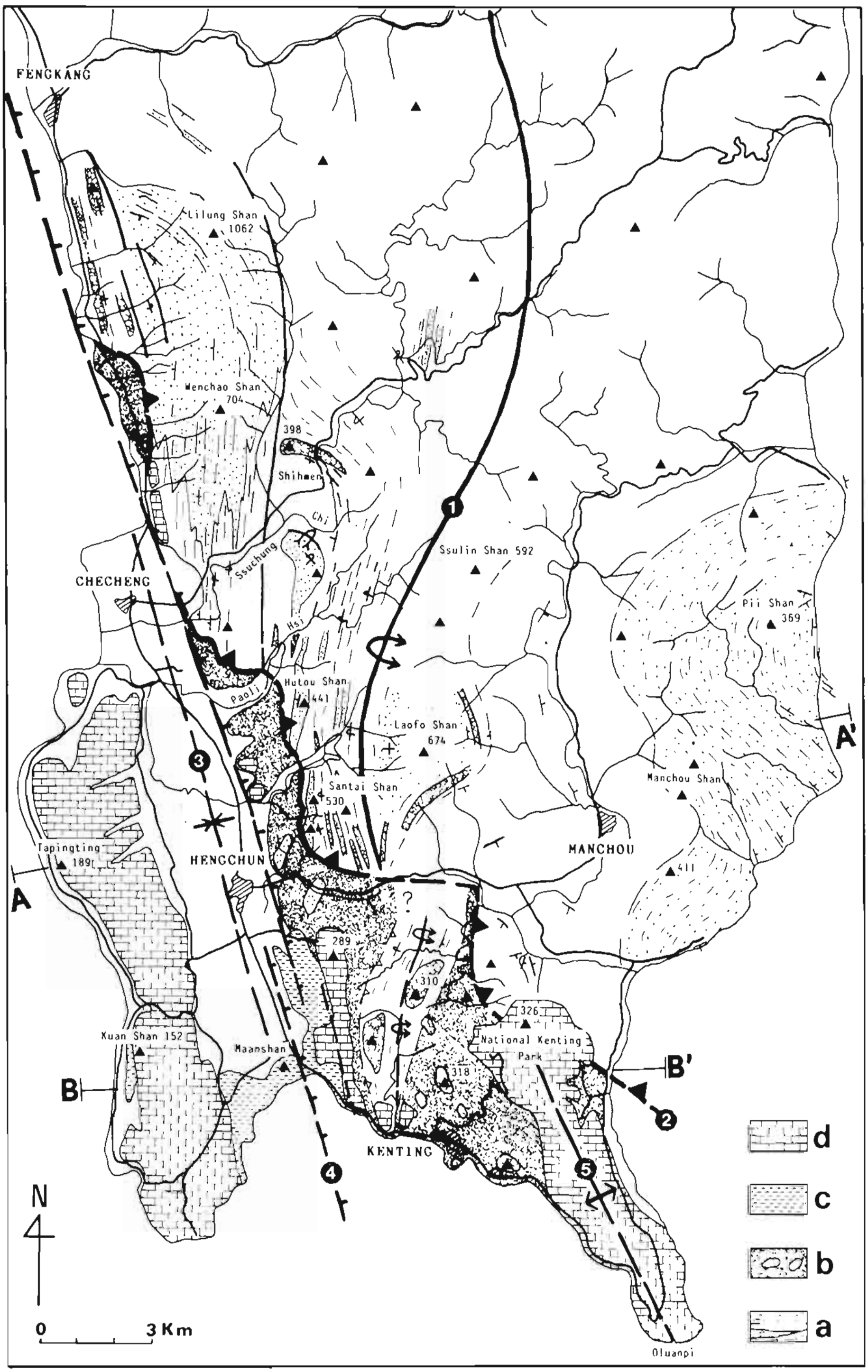
PREVIOUS STUDIES

The first studies dealing with the Hengchun peninsula were made by Rokkaku and Makiyama (1934) who described the Hengchun Formation. Chang (1963, 1964, 1965, 1966) attributed a Miocene age to this formation. Tsan (1974a, b) published the first geological map of this area. He subdivided the sedimentary deposits into several formations, and described a chaotic formation (Kenting Formation) containing gigantic conglomerates with ultrabasic material. Since then many authors have discussed the origin of the Kenting mélange (Biq, 1977; Ho, 1977; Ho and Tsan, 1981). Recently, two very detailed studies were published concerning the age and nature of the blocks (Chi, 1982; Page and Lan, 1983). New results, obtained during 1983 from field and laboratory studies, will be added to these previous ones, especially those of Page and Lan (1983).

MAIN STRUCTURAL FEATURES OF THE HENGCHUN PENINSULA (Figs. 3 and 4)

The most distinct structures are of Quaternary age. They correspond to the recent emersion of the peninsula. These are gentle folds with N160°E axes and faults affecting the Plio-Quaternary sequences (Maanshan Formation and reefal limestones of Hengchun). From west to east one can recognize the Hengchun Valley syncline, the Hengchun fault (Tsan, 1974b) which is oriented parallel to the Hengchun valley, and the Kenting Park anticline.

The Plio-Quaternary formations overlie unconformably the intensively deformed Miocene sequences. Only the latter will be described in detail. They are exposed east



FENGKANG
Lilung Shan
1062
Wenchao Shan
704
398
Shihmen
Ssuchung
Chi
Hsi
CHECHENG
Paoli
Hutou Shan
441
Ssulin Shan 592
Laofo Shan
674
Santai Shan
530
Pii Shan
369
A'
Manchou Shan
MANCHOU
411
Tapingting
189
A
HENGCHUN
289
310
326
National Kenting
Park
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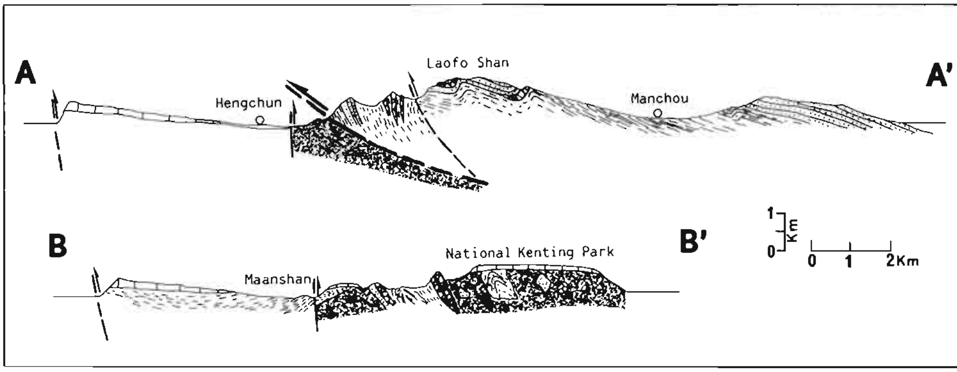


Fig. 4. Synthetic structural cross-sections (see Fig. 3 for location and legend).

of the Hengchun fault extending northward to the center of the Kenting Park anticline. They consist of a thick Miocene series which is called in the following Ssuchung Chi series. It is folded with N–S to N20 axes, overturned westward and thrust over the Kenting mélange. In comparison to Tsan (1974a) and Page and Lan (1983), the extension of the Kenting mélange is very reduced on our map. We have not used the formation names proposed by Tsan (1974a), because the Ssuchung Chi series includes a part of the Kenting mélange as defined by Tsan (1974a).

STRATIGRAPHY AND SEDIMENTOLOGY

The Ssuchung Chi series

The Ssuchung Chi series has the widest distribution in the area being studied (Fig. 3). It consists of a thick succession of siltstones, sandstones and conglomerates. Fossils are rare. Only a few samples contained nannoplankton that gave a Middle Miocene (NN 6) to Late Miocene (NN 11) age (age determinations were given by T.C. Huang and C. Muller). However, an Early Middle Miocene age for the basal part, barren of nannoplankton, is most probable. The thickness of the Middle to Late Miocene sequence is estimated at about 4 km. Although changes in thickness and facies are very frequent and rapid, it is possible to subdivide the series into four

Fig. 3. Simplified geological map of the Hengchun peninsula, southern Taiwan (from Pelletier, 1985). *a* = Shales, sandstones and conglomerates of the Early (?), Middle to Upper Miocene Ssuchung Chi series; *b* = Late Miocene Kenting mélange; *c* = Middle Pliocene to Lower Pleistocene Maanshan formation; *d* = Pleistocene formations with especially the Middle Pleistocene Hengchun reef limestone. *1* and *2*—structures related to the Late Miocene main deformations with the Hengchun peninsula anticlinorium (*1*) and the Hengchun peninsula thrust (*2*); *3*, *4* and *5*—structures related to the recent deformations with the Hengchun valley half syncline (*3*), the Hengchun fault (*4*) and the Kenting Park anticline.

sequences. The best section is located in the river-bed of the Ssuchung Chi (Figs. 3 and 5). In the following we will describe the four sequences from bottom to top. The detailed stratigraphy and sedimentology are given in Pelletier (1985).

Sequence 1. The lowermost one outcrops east of Shihmen (Fig. 3). No age determination was possible. However, its structural position indicates that it is probably of Early Miocene age. It consists predominantly of siltstones with intercalated sandstone layers several centimeters to decimeters thick.

A thick vertical succession (about 100 m) of channel-fill deposits (sandstones) was observed (Fig. 3). The sandstones are of continental origin (quartz, muscovite, biotite, tourmaline). Slumpings and current marks are abundant indicating a west to east direction of transport. The siltstone–sandstone alternations show typical turbidite features. This material was most probably derived from the Asian margin and deposited at its foot.

Sequence 2 is exposed at Shihmen, south of it, in the Ssuchung Chi and Paoli Chi rivers and it forms the Hutou Shan, Santai Shan and Laofo Shan mountains (Fig. 3). The sediments in this sequence are of Middle Miocene age (NN 6 to NN 8–9). They consist predominantly of siltstone and sandstones originating from the Asian continent (quartz, plagioclase, muscovite, biotite, tourmaline). However, they also include a large quantity of basic, ultrabasic and acid material which is present in the form of thick channel conglomerates, blocks included in the slumps, and greenish sandstone layers. The arrival of the latter rocks is dated as Middle Miocene (NN 6 at Shihmen). The greenish sandstones contain angular fragments of quartz, plagioclase, chlorite, amphibole, pyroxene, and pieces of volcanic, metamorphic and sedimentary rocks. Several channels filled with conglomerates were observed (Fig. 3). The best exposure is at Shihmen. It consists of several conglomeratic levels, each of them several tens of meters thick, grading toward the upper part in microconglomerates, then to coarse-grained sandstones and finally to sandstone layers becoming more and more fine-grained alternating with siltstones. Some of the sandstone layers are covered by a few centimeters of carbonates. The size of the components and the thickness of the layers decrease from the base to the top. The clasts are joined and are well rounded. Their size varies between 1 and 15 cm, sometimes reaching 25–30 cm. They are from igneous, metamorphic and sedimentary rocks. In all outcrops basic volcanic rocks are dominant. In decreasing abundance there are basalts, diabases, gabbros, sandstones, amphibolites, keratophyres, granitoids, argillites, quartz veins and limestones. The blocks included in the slumps are several meters to several tens of meters in size. These are blocks of pillow lavas, volcanic breccias and ultrabasic rocks. At Shihmen, blocks of pillow lavas were deposited at the bottom of the channel. The facies of this sequence shows typical features of turbiditic sequences such as flute casts, load casts, traces and the different terms of the Bouma sequence with graded bedding, parallel and oblique laminations. They are proximal turbidites (channel-fill deposits, levees). The slumps, the channel axes and the current figures indicate transport of the material from north (NW to SE) to south.

Sequence 3 is of Late Miocene age (NN 10–NN 11). Outcrops are along the western and eastern coast of the peninsula (Fig. 3).

To the west, this sequence studied by Page and Lan (1983) forms the Lilung Shan and Wenchao Shan mountain ridge. It is a thick succession of continent-derived sandstones and siltstones (at least 2000 m) where two coarsening and thickening upward mega-sequences can be distinguished. The most coarse-grained facies occurs at the top of the second sequence consisting of blue-gray quartz-rich sandstone layers (1–4 m thick) containing quartz, plagioclase, biotite, muscovite, amphibole, tourmaline. Interbedded siltstone layers are either absent or only reach a thickness of a few centimeters. The sandstones contain well preserved plant fragments and a few isolated oysters (up to 10 cm long). The sandstones are characterized by the presence of isolated pebbles or conglomeratic lenses. These lenses are 10 to 20 cm long and show graded bedding; they are often channel fillings. The clasts join each other and are well rounded. Their size varies from few centimeters to 8–10 cm and sometimes 15 cm. Most of the larger clasts are pebbles of dark quartzitic sandstone, rich in muscovite and often with quartz veins. The smaller pebbles are of quartz, basalt, gabbro, and keratophyre. This sequence consists mainly of detrital material of continental origin. But there are also some basic rock components. It is a sequence of proximal turbidites with transport from north to south. The two megasequences with decreasing stratum thickness might indicate an approach of the source (a regression?).

The sandy facies of Lilung Shan and Wenchao Shan pinches out and disappears towards the south in the Ssuchung Chi Valley, where it is replaced by a more silty facies with few levels of sandy channel deposits rich in organic matter. These facies are affected by synsedimentary deformations: slumps, slidings related to listric faults.

To the east, this sequence (about 1200 m thick) forms the mountains east of Manchou (Fig. 3). It consists of several decimeters to meters of thick sandstone layers, separated by thin interbedded siltstones. But some of the siltstone layers are thicker and are often intensively slumped. The bluish-gray sandstones are rich in quartz and organic matter. They show sparsely gradded bedding, but they are often characterized by parallel and oblique laminations at the base and convolutes at the top. This sequence might correspond to a more distal facies of the western sequence.

Sequence 4 (uppermost one) is also of Late Miocene age (NN 11). It outcrops only along the western coast, west of the Lilung Shan ridge. This sequence contains channelized conglomerates with pebbles of sandstone, basalt, diabase, gabbro... These deposits are similar to those of Shihmen, but sandstone pebbles are more common. Towards the south, west of Wenchao Shan ridge, this sequence is replaced by a mainly silty facies. Huge blocks of volcanic breccias (Chien Shan) and conglomerates are present in this area (Fig. 3). However, the stratigraphic relationship of these blocks with the organized series is unclear, due to bad outcrops and vegetation. Possibly these blocks belong to the Kenting mélange. However that may be, the general interpretation does not change because the blocks of the Kenting mélange derive from the Ssuchung Chi series (see Kenting mélange).

To sum up, the Early ? to Late Miocene Ssuchung Chi series is a turbiditic sequence with N–S transport of the material. Based on sedimentological analysis it is possible to recognize several episodes which are particularly important for understanding the geological history of Taiwan:

(1) The Lower Miocene episode is represented by a sequence of detrital material from the continent deposited at the base of the Asian margin.

(2) During Middle Miocene time (NN 6) these sediments were suddenly polluted by the occurrence of magmatic material such as ultrabasic, basic and acid rocks. This change indicates an important event in the north.

(3) The Late Miocene sequences are characterized by the high amount of detrital material deriving from the continent. But there are also some small pebbles of igneous rocks.

(4) The magmatic material reappeared within the uppermost part of the series. Either it came directly from the same reactivated source or from the reworking of Middle Miocene sediments. In both cases, it seems to reflect major tectonic activities in the north.

The Kenting mélange (Fig. 5)

The Kenting mélange was studied by Tsan (1974a, b) and more recently in great detail by Page and Lan (1983). It is exposed west of the Ssuchung Chi series at the foot of the mountains, reaching a larger extension to the south in the area of Kenting (Fig. 3). The mélange was given a wider geographic distribution in previous works. It included part of the Ssuchung Chi series because the channel conglomerates were interpreted as blocks (Tsan, 1974a, b; Page and Lan, 1983).

The mélange consists of a strongly deformed matrix including blocks of different sizes and facies. The most spectacular blocks are in the area of Kenting. They are conglomerates. The mélange also contains numerous blocks of siltstones and sandstones which are difficult to recognize in the landscape. Only the large blocks are represented in Fig. 3.

(1) The silty matrix is intensively sheared and cut up into small curved and shiny spangles with numerous slickensides (several blocks also show striations). This schistosity, often vertical or steeply E to W dipping, is generally oriented N–S. In some places the matrix includes numerous small pebbles of basalt, diabase, gabbro and keratophyre. They never join each other. The pebbles within those layers are very bright because of tectonic polishing. In the best outcrops (northeast of Hengchun) the mélange displays different colors: brown, blue and green. These colored stripes reflect the nature of the included blocks. Some of them contain only sandstones and siltstones (brown), others green sandstones and siltstones (green) or

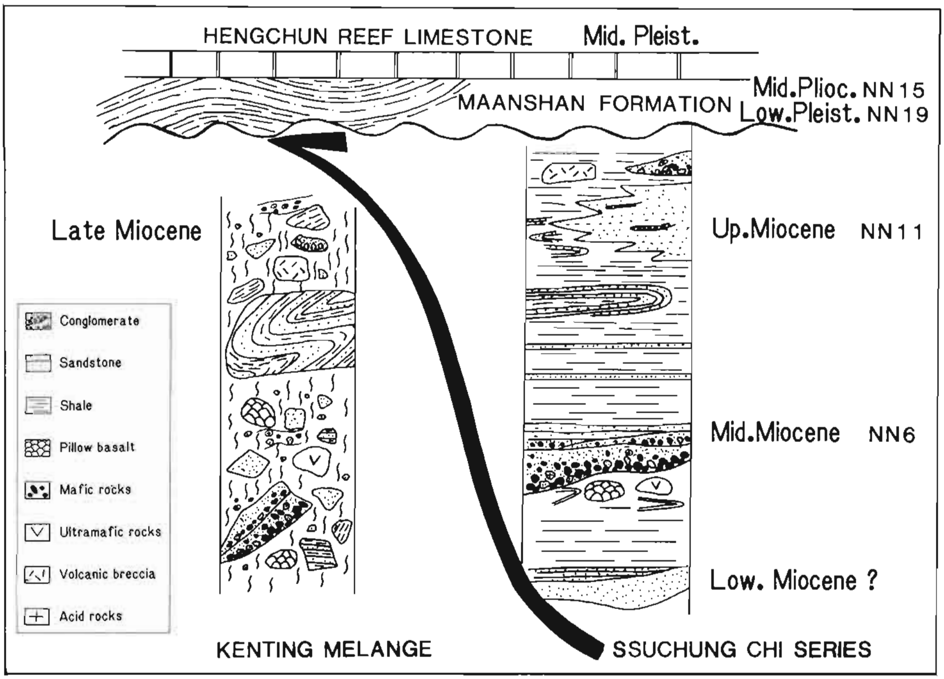


Fig. 5. Stratigraphy and relations between the different formations of the Hengchun peninsula.

well polished pebbles of basalt, gabbro and keratophyre (blue). Page and Lan (1983) assumed this layering to be a sedimentary phenomenon.

(2) The blocks are of different sizes, ranging from a few centimeters to a few kilometers. In decreasing abundance, they consist of siltstones, sandstones, alternations of siltstones and sandstones, conglomerates, pillow lavas, volcanic breccias, peridotites. The siltstones and sandstones are dominant. Different sandy facies are present: blue-gray, rich in quartz; brownish-gray lamina with organic matter; greenish, rich in volcanic material, sometimes with calcareous levels; reddish, parallel and convolute lamina. Very often they show characteristics of turbidites: current features, graded bedding and laminations. The conglomerates blocks are more spectacular due to their size and resistance to erosion. They can be subdivided into three categories: (a) green, with only pebbles of basalt, diabase and gabbro (these are the most common); (b) greenish, with more sandstone pebbles and acid rocks; (c) orange, including mainly quartzitic sandstones. All of them are channel-fill deposits associated with more fine-grained sandstones.

(3) Age of the mélange. Change (1965, 1966) attributed a Middle to Late Miocene age to the formation exposed in the south of the Hengchun peninsula (area of the mélange). Chi (1982) gives different ages based on nannoplankton studies: Oligocene (rare), Miocene (abundant). The youngest species indicate a Late Miocene age (NN 11). Recently, Huang et al. (1983) described an Early Pliocene nannoplank-

ton assemblage (NN 15–NN 16). However, this result is disputable because it was obtained only at one outcrop, probably redeposited, not far from the Plio-Pleistocene Maanshan Formation.

From our investigation of more than 200 samples, about 50 of them have given a Middle to Late Miocene age (Pelletier, 1985; determinations by C. Muller). The youngest age is Late Miocene (NN 11). These results confirm those given by Chi (1982). The blocks are of different ages ranging from Middle Miocene (NN 5) to Late Miocene (NN 11). The age of the silty matrix also ranges from NN 5 to NN 11. This means that the matrix originated from silts and siltstones of different ages. Our lithological and paleontological studies show that the Kenting mélange and the Ssuchung Chi series consist of rocks of the same facies and age. The chaotic formation originated probably from dismantling of the Ssuchung Chi series. The fine-grained members of this series constitute the matrix of the mélange.

Plio-Quaternary (Fig. 5)

The Plio-Quaternary is represented by the Maanshan Formation (Ishizaki, 1942) and the reefal limestones of Hengchun (Rokkaku and Makiyama, 1934). It is slightly deformed and unconformably overlies Miocene sediments. The Maanshan Formation consists of mudstones in its lower part, and calcareous sandstones alternating with shales in its upper part (Cheng and Huang, 1975). The basal contact is not exposed. Its thickness is at least 100 m (borehole of the "Taiwan Power Company" —in: Page and Lan, 1983). Rich and well diversified fossil assemblages gave an Early Pliocene (NN 15–N 20) to Early Pleistocene (NN 19–N 22) age (Cheng and Huang, 1975; Chi, 1982). The Hengchun reefal limestones lie unconformably upon the Maanshan Formation, and in the area of the Kenting National Park they directly overlie the Kenting mélange. They are probably of Middle Pleistocene age (Cheng and Huang, 1975; Page and Lan, 1983).

NATURE, AGE AND ORIGIN OF THE MAGMATIC MATERIAL FROM THE HENGCHUN PENINSULA

The occurrence of reworked coarse magmatic material in the Ssuchung Chi series since Middle Miocene time, and its redeposition in the Kenting mélange, raise three fundamental questions about its nature, age and origin. The nature and origin of this material have already been discussed by Tsan (1974a), Biq (1977), Ho (1977) and particularly by Page and Lan (1983).

Nature and age

The material can be subdivided into two groups in spite of its occurrence in the same layers: (1) material of basic–ultrabasic nature; (2) material of acid nature.

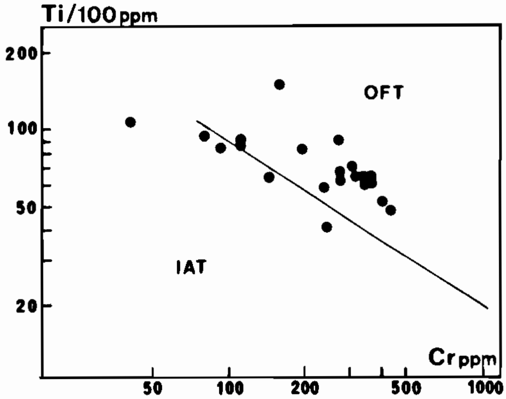


Fig. 6. Ti versus Cr diagram from Pearce (1975) illustrating the oceanic affinity of the volcanic rocks of the Hengchun peninsula. *OFT*—Ocean Floor Tholeiites; *IAT*—Island Arc Tholeiites.

The first group is the most abundant (97%); it includes pillow lavas, volcanic breccias and ultrabasic rocks as blocks in slumps and basalts, diabases, gabbros and amphibolites as pebbles (30–40 cm max.) in the conglomeratic levels.

Pillow lavas occur as boulders which can reach 20 to 30 m in diameter. About twelve of these big blocks have been found on the peninsula. The spaces between the pillows are filled with sediments which have been dated from Oligocene to uppermost Lower Miocene (Muller et al., 1986).

The volcanic breccias are homogeneous (autobrecciation of pillow lava) or heterogeneous with fragments of basalt, diabase and gabbro. This indicates that during the formation of the breccias different rock types were exposed (Page and Lan, 1983). The best outcrop of the breccia is at Chien Shan along the west coast. It consists predominantly of basalt and diabase fragments surrounded by red clays.

Blocks of ultrabasic rocks are also present. These are bluish, vesicular rocks entirely transformed to quartz and calcite with remains of chromium spinels (Chu et al., 1983). Chromitite and pyroxenite blocks associated with these ultrabasics have been found.

Analysis of 27 pebbles basic rocks (21 basalt-diabases and 6 gabbros) were carried out by atomic absorption (Pelletier, 1985). The content of major elements and particularly of the trace elements such as Cr, Ni and V indicate that the rocks are of oceanic crust affinity (Fig. 6). These results confirm those given by Page and Lan (1983) and Biq's hypothesis (1977). These rocks have undergone metamorphisms of different intensities ranging from very weak greenschist facies to amphibolite facies (Page and Lan, 1983). This variability indicates local metamorphism: such phenomena are common and well known from the oceanic crust. K–Ar dating of the amphiboles of layered magmatic amphibolites (hornblendites) gave an earliest Miocene age (22–23 Ma: Pelletier and Bellon, 1984).

The second group comprising pebbles of keratophyres and granitoids is not abundant (3%).

The keratophyres are of two types, one containing plagioclase and quartz phenocrysts (former rhyolite?), the other carrying only plagioclase phenocrysts (former andesite? dacite?). Both have an entirely recrystallized matrix of greenschist facies. As such rocks have been described in ophiolitic assemblages (Coleman and Peterman, 1975), they are probably related to the same ophiolite suite as basic and ultrabasic rocks (Page and Lan, 1983).

Granitoids are much less abundant than keratophyres. Four samples of granitoids were analysed (Pelletier, 1985) and dated (Pelletier and Bellon, 1984). Their paragenesis (quartz + plagioclase An 10–15 + amphibole/biotite + chlorite + sphene + epidote) shows these rocks correspond to amphibole or biotite tonalite–trondhjemite. The mineralogy (absence of alkali-feldspar) and the geochemistry (very low content of K and Rb) are typical for oceanic plagiogranites. Whole rock K–Ar datings also gave an Earliest Miocene age (18–24 Ma), which is in good agreement with the results obtained from the hornblendites.

According to these results it seems that the basic, ultrabasic and acid rocks reworked in the Ssuchung Chi series are all of oceanic crust affinity. They probably originated from the same ophiolitic complex of Early Oligocene to Late Lower Miocene age.

DISCUSSION ON THE ORIGIN

This ophiolitic suite described above presents a great deal of similarities with the so-called East Taiwan Ophiolite (Liou et al., 1977) embedded in the Lichi mélange which is exposed in the southwest of the Coastal Range (Fig. 2). The Lichi mélange is interpreted as a Pliocene olistostrome interbedded in the thick Plio-Pleistocene cover of the Coastal Range (Page and Suppe, 1981). It was recently dated as Early Pliocene (NN 15: Chi et al., 1981; Barrier and Muller, 1984). The mélange includes, besides other rocks, all elements of an ophiolitic complex of oceanic origin (Liou et al., 1977; Suppe et al., 1981; Page and Suppe, 1981). The largest blocks can reach a size of more than 1 km. It represents an atypical part of the oceanic crust because it consists only of breccias of peridotite, gabbro, basalt and pillow lavas (Suppe et al., 1981). The voids between the fragments of the breccia and the pillows are filled with red clay which has been dated as Middle Miocene (NN 5, Huang et al., 1979). The East Taiwan Ophiolite is considered as a fragment of a South China Sea transform fault (Suppe et al., 1981). The similarity of the ophiolitic rocks from the two areas was already mentioned by Liou et al. (1977) and Page and Lan (1983). The comparison between basalts, diabases, gabbros, amphibolites and plagiogranites from the Hengchun peninsula, three basalts from the Lichi mélange, and the analysis given by Liou et al. (1977) show that these rocks have the same texture, mineralogy and geochemistry. Furthermore it can be pointed out that the same ultrabasic rocks with chromium spinels described earlier in the Hengchun area have also been found in the Lichi mélange and that the intra-pillow sediments in both areas are partially of the same lithology (red clays) and age. In both cases heterogeneous breccias indicate that different rock types were exposed on the seafloor (fault escarpment, transform fault as mentioned by Suppe et al., 1981; Page and Lan, 1983). It can be concluded that the rocks of both areas were derived from the same Early Oligocene (30–35 Ma) to early Middle Miocene (15 Ma) ophiolitic complex. The ages correspond approximately with those given for the South China Sea (32–17 Ma: Taylor and Hayes, 1983). However, they are slightly older and also slightly younger. But these differences might not be embarrassing because the age given for the South China Sea is based only on identification of magnetic anomalies, and because the eastern part which disappeared by subduction may not necessarily be exactly of the same age as the existing western part.

Although the ophiolitic fragments of the Lichi mélange and the Hengchun peninsula are comparable, there are differences concerning their size and the place and age of their setting. The blocks are much bigger within the Lichi mélange. On the Hengchun peninsula, we are dealing essentially with boulders from conglomerates and slumps. The fragments of the Lichi mélange were reworked during Middle Pliocene time (NN 15) on the western edge of the Philippine Sea plate, whereas in the Hengchun area they occurred after Middle Miocene time (NN 6) within the sediments deposited at the base of the Chinese margin. Since the most recent age of the oceanic rocks is early Middle Miocene (NN 5), and the older sediments containing them are Middle Miocene (NN 6), the common source must have been incorporated in the margin during early Middle Miocene times (near the boundary NN 5/NN 6, 13–14 Ma).

According to the shape of the pebbles and the direction of transport, the source was emerged and eroded during Middle Miocene times and was located north of the Hengchun peninsula. However no Oligo-Miocene ophiolite complex is known in central and northern Taiwan. The only basic and/or ultrabasic rocks known in Taiwan outcrop respectively in the western and eastern side of the Central Range. The first group of rocks corresponds to alkaline pillow-lava flows interbedded in Middle Miocene clastics of the Chinese margin (Ho, 1982). It represents intra-continental volcanism on the passive margin. The second group corresponds to the metaophiolites of the Yuli belt (Liou, 1981; Lan and Liou, 1981); however, they are considered to be of pre-Tertiary age and unconformably covered by an Eocene sequence (Ho, 1975, 1982).

So it appears that these rocks cannot be the source for the ophiolitic debris found in the Middle Miocene sediments of the Hengchun peninsula and the Pliocene Lichi mélange. It seems therefore that the source has disappeared by erosion and/or burial in connection with the collision.

DEFORMATIONS

Three phases of deformation have been recognized on the Hengchun peninsula: a Middle to Late Miocene deformation by gravity tectonics, a main folding phase of Latest Miocene age, and a Subrecent to Recent One. For detailed descriptions see Pelletier (1985).

(1) The entire Ssuchung Chi series has been affected by gravity tectonics oriented towards the south. It is characterized by: (a) folding with E–W axes of an already lithified sedimentary sequence. Some of them are isoclinal without schistosity; thus, changes can be observed within a few meters from normal to overturned sequences. The best example is exposed in the Ssuchung Chi river (see also photo d, plate III of Page and Lan, 1983); (b) reversed sequences are intercalated for several hundred meters in normal series. These deformations are clearly linked originally to listric faults (several tens of meters long) which were turned to vertical during the following main folding phase. On the map, these faults delineate imbricated structures (Fig. 3). The now vertical Ssuchung Chi series enables a N–S section to be reconstructed before the main folding. These large slidings can be related either to landslides, destabilization of the margin or to a northern uplift. In fact, seismic profiles perpendicular to the Chinese margin, several hundred kilometers southwest of the Hengchung peninsula (therefore far away from the collision zone) show these phenomena (Damuth, 1980). The slidings might be the result of both phenomena i.e. the sudden arrival of Late Miocene sandmasses and the northern uplift due to the onset of the collision in North Taiwan. This tectonic event is also suggested by the nature of the uppermost sequence of the Ssuchung Chi series which seems to indicate a reactivation of the ophiolitic source or a reworking of Middle Miocene deposits. These synsedimentary gravity deformations are especially frequent in the zone of lateral facies change in sequence 3 of the Ssuchung Chi series.

(2) The *main folding phase* has created a N–S to N 20 trending anticlinorium overturned westward (Fig. 4). The front of schistosity appears in the center of the anticlinorium, in the northern part of the area being studied. Along a section going to the core of the anticlinorium, the schistosity first appears only in the overturned flanks of the folds and then, becoming stronger, affects overturned as well as normal flanks of the folds. Some isoclinal folds have also been observed.

During this phase, the Ssuchung Chi series was overthrust toward the west, causing the formation of the Kenting mélange at its front. The contact between the Ssuchung Chi series and the mélange is sometimes difficult to recognize. However, it is clear north of Hengchun, and a tectonic origin is proposed based on the following arguments. On the map, the contact cuts the series: in the north, the sediments at the contact are of Late Miocene age (NN 10–11), southward and west of Santai Shan they are of Middle Miocene age (NN 8). The best section and landscape (NE of Hengchun town) show the strongly sheared mélange west and south of the Ssuchung Chi series. The mélange outcrops only at the base of the mountains which correspond to an overturned flank dipping eastward. Although the contact is not visible due to bad outcrop and vegetation, the geometrical relationship implies a thrust fault dipping gently towards the east (Pelletier and Hu, 1984). In the south, in the Kenting area, the contact is not so easy to trace. It seems that this area consists of huge slices of the Ssuchung Chi series separated from each other by strongly deformed levels.

The Kenting mélange is interpreted as a tecto-sedimentary mélange created at the front of an overthrust during the main folding phase. It results from sedimentary as well as tectonic phenomena. The material came from the Ssuchung Chi series. It was sheared and deformed by the advance of the nappe. The age of the mélange and the tectonics predate the Middle Pliocene (NN 15) Maanshan Formation. The most recent fossils found in the mélange are of Late Miocene age (NN 11). Thus, we propose that the setting of the mélange occurred at the Mio-Pliocene boundary (about 5 Ma ago). However, a slightly earlier genesis within the Late Miocene is possible since zone NN 11 represents an interval of almost 4 Ma.

We explain this main tectonic event by the Luzon arc–Asian margin collision. It is the beginning of the collision which tectonized the turbiditic sequences deposited at the foot of the margin. Due to the oblique convergence between the arc and the margin (Seno, 1977; Suppe, 1981), the collision probably started earlier in northern Taiwan, that is to say during the Late Miocene (6–7 Ma ?). This early tectonics is also suggested by sedimentological evidence (sequence 4) and the gravity tectonics.

Today, the overthrust in the south of the Hengchun peninsula (Fig. 3) is inactive because the deformation front is migrating westward in connection with the growth of the structure and the development of the collision. One of the active fronts is located west of the peninsula and joins the Pintung valley to the north. It corresponds to the overthrust of the Central Range upon the foothills area (Figs. 1 and 2).

The *Subrecent to Recent phase* is characterized by broad folds with N160 axes and faults oblique to older structures (Fig. 3). It comprises several phases: deformation of the Maanshan Formation, unconformity of the Hengchun reefal limestones and their folding. The limestones are faulted: reverse faults at the anticline–syncline boundary (Hengchun fault) and normal faults.

The Hengchun peninsula emerged during the Quaternary. The uplift is a consequence of collision. The Hengchun peninsula is still rising as is shown by several young terraces (1000–8000 yrs, Taira 1975). The rate of uplift is estimated at 5 mm/yr for the last 9000 years (Peng et al., 1977).

EVOLUTIONARY MODEL

The Hengchun peninsula at the southern extremity of Taiwan belongs to the youngest part of the collision zone. It is the closest part to latitude 21°30′N (50 km) where the transition between active subduction and active collision is situated. The thick Miocene turbiditic series forming the backbone of the peninsula was deposited at the base of the Chinese passive margin. The folding and westward thrusting of this sequence were essentially pre-Early Pliocene in age (pre-Maanshan Formation) and more precisely of Latest Miocene age according to the dating of the Kenting mélange.

The Recent tectonics, responsible for the uplift of the peninsula, created gentle folds and oblique faults of 20° to 40° on the older structural trend.

Our observations demonstrate that the deformation at the foot of the Chinese passive margin in the area of the Hengchun peninsula started at least 5 Ma ago, which makes the beginning of the collision older than that proposed by Suppe (1981). This means that if the obliquity of the interaction between the Luzon arc and the Chinese margin is taken into account (Suppe, 1981), the collision could have started even earlier in the northern part of Taiwan, i.e. within the Upper Miocene. However, it is impossible to date precisely the onset of the collision since neither the direction nor the rate of the convergence between the Eurasian and Philippine Sea plates are known for this period. For the following reconstruction we took arbitrarily a 6–7 Ma age: however, it could be older (8–9 Ma).

But the collision is not the first major event which affected the Chinese margin. We have shown that the ophiolitic fragments present in the thick Middle Miocene ($\simeq$ 13 Ma) turbiditic sequence deposited at the base of the Chinese passive margin are part of an oceanic crust dated as Oligocene–Early Miocene (paleontological data, K–Ar dating). They are very similar to the East Taiwan Ophiolite included as large olistoliths in the Lichi mélange, as mentioned by Page and Suppe (1981) and Page and Lan (1983). According to these authors the ophiolite was incorporated in an accretionary wedge on the western edge of the Philippine Sea plate during the subduction of the South China Sea to the east. It was exposed and eroded at the beginning of the collision and provided the fragments found in the Lichi mélange.

Our investigations in the Hengchun peninsula suggest a different scenario, because the ophiolitic material has been reworked in the margin deposits since the Middle Miocene. Therefore it can be inferred that the same oceanic crust slice, obducted on the Chinese margin, provided blocks in the channels of the Hengchun peninsula during the Middle Miocene and in the Lichi mélange during the Early Pliocene. These ophiolites come without any doubt from a nearly oceanic domain. The South China Sea oceanic basin, before the disappearence of a large part of it by subduction, seems to be the best candidate.

Within the last few years, very detailed biostratigraphic and sedimentologic studies based essentially on nannoplankton have been published on the different geological provinces of Taiwan, for example: Chi et al. (1981), Page and Suppe (1981), Barrier and Muller (1984) concerning the geology of the Coastal Range; Chou (1973, 1980) for the sedimentology of the Foothills; Huang (1982) and Chang and Chi (1983) concerning respectively the Tertiary and Neogene nannoplankton stratigraphy in Taiwan. Taking into account these works and our results on the Hengchun peninsula, we propose the following evolutionary model for Taiwan from the Oligocene to the Recent (Figs. 7 and 8). The detailed nannoplankton stratigraphy allows us to define precisely the different steps of the model.

Oligocene to Early Miocene: birth of a passive margin (Figs. 7-1 and 8-1)

According to Taylor and Hayes (1983) the opening of the South China Sea occurred from 32 to 17 Ma along an E–W spreading center cut by N–S transform faults. During this period clastic sediments coming from the Asian continent are deposited on the new Chinese passive margin. The turbiditic facies drapes the foot of the margin (Hengchun peninsula).

Middle Miocene (NN 5-6: ~ 13–14 Ma): obduction (Figs. 7-2 and 8-2)

A slice of oceanic crust from the South China Sea is obducted upon the Chinese passive margin. Obduction could have taken place along a N–S transform fault. This origin has been suggested by Suppe et al. (1981) based on petrological arguments. The transform fault hypothesis also explains quite well the diversity of the ages encountered on the ophiolitic fragments. As a result of the obduction, ophiolitic pebbles and blocks suddenly appear in slumps and channels downslope in the Hengchun area. The obduction occurs exactly at the end of the South China Sea opening. Such a correlation between the end of spreading and the obduction of oceanic crust has also been demonstrated for the Oman ophiolite (Coleman, 1981).

Middle to Late Miocene (Figs. 7-3 and 8-3)

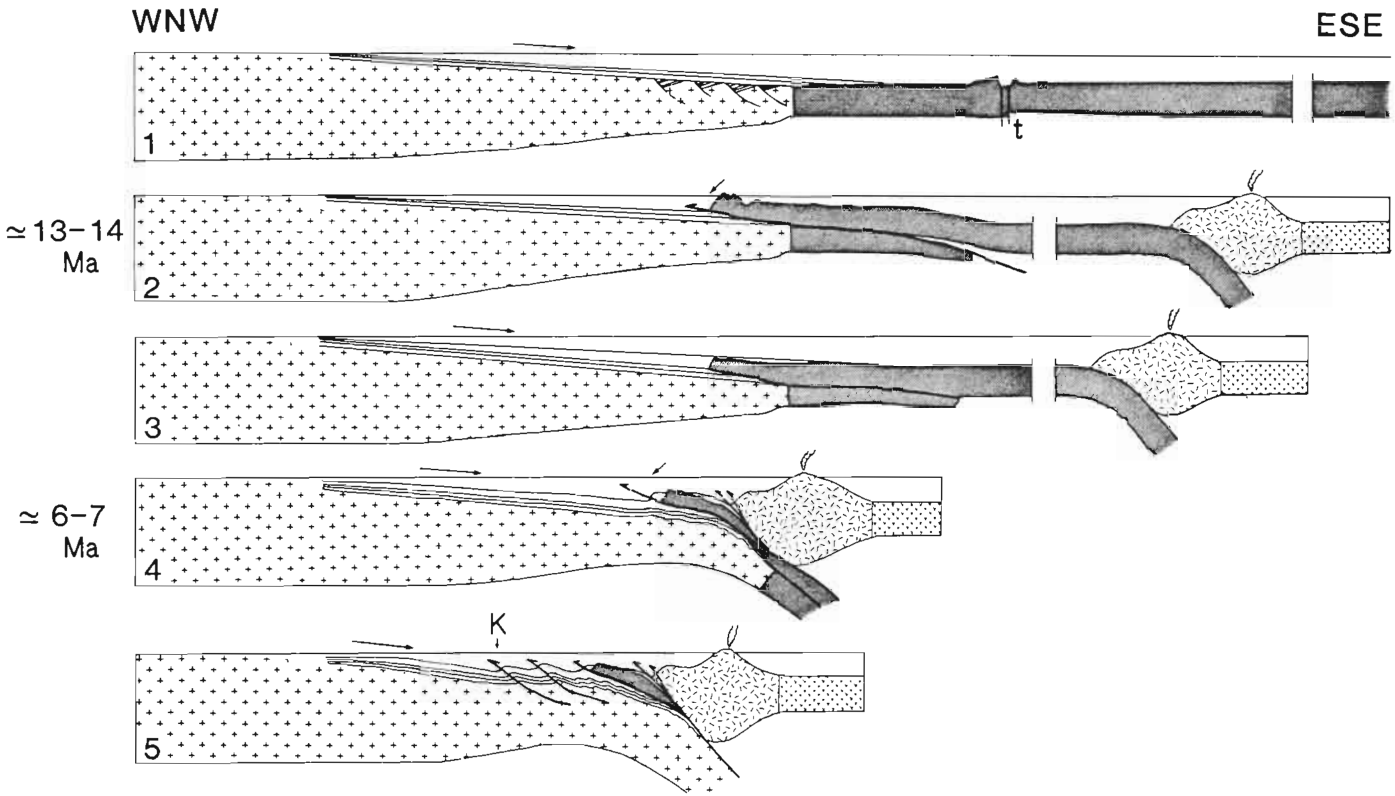
The new margin subsides due to the weight of the oceanic slide and is covered during the Middle to Late Miocene by the continuous arrival of Asian detrital sediments. At that time the South China Sea oceanic crust is being subducted along the Manila trench, allowing the arrival of the Luzon arc towards the Chinese margin.

Late Miocene (NN 11: 6–7–8 Ma?): beginning of collision in northern Taiwan (Figs. 7-4 and 8-4)

The Luzon arc enters into oblique collision with the Chinese passive margin. The ophiolites are then again exposed and eroded. The debris forms the upper part of the Ssuchung Chi series on the Hengchun peninsula.

Late Miocene (NN 11) (Fig. 7-5)

Collision becomes more intense, and a west vergent deformation affects the margin. The deformation front migrates westward, creating imbrications which may have again taken up the boundaries of tilted blocks typical of the passive margin. Uplift follows accretion, resulting in gravity slidings towards the south, as observed on the peninsula.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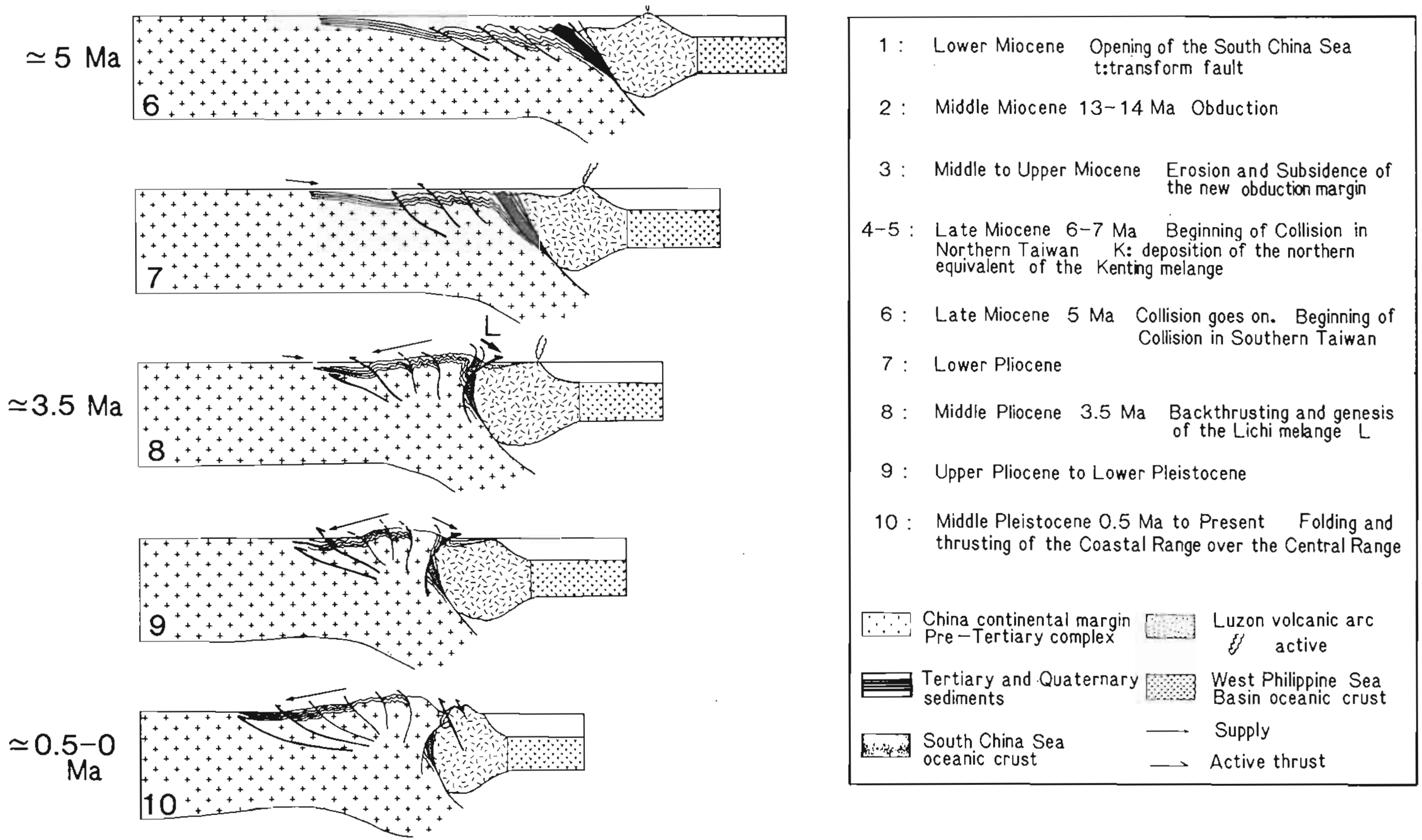

Fig. 7. Schematic cross-sections illustrating the geodynamic evolution of Taiwan (comment in the text). The crustal thicknesses in section 10 are from Tsai et al. (1977).

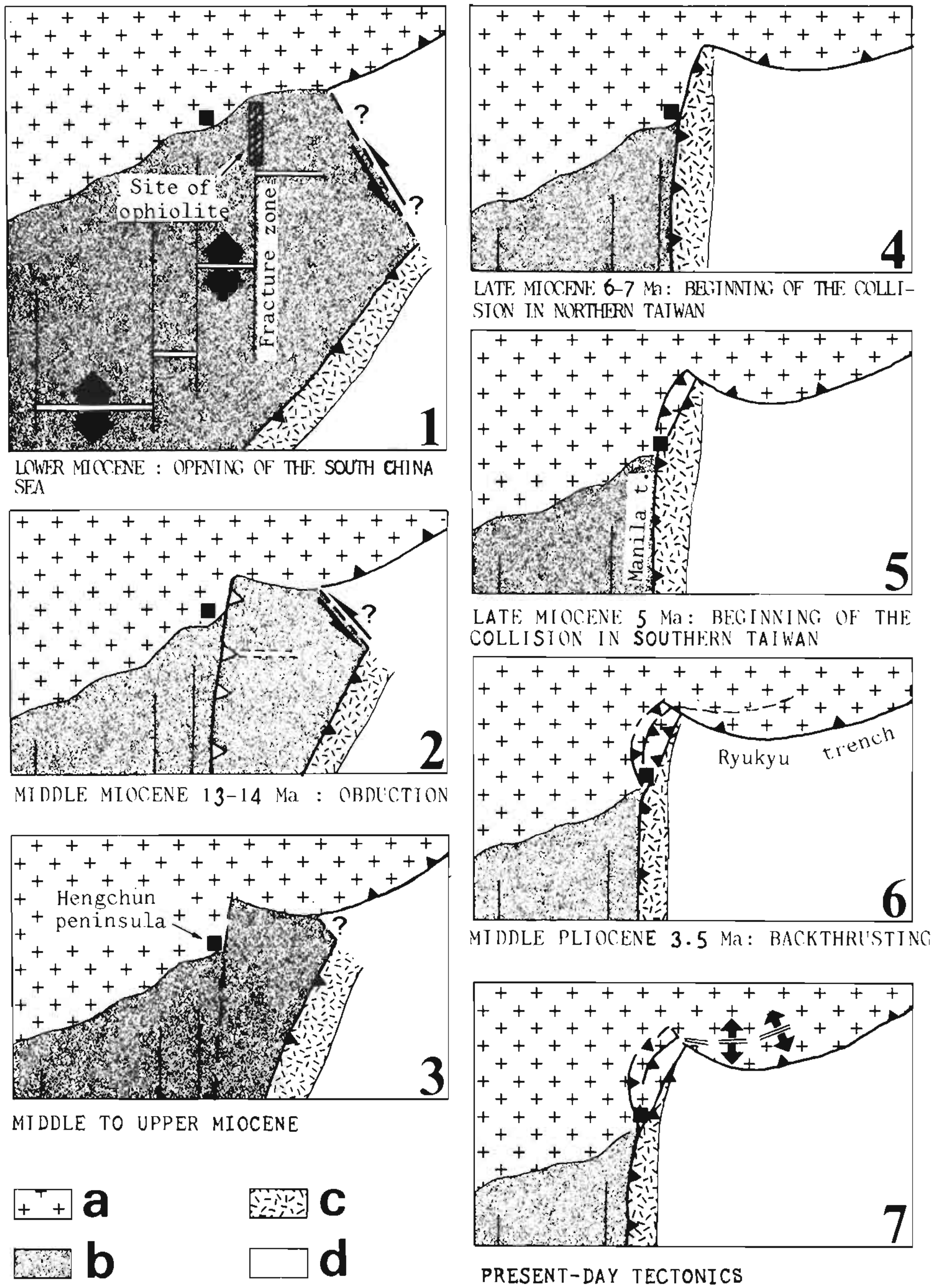

Fig. 8. Platetectonic evolution of the Taiwan Luzon area (comment in the text). *a* = Chinese margin; *b* = South China Sea oceanic crust; *c* = Luzon volcanic arc; *d* = West Philippine Sea basin.

Miocene–Pliocene boundary (~ 5 Ma): beginning of the collision in southern Taiwan (Figs. 7-6 and 8-5).

The collision area extends at the same time towards the west and south. The turbidites at the foot of the margin belonging to the present day Hengchun peninsula are folded and thrust to the west. The Kenting mélange is formed in front of the thrust as a sole of the nappe.

Early Pliocene (Fig. 7-7)

Collision and uplift continue. The thickness of the crust on the margin increases by imbrication. The Foothills basin is still supplied by the Asian continent (Chou, 1973).

Middle Pliocene (NN 15: ~ 3–5 Ma): eastward backthrusting (Figs. 7-8 and 8-6).

The proto-Central Range emerges and is backthrust eastward upon the Luzon arc. This backthrusting is argued by the eastward vergence of record generation of microfolds and slate cleavage first described by Stanley et al. (1981) along the central eastern side of the Central Range and recently by Pelletier and Hu (1986) along the southeastern part. We propose that the genesis of the Lichi mélange, previously dated as Middle Pliocene (NN 15) by Chi et al. (1981) and Barrier and Muller (1984), occurs at the front of this backthrust. Although resembling the models of Page and Suppe (1981) and Barrier and Muller (1984), our interpretation differs from theirs in the following points: the Lichi mélange does not mark the beginning of the collision and the mélange is interpreted here as a tecto-sedimentary mélange. At this time, following the data of Chou (1973) and Chang and Chi (1983), the almost emerged proto-Central Range begins to provide the external zone to the west (Foothills) with detrital material.

Late Miocene–Early Pleistocene (Fig. 7-9)

According to the sedimentologic and stratigraphic studies (Chou, 1973; Chi et al., 1981; Chang and Chi, 1983), erosion affects deeper levels of the Central Range, feeding the external zone in the west (basin in front of the collision) and in the east the basin migrating eastward on the arc (basin behind the collision).

Middle Pleistocene (~ 0.5 Ma) to Recent: formation of the Coastal Range (Figs. 7-10 and 8-7).

The basin behind the collision zone and the Miocene volcanics are folded and thrust westward over the Central Range. This deformation has been active since the Middle Pleistocene (top of NN 19 zone: Chi et al., 1981). It corresponds to the

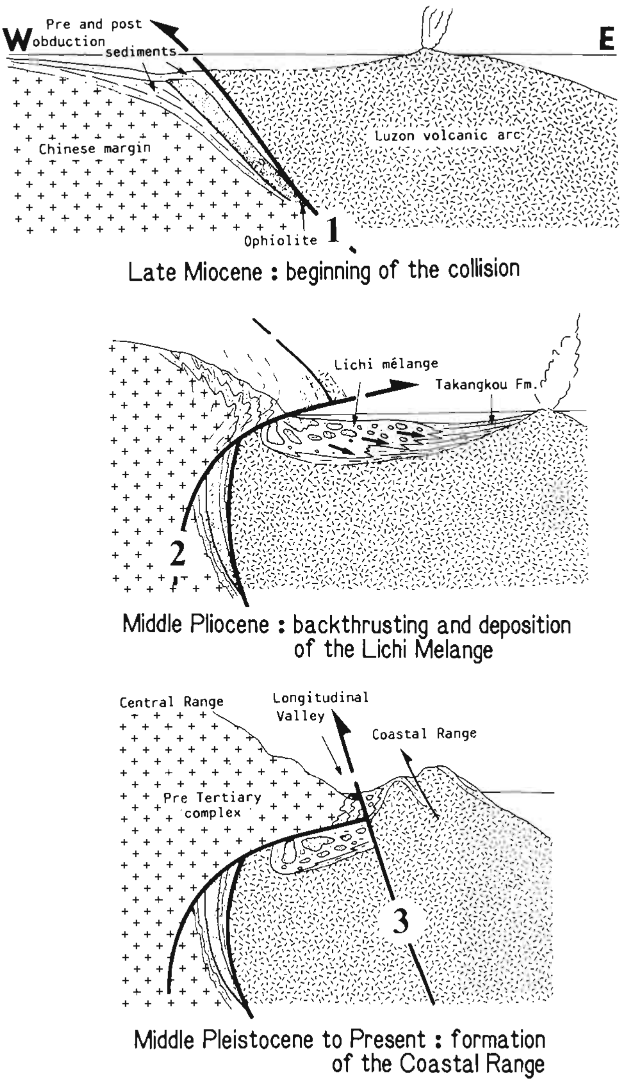

Fig. 9. Successive geometry of the suture zone between the Philippine Sea and Eurasia plates during the collision of Taiwan.

Late Miocene: Beginning of the collision between the Luzon volcanic arc (Philippine Sea plate) and the Chinese margin (Eurasia plate). The margin is constituted by a pre-Tertiary complex (in cross) and a Tertiary sedimentary cover including a slice of previously obducted Oligo-Miocene ophiolite. At the beginning of the collision the margin is folded, imbricated and thrust towards the west (see Fig. 7). Only one thrust fault (thrust 1) is drawn on the figure; it symbolizes the suture.

Middle Pliocene: The collision process is going on; the deformed margin is now backthrust towards the east over the Luzon arc (thrust 2). At the front of the thrust, blocks of various sizes and types (Miocene oceanic crust, China margin clastics and Luzon arc andesites) fall down and are incorporated in a chaotic formation which is progressively squeezed and pushed forward. This tectosedimentary complex, i.e. the Lichi mélange, slides towards the newly created eastern trough where it is finally intercalated in the Pliocene clastic sedimentation (= Takangkou Fm.).

Middle Pleistocene to Present: This cross section shows the present-day structure of the suture zone. The eastern part of the arc and its sedimentary cover are folded and thrust over the pre-Tertiary rocks of the margin along the Longitudinal Valley fault (thrust 3). Note that in this interpretation a large part of the Lichi mélange, the Luzon arc and Oligo-Miocene ophiolite are burrowed below the eastern part of the pre-Tertiary complex.

structuration of the Coastal Range. To the South, the Hengchun peninsula emerges and the collision front migrates farther to the west while the external zone is deformed.

Conclusions

Three major points in this evolutionary model can be put forward:

(1) Obduction occurs largely before the collision: the gap is about 6–8 Ma old. The two processes can be clearly separated. It can be noted that this event not only affected the Taiwan area but also the Mindoro island (Central Philippines) (Rangin et al., 1985). This Middle Miocene obduction seems to be related to the major kinematic reorganization which occurred at the end of the South China Sea opening (Stephan et al., 1986).

(2) The Taiwan mountain building shows that during the collision, the continental margin is first of all (from the Late Miocene onwards) intensively deformed and imbricated. Indeed the tectonized margin constitutes the major part of the island. The volcanic arc is deformed in a later stage (Quaternary) and occupies a very small surface (i.e. the Coastal Range). This is not the kind of pattern that one would expect in a continent–arc collision. One would imagine a large overthrusting of the arc over the margin. In fact the geodynamic scenario is quite different. The beginning of the collision (= end of the subduction) corresponds to a slight thrusting of the arc over the margin. In a second stage the arc seems to push forward the sediments and the basement of the margin which grows rapidly by succesive imbrications. Thus the crustal thickness increases allowing a mushroom-like structure to appear by eastward backthrusting of the tectonized margin above the arc domain. The backthrusting induces to the east the subsidence of the arc and the development of a new basin, migrating progressively eastward. The Lichi mélange is here interpreted as a tecto-sedimentary mélange formed at the front of this backthrusting and slid into the basin. Finally, the eastern part of the arc with its sedimentary cover is folded and thrust westward over the margin along the Longitudinal Valley Fault. This sudden reversal of the tectonic vergence could be due to density problems; the arc can no longer sink below the imbricated margin. The complex successive relationships between the margin and the arc are schematized in Fig. 9.

(3) The Taiwan mélanges reflect the major tectonic events of the collision. The Kenting mélange marks the beginning of the collision and the Lichi mélange the backthrusting of the previously deformed margin over the volcanic arc.

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