From continental margin extension to collision orogen: structural development and tectonic rotation of the Hengchun peninsula, southern Taiwan

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Abstract

As a result of oblique collision, the Taiwan orogen propagates southward. The Hengchun peninsula in the southern tip of the Taiwan Central Range, preserving the youngest, the least deformed and the most complete accretionary prism sequences, allows therefore better understanding of the tectonic evolution of Taiwan orogen. On the Hengchun peninsula, four main stages of paleostress can be recognized by the analysis of brittle tectonics. After recording the first two stages of paleostress, rocks of the Hengchun peninsula (the Hengchun block) have undergone both tilting and counterclockwise rotation of about 90°. The structural boundaries of this rotated Hengchun block are: the Kenting Mélangé zone in the southwest, the Fongkang Fault in the north, and a submarine backthrust in the east. The angle of this rotation is principally calculated by the paleomagnetic analysis data and a physical model experiment. Through a systematic back-tilting and back-rotating restoration, the original orientations of the four paleostress stages of Hengchun peninsula are recognized. They are, from the ancient to the recent, a NW–SE extension, a combination of NW–SE transtension and NE–SW transpression, a NE–SW compression, and finally a combination of NE–SW transtension and NW–SE transpression. This result can be explained by a phenomenon of stress axes permutation, instead of a complex polyphase tectonism. This stress axes permutation is caused by the horizontal compression increase accompanying the propagation of the accretionary prism. Combining the tectonic and paleomagnetic data with paleocurrent and stratigraphic data enables us to reconstruct the tectonic evolution of the Hengchun peninsula. This reconstruction corresponds to the deformation history of a continental margin basin, from its opening to its intense deformation in the accretionary prism.

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Keywords: Arc-continent collision; Hengchun peninsula; Stress axes permutation; Tectonic rotation; Taiwan

1. Introduction

Taiwan, located at the boundary between the Philippine Sea plate and the Eurasian plate, is a product of arc-continent collision (Chai, 1972; Biq, 1973; Bowin...
et al., 1978) (Fig. 1). Because this collision takes place in an oblique direction to the convergent boundary, the orogenic belt of Taiwan has been propagating southward (Suppe, 1984). This provides a good opportunity to observe the ongoing convergent process by simply moving from north to south along the Taiwan orogenic belt.

As a newly emerged accretionary prism at the southern tip of Taiwan orogen, the Hengchun peninsula exhibits the youngest, least deformed and most

Fig. 1. Tectonic framework of the Taiwan collision belt between the Eurasian continent and the Philippine Sea plate. Large black arrow shows convergence between the volcanic arc and the continent margin (Yu et al., 1997). The study area of this paper is shown as a small rectangular frame (Fig. 2). CeR = Central Range; CoR = Coastal Range; DF = deformation front; HCR = Hengchun Ridge; LV = Longitudinal Valley; NLR = North Luzon Ridge.
complete accretionary prism sequences in Taiwan (Fig. 1). This peninsula is therefore a key area to understand the orogenic evolution of Taiwan. In this paper, we take advantage of the opportunity to carry out detailed study in this emerged area. We consequently focus on the structural evolution of the accreting sediments in the Hengchun peninsula, in order to clarify the process of accretion in the growing prism.

2. Geological setting of the Hengchun peninsula

The Longitudinal Valley between the Central Range and the Coastal Range represents the most obvious onshore plate boundary between the Eurasian plate and the Philippine Sea plate (Tsai, 1986; Ho, 1986) (Fig. 1). In southern offshore of Taiwan, this Longitudinal Valley extends as the arc-prism boundary, which separates the volcanic arc domain (North Luzon Ridge) to the east and the accretionary prism domain (Hengchun Ridge) to the west. The N–S trending submarine Hengchun Ridge in the west of this boundary gradually shoals and emerges northward as the Hengchun peninsula and as the Central Range in further north.

Before engaging in the tectonic investigation, the three main tectonostratigraphic units of the Hengchun peninsula deserve specific examination (Fig. 2). They are the Middle–Late Miocene deep-marine turbidites in the central peninsula, the Plio-Pleistocene shallow-marine foreland sequences in the west, and the Kenting Mélangé at the boundary between these two major units (Fig. 2).

2.1. The Middle–Late Miocene turbidite sequences

The Middle–Late Miocene turbidite sequences (planktic foraminiferal zone N14–17; Chang, 1964) constitute the body of the Hengchun peninsula. They can be considered as a single major formation, the Mutan formation (Sung, 1991). This Mutan formation (Figs. 2 and 3) is mainly composed of alternated sandstones and shales, with numerous lenticular bodies of sandstones and conglomerates at variety of scales. The main lenticular bodies include the Shihmen Conglomerate, the Loshui Sandstone, the Lilongsan Sandstone and the Shitzutou Sandstone (Fig. 2). They represent typical deposits of submarine channels or canyons and deep-sea fans from the continental slope to the base of the slope (Pelletier and Stephan, 1986; Sung, 1991).

Sedimentological analyses of the pebble compositions and lithic fragments, showing low-grade metamorphism, also suggested that the Mutan formation could have derived from the rifted Asian continent margin to the northwest (Page and Lan, 1983). Until now, no evidence has been found to suggest that some clasts might come from the proto-Taiwan orogen. With respect to the Late Cenozoic Taiwan orogeny, it thus seems reasonable to consider the Mutan Formation of the Hengchun peninsula as pre-tectonic.

2.2. The Kenting Mélangé

The Kenting Mélangé was defined by Tsan (1974a,b). This mélangé zone generally crops out in a narrow area of low hills that bound the mountainous Miocene turbidites to the west (Fig. 2). In the Kenting Mélangé, sheared polygenic clasts of millimeter to hundred-meter size were embedded in a scaly argillaceous matrix. A typical badland topography is common in this area (Fig. 4a). The most characteristic lithological feature of the Kenting Mélangé lies in the presence of intensely sheared mudstones without distinctive stratification and the most common mesoscopic structure is the scaly foliation. The curvilinear surfaces of this penetrative scaly foliation are generally polished and bear aligned minerals and slickenlineation (Fig. 4b,c), which indicate the direction and sense of the shear deformation.

In point of structural geology, the Kenting Mélangé can be considered as a mega-sheared fault zone (about 1 km wide and 20 km long), which cuts across the Miocene Mutan Formation (Fig. 2). The geometrical distribution of the shear features in the Kenting Mélangé suggests that this zone dips to the east with an angle of about 30° or less. In order to avoid confusion, we thus propose to name the shear zone as the “Kenting Fault”. To the east, in the hanging wall of the Kenting Fault, the Mutan Formation has been thrust westward along the Kenting Mélangé and formed the principal mountain range of the Hengchun peninsula (Fig. 2). To the west, in contrast with the sinuous upper boundary of the mélangé zone, the western boundary of the Kenting Mélangé is a linear structure (Fig. 2), which is cut by the steeply east-
Fig. 2. General geological map and profiles of the Hengchun peninsula (data compiled after Tsan, 1974b; Pelletier, 1985; Sung, 1991 and this study). Locations of Figs. 3 and 4 are indicated. The strike-slip component of strike-slip motion is indicated in the cross-sections by small circles with cross and dot.
dipping Hengchun Fault (Pelletier, 1985; Sung, 1991). As the outcrops of the Hengchun Fault are generally covered by the quaternary sediments, the dip of this fault is mainly documented by a recent seismic reflection profile (Li et al., 2001). Moreover, because of the presence of both the Hengchun Fault and the Quaternary formations, the base of the mélangé zone is not yet directly observable.

2.3. The Plio-Pleistocene shallow marine strata

The Plio-Pleistocene shallow marine strata of the Hengchun peninsula include the Maanshan formation (Ishizaki, 1942) and the Hengchun Limestone (Rokkaku and Makiyama, 1934). These formations were deposited in a foreland basin located west of the Miocene turbidite terrane (the West Hengchun Hill); however, some outcrops of both these formations were also found east of the Hengchun Fault, where they apparently unconformably overlie the Kenting Mélangé (Fig. 2). These foreland sequences indicate an upward-shallowing marine environment (Huang, 1988): the Plio-Pleistocene siliciclastics in the lower part were unconformably covered by the latest Pleistocene reef-lagoonal complex and fluvial deposits at the top. Round pebbles of grabbro and meta-sandstone derived from deformed Late Miocene feeder channel conglomerates of the Mutan formation are present in the Plio-Pleistocene formation of the West Hengchun Hill (Fig. 2). Furthermore, reworked Late Miocene deep-water foraminifers were discovered in the Late Pleistocene shallow-marine reef-lagoon complex (the Hengchun Limestone in Fig. 2). All these suggest that the Plio-Pleistocene foreland sequences were deposited after the major deformation and the uplift of the accretionary prism.

3. Tectonic mechanisms of the Hengchun peninsula

Few backthrusts being left apart, most faults and folds of the Hengchun peninsula are western verging, as shown in the two profiles of Fig. 2. The N–S trending structural pattern of the peninsula suggests that most of the deformation resulted from an E–W directed compressional tectonic regime during the period of tectonic uplift. However, there are many geological evidences of polyphase tectonism, indicating that the present-day structure of the Hengchun peninsula results from a succession of tectonic events with various types and orientations of tectonic regimes. To decipher this structural evolution, we carried out an investigation involving not only struc-
nural analysis but also based on paleostress and paleomagnetic analyses as well as consideration of the present-day deformation. The consistency of the results is highlighted by a simple analogue modelling experiment.

3.1. The paleostress record

To determine the paleostress distribution and its evolution, we have analysed the brittle deformation in the Hengchun peninsula. The measured structures...
concentrate in the principal mountain range of the Hengchun peninsula, inside the Mutan Formation and the Kenting Mélange. Concerning the Plio-Pleistocene shallow marine strata, the deformation is minor so that not enough brittle structures could be found to carry out a comprehensive tectonic analysis.

We have studied more than 40 sites in detail (Fig. 5a). The measured faults are analysed by computer
Table 1
Results of paleostress determination using fault-slip data sets in the Hengchun peninsula

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Locations and distribution of paleostress trends shown in Fig. 5. Methods: Angelier (1989, 1990). All angles are in degrees. Ratio Φ defined in text. N = number of fault slips used; D = trend of axis; P = plunge of axis; ANG = average angle (degrees) between actual slip and computed shear; RUP = mean value (in %) of the function v defined by Angelier (1990) from 0% to 200%; Q = estimated quality (decreasing from A to E).

For a given fault slip data set, we calculated the average stress tensor inducing on each fault plane a shear stress as close as possible to the actual striae. We thus determined the orientations of three main stress axes (r₁, r₂, r₃), as well as the ratio of the principal stress differences, Φ=(r₂−r₃)/(r₁−r₃), which ranges from 0 to 1.

Particular attention was paid to the geometrical relation of fault-fracture systems to bedding attitudes and fold shapes. This was because the geometrical analysis allowed distinction between pre-folding, syn-folding and post-folding brittle tectonic events. By considering the attitudes of the computed principal stress axes relative to the bedding planes at sites where significant tilting has occurred (especially for stratal dips steeper than about 30°), it was possible to distinguish the faulting events that predated or post-dated folding. In post-folding faulting, one axis is usually found nearly vertical (r₁, r₂ or r₃, depending on whether normal, strike-slip or reverse faulting mode dominated). In contrast, where pre-folding faulting has occurred, this axis is not vertical, but approximately perpendicular to tilted bedding.

Based on differences in the types and orientations of the tectonic regimes, we thus distinguished four main periods of faulting in the Hengchun peninsula. To summarise, the first tectonic regime is normal in type, with a NE–SW trending σ₃; the third regime is mainly reverse in type, with a NE–SW trending σ₁; for the other two regimes (the second and fourth stages), the directions of the σ₁ and σ₃ axes are approximately NW–SE and NE–SW, respectively. A summary of the trends of σ₁ and σ₃ axes is given in Fig. 5a. The orientations of the main stress axes and the misfit estimators for each site are given in Table 1. A few examples of paleostress reconstructions for the four tectonic stages are also shown in Fig. 5b.

Note that these orientations deal with the present-day configuration; it will be shown, in a later subsection, that the original orientation was in some cases quite different, because of a later block rotation. For each stage, it is also important to consider the chronological relation to the widespread folding that affected the Hengchun peninsula. The first and second stages are pre-folding; the third and fourth stages are syn-folding and post-folding (Fig. 5). To account for this chronological relationship, a systematic back-tilting restoration was applied to the main stress axes of the two pre-folding stages.

The latest stress record in the Hengchun peninsula (the fourth stage of paleostress in Fig. 5) concentrated in and around the Kenting Mélangé zone. Because this tectonic regime may have occurred recently and still prevail, we paid particular attention to compare it with the present-day deformation.

3.2. The present-day and recent tectonic regime

With the aim at defining the present-day deformation, we simply analyse the result from two GPS mobile stations in Hengchun peninsula, using the data collected by Yu et al. (1997) from 1990 to 1995. These two stations (S021 and S041) were located on the Western Hengchun Hill and on the terrace of Oluanpi, respectively (Fig. 6a). Note that the displacement velocities of the GPS stations are relative to a reference station at the Penghu Island, on the Chinese continental shelf (location in Fig. 1).

Comparing the displacement velocity vectors of these two stations, their relative divergent velocity (Vhc in Fig. 6b) is 13.8 mm/year in the direction of 207°. Considering an average strike of N20°W for the tectonic discontinuity (the Kenting Mélangé zone
and the high angle Hengchun Fault) between these two stations, one obtains an extensional movement of 10.2 mm/year across it and a left-lateral strike-slip movement of 9.5 mm/year along it (Fig. 6c). We infer that transtension occurs approximately in the direction of $V_{hc}$, while transpression occurs in the perpendicular direction (couple arrows in Fig. 6c), which reveals the most likely tectonic regime that prevails and controls the movement of this fault zone. Interestingly, this kinematics reconstruction is consistent with the results of our independent fault slip data analysis in the Kenting Mélange (Fig. 5a, latest event). Because the directions of compression and plate convergence are similar, this tectonic regime probably reflects the oblique convergence of the volcanic arc (Fig. 1).

Before this latest, and fourth stage, NE–SW compression predominated during the third stage (Fig. 5a). However, the paleostress direction of the first and second stages (I and II in Fig. 5a) is difficult to explain in considering the present tectonic setting of Taiwan. In contrast with the stages discussed above (III and IV in Fig. 5a), these first two stages of the paleostress record are pre-folding, and may have undergone tectonic rotation. Before using our paleostress data in explaining the regional tectonic history, not only the back-tilting restoration already mentioned, but also a back-rotating restoration in the horizontal plane, are thus necessary. To be able to...
do this restoration, we carried out, a necessary paleomagnetic study in the Hengchun peninsula.

3.3. Paleomagnetic record

As a subtropical area with dense vegetation and high weathering, the Hengchun peninsula provides very poor site localities for paleomagnetic study. Despite this obstruction, a total of four sites (Fig. 8) were sampled in the Mutan Formation. In this study, rock samples for paleomagnetic study were principally collected from argillite, of which the major magnetic carrier is magnetite. Standard paleomagnetic orientation techniques were employed to orientate the cores. From analysing the pilot samples, the thermal demagnetization method was calibrated and then employed for analysing the characteristic directions of the samples. After each demagnetization step, the bulk susceptibilities of each specimen were measured, in order to prevent overdemagnetization of the samples that might result from changes in magnetic minerals during the thermal processes. Stable components of the natural remanent magnetization (NRM) in our specimens were determined by applying the linear regression method on directions of several final demagnetization steps. The analysed results were projected on the stereonet and are shown in Fig. 8 and Table 2.

The sites mean directions show that result after tilting correction is better than that before tilting correction (Fig. 8 and Table 2). This indicates that remanent magnetization was acquired before formation tilted. The present day magnetic direction in the study area is of about 355–360 and 35–40 for the declination and inclination, respectively. In our samples, the backtilted declination and inclination are distributed between 060° and 150° and from about −20 to −40, except for some samples in site HT3 (Fig. 8 and Table 2). To investigate the tectonic movement at the study area, the mean of reversed paleomagnetic direction of all our samples were flipped to the corresponding normal polarity direction (Fig. 8, the arrows). In the backtilted case, the corresponding normal polarity reveals a rotation of about 90° counterclockwise.

A crucial question deals with the driving mechanism of the counterclockwise rotation in Hengchun peninsula. From the geotectonic point of view, the oblique compression related to the collision of the volcanic arc is the main factor responsible for this rotation. As a result of oblique arc-continent collision, the deformation of Taiwan orogen usually accompanies both tilting and rotation, as documented in the Coastal Range (Lee et al., 1990) and the northern Taiwan belt (Lee et al., 1991). The relationships between collision and rotation have been explained through several models (e.g., Lu and Malavielle, 1994). However, most of the rotations were limited in amount (about 20–30°); a counterclockwise rota-
tion of about 90° should thus be regarded uncommon. Before applying this rotation to restore our paleostress directions, an analogue modelling experiment was therefore carried out as presented below.

3.4. Tectonic rotation: insights from analog modelling

In this section, a physical model experiment was conducted to illustrate the possible mechanism to develop a counterclockwise rotation in an oblique arc-continent collision terrane. The apparatus is similar to that used by Davis et al. (1983). A 7-cm-thick horizontal sand layer, relatively weak material, representing the sediments on the continental margin, was built on a woody plate (Fig. 9a). The dry cohesionless sand has been sieved to obtain characteristics similar to those of many sedimentary rocks through scaling laws. The colouring liquid used to define several 1.5-cm-wide parallel zones in the sand layer did not significantly modify the noncohesive nature of the...
Table 2
Paleomagnetic analysis results

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Angles are in degrees. Stereographic plots and locations are shown in Fig. 8.
Dg, Ig: declination and inclination before tilting correction.
Dc, Ic: declination and inclination after tilting correction.
$\kappa/\sigma_{55}$: precision parameter and 95% confidence interval.

sand grains after drying. A mobile PVC plate, as a relatively rigid backstop, represented the Philippine Sea plate lithosphere; it laterally pushed the sand layer at low speed (5 cm/min), in the direction of propagation of the Luzon arc with respect to the Chinese margin (Fig. 9a). In this experiment, the deformation of the coloured zone of the sand layer allowed us to reconstruct the kinematics of the surface deformation of the continental margin sediments.

The deformation within the sand layer included a combination of shortening, rotations and stretching, which locally resulted in a partitioning between thrusting, strike-slip faulting and normal faulting. We do not attempt to present an exhaustive description of the experiment for each step of the deformation, but simply focus on the main stages that account for the origin and evolution of the tectonic rotation. Four stages were used to illustrate the rotation kinematics in this oblique collision framework (stages 1, 2, 3 and 4 in Fig. 9b): the first stage represents the initial situation and the fourth stage represents the final one. Counterclockwise tectonic rotation was obvious in the middle part of the fourth stage (Fig. 9b). To compare this experimental result with the real
structures, we enlarge the final situation of experiment and compare it with a morpho-structural map of southern Taiwan (Fig. 10).

A rhombohedral block, which has been rotated in Fig. 10a, was limited by three linear structures: A lateral strike-slip (KF) in the left, another lateral...
strike-slip (FF) at the top and a back-thrust (BT) in the right. A likely tectonic analogue of the rotated rhombohedral block in the terrane of southern Taiwan is the “Hengchun block” (HCB in Fig. 10b). We can distinguish three large faults around this block, according to the regional morphology and structure: the left-lateral strike-slip Kenting Mélangé fault zone (KF) in the west, the left-lateral strike-slip Fongkang Fault (FF) in the north (Sung, 1991), and a possible back-thrust (BK) in the eastern offshore of the “Hengchun block” (Fig. 10b). This geometric correspondence between our physical model experiment and the actual Taiwan accretionary prism gives us some confidence concerning the otherwise surprising counterclockwise rotation of about 90° that affected the “Hengchun block”. In the next section, we need to take into account this tectonic rotation while restoring our paleostress data.

4. Tectonic evolution of the Hengchun peninsula

4.1. Paleostress evolution

As mentioned in Section 3.1, the first two stages of our paleostress record predate folding, and hence have probably been affected by the tectonic rotation. Considering both the paleomagnetic result and the physical model experiment, a back-rotation is compulsory to reconstruct the tectonic regimes in their original attitudes. Knowing that the rotation maybe nonuniform in the Hengchun peninsula, we consider in the first approximation a simple 90° counterclockwise rotation affecting the “Hengchun block” in our restoration. The restored paleostress directions are shown in Fig. 11a. Note that no correction was needed for the last two stages. The tectonic regimes are thus reconstructed (1) a NW–SE extension, (2) combined NW–SE transtension and NE–SW transpression, (3) a NE–SW compression, and (4) combined NE–SW transtension and NW–SE transpression. To account for the changes between these four stages of paleostress, especially the first three stages, we involve a phenomenon of permutations of paleostress axes, as shown in Fig. 11b.

While reconstructing paleostresses from fault slip data, one often identifies several stress tensors recorded in a single site. Some tensors correspond to distinct tectonic movements; they may reflect either polyphase tectonism, or changes within a single event (e.g., block rotation). Other tensors, which have common symmetry axes, may result from linked...
mechanisms, which often occurred almost contemporaneously. Such changes in time and space are described as permutations of stress axes (Angelier et al., 1985; Letouzey, 1986; Hippolyte et al., 1992). In common cases, the intermediate principal stress $\sigma_2$ is replaced either by the maximum compressional stress $\sigma_1$, or by the minimum stress $\sigma_3$ (permutations $\sigma_1/\sigma_2$ and $\sigma_2/\sigma_3$, respectively). The tectonic evolution of the Hengchun peninsula can be described and interpreted in such terms. During the first stage, normal faults accommodated synsedimentary NW–SE extension during the Mid–Late Miocene time (Lin and Watts, in press), with nearly vertical maximum compressional stress ($\sigma_1$) axis (Fig. 11b). At the Late Miocene time, continued subduction along the Manila subduction system guided the Eurasian continental margin closer to the Luzon arc and resulted in a tectonic compression in a direction close to that of the accretionary prism propagation. During this second stage, the sediments on the continental margin underwent the NE–SW compression from the accretionary prism but were not strongly deformed; strike-slip faults corresponding to this compression were therefore mainly recorded in this area. Accordingly, the intermediate principal stress $\sigma_2$ recorded in the sediments at this stage, which corresponds to a permutations $\sigma_1/\sigma_2$ (Fig. 11b).
The third stage approximately prevailed during the Pliocene time. As a result of the continuing propagation of the Taiwan accretionary prism, the sediments of the Hengchun peninsula on the continental margin were incorporated into the accretionary prism and affected by thrust faults. The NE–SW compression deeply affected the structure of this area, the intermediate principal stress $\sigma_2$ being replaced by the minimum stress $\sigma_3$ once again (permutation $\sigma_2/\sigma_3$), which resulted in a prevailing reverse-type tectonic regime (Fig. 11b). From the Pleistocene time to the Present, as a result of the increasing collision propagating southward, the Hengchun peninsula was deformed by a tectonic regime dominated by a NW–SE transpression and a NE–SW transtension. These regimes are caused by the compression from the northwestward-converging neighbouring Luzon volcanic (Fig. 11b). We consider that the change of the main stress axes between the third and the fourth stages reflects a phenomenon of structural partitioning at the regional scale, rather than a simple permutation of stress axes as had occurred before.

From the first stage to the third stage, the horizontal minimum and maximum stresses kept very similar directions (Fig. 11b). This suggests that at the plate boundary scale the tectonic regime of the southern Taiwan was rather stable before the arc-continental collision. In contrast, many variations in states of stress were related to stress permutations at the more local scale. It is important to note first that an extensional regime has been replaced by a compressional one, and second that this evolution occurred through a succession of stress permutations, which reveals an evolution in boundary conditions as convergence was continuing, rather than drastic geodynamic changes.

4.2. Paleocurrent distribution

In the eastern part of the Hengchun peninsula, the Loshui Sandstone is a member of thick fine to medium grained sandstone, which has a lithic composition similar to that of the Mutan formation (Fig. 2). However, Cheng et al. (1984) and Sung and Wang (1986) have documented a paleocurrent from south to north, based on more than 1000 paleocurrent measurements at nearly 100 localities in the Loshui Sandstone (Fig. 12a). This orientation is unusual, not only for the Hengchun peninsula but also for the whole of southern Taiwan, because in other sedimentary units paleocurrent data generally indicate transport from north to south (Byrne, 1998).

To explain the paleocurrent transport from south to north in the Loshui Sandstone, the presence of a morphological high such as an emerged subduction wedge or a separated micro-continent southeast of the depositional area of the Loshui Sandstone has been proposed (Cheng et al., 1984; Sung and Wang, 1986; Byrne, 1998). However, such an interpretation raises difficulties. First, the Loshui Sandstone was deposited during the Miocene time, when the accretionary prism was still far away from the depositional area of the Loshui Sandstone. Second, there is no any evidence for the existence of a micro-continent.

Based on the studies of facies associations and paleocurrent distribution, the sandstone deposits of the Hengchun peninsula belonged to two major submarine fan systems, the Mutan fan to the north and the Loshui fan to the south (Cheng et al., 1984; Sung and Wang, 1986). As shown in Fig. 12b, assuming the source area of these two fans is unique and combining all the paleocurrent data, the only remaining possible source area is at the southwest of the Hengchun peninsula, because almost no datum has indicated paleocurrent towards the southwest. Note that the formations of Hengchun peninsula are composed of terrigenous deposits, originating from the continental margin, which was located northwest of the Hengchun peninsula during the Miocene time. This distribution is quite compatible with the rotation of about 90° counterclockwise mentioned before, because the restored paleocurrent direction that corresponds to the NE-directed one is SE-directed.

In Fig. 12c, the “present-day position” shows the rose diagrams of the measured paleocurrent directions and some important structures of the present Hengchun peninsula. Considering the tectonic rotation, the original position of the paleocurrent distribution and the paleomorphology of the Hengchun peninsula region are reconstructed (Fig. 12c, “original position”). In the restored original position, a uniform 90° clockwise rotation has been used; the directions of paleocurrent of the Mutan and Loshui fans are parallel but opposite in sense; furthermore, they coincide with the bathymetric contours. Such a margin-parallel distribution is common for submarine fans in the continental slope of a passive margin, like the “contour currents” (Sheridan,
Fig. 12. (a) Paleocurrents (thin arrows) measured in the Miocene turbidites of the Hengchun peninsula (data compiled after Cheng et al., 1984; Sung, 1991). (b) Rose diagram of paleocurrents in the Mutan Formation and the Loshui Sandstone. PSA = possible source area. (c) Reconstruction of the paleocurrent distribution recorded in the Hengchun peninsula domain, before and after the tectonic rotation. SLT = Southern Longitudinal Trough. More explanation in text.
1981; Einsele, 1992). During the deformation process related to collision, the Hengchun block underwent tectonic rotation, so that the directions of paleocurrents of these two fans changed and constituted the present-day, apparently unusual pattern (Fig. 12a–c).

5. Discussion

The data presented herein concerning the tectonic evolution of the Hengchun peninsula suggest a new perspective for the deformation of an accretionary prism when oblique arc-continent collision occurs. Combining the paleostress record, the paleomagnetic record and the paleocurrent distribution in light of a physical model experiment, we discuss the structural evolution of the Hengchun peninsula region in terms of four main stages (Fig. 13).

The first stage (Fig. 13a) corresponds to the Middle Miocene time in southern Taiwan. The South China Sea oceanic crust was subducting beneath the Philippine Sea plate along the Manila trench, far away to the east from the Hengchun peninsula domain. The terrigenous sediments of this domain were supplied from the northwest by two submarine fan systems: the Mutan fan and the Loshui fan (Cheng et al., 1984; Cheng et al., 1984;...
Series of normal faults were produced by a synsedimentary NW–SE extension at this stage (the first stage of paleostress record, see also Sections 3.1 and 4.1). Note that the slope-perpendicular orientation of this extension (Fig. 13a) is quite consistent with the expected tectonic behaviour of the passive continental margin.

The second stage (Fig. 13b) corresponds to the Late Miocene time in southern Taiwan. The accretionary prism was gradually approaching the Hengchun peninsula domain where the sedimentary processes were continuing. The sediments began to be submitted to compression but were not yet strongly deformed. As a result of the increasing lateral confining pressure along the edge of the accretionary prism, the sediments of the Hengchun peninsula domain underwent a combination of NW–SE transtension and NE–SW transpression (second stage of paleostress record in this study), replacing the previous NW–SE extension.

The third stage (Fig. 13c) corresponds to the Plio-Pleistocene time in southern Taiwan. The Miocene sediments of the Hengchun peninsula were incorporated into the accretionary prism by large thrust faults. The NE–SW compression prevailed as a mainly reverse-type tectonic regime (third stage of paleostress record in this study). Because of the oblique geometry of the propagation convergence, the continuing compression between the volcanic arc and the continental margin had rotated the Miocene formations of the Hengchun peninsula of about 90° counterclockwise. Not only did this rotation affect the paleocurrent record (see Section 4.2), but also the paleostress record was deeply modified. In the present-day pattern, the apparent occurrence of NW–SE and NE–SW compression (second and third stages in Figs. 5 and 11) thus simply results from the rotation of about 90° occurring during a single NE–SW compression (see also Sections 3.1 and 4.1). Following the tectonic growth and uplift of the accretionary prism, a shallow-marine reef-lagoon complex (the Hengchun Limestone in Fig. 2) began to develop in the western and southern Hengchun peninsula. Because this reef-lagoon complex postdated the large compressional deformation of the third stage (folding and rotating), the brittle structure is not dominant.

During the fourth stage (Fig. 13d), the Hengchun peninsula was emerged and underwent erosion. The front of the Manila subduction system had jumped to the southwestern offshore of the Hengchun peninsula. As a consequence, the Hengchun peninsula was now submitted to the typical tectonic regime of the Taiwan mountain belt, that is, a combination of NW–SE transpression and NE–SW transtension (fourth stage of paleostress record in this study). This tectonic regime is also consistent with GPS data (Yu et al., 1997), focal mechanism data (Yeh et al., 1991), and other fault slip data analysis results (e.g., Barrier and Angelier, 1986) in southern Taiwan.

In our tectonic model, a crucial problem is the significance of the tectonic rotation of Hengchun block within the frame of Taiwan orogen. Should it be regarded as a particular case or does it represent a systematic structural behaviour? This is important to consider because in the latter case the same mechanism might have repeated by affected various areas within the northern mountain range, and would also occur in the future as collision will propagate to the southwest. On the other hand, the present distribution of directional geological data in the area north of the Fongkang Fault (that is, both the earlier paleostress and the paleocurrent records) seem consistent with reasonable views about a continental margin sedimentary formation (Chang, 2001), which suggests that rotation is limited, if any.

Because the Taiwan orogen propagated southward, the area north of the Fongkang Fault certainly emerged before the Hengchun peninsula domain, and hence underwent erosion for a longer time. The erosion rate of the Taiwan orogen is rapid enough (>5 mm/year, e.g., Li, 1976) to have removed thousands meters of sediments in this area. As shown in Fig. 2, the thickness of the Hengchun block depends on the depth of the Kenting Mélange zone, the major tectonic décollement that probably separates the upper rotated Hengchun block and the lower stable basement. If the Hengchun peninsula behaviour represents a general case of rotating block in the Taiwan accretionary prism, the thickness of such blocks maybe limited to very shallow crust levels, e.g., less than several thousand meters. The absence of tectonic rotation in the northern part of the Fongkang Fault may thus be attributed to the high erosion rate, and not only to an absence of rotation. Note also that many strike-slip faults have been found from marine studies offshore southwestern Taiwan (Reed et al., 1992; Fuh et al.,...
1997) (Fig. 13d). Such strike slip faults, according to our physical model experiment (Fig. 9), are expected to play a major role to accommodate the horizontal rotation. Based on these considerations, we cannot exclude that the tectonic rotation of the Hengchun block represents a general phenomenon in Taiwan oblique arc-continent collision, and may have occurred many times from north to south during the propagation of the collision along the margin.

6. Conclusion

Because of its location near the present-day transition zone between collision (to the north) and subduction (to the south), the Hengchun peninsula at the southern tip of the Taiwan mountain belt (Fig. 1) plays a key role for understanding the early phase deformation of the orogen. Moreover, although many previous studies revealed that the deformation of the Taiwan orogen usually involves both tilting and rotation (Lee et al., 1990, 1991; Lu and Malavieille, 1994), the existence of tectonic rotations remains problematic in the Central Range of Taiwan, where large uplift and erosion have occurred. The Hengchun peninsula shows the youngest, least deformed and most complete accretionary prism sequences of the Taiwan orogen, thus providing a case study for the tectonic rotation.

In this study, we identified four stages of paleostress according to brittle tectonic analysis in the Hengchun peninsula. After combining this result with the paleomagnetic data, the physical modelling result and the paleocurrent record, we reconstruct the tectonic evolution of the Hengchun peninsula from the Middle Miocene (the extension stage) to the Present (the collision stage). In this reconstructed model, a tectonic rotation of 90° counterclockwise has been considered.

It is necessary to mention that the Hengchun block is probably not a solid uniform block. There are many faults and folds inside this area (Fig. 2). Thus, the rotation may be nonuniform, a target for future paleomagnetic studies. In fact, the scatter of paleomagnetic orientation (Fig. 8) already suggests such a heterogeneous rotation. It is nevertheless interesting to observe that even the simple rotation hypothesis suffices to satisfactorily account for the original directions of paleocurrents and paleostresses within a reasonable geodynamic frame.

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References


