Accepted Manuscript

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PII: S1342-937X(15)00288-9
DOI: doi: 10.1016/j.gr.2015.11.010
Reference: GR 1555

To appear in: *Gondwana Research*

Received date: 15 June 2015
Revised date: 18 October 2015
Accepted date: 15 November 2015

From convergent plate margin to arc-continent collision: formation of the Kenting Mélange, southern Taiwan

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Abstract

The Kenting Mélange on the Hengchun Peninsula, Taiwan, formed through tectonic shearing of subduction complex lithologies, probably within the plate boundary subduction channel between the Eurasian and Philippine Sea plates, with further deformation and exhumation in the Pliocene-Pleistocene during arc-continent collision. Field relations reveal a structural gradation from normal stratified turbidite sequence (Mutan Formation) through broken formation to highly sheared Kenting Mélange containing allochthonous polygenic blocks. This gradation is consistent with an increase of average vitrinite reflection values from ~0.72% in the Mutan Formation through ~0.93% in the broken formation to ~0.99% in the mélange, suggesting temperatures of at least 140 ºC during formation of the Kenting Mélange. Zircons from gabbro in the Kenting Mélange are dated as 25.46 ± 0.18 Ma, which together with geochemical data constrains the source to South China Sea oceanic lithosphere. In combination with the field relationships, vitrinite reflectance values, microfossil stratigraphy and offshore geophysical data from S and SE Taiwan, we propose that the Kenting Mélange initially formed at the subduction plate boundary from offscraped trench deposits. Minor Plio-Pleistocene microfossils (<5%) occur within the mélange in proximity to slope basin of equivalent age and were likely sheared into the mélange during out-of-sequence thrusting associated with active arc-continent collision, which in the Hengchun Peninsula commenced after 6.5 Ma.

Key worlds: Accretionary complex; Kenting Mélange; vitrinite reflectance; SHRIMP U-Pb dating; Splay fault

1. Introduction

Mélanges are mappable, sheared bodies of rocks that lack internal continuity of units and contain a chaotic mixture of locally-derived and exotic blocks of variable size (mm to km), typically forming a block-in-matrix texture (Silver and Beutner, 1980; Raymond, 1984; Cowan, 1985; Festa et al., 2010). Mélanges occur in a variety of tectonic settings including transform boundaries, rifted margins and gravitationally unstable passive margins (Raymond, 1984; Festa et al., 2010), but they are commonly associated with accretionary complexes at convergent plate margins (Cawood et al., 2009; Cloos and Shreve, 1988a, b; Hamilton, 1969; Hsü, 1968, 1971; Ikesawa et al., 2005; Hara et al., 2009; Kim et al., 2011; Rao et al., 2011). In accretionary complexes, their formation is ascribed to shearing and tectonic mixing during off-scraping of material from the downgoing plate, notably within the subduction channel (Closs and Shreve, 1988a, b; Santosh et al., 2009; Santosh, 2010a, b; Kitamura and Kimura, 2012). In this paper we document field relations, vitrinite reflectance, SHRIMP U-Pb dating and micropaleontological data from the Kenting Mélange, southern Taiwan, to outline a complex record of off-scraping of the protoliths to the mélange in the subduction zone of the Manila Trench followed by further tectonic mixing during arc-continent collision between the Luzon arc and Eurasian continental margin in the last 2 Ma.

Taiwan is located at the boundary between the Eurasian Plate and the Philippine Sea Plate (Fig. 1). Extension along the eastern margin of Eurasia (Li and Rao, 1994) led to formation of the South China Sea in the Oligocene-Middle Miocene (sea floor spreading between 32-17 Ma, Taylor and Hayes, 1983; 32-16 Ma, Briais et al., 1993; 31-20.5 Ma, Barckhausen and Roeser, 2004; 37-15 Ma, Hsu et al., 2004). The cessation of spreading was followed by the initiation of subduction of the South China Sea oceanic lithosphere along the Manila Trench beneath the west-moving Philippine Sea Plate. Subduction-related off-scraping created the Central Range-Hengchun Peninsula-Hengchun Ridge accretionary complex and the Luzon arc and forearc basin (Fig. 1; Huang et al., 1992; Reed et al., 1992). In the late Miocene, at about 6.5 Ma, a transition from subduction of oceanic lithosphere to arc-continent collision commenced. The collision is oblique and is propagating southward from northern Taiwan to the Hengchun Peninsula in the south, with the latter marking the location of the Kenting Mélange (Suppe, 1984; Huang et al., 1997). Thus, southern Taiwan (Hengchun Peninsula) and its offshore extension on the Hengchun Ridge to the north of 21^{o}N are in the early stage of mountain building due to active collision, which began latter than that of the north part at about 5 Ma. South of 21^{o}N, the offshore Hengchun Ridge likely represents the 'pre-collision' conditions of the southern Chinese margin and Manila trench subduction system (Byrne and Liu, 2002;

McIntosh et al., 2013). Thus, the Hengchun Peninsula records a history of the intra-oceanic subduction prior to 5 Ma and since then it has been a site of arc-continent collision (Fig. 1).

Previous work on the Kenting Mélange has focused on petrography and biostratigraphy. Due to the presence of polygenetic blocks in a sheared scaly matrix, the age of the Kenting Mélange has been controversial with a range of ages recorded including Middle to Late Miocene (Chang 1966); Eocene (rare) to Mid-Late Miocene (most abundant) (Chi, 1982); Late Miocene (foraminiferal zone NN11) to Middle Pliocene (NN15) (Page and Lan, 1983); Oligocene-Miocene (Muller et al., 1984); Late Pliocene (NNH16) or even more recent ages (Huang et al., 1983); and Late Miocene (N14 with N17) to Early Pleistocene (N22) (Huang, 1984). This range of age data in combination with field settings has led to a number of different models for formation of the mélange, including Late Miocene sedimentary slumping (olistostrome) on a passive continental margin (Tsan, 1974; Pelletier and Stephan, 1986; Sung and Wang, 1986), or a Plio-Pleistocene or Late Miocene tectonic subduction mélange as part of the accretionary wedge to the east of the Manila Trench (Biq, 1977; Page and Lan, 1983; Lu and Hsü, 1992; Byrne, 1998). In this paper, we provide a systematic analysis of the Kenting Mélange integrating previous and new data to document an evolving tectonic setting from subduction zone to arc-continent collision.

2. Geological setting of the Hengchun Peninsula

Geology of Taiwan provides a modern example of the transition from active subduction to oblique arc-continent collision (Biq, 1971, 1972; Huang et al., 1997). It is composed of four distinct tectonic units, which from west to east are: the Coastal Plain, Western Foothills, and Hsuehshan Range (passive Asian continental margin deposits now deformed into a fold-and-thrust belt); western Central Range–Hengchun Peninsula-Hengchun Ridge (accretionary complex); eastern Central Range (underthrust Eurasian continent); and the Coastal Range (accreted Luzon Arc) (Fig. 1A). These units are separated by major faults, including the Lishan-Laonung Fault, which represents the former boundary between the Eurasian plate and the Philippine Sea plate, and maybe connect south to the Kenting Fault (Huang et al., 1997). In comparison, the Longitudinal Valley (Fig. 1A), situated between the Central Range and the Coastal Range, marks a newly developed suture after the collision. Four geodynamic processes, starting from intra-oceanic subduction before latest Miocene, through to initial arc-continent collision, advanced arc-continent collision, and to the final arc collapse/subduction in the last 2 Ma, have been sequentially operating southward from 24°30′N - 19°N (Fig. 1A; Huang et al., 2000).

The Hengchun Peninsula in southernmost Taiwan marks the most recent exposed portion of the accretionary complex. It is composed primarily of Middle-Late Miocene turbidite sequences (Mutan Formation), shallow-marine Plio-Pleistocene slope basin strata (Maanshan Formation) and the Late Miocene Kenting Mélange (Fig. 1B). The turbidite sequences represent Asian passive continental margin sediments that were primarily derived from the Cathaysia Block (Zhang et al., 2014). These sediments were scraped off and accreted into the accretionary complex (the Central Range-Hengchun Peninsula-Hengchun Ridge) during the subduction of the South China Sea oceanic lithosphere. The Plio-Pleistocene shallow-marine strata (Maanshan Formation) are interpreted to have been deposited in slope basins unconformably on the deformed Miocene flysch sequences during arc-continent collision (Fig. 1B-C) (Huang et al., 1997). Detritus within these shallow-marine slope basin sedimentary rocks are derived from the exposed accretionary complex to the north (Huang et al., 2006). Planktonic foraminiferal assemblages recovered from the basal part of the slope basin (Maanshan Formation at West Hengchun Hill) suggest an age of 4.3-3.6 Ma (Early Pliocene; Cheng and Huang, 1975; Huang et al., 2006). The Kenting Mélange is a highly sheared chaotic unit containing disrupted Miocene turbidite layers and fragments of allochthonous volcanic rocks inferred to have been derived from South China Sea oceanic lithosphere (Page and Lan, 1983). It was named the "Kenting Formation" by Tsan (1974) and renamed the Kenting Mélange by Biq (1977). The geographic extent of the Kenting Mélange was greater in some previous studies as parts of the Mutan Formation were included because the channel conglomerates within the unit were interpreted as exotic blocks (Tsan, 1974; Page and Lan, 1983). Similarly deposits at Cingwashih, which contain igneous blocks and sediments derived from sedimentary reworking of Kenting Mélange (Fig. 1B; Page and Lan, 1983; Pelletier and Stephan, 1986), are now excluded from it. The Kenting

Mélange is well exposed in the Paoli and Dongmen rivers (Figs. 1B, 2) and is similar in appearance to the Lichi Mélange in the southwestern Coastal Range (forearc basin and volcanic arc; Fig.1A).

3. Lithological and structural characteristics of the Kenting Mélange

The overall structural trend of the Kenting Mélange is NW-SE, parallel to the northern axis of the Manila trench and the adjoining Gaoping Slope (Fig. 1). It is currently being thrust westward over Plio-Pleistocene shallow-marine slope basin strata (Maanshan Formation, Figs. 1B-C). Detailed mapping of the mélange along the Paoli and Dongmen river sections has led to the recognition of three lithotectonic associations (Figs. 1B, 2): coherent bedded sedimentary units such as the Mutan Formation; a broken formation of sheared sedimentary rocks that lack any igneous blocks; and mélange consisting of sheared turbidities without discernible stratification and containing exotic igneous blocks (Figs. 3, 4). Boundaries between units are marked by zones of shearing (Fig. 4A).

The coherent sedimentary units consist of well-bedded shale and turbiditic sandstones, the latter up to 0.5 m thick. These include the Mutan Formation (Fig. 2B) as well as sedimentary blocks engulfed in sheared broken formation and mélange (Fig. 2A) and interpreted to represent the protolith of the sheared units.

Outcrops of broken formation and mélange display a pervasively sheared scaly matrix (Fig. 4B). White to cream colored dickite occurs in veins or thin patches through the matrix (Fig. 3A). In the Kenting Mélange, sheared polygenic clasts ranging from millimeter to hundred-meter size of mudstone, siltstone, sandstone, conglomerate (all part of the autochthonous Miocene turbidite sequences) and pillow lavas, volcanic breccia, diabase, gabbro and chrome spinel-bearing serpentinized peridotite (allochthonous blocks) occur within a scaly argillaceous matrix (Figs. 3B-F, 4C-H), while the broken formation does not contain blocks of oceanic material. Some sedimentary blocks retain original bedding (Fig. 3F). Sandstone in interbedded shale-sandstone blocks is often boudinaged and filled by calcite veins (Figs. 4F, G). The sandstone and siltstone blocks contain step fractures that extend from the surface for up to several centimeters into their interior of the blocks (Fig. 4D). Similar tensional features have been interpreted to form during flow in a subduction channel (Harris, et al., 1998; Fukui and Kano, 2007). Basalt and andesite within the mélange often display multiple generations of cross-cutting calcite or quartz veins, which cut through the rock-forming minerals, such as plagioclase and pyroxene, suggesting late tectonic reworking (Fig. 5). In addition, some basalt blocks are intruded by mudstone (Fig. 4C) and show a web structure (Fig. 4H), which could have formed in a high pressure environment (Kitamura et al., 2005; Kitamura and Kimura, 2012) and together with the evidence for hydrofracture (Fig. 4D), show that the Kenting Mé lange is most likely tectonic in origin and formed in deep within a subduction system.

4. Analytical methods

Twenty-four mudstone samples, including coherent sedimentary units of the Mutan and Maanshan formations, broken formation, and mélange were collected for vitrinite reflectance analysis. Six samples of the Lichi Mélange were analyzed for comparison. Kerogen for the reflectance measurements was extracted from 200 grams of sample. Random vitrinite measurements (Ro expressed in %) were made following the procedures of the International Commission of Coal Petrology (ICCP, 1998) on polished sections of concentrates of kerogen using an "Axio Scope. A 1" A Pol and MSP 400.

Tmax (ºC) for the analyzed samples were calculated by equations of T (ºC) = 158 + (90 [ln percentage Ro]) (heating time is 10 Ma), T (ºC) = 174 + (93[ln percentage Ro]) (heating time is 1 Ma) (Sweeney and Burnham, 1990) and T (ºC) = 148 + (104[ln percentage Ro]) (time-independent equation) (Barker, 1988), respectively. The heating time is defined as the period between the maximum temperature and a temperature of 15 ºC lower than the maximum temperature (Sekiguchi and Hirai, 1980); this time is typically between 1 Ma to 10 Ma at active margins (Laughland and Underwood, 1993; Ohmori et al., 1997). The error associated with these equations is ± 30 ºC in temperature.

Zircons obtained from a large gabbro block in the Kenting Mélange at Cingwashih (KT9; GPS: N21°56´16´´, E120°48´00´´) (Fig. 1B) were extracted through standard techniques for mineral separation, mounted in epoxy resin and polished to remove the upper one third of the grain. Cathodoluminescence (CL) images were obtained using a CAMECA electron microprobe operating at 15 kV at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS) in Beijing, in order to identify internal structures and choose potential target sites for U-Pb analyses. U-Pb dating of zircons was performed using a CAMECA IMS-1280 ion microprobe (CASIMS) at IGGCAS, following the analytical procedures described in Li et al. (2009). $^{207}Pb/^{206}Pb$, $^{206}Pb/^{238}U$, $^{207}U/^{235}U$ ($^{235}U=^{238}U/137.88$), $^{208}Pb/^{232}Th$ ratios were corrected by using 91500 as external standard (Wiedenbeck et al., 1995). Analyses of standards were interspersed with those of unknown grains. The reported weighted mean U-Pb ages and concordia plots were processed using ISOPLOT (Ludwig, 2001).

5. Results

All Ro values obtained in this study are listed in Supplementary Material 1, and range from 0.56% (average value) in the Lichi Mélange in the Coastal Range of eastern Taiwan to 0.99% (average value) in the Kenting Mélange in the Hengchun Peninsula accretionary complex (Figs. 1, 2, 6). In the Kenting area, vitrinite values correspond with degree of stratal fragmentation and increase from average values of ~0.72% in the coherent strata of the shallow marine slope basin Maanshan Formation and the accretionary complex Mutan Formation through ~0.93% in broken formation to ~0.99% in mélange.

The concordia plots and the weighted age of zircons from the gabbro are shown in Figure 8. Most of the zircons show oscillatory zoning under CL, typical of a magmatic origin (Wu et al., 2010). The analyzed sample (KT9) yielded a U-Pb age of 25.46 ± 0.18 Ma (Fig. 8; Supplementary Material 2), which together with detailed geochemical data that the mafic rocks in the Kenting Mélange are low in both P_2O_5 (less than 0.2 wt. %) and TiO_2 (less than 1.2 wt. %), typical of mid-ocean ridge basalt and in contrast with the higher values of oceanic island tholeiites and alkaline basalt. The content of major elements and particularly of the trace elements such as Cr, Ni and V indicate the igneous pebbles in the Kenting Mélange are also of oceanic crust affinity (Page and Lan, 1983; Pelletier, 1985; Pelletier and Stephan, 1986). Thus the geochemical data indicate that the igneous blocks were likely sourced from South China Sea oceanic lithosphere, which records sea floor spreading between 37-15 Ma.

6. Discussion

6.1 The origin of the Kenting Mélange

The following observations suggest a tectonic rather than slumped sedimentary (olistostromal) origin for the Kenting Mélange. The pervasive scaly foliation of the argillaceous matrix within the broken formation and mélange, and its location adjacent to thrusts in the Mutan Formation, suggest formation through tectonic disruption (Shibata and Hashimoto, 2005) (Fig. 4B).

Boudinage structures within the turbidite sequence ranging from pinch-and-swell of bedding through to the disruption of sandstone beds into isolated blocks with the shale matrix displaying flow away from the swells of the boudins and toward the necked or cracked parts indicates tectonic extension, as do calcite fibers aligned perpendicular to margins of the sandstone blocks. If the block-in-matrix texture was formed on superficial process such as olistostromal related slumps, then syn-deformational crack-filling veins would not be unexpected (Figs. 4F-G). These structures together with injection of mud veins into basalt blocks and web structure in basalt (Figs. 4C, 4H) are similar to features ascribed to tectonic disruption taking place at depths of up to tens of kilometers within subduction channels such as the Nankai Trench (Sakaguchi, 1999; Ikesawa et al., 2005; Matsumura et al., 2003; Kitamura and Kimura, 2012)

The overall east to west change in the character of stratal units across the Hengchun Peninsula from coherent sequence to broken formation to mélange is also consistent with a tectonic rather than a sedimentary origin through slumping. The mélange contains igneous blocks (pillow lavas, volcanic breccia, diabase and gabbro) (Page and Lan, 1983; Chu et al., 1988) yielding early Miocene U-Pb zircon and K-Ar hornblende ages (25-22 Ma; Fig. 8) (Pelletier and Bellon, 1984). Geochemical data from basalt, diabase and gabbro clasts indicate oceanic crust affinity (Pelletier, 1985). Together, the age and geochemical data constrain igneous rocks to fragments of oceanic lithosphere, which now occur in a matrix mixed with sandstone and mudstone most likely via offscraping from the downgoing South China Sea oceanic crust.

Vitrinite reflectance (Ro) values of the Kenting Mélange range from 0.9 % to 1.1 %, which corresponds to a maximum paleotemperature of 146-164 ºC based on the conversion method of Sweeney and Burnham (1990) (heating time is 1 Ma) (Supplementary Material 1; Fig. 6). And then a specific depth of ~10.8-11.7 km can be calculated assuming the surface temperature and the geothermal gradient is 0℃ and 15℃/km, respectively. This depth is speculative because of the lack of information about geothermal gradient here. These Ro values are greater than those of the Mutan Formation accretionary complex and the Maanshan Formation, suggesting that the Kenting Mélange developed in a deeper tectonic setting and is again consistent with a tectonic origin.

6.2 Stratigraphic constraints and active subduction-collision for the Kenting Mélange

Age data from microfossils in the matrix of the Kenting Mélange constrain the timing of formation of the mélange and the origin of the protolith strata.

Figure 7 shows the distribution of planktonic foraminiferal and calcareous nannofossil data for the matrix of the Kenting Mélange (Chang, 1966; Chi, 1982; Huang et al., 1983; Huang, 1984). Late Miocene blocks (NN9/11 of nannofossils and N15/17 of foraminifera) within the Kenting Mélange are adjacent to the coherent Late Miocene turbidite succession of the Mutan Formation. In contrast, diverse ages of the mélange are obtained in the samples close to the Hengchun fault and Plio-Pleistocene slope-basin sequences (Fig. 9).

Chi (1982) reported calcareous nannofossils from core E-2 along with some samples from surface mélange exposures near Nanwan and proposed the Kenting Mélange was an olistostrome origin (Fig. 7). Chi (1982) found abundant Late Miocene nannofossils in the matrix of the Kenting Mélange (NN9-11), while a small amount of Middle Miocene (NN5, NN8), early Miocene (NN3), Middle Eocene and Mesozoic microfossils were also recovered in the sedimentary blocks. Comparing foraminiferal and nannofossil studies in this core, Huang (1984) and Huang et al (1985) found some Plio-Late Pleistocene foraminiferal from the matrix of the Kenting Mélange and then proposed that the proto-Kenting Mélange was of sedimentary origin and of Miocene age that was then sheared and faulted to form the Kenting Mélange in Plio-Late Pleistocene. However, the occurrence of the Eocene and Mesozoic calcareous nannofossils mixed with the chaotic and intensively sheared mélange along with Plio-Early Pleistocene and Miocene foraminifers in core E-2 indicates that the previously proposed derivation of the mélange through olistostromal slumping from the Central Range in Late Miocene (Chi, 1982) is unlikely because non-metamorphosed Eocene and Mesozoic rocks are not found in onshore Taiwan. On land Eocene and Mesozoic rocks constitute the metamorphosed basement of the eastern Central Range, which underlies the Hengchun accretionary complex, and represents the underthrust Eurasian continent. These rocks were deformed and exhumed during the advanced stage of arc-continent collision in the last 2.5 Ma (Huang et al., 1997).

Huang, et al. (1983) reported a Pliocene sedimentary block with nannofossils of Zone NN16 (3.0-2.4 Ma) Ma and planktonic foraminifera of Zone PL4 (3.0-2.8 Ma), embedded in Late Miocene (Zone NN11, 8.2-5 Ma) pervasively scaly, argillaceous matrix. This is in contrast to the features predicted in the case of a sedimentary olistostromal model where a younger block slumps into an older matrix.

The occurrence of Late Miocene foraminifera throughout the Kenting Mélange suggests the Late Miocene accretionary complex constituted the main protolith lithology for the mélange. In addition, Neogene and Quaternary foraminifera obtained in the samples close to the Hengchun fault and the Plio-Pleistocene slope-basin deposits suggest additional localized tectonic shearing resulting in the incorporation of these younger units. This relationship is also observed on a seismic profile over the offshore frontal Hengchun Ridge, which shows that the accretionary complex, especially the frontal part, has been intensively deformed with thrusting extending upward into the Recent slope basin sediments deposited on the top of the complex (Lin et al., 2009).

6.3 Tectonic implication of the Kenting Mélange

The Kenting Mélange extends as a NW-SE trending band for nearly 20 km along strike and is up to 1 km wide parallel to the Manila trench axis (Fig. 1). This is similar to a number of subduction related mélanges, such as the Bobonaro Mélange, which is aligned parallel to the Timor Trough (Masson et al., 1991; Harris et al., 1998; ; Harris, 2011) and the Mugi Mélange parallel to the Nankai trench (Sakaguchi, 1996; Park et al., 2002; Hashimoto et al., 2003; Moore et al., 2007).

The pressure-temperature conditions of the Kenting Mélange and the broken formation were inferred to be more than 140 ºC, equivalent to a depth of several to ten kilometers based on Ro values and field relations (Figs. 4, 6). The Kenting Mélange and the broken formation are mutually associated and may occur repeatedly southward later. In addition, the oceanic blocks occur in the western part of the broken formation, which means that they may be sourced from the down-going oceanic plate facing eastward. Basaltic blocks mixed in the Kenting Mélange are dated at about 26-22 Ma (Pelletier and Bellon, 1984 and data in this text) (Fig. 8), and most likely represent off-scraped fragments of the South China Sea oceanic lithosphere. Integration of onshore and offshore geology allows reconstruction of the tectonic evolution of the Kenting Mélange from an initial intra-oceanic subduction related setting through to the current arc-continent collision environment. Six multi-channel seismic reflection profile data were collected across the northern Manila Trench during two cruises (ORI693 in September 2003 and ORI689 in July 2003). Structural analysis of marine seismic reflection shows that the volcanic basement of the northern South China Sea basin generally deepens toward the Manila Trench and the Philippine Sea Plate overrides the Eurasian Plate along the east-dipping Manila Trench between

Taiwan and Luzon islands (Hsu et al., 2004; Yeh and Hsu, 2004; Ku and Hsu, 2009). Based on the seismic reflection data between 14°N and 19°N, Hayes and Lewis (1984) have shown a major structural décollement in the vicinity of the Manila Trench. Seismic-reflection line 973, from offshore southwestern Taiwan, also displays clear evidence for thrust faulting, a subduction channel, and the plate boundary décollement as well as two major out-of-sequence mega-thrusts (Lin et al., 2009). Studies on similar structures in the Nankai complex of Japan (Kimura and Mukai, 1991; Ikesawa et al., 2005; Sakaguchi et al., 2011), Talkeetna arc terrane of Alaska (Clift et al., 2012; Draut and Clift, 2013) and the Banda arc-continent collision (Harris et al., 1998) demonstrate that accreted and subduction eroded materials in the subduction channel (e.g. tectonic mélange) can be transported upward along these mega-thrusts. Moreover, new marine seismic reflection and coincident wide-angle ocean-bottom seismometer data acquired offshore Taiwan show a chaotic area underlying the Hengchun Ridge accretionary complex (Lester et al., 2013). This may represent the early syn-subduction stage of formation of the Kenting Mélange, which was then transported to the shallow level in the accretionary complex.

All the above lines of evidence suggest that the Kenting Mélange was most likely formed along the plate interface between the underthrusting oceanic plate and overlying accretionary complex, and can be regarded as representing plate boundary rocks. During subduction, pelagic through to terrigenous sediments deposited on the oceanic crust, together with underlying oceanic crust fragments, and sediments eroded from the overlying accretionary complex were offscraped and incorporated into subduction channel to form mélanges, and finally exposed through the out-of-sequence thrust faulting (Fig. 9). The widespread occurrence of Late Miocene foraminifera show that the protolith units of the Kenting Mélange were mainly derived from Late Miocene strata, and evolved into the full mélange complex during latest Miocene to early Pleistocene shearing. The occurrence of Mid-Late Pliocene to Pleistocene foraminifera (<5% in abundance) may be the result of the involvement of the slope basin deposits when out-of-sequence thrusts cut through the complex during active subduction-collision tectonics (Fig. 9).

6.4 Temporal and spatial relations between the Kenting and Lichi mélanges

The Lichi Mélange in the Coastal Range of eastern Taiwan is similar in appearance with the Kenting Mélange in the Hengchun Peninsula of southern Taiwan. The fossil age of the matrix of the Lichi Mélange is well constrained at 3.5-3.7 Ma, whereas the Kenting Mélange has a much larger range of ages with a peak during Miocene. The age differences between the two, both in the blocks and the time of mélange formation suggests that they are unrelated temporally as well as spatially. The position of the Lichi Mélange with respect to the major tectonic subdivisions of Taiwan (Fig. 1) suggests it formed in a forearc basin, in contrast to the subduction complex setting of the Kenting Mélange. Moreover, the markedly low Ro values of the Lichi Mélange reported herein (Supplementary Material 1; Fig. 6) argue against significant burial of the unit. The origin of the mélange has been related to both sedimentary (Page and Suppe, 1981; Barrier and Muller, 1984) and tectonic processes (Harris and Huang, 2008; Huang et al., 2008; Chi et al., 2014). Its forearc setting argues against a plate boundary origin and it likely formed during tectonic closure of the forearc when the Luzon arc started to collide with the Eurasian continent margin (Fig. 9; Huang et al., 2008; Chi et al., 2014).

7. Conclusion

Field structures, vitrinite reflectance data and SHRIMP U-Pb age dating reveal that the Kenting Mélange in the Hengchun Peninsula accretionary complex formed through shearing under high enough pressures to cause hydrofracturing and veining along the plate boundary between the Eurasian and Philippine Sea plates. It constituted part of the Manila trench subduction complex in the Late Miocene that was likely pervasively sheared in the subduction channel. Subsequent deformation during Pliocene-Pleistocene arc continent collision leads to further deformation, including the incorporation of Pliocene-Pleistocene slope deposits and the exhumation of the mélange to form the Hengchun Peninsula.

Ro values and field structures indicate a thermal history for the Kenting Mélange of more than 140 ºC, equivalent to a depth of several kilometers in the subduction zone. Exotic igneous blocks within the mélange yield early Miocene ages (22-26 Ma) and geochemically resemble E-MORB , N-MORB or OIB are interpreted to represent off-scraped South China Sea oceanic lithosphere. Microfossil stratigraphy data indicate that the embryo of the Kenting Mélange contains blocks ranging in age from Mesozoic to Middle Miocene. The bulk of the ages of the matrix are Late Miocene were likely derived from the adjoining turbidite sequences (Mutan Formation) that represent offscraped Asian passive margin deposits derived from the down-going plate. The minor Plio-Pleistocene microfossils (<5% in abundance) within the mélange are interpreted as the result of the involvement of the slope basin deposits (Maanshan Formation), which were incorporated when thrusts cut through the complex during the modern active subduction-collision.

Acknowledgments

We would like to thank Y.-H Shan for the fieldwork help and sample collecting. We are grateful to two anonymous reviewers along with the associate editor Sanghoon Kwon for their critical reviews and helpful suggestions. This work was financially co-supported by the GIGCAS 135 Project (grant Y234031001), the National Natural Science Foundation of China (grant 41176041, 91128211), and the National Basic Research Program of China (grant 2014CB440901).

Reference

Barrier, E., Muller, C., 1984. New observation and discussion on the origin and age of the Lichi

Mélange. Memoir of the Geological Society of China 6, 303-326.

Barker, C.E., 1988. Geothermics of petroleum systems: implications of the stabilization of kerogen thermal maturation after a geologically brief heating duration at peak temperature. Petroleum systems of the United States: US Geological Survey Bulletin 1870, 26-29.

Barckhausen, U., Roeser, H.A., 2004. Seafloor spreading anomalies in the South China Sea revisited // Clift P, Wang P, Kuhnt W, Wang P and Hayes P. Continentocean interactions within East Asian marginal seas. AGU Geophysical Monograph Series 149, 121-125.

Biq, C.C., 1971. Comparison of mélange tectonic in Taiwan and in some other mountain belts. Petroleum Geology of Taiwan 9, 79-106.

Biq, C.C., 1972. Dual-trench structure in the Taiwan-Luzon region. Proceedings of the Geological Society of China 15, 65-75.

Biq, C.C., 1977. The Kenting mélange and the Manila trench. Proceedings of the Geological Society of China 20, 119-122.

Briais, A., Patriat, P., Tapponnier, P., 1993. Updated interpretation of magnetic anomalies and seafloor spreading stages in the South China Sea: Implications for the Tertiary tectonics of Southeast Asia. Journal of Geophysical Research: Solid Earth (1978–2012) 98(B4), 6299-6328.

Byrne, T., 1998. Pre-collision kinematics and a possible modern analog for the Lichi and Kenting Mélange, Taiwan. Journal of the Geological Society of China 41, 535-550.

Byrne, T.B., Liu, C.S., 2002. Preface: Introduction to the geology and geophysics of Taiwan. In: Byrne, T.B., Liu, C.-S. (Eds.), Geology and Geophysics of an Arc-Continent Collision, Taiwan. The Geological Society of America, Boulder, Co.,pp. i–iv.

Cawood, P.A., Kröner, A., Collins, W.J., Kusky, T.M., Mooney, W.D., Windley, B.F., 2009. Accretionary orogens through Earth history. In Cawood, P.A. and Kröner, A. (eds). Earth Accretionary Systems in Space and Time. Geological Society Special Publication No. 318, p. 1-36. doi:10.1144/SP318.1.

Chang, L.S., 1966. A biostratigraphic study of the Tertiary in the Hengchun Peninsula, Taiwan, based on smaller foraminifera (III: Southern part). Proceeding of the Geological Society of China 9, 55-63.

Chang, C. P., Angelier, J., Lee, T. Q., Huang, C. Y., 2003. From continental margin extension to collision orogen: Structural development and tectonic rotation of the Hengchun Peninsula, southern Taiwan. Tectonophysics 361: 61-82.

Cheng, Y.M., Huang, C.Y., 1975. Biostratigraphy in the West Hengchun Hill. Acta Geologica Taiwanica 18, 49-59.

Chi, W.R., 1982. The calcareous nannofossils of the Lichi Mélange and the Kenting Mélange and their significance in the interpretations of plate tectonics of the Taiwan region: Ti-Chih (Geology) 4, 99-112 (in Chinese with English abstract).

Chi, W.C, Chen, L., Liu, C.S., Brookfield, M., 2014. Development of arc-continent collision mélanges: Linking onshore geological and offshore geophysical observations of the Pliocene Lichi Mélange, southern Taiwan and northern Luzon arc, western Pacific. Tectonophysics 636, 70-82. doi.org/10.1016/j.tecto.2014.08.009.

Chu, H.T., Shen, P., Jeng, R.C., 1988. The origin of chromitite from the Kenting mélange, southern Taiwan. Proceedings of the Geological Society of China 31, 33-58.

Cloos, M., Shreve, R.L., 1988a. Subduction-Channel Model of Prism Accretion, Melange Formation, Sediment Subduction, and Subduction Erosion at Convergent Plate Margins: 1. Background and Description. PAGEOPH 128(3/4), 455-500.

Cloos, M., Shreve, R.L., 1988b. Subduction-Channel Model of Prism Accretion, Melange Formation, Sediment Subduction, and Subduction Erosion at Convergent Plate Margins: 2. Implications and Discussion. PAGEOPH 128(3/4), 501-545.

Clift, P.D., Wares, N.M., Amato, J.M., Pavlis, T.L., Hole, M.J., Worthman, C., Day, E., 2012. Evolving heavy mineral assemblages reveal changing exhumation and trench tectonics in the Mesozoic Chugach accretionary complex, south-central Alaska. Geological Society of America Bulletin 124(5/6), 989-1006.

Cowan, D.S., 1985. Structural styles in Mesozoic and Cenozoic mélanges in the western Cordillera of North America. Geological Society of America Bulletin 96, 451-462.

Draut, A.E., Clift, P.D., 2013. Differential preservation in the geologic record of intraoceanic arc sedimentary and tectonic processes. Earth-Science Reviews 116, 57-84. doi.org/10.1016/j.earscirev.2012.11.003

Festa, A., Pini, G.A., Dilek, Y., Codegone, G., 2010. Mélanges and mélange-forming processes: a historical overview and new concepts. International Geology Review 52(10-12), 1040-1105.

Fukui, A., Kano, K., 2007. Deformation process and kinematics of mélange in the Early Cretaceous accretionary complex of the Mino-Tamba Belt, eastern southwest Japan. Tectonics 26, 1-14.

Hamilton, W., 1969. Mesozoic California and the under flow of Pacific mantle. Geological Society of America Bulletin 80, 2409-2430.

Harris, R.A., Sawyer, R.K., Audley-Charles, M.G., 1998. Collisional mélange development: Geologic associations of active mélange-forming processes with exhumed mélange facies in the western Banda orogen, Indonesia. Tectonics 17(3), 458-479.

Harris, R.A. and Huang, C.Y., 2008. Linking mélange types and occurrences with active mélange-forming process in Timor and Taiwan, Geol. Soc. of America, Abstracts with Programs, Tectonic Crossroads: Evolving Orogens of Eurasia-Africa-Arabia, Ankara, Turkey, p. 84-85.

Harris, R., 2011. The Nature of the Banda Arc-Continent Collision in the Timor Region, In: D. Brown and P.D. Ryan, Arc-Continent Collision. Frontiers in Earth Sciences, Springer-Verlag Berlin Heidelberg, pp. 163-211. doi: 10.1007/978-3-540-88558-0_7.

Hashimoto, Y., Enjoji, M., Sakaguchi, A., Kimura, G., 2003. In-situ pressure–temperature conditions of a tectonic mélange: constraints from fluid inclusion analysis of syn-mélange veins. Island Arc 12, 357-365.

Hara, H., Wakita, K., Ueno, K., Kamata, Y., Hisada, K.,Charusiri, P., Charoentitirat, T., Chaodumrong, P., 2009. Nature of accretion related to Paleo-Tethys subduction recorded in northern Thailand: Constraints from mélange kinematics and illite crystallinity. Gondwana Research 16, 310-320.

Hayes, D.E., Lewis, S.D., 1984. A geophysical study of the Manila trench, Luzon, Philippines, 1. Crustal structure, gravity, and regional tectonic evolution. Journal of Geophysical Research

89, 9171-9195. doi: 10.1029/JB089iB11p09171.

Hsü, K.J., 1968. Principles of mélanges and their bearing on the Francisian-Kanoxville paradox. Geological Society of America Bulletin 79, 1063-1074.

Hsü, K.J.,1971. Franciscan mélanges as a model for eugeosynclinal sedimentation and underthrusting tectonics. Journal of Geophysical Research 76, 1162-1170

Hsü, S.K., Yeh, Y.C., Doo, W.B., Tsai, C.H., 2004. New bathymetry and magnetic lineations identifications in the northernmost South China Sea and their tectonic implications. Marine Geophysical Researches 25, 29-44.

Huang, T.C., Ting, J. S., and Muller, C., 1983, A note on Pliocene microfossils from the Kenting mélange. Proceedings of the Geological Society of China 26, 57-66.

Huang, C.Y., 1984. Some planktic foraminifers from the olistostromes of the Kenting Formation, southern Hengchun Peninsula. Acta Geologica 22, 22-34.

Huang, C.Y., Cheng, Y.M., and Jeh, J.J., 1985. Genesis of the Kenting Formation in the Hengchun Peninsula, Southern Taiwan. Ti-Chih 6(1), 21-38 (in Chinese with English abstract).

Huang, C.Y., Shyu, C.T., Lin, S.B., Lee, T.Q., Sheu, D.D., 1992. Marine geology in the arc-continent collision zone off southeastern Taiwan: Implications for late Neogene evolution of the Coastal Range. Marine Geology 107, 183-212.

Huang, C.Y., Wu, W.Y., Chang, C.P., Lin, C.W., 1997. Tectonic evolution of the accretionary prism in the arc-continent collision terrane of Taiwan. Tectonophysics 281, 31-51.

Huang, C.Y., Yuan, P.B., Lin, C.W., Wang, T. K., Chang, C. P., 2000. Geodynamic processes of Taiwan arc–continent collision and comparison with analogs in Timor, Papua New Guinea, Urals and Corsica. Tectonophysics 325, 1-21.

Huang, C.Y., Yuan, P.B., Tsao, S.J., 2006. Temporal and spatial records of active arc-continent collision in Taiwan:A synthesis. Geological Society of America Bulletin 118(3/4), 274-288.

Huang, C.Y., Chien, C.W., Yao, B., Chang, C.P., 2008. The Lichi Mélange: A collision mélange formation along early arcward backthrusts during forearc basin closure, Taiwan arc-continent collision. Geological Society of America Special Papers 436, 127-154.

International Committee of Coal Petrology(ICCP), 1998. International Committee of Coal Petrology, The new vitrinite classification (ICCP System 1994), Fuel 77, 349-358.

Ikesawa, E., Kimura, G., Sato, K., Ikehara-Ohmori, K., Kitamura, Y., Yamaguchi, A., Ujiie, K.,Hashimoto, Y., 2005. Tectonic incorporation of the upper part of oceanic crust to overriding plate of a convergent margin: An example from the Cretaceous-early Tertiary Mugi Mélange, the Shimanto Belt, Japan. Tectonophysics 401, 217-230.

Kimura, G., Mukai, A., 1991. Underplated units in an accretionary complex: mélange of the Shimanto Belt of eastern Shikoku, southwest Japan. Tectonics 10, 31-50.

Kimura, G., Yamaguchi, A., Hojo, M., Kitamura, Y., Kameda, J., Ujiie, K., Hamada, Y., Hamahashi, M., Hina, S., 2012. Tectonic mélange as fault rock of subduction plate boundary. Tectonophysics 568-569, 25-38.

Kitamura, Y., Sato, K., Ikesawa, E., Ikehara-Ohmori, K., Kimura, G., Kondo, H., Ujiie, K.,Onishi, C.T., Kawabata, K., Hashimoto, Y.,Mukoyoshi, H., Masago, H., 2005. Mélange and its seismogenic roof décollement: a plate boundary fault rock in the subduction zone-an example from the Shimanto Belt, Japan. Tectonics 24, TC5012.

Kim, S.W., Santosh, M., Park, N., Kwon, S., 2011. Forearc serpentinite mélange from the Hongseong suture, South Korea. Gondwana Research 20, 852-864. doi:10.1016/j.gr.2011.01.012.

Kitamura, Y., Kimura, G., 2012. Dynamic role of tectonic mélange during interseismic process of plate boundary mega earthquakes. Tectonophysics 568-569, 39-52.

Ku, C.Y., Hsu, S.K., 2009. Crustal structure and deformation at the northern Manila Trench between Taiwan and Luzon islands. Tectonophysics 466, 229-240.

Laughland, M.M., Underwood, M.B., 1993. Vitrinite reflectance and estimates of paleotemperature within the Upper Shimanto Group, Muroto Peninsula, Shikoku, Japan, Geological Society of America Special Papers 273, 103-114.

Lester, R., McIntosh, K., Van Avendonk, J. A. H., Lavier, L., Liu, C.S., Wang, T.K., 2013. Crustal accretion in the Manila trench accretionary wedge at the transition from subduction to mountain-building in Taiwan. Earth and Planetary Science Letters 375, 430-440.

Li, P., Rao, C., 1994. Tectonic characteristics and evolution history of the Pearl River Mouth Basin. Tectonophysics 235, 13-25.

Li, X.H., Li, W.X., Li, Z.X., Lo, C.H., Wang, J., Ye, M.F., Yang, Y.H., 2009. Amalgamation between the Yangtze and Cathaysia blocks in South China: constraints from SHRIMP U-Pb zircon ages, geochemistry and Nd–Hf isotopes of the Shuangxiwu volcanic rocks. Precambrian Research 174, 117-128.

Lin, A.T., Yao, B.C., Hsu, S.K., Liu, C.S., Huang, C.Y., 2009. Tectonic features of the incipient arc-continent collision zone of Taiwan: Implications for seismicity. Tectonophysics 479, 28-42.

Lu, C.Y., Hsu, K.J., 1992. Tectonic Evolution of the Taiwan Mountain Belt. Petroleum Geology of Taiwan 27, 15-35.

Ludwig, K.R., 2001. Users manual for Isoplot/Ex rev. 2.49. Berkeley Geochronology Centre Special Publication, 1a. 56pp.

Masson, D.G., Milsom, J., Barber, A.J., Simumbang, N., Dwiyanto, B., 1991. Recent tectonics around the island of Timor, eastern Indonesia. Marine and Petroleum Geology 8(1), 35-49.

Matsumura, M., Hashimoto, Y., Kimura, G., Ohmori-Ikehara, K., Enjohji, M., Ikesawa, E., 2003. Depth of oceanic-crust underplating in a subduction zone: inferences from fluid-inclusion analyses of crack-seal vein. Geology 31, 1005-1008.

McIntosh, K., van Avendonk, H., Lavier, L., Lester, W.R., Eakin, D., Wu, F., Liu, C. S., Lee, C.S., 2013. Inversion of a hyper-extended rifted margin in the southern Central Range of Taiwan. Geology, 41(8): 871−874.

Moore, G.F., Bangs, N.L., Taira, A., Kuramoto, S., Pangborn, E., Tobin, H.J., 2007. Three-dimensional splay fault geometry and implications for tsunami generation. Science 318, 1128-1131.

Muller, C., Pelletier, M., Schaaf, A., Glacon, G., Huang, T.C., 1984. Age determination of the ophiolitic materials from the Hengchun Peninsula(South Taiwan) and their tectonic implication. Memoir of the Geological Society of China 6, 327-334.

Ohmori, K., Taira, A., Tokuyama, H., Sakaguchi, A., Okamura, M., Aihara, A., 1997. Paleothermal structure of the Shimanto accretionary prism, Shikoku, Japan: role of an out-of-sequence thrust. Geology 25, 327-330.

Page, B.M., Suppe, J., 1981. The Pliocene Lichi Mélanges of Taiwan: its plate tectonic and olistostromal origin. American Journal of Science 281, 193-227.

Page, B.M., Lan, C.Y., 1983. The Kenting Mélange and its record of tectonic Events. Memoir of the Geological Society of China 5, 227-248.

Park, J.O., Tsuru, T., Kodaira, S., Cummins, P.R., Kaneda, Y., 2002. Splay fault branching along the Nankai subduction zone. Science 297, 1157-1160.

Pelletier, B., Bellon, H., 1984. Sur l'affinité, l'âge et l'origine des roches magmatiques remaniées dans les formations sédimenaires de la péninsule d' Hengchun (Sud Taiwan). C.R. Acad. Sci. Paris 299(7), 371-374.

Pelletier, 1985. De la fosse de Manille à la chaîne de Taiwan, étude géologique aux confins d'une subduction et d'une collision actives; modèle géodynamique. Thèse, Univ. Brest, Brest, 268.

Pelletier, B., Stephan, J. F., 1986. Middle Miocene obduction and late Miocene beginning of collision registered in the Hengchun Peninsula: geodynamic implications for the evolution of Taiwan. Tectonophysics 125, 133-160.

Raymond, L.A., 1984. Classication of mélanges. In: Raymond, L.A. (Ed.), Mélanges: their nature, origin, and significance. Geological Society of America Special Papers 198, 7-20.

Rao, C.V.D., Santosh, M., Wu, Y.B., 2011. Mesoproterozoic ophiolitic mélange from the SE periphery of the Indian plate: U-Pb zircon ages and tectonic implications. Gondwana Research 19, 384-401.

Reed, D.L., Lundberg, N., Liu, C.S., Luo, B.Y., 1992. Structural relations along the margins of the offshore Taiwan accretionary wedge: Implications for accretion and crustal kinematics. Acta Geologica Taiwanica Science Reports of the National Taiwan University 30, 105-122.

Sakaguchi, A., 1996. High paleogeothermal gradient with ridge subduction beneath the Cretaceous Shimanto accretionary prism, southwest Japan. Geology 24, 795-798.

Sakaguchi, A., 1999. Thermal maturity in the Shimanto accretionary prism, southwest Japan, with the thermal change of the subducting slab: fluid inclusion and vitrinite reflectance study. Earth and Planetary Science Letters 173, 61-74.

Sakaguchi, A, Chester, F., Curewitz, D., Fabbri, O., Goldsby, D., Kimura, G., Li, C.F., Masaki, Y., Screaton, E.J., Tsutsumi, A., Ujiie, K., Yamaguchi, A., 2011. Seismic slip propagation to the updip end of plate boundary subduction interface faults: Vitrinite reflectance geothermometry on Integrated Ocean Drilling Program NanTro SEIZE cores. Geological Society of America 39(4), 395-398.

Santosh, M., Maruyama, S., Sato, K., 2009. Anatomy of a Cambrian suture in Gondwana: Pacific-type orogeny in southern India? Gondwana Research 16, 321-341.

Santosh, M., 2010a. Assembling North China Craton within the Columbia supercontinent: the role of double-sided subduction. Precambrian Research 178, 149-167.

Santosh, M., 2010b. A synopsis of recent conceptual models on supercontinent tectonics in relation to mantle dynamics, life evolution and surface environment. Journal of Geodynamics 50, 116-133.

Sekiguchi, K., Hirai, A., 1980. Estimation of maturation level of organic matter (in Japanese with English abstract), J. Jpn. Assoc. Pet. Technol. 45, 39-47.

Shibata T., Hashimoto Y., 2005. Deformation Style of slickenlines on Mélange Foliations Change in Deformation Mechanisms Along Subduction Interface: Example from the Cretaceous Shimanto Belt, Shikoku, Japan. Gondwana Research 8(3), 433-442.

Shan, Y.H., Nie, G.J., Yan, Y., Huang, C.Y., 2013. The transition from the passive to active continental margin: a case study of brittle fractures in the Miocene Loshui Sandstone on the Hengchun Peninsula, southern Taiwan. Tectonics 32, 65-79.

Silver, E.A., Beutner, E.C., 1980. Mélanges. Geology 8, 32-34.

Strasser, M., Moore, G.F., Kimura, G., Kitamura, Y., Kopf, A., Lallemant, S., Park, J-O., Screaton, E.J., Su, X., Underwood, M.B., Zhao, X., 2009. Origin and evolution of a splay fault in the Nankai accretionary wedge. Nature Geoscience 2, 648-652.

Sung, Q.C., Wang, Y., 1986. Sedimentary environments of the Miocene sediments in the Hengchun Peninsula and their tectonic implications. Memoir of the Geological Society of China 7, 325-340.

Suppe, J., 1984. Kinematics of arc-continent collision, flipping of subduction, and back-arc spreading near Taiwan. Memoir of the Geological Society of China 6, 21-33.

Sweeney, J.J., Burnham, A.K., 1990. Evaluation of a simple model of vitrinite reflectance based on chemical kinetics, Am. Assoc. Pet. Geol. Bull. 74, 1559-1570.

Taylor, B., Hayes, D.E., 1983. Origin and history of the South China Sea basin. In:Hayes, D.E., (Ed.), The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands: Part 2. Geophys. Monogr. Ser., AGU, Washington, D.C., vol. 27, 23-56. doi:10.1029/GM027p0023.

Tsan, S.F., 1974. The Kenting Formation: A note on Hengchun Peninsula stratigraphy. Proceedings of the Geological Society of China 17, 131-134.

Wiedenbeck, M., Alle, P., Corfu, F., Griffin, W.L., Meier, M., Oberli, F., Vonquadt, A., Roddick, J.C., Speigel, W., 1995. Three natural zircon standards for U-Th-Pb, Lu-Hf, trace-element and REE analyses. Geostandard Newsletter 19, 1-23.

Wu, F.Y., Ji, W.Q., Liu, C.Z., Chung, S.L., 2010. Detrital zircon U-Pb and Hf isotopic data from the Xigaze forearc basin: Constraints on Transhimalayan magmatic evolution in southern Tibet. Chemical Geology 271(1), 13-25.

Yeh, Y.C., Hsu, S.K., 2004. Crustal structures of the northernmost South China Sea:seismic reflection and gravity modeling. Marine Geophysical Researches 25, 45-61.

Zhang, X.C., Yan, Y., Huang, C.Y., Chen, D.F., Shan, Y. H., Lan, Q., Chen, W.H., Yu, M.M., 2014. Provenance analysis and its geological significance to the Miocene accretionary prism of Hengchun Peninsula, southern Taiwan. Journal of Asian Earth Sciences 85, 26-39.

Captions of Figures

Fig.1. (A) Geological sketch map of Taiwan and surrounding areas. Taiwan is located between the Manila and Ryukyu subduction systems. (B) Simplified geological map of the Hengchun Peninsula, southern Taiwan. Three units of Plio-Pleistocene shallow-marine slope basin sequences (Maanshan Formation), the Kenting Mélange and the Mid-Late Miocene turbidite sequences (Mutan Formation, main body of the

Hengchun Peninsula accretionary complex) can be divided from the west to the east. (C) Cross section of (B) shows the relationships of each unit. The red lines represent faults. Asterisk marks part of the samples for vitrinite reflectance analysis and red dot marks the sample for SHRIMP age dating (modified after Huang et al., 1997; Chang et al., 2003; Shan et al., 2013).

Fig. 2. Geological map of Dongmen (A) and Paoli (B) river areas (the locations have been marked in Fig. 1B; red asterisks represent samples for vitrinite reflectance analysis).

Fig. 3. Photographs of the Kenting Mélange, Hengchun Peninsula (A-E: in the Paoli and Dongmen rivers; G-H: in the Cingwashih area). (A) White to cream colored dickite occurs in veins or thin patches through the matrix; (B-E) Allochthonous basalt blocks, andesitic agglomerate, breccia and spinel rocks occur in the mud matrix of the Kenting Mélange; (F) Residual turbidite blocks mixed in the mud matrix of the Kenting Mélange, which still retain its original sedimentary structures; (G) Outcrops which redeposited from the Kenting Mélange nearby show a well bedding; (H) Blocks mixed in the outcrops are mostly poorly sorted and angular to sub-rounded in shapes.

Fig. 4. Structural features in the Kenting Mélange, Hengchun Peninsula. (A) The dark gouge, containing mainly fault breccia, represents the tectonic contact line between

broken formation and mélange; (B) Outcrops of broken formation and mélange display a pervasively sheared scaly matrix; (C) Mud veins intruded in the basalt under high pressure; (D) Hydro-fractures with extensional structures extending from surface downward for several centimeters depth are observed in sandstone and siltstone blocks; (E) Plastic flow structures spread all over basalt blocks; (F) Pinch-and-swelled structures or pinched-out boudins with various wavelengths in sandstone blocks; (G)Sandstone in interbedded shale-sandstone blocks is often filled by calcite veins；(H)Web structure in the surface of basalt blocks mixed in the matrix of the Kenting Mélange.

Fig. 5. Photomicrographs of the allochthonous blocks scattered in the Kenting Mélange. Basalt (A) and andesite (B) within the mélange often display multiple generations of cross-cutting calcite or quartz veins, which cut through the rock-forming minerals (e.g. Pyroxene in A and Plagioclase in B).

Fig. 6. Paleothermal structure determined from vitrinite reflectance (Ro). Temperature is estimated in the following approach of Sweeney and Burnham (1990). Heating time is 1 Ma and each bar shows a range of data set for each location. (M-1 and M-2, ZKX2, S04 and JLS13, MK01-06 are collected from the Maanshan Formation, the Mutan Formation and the Lichi Mélange, respectively)

Fig. 7. (A) A compilation of the ages of the Kenting Mélange. (B) The ages of the matrix of the Kenting Mélange and sedimentary blocks from core E-2. (C) Stratigraphic column in the Kenting Mélange. Data source: Chang (1966; ●), Chi (1982; ○), Huang et al. (1983; □) and Huang (1984; Δ) (N22:~2.5-0.07Ma; N18/19: ~5.5Ma; N14-17: ~11.6-6.4Ma; NN19: ~1.8 Ma; NN16:~3.0-2.4 Ma; NN11:~8.2-5 Ma; NN8/9: ~11.4-9Ma; NN5: ~13.8 Ma; NN3: ~ 16Ma; PL4 ~2.8-3.0 Ma)

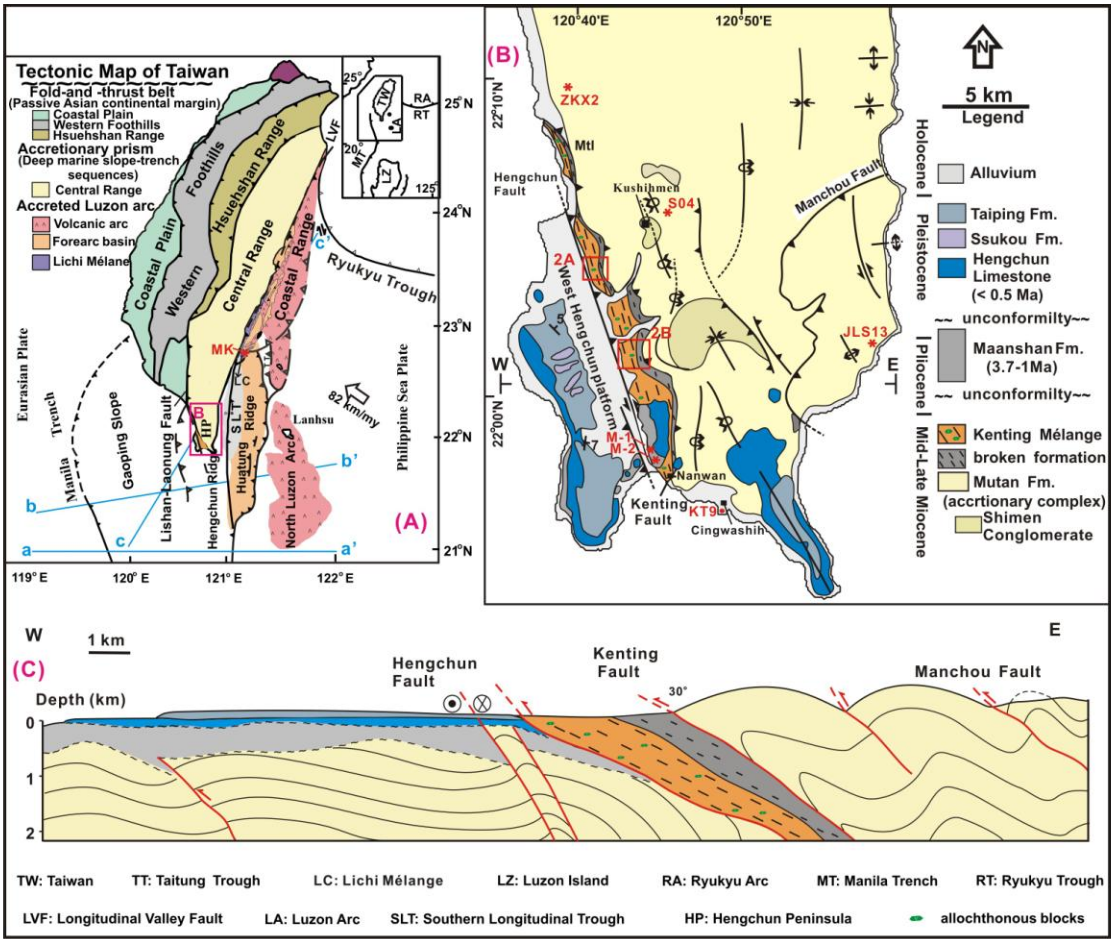
Fig. 8. The concordia plots and the weighted age of zircons from the gabbro block (KT9) mixed in the matrix of the Kenting Mélange.

Fig. 9. The tectonic evolution of the Kenting Mélange in the active subduction and initial arc-continent collision periods based on seismic profiles of offshore S and SE Taiwan (~19°N-22°40′N) (modified from Ku and Hsu, 2009; Huang et al., 2008; Lin et al., 2009; Lester et al., 2013) and the tectonic collision model for the original of the Lichi Mélange (Huang et al., 2008) (see Fig. 1A for profile locations).

Captions for supplementary data

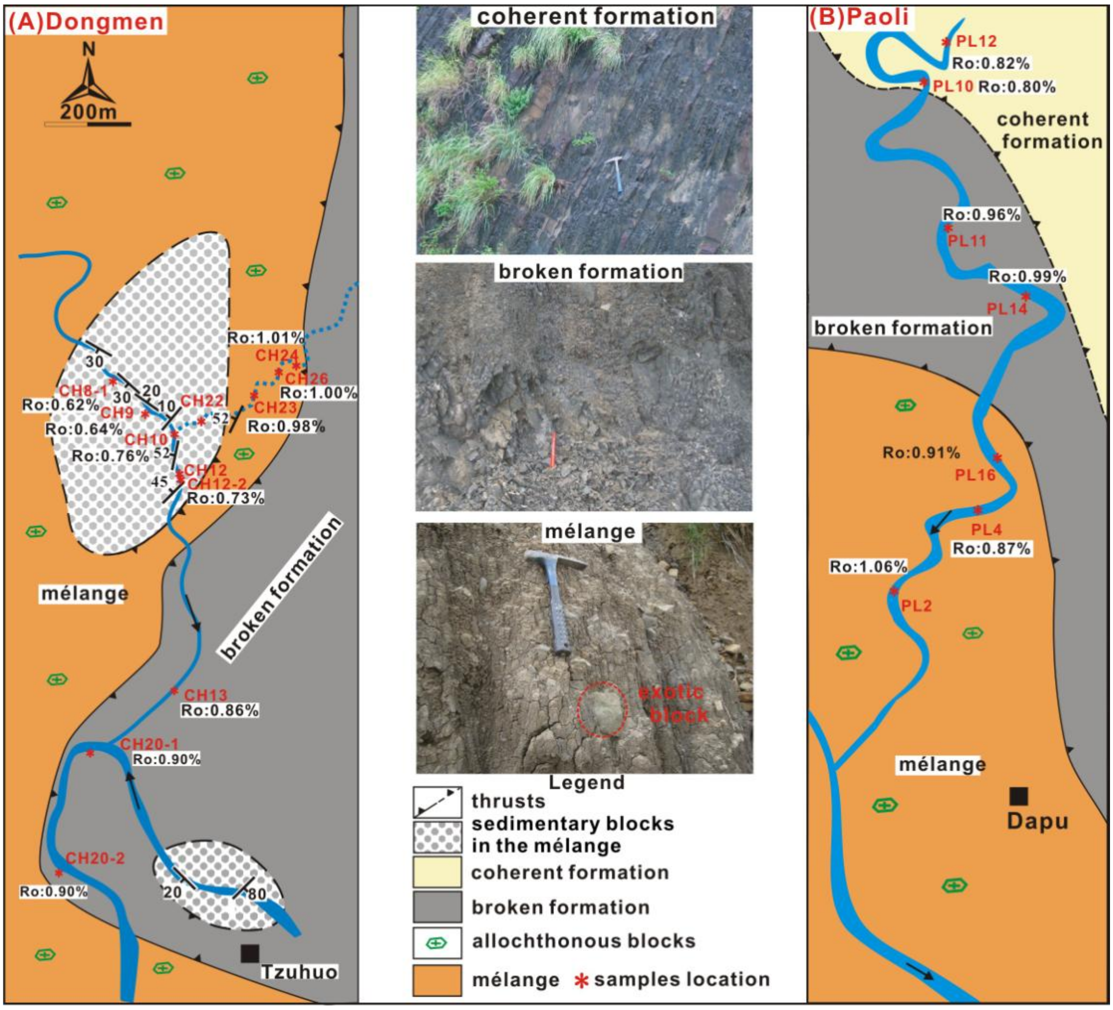
Supplementary Material 1. Vitrinite reflectance values and their calculated paleogeotemperature.

Supplementary Material 2. SHRIMP zircon U-Pb age data from a gabbro block mixed in the Kenting Mélange.



Tectonic Map of Taiwan
Fold-and -thrust belt
(Passive Asian continental margin)
Coastal Plain
Western Foothills
Hsuehshan Range
Accretionary prism
(Deep marine slope-trench sequences)
Central Range
Accreted Luzon arc
Volcanic arc
Forearc basin
Lichi Mélane
Ryukyu Trough
Philippine Sea Plate
Eurasian Plate
Manila Trench
Gaoping Slope
Lishan-Laonung Fault
Hengchun Ridge
Huatung Ridge
North Luzon Arc
Lanhsu
82 km/my
(A)
(B)
5 km
Legend
Alluvium
Taiping Fm.
Ssukou Fm.
Hengchun Limestone (< 0.5 Ma)
~~ unconformilty~~
Maanshan Fm. (3.7-1Ma)
~~ unconformilty~~
Kenting Mélange
broken formation
Mutan Fm. (accrtionary complex)
Shimen Conglomerate
Holocene
Pleistocene
Pliocene
Mid-Late Miocene
Manchou Fault
Hengchun Fault
Kenting Fault
West Hengchun platform
Kushihmen
Nanwan
Cingwashih
(C)
1 km
Depth (km)
W
E
TW: Taiwan
TT: Taitung Trough
LC: Lichi Mélange
LZ: Luzon Island
RA: Ryukyu Arc
MT: Manila Trench
RT: Ryukyu Trough
LVF: Longitudinal Valley Fault
LA: Luzon Arc
SLT: Southern Longitudinal Trough
HP: Hengchun Peninsula
allochthonous blocks

Figure 1



(A)Dongmen
N
200m
Ro:1.01%
CH24
CH26
Ro:1.00%
CH8-1
Ro:0.62%
CH9
CH22
CH23
Ro:0.98%
Ro:0.64%
CH10
Ro:0.76%
CH12
CH12-2
Ro:0.73%
mélange
broken formation
CH13
Ro:0.86%
CH20-1
Ro:0.90%
CH20-2
Ro:0.90%
Tzuhuo
coherent formation
broken formation
mélange
Legend
thrusts
sedimentary blocks in the mélange
coherent formation
broken formation
allochthonous blocks
mélange
samples location
(B)Paoli
PL12
Ro:0.82%
PL10 Ro:0.80%
coherent formation
Ro:0.96%
PL11
Ro:0.99%
PL14
broken formation
Ro:0.91%
PL16
PL4
Ro:0.87%
Ro:1.06%
PL2
mélange
Dapu

Figure 2

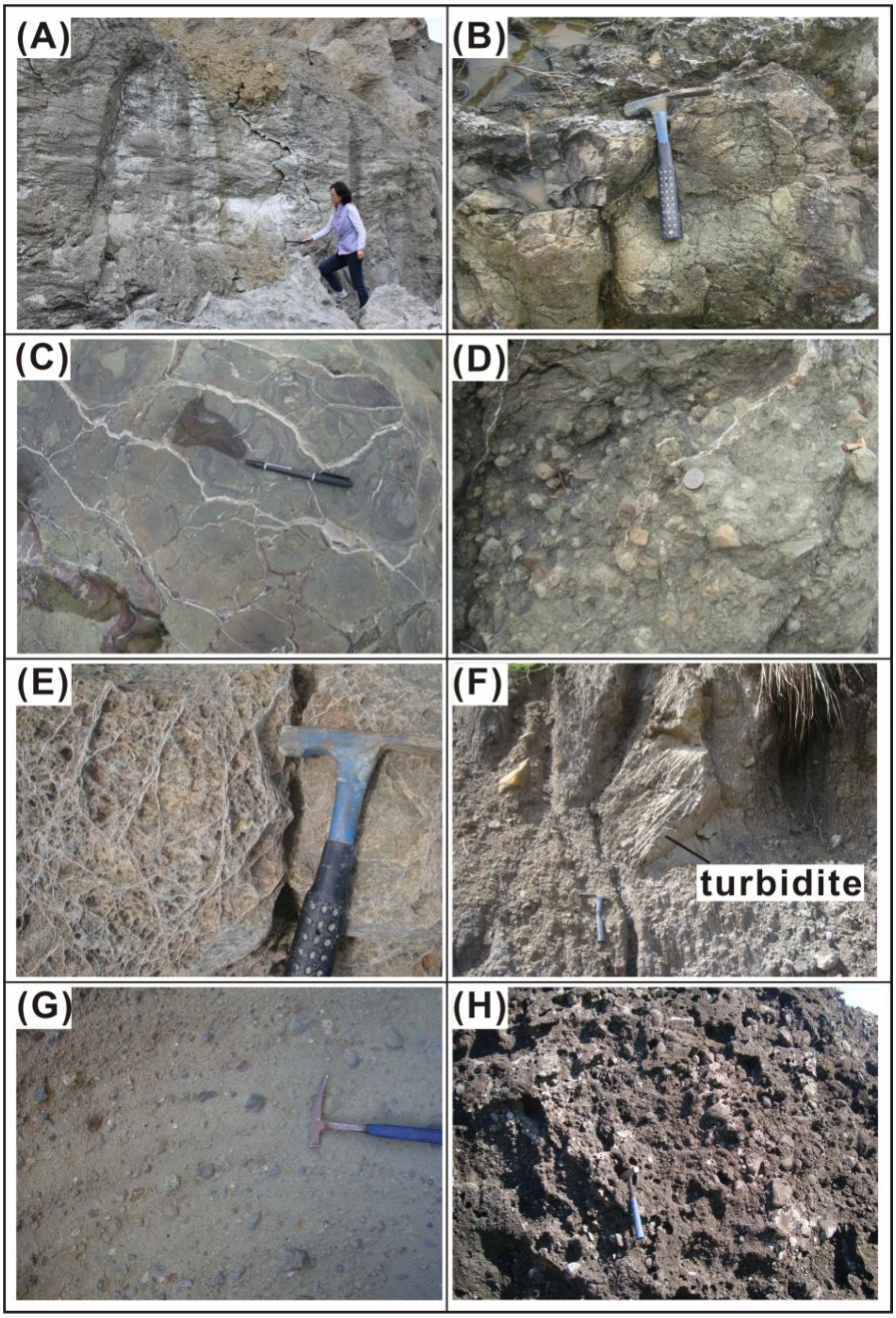


Figure 3

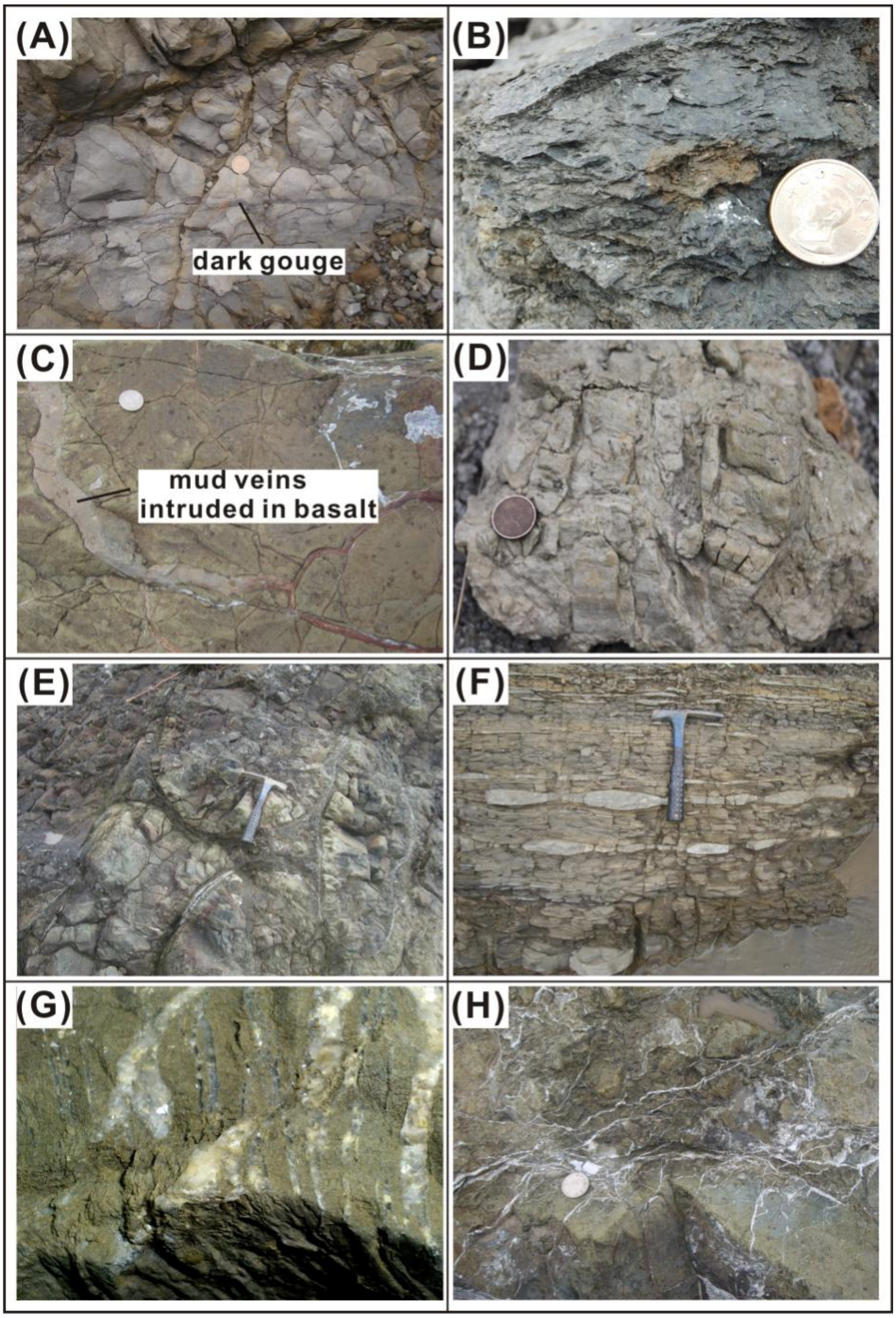
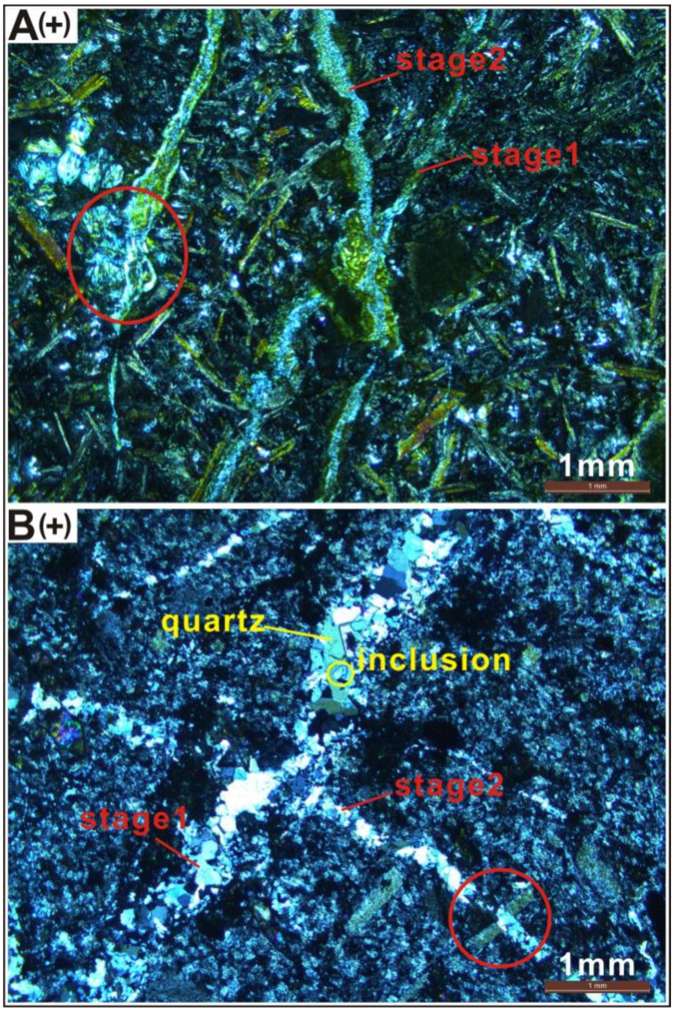


Figure 4



A(+)
stage2
stage1
1mm
1 mm
B(+)
quartz
inclusion
stage2
stage1
1mm
1 mm

Figure 5

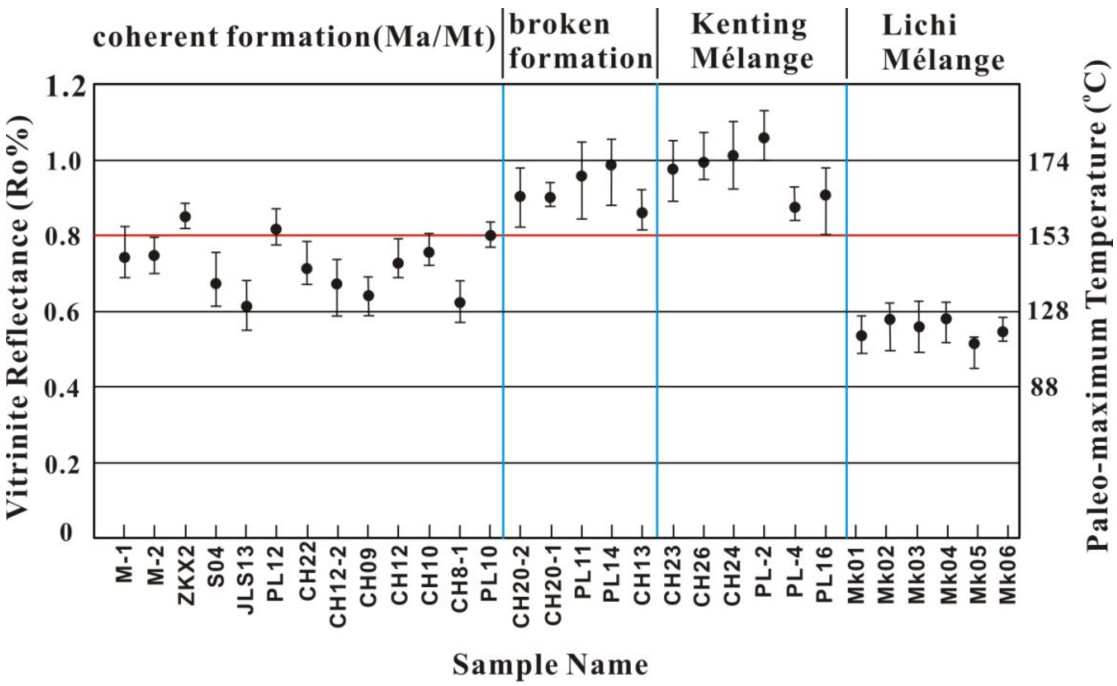
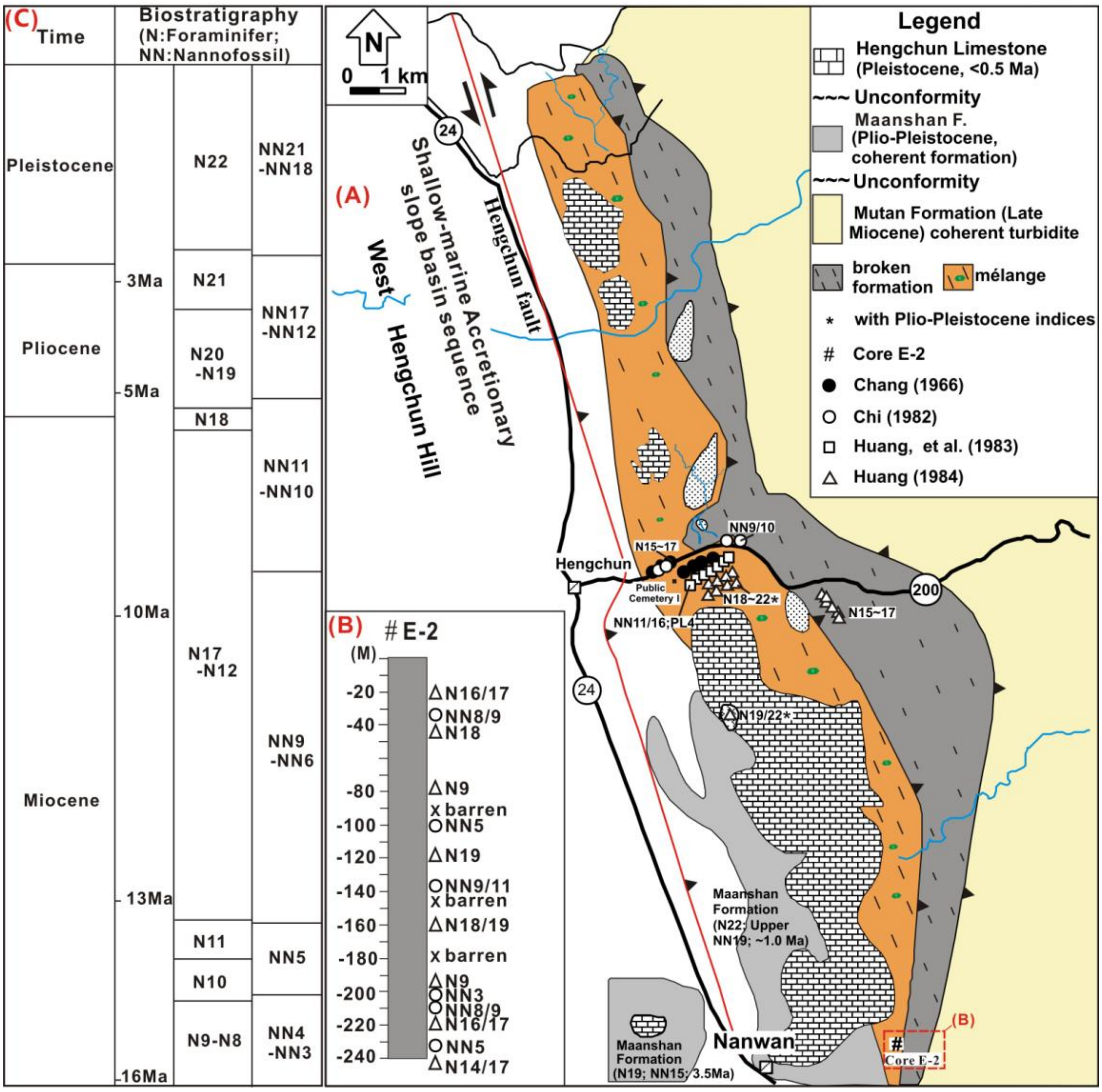
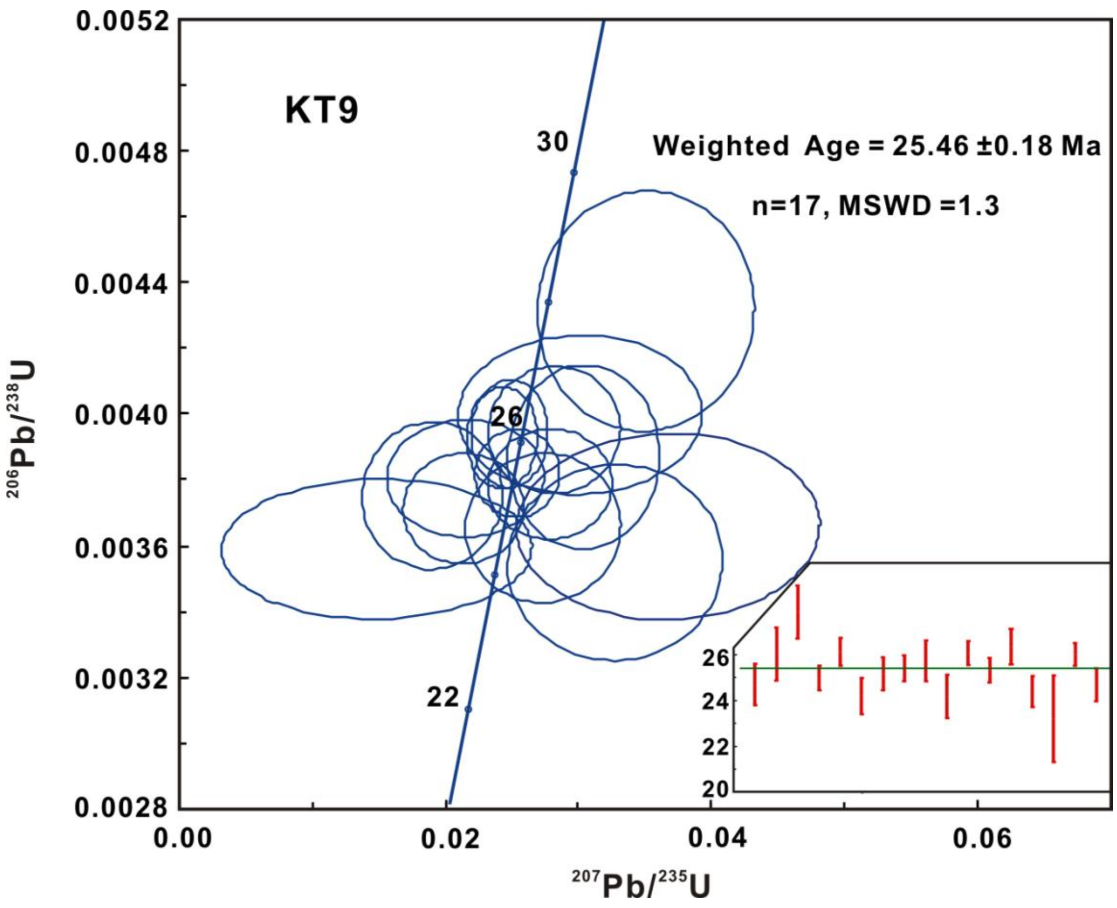

coherent formation(Ma/Mt)
broken formation
Kenting Mélange
Lichi Mélange
Vitrinite Reflectance (Ro%)
1.2
1.0
0.8
0.6
0.4
0.2
0
Paleo-maximum Temperature (°C)
174
153
128
88
M-1
M-2
ZKX2
S04
JLS13
PL12
CH22
CH12-2
CH09
CH12
CH10
CH8-1
PL10
CH20-2
CH20-1
PL11
PL14
CH13
CH23
CH26
CH24
PL-2
PL-4
PL16
Mk01
Mk02
Mk03
Mk04
Mk05
Mk06
Sample Name

Figure 6



(C) Time
Biostratigraphy (N:Foraminifer; NN:Nannofossil)
Pleistocene
Pliocene
Miocene
3Ma
5Ma
10Ma
13Ma
16Ma
N22
N21
N20 -N19
N18
N17 -N12
N11
N10
N9-N8
NN21 -NN18
NN17 -NN12
NN11 -NN10
NN9 -NN6
NN5
NN4 -NN3
(A)
N
0 1 km
24
Hengchun fault
Shallow-marine Accretionary slope basin sequence
West Hengchun Hill
Legend
Hengchun Limestone (Pleistocene, <0.5 Ma)
Unconformity
Maanshan F. (Plio-Pleistocene, coherent formation)
Unconformity
Mutan Formation (Late Miocene) coherent turbidite
broken formation
mélange
with Plio-Pleistocene indices
Core E-2
Chang (1966)
Chi (1982)
Huang, et al. (1983)
Huang (1984)
NN9/10
N15~17
Hengchun
Public Cemetery I
N18~22*
N15~17
200
NN11/16;PL4
N19/22*
Maanshan Formation (N22; Upper NN19; ~1.0 Ma)
Maanshan Formation (N19; NN15; 3.5Ma)
Nanwan
(B)
Core E-2
(B) # E-2
(M)
-20
-40
-80
-100
-120
-140
-160
-180
-200
-220
-240
N16/17
NN8/9
N18
N9
barren
NN5
N19
NN9/11
barren
N18/19
barren
N9
NN3
NN8/9
N16/17
NN5
N14/17

Figure 7



KT9
Weighted Age = 25.46 ±0.18 Ma
n=17, MSWD =1.3
30
26
22
0.0052
0.0048
0.0044
0.0040
0.0036
0.0032
0.0028
0.00
0.02
0.04
0.06
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$
26
24
22
20

Figure 8

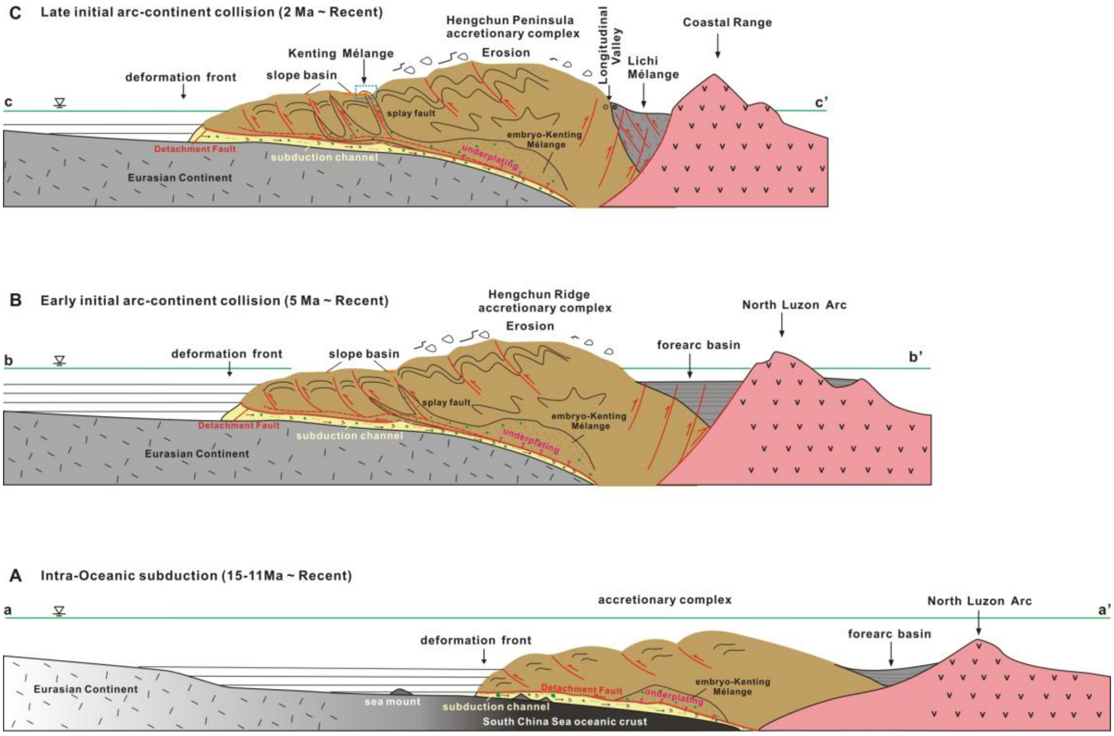
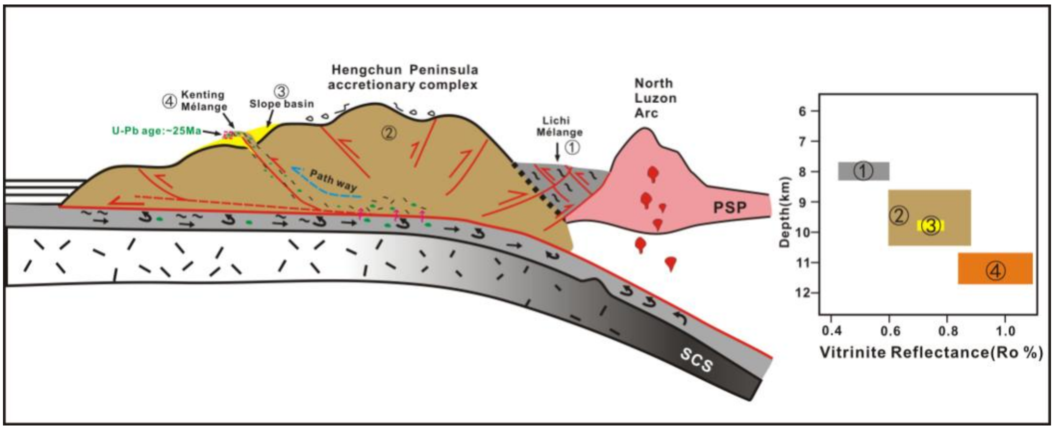

C Late initial arc-continent collision (2 Ma ~ Recent)
Hengchun Peninsula accretionary complex
Longitudinal Valley
Coastal Range
Kenting Mélange
Erosion
Lichi Mélange
deformation front
slope basin
c
c'
splay fault
embryo-Kenting Mélange
Detachment Fault
subduction channel
underplating
Eurasian Continent
B Early initial arc-continent collision (5 Ma ~ Recent)
Hengchun Ridge accretionary complex
Erosion
North Luzon Arc
forearc basin
b
deformation front
slope basin
b'
splay fault
embryo-Kenting Mélange
Detachment Fault
subduction channel
underplating
Eurasian Continent
A Intra-Oceanic subduction (15-11Ma ~ Recent)
accretionary complex
North Luzon Arc
a
a'
deformation front
forearc basin
Eurasian Continent
Detachment Fault
embryo-Kenting Mélange
underplating
sea mount
subduction channel
South China Sea oceanic crust

Figure 9



Graphical abstract

Highlights

1. Gabbro dated as 25Ma in Kenting Mélange was soured from the SCS.
2. High Ro values of Kenting Mélange show it was formed in a deep condition.
3. Minor young fossils occur within mélange indicate slope basin sequence was involved.
4. Kenting Mélange records process from subduction to arc-continent collision.