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Origin and evolution of a mélange: the active plate boundary and suture zone of the Longitudinal Valley, Taiwan

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Abstract

Juxtaposed against the remnant forearc basin sequences along thrust faults, the Lichi Mélange of the Coastal Range of Taiwan is composed of exotic ophiolite and sedimentary blocks, metric to kilometric in size, and coherent turbidite beds, all embedded in a sheared scaly argillaceous matrix. The Lichi Mélange is controversial in origin, being interpreted either as a subduction complex, or as an olistostrome. By separating four main deformation levels within the Lichi Mélange and adjacent sedimentary rocks, we establish detailed geological maps and structural profiles in two key areas of the Lichi Mélange. We reconstruct also the evolution in cross-section and calculate the approximate minimum amount of shortening that corresponds to folding and thrusting in these areas. Our field studies suggest that the Lichi Mélange most likely arose from the shearing of lower forearc sequences rather than from a subduction complex or an olistostrome. This conclusion is supported by the structural analysis, the clay mineral distribution, and some interfingering sedimentary relationships between the Lichi Mélange and the lower Takangkou Formation. We also undertake a comprehensive tectonic analysis of the shear surfaces in the Lichi Mélange. The direction of the maximum compressional stress that we obtain is N100° ~120°E, compatible with that of plate convergence. During the most recent stage of collision, between the Eurasian plate (eastern Central Range of Taiwan) and the Philippine Sea plate (Coastal Range), a major fault zone developed along the innately weak zone of mélange, further increasing the shear deformation pattern of the Lichi Mélange. This Longitudinal Valley Fault separates the Eurasian plate and the Philippine Sea plate and is one of the most active faults in Taiwan. It can be considered as the present plate boundary in the Taiwan arc–continent collision terrane. According to our reconstruction, this plate boundary of the Longitudinal Valley originated as a submarine arc–prism boundary.

Keywords: arc–continent collision; Coastal Range; Lichi Mélange; Longitudinal Valley; North Luzon arc; Taiwan

1. Introduction

Taiwan is located on the southeastern margin of the Eurasian plate, and the active Taiwan orogeny is surrounded by two subduction systems: the Ryukyu subduction system to the northeast and the Manila subduction system to the south (Fig. 1). The arc–continent collision is the principal mechanism for the emergence of Taiwan island (Biq, 1971, 1973; Chai, 1972; Karig, 1973); and under this prerequisite, the Coastal Range of eastern Taiwan can be regarded as the northern segment of the North Luzon arc that has been accreted onto the continental margin (Biq, 1972;

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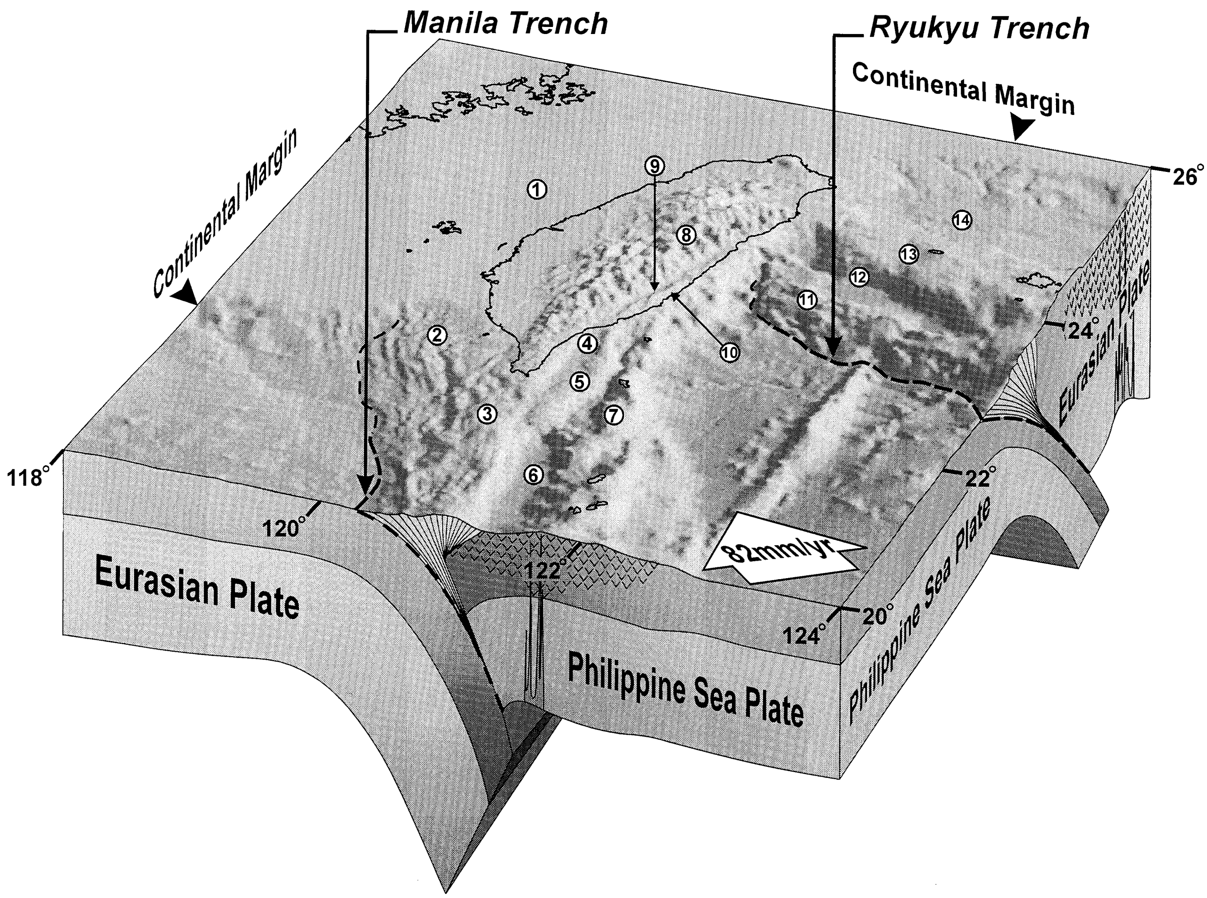

Fig. 1. Block diagram showing the arc–continent collision and tectonic setting of Taiwan, between the Eurasian continent and the Philippine Sea plate. East of Taiwan, the Philippine Sea plate is being consumed beneath the Eurasian continent along the Ryukyu trench. South of Taiwan, along the Manila trench, the oceanic crust of the South China Sea (32–15 Ma) is subducting beneath the Philippine Sea plate. To summarize, east of Taiwan the Eurasian plate including the Ryukyu arc overrides the Philippine Sea plate, whereas south of Taiwan the Philippine Sea plate including the Luzon arc overrides the Eurasian plate that comprises the South China Sea. In Taiwan, collision occurs between the Luzon arc system and the Chinese continental margin. Because the Quaternary collision that forms the Taiwan island is a typical oblique arc–continent collision, the orogenic belt has been propagating southward along the new formed plate boundary of the Longitudinal Valley (Suppe, 1984) between the Central Range and the Coastal Range. Circled numbers refer to locations of main geomorphologic units: 1 = Taiwan Strait, 2 = Kaoping Slope, 3 = Hengchun Ridge, 4 = Southern Longitudinal Trough, 5 = Huatung Ridge, 6 = North Luzon Trough (Taitung Trough in the northern part), 7 = North Luzon Ridge (Lanhsu–Lutao Ridge in the northern part), 8 = Central Range, 9 = Longitudinal Valley, 10 = Coastal Range, 11 = Yaeyama Ridge, 12 = Nanao Basin, 13 = Ryukyu Arc, 14 = Okinawa Trough.

Chai, 1972; Page and Suppe, 1981) (Fig. 1). The study of the Coastal Range thus provides a geological key to reconstruct and understand the evolution of the arc–continent collision in Taiwan.

The Coastal Range is juxtaposed against the metamorphic rocks in the eastern Central Range along the Longitudinal Valley (Fig. 2a). The sequences of the Coastal Range include the Miocene volcanics of the Tuluanshan Formation unconformably overlain by Pliocene–Pleistocene deep-sea turbidites of the Takankou Formation. In the southwestern flank of the Coastal Range, the *Lichi Formation* is a distinct unit composed of chaotic mudstones intermixed with exotic blocks of various size and lithology. The type outcrop of the *Lichi Formation* was defined near the Lichi

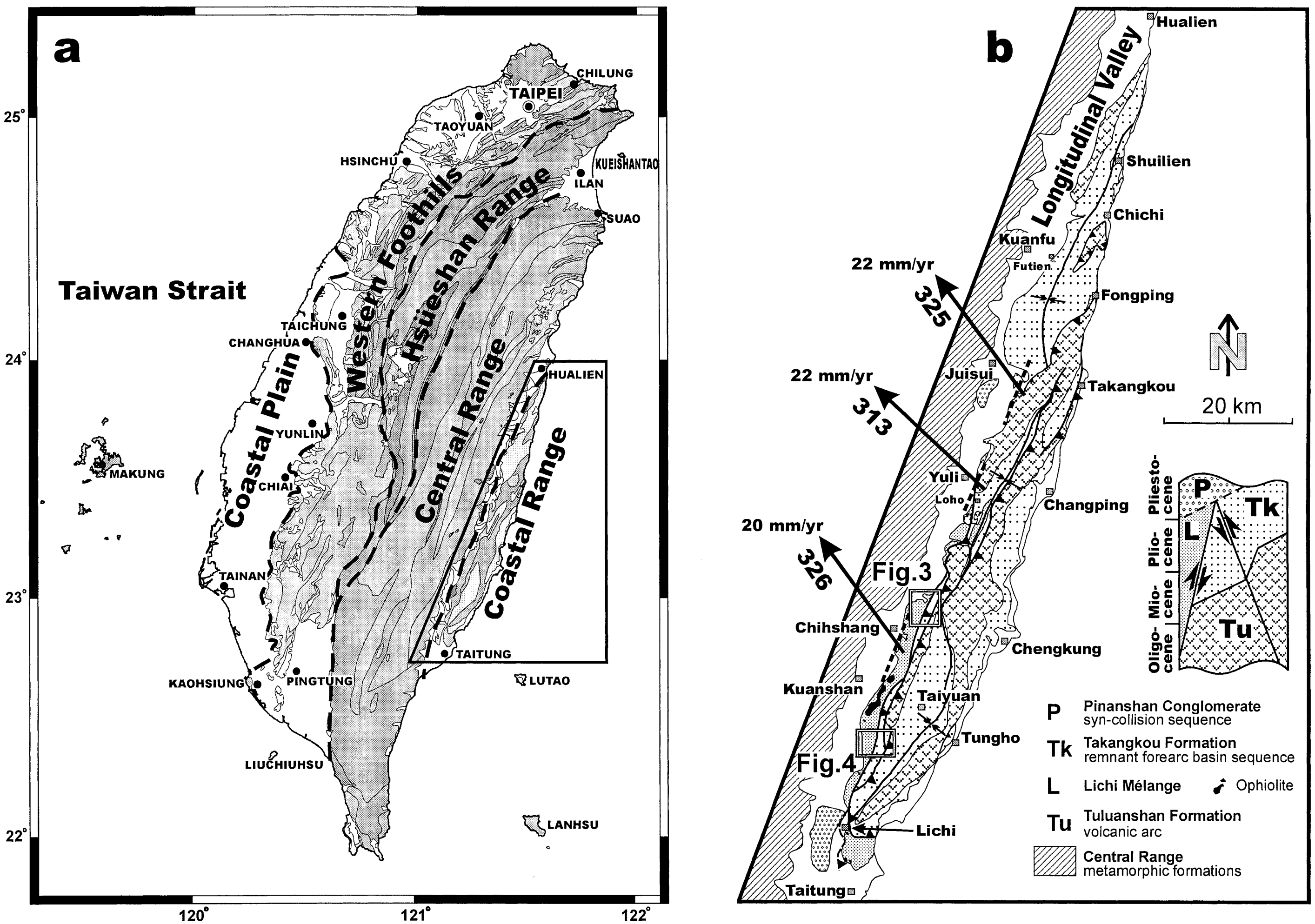

Fig. 2. (a) Main geologic units of Taiwan, with location of map (b). (b) Geologic map of the Coastal Range and present-day displacement across the Longitudinal Valley Fault Zone. Note the particular distribution of the Lichi Mélange: along the western flank of the southern Coastal Range, around the southern tip of the Coastal Range, and also near the Futien village in the northern Coastal Range (Teng, 1981), near the Fongping village in the eastern Coastal Range (Chen, 1988) and in the Loho basin of the central Coastal Range. The study areas of Figs. 3 and 4 are shown as two rectangular frames. Large arrows (after Lee and Angelier, 1993) indicate the displacement of the upthrust, eastern block of the Longitudinal Valley Fault relative to the Central Range, with computed azimuths of displacement in degrees and computed velocities in mm yr^{-1}.

village in the southwestern Coastal Range (Hsu, 1956) (Fig. 2b).

The chaotic clayey mudstone of the Lichi Formation (Hsu, 1956) was first recognized as a mélange by Biq (1956). Biq (1969, 1971) further interpreted the Lichi Mélange as an olistostrome resulting from gravity sliding of marine sediments, with the additional incorporation of ophiolitic blocks during the subsequent convergence of the continental and oceanic plates in eastern Taiwan (Fig. 1). Because of its lithologic associations and tectonic significance, the Lichi Mélange has attracted extensive investigation by numerous geologists. These studies have focused on the stratigraphic and lithologic characteristics of the exotic blocks, regional field relations, and tectonic reconstruction of the Lichi Mélange and the Coastal Range of Taiwan (e.g. Hsu, 1956; Ho, 1967; Biq, 1969, 1971; Liou et al., 1977a; Page and Suppe, 1981; Teng, 1981; Chen, 1997). Despite significant achievements, the origin of the Lichi Mélange is still controversial, the two main end-member hypotheses being those of subduction complex or olistostrome origin.

Because of the intense scaly foliation and the existence of the exotic blocks, many geologists first considered the Lichi Mélange as a subduction complex formed along Manila trench by the subduction of the South China Sea oceanic crust (Biq, 1971, 1973; Karig, 1973; Teng, 1981; Hsu, 1988; Chen, 1988, 1991, 1997). According to this model, the Longitudinal Valley represented the plate boundary before the arc–continent collision. On the other hand, because pieces of well-bedded units as well as coherent turbidites are locally preserved in the Lichi Mélange, many other geologists considered the Lichi Mélange as an olistostrome (Wang, 1976; Ernst, 1977; Ho, 1977, Ho, 1979; Liou et al., 1977b; Liou and Ernst, 1979; Hsu, 1956; Page and Suppe, 1981; Lee, 1984; Barrier and Muller, 1984). Following this interpretation, this olistostrome would have developed between an outer arc and a forearc basin.

Recent field evidence from outcrops of the Lichi Mélange suggests, however, that rather than being part of a subduction complex or an olistostrome the Lichi Mélange originated from thrusted forearc basin units, so that it can be considered as a sheared sedimentary sequence of lower forearc basin origin (Chang et al., 2000). As a result of its later tectonic evolution (thrusting, backthrusting and diapir extrusion), the Lichi Mélange is now widely exposed along the western boundary of the Coastal Range and along some large fault zones inside the Coastal Range. In terms of tectonic evolution, the present-day structure results from both the early shear deformation and the late collisional contraction, and hence cannot be single-phase. To clarify this evolution, we undertook a systematic analysis of the Lichi Mélange and surrounding formations.

2. Geological setting of Taiwan and Coastal Range

Rifting in the Paleocene–Eocene led to the development of a series of NE trending grabens in the SE Asian continental margin (Sun, 1982). From the Oligocene to the Middle Miocene, widespread rifting and sea-floor spreading resulted in the formation of the oceanic lithosphere of the South China Sea (Taylor and Hayes, 1983). Soon after it was generated in the Early Miocene, the South China Sea oceanic lithosphere was subducted beneath the west-moving Philippine Sea plate along the Manila trench. The present Luzon arc thus formed on the Philippine Sea plate. Continued subduction finally resulted in the collision between the Luzon arc and the Eurasian continent in the Late Miocene (Suppe, 1984; Ho, 1986).

From the kinematic point of view, it is likely that, between the northern tip of the Luzon arc and the southwestern tip of the Ryukyu subduction zone, a large zone of left-lateral transform motion accommodated the opposite-vergent subductions, as the Taiwan–Luzon transform zone (Angelier, 1990a) (Fig. 1). The present Taiwan island is a product of arc–continent collision (Chai, 1972; Biq, 1973; Bowin et al., 1978), and because this arc–continent collision is an oblique collision, the orogenic belt has been propagating southward (Suppe, 1984). As a consequence, one can reconstruct the tectonic evolution from subduction to collision by simply comparing the southern section of the Taiwan belt with the northern section.

The Taiwan island consists of five morphotectonic units, all separated by major faults (Fig. 2a): the Coastal Plain, the Western Foothills, the Hsüehshan Range, the Central Range, and the Coastal Range. In western Taiwan, the Coastal Plain, the Western Foothills, and the Hsüehshan Range are composed of Cenozoic shallow-marine siliciclastics unconformably overlain by Quaternary alluvial terraces formations. The western Central Range is composed of Miocene deep-marine turbidites and the eastern Central Range is composed of Mesozoic to Late Paleozoic metamorphic rocks. The age and lithology of these formations and their relationships with the adjacent rocks suggest that they belong to the upper material on the underthrusting Eurasian continent (Ho, 1988). In contrast, in eastern Taiwan, the long and narrow Coastal Range is composed of Miocene volcanic rocks overlain by 5–6 km thick Plio–Pleistocene turbiditic formation (Dorsey and Lundberg, 1988). The Coastal Range belongs to the Philippine Sea plate, and represents a northern segment of the Luzon arc that has been accreted onto the uplifting Eurasian continent (Chai, 1972; Biq, 1972) (Fig. 2b).

On the western side of the Taiwan mountain belt, the large seismic activity in the foothills indicates that the orogenic wedge continues to override the China continental basement. On the eastern side of the Taiwan mountain belt, the Longitudinal Valley between the Central Range and the Coastal Range, marks one of the most active plate boundaries between the Eurasian plate and the Philippine Sea plate (Tsai et al., 1977; Tsai, 1986). Across this valley, a present-day relative velocity of about 3 cm yr^{-1} has been detected (Fig. 2b) by geodetic means (Yu and Liu, 1989; Lee and Angelier, 1993; Yu et al., 1997).

From the geology, it is clear that the Longitudinal Valley became a major tectonic boundary long before the most recent Taiwan collision, probably as a submarine arc–prism boundary (Chang et al., 2000). This inference is principally supported by the observations from the Lichi Mélange in the Coastal Range. For this reason, understanding the evolution of the Lichi Mélange is crucial to reconstruct the tectonic evolution of the active plate boundary that evolved during the arc–continent collision. This is why the primary subject of the present paper deals with the origin and the structural evolution of the Lichi Mélange. Particular attention is paid to outcrop evidence, starting from the two case examples located in Fig. 2b.

3. Lithology and origin of the Lichi Mélange

The Lichi Mélange is distributed around the southwestern flank of the Coastal Range, and is composed of strongly sheared chaotic mudstones that contain many exotic blocks of various sizes and lithologies. Most of the Lichi Mélange crops out as a narrow belt with a length of about 65 km along the Longitudinal Valley, but smaller outcrops have been found in other areas of the Coastal Range (Fig. 2b). The best examples are located inside the Coastal Range, near the village of Futien in the north (Teng, 1981), near the village of Fongping to the east (Chen, 1988), and in the Loho basin of the central part of the Coastal Range (Hsu, 1956; Song, 1986).

The most characteristic lithological feature of the Lichi Mélange is the presence of intensely sheared mudstones without distinctive stratification. However, layers of pebbly mudstones and coherent stratifications have been reported locally (Chang, 1967; Liou et al., 1977b; Page, 1978; Lee, 1984; Barrier and Muller, 1984; Chang, 1996). Some blocks inside the mélange may reach kilometric size and they are generally angular in shape. Most small blocks (decametric or smaller) are heavily sheared, but many large blocks remain almost intact (Teng, 1988). In terms of lithology, the exotic blocks belong to three types; (1) the ophiolitic suite, including peridotite, gabbro, and basalt; (2) the sedimentary suite, including various kinds of sedimentary clasts derived from the Takangkou Formation or other submarine sequences of shelf or continental slope environment, such as turbidites, sandstones, quartz-rich sandstone (Miocene in age), sandstone/shale interbeds, shales, conglomerates, mudstones, and limestones; and (3) the andesitic suite, including volcanic breccias, tuffs, andesitic agglomerates, and volcaniclastic turbidites, all derived from the

Tuluanshan Formation (Hsu, 1976; Liou et al., 1977a; Page and Suppe, 1981). Both the composition of the sedimentary blocks and their relationships at the contact with the matrix of the Lichi Mélange deserve particular attention, because they have the potential to highlight the origin of the Lichi Mélange. These aspects are discussed below.

In fact, two kinds of sedimentary source materials coexist within the Lichi Mélange (Lin and Chen, 1986). One of these sources involves the continental materials, which are rich in illite and chlorite and were transported into the marine basin from the eastern Asian continent and/or the accretionary prism of the subduction zone (such as the ancient Central Range and its southern extension). The other source involves the volcanic arc material, which is rich in kaolinite and smectite and was transported from the volcanic arc in a tropical area (such as the Philippine islands). These two kinds of source materials were simultaneously deposited in the same sedimentary basin, that of the future Lichi Mélange. As indicated by the presence of large amounts of kaolinite in the mélange, part of the source area for the primary strata precursor of the Lichi Mélange had a humid, warm climate with much rainfall. This context fits well with the Miocene paleo-position of the Luzon arc, far to the southeast of the present location of the Lichi Mélange in Taiwan. In contrast with the Lichi Mélange, the kaolinite is rare or almost absent in the clay fractions of the adjacent Takangkou Formation. This suggests that contrary to the Lichi Mélange situation, the typical Takangkou forearc basin received much material from a continental source (like the ancient Central Range) than from a volcanic arc source (Lin and Chen, 1986; Chang, 1996).

Although the contact between the Lichi Mélange and the other rock units is mainly tectonic (Hsu, 1976), interdigitation of stratigraphic origin with strata of the Takankou Formation might exist locally (Page and Suppe, 1981; Lee, 1984; Barrier and Muller, 1984; Chang, 1996). The best evidences for stratigraphic interfingering occur between the Lichi Mélange and the lower Takangkou flysch, which is lower Pliocene in age according to NN14–NN15 nannoplankton zones in the Mukenhsi area (Lee, 1984). Because of the existence of some evidence for interfingering, Page and Suppe (1981) considered that the contact between the Lichi Mélange and the Takangkou Formation is quasi-conformable in type. Our mapping confirmed the existence of such stratigraphic relationships, which result in major constraints while reconstructing the tectonic evolution of the Lichi Mélange area.

4. Structural setting of the Lichi Mélange

The scaly foliation is a very common and pervasive structure in the Lichi Mélange, but field mapping reveals large variations in intensity. This gave rise to the idea that, based on observation of the structural framework, it is possible to distinguish different domains within the Lichi Mélange and the adjacent rock formations. Four main domains with different degrees of deformation were thus identified according to the method of Raymond (1984). The first degree corresponds to the case of a coherent unit (unit α): it applies to stratigraphic units where the internal stratal continuity is fully preserved. The second degree is that of broken unit (unit β): the rock in this unit is locally disrupted but most of the stratal continuity remains preserved. The third degree describes a dismembered unit (unit γ): there is no internal stratal continuity in this unit, but exotic blocks are still absent. The fourth degree is the actual mélange (unit δ): in this extensively sheared mélange, not only is there no internal stratal continuity, but exotic blocks are also present. Based on this classification, we undertook a detailed structural study of the Lichi Mélange in two key areas, Biehhsi and Mukenhsi. Figs. 3 and 4 show the geological maps and the structural profiles of these areas.

In the Biehhsi area, three main fault zones can be identified (Fig. 3): to the west, the Lichi Mélange (units γ to δ) overthrusts the Quaternary alluvial conglomerates. The thrust fault is clearly observable, with a strike N20°–40°E and an eastward dip of 70°–80°. This thrust is a segment of the active Longitudinal Valley Fault. At the eastern boundary of the Lichi Mélange, another major thrust, the Yungfong Fault, is a backthrust over

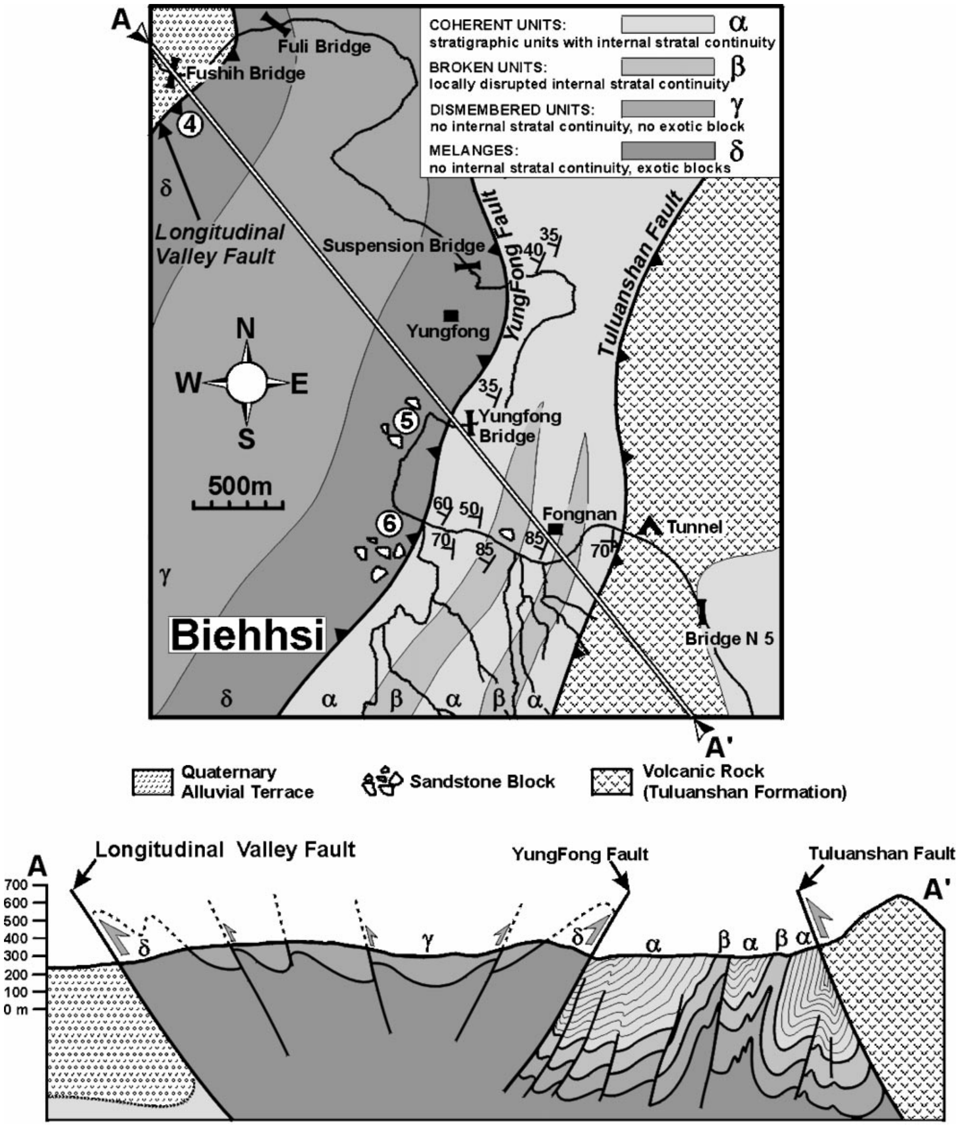

Fig. 3. Detailed geologic map of the Biehhsi valley area and geologic cross-section. Unit α can be considered as Takankou Formation, units γ and δ can be considered as Lichi Mélange and unit β is an intermediate member between Takankou Formation and Lichi Mélange (definitions and discussion in text). Circled numbers 4, 5 and 6 refer to sites of brittle tectonic analysis in the Lichi Mélange (stereoplots in Fig. 7).

the Takankou Formation (unit α), with a fault plane striking N20°E and dipping westward 70°–50°. Within the Takankou Formation, we found two small sheared zones about 100 m wide each with some features of the Lichi Mélange (especially, clay matrix and sandstone blocks). Because the fracturing is less intense in comparison with the typical Lichi Mélange outcrops, we consider these shear zones as units β to γ. At the eastern boundary in the Biehhsi area (Fig. 3), the Takankou Formation is overthrust by the Tuluanshan Formation, along the west-vergent Tuluanshan Fault.

In the Mukenhsi area (Fig. 4), the Lichi

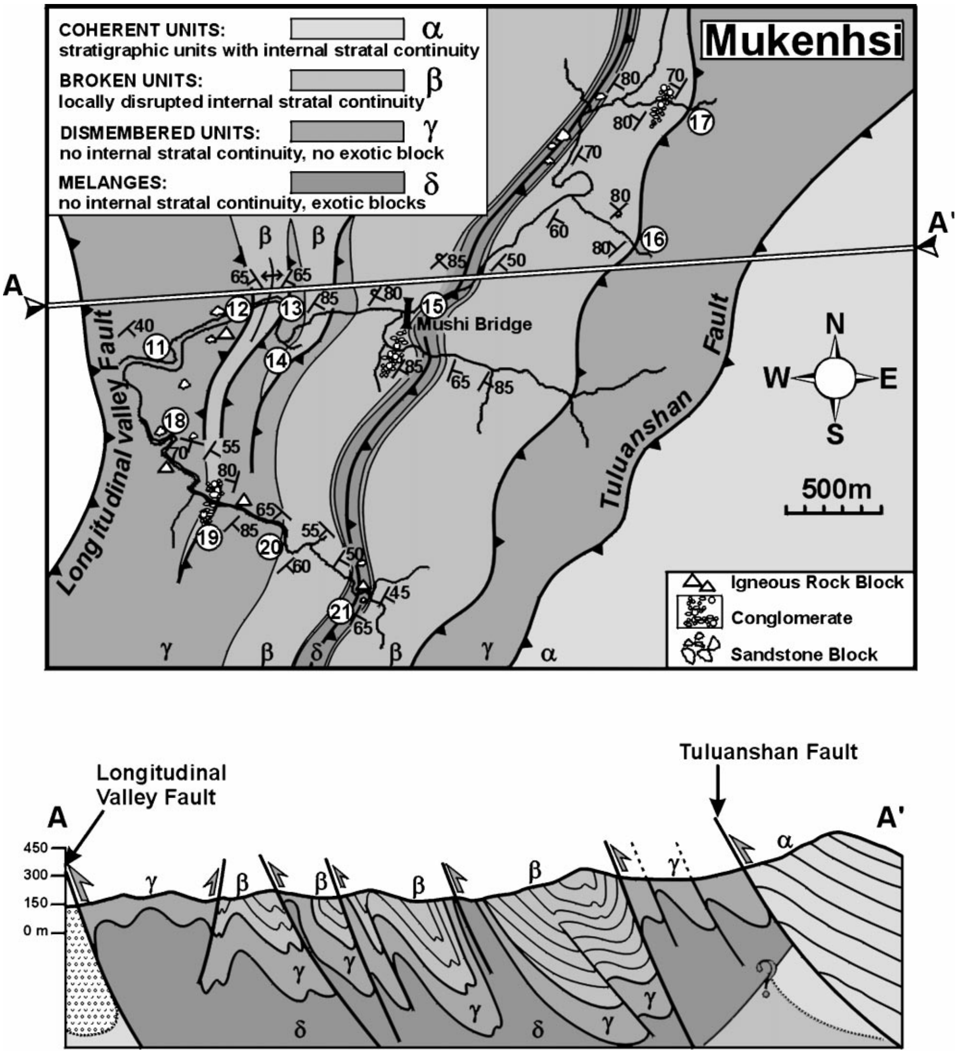

Fig. 4. Detailed geologic map of the Mukenhsi valley area and geologic cross-section. Circled numbers 11–21 refer to sites of brittle tectonic analysis in the Lichi Mélange (stereoplots in Fig. 7).

Mélange (units γ and δ) consists of strongly sheared mudstone, with many intercalations non-sheared and well-bedded coherent turbidites (units α and β). The thickness of the sheared and non-sheared coherent turbidite sections ranges from plurimetric to plurihectometric. The contacts between these turbidites and the matrix of the Lichi Mélange vary in nature. Sometimes, there are clearly faults, but in many other cases there is no sharp boundary between the turbidites and the typical mélange, only a gradual change. This observation is of particular importance because it strongly suggests that the initial relationships were stratigraphic in nature and that the Lichi Mélange and Takangkou Formation should not be interpreted in terms of sedimentary zones initially located at large distances.

In the geological profiles of Figs. 3 and 4, the strongly sheared mudstone observed at present at the surface was originally distributed in the lowermost strata and subsequently extruded along a major fault. These geological profiles correspond with the clay mineral distribution. The observations on clay mineral contents in the Lichi Mélange and adjacent Takangkou Formation, as mentioned before, fit well with the hypothesis of the Luzon arc being closer to the continental margin at the time of the Takangkou flysch deposition. This is also consistent with the relative ages, the Lichi Mélange being older generally than the Takankou Formation in the Mukenhsi area (Lee, 1984). As a mélange, the Lichi Mélange most likely arose from the shearing of the lower forearc sequences during the arc–continent collision. The extrusion path of the principal faults later resulted in generally sharp tectonic boundaries. As a consequence, observing gradual changes between the Lichi and Takangkou units is now unusual, although sedimentary contacts are preserved in some outcrops. Accompanying the strongly sheared mudstones, the deeper Miocene sandstones and the ophiolites have been heavily dismembered, displaced into the mudstones, and subsequently exposed.

5. Structural evolution and shortening in the Lichi Mélange

Figs. 5 and 6 show the schematic structural evolution of the Biehhsi and Mukenhsi profiles, respectively. It is important to mention first that in this structural analysis no control could be exerted on the subsurface geometry and structure, in the absence of drill-holes and seismic reflection profiles. As a result, the geometry in these sections was reconstructed based on the geological information from surface geological mapping solely. The loose geometrical constraints at depth still preclude any advanced balancing of the geological cross-sections in this area. Despite this strong limitation, the reconstructions shown in Figs. 5 and 6 follow the principles of cross-section balancing, even though the large uncertainties on some thicknesses and the significant internal deformation of formations (including small-scale folding and faulting) increase the difficulty of the geometrical reconstruction.

Drastic simplification was thus necessary in Figs. 5 and 6. For instance, the initial configuration for the bottom of the forearc basin was considered as a simple horizontal plane. The units A, B, C and D (from top to bottom) represent the original position of the forearc basin sequences at the first period (stage 1). For the last period (stage 5), these units are equivalent with the four units α, β, γ and δ discussed before based on the method of Raymond (1984) and shown in Figs. 3 and 4. Strong internal deformation has occurred, especially for units β to δ; it involved a decrease in rock volume (principally during syn-depositional tectonism) as well as a significant amount of shear deformation oblique to section trend (especially related to pervasive strike-slip and oblique-reverse slip on numerous minor faults). This explains why the surface in the section was not strictly constant but generally diminished as deformation went on.

Because of these limitations, the geometrical restoration of Figs. 5 and 6 was mainly carried out based on consideration of the length of bedding interfaces in the section. As an other consequence of the lack of subsurface data (drill-holes or seismic reflection profiles) in the area investigated, it is impossible to determine reliably the stratigraphic position(s) of the probable décollement surface(s) and to trace them at depth. For this reason, we did not consider any definite décollement level while restoring the structural evolution in geological cross-sections. It should be noticed, however, that the stratigraphic interface between the Lichi–Takangkou basin formations and the underlying basement formations of the Luzon volcanic arc (the Tuluanshan Formation, with igneous bodies) is a good candidate for such a décollement. The thicknesses of units B and C could be roughly estimated in Figs. 5 and 6 based on field observation, thus allowing raw quantitative evaluation of the deformation. Because of the compaction and water escape that affected the compressed mudstones, and also because of the non-planar shear deformation mentioned before, we considered a surface reduction of about 20% from stage 1 to stage 5 in the sections of Figs. 5 and 6, and we took this reduction into account while reconstructing the initial state of the forearc basin.

In the Biehhsi profiles (Fig. 5), we assumed that the locations of the present-day Longitudinal Valley Fault and Tuluanshan Fault represent the

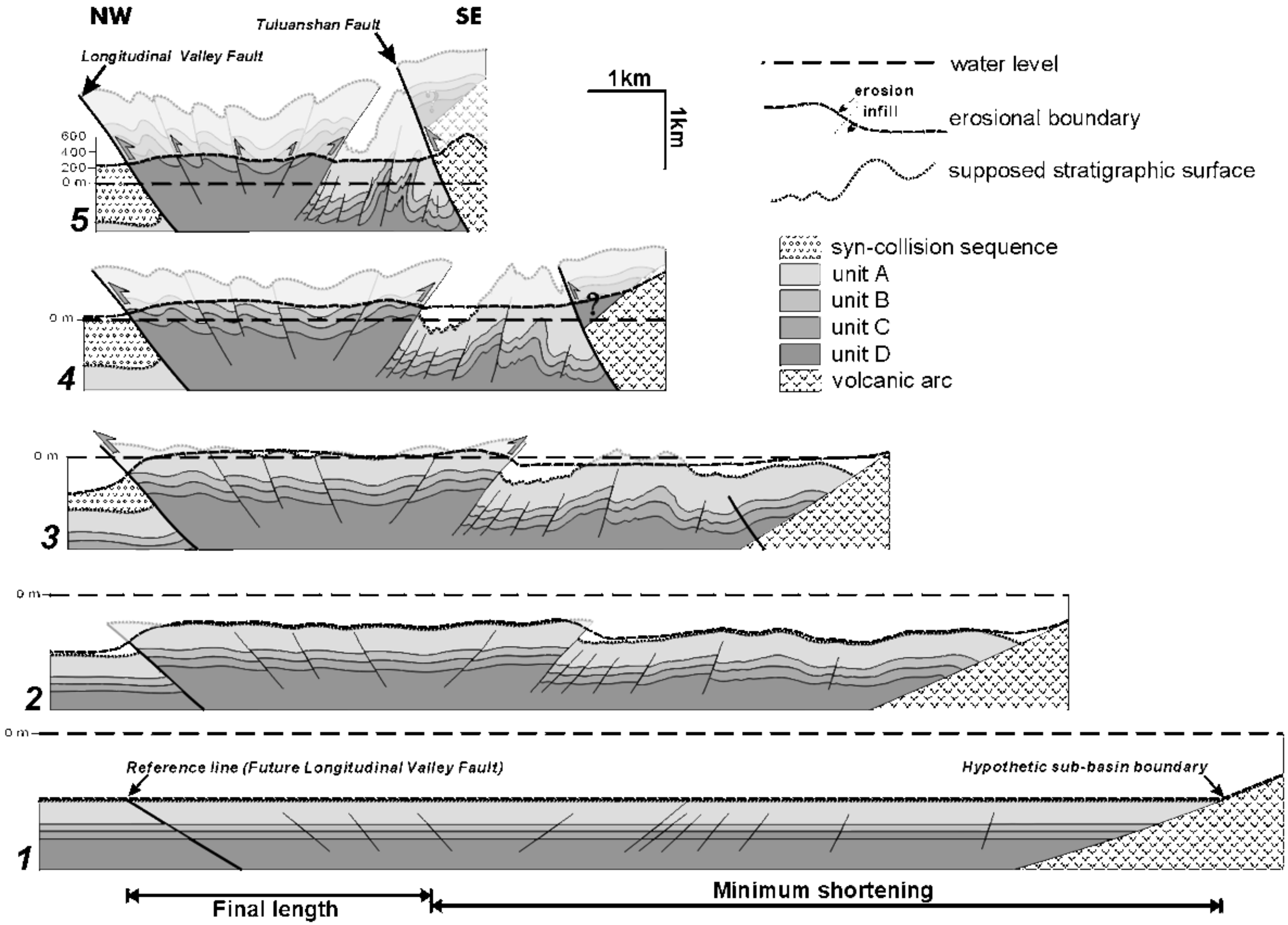

Fig. 5. Structural evolution of the Biehhsi profile. Geometrical assumptions and limitations are discussed in text. The initial configuration for the bottom of the forearc basin is considered as a simple horizontal plane. Units A, B, C and D (from top to bottom) represent the original position of forearc basin sequences at the first period (stage 1). For the last period (stage 5), these units are equivalent with the four units α, β, γ and δ discussed in the text and shown in Fig. 3. Geometrical restoration was carried out based on consideration of length of bedding interfaces. Because of the lack of subsurface data (drill-holes or seismic reflection profiles) in the area investigated, décollement surfaces could not be located. To account for compaction and water escape in compressed mudstones, and also for non-planar shear deformation, a surface reduction of about 20% is applied between stage 1 and stage 5. According to this reconstruction, extensively sheared mudstones came from the lowest position in the basin, whereas weakly sheared mudstones came from the uppermost position and underwent a shorter extrusion path. The minimum shortening between the Longitudinal Valley Fault and the Tuluanshan Fault is about 10 km.

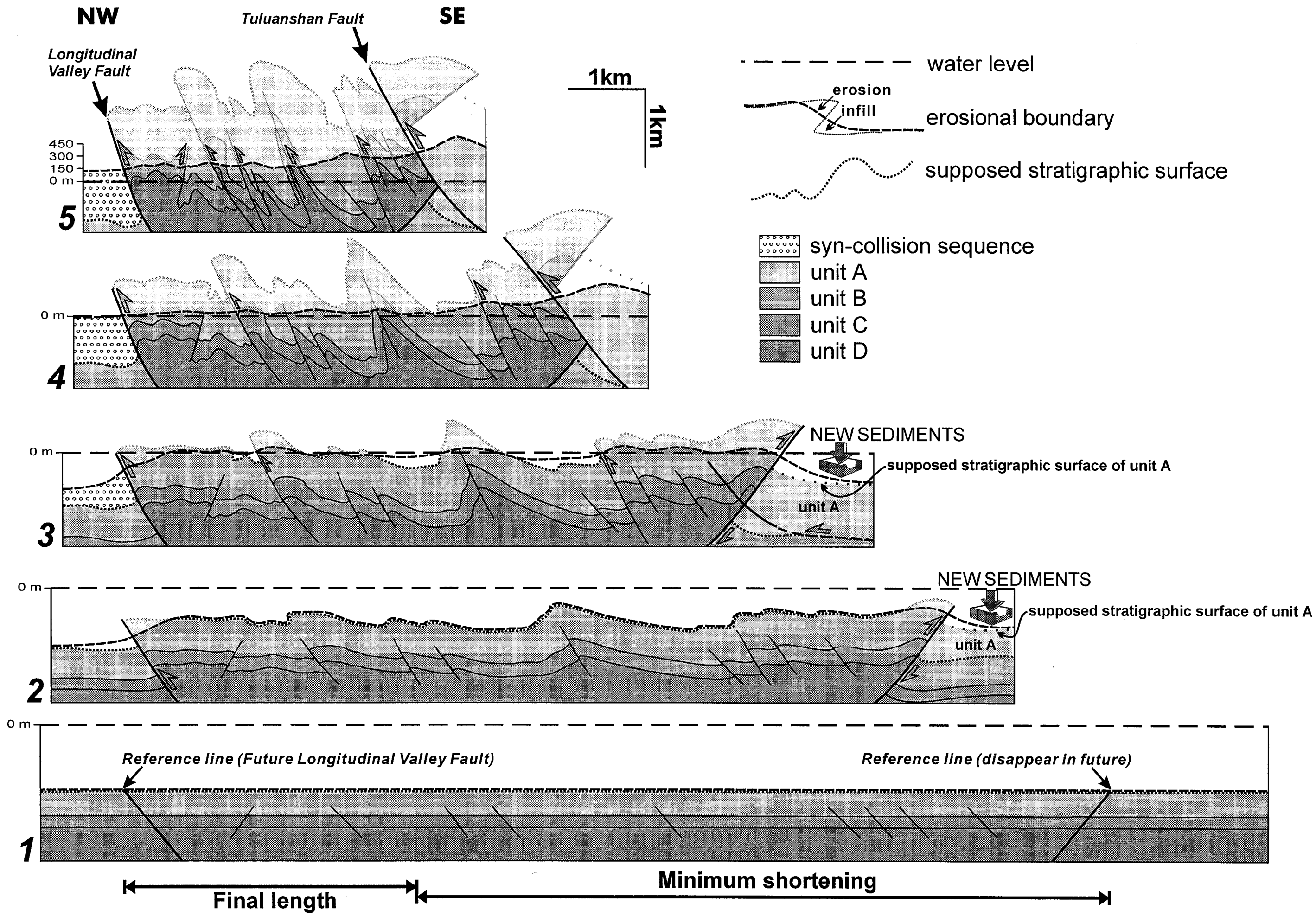

Fig. 6. Structural evolution of the Mukenhsi profile. Principle of restoration as for Fig. 5. Between the Longitudinal Valley Fault and the Tuluanshan Fault, the minimum shortening is about 9 km. Note the particular evolution of the backthrust, which explains the final structure with the younger Takankou Formation (unit A) overriding the older Lichi Mélange (unit C and unit D) across the Tuluanshan Fault.

western and eastern structural boundaries of the studied basin, respectively. This is obviously a minimum hypothesis; the basin may have been much wider, but its western and eastern boundaries cannot be reconstructed because of subsequent erosion. Thus, these western and eastern limits must be viewed as reference boundaries defining the section segment where the deformation can be reconstructed, rather than as actual basin edges. The Biehhsi profile underwent a minimum shortening of about 10 km according to our calculation (Fig. 5). The last steps in the compressional tectonism implied increasing dips for both the fold limbs and the thrusts, which explains the abnormally steep thrust dips in the present-day section, a consequence of severe shortening combined with limited escape possibilities.

As the result of the arc–continent collision, a series of thrusts and backthrusts developed in the forearc basin, these thrusts and backthrusts sheared and uplifted the lower forearc basin sequences and thus formed the precursor of the Lichi Mélange (probably as a submarine ridge) during the early–middle Pliocene times. Despite later reactivation, these thrusts and backthrusts can be tentatively identified in the present Biehhsi area. In this profile, the Tuluanshan Fault is typically a structure of the latest stage, as a product of the final arc–continent collision. In contrast, the Longitudinal Valley Fault was probably active during both this latest stage and the earlier tectonic evolution.

In the Mukenhsi profile, we also assumed that the Longitudinal Valley Fault and the Tuluanshan Fault represent the western and eastern boundaries of the studied section segment, respectively. Between the two boundaries, we reconstruct a minimum shortening of about 9 km in the Mukenhsi section (Fig. 6). The situation near the eastern tip of the section differs, however, from the previously studied one: the formations on the eastern side of the Tuluanshan Fault are younger (unit A) than the formations that crop out on the western side (unit C). We interpreted this particular situation in terms of westward thrusting affecting a backthrust zone (Fig. 6, see stage 3). Because the Tuluanshan Fault developed as a late structure (stage 4 in Fig. 6), it cut across the pre-existing backthrust (stage 3) that had already uplifted the Lichi Mélange to a higher position (stage 2). This observation not only shows that the basin was extending far to the east, but also highlights the complex evolution of large thrust zones, where reversal in motion took place during the compressional history.

According to these reconstructions, a major difference between the Mukenhsi section and the Biehhsi section lies in the absence of a large, east-verging backthrust in the former. In the Mukenhsi section, the westward vergent fold and thrust structures are dominant because the main backthrust was cut and replaced by a westward thrust as mentioned above (Figs. 4 and 6). In the Biehhsi section, the YungFong Fault remained active as the largest backthrust, which resulted in the development of two major structures, anticlinal to the west and synclinal to the east, with double vergence, steep thrusts and tight folds (Figs. 3 and 5).

In a more general way, it is likely that the backthrusts played an important role in the initial period, and that the present attitude of some faults principally results from the latest evolution, involving strong shortening and west-verging thrusting. Such backthrusts form conjugate systems with the thrusts, and hence contributed to uplift the forearc basin sequences. At the latest stage, strong shortening and west-verging thrusting resulted in a rearrangement of the regional structural pattern (stages 4 and 5 in Figs. 5 and 6). This final evolution explains why the younger Takankou Formation could be locally thrusted westwards over the older Lichi Mélange along the Tuluanshan Fault (Figs. 4 and 6), a situation difficult to understand otherwise.

6. Directions of compression in the Lichi Mélange

The most common mesoscopic structure in the Lichi Mélange is the scaly foliation. The curviplanar surfaces of the penetrative scaly foliation are generally polished and bear aligned minerals and slickensides (Chen, 1997). Although the scaly foliation and the slickensides are widespread and easily observable, the sense of the shear movements is often difficult to determine in the Lichi Mélange. This difficulty arises because most of the usual shear sense criteria on fault surfaces are rare, or absent in the clay matrix. For this reason, some of our paleostress reconstructions are subject to uncertainty, although most of them were based on reliable senses of fault motion.

Despite this limitation, we could undertake a comprehensive tectonic analysis of the shear surfaces within the Lichi Mélange, which contributed to reconstruct its tectonic evolution. We determined as many senses of shear as possible, and extrapolated these senses to the other shear surfaces with similar orientations (for both the plane and the lineation) in the same outcrops. The tectonic analysis was carried out based on the numerical inversion of fault slip data. The inversion methods that we used have been described in detail by Angelier (1984, 1990b).

In Fig. 7, we show our tectonic data and results in the Biehhsi and Mukenhsi areas. In both these areas, a NW–SE trending compression clearly prevailed. An interesting aspect is that in most cases the minor fault slip patterns exhibit nearly vertical and horizontal symmetry planes (provided that conjugate subsets are present), whereas the folded layers that they affect show a variety of attitudes. This strongly suggests that in most cases the observed slickenside lineations developed at a late stage in the tectonic history. This does not indicate that faulting occurred recently, but shows that prefolding striations have often been erased and replaced by post-folding ones in most minor fault surfaces in the clay matrix of the Lichi Mélange. For this reason, it was not indispensable to carry out systematic backtilting restoration in our fault slip analysis (which would have been difficult because of the complex shapes of folds in the Lichi Mélange).

In more detail, some outcrops have undergone polyphase tectonism. For instance, in the Mukenhsi area (Fig. 4), the minor fault slip patterns at sites 11, 17 and 18 have recorded one stage of compression (a) and one stage of extension (b). At site 11, the directions of compression and extension are almost identical and at sites 17 and 18 they are similar. Because some senses of slip were difficult to determine on polished fault surfaces in mudstones, some doubt remains concerning the separation between these sub-events. This local uncertainty does not affect the general picture, which reveals widespread NW–SE compression and indicates that some extension may occur.

Furthermore, the crosscutting relationships of the scaly foliations suggest that the compression occurred first, and the extension second. A simple explanation for this kind of stress evolution involves the vertical extrusion that often accompanied folding and thrusting: when the layers were at depth, they mainly underwent the widespread tectonic compression. They locally experienced extension when they came closer to the surface as result of block exhumation and warping. The fold geometry played an important role: for instance, the uppermost layers commonly exhibit tension fractures and minor normal faults indicating extension at outer hinges of anticlines.

This interpretation is supported, at least locally, by the similarity in trend of extension and compression (Fig. 7). Rather than adopting a complicated scenario of alternating compressional and extensional events, which would not find support in the large-scale structural pattern, we have a strong preference for this explanation. This suggests that the tectonic evolution of the area during the Plio–Quaternary does not necessarily involve contrasting far-field regimes, but may simply result from continuing WNW–ESE compression.

The distribution of the maximum compressional stress axes (σ_1) in the Lichi Mélange reveals a systematic orientation. Fig. 8 shows the results at 26 sites (corresponding to a total of more than 800 shear surfaces with slickensides). 24 sites lie in the typical Lichi Mélange, two sites (7 and 8) lie in the Takangkou Formation near the Tuluanshan Fault. The results shown in Fig. 7 are included in this synthesis, and the results obtained at other sites have been added. The azimuthal distribution of the paleostress axes (Fig. 8) indicates a strongly predominant N100°–120°E trend of compression. In detail, a secondary N140°–170°E trend of compression is also present, and few sites reveal extension as discussed before.

However, at a few sites (Fig. 8, sites 9, 22 and 26) different results were obtained. Significantly, these sites are located very close to major exotic

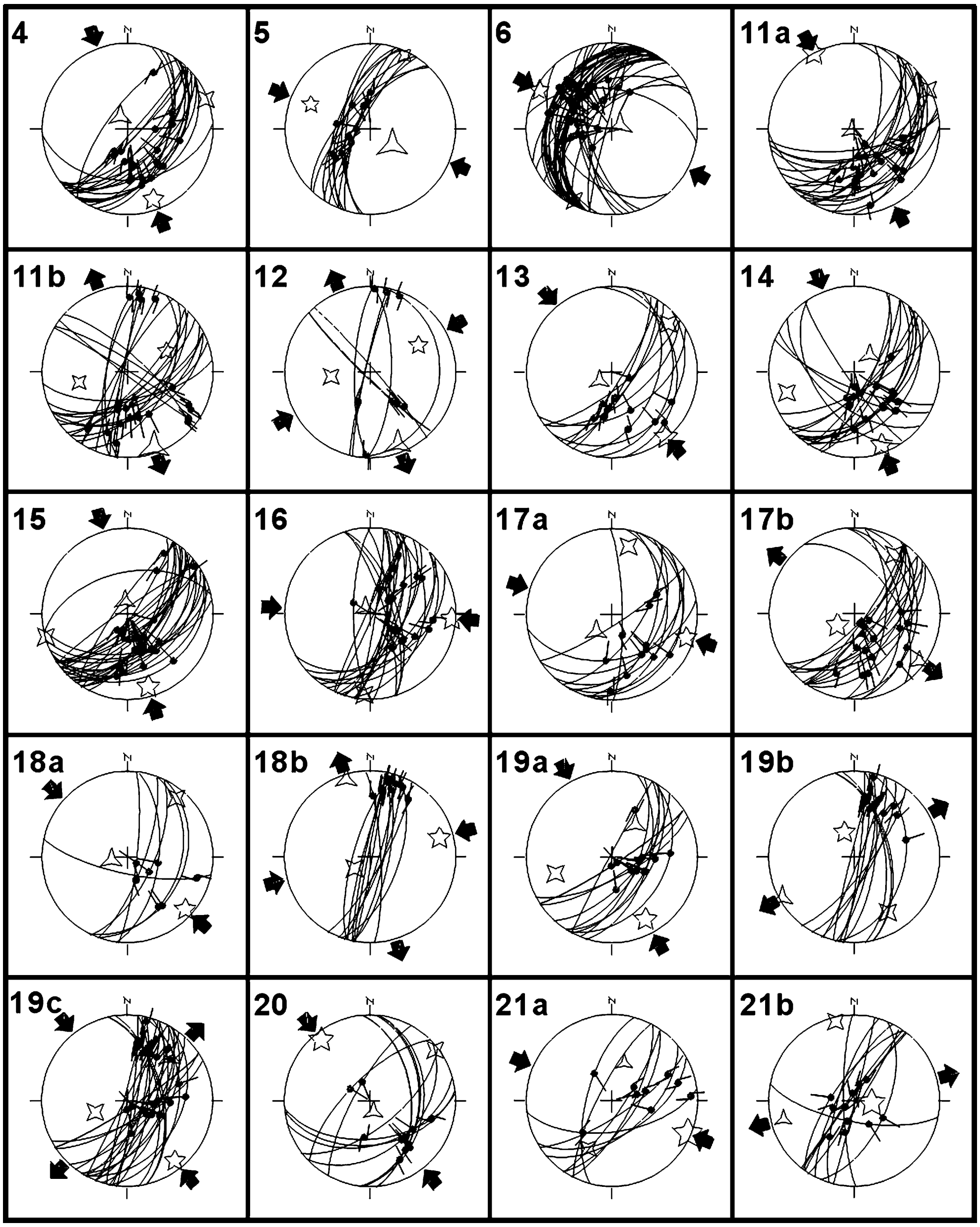

Fig. 7. Stereographic plots of striated scaly foliations measured in areas of Figs. 3 and 4. Lower hemisphere equal-area projection, striated faults as thin curves with dots; inward directed segments for reverse slip, outward directed ones for normal slip, double half segments for strike-slip; paleostress axes as 5-, 4- and 3-branch stars for maximum compressive stress, intermediate stress and minimum stress respectively. Large convergent and divergent arrows indicate directions of compression and extension, respectively. Some limitations are discussed in text.

blocks: site 9 lies near by the plurikilometric block of Kuanshan ophiolite, site 22 is at the border of the Luliaotungshan andesite block, and site 26 is on the side of the Hutoushan ophiolite block. The clay matrix typical of the Lichi Mélange underwent compressional ductile deformation and extensive

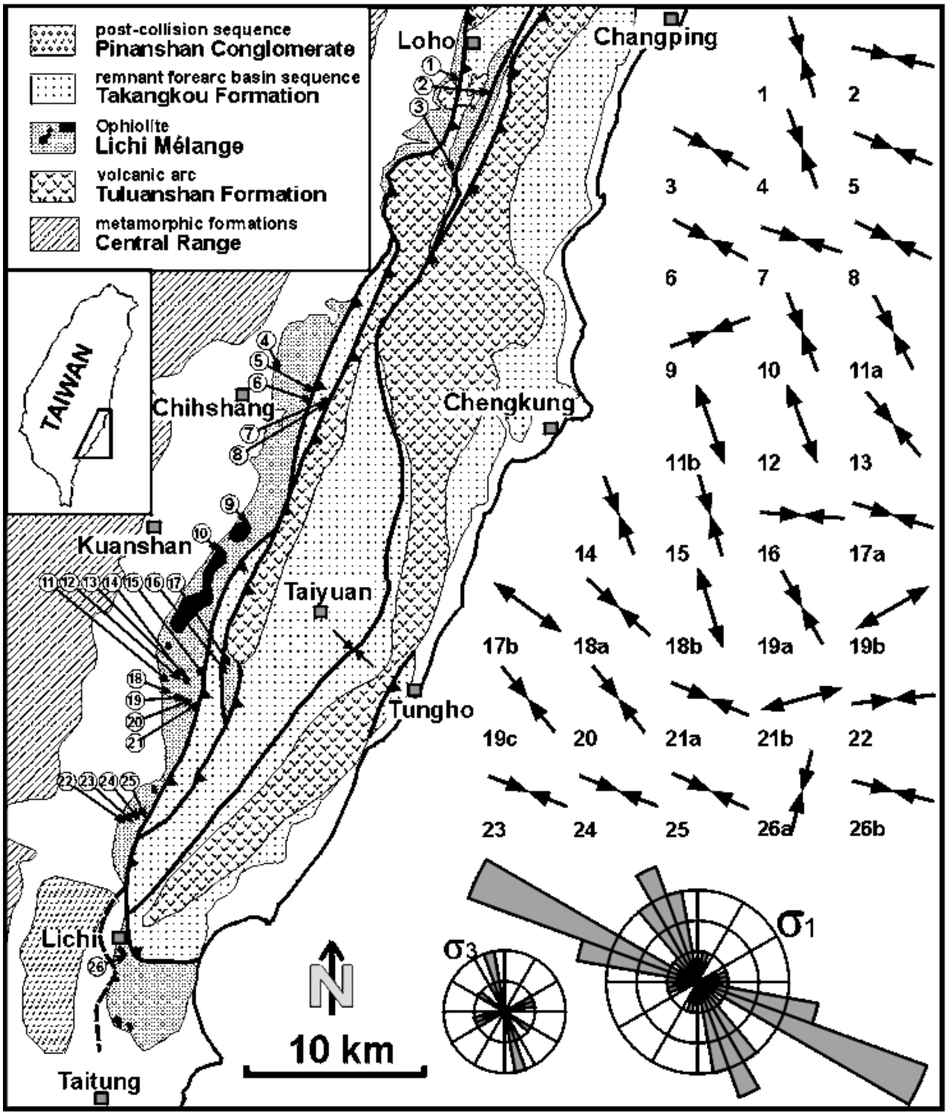

Fig. 8. Distribution of paleostress axes reconstructed in the Lichi Mélange, and statistical distribution of the trends of compression (convergent arrows) and extension (divergent arrows). Numbers near arrows refer to site location in map. For the stereoplots shown in Fig. 7, the same numbers are used. Determination of paleostress tensors based on inversion of fault slip data sets according to Angelier's method (Angelier, 1984, 1990b). The rose diagram of σ_1 trends shows a main regional trend N100°–120°E and a secondary trend of N140°–170°E.

shearing, whereas the blocks of sandstones, volcanic rocks, ophiolitic rocks and even coherent turbidites contained in the Lichi Mélange behaved as mechanically harder material. Around the large blocks, the mesoscopic structures that we used to reconstruct the local tectonic regimes reflect the strong perturbations related to sharp contrasts in rheology, and the accommodation of the compressional deformation near block boundaries. We infer that although the regional stress is clearly expressed in the statistical figure issued from fault slip data analyses (Fig. 8), the mechanically inhomogeneous structure of the Lichi Mélange favours local variations.

A detailed analysis of Late Cenozoic faulting had been carried out in the Coastal Range by Barrier and Angelier (1986). Most of their measurements have been collected in the Takangkou Formation (62% in the Takangkou Formation, 32% in the Tuluanshan Formation and 6% in the Pinanshan Conglomerate). According to their results, the direction of the maximum compressional stress σ_1 has remained constant, with 25% of reconstructed σ_1 axes trending approximately N120° and 90% trending between N90°–140°E. Our new results obtained in the Lichi Mélange (Fig. 8) are quite consistent with these earlier determinations in the other formations of the Coastal Range.

7. Discussion

The GPS data in the Taiwan area showed that the North Luzon arc moves towards the Eurasian continent with a velocity of about 8.2 cm yr^{-1} in the azimuth about 306° (Yu et al., 1997). Because the orientation of the pre-collision Eurasian continental margin was N60°E and the trend of the North Luzon arc is N5°W, the Taiwan arc–continent collision is a typical oblique collision. As a result, the Taiwan orogen propagates southward and collision has not begun yet in the south offshore Taiwan. Because of this obliquity of the convergence, one can use the present geological situation of a southern section to reconstruct the past framework of a northern one. The discussion below follows this principle.

The present plate boundary in the late collision zone was inherited from the submarine arc–prism boundary in an ancient arc–continent collision zone. Fig. 9 presents the tectonic evolution of this active plate boundary (the Longitudinal Valley) and the Lichi Mélange. We use some names of geomophological units off southeastern Taiwan to assist our explanation; these names are all shown in Fig. 1. The topography shown in Fig. 9 does not completely fit the present real topography. For the sake of clarity, in order to better illustrate the structural evolution of the Lichi Mélange, we exaggerated the topography and put emphasis on the geographic distribution of the Lichi Mélange; accordingly, the geographic extent of the undeformed domain of the forearc basin is underestimated.

Stage A (Fig. 9a) represents the pre-collision geological framework between the accretionary prism and the volcanic arc. This stage corresponds to the Miocene in Taiwan, when the Manila trench was the boundary between the Eurasian plate and the Philippine Sea plate. East of this subduction zone, a submarine ridge was the newly developing subduction wedge, like the present Hengchun Ridge (we compare the general geological situation of this stage with a present-day cross-section at 21°N, as Fig. 1 shows). Because the collision had not occurred yet at this area, the Longitudinal Valley and the Lichi Mélange did not exist at this early stage.

In the latest Miocene, the Taiwan arc–continent collision began to occur. The stage B (Fig. 9b) can be considered as the Pliocene in Taiwan. The Lichi Mélange developed initially as the result of series of thrusts and back-thrusts affecting of forearc sediments in the forearc basin (Fig. 9b), like the present Huatung Ridge in the southeastern offshore Taiwan (Huang et al., 1992). Between the precursor of the Lichi Mélange (as the present Huatung Ridge, named the proto-Lichi Ridge herein) and the accretionary prism (as the present Hengchun Peninsula), the precursor of the Longitudinal Valley formed. It corresponds to the present Southern Longitudinal Trough. This intervening basin received a large supply of sediments from the uplifted and exposed accretionary prism. East of the proto-Lichi Ridge, the remnant forearc basin was reduced and subsiding (it can be considered as the present Taitung Trough as the Fig. 1 shown). In comparison with the Southern Longitudinal Trough, this narrow forearc basin received less, and finer-grained sediments.

The third stage is well represented in the present Taiwan island (Fig. 9c). The volcanic islands and the forearc basin on the Philippine Sea plate were all accreted onto the uplifted Eurasian continent and became the present Coastal Range. The proto-Lichi Ridge between the volcanic arc and the Eurasian continent was thus extruded and exposed

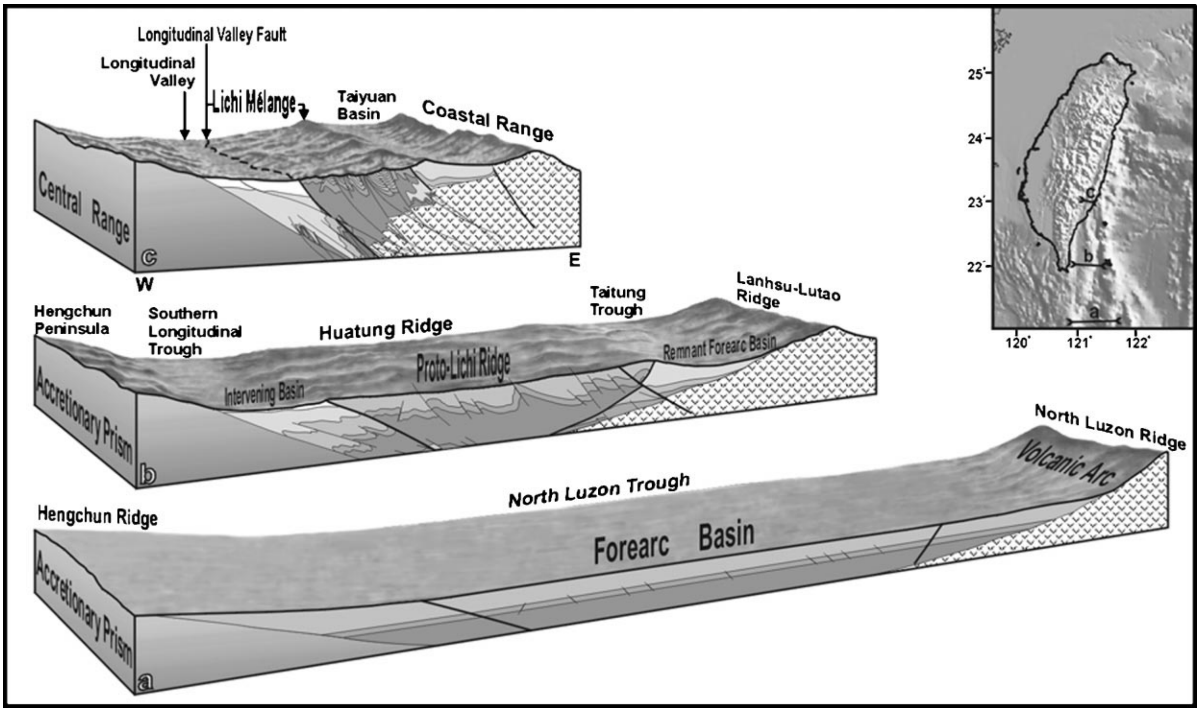

Fig. 9. Structural evolution of the Lichi Mélange and the Longitudinal Valley Fault. Three bars in the topographical map (upper right inset) indicate the approximate locations of staged evolution profiles a, b and c. Because the Taiwan arc–continent collision is a typical oblique collision, the collision and Taiwan orogen propagate southward, so that one reconstructs the tectonic evolution by comparing geological cross-sections at different latitudes. Thus, for stages A and B, some names of geomorphologic units located off southeastern Taiwan at the present are used to support the explanation. Stage C is directly observed in the study area of this paper. The topography shown in figure does not completely fit the present real topography: to illustrate the structural evolution better, the topography and geographic distribution of the Lichi Mélange were exaggerated; and the geographic extent of the undeformed domain of the forearc basin was underestimated. According to this model, the Longitudinal Valley Fault originated as an arc–prism boundary and because of arc–continent collision, developed as the main plate boundary in the weak zone between the accretionary prism (the Central Range derived from the Eurasian continent) and the Luzon arc (the Coastal Range on the Philippine Sea plate side).

at the western border of the Coastal Range to form the Lichi Mélange of eastern Taiwan. About 1 Ma ago, much of the underthrust Eurasian continent was exposed, and the accretionary prism became the principal mountain belt in Taiwan; a major compressive structure, the Longitudinal Valley Fault, developed as the main plate boundary in the weak zone between the accretionary prism (derived from the Eurasian continent) and the Luzon arc (on the Philippine Sea plate). The presence of this major zone of weakness resulted in increasing deformation and shearing of the Lichi Mélange. This multistep tectonic evolution explains why the present Lichi Mélange has such a complex structural framework. In terms of general structural geology, the Lichi Mélange can be considered as a thick fault zone (Fig. 9c). This fault zone is composed of many smaller faults, which usually concentrate on the western flank of the Coastal Range. In some cases, however, the Lichi Mélange occurs inside the Coastal Range (such as for the Loho basin and the Fonping area as Fig. 2b shows), which highlights both its relationships with the lower Takangkou Formation and the presence of shear zones inside the Coastal Range domain.

The origin of the ophiolite in the Lichi Mélange (the East Taiwan Ophiolite, Liou et al., 1977a) and quartzose sandstone block needs to be discussed. Both the ophiolite and quartzose sandstone blocks are found only in the intensively sheared zones of the Lichi Mélange. The quartzose sandstones differ in composition from rocks of non-sheared coherent turbidites, which had Cenozoic volcanic and metamorphic sources (Teng, 1979). However, provenance studies showed that the quartzose sandstones are similar in composition to those exposed in the Hengchun Peninsula (Sung, 1991) and inferred in the subduction wedge, which derived from Mesozoic and older rocks of the SE Asian continent. The ophiolite blocks were part of oceanic crusts generated in the South China Sea (Liou et al., 1977a; Suppe et al., 1981; Yui and Yang, 1988), which is also found in the Hengchun Peninsula. It is therefore possible that both the exotic ophiolite and the quartzose blocks in the Lichi Mélange represent debris offscrapped from the subduction wedge to the west and subsequently backthrusted and incorporated in the mélange.

8. Conclusion

The Lichi Mélange in the Coastal Range plays a key role in the reconstruction of the active plate boundary evolution before the present-day Longitudinal Valley. The relationship between the Takankou Formation and the matrix of the Lichi Mélange is complex. Detailed field mapping (Figs. 3 and 4) bring new data, highlighting both the tectonic and stratigraphic aspects of these relationships, which have strong inferences for the pre-suturing evolution (Figs. 5, 6 and 9). Field evidence from the Lichi Mélange outcrops suggests that the Lichi Mélange originated from thrust forearc basin rocks, rather than being part of a subduction complex. The Lichi Mélange can be considered as a sheared lower forearc basin sediment sequence. Because of the later development of the structure (thrust, backthrust or diapir extrusion), it is presently exposed along the western boundary and some main fault zones of the Coastal Range. The mesoscopic structures in the Lichi Mélange reveal compression that trends N100°–120°E. This direction of Quaternary compression is fairly consistent with both the N54°W present-day direction of convergence between Lanhsu (Luzon arc) and Paisha (Taiwan strait) given by satellite geodesy (GPS) analyses (Yu et al., 1997) and the N51°W direction of plate convergence (Seno, 1977; Seno et al., 1993).

Finally, the general evolution of the present plate boundary (the Longitudinal Valley), along which the Lichi Mélange crops out, is highlighted through a comparison of the geological situations in the southern and northern segments of the convergence zone (Fig. 9). Before 5 Ma ago, during the subduction stage, the proto-Manila trench was the boundary between the Eurasian and Philippine Sea plates. This subduction zone was bounded to the east by a subduction wedge with Miocene deep-sea sediments (now exposed in the western Central Range and the Hengchun Peninsula). However, since the arc–continent collision had begun, the subduction wedge was pushed to the west, and hence the trench turned into a thrust front (now represented in the southwestern offshore Taiwan). The forearc basin sequences underwent thrusting, backthrusting, shearing and uplift (Fig. 9b and c). At present, the thrust front is located west of the Western Foothills and the offshore Kaoping Slope off SW Taiwan. As a result of continuing convergence, the Luzon arc has been accreted onto the Eurasian continent, thus becoming the Coastal Range (Fig. 9c). The metamorphic basement rocks of the underthrust Eurasian continent were also thrusted and uplifted, resulting in the eastern Central Range. A new active plate boundary between the Eurasian continent and the Philippine Sea plate thus developed along the Longitudinal Valley in eastern Taiwan.

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