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THE PLIOCENE LICHI MÉLANGE OF TAIWAN: ITS PLATE-TECTONIC AND OLISTOSTROMAL ORIGIN

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ABSTRACT. The unlithified Pliocene Lichi mélangé was formed during the initial stages of collision of the Luzon island arc with the stable Chinese continental margin in Taiwan. The mélangé is composed of sheared scaly-mudstone matrix containing millimeter- to kilometer-long exotic blocks and slabs. The exotic blocks are largely deep-water sandstones and shales interpreted to be continental-rise and abyssal-plain sediments of the now subducted part of the South China Sea and ophiolitic rocks interpreted to be deposited along a now subducted transform fault of the China Basin Ridge system, discussed by Suppe, Liou, and Ernst (this issue, p. 228-246). The mélangé exhibits crude 1 to 10 m layers that are shown to be largely olistostromes of exotic sedimentary rocks with minor interlayered serpentinite olistostromes and non-exotic mudstones and pebbly mudstones. Although the Lichi mélangé is largely composed of exotic blocks of oceanic materials, it was not formed in a trench or subduction zone because the mélangé is contained within the stratigraphic sequence of the volcanic island arc. The mélangé positionally overlies mudstone and sandstone of the late Miocene and Pliocene Takangkou Formation, which in turn overlies volcanic rocks of the west flank of the Luzon volcanic arc in eastern Taiwan. The contact between the mélangé and the Takangkou Formation is quasi-conformable with some evidence for interfingering; ripped-up blocks of Takangkou mudstone are contained within the mélangé. Immediately below the mélangé contact, the Takangkou Formation displays sea-floor sedimentary-slump folds indicating a northwestern source for the mélangé. Subaerially eroded ophiolitic detritus in Lichi and Takangkou pebbly mudstones indicates that part of the source area was exposed above sealevel. Estimated water depths based on benthonic forams and paleogeographic considerations indicate that the basin of Lichi-Takangkou deposition was the now destroyed northern continuation of the Luzon Trough forearc basin, which lies between the volcanic arc and the accretionary wedge (outer non-volcanic arc). The Lichi mélangé is interpreted to be a fault-scarp olistostromal facies of the Takangkou Formation deposited on the west flank of the Luzon Trough during the collapse of the forearc basin during initial stages of continental collision. The source of the mélangé was the expanding accretionary wedge to the west. Present-day bathymetry 100 km south of Taiwan, where the arc-continent collision is just now beginning, is similar to that inferred for late Pliocene Lichi-Takangkou deposition. Mélanges similar to the Lichi mélangé can be expected to have formed widely in the geologic past during arc-continent collision and should not be confused with trench-subduction zone mélanges.

THE PLIOCENE LICHI MÉLANGE OF TAIWAN: ITS PLATE TECTONICS AND OLISTOSTROMAL ORIGIN

The young Lichi mélangé of eastern Taiwan provides insights into the origin of mélanges that are not generally available in more ancient and complex mountain belts. The mélangé is probably middle to late Pliocene (~2-3 m.y.) in age, is unmetamorphosed, and has experienced a relatively short, uncomplicated, and still on-going tectonism; moreover, its plate-tectonic context is clearer than that of most ancient mélanges.

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The Lichi mélange forms the bulk of the Lichi Formation of Hsu (1956), which also contains minor normally stratified sediment. This largely chaotic formation was studied and mapped by T. L. Hsu and C. S. Wang (Hsu, 1956), whose observations stimulated discussion by Big (1969, 1971), Jahn (1972), Chai (1972), Ho (1977), and others. Additional work was done by Page (1974, 1978), Hsu (1976a), Wang (1976), and Liou and others (1977a). The Lichi mélange contains the Miocene East Taiwan Ophiolite, discussed in the companion paper (Suppe, Liou, and Ernst, this issue, p. 228-246). The general geology of Taiwan has been summarized by Chai (1972) and Ho (1975).

REGIONAL SETTING

The Island of Taiwan, locally almost 4 km high, rises from the otherwise stable continental shelf of China, because it is situated on a compressive boundary between the Asian and Philippine Sea plates (fig. 1). According to Seno (1977) the rate of present plate convergence is about 7 cm/yr in a northwest-southeast direction ($\omega = 1.2^\circ/\text{m.y.}, 45.5^\circ\text{N}, 150.2^\circ\text{E}$). To the east and northeast of northern Taiwan, the Philippine Sea plate is subducting northwestward beneath the Ryukyu island arc. In contrast, south of Taiwan, the Philippine Sea plate is overriding the lithosphere of the South China Sea, which is part of the Asian plate, along the Manila Trench. Taiwan occupies a region between these two well-defined subduction systems of opposite polarity. Seismicity does not clearly define a deep subduction zone at present in the immediate vicinity of Taiwan except in the north where the Ryukyu arc is accompanied by a Benioff zone (Tsai and others, 1977; Wu, 1978). Nevertheless, convergence must be occurring because the structure of Taiwan is dominated by northwest-vergent thrusting accounting for 150 to 200 km of shortening in the Pleistocene and late Pliocene (Suppe, 1980) and because geomorphology and historic faulting indicate that thrusting continues (for example, Bonilla, 1977).

Morphotectonic continuity between Taiwan and the Luzon arc to the south shows that the structure of Taiwan is more closely allied with the subduction of the Asian plate south of Taiwan along the Luzon arc than with that of the Philippine Sea plate along the Ryukyu arc (fig. 1). The Luzon volcanic arc (including Babuyan, Batan, and Lu Tau Islands, fig. 1) continues northward into the low Coastal Range of eastern Taiwan where Neogene island-arc volcanic rocks are exposed (fig. 2). The submerged outer non-volcanic arc (accretionary wedge) expands continuously toward the north rising above sealevel to merge morphologically with the great Central Mountains of Taiwan (fig. 1), which are constructed of the west-vergent thrust sheets mentioned above.

The Luzon Trough, a forearc basin, narrows and shallows toward the north and projects directly into the southern Coastal Range, which contains the Lichi mélange (figs. 1 and 2). The southward bathymetric continuation of the Coastal Range is a narrow submarine ridge that dies out within the Luzon Trough about 50 km to the south. This observa-

tion raises the suspicion that part of the floor of the Luzon Trough might have been uplifted and deformed to form part of the Coastal Range. However, the linear, north-northeast trending Longitudinal Valley (fig. 2) is best considered the morphotectonic equivalent of the Luzon Trough in Taiwan.

The Longitudinal Valley contains important active faults affiliated with the Philippine Sea-Asian plate boundary and is regarded by some as *the* plate boundary; however, current crustal deformation spreads over the width of Taiwan with many of the major historic earthquakes in western Taiwan (Bonilla, 1975; Wu, 1978). Furthermore the Manila Trench, which is normally considered the plate boundary south of Taiwan, has been traced as a sediment-filled structure at least as far north as 22°N latitude, west of southernmost Taiwan (Ludwig, Kumar, and

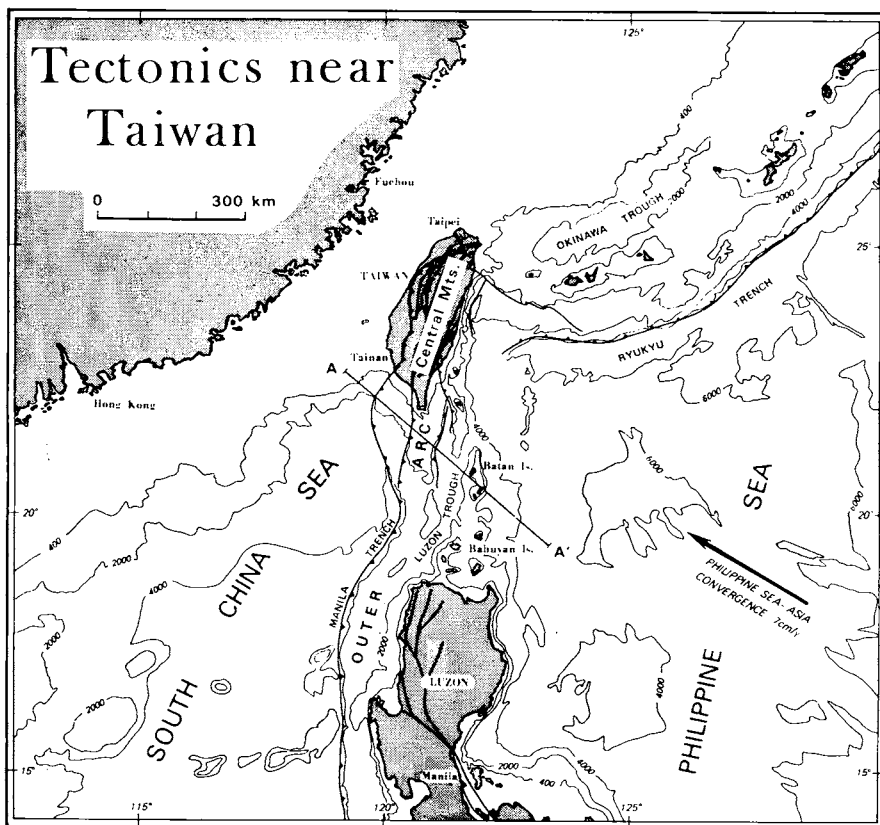


Fig. 1. Map illustrating the principal present-day tectonic features near Taiwan. The instantaneous Philippine Sea-Asia plate convergence of about 7 cm/yr near Taiwan is from Seno (1977). The Asian plate is subducting along the Manila Trench and its northern sediment-filled continuation, the foredeep of western Taiwan. Northeast of Taiwan the Philippine Sea plate is subducting along the Ryukyu Trench. The subduction changes polarity in northernmost Taiwan (see Tsai and others, 1977; Wu, 1978). Bathymetry after Scripps Institution of Oceanography (1969); contours in meters. Section A-A' is shown in figure 7.

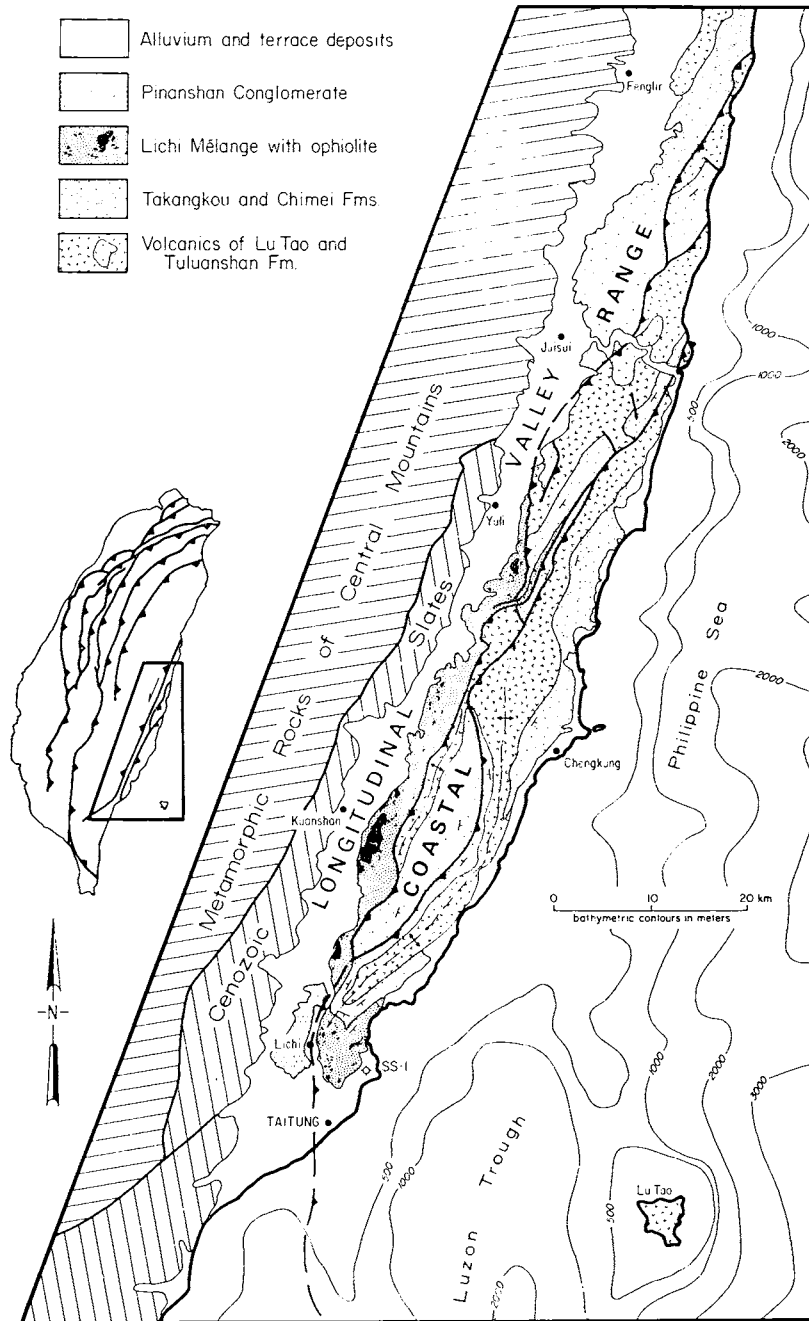


Fig. 2. Geologic map of the Coastal Range of eastern Taiwan, modified from Hsu (1976a) and Ho (1975).

Houtz, 1979). Leaving these considerations of plate boundaries, the Longitudinal Valley marks the boundary between the Coastal Range to the east underlain by island-arc volcanic rocks and the Central Mountains to the west underlain by deformed rocks of the Chinese continental margin. It is an alluviated topographic and structural feature containing active faults and several independent drainage systems (Hsu, 1956, 1962, 1976b; Allen, 1962; Biq, 1965; Bonilla, 1975; Wu, 1978). Both east- and west-vergent thrust faulting and left-lateral strike-slip faulting characterize the zone.

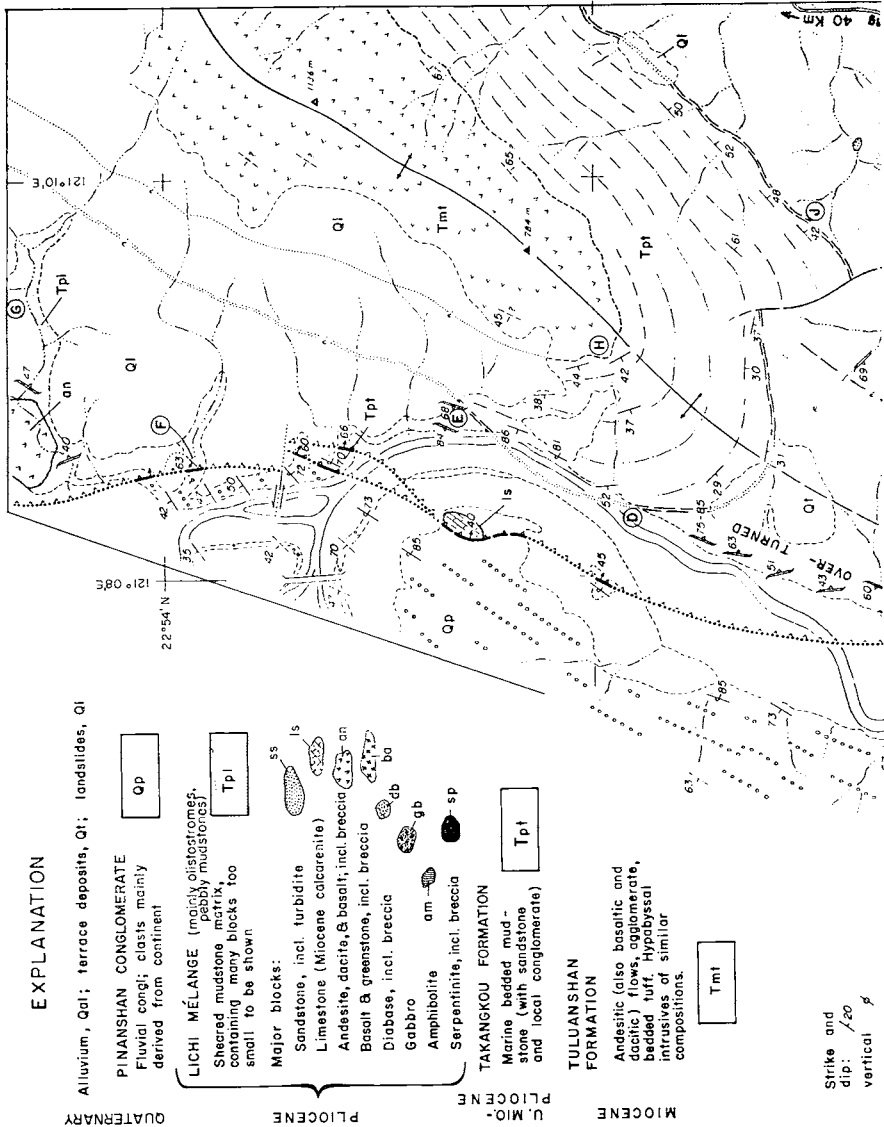
The bulk of Taiwan, comprising the Central Mountains and western Coastal Plain, lies west of the Longitudinal Valley and is underlain largely by miogeoclinal clastic sedimentary rocks of the Chinese continental shelf, slope, and rise (Ho, 1975). These rocks range from Paleogene through lower Pliocene and are derived from China Mainland to the west. They are strongly folded and imbricated by west-vergent thrusts and become increasingly metamorphosed in the eastern half of the Central Mountains. Along the eastern side of the Central Range, where relatively deep rocks and structures have been exposed through thrust imbrication, the miogeoclinal sediments are seen to rest unconformably on Mesozoic and upper Paleozoic basement rocks, which are presumed to belong to the Asian continent (Suppe and others, 1976). On the whole, the structure west of the Longitudinal Valley resembles that of the Central and Southern Appalachians from the Blue Ridge west (Chai, 1972; Suppe, 1976, 1980).

In western Taiwan the folded and imbricated Neogene miogeoclinal strata are conformably overlain by thick Pliocene mudstones and sandstones, which reflect the trapping of sediment between the Asian mainland and the approaching island arc at the edge of the Philippine Sea plate. These strata are in turn overlain, largely conformably, by floods of coarse nonmarine Pleistocene gravel derived from the east, which record the rising Central Mountains accretionary wedge, as the island arc collided with the edge of the Asian continent (Chou, 1973, 1977). This collision is just now beginning at the southern tip of Taiwan but began in Pliocene in northern Taiwan (see figs. 1 and 8).

We now move on from the general geologic setting of Taiwan to consider the stratigraphy of the Coastal Range, which is fundamental to understanding the origin and tectonic significance of the Lichi *mélange*.

Coastal Range Stratigraphic Sequence

The relatively low Coastal Range lies between the Longitudinal Valley and the eastern shoreline of Taiwan (fig. 2). It is 133 km long but only 3 to 7 km wide and only locally rises more than 500 m above sea-level. The geology has been described by Hsu (1956) and briefly summarized by Chai (1972), Ho (1975), and Wang (1976). The basic stratigraphic sequence pertinent to the tectonic history is given in the legend of figure 2; representative parts of the sequence are shown in greater detail in the geologic map of the southern tip of the Coastal Range (fig. 3).



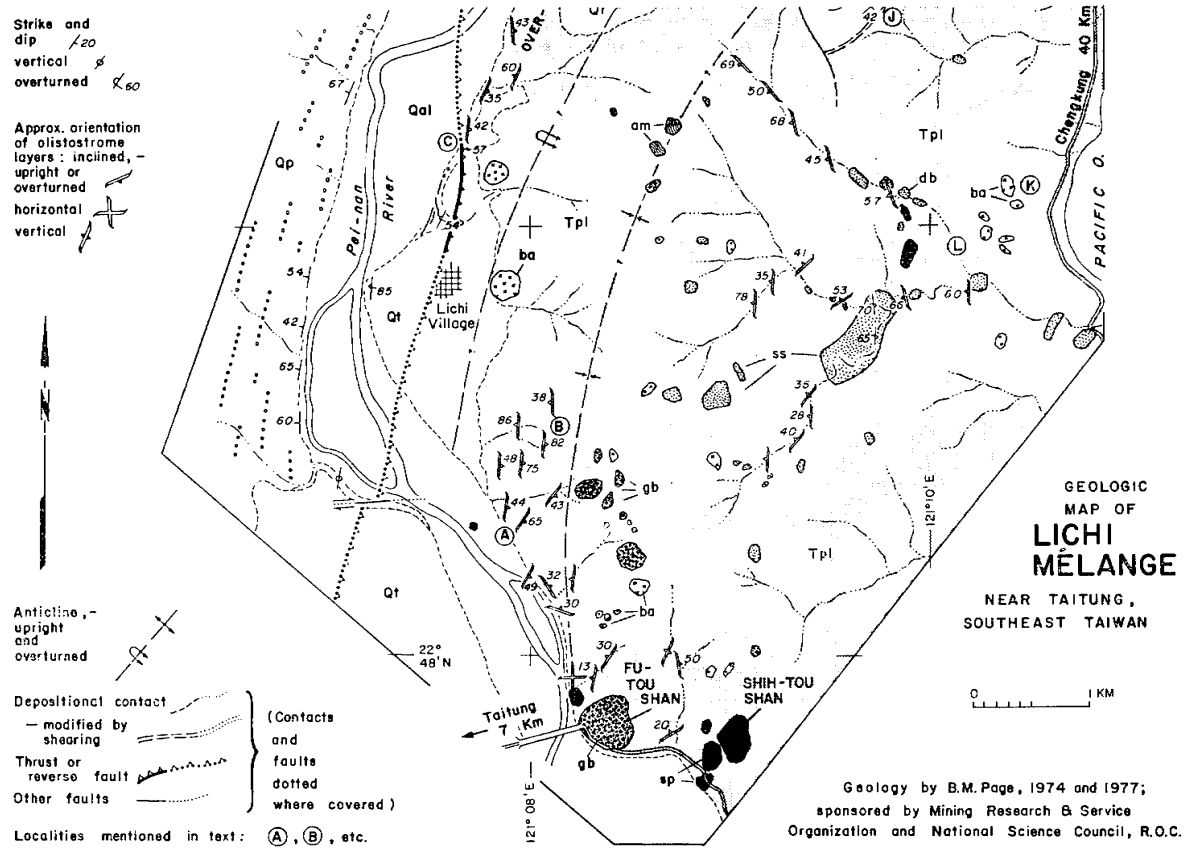


Fig. 3. Geologic map of Lichi mélange in southern tip of Coastal Range of Taiwan.

Tuluanshan-Chimei island-arc assemblage.—The deepest exposed stratigraphic unit of the Coastal Range is the Tuluanshan Formation (Hsu, 1956) and the associated Chimei Igneous Complex.

The Tuluanshan Formation consists of volcanic flows, breccias, agglomerates, tuffs, and volcanoclastic sediments. The material is largely andesitic but includes basaltic andesite, basalt, and dacite. The deeper parts of the extrusive pile are cut by dikes of andesite and basalt, and by bodies of diorite. An assemblage 8 km east of Juisui (fig. 2) containing abundant intrusives has been called the Chimei Igneous Complex. The Tuluanshan Formation is at least 1400 to 1500 m thick (Hsu, 1956). Chemical and petrographic data support the interpretation that the magmatic suite originated in an island-arc setting (Chen, 1975; Yen, 1968, 1977). The arc rocks probably rest upon oceanic lithosphere because xenoliths and clasts of serpentinite, peridotite, and gabbro are reported from the intrusive and volcanoclastic rocks on the east side of the Coastal Range and from the Island of Lanshu, 90 km southeast of Taitung (Yen, 1968; Wang, 1976; Ho, 1975), whereas sialic basement rocks are not found as xenoliths.

Whole-rock K-Ar dates of 9 to 22 m.y. (Miocene) were reported for six samples of the Chimei Complex by Ho (1969), who thinks the youngest date may reflect metasomatism and metallization. Judging from the older dates and from the middle Miocene age reported for the Kangkou Limestone, which locally overlies the Tuluanshan Formation, the arc assemblage exposed in the Coastal Range could be largely Lower Miocene, although more complete information is needed because complex facies relations are possible in island arcs. Radiometric dates ranging from 13 to 7 m.y. (late Miocene) are reported for volcanic rocks on the Island of Lanshu, 90 km southeast of Taitung (Ho, 1975). Active and dormant volcanoes are present farther south in the Luzon arc (fig. 1), including the Batan and Babuyan Islands and Luzon Island (Van Padang, 1953).

Kangkou Limestone.—A shallow-water limestone, called the Kangkou Limestone, overlies the Tuluanshan volcanic rocks discontinuously and unconformably (Hsu, 1956). It is generally only 0.5 to 10 m thick and is absent in the area shown in figure 3. It is valuable regionally because of its reported middle Miocene age (Chang, 1967). Ingle (1975) tentatively places the unit in planktonic foraminiferal zone N8/9 of Blow (1969), probably corresponding to an age of about 16 m.y. There is no indication that island-arc volcanism continued in the immediate vicinity after the limestone deposition.

Takangkou Formation.—The Lichi mélange is closely associated with the Takangkou Formation, which was named and described by Hsu (1956) and which, in this paper, includes the Chimei Formation (not to be confused with the Chimei Igneous Complex). The Takangkou sediments are a marine clastic sequence, which was apparently deposited in the forearc basin (Luzon Trough) west of the volcanic arc and which overlapped parts of the arc itself where volcanism had terminated locally. In some localities, the basal beds of the Takangkou Formation contain pebbles and cobbles of Tuluanshan andesite (for example, loc. H, fig. 3).

In the southern half of the Coastal Range where the Lichi mélange is exposed, much of the Takangkou Formation is stratified mudstone and siltstone with thin sandy interbeds and only a few prominent sandstone beds. Locally, there is limited

pebbly mudstone with ophiolitic clasts similar to pebbly mudstone in the Lichi Formation (Hsu, 1956; Liou, Suppe, and Ernst, 1977).

In the northern Coastal Range, where the Lichi mélangé is missing (fig. 2), the lower half of the Takangkou Formation is chiefly mudstone and siltstone as just described (pl. 7-A), but thick conglomerate lenses occupy the middle of the section (fig. 4). The conglomerates contain pebbles and boulders similar to Central Mountains rock types, although ophiolitic fragments are also present, implying that collision was in progress and mountains were rising on the edge of the Asian continent nearby to the west or northwest. This will be discussed later. Above the conglomerate, flysch-type alternating beds of turbidite sandstone and intervening mudstone are exposed (fig. 4).

The bulk of the Takangkou mudstone and sandstone reflects fairly deep-water conditions. The sandstone is commonly graded and locally shows convolute bedding and flute casts, especially in the upper half. Both sandstone and mudstone lack molluscan fossils, but the mudstone contains foraminifera of which the benthonic species indicate minimum water depths of perhaps 1700 to 1800 m (Ingle, 1975), similar to the depth of the Luzon Trough (figs. 1, 2, and 8).

According to Chang (1967, 1968, 1969) and Chang and Chen (1970), virtually the entire sequence, approaching 4 km in thickness in some localities, falls within the *Sphaeroidinella dehiscens* zone, which they regarded as Pliocene. They perceived a time gap between the lowest clastic beds and the Kangkou Limestone. Ingle (1975) suggests that the formation includes foraminiferal zones N 17 to 20 of Blow (1969), which would imply an approximate age of 7 to 3 m.y. (latest Miocene and Pliocene).

The Takangkou Formation is generally in fault contact with the Lichi mélangé (fig. 2); however, at the southern tip of the Coastal Range (fig. 3) the Lichi mélangé depositionally overlies and probably locally interfingers with part of the Takangkou Formation, as discussed below.

New biostratigraphic and sedimentologic studies of the Takangkou Formation and Lichi Mélangé after this paper went to press (Chi, Namson, and Suppe, 1981) show that the Takangkou Formation ranges in age from latest Miocene through middle Pleistocene (nannofossil zones NN-12 to upper NN-19; ~6 to 0.8 m.y.). Lichi-like olistostromes within the Takangkou Formation range in age from 3.5 to 2.5 m.y.

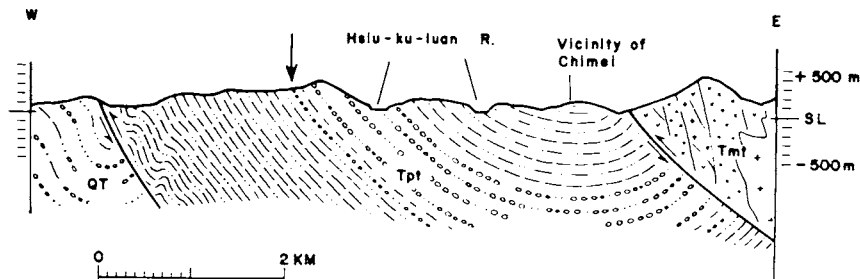


Fig. 4. Cross section of part of northern Coastal Range east of Juisui (fig. 2) showing lower Pleistocene conglomerates in the upper Takangkou Formation (Tpt) that record the rising Taiwan source area to the west. Below the conglomerate is a chiefly mudstone section; above is interbedded sandstone and shale. Tmt = Tuluanshan-Chimei volcanic arc sequence. Q = Pleistocene nonmarine sediments.

(NN-14 to NN-16) based on the ages of underlying and overlying bedded strata. These new data support our conclusion that the Lichi Mélange is an olistostromatic facies of the Takangkou Formation.

Pinanshan Conglomerate.—The Pinanshan Conglomerate (Hsu, 1956) is a synorogenic fluvial accumulation more than 3250 m thick in the type area 7 to 15 km north of Taitung (fig. 2). It mainly consists of fluvial gravel and boulders of rocks that were eroded from rapidly rising Central Mountains to the west. The clasts are dominated by moderately foliated quartz–mica metasediments, quartz–muscovite schist, graphitic schist, vein quartz, phyllite, slate, banded gray and white limestone, and conspicuous white marble, all of presumed Central Mountains derivation. In addition, the conglomerate contains relatively sparse clasts of andesite possibly derived from the Coastal Range and gabbro and serpentinite from the Lichi mélange or some now-vanished source.

The Pinanshan Conglomerate is not well dated but is probably middle or late Pleistocene. It is seen to rest unconformably on the Lichi mélange at a single exposure (loc. F in fig. 3); therefore it is younger than the Pliocene Lichi and Takangkou Formations, and it is younger than the formation of the chaotic mélange structure. The Pinanshan Conglomerate is strongly folded on a map scale, is locally overturned, and is truncated by the topographic surface, so that it is distinctly older than the nearly horizontal river-terrace deposits of the region (for example, fig. 3).

THE LICHİ MÉLANGE

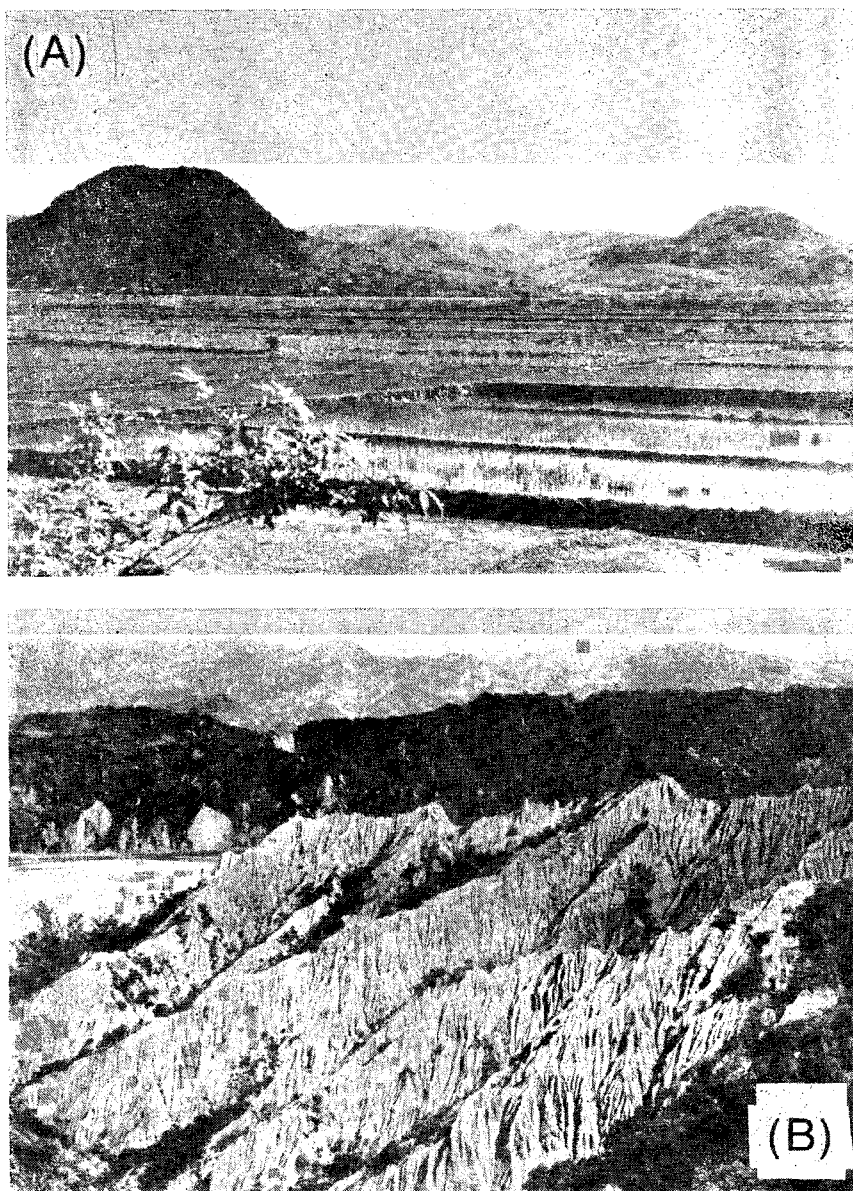
General

The Lichi Formation (Hsu, 1956) underlies a narrow 3 to 5 km-wide belt of low rolling hill country along the western foot of the southern Coastal Range from Taitung to Yuli, a distance of about 65 km (fig. 2). The best exposures are near Taitung in the vicinity of Lichi, especially along and near the Pei Nan River (fig. 3). The Lichi Formation is largely chaotic mélange; however, it also contains non-chaotic mudstone, pebbly mudstone, sandstone, and conglomerate (Liou, Suppe, and Ernst, 1977).

The Lichi mélange consists of disturbed scaly-mudstone matrix and chaotically distributed blocks and fragments, largely of sandstone and ophiolitic rocks. Some of the larger more resistant blocks form conspicuous small hills (pl. 1-A). The presence of the blocks, the weakness of the mudstone, and the lack of normal stratal continuity produce a “humpy” topography with hillocks and depressions. The terrain includes many landslides, rapidly growing gullies, and local areas of “badland” erosion (pl. 1-B). The mélange has an apparent thickness of more than 1 km, as determined from an exploratory drillhole (fig. 2, SS-1, 6.5 km southeast of Lichi Village) that penetrated 1061 m without reaching the base of the mélange (Meng and Chiang, 1965).

Most of the significant features of the mélange are well displayed near Lichi Village, in the type locality which is described next. Additional features will then be summarized from a larger area around the type locality (fig. 3) and also from the vicinity of Kuanshan 15 km north

PLATE 1



A. Lichi mélange terrain viewed from south near Taitung. The dark hill on the left, Fu-tou Shan (fig. 3), is a 500 m block of gabbro in the Lichi mélange. Shih-tou Shan on the right (fig. 3) is a 300 m block of serpentinite breccia. The intervening low country is underlain by chaotic mudstone containing smaller blocks of sandstone, shale, and ophiolitic rocks.

B. Badland topography of Lichi mélange about 2 km south-southeast of Lichi Village (fig. 3, near loc. B). The bare, gullied slopes are underlain by chaotic mudstones containing light-colored sandstone blocks; the olistostromatic layers dip to the left. The view looks west; steep-dipping Peinanshan Conglomerate (fig. 3) underlies the dark hills just beyond the Pei Nan River in the middle distance. The Central Mountains may be seen in the clouds beyond.

(fig. 2). We emphasize aspects that may help us distinguish between the two main alternative explanations for mélange formation: (1) olistostromal origin resulting from submarine slides or flows, and (2) tectonic-mélange origin resulting from shearing at depth perhaps in a subduction zone (for example, Hsü, 1968, 1974). Diagnostic evidence appears to indicate an olistostromal origin, as will be seen below.

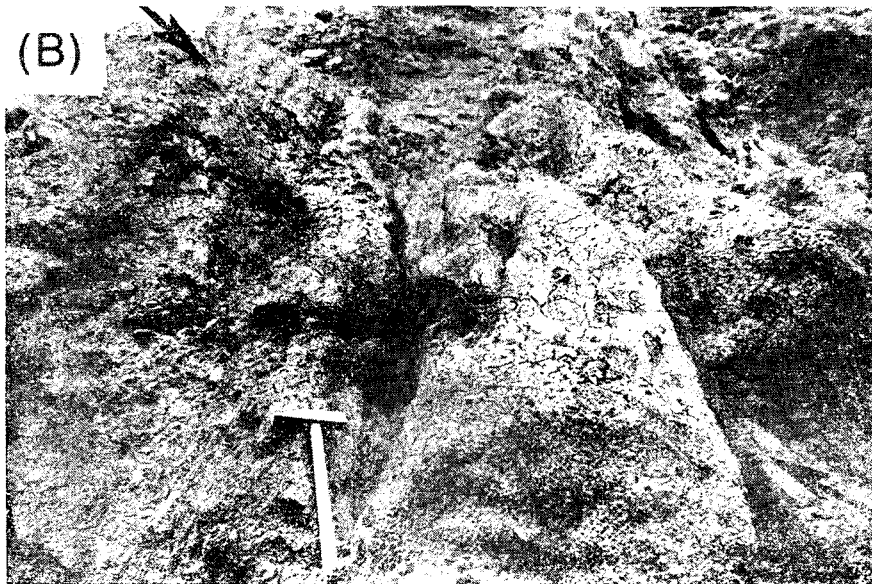
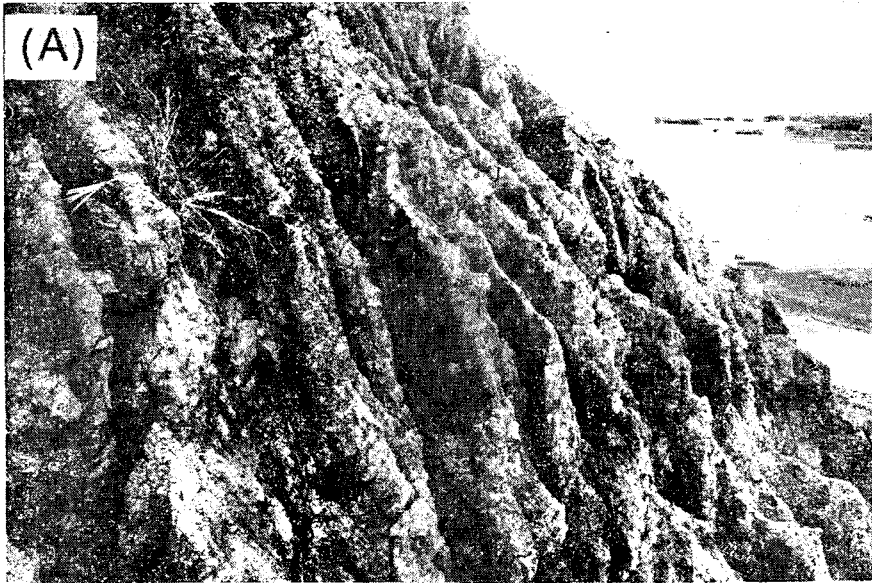
Primary Features of Mélange near Lichi Village

The most instructive outcrops of the Lichi mélange are rilled and gullied cliffs, up to 50 m high, extending several kilometers south and north of Lichi Village (fig. 3) along the east bank of the Pei Nan River (or Pinanta Chi). These river cliffs and nearby badlands are the type locality of the Lichi Formation (Hsu, 1956). With proper illumination, a series of subtle bands of color in shades of gray, tan, and brown can be seen passing diagonally across the outcrop (pls. 1-B; 2-A—tip-in, p. 224). The bands differ from one another in roughness or smoothness of surface texture. Detailed examination and mapping of a cliff exposure (fig. 3, loc. A) on a photographic base (scale 1:250) revealed three main types of lithologic layering as shown on plate 2: (1) Most of the color bands correspond to internally chaotic layers (1-10 m thick) containing blocks and slabs, principally of sandstone, enveloped in a scaly-mudstone matrix. These chaotic layers differ from one another in the concentration of blocks and in the color of the matrix. Only selected larger blocks and slabs are differentiated in plate 2-B. (2) A second type of layer is much thinner (1 cm-3 m) and is composed largely of fragments of serpentinite. (3) Finally, there are layers of mudstone and pebbly mudstone that contain relatively few blocks.

1. *Chaotic layers with blocks of sedimentary rocks.*—In the first type of layer, sandstone blocks and slabs are dispersed chaotically throughout the layer or in crudely aligned trains; one such train shown in plate 2 is 40 m long and 1 to 2 m thick. Plate 3-A is a photograph of a typical outcrop of this material. Some layers are composed of angular shale breccia with little mud matrix. The most prevalent blocks are unfossiliferous quartz-rich, micaceous sandstone with interbedded well lithified shale. The sandstone and shale are quite different from *in-situ* Coastal Range rock types and are unlike sediments that might be derived from a volcanic island-arc source; therefore, most of the blocks are considered exotic to the Coastal Range.

Blocks that are tabular show an imperfect preferred orientation parallel with the enclosing layer. Graded bedding and sole marks were used to determine the sedimentary "facing" for about 40 tabular fragments in the cliff shown in plate 2-B. In the left half of the cliff the facing is randomly right-side up and overturned, whereas in the right side the facing is consistently overturned below the fault and right-side up above the fault. Thus some layers contain blocks that are tumbled, whereas other layers contain blocks that, assuming an olistostromal origin, presumably slid and dismembered without turning over individually. Where overturning is consistent among many layers either part of

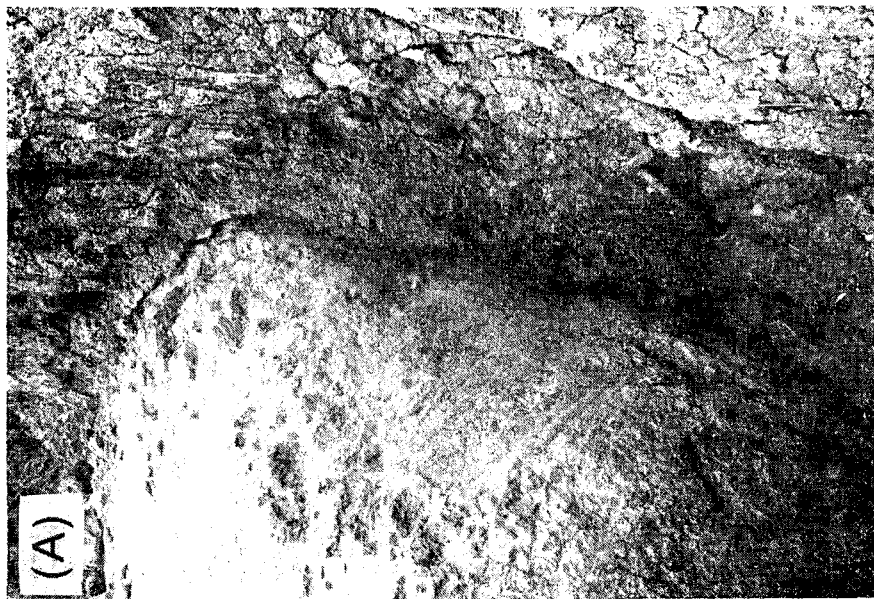
PLATE 3



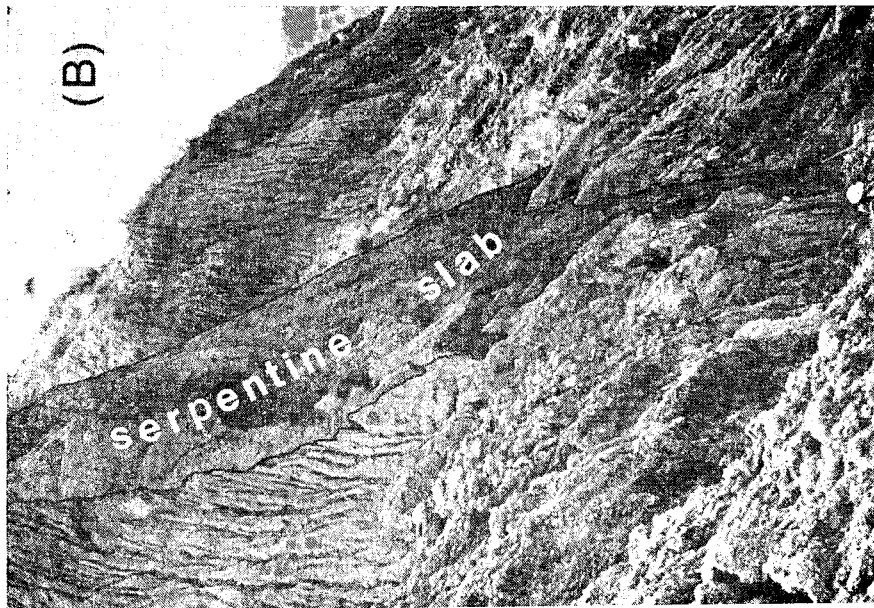
A. Outcrop of typical block-rich olistostrome in Lichi mélangé along the Pei Nan River 20 m south (right) of plate 2. Left edge of outcrop about 3 m high. Pei Nan River below; Taitung in the far distance.

B. Outcrop of Lichi mélangé showing a thin discontinuous light colored serpentine-olistostrome layer (between arrows) with brown-weathering olistostrome unit below and tan weathering olistostrome unit above (leftmost serpentine layer in pl. 2). Hammer is 25 cm long.

PLATE 4



A. Rounded 1.7 m serpentinite boulder imbedded in Lichi mélange. Part of the outer surface of the boulder is composed of sand cemented to the serpentinite, suggesting that the boulder has been resedimented. Near south (right) edge of plate 2.



B. Slab of serpentinite ($4 \times 30 \times 30$ m) viewed end on, imbedded in steeply dipping olistostromes and pebbly mudstones of Lichi mélange along the Pei Nan River about 0.5 km south of locality D (fig. 3), looking south. Olistostromal layering shown by color bands in background, dipping steeply to the right.

the parent formation was overturned before sliding, or the mélangé itself is overturned.

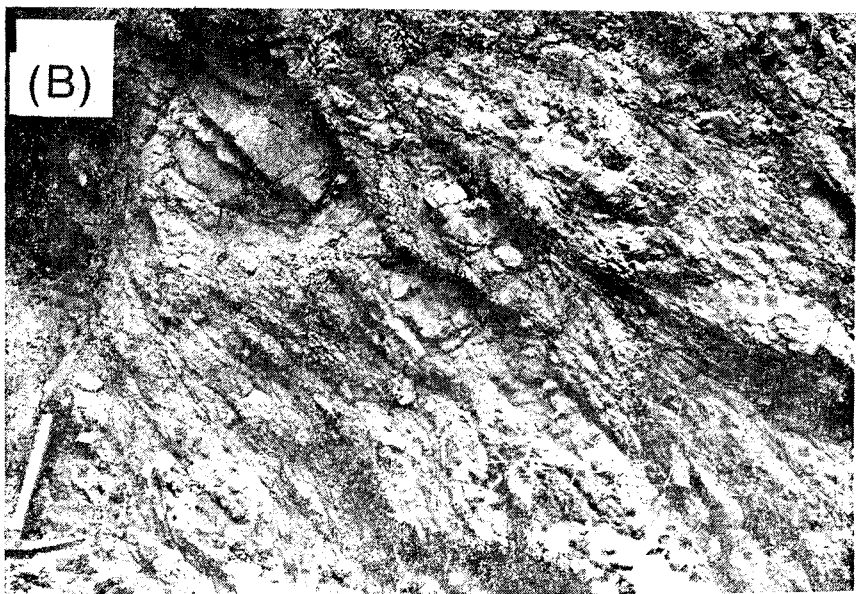
The muddy matrix of the chaotic layers is itself chaotic and fragmental on the scale of a hand specimen or thin section (pl. 5-A, -B, -C). The small fragments are largely mudstone. The scaly fabric of the mudstone matrix is variable in degree of development and is not generally parallel to the major lithologic layering shown on plate 2. Samples of the mudstone matrix have been observed under the microscope with ultrathin sections; the scaly surfaces are seen to be narrow plastic shear bands of phyllosilicates in strong preferred orientation, whereas the mudstone between the shear bands has phyllosilicate plates in random orientation.

For cartographic purposes the chaotic layers of sedimentary rocks were divided into the following lithologic types (pl. 2-B): (A) light tan-weathering layers rich in micaceous-quartzose sandstone blocks, (B) brown-weathering layers rich in reddish-brown shale fragments, and (C) gray-weathering layers rich in gray shale fragments. The subtle color differences are only partially recorded on panchromatic film (pl. 2-A); however, the proportion of sandstone blocks is reflected in the relief and surface texture of the layers. The chaotic layers are generally subparallel with each other and with the serpentinite-bearing layers, but in the center of the cliff shown in plate 2 there are local mutually cross-cutting relations. These relations are believed to be the result of minor *in-situ* slumping on the sea bottom and subsequent renewed deposition of olistostromes. Non-depositional explanations seem tenuous, particularly in light of the cross-cutting serpentinite layer (see also below).

2. *Layers of serpentinite fragments.*—The layers of fragmental serpentinite show most clearly the depositional, as opposed to tectonic, origin of the layering. In the area of plate 2, twenty thin layers of fragmental serpentinite 1 cm to 3 m thick were traced for distances of 5 to 50 m before they were lost in inaccessible parts of the cliff (for example see pl. 3-B). The serpentinite layers are in detail discontinuous; where necessary, the mudcracked outer crust on the outcrop surface was scraped away to expose trains of individual millimeter-size grains or groups of serpentinite grains along the projection of the outcropping layers. In this way the serpentinite-bearing horizons were traced and found to be parallel with the thicker chaotic layers (pl. 2).

The fragmental serpentinite layers do not have the scaly, lustrous, anastomosing shear surfaces typical of serpentinites along fault zones; instead, they generally have a somewhat granular appearance. Thin sections show a clastic mixture of texturally distinct serpentinite grains, closely packed, and unsheared; therefore any postulated structural origin, such as faulting, is unlikely. The discontinuous serpentinite-bearing layers appear to be sedimentary and may be the distal parts of submarine ophiolitic olistostromes. The implication is that the layered sequence displayed in the cliff is sedimentary rather than structural, and that the

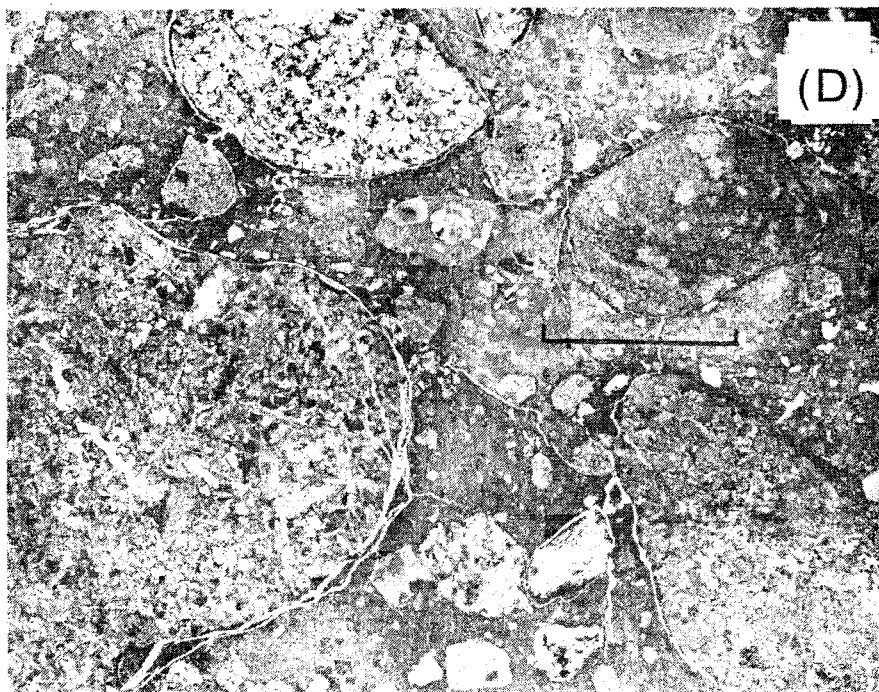
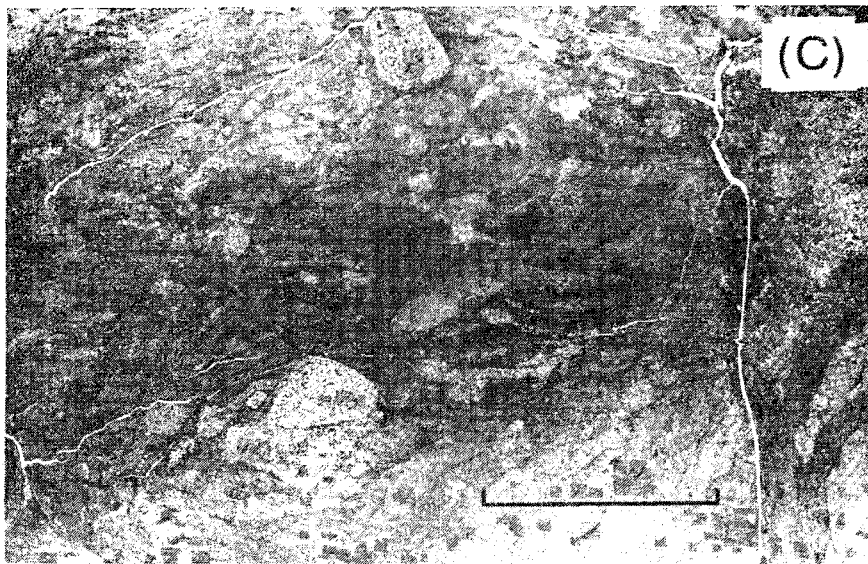
PLATE 5



A. Matrix of Lichi mélangé freshly exposed in stream bed, with some blocks exhibiting disoriented bedding outlined with ink; all material is mudstone. The lack of penetrative shearing is somewhat uncommon in the Lichi mélangé (compare B and C). Approx 0.8 km west of locality G (fig. 3).

B. Strongly sheared mélangé matrix with mainly quartzose micaceous sandstone fragments (not discernible in photo). The strong shearing is believed to be post depositional. Creek bank at Lichi Village.

PLATE 5



C. Photomicrograph of olistostromal matrix from area of plate 2 showing a mixture of mudstone and very fine-grained sandstone fragments in a finer grained matrix showing plastic shear bands. Bar scale 0.5 cm.

D. Photomicrograph of fine-grained pebbly mudstone containing a variety of rounded to subrounded pebble and sand grains of ophiolitic rock (area of pl. 2). Bar scale 0.5 cm.

Lichi mélange is a chaotic stratigraphic sequence rather than a tectonic mélange in the sense of Hsü (1974).

In addition to the fragmental serpentinite layers, eight isolated boulders, blocks, and slabs of serpentinite (25 cm-4.5 m) were found in the cliff shown in plate 2. These isolated serpentinite fragments are imbedded in the non-serpentinite chaotic layers; a 1.7 m boulder is shown in plate 4-A.

3. *Mudstone and pebbly mudstone.*—The third type of layer in the Lichi Formation along the Pei Nan River consists of mudstone and pebbly mudstone, in part scaly, with relatively few blocks. Two layers are shown in the right side of plate 2, and others are widespread in the cliffs to the south. These sediments contain a small number of poorly consolidated sandstone blocks up to 5 m across that are petrographically quite different from the lithified quartzose-micaceous turbiditic sandstones in the olistostromal layers described above. The poorly consolidated sandstones are variously serpentinite-rich, quartz-serpentinite rich, and ophiolite-rich. In many places the mudstone contains “floating” well rounded and polished pebbles and cobbles of gabbros, diabase, basalt, and quartzose-micaceous sandstone (pl. 5-D). All these materials are petrographically similar to the materials in the chaotic olistostromal units described above and are similar to blocks and slabs of the ophiolite found widely dispersed in the Lichi mélange. The rounding of the clasts indicates subaerial erosion of the source terrain. Ophiolite-rich sediment is also widespread in the non-chaotic part of the Lichi Formation (Liou, Suppe, and Ernst, 1977). The pebbly mudstones and particularly the thick massive mudstones give no indication of being olistostromal. We interpret them as normal sediments interbedded with the sedimentary and ophiolitic olistostromes that dominate the outcrop (pl. 2).

Nature of Blocks and Fragments in Lichi Mélange

We now leave the representative outcrop along the Pei Nan River and consider the complete range of blocks and fragments we have observed in the Lichi mélange. The dimensions range from less than 1 cm to more than 1 km, and the shapes include polygonal forms with angular flat surfaces, rounded chunks, lenticular bodies, phacoids, and slabs (pls. 4, 5). Shapes indicative of Coulomb- or ductile-fracture and tensile-fracture regimes are represented. Probably some shapes were determined by initial fracture and dismemberment of the parental rock body; however, the deformational history within the mélange may also be reflected. Rounded, lenticular, and phacoidal bodies commonly have polished and striated surfaces (pl. 4-A). Phacoids and lenses of competent rock are generally close to, or in contact with, similar fragments (pl. 5-B), whereas polygonal and rounded bodies are commonly dispersed (pls. 3, 5-A).

The most abundant blocks in the size range 0.1 to 10 m are sandstone (pl. 3-A). Less conspicuous blocks of siltstone, shale, and well-bedded mudstone are numerous, especially in small sizes ranging from millimeters to decimeters (pl. 5-A, -C). Minor amounts of limestone and conglomerate have been noted. Ophiolitic blocks representing the

full range of ophiolitic rock types are widespread within the *mélange* (Liou and others, 1977) but are generally less abundant than sedimentary types. Some rock types that are well known as blocks in ophiolite-bearing *mélanges* elsewhere in the world are missing here. For example, blueschist-facies metamorphic rocks and pelagic radiolarian chert, such as those in the Franciscan Complex of the California Coast Ranges, seem to be entirely absent. Pelagic limestone is rare. There are no blocks of continental basement rocks such as those in certain chaotic allochthonous of the northern Apennines or in *mélanges* of central Java.

Ophiolitic blocks.—The most striking components of the *mélange* are the mafic and ultramafic blocks of the Miocene East Taiwan Ophiolite. The largest and most diversified exposures are a train of disrupted blocks about 8 km long near Kuanshan (fig. 2) which is the type region of the East Taiwan Ophiolite. The stratigraphy, petrology, and paleogeographic history of the ophiolite is summarized in the companion article (Suppe, Liou, and Ernst, this issue) based largely on the Kuanshan exposures (fig. 2) where the ophiolite has been studied by many workers. Rocks similar to those at Kuanshan are found as blocks throughout the *mélange* (Hsu, 1976a), including the Taitung region (fig. 3) where a nearly complete suite of ophiolitic rock types is represented by scattered blocks, as summarized below.

Ultramafic blocks include small bodies of massive serpentinite with relict harzburgite texture, highly sheared serpentinite (the shearing predating the *mélange*), serpentinite breccia, and rare pyroxenite. Some blocks of serpentinite contain small dikes of gabbro. A slab of serpentinite breccia 30 m long (plutonic breccia unit of Suppe, Liou, and Ernst, this issue) immersed in the Lichi *mélange* is shown in plate 4-B. A prominent hill (Shih-tou Shan) east of the highway bridge across the Pei Nan River (pl. 1-A, fig. 3) is a 300 m block of serpentinite breccia. An adjacent conspicuous hill (Fu-tou Shan) overlooking the bridge (pl. 1-A, fig. 3) is a 500 m block of texturally heterogeneous gabbro, locally containing gabbroic pegmatite, wisps of anorthosite, and cross-cutting diabase dikes. Many smaller gabbroic blocks are scattered elsewhere in the Taitung region, although some parts of the *mélange* lack these components. Rare blocks of anorthosite and plagiogranite, 1 to 2 m across, are present. One large block and several boulder-sized fragments of amphibolite were noted; one is transected by small anorthosite dikes. In one case, amphibolite shows intense cataclasis, now healed, which predates emplacement in the *mélange*. Parts of an ophiolitic dike complex may be represented by a few small blocks of diabase intruded by finer grained diabase or basalt. Larger blocks of diabase breccia are more abundant.

A mafic extrusive suite is represented by many blocks of basalt, including massive basalt and basaltic breccia, generally altered to greenstone and locally amygdaloidal. Pillow basalt is rather uncommon. A few prominent blocks of glassy-basalt breccia occur 9 km northeast of Taitung (fig. 3, loc. K); one contains interbedded stratified tuff consisting of fine particles of unaltered crystals and glass.

Sedimentary blocks.—Some of the sedimentary blocks in the Lichi *mélange* have been described briefly by Wang and Chen (1966), Yen (1969), Hsu (1976a), and Liew and Lin (1974a,b). Our most intensive survey has been in the area of plate 2, where hundreds of blocks have been examined in hand specimen and about 40 in thin section. A more widespread but less detailed census has been made in the area of figure 3.

Two major petrologic categories of sandstone and related rocks have been recognized among the blocks in the *mélange*. They have already been noted in the description of the cliff exposure south of Lichi Village

(pl. 2), but regionally they are more diverse than in the type locality near the village. The two main categories are: (1) lithified deep-water quartzose–micaceous sandstones, commonly with interbedded lithified shales, and (2) poorly consolidated ophiolitic sandstones (generally moderately quartzose) and conglomerates, many of which appear to be of shallow-water environment. In addition to rocks of the two principal categories, several less abundant sedimentary types are also present as blocks.

Blocks of lithified deep-water sandstones and shales.—By far the largest number of sandstone blocks are lithified fine- to coarse-grained subgraywacke and quartz arenite of the first category (above). Many display turbidite structures (Wang and Chen, 1966) including sole marks, graded bedding, cross laminations, and convolute laminations. These features indicate that the “facing” (sedimentary tops of the beds) varies in orientation from block to block, as in plate 2. Even some of the largest blocks, including one nearly 1 km long (near loc. L, fig. 3), are overturned.

Numerous blocks containing multiple beds have a fairly high sandstone-shale ratio and show features of turbidite facies C of Mutti and Ricci-Lucchi (for example, Ricci-Lucchi, 1975)—a facies believed to be common in deep-sea mid-fan and outer fan domains. Many other blocks of petrographically identical sandstone are laminated and display no facing indicators. They may be turbidites of Bouma divisions T_b – T_c , or they may possibly reflect traction by deep contour currents.

Petrologically, most rocks of the first category are subrounded to subangular quartzose sandstones with 20 to 30 percent phyllosilicate and calcite matrix, very minor plagioclase, and a little potassium feldspar (0.5–5 percent). As a group, these sandstones display a sprinkling of prominent, large, detrital mica flakes on bedding surfaces. The feldspar lacks the oscillatory zoning of arc-derived feldspar seen in some sandstones near the base of the Takangkou Formation.

This assemblage of turbiditic and laminated quartzose micaceous sandstones and related shales is apparently of continental derivation, and we postulate that they are deep-sea fan and continental rise equivalents of the Chinese shelf and slope deposits that are exposed in central and western Taiwan. If so, they were deposited on the now-subducted part of the South China Sea floor (Suppe, Liou, and Ernst, this issue, fig. 7). These sediments must have undergone burial and moderate tectonism prior to incorporation in the Lichi mélange, because they are relatively well lithified and some contain veins of calcite or quartz. The calcite in veins and matrix shows twin lamellae, whereas calcite in sandstones of the second (ophiolitic) category is not twinned. This lithification and deformation probably occurred as the rocks were incorporated into the accretionary wedge (outer arc) of the Luzon island arc (fig. 1).

Blocks of poorly consolidated ophiolite-bearing sediments.—The second category of sedimentary blocks is less abundant than the quartzose micaceous sandstones; however, we have observed the assemblage throughout the length of the southern Coastal Range (see Liou, Suppe, and Ernst, 1977). The sandstones of this category are characterized by generally poor lithification, a mixture of both ophiolitic and quartzose detritus, and some evidence for shallow-water deposition including lack

of turbiditic structures and the presence of shelly-fossil fragments. Material of this type is not confined to blocks but also exists as sediment in the interbedded pebbly mudstone, conglomerate, and sandstone of the Lichi Formation (Liou, Suppe, and Ernst, 1977). The blocks are most abundant as bed fragments in the pebbly mudstones; however, they have been also observed mixed with quartzose micaceous sandstone blocks in several of the olistostrome layers of plate 2.

The sandstones of the second category are heterogeneous, ranging from massive to cross-bedded, well-sorted and -rounded quartz arenites with relatively little ophiolitic (generally serpentinite) matrix to poorly sorted ophiolitic sandstone with little quartz. Most of the pebbles and cobbles are well rounded although some subrounded to subangular conglomerate was observed (Liou, Suppe, and Ernst, 1977). From sample to sample the proportions of quartz, serpentinite, gabbro, diabase, and basalt are quite variable. The parent rock types are most easily recognized in the pebbly sandstone, pebbly mudstones, and conglomerates (for example pl. 5-D). The clasts of these sediments include most of the rock types observed in the olistoliths of East Taiwan Ophiolite (Liou, Suppe, and Ernst, 1977). In addition, pebbles and cobbles of quartzose micaceous sandstone are locally present in minor abundance.

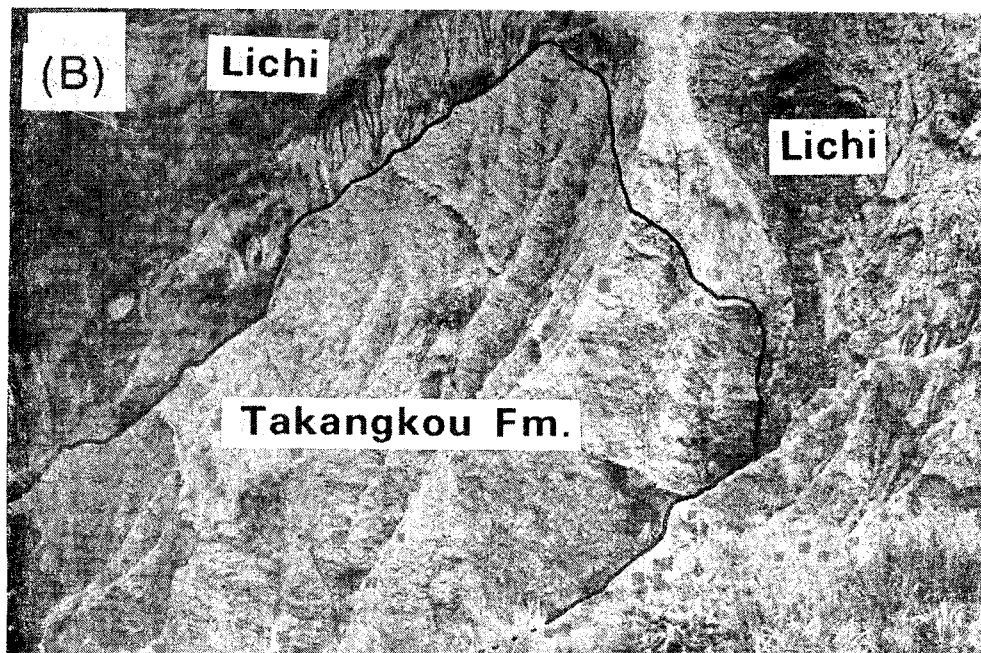
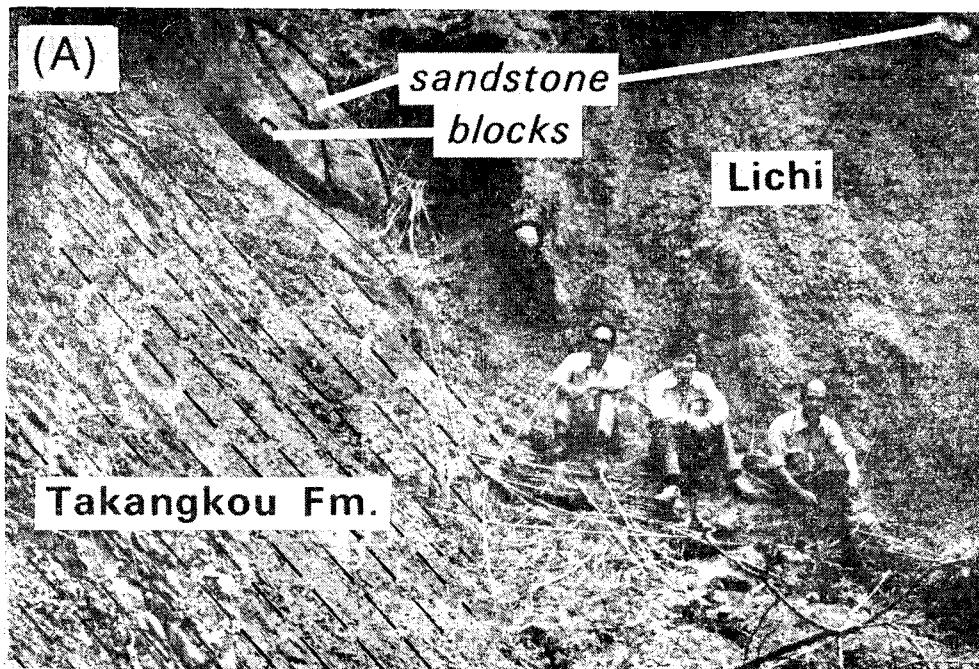
About ten conglomerate blocks were observed in the Taitung region. They consist largely of clasts of mafic and ultramafic rocks: basalt, diabase, gabbro, amphibolite, and serpentinite, with chert, occasional keratophyre, tuff, and other materials. Interstitial sand contains angular quartz grains as well as plagioclase and lithic particles. At least one block contains granule conglomerate of mafic igneous rocks and sandstone beds with mollusc fragments. A prominent block 30 to 50 m long, alongside the Pei Nan River 1.5 km north of Lichi Village, contains angular to subrounded pebbles, cobbles, and boulders of mafic igneous rocks, altered amphibolite, andesite and andesitic breccia (like parts of the Tuluanshan suite), lithic graywacke, flysch-type sandstone, siltstone, and limestone containing corals and Foraminifera.

We may conclude that all the materials that exist as olistoliths in the Lichi *mélange* also exist as subaerially eroded detritus in both non-olistostromal sediments of the Lichi Formation and as blocks within olistostromes and pebbly mudstones. Therefore, during deposition of the Lichi Formation, the source terrain for the olistostromes was uplifted above sealevel at times and was eroded subaerially.

Other types of blocks.—Several other rock types have been observed in the *mélange*.

Siltstone and mudstone blocks are generally measured in millimeters or centimeters (pl. 5-A, -C) but rarely are as large as tens of meters. The larger blocks may be more numerous than their infrequent exposure would suggest, because they may be too soft to crop out. Some siltstone is an unfamiliar, massive type. However, rhythmically bedded mudstone, some with thin flysch-type sandstone at intervals, is almost certainly derived from the Takangkou Formation of the Coastal Range. A 30 to 50 m wide Takangkou block is shown in plate 6-B; similar blocks in a variety of orientations are exposed at locality G along a stream 10 km north of Lichi Village. Several mudstone blocks show soft-sediment folds like parts of the autochthonous Takangkou Formation (pl. 7-B), as discussed below.

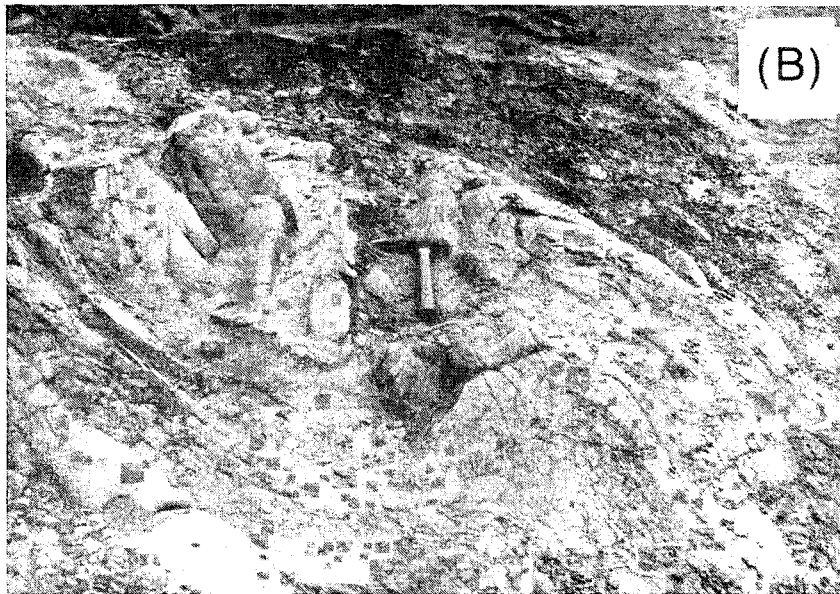
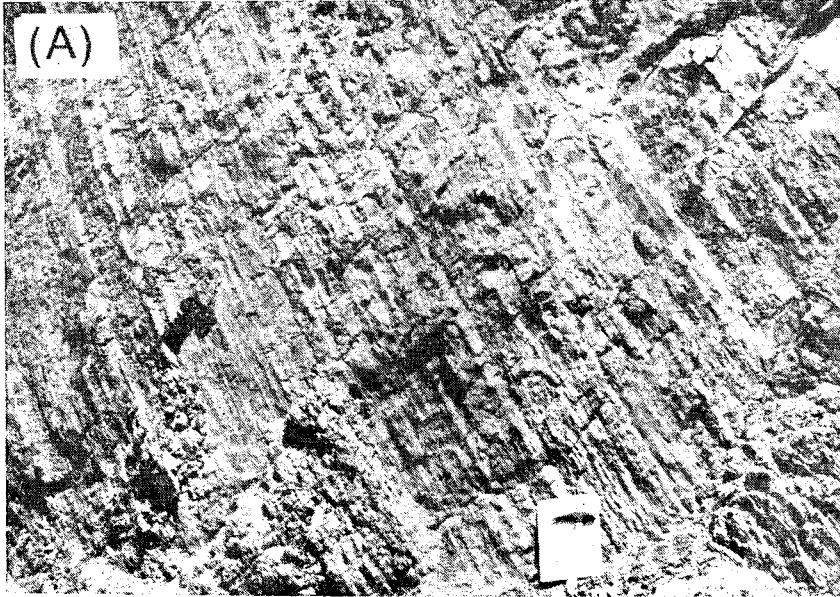
Calcarenic limestone forms two large prominent blocks, 3 km and 13 km north-northwest of Taitung, which are more than 100 m long and composed of



A. Approximately concordant contact between Lichi mélangé and underlying mudstones of Takangkou Formation (uniform dip of bedding accentuated with inked dashes). The chaotic, unbedded mudstone of Lichi mélangé contains well lithified sandstone blocks, whereas the underlying Takangkou Formation is mudstone for hundreds of meters and much less lithified. Locality J, figure 3.

B. Block of bedded Takangkou mudstone, 30 to 50 m wide, within chaotic mudstone of the Lichi mélangé. Locality B, figure 3.

PLATE 7



A. Typical outcrop of Takangkou Formation in the central Coastal Range east of Juisui (fig. 2). Dark mudstone with rhythmic interbeds of siltstone and lighter very fine turbidite sandstone.

B. Soft-sediment fold in sandstone and mudstone of Takangkou Formation just below contact with Lichi mélange. Locality D, figure 3.

whole and fragmental foraminiferal tests, bits of calcareous algae, bryozoans, and other biogenic material. The foraminifera of both blocks are considered to be Miocene, and those of the block closest to Taitung (Mao Shan) are believed by Chang (1967) to be middle Miocene. In addition to the two prominent blocks, rare small fragments of limestone are widely scattered in the mélangé. Most of these are foraminiferal calcarenite, but a few are different, being very fine grained, possibly pelagic.

The mélangé contains rare andesitic blocks, presumably derived from the Tuluanshan volcanic complex. One of the largest (top of fig. 3) is more than 1 km long and consists largely of unstratified volcanic breccias, variously composed of andesite, basaltic andesite, and quartz-bearing andesite or dacite. Other smaller (1-4 m) olistoliths of andesitic breccia, one with a basaltic dike, are exposed 6 to 9 km north-northeast of Taitung.

A large, partly volcanoclastic block near Yuli (Antung) was reported by Wang (1976). The stratigraphic sequence within this block includes 20 m of andesitic tuffaceous sandstone with graded bedding and sole marks with intercalated mudstone layers. The tuffaceous sandstone is overlain, with a channeled contact, by 2 m of andesitic sedimentary breccia which in turn is overlain by more than 10 m of very massive tuffaceous sandstone. Similar strata are seen in the marine facies of the autochthonous Tuluanshan volcanic complex.

Deformation of the Mélangé

Most of the mélangé is intricately sheared, judging from stream-cut exposures. Some slip surfaces are well-defined and slickenslided; they are quasi-planar and tend to curve, bifurcate, and merge with others, collectively subdividing the mélangé matrix into sphenoidal, curving, or lenticular slices. Lenticular and phacoidal sandstone blocks are commonly oriented parallel with the average orientation of the shear surfaces (for example, pl. 5-B). There is commonly some shearing parallel with the olistostromal layering; however there are important exceptions. For example, shear surfaces are heterogeneously oriented over the exposures of plate 2 and not generally parallel with the olistostromal layering. There is generally no simple homogeneous pattern to the orientation of the shear surfaces, except that they commonly exhibit the regional strike of the Coastal Range. Presumably much of the internal shearing developed during and following folding of the mélangé, but some may have formed during deposition when semi-consolidated masses moved downslope by gravity. In addition to the anastomosing shears just described, there are through-going small faults that offset olistostrome layers a few centimeters or a few meters.

There are indications that the Lichi mélangé has been folded. In the Taitung region (fig. 3) an attempt was made to map the orientation of the chaotic olistostromal layers (for example, pls. 1-A, 2, 4-B). The relatively few measurements suggest that the mélangé is folded about north to northeast trending axes. The inferred folds do not coincide exactly with the simply south-plunging anticline exposed in underlying Tuluanshan and Takangkou Formations to the north; therefore a noncylindrical or disharmonic aspect to the map-scale structure exists. The steep dips and prevailing northeast strike of the mélangé layers indicate substantial northwest-southeast compression, as is typical of Taiwan.

CONTACT RELATIONS, AGE, AND DIRECTION OF TRANSPORT

Contact relations.—The contact relations of the Lichi mélange and the Takangkou Formation have an important bearing on the origin of the mélange. If the Lichi were a tectonic mélange, it would probably not exhibit the observed contact relationships.

Some geologists have envisaged exclusively tectonic contacts between the Lichi mélange and older rocks (for example, Big, 1969, fig. 4; Hsu, 1976, pl. 4); indeed the Tuluanshan assemblage has been thrust over the mélange throughout most of the southern Coastal Range (fig. 2). Nevertheless in the Taitung region we find that the mélange lies quasi-concordantly above the Takangkou Formation, based on the map pattern of the south-plunging anticline (fig. 3) and on a few well-exposed outcrops.

The contact is clearly exposed in a small valley 4.5 km northeast of Lichi Village (fig. 3, loc. J) as shown in plate 6-A. On one side of the contact unshaped and well-bedded Takangkou mudstone with thin siltstone interbeds forms a homocline that extends for hundreds of meters to the north. On the other side of the contact, the basal Lichi mélange consists of strongly sheared mudstone that differs from the Takangkou mudstone in its disturbed aspect, lack of bedding, and the presence of lithified, angular sandstone blocks. The contact and the sheared fabric of the mélange are both nearly parallel with bedding in the Takangkou mudstone. The sheared mudstone contains a sandstone block within a few centimeters of the contact and others as large as 2 by 5 m are nearby. The sandstones are probably exotic, because they are much better lithified than the neighboring Takangkou sediments, and there is no similar sandstone in the underlying section, which is largely mudstone. Small ophiolitic blocks occur 200 to 300 m south of the contact. Similar contact relations, albeit poorly exposed, were seen in a stream valley 3 km to the northeast.

A series of cliffs along the Pei Nan River 4 to 6 km north of Lichi Village crosses the curving Lichi-Takangkou contact twice at an acute angle (fig. 3, loc. D-E). The cliffs expose the section on both sides of the boundary, but the contact plane itself is not exposed. Nevertheless, bedding in the Takangkou Formation and lithologic layering in the Lichi mélange (for example, pl. 7-B) are parallel across the contact. The Takangkou sequence dips steeply to vertically in a west-facing homocline; near the top of which many small sedimentary-slump folds appear (pl. 7-B), with some erosional truncations indicating that they formed at the sea floor. The direction of slumping, as deduced from these folds, is discussed below. Adjacent to and stratigraphically above the Takangkou Formation is strongly sheared Lichi mudstone, which from the very base contains blocks of the presumably exotic quartzose-micaeous sandstone. A few blocks and slabs of gabbro and serpentinite occur in the mélange 100 to 200 m from the contact and others are nearby (pl. 4-B). The sandstone blocks are commonly polygonal, are more lithified than nearby Takangkou sandstones, and lack soft-sediment folds.

In the cliff exposures along the Pei Nan River, we place the lower boundary of the Lichi mélange at the first chaotic sediments (olistostromal, we believe) containing well-lithified exotic sandstone blocks. Only slumped Takangkou Formation is seen below this level. The previously described outcrops south of Lichi Village (pl. 2) show stratigraphically higher olistostromes with interbedded non-olistostromal mudstone and pebbly mudstone.

A possible intertonguing relationship between the Takangkou Formation and Lichi mélange was observed in a gully (fig. 3, loc. E) nearly 6 km north-northeast of Lichi Village. The lower part of the mélange, apparently within 50 to 150 m of the base, is interrupted by 40 m of bedded Takangkou mudstone. Alternative explanations of the exposed relations are that the 40-m Takangkou body is a fault slice repeating the contact or is a detached but non-rotated block or slab in the mélange rather than a stratigraphic member.

Further evidence for an intertonguing relationship between the Lichi and Takangkou Formations is provided by the presence of ophiolite-bearing sediments in both. Hsu (1956, and personal commun., 1979) observed pebbly mudstones 100 to 150 m thick within the Takangkou Formation of the southern Coastal Range that contain pebbles of gabbro and serpentinite. We have not seen the localities, but judging from Hsu's descriptions the sediments are similar to the pebbly mudstones south of Lichi Village (pls. 2, 5-D) and are similar in source to other ophiolitic sediments in the Lichi Formation (Liou, Suppe, and Ernst, 1977).

Age of the Lichi mélange.—The age of the Lichi Formation, including the time of mélange genesis, is believed to be Pliocene (Ingle, 1975; Hsu, 1976; Wang, 1976; Page, 1978), based on fossil data and contact relations with the Takangkou and Pinanshan Formations.

Paleontological dating of the mélange is somewhat uncertain, because generally we do not know whether reported fossils are from exotic blocks or matrix of exotic or coeval material. Miocene microfossils have been reported from limestone blocks (for example, Chang, 1967) and from red pelagic shale in blocks of the East Taiwan Ophiolite (Huang, Chen, and Chi, 1979). Foraminifera from mudstone in the mélange include Pliocene assemblages similar to those of the Takangkou Formation and, in addition, re-worked Miocene forms (Chang, 1967; Huang, 1969; P. Hasson, personal commun., 1977). Uniquely Pleistocene forms have not been reported.

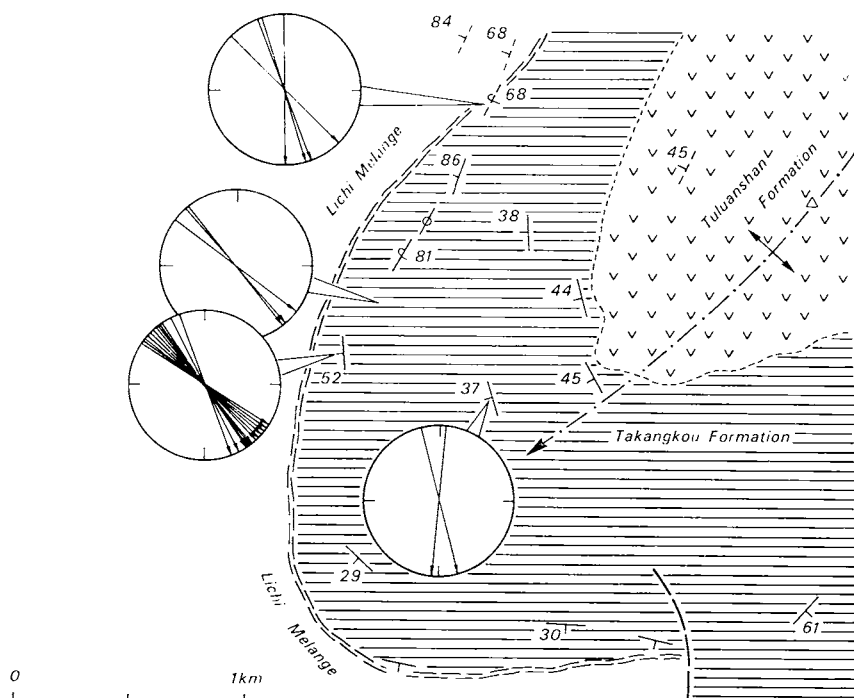
New biostratigraphic and sedimentologic studies of the Takangkou Formation and Lichi Mélange after this paper went to press (Chi, Namson, and Suppe, 1981) show that the Lichi Mélange contains mixed fossils ranging from Miocene through lower Pliocene (nannofossil zones NN-3 to NN-15; 19.3 m.y.), whereas the bedded Takangkou Formation ranges in age from late Miocene to middle Pleistocene (nannofossil zones NN-12 to upper NN-19; 6-0.8 m.y.). Olistostromes within the Takangkou Formation contain fossil assemblages similar to the Lichi Mélange

and similar blocks of quartzose micaceous sandstone and ophiolite. The Takangkou olistostromes are Pliocene in age based on the ages of overlying and underlying bedded strata (3.5-2.5 m.y.; NN-14 to NN-16). These new data support our conclusion that the Lichi Mélange is an olistostromatic facies of the Takangkou Formation.

Direction of transport of Lichi mélange.—The most direct available evidence for the direction of transport of the Lichi mélange comes from the sedimentary-slump folds in the immediately underlying Takangkou Formation, already described. Most of the exposed folds are a few hundred meters north of locality D in figure 3; a few were found elsewhere. Only 21 unambiguous determinations of the sense of overturning could be made; however the results are consistent (fig. 5), showing a

VERGENCE OF SOFT-SEDIMENT FOLDS
IN TAKANGKOU FORMATION

(Mean of 21 Measurements: $S 34^{\circ}E$)



B. Page

Fig. 5. Vergence of seafloor sedimentary-slump folds in the upper Takangkou Formation in the area of figure 3, after correction for dip of enclosing strata. The data indicate a southeasterly slope of the Takangkou sea bottom in this area. By implication the immediately overlying olistostromes of the Lichi mélange were derived from the northwest.

mean vergence of S 34° E after the enclosing strata are unfolded to the horizontal. Therefore we conclude that the Takangkou sea floor sloped to the southeast immediately prior to the onslaught of Lichi deposition. Apparently the Lichi olistostromes and pebbly mudstones were derived from the northwest. This conclusion is supported by the lack of bathymetric evidence for a source to the east (fig. 2). However, a possibility of a minor eastern source is raised by the andesitic blocks, although a western source is not impossible in light of the andesitic basement the Takangkou Formation (compare fig. 6).

OLISTOSTROMAL ORIGIN: SUMMARY

The two main alternative explanations for the origin of the Lichi mélange are: (1) it is an olistostromal deposit (Flores, 1955) of submarine slides and debris flows, or (2) it is a tectonic mélange (Hsü, 1974) produced by shearing at depth, perhaps during underthrusting in a subduction zone.

Most evidence indicates an olistostromal origin for the Lichi mélange. We have shown that the mélange is underlain quasiconformably by marine sediments of the Takangkou Formation (for example, fig. 3 and pl. 6-A) and that the mélange may interfinger with these sediments. The immediately underlying sediments display sedimentary-slump folds indicating slope instability just before Lichi deposition (pl. 7-B and fig. 5). The crude lithologic layering within the mélange is widely observed and was emphasized in the description of exposures near Lichi Village (pl. 2), where numerous chaotic sedimentary and serpentinite layers are interlayered with each other and with less lithified mudstone and pebbly mudstone. It could be argued that these layered outcrops are composed of originally non-chaotic stratigraphic layers that were broken up tectonically *in situ* (namely *broken formation* of Hsü, 1968); however this is effectively ruled out by the thin interbedded serpentinite layers displaying an unsheared granular texture and by the interbedded much less lithified mudstones and pebbly mudstones. These observations suggest an olistostromal origin for the Lichi mélange.

The main indication of possible tectonic origin of the Lichi mélange is its widespread and commonly pervasive sheared structure. In addition, some of the blocks are slickensided (pl. 4-A) and locally appear to have been shaped and oriented in shear zones (pl. 5-B). These effects are tectonic; however, in light of the stratigraphic properties of the mélange described above, we consider the shearing to be largely post-depositional and not responsible for the primary chaotic character of the mélange.

We therefore accept an olistostromal origin for the Lichi mélange and consider it a chaotic facies of the lower Takangkou Formation. The major paleogeographic properties of this olistostromal deposition are summarized on a diagrammatic cross section in figure 6. The olistostromes are shown to come from the northwest, based on the vergence of sedimentary-slump folds in the immediately underlying Takangkou Formation (fig. 5). The estimated minimum water depth, based on

benthonic foraminifera in the Takangkou Formation, is about 2000 m (Ingle, 1975), similar to the depth of the Luzon Trough.

The source terrain of the Lichi mélange no longer exists, but several properties of this source may be inferred from the mélange; these are summarized graphically in figure 6. Most of the Lichi materials are allochthonous and exotic to the Coastal Range stratigraphy; therefore, we infer a major fault zone between the source terrain and the basin of Lichi deposition. This fault zone serves to juxtapose the contrasting geology and produce relief and instability for olistostrome formation. The source terrain of deep-water sedimentary and ophiolitic materials was uplifted relative to sealevel, as shown by evidence of subaerial erosion. Shallow-water clastic sediments are shown flanking the eroding source terrain in figure 6, based on the poorly consolidated, shallow-water ophiolitic sandstone blocks in Lichi pebbly mudstones and olistostromes.

The schematic cross-sectional paleogeography of the Pliocene Lichi mélange (fig. 6) is based on direct geologic observations in the southern Coastal Range and straightforward inference without any consideration of the regional tectonic setting or the plate-tectonic history. We now explore the tectonic associations of the Lichi mélange.

TECTONICS OF LICHI MÉLANGE

Site of mélange accumulation in arc-trench system.—It is evident from the bathymetry near Taiwan (figs. 1 and 2) that the Lichi mélange lies on the western flank of the Luzon volcanic arc. At this latitude the Luzon Trough projects into the southern tip of the Coastal Range.

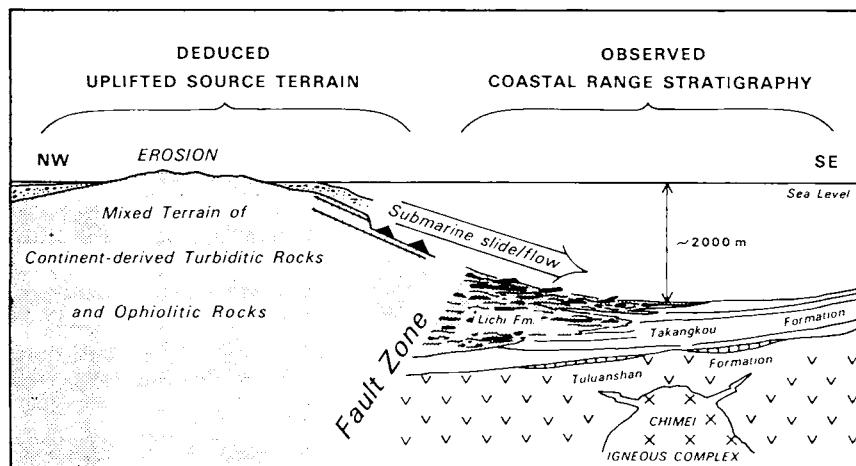


Fig. 6. Schematic Pliocene paleogeographic cross section during deposition of the Lichi mélange. The right half is inferred from observed stratigraphic relations in the southern Coastal Range. The source terrain to the left is deduced from fragments within the Lichi Formation. Regional tectonic considerations, discussed in the text, indicate that the depositional basin was the Luzon Trough forearc basin and that the source terrain was the uplifted accretionary wedge (outer nonvolcanic arc) to the northwest. The crest of the Pliocene volcanic arc lay to the southeast.

Furthermore, the inferred minimum water depth (about 2000 m) of Takangkou deposition is similar to typical water depths of the Luzon Trough. Therefore we conclude that the basin of Lichi mélange and Takangkou deposition (fig. 6, right half) was the northern continuation of the Luzon Trough, floored by Miocene arc volcanic rocks (Tuluanshan Formation).

If we accept the Luzon Trough (forearc basin) as the site of Lichi and Takangkou deposition, then the inferred source terrain immediately to the northwest (fig. 6) must be the outer nonvolcanic arc (accretionary wedge), lying between the Luzon Trough and the Manila Trench (fig. 1). The presence of ophiolite and probable deep-sea fan and continental-rise sediments in the Lichi mélange is appropriate for an accretionary-wedge source terrain. The lack of substantial metamorphism suggests a shallow position in the accretionary wedge.

The normal water depth of the outer nonvolcanic arc south of Taiwan is more than 1000 m, much deeper than the inferred, subaerially exposed source terrain (fig. 6). Therefore, the paleobathymetry of Lichi deposition is not the normal situation within the Luzon arc. We believe that the Lichi mélange reflects special bathymetric and tectonic aspects of the collision of the Luzon arc with the continental margin of Asia, as discussed below. This collision forming Taiwan has been recognized in one form or another by many workers, including Biq (1971, 1972), Chai (1972), Karig (1973), Murphy (1973), Hsu (1976a), Wang (1976), Roeder (1977), and Bowin and others (1978).

Present-day analogue of Lichi paleogeography.—The continental margin of China is oriented northeast-southwest, whereas the Luzon island arc and Manila Trench are oriented north-south, along the Asia-Philippine Sea plate boundary (fig. 1). Therefore the Luzon arc has collided with the China continental margin first at Taiwan; parts of the arc to the south will collide successively later. Because of this non-synchronous collision, we must look to the south for present-day analogues of earlier stages of the collision in Taiwan. Bathymetric charts (for example, Scripps Inst. Oceanog., 1969) of the Luzon arc show an area 75 to 100 km south of Taiwan with bathymetry similar to the paleogeography inferred (fig. 6) from the Coastal Range. In this area, Lichi-like tectonics and deposition may be proceeding today, as suggested by Liou and others (1977). We described this region below.

As we proceed north from Luzon along the outer nonvolcanic arc (accretionary wedge), it becomes distinctly broader and shallower at about 20° to 21° North latitude (fig. 1). To the south the outer arc has a width of about 50 km and a water depth of 1500 to 2000 m; to the north the arc widens to about 100 km and shallows, in places, to less than 100 m water depth. This growth of the accretionary wedge, which is accompanied by westward swing and shallowing of the Manila Trench, correlates with the impingement of the Luzon arc on the continental rise of China in the South China Sea (fig. 1). Apparently the thick continental-rise sediments (Ludwig, Kumar, and Houtz, 1979)

have been incorporated into the outer arc by imbrication. We believe that this shallow expanded outer arc, which in places would stand above sealevel if the sea were slightly lower, is a present-day analogue of the eroding source terrain of the Lichi deposits, including the olistostromes (left side of fig. 6). Immediately to the east a steep slope descends to a depth of 2000 to 3000 m in the Luzon Trough, which could produce slides or debris flows similar to those of the Lichi mélange.

The steep slopes do not exist along the west flank of the Luzon Trough south of about 21° North latitude. To the north the Luzon Trough narrows until the outer arc impinges on the volcanic arc near 22° North latitude. Apparently the steep slopes are an expression of faulting along the west flank of the Luzon Trough at this latitude; multichannel seismic data apparently support this conclusion (R. M. Anderson, personal commun., 1977). We infer that the faulting is east-vergent thrust faulting because the Luzon Trough narrows markedly between 21° and 22° North latitude, the region in which the steep slopes are well-displayed.

A cross section (fig. 7) is drawn through the region of the present-day analogue of Lichi deposition along a line parallel to the plate convergence (fig. 1, along line A-A'). The bathymetry is the present bathymetry, whereas the stratigraphy and geologic details are based on the inferred Pliocene paleogeography of Lichi deposition based on observations in the Coastal Range (fig. 6). Therefore the cross section is thought to portray both present-day tectonics south of Taiwan and the approximate tectonic situation during Lichi deposition, 200 km to the north.

Pliocene paleogeography.—If we reverse present-day Asia-Philippine Sea plate convergence of 7 cm/yr (Seno, 1977), going back to the time of Lichi deposition (Pliocene, approx 2.5 m.y.) we may locate the position of the Luzon volcanic arc and the Coastal Range relative to the present-

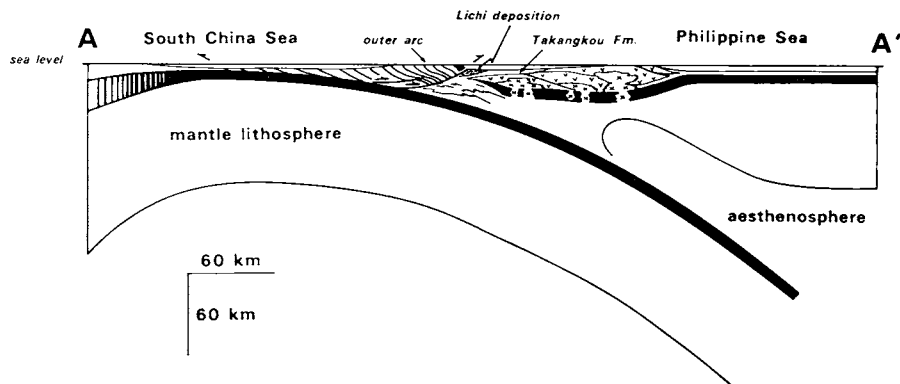


Fig. 7. Regional cross section showing inferred position of Lichi mélange deposition. The general bathymetry is that of the Luzon arc just south of Taiwan (A-A', fig. 1) where bathymetry similar to that inferred for Lichi deposition (fig. 6) exists today. The stratigraphic relations are those of the southern Coastal Range (fig. 6). The cross section is thus both a present-day section south of Taiwan and late Pliocene section through the southern Coastal Range.

day position of Taiwan and to the Asian plate (fig. 8). We have extrapolated the Chinese continental shelf, slope, and rise toward the northeast into the region of now deformed and subducted Asian plate. Therefore, we have translated present-day geography of the Luzon trough, outer nonvolcanic arc, and Taiwan Island northward along the Luzon arc, relative to the Philippine Sea plate, to arrive at the 2.5 m.y. proto-Taiwan and surrounding schematic bathymetry. The southern half of the Coastal Range is shown to be within the northern, now destroyed, projection of the Luzon Trough, as inferred from water depths of the Takangkou Formation.

The eroding source area of the ophiolitic sediments in the Lichi Formation (fig. 6) is shown as the long southern peninsula of proto-Taiwan (fig. 8). If this is correct, then the ophiolitic sediments also were transported toward the southwest to be deposited on the west flank of the outer arc and in the trench and are possibly preserved today in ophiolitic pebbly mudstones and conglomerates of the Kenting mélange exposed in the southern peninsula of Taiwan (Tsan, 1974; Biq, 1977; Ho, 1977; Page, 1977), as suggested by Liou and others (1977).

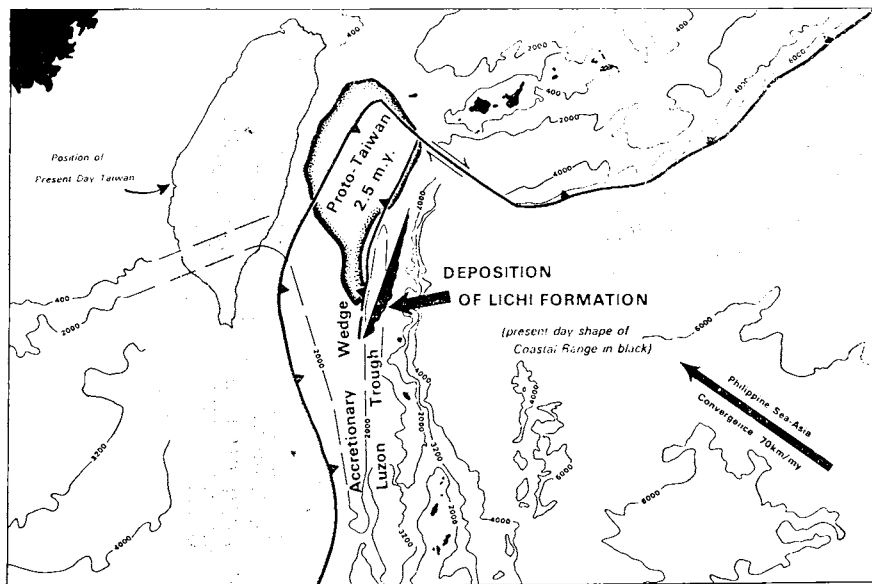


Fig. 8. Late Pliocene (2.5 m.y.) paleogeographic map showing the site of Lichi deposition (present-day shape of Coastal Range shown in black). The lithosphere consumed by plate convergence of the last 2.5 m.y. is shown in gray, based on instantaneous plate motions of Seno (1977). Bathymetry of the Chinese continental shelf has been extrapolated into the region of consumed lithosphere. The present bathymetry near southern Taiwan has been translated northward relative to the Luzon volcanic arc until the southern peninsula of proto-Taiwan has the same position relative to the 2.5 m.y. continental shelf as the peninsula today has to the present-day continental shelf. The southern Coastal Range is shown to lie in the now deformed northern continuation of the Luzon Trough forearc basin.

Possible general applicability of Lichi mélange genesis.—The site that is indicated for the origin of the Lichi mélange is a forearc basin, rather than the trench or subduction-zone site that is commonly proposed for mélanges containing oceanic sediments and ophiolites. However, we suspect that the origin of the Lichi mélange is not unique. In essence, the Lichi mélange is a moderately deep-water, fault-scarp sedimentary facies associated with the collapse of a forearc basin (Luzon Trough) during an arc-continent collision (figs. 6, 7, 8). The collapse of such a basin is mechanically inevitable during collision because of the relatively thin crust in forearc basins (fig. 7). Therefore, Lichi-type mélanges may form rather widely during similar events.

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