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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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Crustal accretion and metamorphism in Taiwan, a post-Palaeozoic mobile belt*

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Taiwan consists chiefly of Permo-Mesozoic basement unconformably overlain by Cainozoic cover strata; on the east, this complex is juxtaposed along the Longitudinal Valley against the Neogene Coastal Range, the northern extension of the Luzon calc-alkaline arc and intervening fore-arc basin.

Accumulation of well-ordered sandstones, shales, limestones and intercalated basaltic units, and outboard argillite melange along the eastern margin of Asia in Permian and early to mid-Mesozoic time was terminated by a major late Cretaceous (85–90 Ma) dynamothermal event that produced the composite basement complex of Taiwan, and also affected much of southeastern China. This basement consists of a westerly Tailuko belt, separated from the easterly Yuli belt by a major fault. The miogeoclinal Tailuko belt is characterized by chloritic and biotitic greenschist facies low-pressure assemblages, except in the north where amphibolite facies assemblages are associated with emplacement of remobilized granitic rocks; metamorphic grade increases gradually eastward. The eugeoclinal Yuli belt lacks marble layers and granitic intrusions, and instead contains serpentinite bodies and associated rare high-pressure epidote-bearing barroisitic amphibolite tectonic lenses. Tailuko quartzo-feldspathic rocks contain mineralogic and geochronologic evidence of Palaeogene and Neogene reheating. Mafic tectonic blocks in the Yuli belt show partial conversion to glaucophanic assemblages; radiometric ages for the blueschist metamorphism are 8–14 Ma.

The Cainozoic slate sequence was deposited on the basement complex following renewed Palaeogene rifting. It consists largely of sedimentary strata (and intercalated basalts) laid down on the Asiatic passive margin and seaward in the South China Sea as continental slope deposits. An accretionary wedge was constructed adjacent to the approaching Neogene Luzon arc, marking the non-subducted western margin of the Philippine Sea plate. During Plio-Pleistocene collision of the Luzon arc with the Chinese continental margin, the landward Cainozoic shelf and slope units were imbricated and thrust westward; increased pressure (P) and temperature (T) during this loading evidently promoted recrystallization of the basement and passive margin cover. Metamorphism ranged from diagenetic and zeolite facies in the Western Foothills to upper greenschist and locally amphibolite facies in the basement complex. No metamorphic hiatus between Mesozoic basement and Cainozoic cover is recognized. The accretionary terrane lying east of the Longitudinal Valley is virtually unmetamorphosed. However, the East Taiwan Ophiolite, occurring as clastic debris and slide blocks in the unmetamorphosed olistostromal, largely Pliocene, Lichi Melange of the Coastal Range fore-arc basin, carries the effects of a mid-Miocene oceanic-ridge recrystallization of actinolite hornfels facies, overprinted by a late Miocene ocean-floor zeolitization.

Large portions of the sialic crust making up Taiwan evidently formed approximately *in situ*, then were deformed and thrust landward during subsequent tectonic events,

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but far-travelled terranes and allochthonous fragments of oceanic material played an important role in accretion. Recognized and suspected exotics include: (1) Lower or mid-Mesozoic meta-ophiolites, now greenstones, amphibolites and minor serpentinites, previously obducted into the Upper Mesozoic Tailuko belt; amphibolites also occur as enclaves in granitic intrusives 85–90 Ma old; (2) the entire Upper Mesozoic Yuli belt; (3) Mio-Pliocene tectonic blocks of blueschistic meta-ophiolite, emplaced in the east-central part of the Yuli terrane; (4) olistostromal ophiolitic debris (preexisting Miocene oceanic crust of the South China Sea) within the Pliocene Lichi Melange of the Coastal Range; and (5) the Neogene calc-alkaline Luzon arc, which began to collide with Asiatic continental crust in Plio-Pleistocene time. The Cainozoic slate series represents an additional, parautochthonous terrane, which was deposited as the Tertiary miogeoclinal cover along the Asiatic passive margin, and was thrust westward during Plio-Pleistocene arc collision.

Among the suspected allochthonous units, Mesozoic amphibolites of both Tailuko and Yuli belts have been identified as of chiefly normal MORB affinites from their chemical and Nd and Sr isotopic compositions. The clearly oceanic East Taiwan Ophiolite apparently formed along a transform-interrupted spreading centre of the South China Sea marginal basin, based on mineralogic, chemical and isotopic evidence.

Introduction

The southeastern portion of Asia consists of two major, late Archaean–Proterozoic cratons, transected and rimmed by Phanerozoic fold belts (Huang 1978, 1980). The more northerly, Sino–Korean platform underwent its latest orogeny about 1700–1800 Ma ago, whereas the more southerly, Yangtze platform became quiescent only 1 Ga later (Ma & Wu 1981). This age progression, seemingly applicable to the seven principal shield areas of the entire Eurasian plate, and a general younging of ancient and more recent blueschistic suture zones to the southeast, led Miyashiro (1981) to postulate an overall accretionary growth with time of the continent towards the Pacific Ocean. The Phanerozoic ages of most ophiolite and blueschist belts in China caused Zhang *et al.* (1984) to question details of this model of continental evolution; moreover, Klimetz (1983) has presented evidence supporting a mid-to late Mesozoic assembly of eastern China. However, it is clear from geologic relations presented by all the above-cited authors that Korea, northeastern and southeastern China, and the Hida region of central Honshu, Japan, all contain Precambrian sialic crust, with progressively more peripheral orogenic belts reflecting successive Palaeozoic, Mesozoic and Cainozoic additions. The overall geology of southeastern Asia, showing the marginal position of Taiwan, is summarized in figure 1.

A broad zone up to 2000 km wide, characterized by felsic volcanic–plutonic rocks possessing mid-Mesozoic to early Cainozoic ages, is distributed throughout eastern China and contiguous western Pacific areas, superimposed across the pre-existing terranes (Jahn *et al.* 1976; Wu & Qi 1985; Zheng 1985). Miyashiro (1981) and Zhang *et al.* (1984) drew a comparison with the Basin and Range province of the western conterminous U.S. Similar to the American analogue, post-Palaeozoic igneous activity of the eastern portion of the Eurasian plate interior appears to reflect crustal attenuation, high heat flow, and anatexis of basal sialic units accompanying mantle upwelling, whereas calc-alkaline melt generation adjacent to the plate margin evidently was a consequence of subduction of a Palaeo-Pacific plate (probably the Kula plate, according to Uyeda & Miyashiro 1974) beneath the Chinese margin.

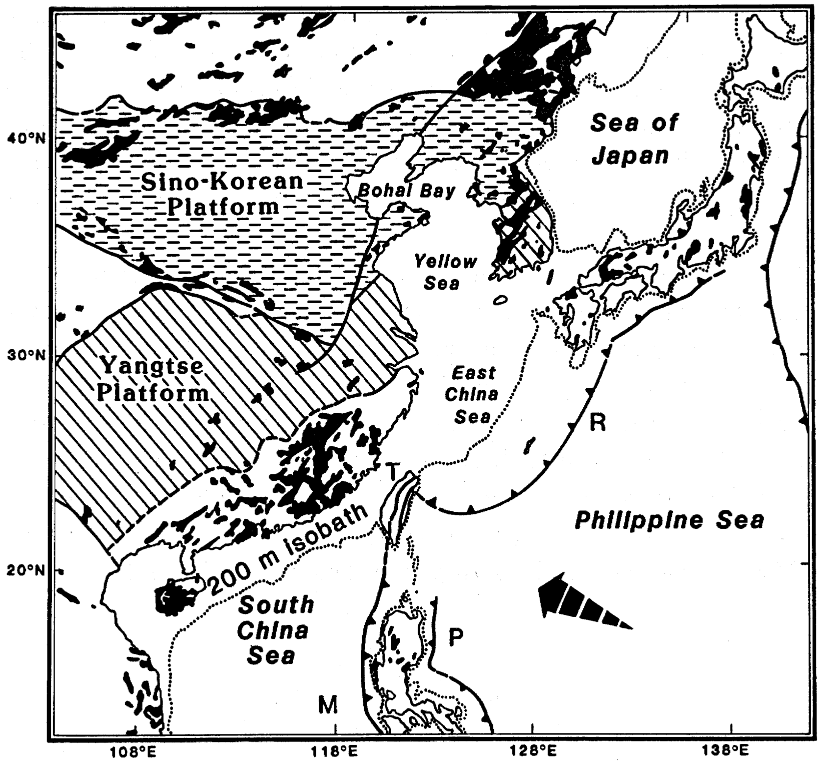

FIGURE 1. Regional plate tectonic setting of Taiwan (T) at the intersection of the Ryukyu (R) and Manila (M) trenches with the continental margin of Asia, largely after Hamilton (1979), Li *et al.* (1982) and Lee (1984). Cratons are patterned; Phanereozoic granitoids are shown in black. The arrow indicates the approximate motion of the Philippine Sea plate relative to Asia, 7 cm a^{-1} (Seno 1977), and points to Taiwan. The Philippine Sea plate is descending obliquely beneath the Ryukyu arc, but is being thrust over the South China Sea and Chinese continental margin. Thus, relative to the Asiatic plate, the Manila trench is moving westward with time. The Philippine trench (P) appears to be propagating northward (Lewis & Hayes 1983).

Modern plate tectonic setting of Taiwan

Taiwan is located along the rapidly evolving eastern margin of the Eurasian sial-capped lithosphere, where Permian and younger continental crust impinges today against the oceanic crust-capped Philippine Sea plate (Biq 1971, 1981; Chai 1972; Bowin *et al.* 1978; Hamilton 1979; Ernst 1983*a*; Suppe 1984). Present-day differential motions of the several plates are well documented by earthquake foci (Tsai 1978, 1986; Hamburger *et al.* 1983). The Philippine Sea plate is moving northwestward relative to Eurasia at a rate of about 7 cm per year (Seno 1977). Convergence is accommodated along its northern boundary by subduction of the Philippine Sea plate beneath the Ryukyu volcanic arc, which has been constructed on oceanic crust directly seaward from the Asiatic continental margin. The Tatun andesitic field at the northern tip of Taiwan probably represents the western termination of this arc. Because of curvature of the surface expression of this convergent plate boundary, the western part of the Ryukyu trench system currently is experiencing chiefly right-lateral strike-slip.

South of Taiwan, convergence is taken up along the western boundary of the Philippine Sea plate by eastward underflow of the South China Sea and incipient subduction of the Chinese continental margin. The northern part of the Philippine Islands, a northward-extending bathymetric high, and the Coastal Range of eastern Taiwan constitute the Luzon calc-alkaline volcanic arc, which has been produced by this eastward subduction of the Eurasian lithospheric plate; modern igneous activity is confined to the southern portion of the arc, but volcanism occurred in the more northerly Coastal Range during Miocene and Pliocene time. Taiwan represents a crustal salient where the Asiatic continent adjacent to the South China Sea in large part has decoupled from the mantle lithosphere as the latter descends beneath the Luzon arc. In the process, this eastern edge of Asia is being structurally compressed, thickened and uplifted.

Taiwan, therefore, consists of portions of two major tectonic entities: (*a*) the Asiatic sialic crust including pre-Tertiary basement; and (*b*) the accreted Luzon arc. Overlying the basement of the continental margin lies an imbricated, westward verging, sedimentary prism of Cainozoic age. Deposited on the Asiatic passive margin, and on the outboard, now-consumed South China Sea oceanic crust, this section is parautochthonous, portions having been thrust westward as much as 160 km towards the mainland during continued convergence (Suppe 1976; Suppe & Wittke 1977). Its contact with the Luzon volcanic arc occurs along the Longitudinal Valley of eastern Taiwan, a currently active left-lateral strike-slip zone (Allen 1962; Biq 1965; Hsu 1976*a*). General relations are sketched in figure 2.

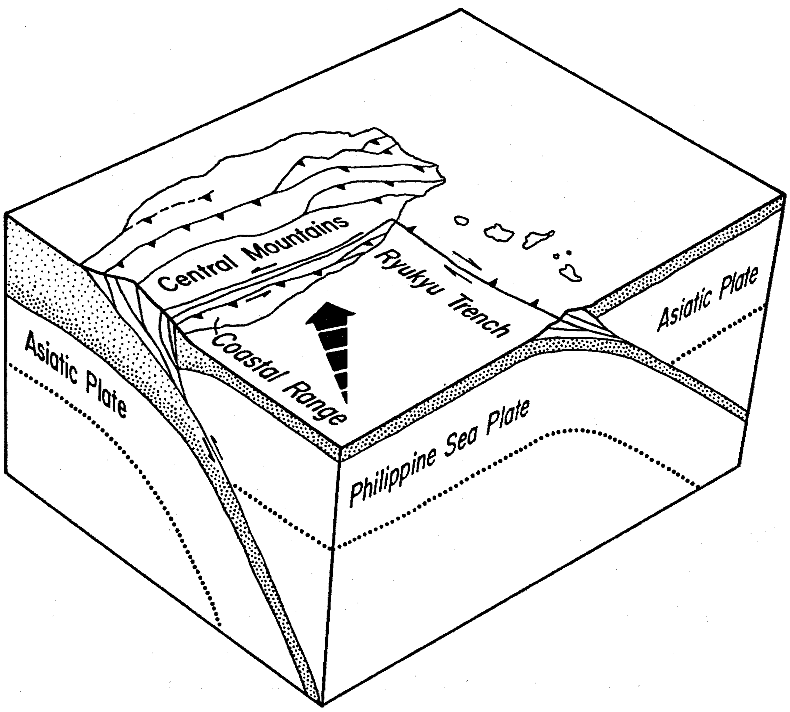

FIGURE 2. Schematic diagram, approximately to scale, showing present plate tectonic configuration of Taiwan (Ernst 1983*a*). The convergent plate junction, located along the Ryukyu trench, is a well-defined, stable linear feature. In contrast, the eastward underflow of the Asiatic plate beneath the Philippine Sea and surmounting Coastal Range (the Luzon calc-alkaline arc) is being choked off due to accumulation of the imbricated Cainozoic passive margin section and underlying basement complex; this collision has generated the distributory thrust fault system present throughout the main part of Taiwan. The Longitudinal Valley lies between the Central Mountains and the Coastal Range. It marks the juxtaposition of the far-travelled Luzon arc (including its Neogene fore-arc basin) with the passive margin miogeoclinal section and its Asiatic basement; a minimum of 150 km left-lateral displacement has taken place along this strike-slip fault system since the Pliocene onset of collision (Tsai 1978).

Prior to collision of the Coastal Range and the Chinese continental margin that began about 4 Ma ago (Chi *et al.* 1981), oceanic crust of the South China Sea lay along the eastern edge of the Eurasian lithospheric plate, as it still does today southwest of Taiwan. Consumption of this intervening oceanic crust allowed: (1) approach and impaction of the Chinese sialic crust, initially in northeasternmost Taiwan, with the northern end of the calc-alkaline Luzon arc; (2) incipient subduction of the Asiatic continental crust; and (3) imbrication and westward thrusting of the passive margin miogeoclinal wedge. Distributory shear apparently has moved westward with time. Impaction has been partly accommodated by sinistral strike-slip as well as by landward thrusting. Thus, a broad composite zone of deformation has been produced, rather than a discrete, well-defined plate boundary. The Longitudinal Valley fault zone simply constitutes a major strand of a rather broad distributory shear system. With continued convergence, the zone of collision has propagated southwestward as more sialic material has become involved in the eastward underflow, and the South China Sea has been progressively consumed (Barrier 1985). Portions of the Asiatic basement have also been transported continentalward (Suppe 1980*a*, 1981). Ultimately, buoyancy forces should stifle the Manila trench subduction zone, and a new west-dipping convergent plate junction will be initiated, probably as conjectured by Bowin *et al.* (1978), as a northward extension of the reactivated Philippine trench (see also Cardwell *et al.* 1980; Lewis & Hayes 1983; Suppe 1984). This process ought to result in future transference of the entire Luzon arc to the Eurasian plate, including surviving remnants of the South China Sea, and stable westward underflow of the Philippine Sea lithosphere beneath Taiwan (Ernst 1983*a*).

Regional geology

The various lithotectonic belts of Taiwan are illustrated in figure 3 (Ho 1982, 1986). From west to east they are: (*a*) the Coastal Plain; (*b*) the Western Foothills, (*c*) the Hsuehshan Range; (*d*) the Backbone Range; (*e*) the basement complex, and (*f*) the Coastal Range. Units (*b*), (*c*) and (*d*) comprise the imbricated, parautochthonous Cainozoic passive margin sequence of slates, argillites and minor intercalated mafic volcanics structurally overlying (*e*) the pre-Tertiary Tananao Schist complex, representing the Asiatic continental crust; (*f*) is the Neogene Luzon calc-alkaline arc and associated volcanogenic sediments as well as the Luzon trough fore-arc basin deposits of the Coastal Range. With the exceptions of (*a*) and (*f*), all sections have been at least weakly recrystallized; the Coastal Range contains the East Taiwan Ophiolite, which was subjected to oceanic metamorphism before incorporation as olistolithic debris in the Luzon accretionary wedge.

Various diastrophic events have been recognized in Taiwan. Ho (1982) referred to two principal mountain building phases: the late Mesozoic multistage Nanao orogeny involving the pre-Tertiary basement, and the Plio-Pleistocene Penglai (=Taiwan) orogeny, resulting in the deformation, progressive metamorphism and uplift of most of the island. These two orogenic episodes are well documented geologically and geochronologically, and reflect major subduction events. Yen (1976; personal communication 1981), in addition, divided the pre-Tertiary deformation into earlier and later Mesozoic stages and distinguished between the Neogene orogenies in the Coastal Range on the one hand, and the rest of Taiwan on the other. These events and a Paleogene heating accompanying rifting have been investigated radiometrically by Jahn *et al.* (1986); principal results are presented in a later section.

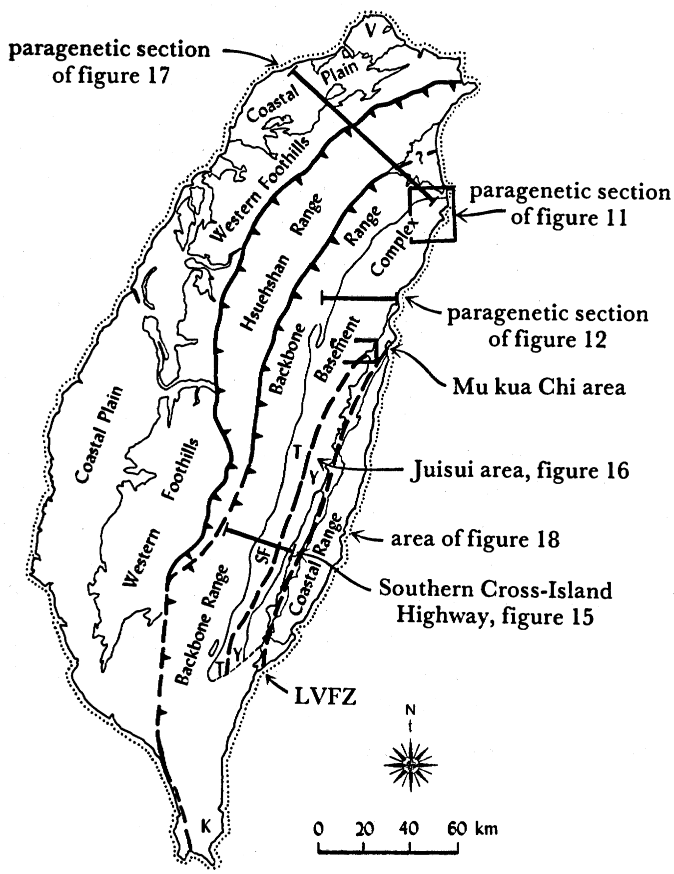

FIGURE 3. Lithotectonic belts of Taiwan, after Ho (1975). The Tatun volcanic group is indicated by V, the Kenting Mélange by K. The Coastal Range of eastern Taiwan is separated from the pre-Cainozoic basement terrane by the Longitudinal Valley, the site of a major left-lateral shear system (LVFZ). The Tananao Schist complex is divided into two belts by the problematical Shoufeng fault (SF); these are the Tailuko belt (T) and the Yuli terrane (Y). Successively more westerly lithotectonic realms of the Cainozoic cover series have been juxtaposed by an east-dipping series of thusts (barbs on upper plates); only a few of these are shown (none for the Western Foothills belt). Paragenetic sections are indicated.

(*a*) *Coastal Plain*

The Coastal Plain consists of Pleistocene and Recent terrace gravels, alluvium and well-bedded, poorly consolidated clastic sediments. This uplifted but practically undeformed section passes westward into epicontinental sediments of the Taiwan Strait; eastern, thicker portions have been deposited upon, or are tectonically overridden by, parautochthonous strata of the Western Foothills.

(*b*), (*c*) *and* (*d*) *Western Foothills and Slate Ranges*

Shallow marine, locally coal-bearing detrital units of the Western Foothills are largely late Oligocene to Pleistocene in age, the Hsuehshan Range contains Eocene, Oligocene and late Miocene quartzose, carbonaceous metasandstones, argillites, and slates, and the Backbone Range consists chiefly of Palaeocene, Eocene and Miocene slaty and phyllitic metaclastic rocks (see, for example, Yen 1973). This non-turbiditic sedimentary prism consists of continental shelf deposits on the west, which gradually give way eastward to units deposited on the Asiatic

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continental slope and rise. The cover series contains intercalated, somewhat alkalic mafic lavas and tuffacous units as well as doleritic dikes. The sedimentary sequence thickens eastward to approximately 10000 m. The dominantly clastic debris is more sandy in the northern and west-central parts; detritus is lithologically similar to the basement, hence probably was locally derived.

These sections consist of a stack of folded, imbricate thrust sheets which appear to root in the vicinity of the Longitudinal Valley. In general, tops face east, but overall the sections young in the opposite direction, suggesting progressive westward tectonic transport of older, right-side-up units over younger, structurally lower strata. Simplified geologic cross sections of portions of northern and west-central Taiwan have been presented by Suppe (1980*a*, *b*). The transported nature of this foreland fold-and-thrust belt is evident; the cumulative shortening is approximately 160 km. However, basal and intraformational conglomerates contain pebbles of the underlying pre-Cainozoic basement (Yen *et al.* 1956; Suppe *et al.* 1976), so lowermost units of the cover series evidently are autochthonous. Metamorphism has affected all units, with grade increasing gradually eastward (Liou 1981*a*; Chen 1981; Chen *et al.* 1983). Deformation and recrystallization of rocks as young as Plio-Pleistocene fix the time of the Penglai orogeny (Law & Aronson 1984).

The Kenting Melange of southernmost Taiwan (see figure 3) appears to represent a Mio-Pliocene deep-water olistostrome deposited within a basin spatially separate from that of the slate series immediately prior to the arrival of the Luzon arc (Page & Lan 1983; Pelletier & Hu 1984; Pelletier & Stephan 1986).

(*e*) *Tananao Schist*

The pre-Cainozoic basement of Taiwan (Yen 1954*a*, *b*, 1960; Ho 1975, 1979) crops out as a narrow belt immediately west of the Longitudinal Valley. It bears evidence of polymetamorphism and multiple deformation (Yen 1967, 1976; Wang 1979). As indicated in figure 3, two principal lithotectonic zones have been recognized, separated by the poorly exposed Shoufeng fault (Yen 1963; Yen *et al.* 1984). In the vicinity of the Southern Cross-Island Highway, this break appears to be a steeply west-dipping imbricate fault zone (Stanley *et al.* 1981) but elsewhere its presence and attitude are equivocal.

On the west lies the Tailuko belt, consisting of Permian and lower Mesozoic pelitic schists, quartzofeldspathic gneisses, platform carbonates (Jahn *et al.* 1984*b*), intercalated mafic and tuffaceous metasediments, greenschists and amphibolites and minor lenses of serpentinite (Fuh 1962; Liou *et al.* 1981). Permo-Triassic limestones and interlayered clastics appear to be the oldest rocks exposed in Taiwan (Yen *et al.* 1951; Ho 1982). In the north, this belt has been locally intruded by granitic rocks of late Mesozoic age (Wang-Lee 1981; Jahn *et al.* 1986). The occurrence of exclusively plutonic, peraluminous granitic rocks indicates that relatively deep levels of this sialic arc were remobilized in the later Mesozoic. The Tailuko belt contains traces of several pre-Cainozoic metamorphic events in addition to the Palaeogene and Plio-Pleistocene overprintings (Liou *et al.* 1981; Lo & Wang-Lee 1981; Ernst *et al.* 1981; Ernst 1983*a*). These include: (1) production of amphibolite facies assemblages in earlier Mesozoic time (90–200 Ma); (2) emplacement of calc-alkaline granitoids and localized thermal upgrading of country rocks to upper amphibolite facies during the late Mesozoic (85–90 Ma according to Jahn *et al.* 1986); and (3), late Cretaceous deformation of the granitic rocks and retrograde formation of lower grade mineral assemblages (Yen & Rosenblum 1964). The highest grade metamorphics occur adjacent to the felsic plutons, and both are confined to the northernmost portion of the belt (Chu 1981; Wang-Lee 1981). Although the absolute timings of the various recrystallization events are difficult to establish, the relative age sequence and association with stages of intrusion and deformation are clear.

East of the Tailuko belt lies a monotonous melange of pre-Cainozoic pelitic, argillitic and less voluminous mafic plus ultramafic schists of oceanic affinities (Liou 1981*a*; Lan & Liou 1984), collectively termed the Yuli belt; carbonate strata and granitoids are conspicuously absent from this terrane. The provenance of the clastic sediments is not well constrained. Rocks of the Yuli belt exhibit dominantly high-rank greenschist facies mineral compatibilities, chiefly ascribable to the Plio-Pleistocene overprinting, as noted in the eastern Mu-kua Chi area (Ernst & Harnish 1983). However, melange matrix and the enclosed ophiolitic tectonic blocks (associated with serpentinite lenses) in the east-central portion of the belt attest to the late Cretaceous crystallization of relatively high-pressure barroisitic amphibolites and the late Miocene production of blueschists (Yen 1966; Liou *et al.* 1975; Lan & Liou 1981; Liou 1981*a*; Jahn *et al.* 1981).

The problematic Shoufeng fault has been compared with the Median Tectonic Line of southwestern Japan (Miyashiro 1961; Yen 1966). Similarly, it juxtaposes a continentalward calc-alkaline magma-intruded, thermally upgraded and recrystallized, largely miogeoclinal and/or continental slope section against a more seaward trench-argillite lithotectonic zone lacking felsic igneous rocks but containing alpine-type serpentinized peridotites and mafic igneous bodies. In general, open folding appears to characterize the Tailuko belt, whereas disharmonic folding and oceanward vergence typify the Yuli terrane (Yen 1967; Biq 1971; Stanley *et al.* 1981; Ernst 1983*a*, *b*). Thus, these two Mesozoic belts possess some of the contrasts that characterize coeval landward Circumpacific volcanic–plutonic arcs and outboard subduction complexes (Ernst 1977*a*).

(*f*) *Luzon Arc*

The Neogene Coastal Range of eastern Taiwan consists of calc-alkaline volcanic units and associated strata which are lithologically distinct from, and everywhere in fault contact with, belts lying to the west of the Longitudinal Valley. The structure of the Coastal Range is complicated by low-angle (horizontal to east-dipping), imbricate thrust faults: in general, older rocks are exposed towards the centre of the range as the cores of NNE-trending anticlines, with younger units disposed peripherally. The stratigraphy (Hsu 1956, 1976*b*; Chi *et al.* 1981; Ho 1982) is summarized below.

The oldest rocks exposed in the Coastal Range are Lower Miocene andesitic volcanics, agglormerates, tuffs and associated volcanogenic sediments of the Tuluanshan Formation, and hypabyssal andesitic–dioritic plugs of the Chimei Complex. The latter possesses whole-rock K–Ar dates as old as 22 Ma (Ho 1969). Lenses of reef limestone near the top of the Tuluanshan yield early to mid-Miocene foraminiferal dates (Chang 1967). Locally, the upper Tuluanshan is middle to late Miocene in age, or younger (C. S. Ho 1985, personal communication). This unit interfingers with, and passes stratigraphically upwards into, turbiditic, volcanogenic clastics of the upper Miocene–Pliocene Takangkou Formation (Chi *et al.* 1981). Dominantly a flysch unit, the Takangkou also contains intercalated calc-alkaline volcanics. Lower portions of the section contain detritus exclusively of arc derivation, but towards the top, detritus from the Cainozoic cover series of the Asiatic passive margin is present (Teng 1979, 1980).

The Takangkou, in turn, passes laterally and vertically into a Plio-Pleistocene muddy olistostrome, the Lichi Melange (Wang 1976; Page & Suppe 1981; Barrier & Muller 1984). The olistostrome contains clasts from several distinct source régimes: the immediately adjacent, more easterly calc-alkaline Luzon arc; the western, Asiatic continental margin; and the crust + uppermost mantle of the South China Sea. Components of the andesitic arc and the sialic basement + passive margin strata are present in the Lichi Melange exclusively as pebbles, but the mafic + ultramafic detritus occurs both as conglomeratic lenses and as slide blocks up to 1 km in length and several hundred metres in thickness (Liou *et al.* 1977; Ernst 1977*b*). Larger blocks exhibit stratigraphic relations that allow reconstruction of the nature of the East Taiwan Ophiolite before its dismemberment and incorporation in the olistostrome (Liou *et al.* 1977). Mafic and ultramafic plutonic members of the suite formed during early Miocene time, probably at a spreading centre, and they have isotopic (Sr, Nd, Pb) and trace element characteristics typical of modern MORB (Jahn *et al.* 1984*a*; Jahn 1986). After a hiatus marked by thermal relaxation and deposition of red, deep-sea clays (Suppe *et al.* 1977), off-axis basaltic lavas covered the plutonic series during the middle Miocene (Suppe *et al.* 1981).

Overlying the Lichi Melange, locally marked by an angular unconformity, are fluvial gravels of the upper Pleistocene Pinanshan Conglomerate; this deposit contains abundant detritus from the metamorphic pre-Cainozoic basement of the Asiatic continental margin, and records the time of docking of the far-travelled Luzon arc.

Except for hydrothermal alteration associated with calc-alkaline volcanism, represented by the Chimei Complex and the Tuluanshan Formation, strata of the Coastal Range are completely unmetamorphosed. The Lichi Melange retains a virtually unrecrystallized clay matrix (Page & Suppe 1981). Thus, metamorphic lithologies present in the East Taiwan Ophiolite were produced during oceanic-ridge and sea-floor recrystallization in the South China Sea (Liou 1979; Liou & Ernst 1979), before incorporation in the Lichi Melange as olistostromal debris.

Geochronology and geochemistry

The succession and timing of tectonothermal events recorded in the crustal materials of Taiwan have been gradually unravelled by recent radiochronometric studies, especially on the Tananao Schist complex (Jahn *et al.* 1981, 1984*b*, 1986). Various isotopic systems (Rb–Sr, U–Pb, Sm–Nd, K–Ar) have been employed, and the data have confirmed the polymetamorphic nature of the complex. Important events are summarized in figure 4.

The crustal history of Taiwan evidently began with clastic and carbonate sedimentary deposition and later emplacement of Mesozoic ophiolitic materials, now represented by various schists and amphibolites of the Tananao Schist complex. Initial $^{87}Sr:^{86}Sr$ ratios ($= I_{Sr}$) for samples of marble best fit the sea-water Sr isotope evolution curve for 200–240 Ma, suggesting deposition during Permo-Triassic time. This result is compatible with the sparse fossil ages reported by Yen *et al.* (1951).

U–Pb zircon dating of two granitic plutons reveal that these bodies were intruded into the Tailuko belts about 85–90 Ma ago (figure 5). Such late Mesozoic silicic magmatism is widespread in southeastern China and throughout the Circumpacific (Jahn 1974; Jahn *et al.* 1976; Wu & Qi 1985; Zheng 1985). The presence of an inherited zircon Pb component suggests that ancient crustal sources (*ca.* 1000–1700 Ma old) were involved in generation of the granitic magmas. The most likely provenance of these old zircon components is the nearby

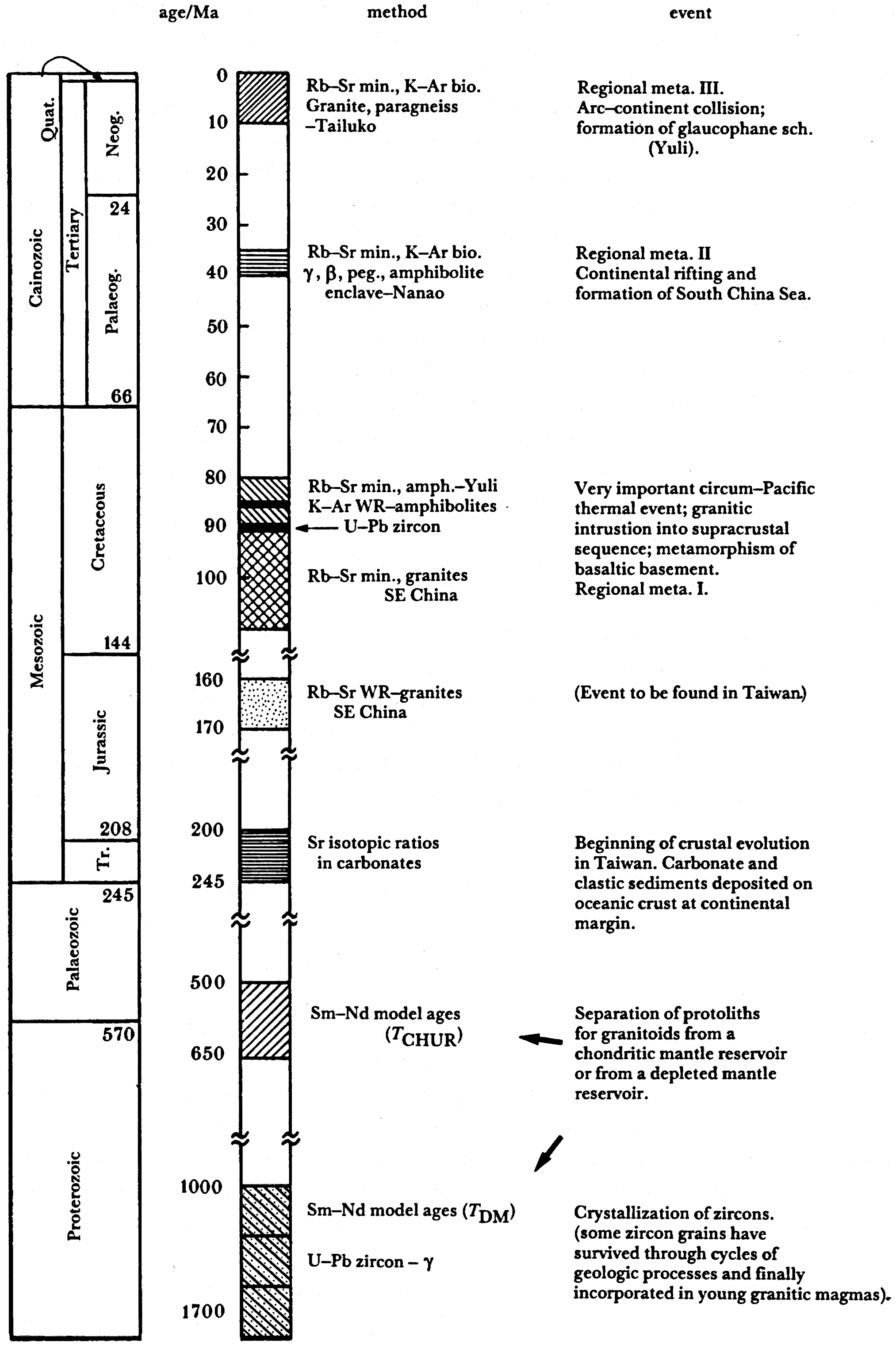

FIGURE 4. Summary of important tectonothermal events for the Tananao Schist complex as revealed by radiochronometric data, by employing a variety of methods (see text; also Jahn *et al.* 1986). Original rock types are abbreviated as follows: β, basalt; γ, granite.

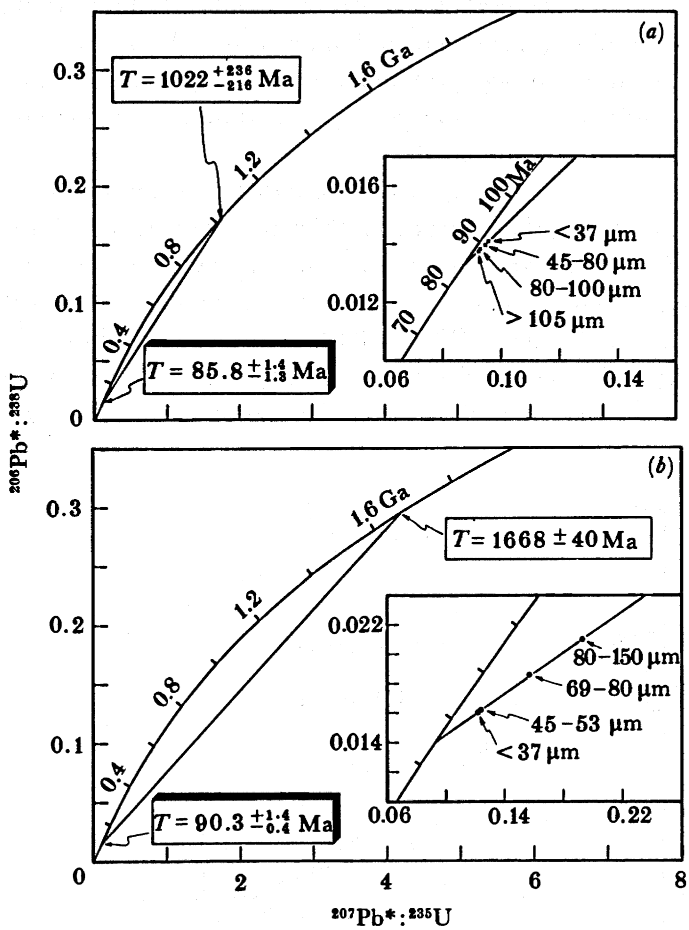

FIGURE 5. U–Pb concordia diagrams for granite samples from Nanao-Suao (*a*) and Tailuko Gorge (*b*) portions of the Tailuko belt. The lower intercept ages represent the period of intrusion; the upper intercept ages, although very imprecise, suggest incorporation of minor inherited old zircon components (hence an ancient crustal source) in the generation of the magmas.

Yangtze Platform. Incorporation of Precambrian sialic material during late Mesozoic magma genesis is supported by available Sm–Nd isotopic data, which yield depleted mantle model ages exceeding 1000 Ma (Jahn *et al.* 1986).

The basement complex has undergone several periods of regional metamorphism beginning in mid(?)-Mesozoic time and culminating 85–90 Ma ago. In the Nanao-Suao region, Rb–Sr and K–Ar isotopic ages of late Mesozoic granites and associated pre-existing polymetamorphic amphibolites indicate an important thermal overprinting 35–40 Ma ago, that may reflect the initial rifting of the South China Basin (see, for example, Taylor & Hayes 1983). Schwan (1985) documented two remarkable, worldwide geodynamic events at about 45 and 37 Ma; these are manifested by orogenesis, granitic plutonism, regional metamorphism, change in rate or direction of sea-floor spreading and global marine regression.

The thermal effect produced by collision of the Luzon arc with the Asiatic continent reset the Rb–Sr and K–Ar isotopic systems of the basement complex near the suture zone. K–Ar and Rb–Sr mineral isochron ages of less than 10 Ma, and as young as 2.5 Ma, have been determined for granitic gneisses of the Tailuko belt near Tailuko Gorge (Jahn *et al.* 1986) and for the adjoining Cainozoic cover series (Law & Aronson 1984). Equally young ages have also been reported for mica-amphibolites and glaucophane schists of the Yuli belt (Jahn *et al.* 1981). Such young, but variable, apparent ages are believed to represent resetting to various extents by the arc-continent collision. However, this youngest thermal event apparently did not affect the Nanao-Suao region in the extreme north.

Granitic orthogneisses occur as lenticular bodies bounded by amphibolite and metasedimentary paragneisses at Nanao-Suao; they intruded a thick marble sequence in the Tailuko Gorge area. Elsewhere, granitic gneisses are scattered as small metaplutonic lenses in the northern part of the Tailuko belt. Chemical compositions of the orthogneisses indicate that they are peraluminous granodiorites (Nanao, $SiO_2 = 60\%$) and adamellites (Tailuko, $SiO_2 = 66–70\%$); quartzofeldspathic paragneisses have almost the same compositions as the granitic orthogneisses. The REE distribution patterns of figure 6 show pronounced negative Eu

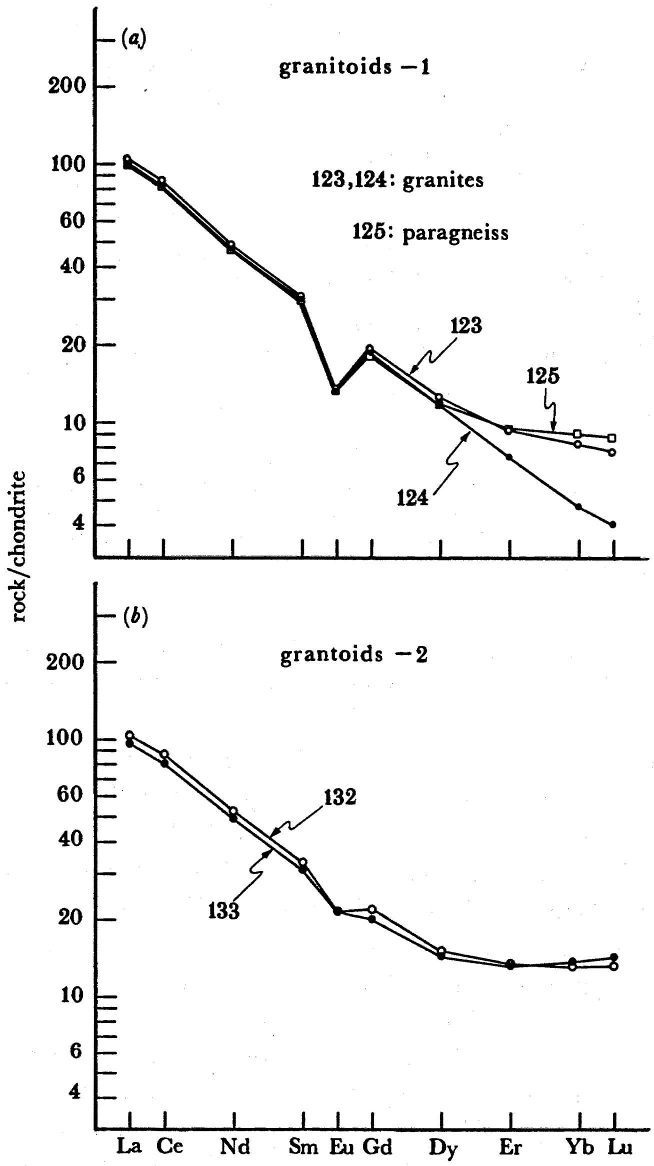

FIGURE 6. REE distribution patterns of two granites (adamellites) and a paragneiss from Tailuko Gorge (*a*), and of two granodiorites from Nanao-Suao (*b*).

anomalies in the Tailuko Gorge adamellites and less fractionated, less pronounced Eu anomalies in the Nanao-Suao granodiorites. The nearly identical REE patterns for a paragneiss and two granites (figure 6*a*) favour their close genetic link. The overall chemical and isotopic compositions (ϵ_{Nd}(90 Ma) = −3.8 to −5.2; I_{Sr} = 0.7075 for Nanao-Suao granodiorites and 0.7090–0.7095 for Tailuko Gorge adamellites) suggest that these granitoids were derived by anatexis of crustal protoliths, instead of predominantly mafic sources as in many island arc environments.

Metamorphosed Mesozoic mafic and ultramafic rocks occur sporadically in the basement complex of the Central Range. Together with the associated recrystallized pelagic sediments and metaplagiogranites, they have been identified as tectonic fragments of oceanic derivation (Liou 1981*a*; Lan & Liou 1984; Ernst *et al.* 1981; Jahn *et al.* 1981). New REE and Nd isotopic analyses of amphibolites from the Nanao-Suao area illustrated in figure 7 demonstrate that they are metamorphosed normal mid-oceanic ridge basalts with characteristic LREE depletions and positive ϵ_{Nd} values (+8 to +11, Jahn *et al.* 1986).

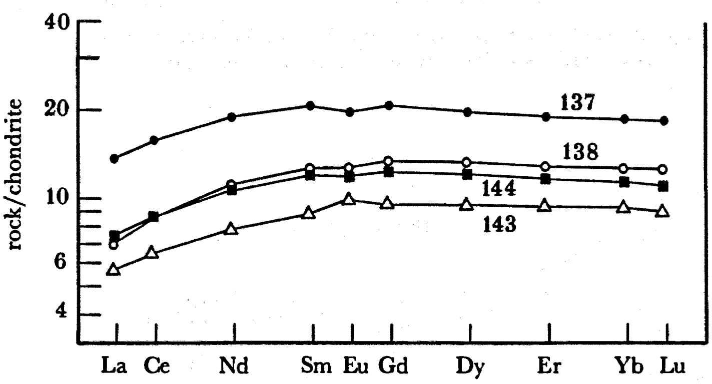

FIGURE 7. REE distribution patterns of amphibolites from the Nanao-Suao area. They show very characteristic light REE depletions typically found in normal-type MORB. Other chemical abundances are: in percentages (by mass), SiO_2 = 47–48, Al_2O_3 = 14–19, MgO = 7.5–10.0, TiO_2 = 0.6–1.6; in parts per million, Zr = 37–97, Y = 16–39, Sr = 120–150, Co = 35–42, V = 190–390, Ni = 70–210.

Unlike the ophiolitic nature of the amphibolites, some metabasaltic rocks (now greenschists) associated with the thick marble formation and intercalated with cherty and calcareous metasediments from the Tailuko Gorge area have trace element abundances (Nb, Zr, Y, Rb, Sr, Ba, Co, Ni, etc.) and LREE-enriched patterns similar to those of continental flood basalts (figure 8); lack of actinolite suggests the possibility that protoliths may have been tuffaceous. Similarly, the Tertiary dolerite dikes intruding the late Mesozoic granitic plutons in the Nanao-Suao area also possess fractionated REE patterns resembling those of continental basalts (figure 8). These rocks are also slightly alkalic in bulk rock chemistry (Liou *et al.* 1981). This compatibility is further confirmed by a single Nd (ϵ_{Nd} = +1.3) datum and by Sr isotopic data ($I_{Sr} \approx 0.705$ for both Mesozoic greenschists and Tertiary mafic dikes). The overall REE abundances and other trace element contents for the dolerites are lower than for the older greenschists, however.

The East Taiwan Ophiolite represents the youngest (*ca.* 15 Ma) among the known ophiolitic complexes of the world. The field evidence, petrographic, geochemical and isotopic characteristics of representative rock types (pillow basalts, gabbros, plagiogranites, ultramafics, red shales, etc.) are very distinctive and strongly argue for a mid-ocean or marginal basin origin of this suite. Unambiguous criteria include: major element compositions; REE distribution

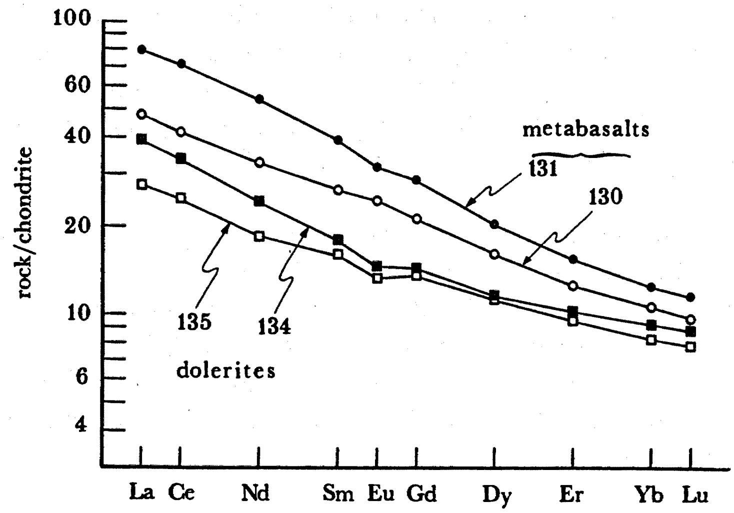

FIGURE 8. REE distribution patterns of two Mesozoic metabasaltic rocks (greenschists) from Tailuko Gorge and two Tertiary dolerite dike rocks from Nanao-Suao.

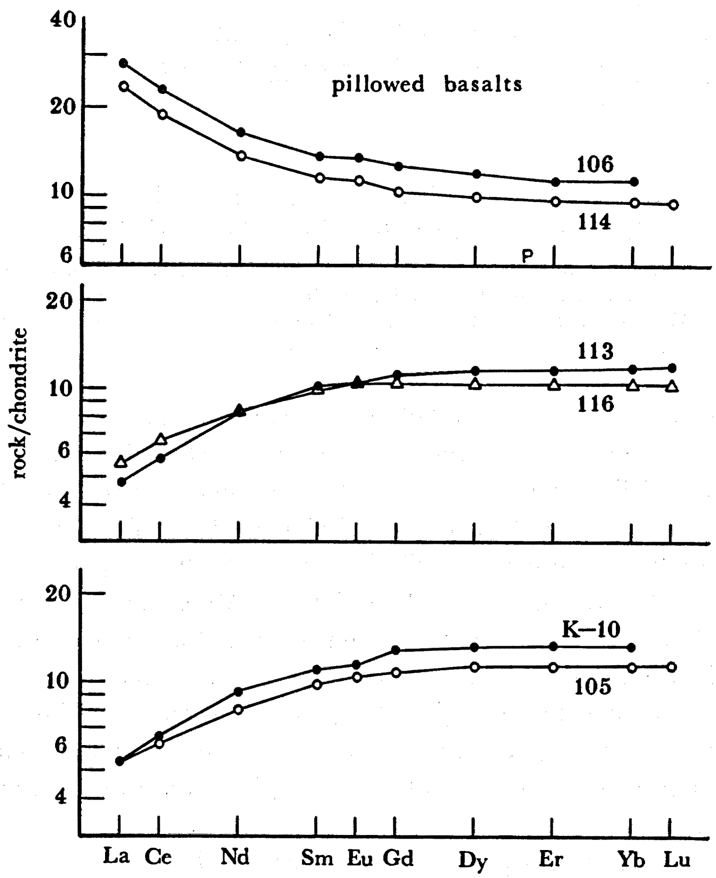

FIGURE 9. REE distribution patterns of glassy basalts of the East Taiwan Ophiolite. Samples 106 and 114 resemble plume-type MORBS, whereas the rest resemble normal-type MORBS.

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patterns of pillowed basalts (figure 9); Nd isotopic ratios ($\epsilon_{Nd} = +8.7$ to $+13.3$); Pb isotopic compositions (figure 10); and the presence and nature of the red shale. This conclusion is supported by previous studies of chemistry and metamorphic evolution of the East Taiwan Ophiolite (Liou *et al.* 1977; Suppe *et al.* 1977, 1981; Liou & Ernst 1979; Ernst & Liou 1984).

In addition to the identification of a spreading centre origin for this lithologic suite, the occurrence of both normal-type and plume-type MORBs in the East Taiwan Ophiolite is also recognized, as shown in figure 9 (Jahn *et al.* 1986). Neither type could have been derived by fractional crystallization from the other, nor by various degrees of partial melting from a common mantle source. Consequently, the genesis of basaltic magmas of the exotic East Taiwan Ophiolite probably involved partial melting and mixing of highly depleted asthenosphere and an enriched plume-type or hot-spot source. The very young age of formation (*ca.* 15 Ma) and the recent tectonosedimentary emplacement by submarine slumpage during arc-continent collision (*ca.* 4–5 Ma ago) suggest that the ophiolite was most likely generated

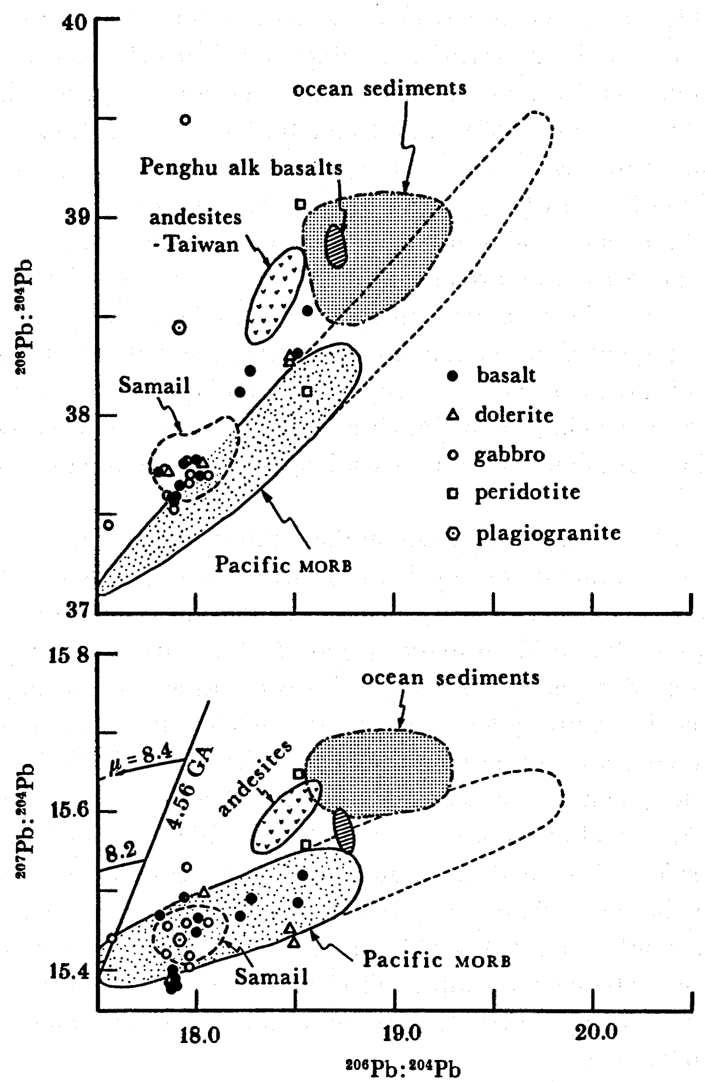

FIGURE 10. Pb isotopic compositions of representative rock types of the East Taiwan Ophiolite. The data generally fall in the Pacific MORB field and are distinct from that of calc-alkaline andesites of Taiwan (Jahn 1986).

at a spreading centre in the South China Sea. This conclusion is supported by age relations in the Coastal Range, and by spreading histories of the South China and Philippine Sea lithospheric plates (Ernst 1977*b*; Ernst & Liou 1984; Suppe *et al.* 1981; Lewis & Hayes 1983; Taylor & Hayes 1983).

Metamorphism

Mineral parageneses

The various stages of progressive recrystallization and contact metamorphism for the different terranes in Taiwan have been studied in many workers, including Yen (1954*a*, *b*, 1963, 1966, 1976), Liou (1981*a*, *b*), Chen *et al.* (1983) and Ernst (1983*a*). Paragenetic relations have been detailed for the northernmost part of the Tailuko belt in polymetamorphosed amphibolite facies rocks exposed at Nanao-Suao (Liou *et al.* 1981; Chu 1981; Chu & Shieh 1981; Ernst *et al.* 1981; Jeng & Huang 1984) and along the Tailuko Gorge transect (Chen 1981; Wang-Lee 1981; Lo & Wang-Lee 1981; Ernst 1983*b*, 1984). Further south, relations have been documented for the Tananao basement paired-belt complex at Mu-kua Chi (Ernst & Harnish 1983) and the Southern Cross-Island Highway (Warneke & Ernst 1984). Sodic amphibole-bearing tectonic blocks of the Yuli belt have been studied at Juisui and nearby areas by Liou *et al.* (1975), Lan & Liou (1981, 1984) and Jahn *et al.* (1981). Oceanic-ridge and sea-floor metamorphism of the East Taiwan Ophiolite have been investigated by Liou *et al.* (1977), Liou (1979), Liou & Ernst (1979), and Ernst & Liou (1984).

Paragenetic relations for metabasaltic lithologies in the northeasternmost exposure of the Tailuko belt near Nanao-Suao are presented in figure 11. A mid-Mesozoic(?) regional amphibolite facies recrystallization was overprinted by a thermal upgrading (locally producing garnet ± sillimanite in metapelites) accompanying the emplacement of late Mesozoic granitoids (85–90 Ma). Biotite grade greenschist facies retrograde metamorphism doubtless accompanied subsequent latest Cretaceous cooling, but definitely attended the late Cainozoic dynamothermal collisional event, as is clear from metamorphic assemblages produced in slate series basalts and dolerite dikes.

Along strike to the southwest, metamorphism in the Tailuko belt reached upper greenschist facies as a maximum, and gradually declined westward, as shown in figure 12. The unconformity between the overlying Cainozoic slaty cover series and the uppermost part of the basement complex (the so-called Pihou(?) Formation) coincides with the biotite isograd. As shown in figures 13 and 14, a gradual change in white mica composition co-existing with chlorite, biotite, albite and quartz in relatively low-variance assemblages, from celadonite-rich on the west to muscovite-rich on the east, accounts for the entrance of neoblastic biotite approximately at the unconformity. The systematic changes in phase compositions suggest a close approach to chemical equilibrium. Figure 14 also illustrates why the chloritic metabasalts lost white mica in the highest grade portion of the belt. As pointed out below, near Nanao-Suao, rocks of the easternmost portion of the cover series carry newly generated biotite. Along the Southern Cross-Island Highway, an infolded syncline of Cainozoic slate series rocks within the high-rank greenschist facies zone of the basement complex also contains neoblastic biotite. Therefore, the disposition of this isograd closely, but not precisely, parallels the Tananao basement-cover series contact in eastern Taiwan.

Systematic element partitionings between co-existing phases in these rocks, both for the northeastern basement areas and further south, lend credence to the hypothesis that equilibrium

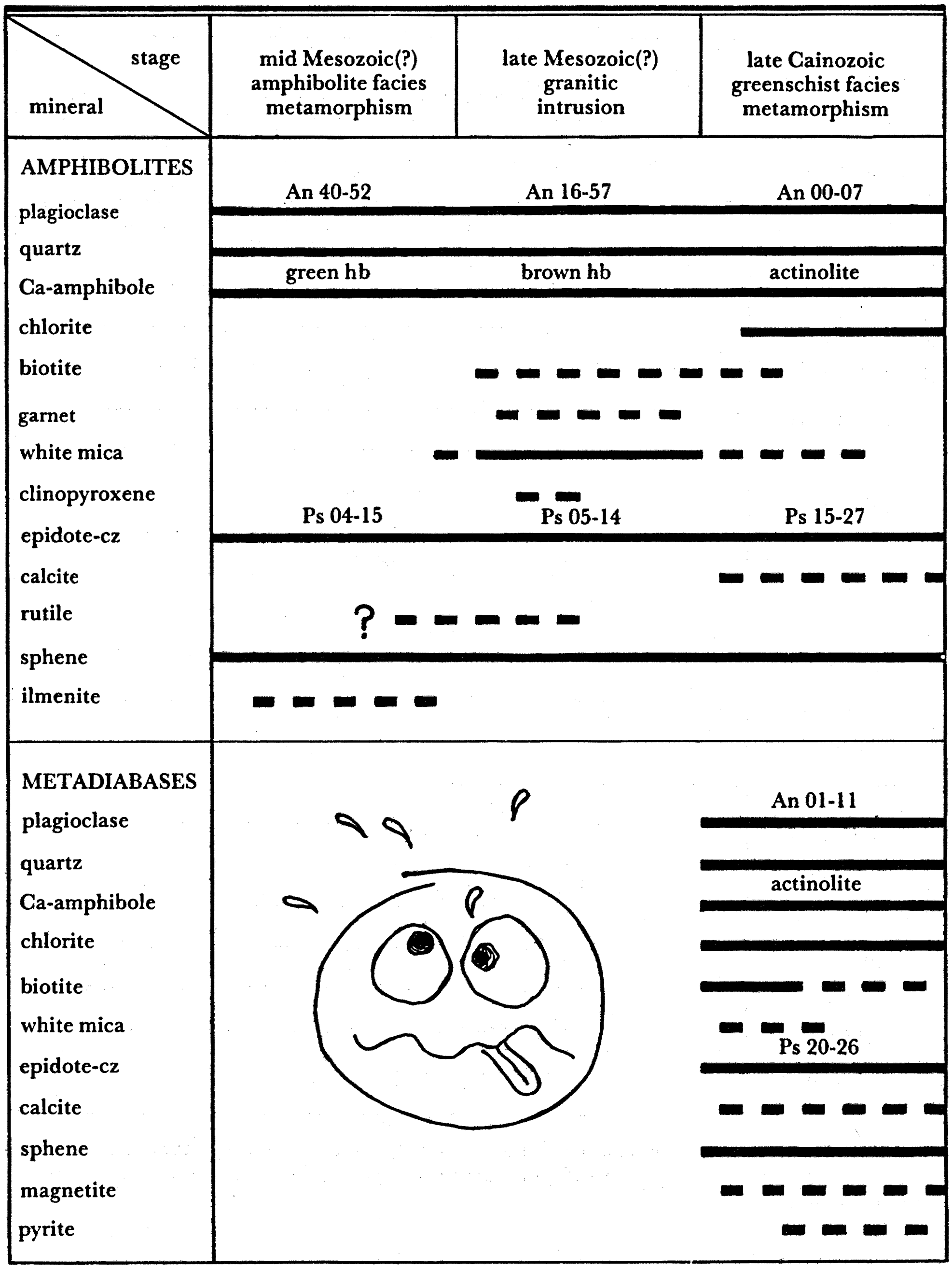

FIGURE 11. Mineral parageneses in metabasaltic lithologies of the Nanao-Suao area (after Liou *et al.* 1981). Note that abscissa represents time; for location, see figure 3.

assemblages have been analysed. Even within the Cainozoic cover series, gradual increase in the degree of ordering in white mica along the Tailuko Gorge transect (Chen 1981) and of carbonaceous material along the Southern Cross-Island Highway, shown in figure 15, support the eastward increase in metamorphic grade previously discussed. Note that there is no break in metamorphic grade at the contact between basement complex and cover strata.

Amphibolitized mafic tectonic blocks and associated siliceous Mn + Fe-rich metasediments

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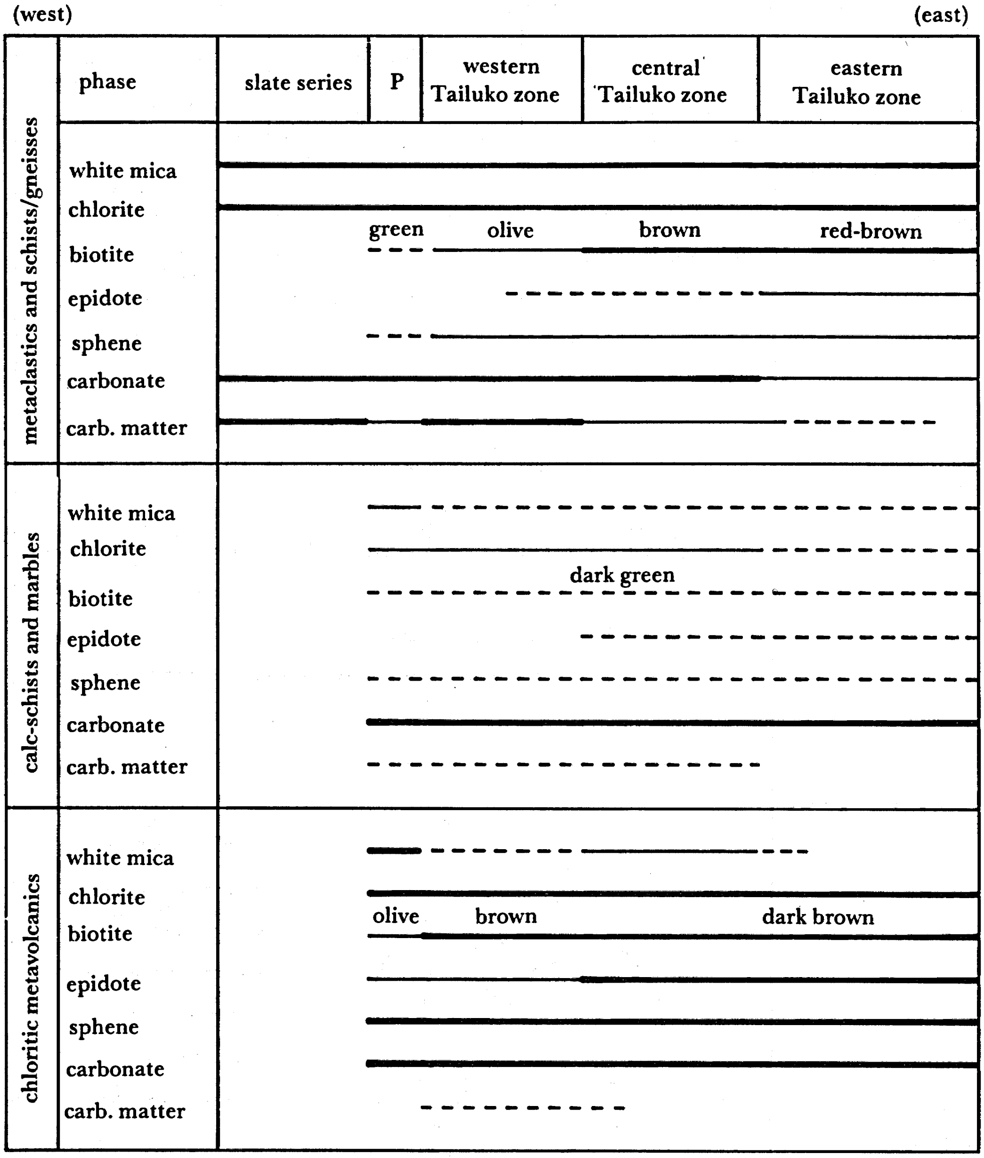

FIGURE 12. Mineral parageneses in the Tailuko Gorge transect (after Ernst 1983*b*, 1984). P stands for Pihou(?) Formation. Note that abscissa represents distance across an apparently synchronous metamorphic zonation; for location, see figure 3.

occur as inclusions within serpentinites in the Juisui area of the central Yuli belt. Phase assemblages developed during late Cretaceous and Neogene events are shown in figure 16. Evidently the two relatively high-pressure metamorphic episodes produced distinct assemblages for these oceanic lithologies; however, only the ambiguous and undiagnostic assemblage quartz + albite + chlorite + white mica ± biotite occurs in the enclosing argillite melange.

The regional metamorphic sequence for northeastern Taiwan, chiefly developed in the Cainozoic cover series, is illustrated in figure 17. The mineral parageneses in this broad region are known only in reconnaissance fashion, but several conclusions nonetheless seem to be well

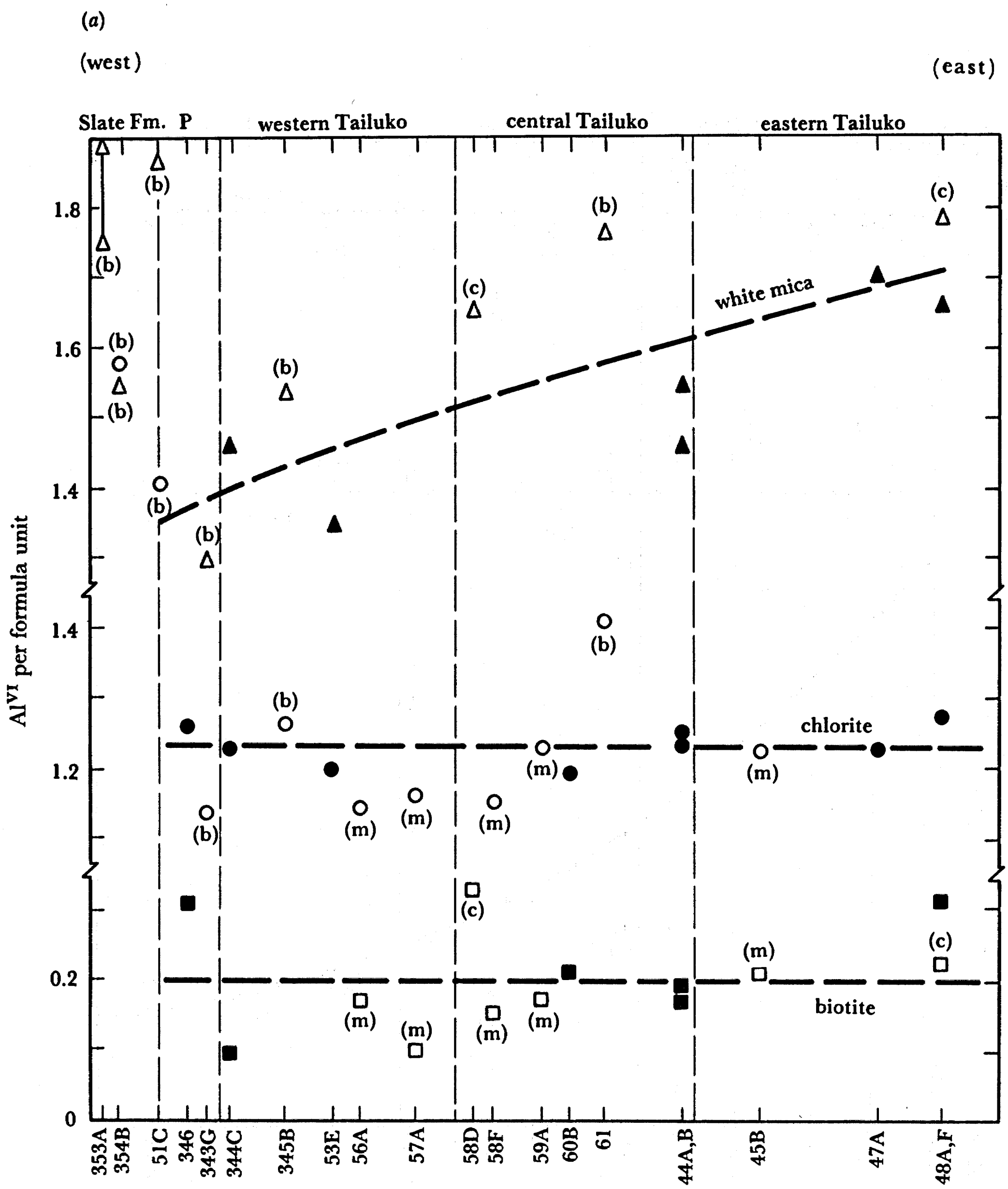

FIGURE 13*a*. For legend see overleaf.

constrained. Grade increases eastward in the slaty and metabasaltic rocks from non-metamorphic and zeolite facies lithologies in the Western Foothills to high-rank greenschist facies in the Cainozoic slates resting on the subjacent Mesozoic Tananao complex. A smooth transition in metamorphic facies occurs, passing from the parautochthonous cover series into the autochthonous Asiatic basement. All rocks could have been metamorphosed, or at least overprinted, in Neogene time.

Mineral parageneses for the East Taiwan Ophiolite are presented in figure 18. These

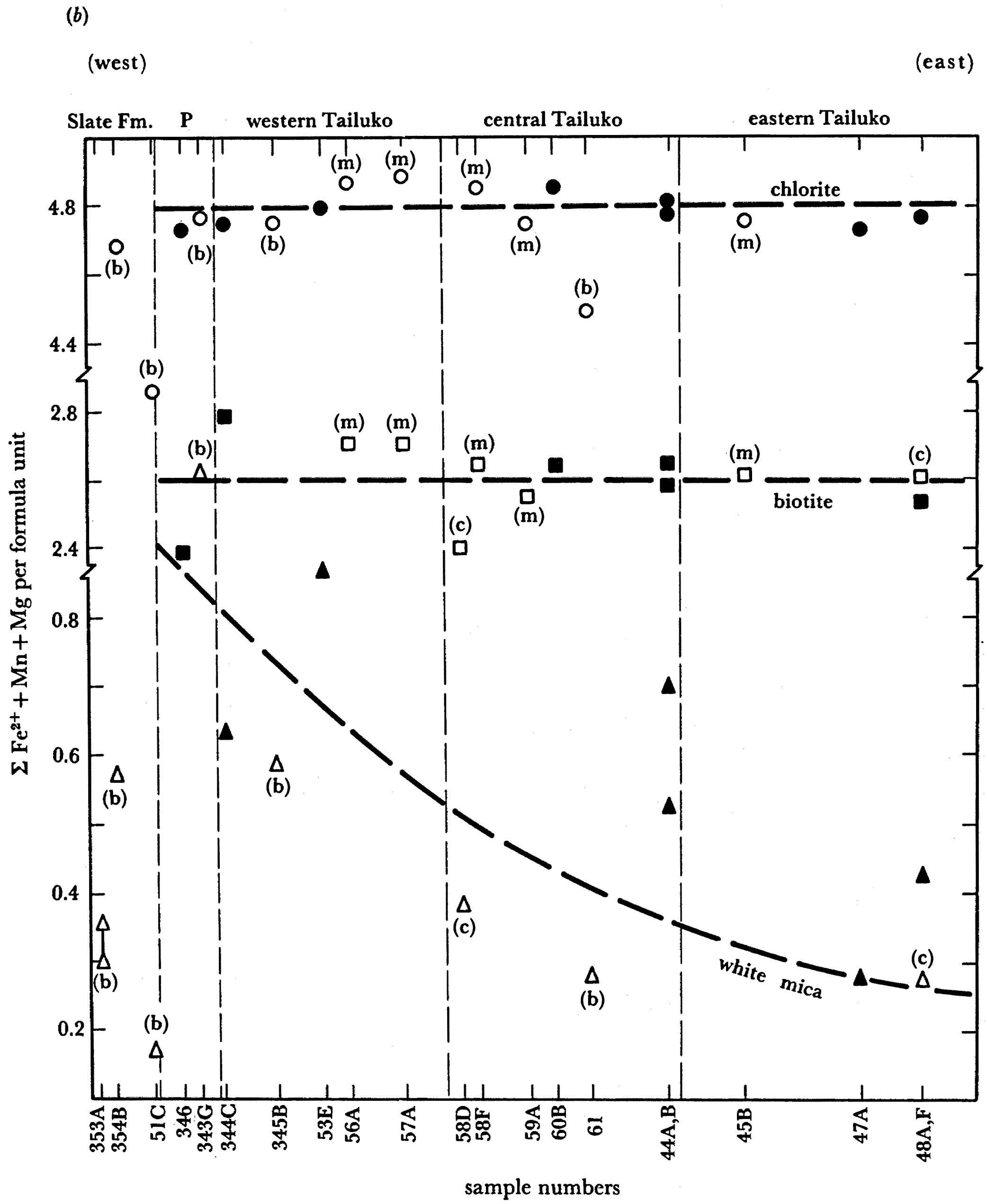

FIGURE 13. Change in (*a*) Al^{VI} and (*b*) $Fe^{2+}+Mn+Mg$ composition of coexisting layer silicates along the Tailuko Gorge transect, as a function of location (Ernst 1984). Excess phases include albite, quartz, sphene and fluid. Filled symbols (triangles, white micas; squares, biotites; circles, chlorites) indicate presence of all three layer silicates; open symbols signify the co-existence of only two layer silicates, with absent phase denoted (m, white mica; b, biotite; c, chlorite).

assemblages were produced within the oceanic realm. They reflect three sequential stages: (1) initial early Miocene(?) igneous crystallization; (2) mid-Miocene subjacent, spreading-centre metamorphism; and (3) late Miocene sea-floor alteration. This recrystallization is unrelated to accretionary growth of the Luzon arc and impaction of the latter with the Asiatic margin; it simply attests to oceanic crystallization–recrystallization within the South China Sea.

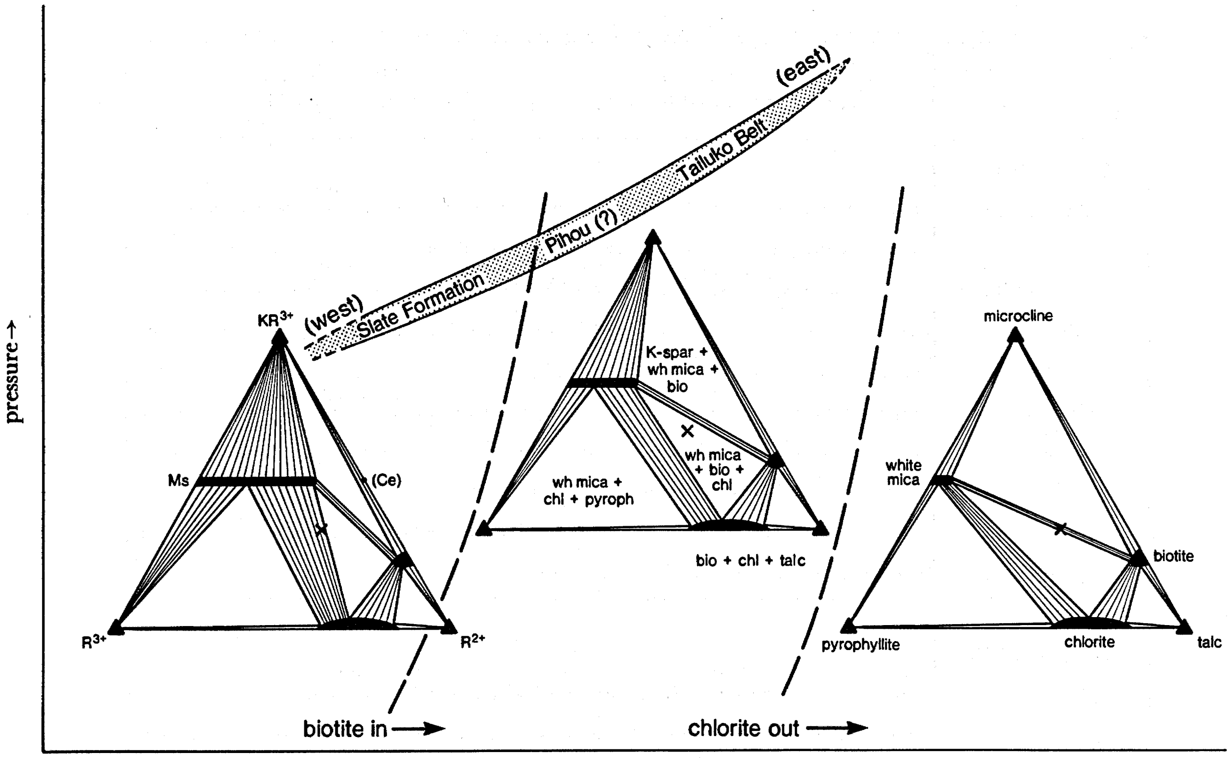

FIGURE 14. Schematic P_{fluid}–T diagram and chemographic relations for the mineral assemblages encountered in the Tailuko Gorge transect (Ernst 1984). Excess phases include albite, quartz, sphene and fluid. Metaclastic rock compositions project into this pseudoternary system near X; mafic metavolcanics would plot closer to chlorite and the R^{2+} corner. The P–T curves are appropriate for metaclastic bulk compositions.

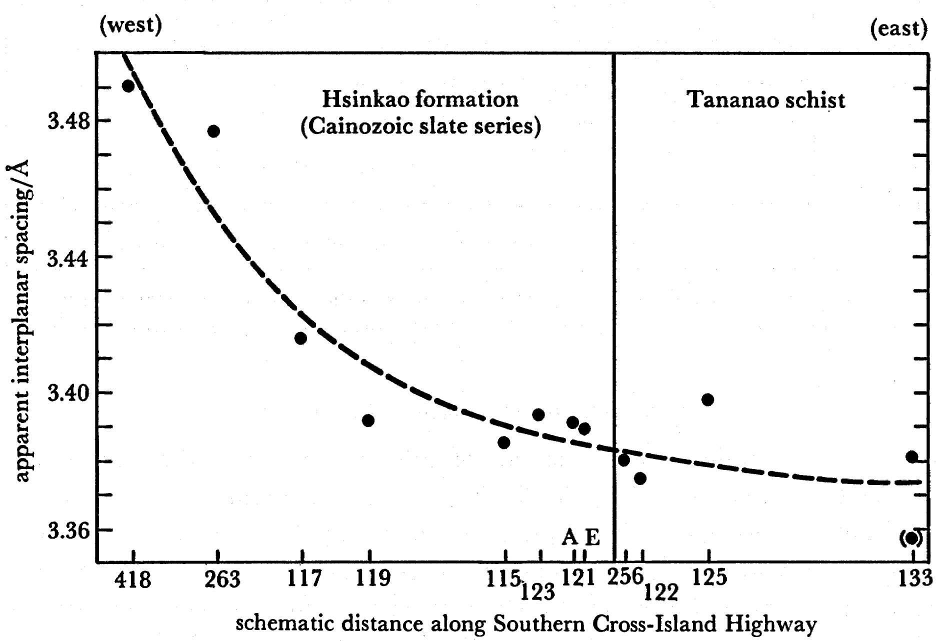

FIGURE 15. Degree of crystallinity in carbonaceous matter along the Southern Cross-Island Highway (after Warneke & Ernst 1984). Note that abscissa represents distance across an apparently synchronous metamorphic zonation; for location, see figure 3. (1Å = 10^{-10} m = 10^{-1} nm.)

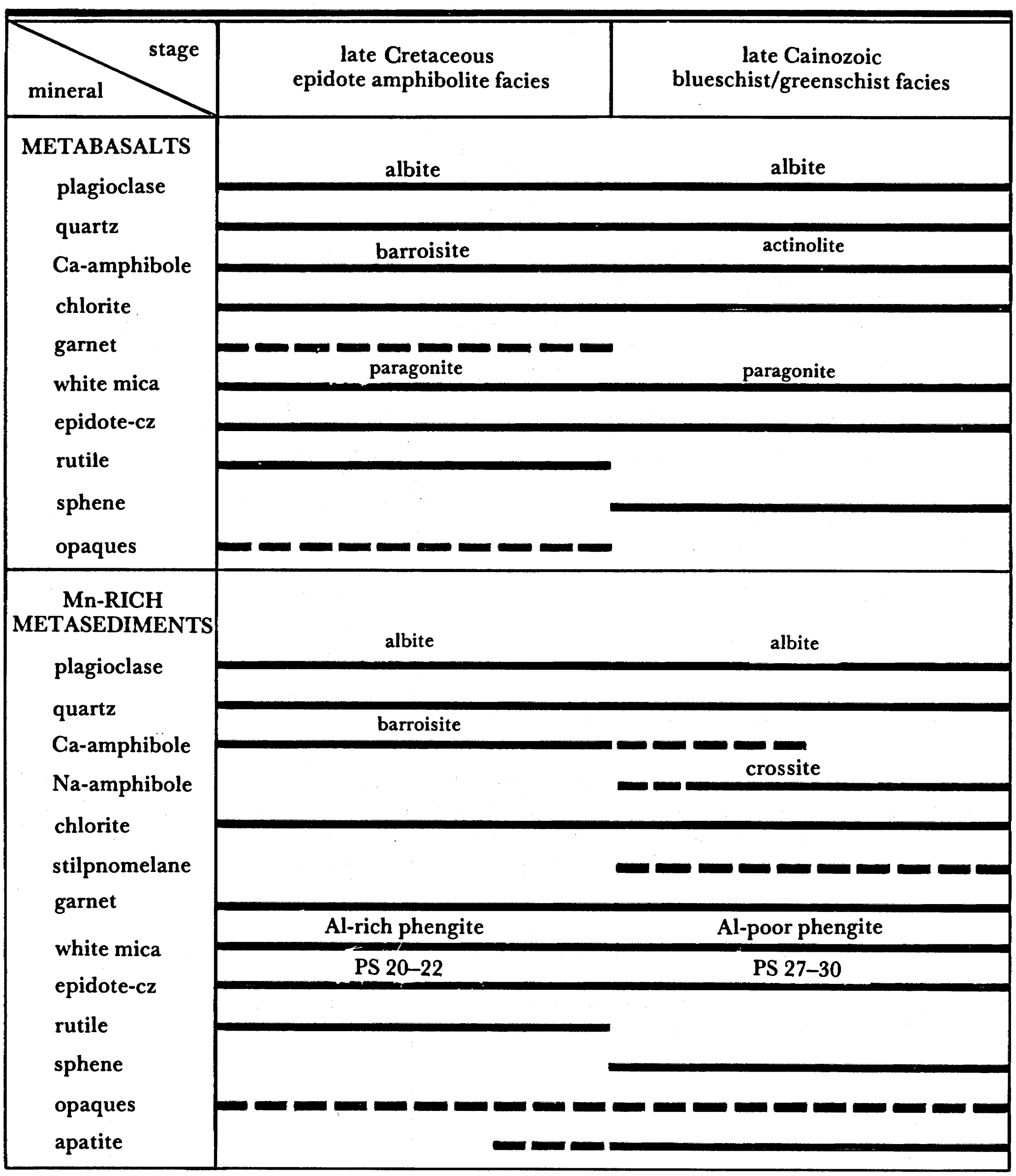

FIGURE 16. Mineral parageneses in mafic amphibolite tectonic blocks of the Yuli belt, associated with serpentinite near Juisui (after Liou *et al.* 1975, 1981*a*). Note that abscissa represents time; for location, see figure 3.

Physical conditions of metamorphism

The P–T conditions attending recrystallization of different portions of the several metamorphic terranes have been investigated by employing the compositional variations of analysed phases (Velde 1967; Ernst 1979; Maruyama *et al.* 1982; Massone & Schreyer 1983), experimental studies of synthetic and natural rock compositions (Liou *et al.* 1974; Spear 1981; Apted & Liou 1983; Maruyama *et al.* 1986), element partitioning between co-existing phases (Ferry & Spear 1978; Spear 1980; Ernst *et al.* 1981; Powell & Evans 1983), as well as oxygen isotope geothermometry (Chu & Shieh 1981). Of course, as pointed out by Richardson (1970), Spear *et al.* (1984), England & Thompson (1984), Thompson & England (1984) and Royden

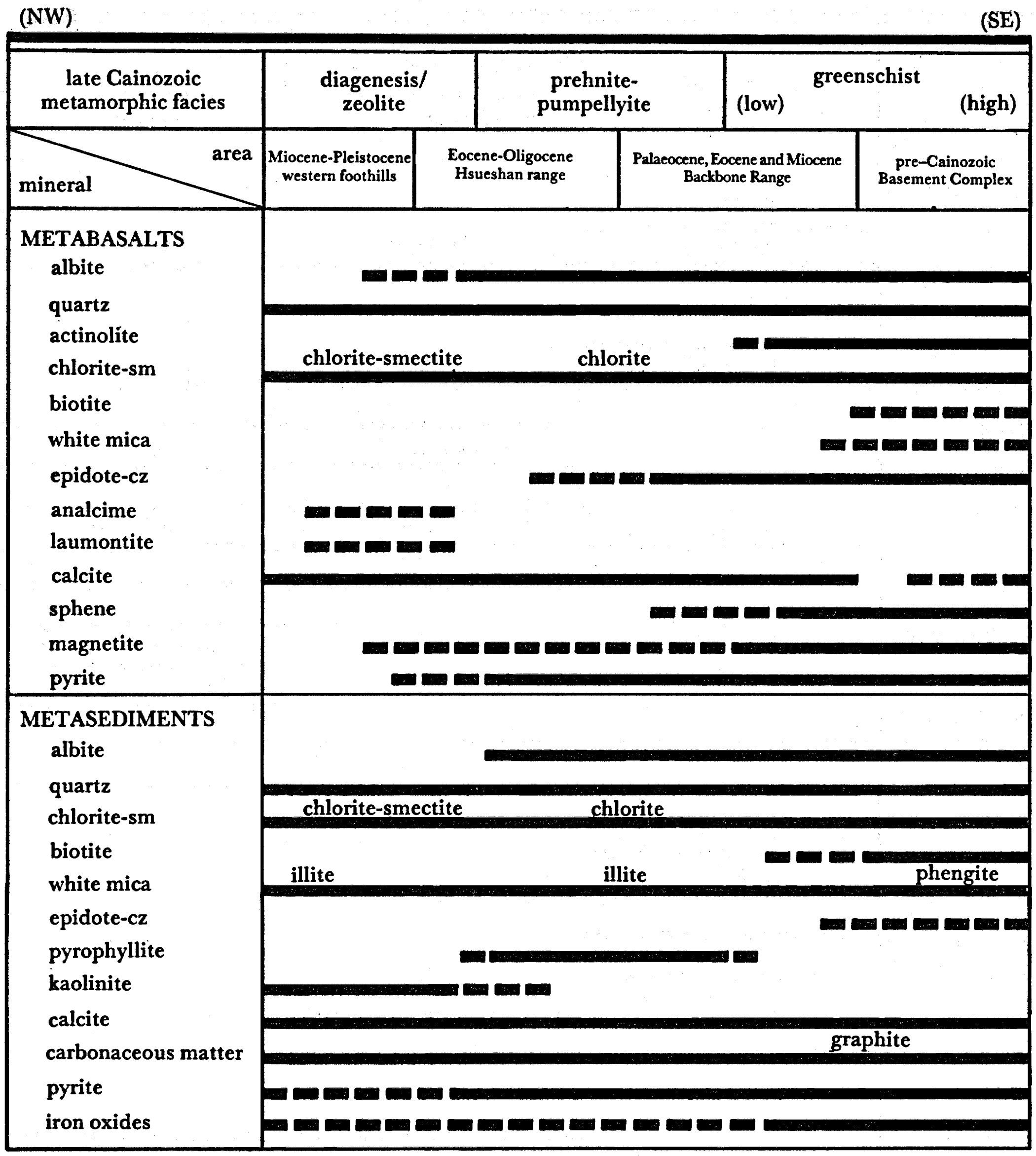

FIGURE 17. Mineral parageneses in a transect across northern Taiwan Cainozoic cover series units (after Liou 1981 *b*). Note that abscissa represents distance across an apparently synchronous metamorphic zonation; for location, see figure 3.

& Hodges (1984), the apparent P–T conditions preserved by the mineral assemblages reflect the particular decompression-annealing paths followed by individual rocks, and in general do not coincide with, or define, the precursor prograde metamorphic gradient. Nonetheless, for lithologic sections exhumed under a set of similar rates, a genetic correlation exists, hence the preserved metamorphic field gradients provide a first approximation to the thermotectonic history of the terranes.

For the Nanao-Suao area, the mid-Mesozoic regional amphibolite facies metamorphism is judged to have occurred at about 550–650 °C, with P_{fluid} approximating 5 kbar†. Localized

† 1 bar = 10^5 Pa.

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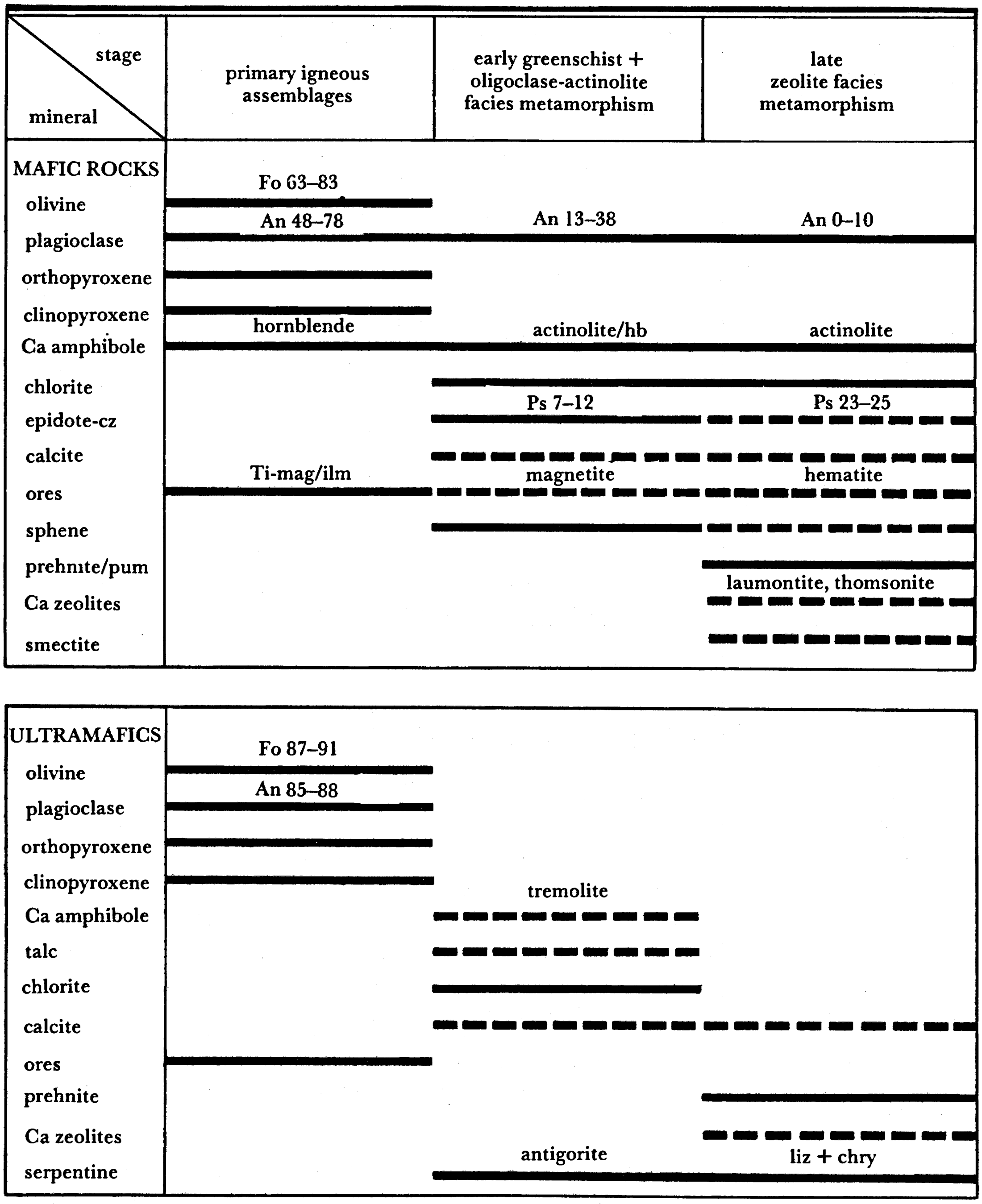

FIGURE 18. Mineral parageneses in mafic and ultramafic rocks of the East Taiwan Ophiolite (after Liou 1979; Liou & Ernst 1979; Ernst & Liou 1984). Note that abscissa represents time; for location, see figure 3.

thermal upgrading during granitoid emplacement produced cpx-bearing amphibolites at about 670–710 °C, and low activity of H_2O. The Neogene and perhaps latest Cretaceous greenschist facies overprinting involved temperatures ranging from 350 °C to 475 °C and aqueous fluid pressures less than 5 kbar (Liou *et al.* 1981; Ernst *et al.* 1981).

Along the Taĭluko Gorge traverse, late Cainozoic recrystallization took place at 325 ± 75 °C

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and 3 kbar in the west, grading to about 425 ± 75 °C and 4 kbar in the eastern part of the Tailuko basement complex. Retrograded Mesozoic gneisses must be relics from a higher-temperature Cretaceous event, as at Nanao-Suao, but in this transect have been re-equilibrated during the Neogene greenschistic event (Ernst 1983 *b*, 1984).

Sparse mineralogic data from the Mu-kua Chi area suggest that, during the latest recrystallization, attendant physical conditions did not exceed 400 ± 75 °C and 3–4 kbar P_{fluid} for Tailuko belt rocks (Ernst & Harnish 1983).

In the vicinity of the Southern Cross-Island Highway, feebly recrystallized slates on the west were subjected to *P–T* conditions of about 200 °C at 2 ± 1 kbar P_{fluid}, with values rising to a maximum of approximately 400 °C at 3 ± 1 kbar P_{fluid} in the axial zone of the Tailuko basement. Yuli belt lithologies lying to the east were subjected to slightly lower temperatures at pressures less than 5 kbar (Warneke & Ernst 1984).

For all of northern Taiwan, the Cainozoic cover series exhibits a gradual eastward intensification of metamorphism, as follows: Western Foothills, 150 ± 50 °C, 1–2 kbar; Hsueh-shan Range, 260 ± 40 °C, 2–3 kbar; Backbone Range, 300 ± 50 °C, 4 kbar; and the Nanao-Suao area, 350–475 °C, 5 kbar (Liou 1981 *b*).

Yuli belt mafic amphibolites and interlayered deep-sea metasediments display an earlier, higher grade barroisitic amphibole-bearing phase compatibility produced at around 500 ± 50 °C, whereas the late, lower-grade crossitic association probably formed at about 400 ± 50 °C; both assemblages reflect relatively high pressures, estimated as approaching 7 kbar (Liou 1981 *a*).

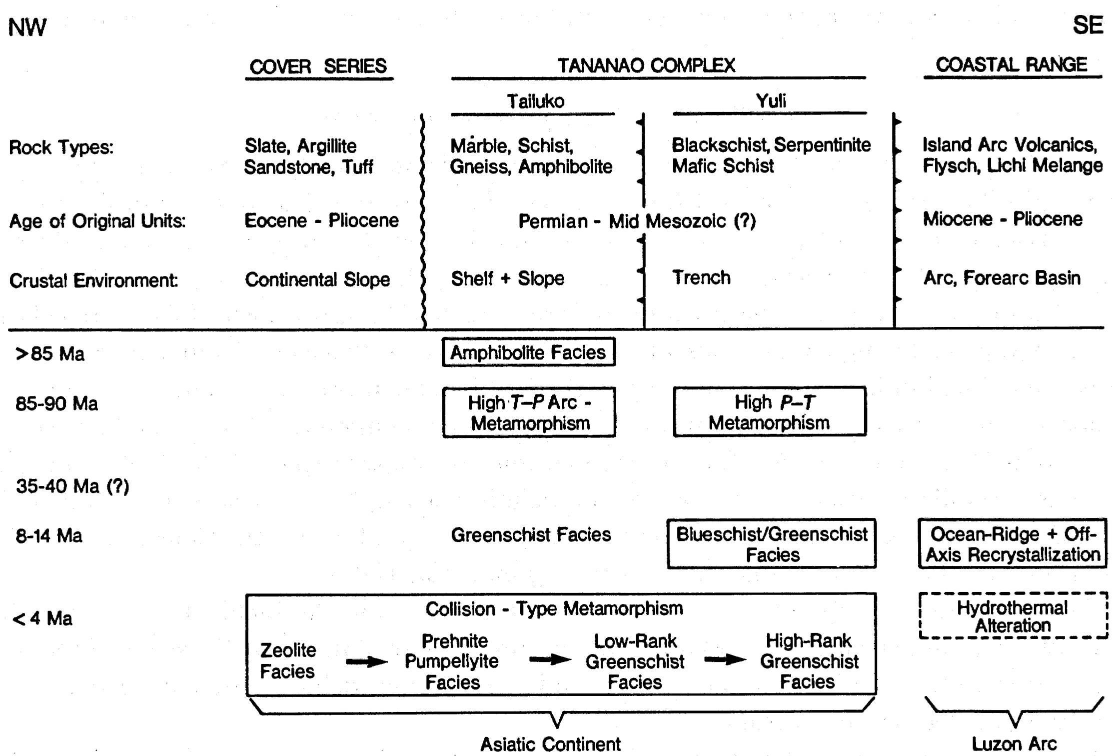

FIGURE 19. Summary of Phanerozoic metamorphic episodes in Taiwan (largely after Yen 1976; Liou 1981 *a*; Ho 1982; Ernst 1983 *a*; Ernst *et al.* 1985). Boxes enclose well-documented mineral assemblages. Tectonic and unconformable contacts are shown by barbed and wavey lines respectively.

The oceanic ridge-type metamorphism of the East Taiwan Ophiolite occurred over the range *ca.* 300–500 °C at about 1 kbar total pressure. In contrast, later zeolitization on the ocean floor appears to have taken place under conditions of approximately 100–300 °C and 1–2 kbar (Liou 1979; Liou & Ernst 1979).

Petrotectonic events

The various recrystallization events recorded in the rocks of Taiwan are closely related to relative plate motions and to large-scale tectonic processes. The recognizable and distinctly different metamorphic stages are illustrated in figure 19, where the generalized natures of the protoliths are also indicated. This figure summarizes the main metamorphic episodes described in previous sections and, by inference, provides constraints regarding lithospheric plate dynamics and reorganization in the Taiwan sector of the Asiatic continental margin.

Crustal evolution

We now attempt to unravel the plate tectonic history of Taiwan in the light of the tectonostratigraphic terrane concept (Coney *et al.* 1980; Jones *et al.* 1983) working backwards through time. Obviously, the interpretation of earlier events becomes progressively more speculative. What should be clear from the scenario now to be presented is that this Permian and younger mountain belt, although small in regional extent, exhibits first-order petrotectonic complications which, while partly understood, are beyond the limits of the present state of knowledge to decipher completely. If a small, young, relatively well-exposed segment of a continental margin is so complicated, what must be the true natures of larger and more ancient analogues?

Plio-Pleistocene closure of the South China Sea

Collision of the Coastal Range with the Asiatic continental margin was a consequence of eastward subduction of the South China Sea oceanic crust-capped plate beneath the Luzon arc (Taylor & Hayes 1983). Impaction was initiated in northeasternmost Taiwan, and has since propagated southwards (Chai 1972; Karig 1975). The gradual approach of the calc-alkaline arc toward the Asiatic continent is recorded by the appearance of slate series clasts in stratigraphically higher portions of the upper Miocene-Pliocene Takangkou and Plio-Pleistocene Lichi units; exposure of the pre-Tertiary basement occurred later, as revealed by minor Tananao detritus in the Lichi Melange and more voluminous debris in the Pleistocene Pinanshan Conglomerate. The Luzon arc, marking the western edge of the Philippine Sea plate, is certainly far-travelled relative to the Asiatic margin, as demonstrated by lithologic dissimilarities juxtaposed across the Longitudinal Valley. In all ways, the Coastal Range fits the definition of a tectonostratigraphic terrane (Jones *et al.* 1983).

The East Taiwan Ophiolite, which occurs as exotic blocks in the Lichi Melange near the suture zone, represents fragments of the now-consumed South China Sea (Ernst 1977*b*; Suppe *et al.* 1981; Jahn 1986). These slide blocks and olistostromal debris represent portions of a largely subducted oceanic terrane.

Another consequence of the attempted subduction of the Asiatic continental crust was the imbrication and westward thrusting of the passive margin cover series and its Mesozoic basement (see, for example, Suppe 1980*a*). The eastward intensification of the Plio-Pleistocene recrystallization and deformation attests to progressively more profound depths of underflow, now recovered (Ernst 1983*a*). In that its contacts with other lithologic units are chiefly faults, the Cainozoic slate series may be regarded as a separate terrane: it is clearly parautochthonous, having been transported westward because of about 160 km of shortening (Suppe 1981). However, its nearly *in situ* origin along the eastern margin of the Asiatic continent is well-constrained, and some basal portions lie with depositional contact on the Tananao Schist belt, hence it bears a genetic relation to the underlying Mesozoic basement, and cannot be considered as truly exotic (Yen *et al.* 1956; Suppe *et al.* 1976).

Cainozoic rifting of the Asiatic Margin

Magnetic anomalies within the South China Sea document sea-floor spreading as old as mid-Oligocene, according to Taylor & Hayes (1983); these authors have speculated that block faulting of the Asiatic margin, which preceded production of the oceanic crust, may have been initiated in latest Cretaceous or Palaeocene time. Certainly, an Atlantic-type continent-ocean transition provided the catchment basin for the superjacent slate series and associated minor intercalated, slightly alkalic basalts and dolerites; the latter probably are related to Palaeogene rifting of the continental margin. Sea-floor spreading ceased in the South China Sea near the end of middle Miocene time (Taylor & Hayes 1983), shortly after formation, oceanic-ridge and possibly sea-floor metamorphism of the East Taiwan Ophiolite. The Neogene closure of part of this basin: (1) had already begun to generate the calc-alkaline arc on the more easterly, non-subducted Philippine Sea lithospheric plate; (2) produced the Mio-Pliocene blueschist tectonic blocks of the Yuli terrane; and (3) culminated in a Plio-Pleistocene–Recent continent-island arc collision. The latter resulted in the aborted subduction and consequent westward transport of the foreland fold-and-thrust belt, including tectonic slices of its Tananao Schist basement as well as superjacent Cainozoic cover series.

The Neogene blueschists attest to at least transitory westward(?) subduction of segments of the South China Sea, and represent fragmentary metamorphic portions of this poorly understood terrane. As previously described, the locally derived passive margin Cainozoic slate section is parautochthonous, being neither strictly in place nor truly exotic.

Inferred Mesozoic rifting and subduction of the Asiatic Margin

Prior to the Cainozoic opening of the South China Basin during Palaeogene sea-floor spreading, the Asiatic margin evidently was the site of a Mesozoic convergent plate junction of the Circumpacific type (Miyashiro 1961, 1967). This situation is indicated by the existence of the landward, calc-alkaline, igneous-metamorphic Tailuko belt, and the seaward, serpentinized peridotite-invaded trench-argillite sequence of the eugeoclinal Yuli belt (Ernst 1983*a*). The poorly exposed Shoufeng fault marks the tectonic contact between these belts along what must represent a major suture. Lack of apparent correspondence of structures, lithologies, and sedimentary provenance across this break suggests that the more easterly, high-pressure, low-temperature melange belt might be allochthonous relative to the Asiatic continental margin. We, therefore, regard the Yuli belt as a suspect terrane (see, for example, Coney *et al.* 1980).

Before construction of this paired belt assemblage in late Mesozoic time, mafic rocks and minor serpentinites evidently were tectonically inserted into a miogeoclinal section consisting of Permian and Lower Mesozoic, well-ordered platform carbonates and interlayered pelitic and psammitic strata. Whether the Tailuko belt was brought as a microcontinental fragment to its present location at the edge of the Asiatic craton through drifting and accretion, or whether it was assembled essentially in place, is not known. The former model could account for the southeastward projection of sialic basement constituting Taiwan, whereas the latter model better accounts for the miogeoclinal nature and age relationships of the pre-Cainozoic strata. The associated metamorphosed mafic+ultramafic lenses appear to be ophiolitic, and may represent lower or mid-Mesozoic oceanic crust+hydrated mantle obducted into a pre-existing passive margin section (Liou *et al.* 1981). Evidently latest Palaeozoic rifting and

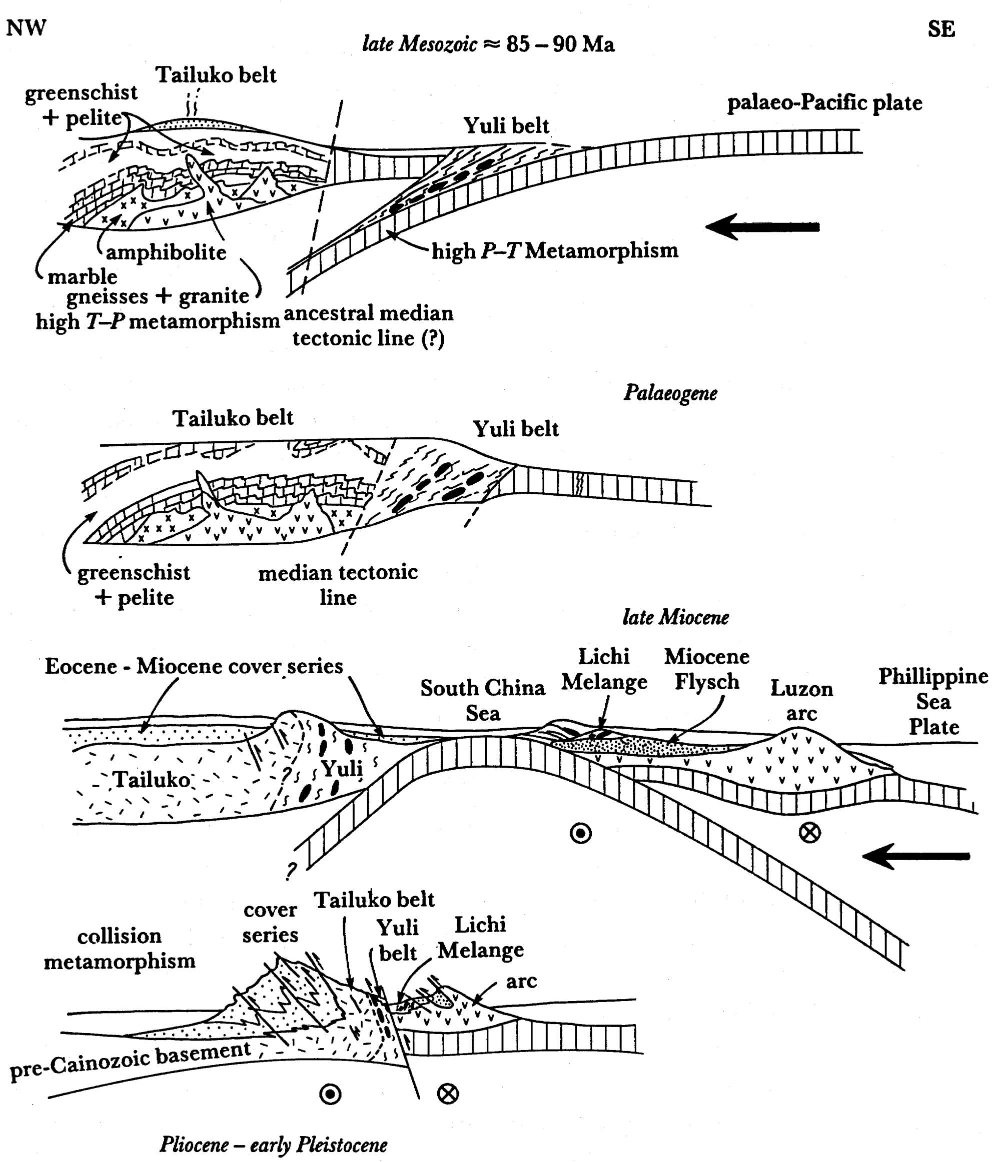

FIGURE 20. Schematic illustration of four stages in the accretionary growth of Taiwan over the past approximately 85–90 Ma. In lower two cross-sections, ⊗ and ⊙ signify relative plate motions possessing large northward and southward components, respectively. Note that a hypothesized late Miocene Molucca Sea-type of double subduction (Hamilton 1979) must have given way in Pliocene time to exclusively eastward underflow of the Eurasian plate. This subduction régime appears to be required to explain the eastward sequence slate series→Tailuko belt→Yuli terrane, in which the latter developed biotitic greenschists during underflow and collision with the Luzon arc in Plio-Pleistocent time.

spreading was succeeded in mid-Mesozoic time by the onset of convergence; underflow culminated in the late Mesozoic construction and assembly of the landward arc and seaward trench belts.

We thus recognize: (1) an autochthonous(?) sequence consisting of the Upper Palaeozoic–Lower to mid-Mesozoic Atlantic margin-type section; (2) tectonically emplaced exotic ophiolitic lenses of portions of a lower or mid-Mesozoic palaeo-Pacific oceanic plate into this passive margin suite; (3) *in situ* conversion of the above to a metamorphosed and granitoid-intruded Tailuko basement complex in late Mesozoic time; and (4) accretion of the outboard upper Mesozoic high-pressure, low-temperature Yuli melange terrane, probably at the time of inboard granitic magmatism (85–90 Ma ago).

Summary

The Phanerozoic crustal evolution of Taiwan has involved a complex interplay of rifting, drifting, subduction polarity reversal and arc collision. Late Mesozoic and younger stages in this development are illustrated diagrammatically in figure 20. Much of the present island evidently has been assembled nearly in place by deposition of miogeoclinal and/or continental slope strata following attenuation and truncation of the sialic crust during sea-floor spreading. Additionally, calc-alkaline plutonic rocks were remobilized and emplaced during convergent plate motion. Most of these rocks show lithologic affinities with the Chinese mainland (Miyashiro 1981). Exotic and suspect terranes and far-travelled ophiolitic scraps have been sequestered in this sector of the Asiatic margin by convergent or oblique underflow. As illustrated in figure 21, foreign arrivals appear to include: (*a*) Lower to mid-Mesozoic

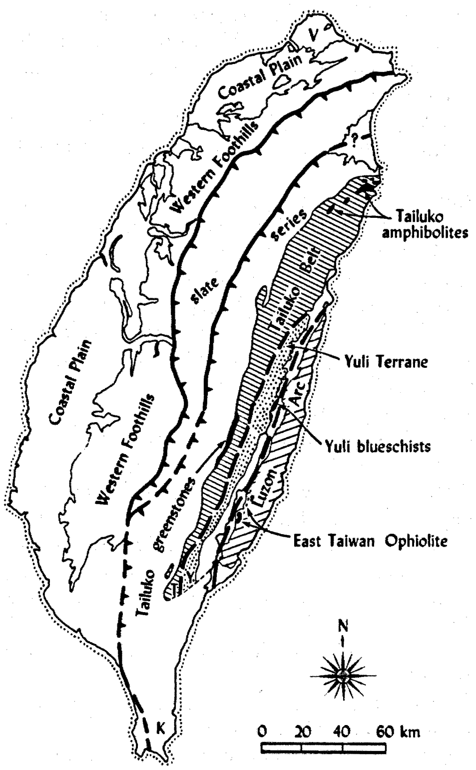

FIGURE 21. Preliminary tectonostratigraphic terrane map for Taiwan (after Ernst *et al.* 1985). See text for discussion.

amphibolite + serpentinite lenses in the Tailuko belt; (*b*) the Upper Mesozoic Yuli trench–argillite + melange complex; (*c*) Mio-Pliocene blueschist tectonic blocks situated in the east-central part of the Yuli terrane; (*d*) the Neogene Luzon arc; and (*e*) the Miocene East Taiwan Ophiolite, supplied as olistostromal debris to the Lichi Melange of the Coastal Range. The Tailuko belt might be far travelled, but relationships remain ambiguous. The passive margin Cainozoic slate series is parautochthonous. In aggregate, these in place, parautochthonous, suspect terranes and exotic oceanic fragments, which exhibit contrasting metamorphic parageneses, constitute the record of intermittent growth for this segment of the Asiatic continental crust.

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