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Provenance Study of Tertiary Sandstones from the Western Foothills and Hsuehshan Range, Taiwan

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Abstract The Western Foothills and Hsuehshan Range in Taiwan are composed of clastic rocks formed mostly in shallow marine environments. An electron probe micro analyzer (EPMA) has been used to measure the ages of more than 5000 detrital monazites from 57 Tertiary and Quaternary sandstones in Taiwan, and from Recent sands which represent their probable provenance areas in East Asia. Most of the Oligocene to Pliocene sandstones from the Western Foothills have monazite age distribution patterns with peaks at ca. 150 Ma, 220–250 Ma, 430–450 Ma and 1870–1900 Ma. Comparison of the Western Foothills data with those of Recent sands has revealed there was little contribution from nearby source regions and that they were derived mainly from the Korean Peninsula with a subordinate contribution from the paleo-Yangtze River. In contrast, the Eocene to Early Oligocene sandstones from the Hsuehshan Range have a monazite age pattern with a major peak at 250 Ma and smaller peaks around 150 Ma and 450 Ma. This pattern is similar to that observed in Recent sands from the Zhu River which flows through the Guangxi and Guangdong provinces. Paleo-current directions in the Eocene to Early Oligocene sediments indicate supply from the northwest. Hence we propose that the Eocene to Early Oligocene terrane in the Hsuheshan Range was formed to the southwest of its present position and was juxtaposed against the Western Foothills by left-lateral fault movements after the Early Oligocene.

Key words: Taiwan, monazite, age, sandstone, Tertiary, tectonics

Introduction

The conventional approach to provenance studies of sandstones is based on determination of paleo-current trends, the nature and modal proportion of the constituent rock and mineral clasts, and chemical analyses of the heavy minerals in the sandstones. While these methods provide a strong basis for the interpretation of provenance, we must also consider the possibility of post depositional dissolution of minerals in Tertiary and older sandstones, and of tectonic displacement.

The development of analytical techniques that allow age determinations to be made on individual mineral grains has provided powerful tools for use in provenance studies. Many age dating methods have been applied to provenance studies of zircon, as for example SHRIMP (Ireland, 1991; Tsutsumi *et al.*, 2003), fission-track (Garver *et al.*, 1999), and ICPMS (Wyck & Norman, 2004; Evans *et al.*, 2001), and of monazite by EPMA (Suzuki, Adachi & Tanaka, 1991; Fan *et al.*, 2004).

The Western Foothills and Hsuehshan Range of Taiwan are composed of clastic rocks of Tertiary age which were deposited in shallow marine and locally paralic environments along the East Asian continental margin and shelf. To deduce the provenance areas for these Tertiary sand-

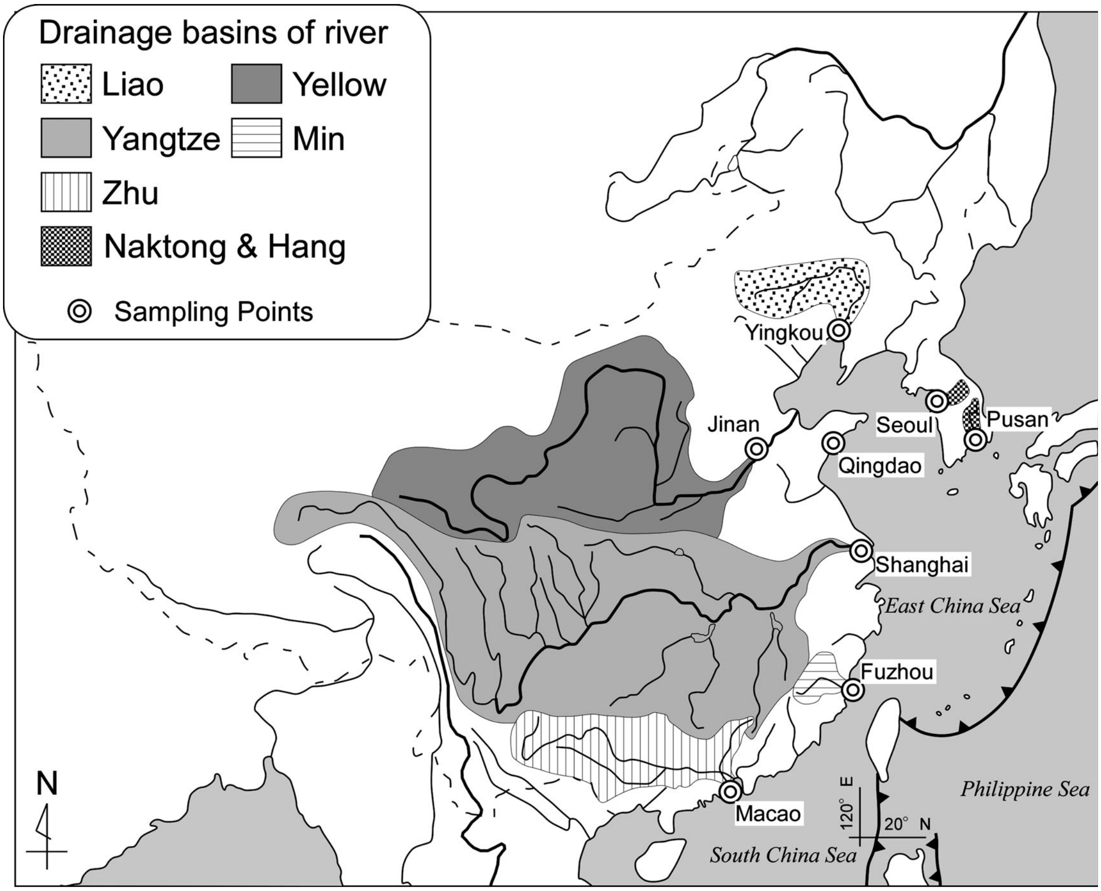


Fig. 1. Drainage systems of rivers running through the East Asian continental margin and sampling localities of Recent sands.

stones, we have analyzed detrital monazites contained in both the Tertiary sandstones from Taiwan and Recent sands from coastal provinces of the East Asian continent (Fig. 1). The age of monazite is calculated from its chemical composition, measured by EPMA, which provides important information about the provenance as has been discussed in many papers (e.g. Suzuki, Adachi & Tanaka, 1991; Fan *et al.*, 2004).

Geological Outline of Taiwan

Taiwan can be broadly divided into three major geologic provinces which form long narrow belts roughly parallel to the long axis of the island and are, from west to east, the Western Foothills, Central Range and Coastal Range (Ho, 1988; Fig. 2).

The Western Foothills are composed of Late Oligocene to Late Pleistocene clastic rocks formed mainly in shallow marine conditions and occasionally intercalated with coal seams; the Coastal Plain developed on the southwestern part of the island (Fig. 2) can also be included in the Western Foothills province.

The Central Range, which forms the backbone ridge system of Taiwan, is subdivided on the basis of lithology, age and metamorphic grade into, from west to east, the Hsuehshan Range, Backbone Range and eastern Central Range. The Hsuehshan Range is a weakly metamorphosed belt of mainly shallow water Eocene to Middle Miocene clastic rocks that have been juxtaposed against the Western Foothills by a major eastward

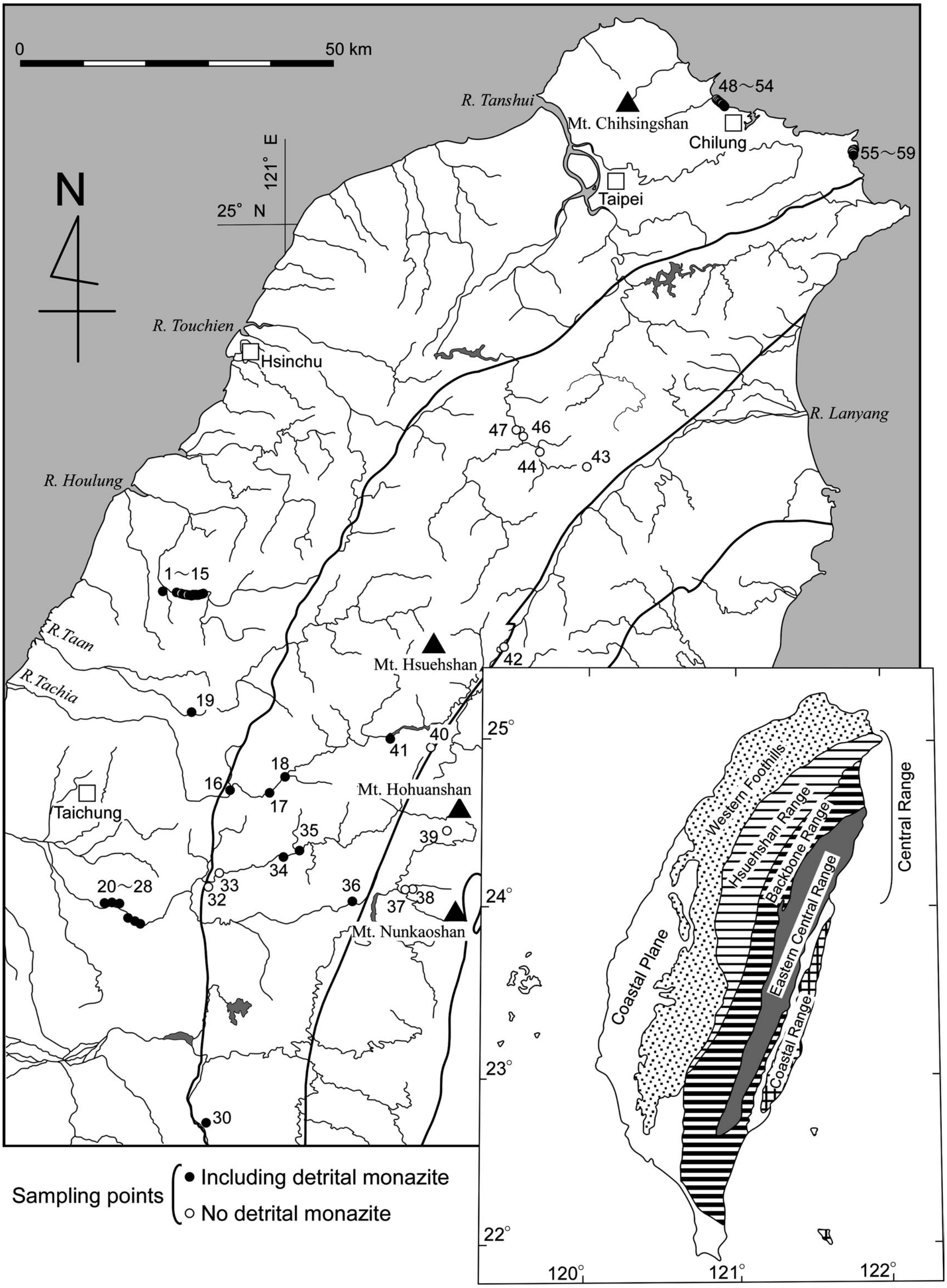


Fig. 2. Geological provinces of Taiwan and sampling localities for the Tertiary sandstones.

dipping fault. The Backbone Range is composed mainly of weakly metamorphosed clastic rocks, ranging in age from Eocene to Middle Miocene but with a marked stratigraphic gap between the Eocene and Late Oligocene sediments. The Backbone Range is underlain by the eastern Central Range pre-Tertiary metamorphic complex which consists mainly of marble, amphibolite, gneiss and various types of schists. A few fusulinids and tetracorals found in the indurated limestones of this metamorphic complex have been assigned a Permian age. Marbles similar in isotopic composition and petrographic characteristics have been recovered from deep drilling on the Coastal Plain of Taiwan (Jahn, Chi & Yui, 1992). The metamorphic rocks have ages ranging from 90 Ma to 3 Ma (^{40}Ar-^{39}Ar, K-Ar and Rb-Sr methods; cf. Lan *et al.*, 1990); the younger ages are probably the result of rejuvenescence of the radiometric ages by successive deformation events.

The Coastal Range of eastern Taiwan is composed of rocks deposited in a Neogene volcano-sedimentary basin associated with a volcanic arc on the western leading edge of the Philippine Sea plate. Sedimentary rocks of the Coastal Range are typically turbidites, formed in a deep sea fan or trench environment, and are different from the shallow marine sandstones in the Western Foothills and Hsuehshan Range. Collision of the Neogene volcanic arc with the other belts began at around 6.5 Ma in northeastern Taiwan (Huang *et al.*, 1997).

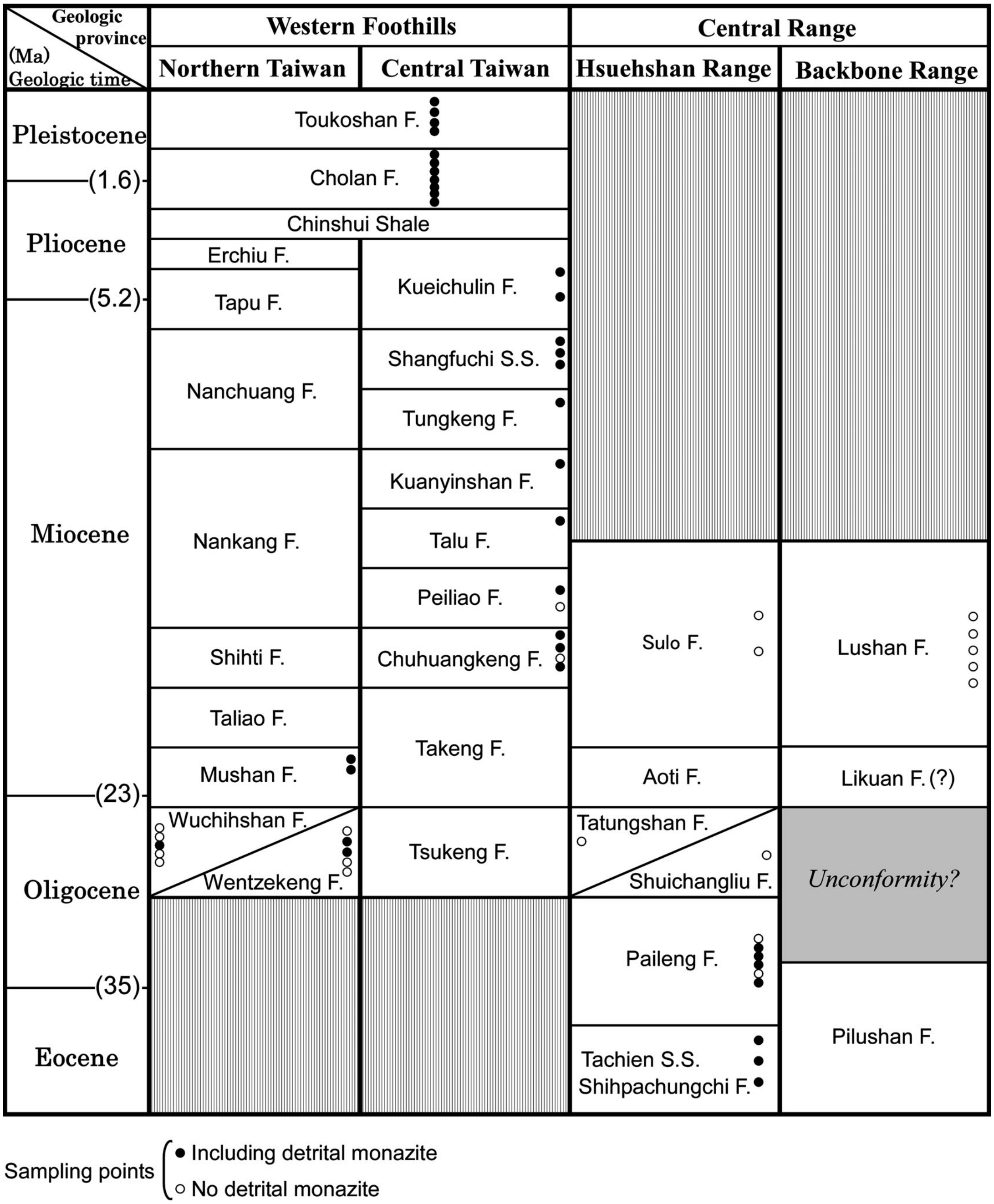
The sedimentary rocks in the Western Foothills have experienced different degrees of deformation and metamorphism from those in the Hsuehshan Range and Backbone Ridge although their depositional ages overlap during the Late Oligocene to Middle Miocene (Table 1). In the Western Foothills, detailed paleo-current studies of the Tertiary sediments have been reported by Chou (1974, 1977, 1980). Chou (1980) inferred that the sources of the Tertiary sediments lay northwest and west of Taiwan with sediments being transported southward and eastward down a gentle paleoslope. In contrast, the Late Pleistocene sediments of the Toukoushan Formation were derived from the Central Range in Taiwan (Chou, 1977). The change in provenance area from the Asian continental to the Central Range has been recognized in the Pliocene sequence of the Chinshui Shale (Chou, 1974).

Chen *et al.* (1992) have described the petrography of sandstones from the central part of the Western Foothills. On the basis of the rock fragments in the sandstones, they concluded that the Middle to Late Miocene sandstones were derived from the Asian continent, whereas those in the Pliocene to Pleistocene were derived from the central part of Taiwan where collision of the Coastal Range with the Neogene volcanic arc caused rapid uplifting and unroofing.

Clastic rocks in the Hsuehshan Range are mostly shallow-marine argillites and quartzose sandstones containing thin and irregular lenses of impure coal. They range in age from Eocene to Middle Miocene without significant unconformity (Table 1). A paleocurrent study of the Hsuehshan Range sandstones has revealed that they were derived from the northwest, i.e. the Fujian Province of the Asian continent (Tan & Youh, 1978). In the central part of Taiwan, the Backbone Range is composed of deep-marine Middle Miocene clastics which are mainly slate and phyllite with a subordinate amount of meta-sandstone (Chang, 1976). The Middle Miocene Lushan Formation in the Backbone Range is correlated to the Taliao, Shihti and the Nankang formations in the Western Foothills, and also to the Sulo Formation in the Hsuehshan Range (Table 1).

No monazite ages have been reported from the Recent sands and sandstones of Taiwan. However, on the Asian continent, monazite ages have been recorded from Recent sands collected along the Yangtze River, and Pliocene to Pleistocene sandstones in drill core at the mouth of the river (Yokoyama & Zhou, 2002; Fan *et al.*, 2004).

Table 1. Stratigraphic correlation of Tertiary sequences in central and northern Taiwan (after Ho, 1988). Open circle: detrital monazite-present, closed circle: monazite-free.



Sample Description and Analytical Procedures

About forty sandstones were collected from the Western Foothills (Figs 2 & 3). Twenty five of the samples were collected from the central part of Taiwan along the same traverses as were sampled by Chen *et al.* (1992). The depositional ages of these sandstones range from Middle Miocene to Early Pleistocene (Table 1). Twelve sandstones were also collected from the Oligocene to Early Miocene Western Foothills sequence of northern Taiwan. Nineteen sandstones with ages from Eocene to Middle Miocene were collected from the Hsuehshan and Backbone ranges but these samples have been subject to weak metamorphism which has produced secondary minerals that can not be used as indicators of provenance.

Seven samples of Recent river sands were collected from coastal provinces on the margin of the Asian continent. The drainage basins of the rivers are shown in Figure 1 and the sands provide indicators of probable provenance areas. Other samples were collected from three beaches around Qingdao, in the assumption that they were derived from the southern side of the Shandon Peninsula.

Procedures for the separation of heavy minerals and their subsequent identification are the same as have been described by Yokoyama *et al*. (1990). Carbonate and micaceous minerals were not subjected to examination, and magnetic fractions were removed prior to the separation of the heavy minerals. Modal proportions of representative heavy and light minerals are shown in Figure 3. All the heavy minerals and their dissolutions were reported and discussed in detail by Tsutsumi *et al*. (2006). Although the light minerals are less source-diagnostic and therefore not a major focus in this provenance study, the samples are composed predominantly of quartz with small amounts of plagioclase and K-feldspar.

The theoretical basis for monazite age calculation is essentially the same as that developed by Suzuki, Adachi & Tanaka (1991). Monazites were analyzed by the electron probe micro-analyzer, EPMA, fitted with a Wavelength Dispersive Spectrometer (WDS), JXA-8800 situated in the National Science Museum, Tokyo. Analytical conditions used have been described by Santosh *et al*. (2003). Age calibrations were carefully performed by comparing data obtained by EPMA dating with those acquired by the SHRIMP technique (e.g. Santosh *et al.*, 2006). Apart from minor shifts due to machine drift and variations in standard conditions, the ages obtained from both techniques were found to have good consistency. Monazites with ages of 3020 Ma and 64 Ma, that were obtained by SHRIMP and K-Ar methods, respectively, have been used as internal standards for age calibrations. The standard deviation of the age obtained depends mostly on the PbO content of the monazite. The errors for the age are within a few percent for most of the analyzed monazites that were rich in ThO_2. If the age error exceeded 25 Ma for Mesozoic to Cenozoic monazites and/or 50 Ma for older monazites, these data were excluded from the figures and further discussion.

Detrital Heavy Minerals

About twenty mineral species were observed in the heavy fractions in the Western Foothills sandstones and the abundance of each of the mineral species has been determined (Table 1). There is a variety of heavy minerals species in the younger sandstones, but a restricted number of species in the older sediments due to the common dissolution of some detrital mineral species in older sandstones (e.g. Pettijohn, 1941; Morton, 1984, 1991). Among the common heavy minerals, zircon and tourmaline are considered ultrastable minerals. The minerals apatite, TiO_2 polymorphs, garnet, Cr-spinel, monazite and xenotime are relatively common in the older sediments and are treated mostly as detrital minerals.

As a result of the dissolution of unstable heavy minerals, zircon and TiO_2 polymorphs are predominant in the heavy fractions of the Miocene sandstones (Fig. 3c–f). Garnet is occasionally abundant. Apatite, tourmaline, spinel and mon-

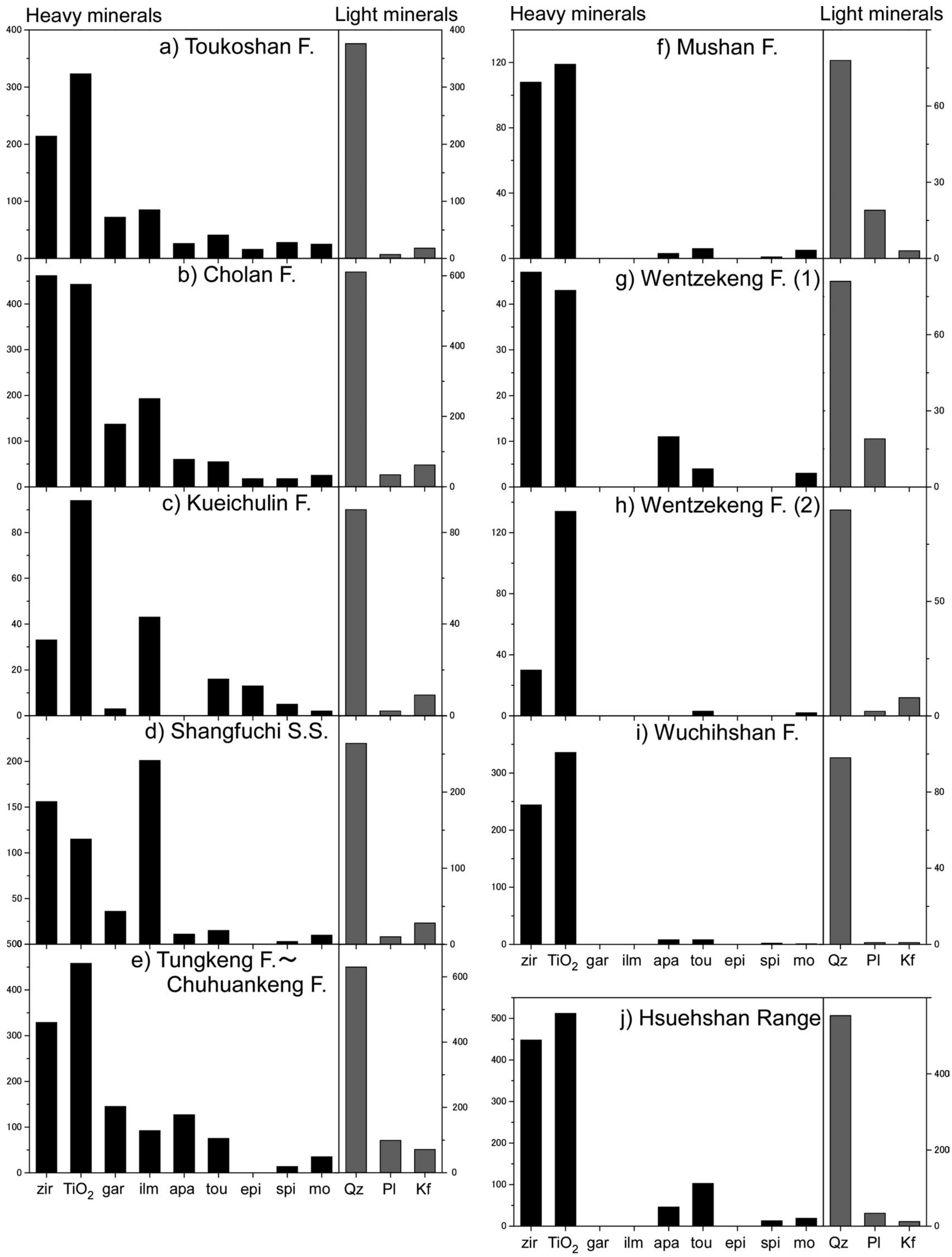


Fig. 3. Modal proportions of representative heavy and light minerals in the Tertiary sandstones in Taiwan. Mineral abbreviations: zir-zircon, TiO_2–TiO_2 polymorphs, gar-garnet, ilm-ilmenite, apa-apatite, tou-tourmaline, epi-epidote, spi-spinel, mo-monazite, Qz-quartz, Pl-plagioclase, Kf-Potash feldspar.

azite are sporadic and mostly found in small amounts. Epidote occurs only in the upper (younger) part of the sequence (Fig. 3a–c). Ilmenite is common in the upper sequence, but is highly decomposed into an aggregate consisting of TiO_2 polymorphs and light minerals in older sediments. There is no systematic change of modal proportion in the sequence except for the abundance of stable minerals in the older sediments.

In the Central Range, the heavy mineral suite has a restricted number of species due to metamorphism. Zircon, TiO_2 polymorphs and tourmaline are common minerals. Garnet is scarce due to its decomposition into chlorite. It is hard to determine the provenance from such mineral assemblages.

Monazite is usually small in amount and less than a few percent of the heavy fraction of the sandstones from the Western Foothills (Table 1). The monazite grains are mostly rounded or subrounded (Figs 4a & b) suggesting a detrital origin. Monazite is observed in many samples from the Late Oligocene to Late Pleistocene sequence of the Western Foothills (Fig. 2 & Table 1).

In the Central Range, monazite is usually rare or absent, and has been observed in only eight sandstones from the Tachien Sandstone and Paileng Formation in the Hsuehshan Range. There are insufficient diagnostic fossils present in these sandstones to allow a definitive determination of the age of sedimentation. The Tachien Formation could be Eocene in age based on the presence of bivalve and gastropoda fossils. The Paileng Formation, which includes the Meichi and Szeleng Sandstones, conformably underlies the Late Oligocene Shuichangliu Formation and has therefore been tentatively assigned to the Early Oligocene or Oligo-Eocene (Ho, 1988). Detrital monazite has not been found in the samples collected from the Late Oligocene to Middle Miocene sandstones from the Hsuehshan Range and the Middle Miocene sandstones from the Backbone Range. Monazite in the Central Range is often decomposed into Th-free monazite aggregate (Figs 4e & f). Occasionally rounded monazite is observed to be surrounded by Th-free monazite rims (Figs 4c & d). Similar Th-free monazites have been described in weakly metamorphosed sandstones from the Japanese Islands (Yokoyama and Goto, 2000), where they are clearly secondary post depositional minerals. Th-free monazite aggregates are also commonly observed in the Pleistocene sandstones in the Western Foothills where rock fragments in the sandstones and clasts in the conglomerates have been derived from the rocks of the Central Range.

Heavy fractions of the river and coastal sands were collected by panning. Although their modal proportions have not been determined, a number of mostly rounded or sub-rounded grains of monazite have been observed in these Recent sands.

Age of Monazite

All the analytical positions were selected from back-scattered electron images and metamictised areas/zones were avoided. The standard deviation of ages within a single grain is mostly less than a few percent in old monazites (>ca. 300 Ma) or less than 25 Ma in younger monazites <ca. 300 Ma). Consistent data were also obtained for the rounded monazites surrounded by secondary Th-free monazite aggregate (Figs 4c & d). One representative age has been selected from each grain. About 1500 and 4000 grains have been analyzed from the Tertiary sandstones in Taiwan and Recent sands from the East Asian continent, respectively.

Ages of monazites from the Western Foothills are presented as frequency and probability diagrams in Figure 5. Probability distributions for monazite ages were calculated with a multi-peak Gauss fitting method (Williams, 1998). The age data obtained from sandstones of the same formation are summarized in the same diagram as either sufficient age data was not obtained or the samples show a similar age distribution. The monazite ages range from ca. 0 Ma to 2700 Ma with strong populations at 100–300 Ma, 400–500 Ma and 1800–2000 Ma. Roughly speaking, in the central part of the Western Foothills,

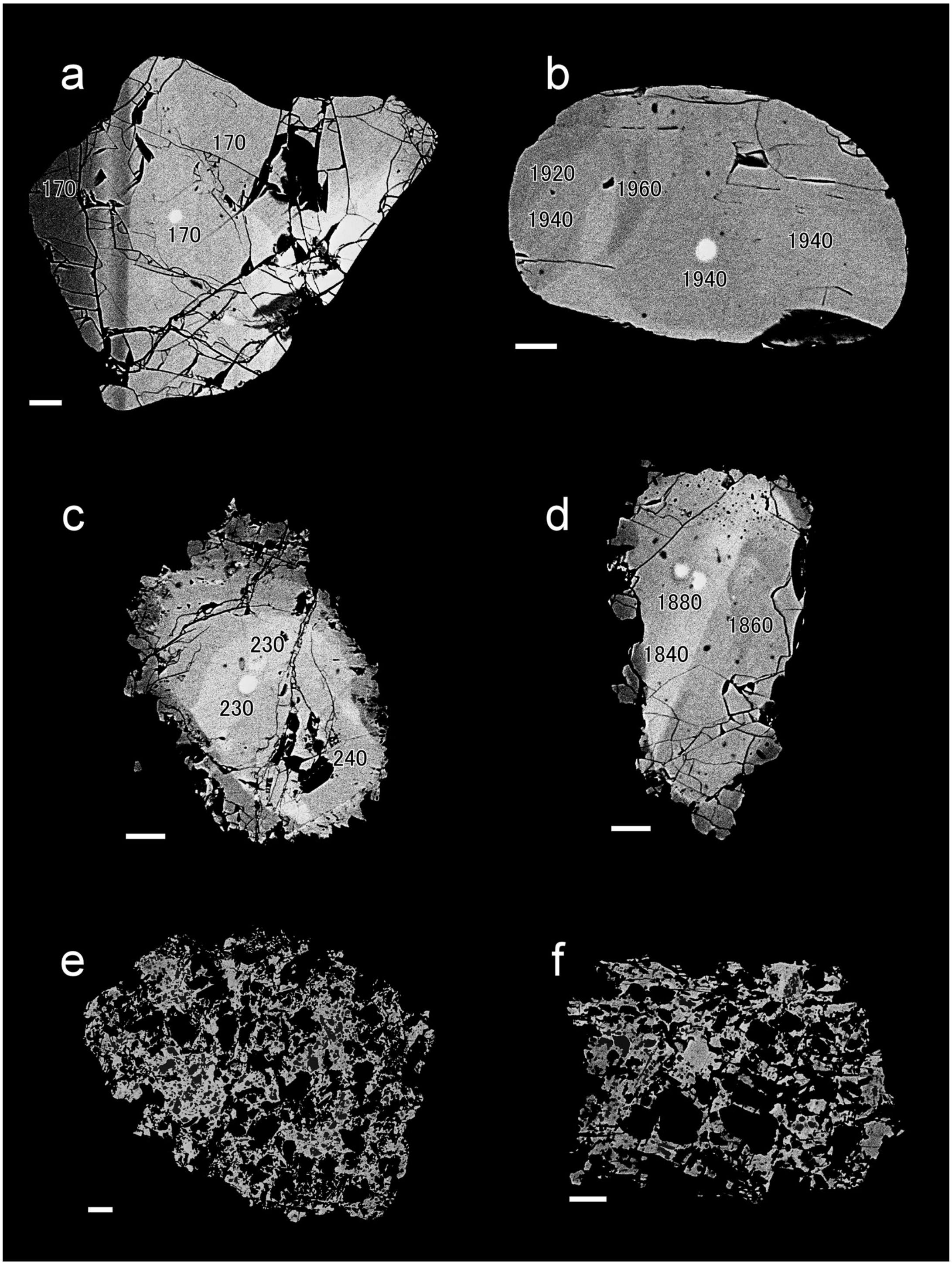


Fig. 4. Back-scattered images of detrital and secondary monazites. a & b: detrital monazites from the Western Foothills, c & d: detrital monazite surrounded by secondary Th-free monazite from the Hsuehshan Range. e & f: aggregate of Th-free monazite in the Hsuehshan Range. The number in each grain shows monazite age (Ma). All the scale bars are 10 microns.

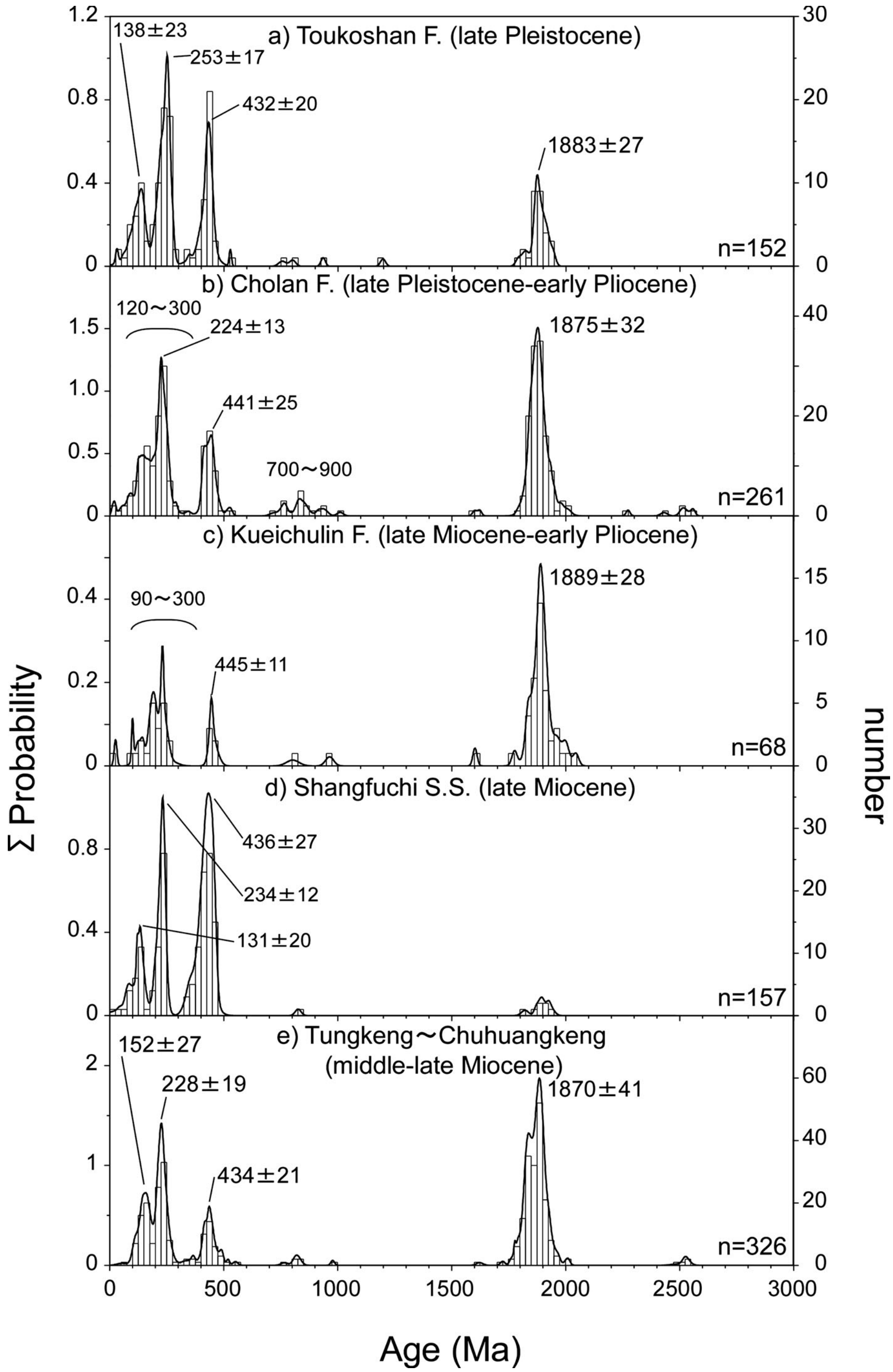


Fig. 5. Frequency and probability distribution diagrams of monazite ages from the sandstones of the central part of the Western Foothills. Numerical value (n) in each diagram denotes the number of analyzed monazite grains.

the sandstones (Figs 5a–c & 5e) have a similar age distribution pattern with a strong peak at ca. 1900 Ma. An exception is the Shangfuchi sandstone (Fig. 5d) which has strong peaks at ca. 230 Ma and 440 Ma, and a very small peak at 1900 Ma. In the northern part of the Western Foothills, the Early Miocene sandstones of the Mushan Formation (Fig. 6a) and one of the Late Oligocene sandstones of the Wentzekeng Formation (Fig. 6b) have similar age distribution patterns to most of the samples in the central part of the Western Foothills, i.e. a strong peak at 1900 Ma and subordinate younger peaks (Fig. 6). The other sandstones in the Wentzekeng Formation (Fig. 6c) have their strongest peaks at 450 Ma and 100–200 Ma with a subordinate peak at 1900 Ma. A notably different age distribution pattern is observed in the sandstone from the Late Oligocene Wuchihshan Formation (Fig. 6d) which has a small peak at 1900 Ma and a generally similar pattern to that observed for the Shangfuchi Sandstone in the central Western Foothills (Fig. 5d).

As detrital monazite is not common in the Eocene to Oligocene sandstones from the Hsuehshan Range, all the available monazite ages are summarized on one frequency diagram (Fig. 6e). The resulting age pattern is quite different from those for other sediments in the Western Foothills, in that there is a large population at 250 Ma, small populations at 450 Ma and 100–200 Ma, and the population at 1900 Ma is far less recognizable.

Monazite ages in the Recent sands collected from eight areas in the Asian continent are shown in Figure 7. Each sample has its distinct age distribution characteristics, reflecting the different rocks within their drainage basins. In the Korean Peninsula (Fig. 7a), monazite ages show a clear bimodal pattern with clusters at 100–300 Ma and 1800–2000 Ma and monazite with ages from 300 Ma to 1800 Ma is scarce. A similar bimodal pattern is observed for the beach sands collected around Qingdao (Fig. 7b) for which a sharp peak around 120 Ma is characteristic, probably due to the basin being small. The sand from the Liao River (Fig. 7c) has characteristic peaks at 490 Ma and 2500 Ma.

Both the Yellow and Yangtze rivers have huge drainage basins. Although sands from both rivers have monazite age peaks at 100–300 Ma, 410 Ma and ca.1900 Ma, the strongest peaks appear at 0–25 Ma and 410 Ma for the Yangtze and Yellow rivers, respectively (Figs 7d & e). The young monazites in the Yangtze River were almost certainly derived from the Himalayan region which has only been part of the river's drainage basin since the earliest Pleistocene (Fan *et al.*, 2004), and they should therefore be excluded from consideration in provenance studies of the Tertiary sandstones of Taiwan. A cluster of ages around 750 Ma in the age distribution pattern of the Yangtze River is relatively high, and is representative of the Yangtze craton (Wang, 1986). The Pliocene and Early Pleistocene sandstones in the drill core from the mouth of the Yangtze River have similar peaks to those of the modern sands except for a shift of the 450 Ma peak in the Pliocene sands to 410 Ma in Recent sand (Fan *et al.*, 2004).

The Min River (Fig. 7f) has a small drainage basin in the Fujian Province that is thought to be the most probable provenance area for the Tertiary sandstones of the Western Foothills and Hsuehshan Range of Taiwan (Chou, 1980; Tan & Youh, 1978). The monazite age from the Min River sand has a strong peak at 450 Ma with subordinate peaks at around 150 and 230 Ma. The sand sample from the Zhu River (Fig. 7g) which flows through the Guangxi and Guangdong provinces has a different monazite age distribution pattern compared with other samples. It has a strong peak at 250 Ma and very weak peaks at 400–500 Ma and 800–900 Ma. No clear peak at 1900 Ma has been recognized in sands from either the Min or the Zhu rivers.

Discussion

The modal proportions of heavy minerals in the sandstones have not thus far produced any significant information on the provenance of the

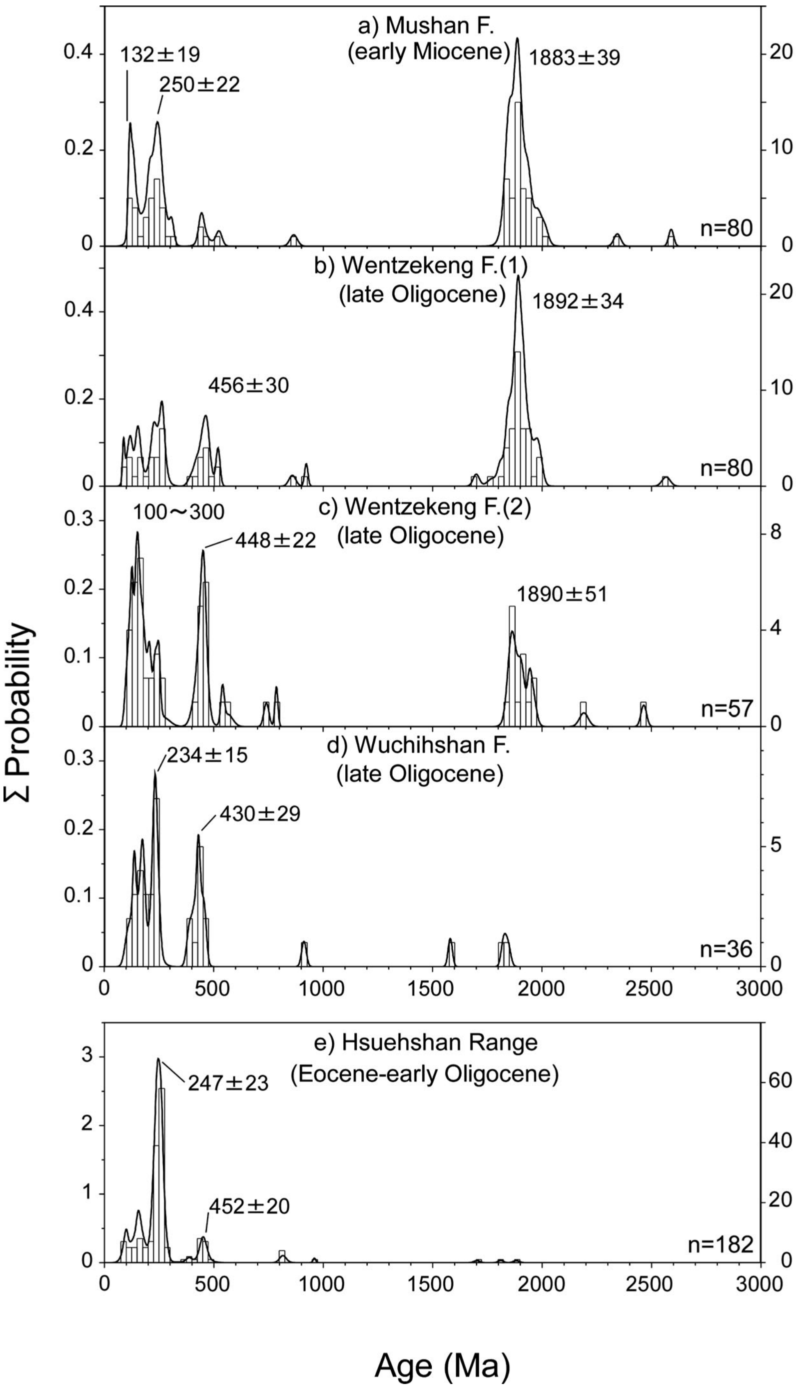


Fig. 6. Frequency and probability distribution diagrams of monazite ages in the sandstones from the northern part of the Western Foothills and Hsuehshan Range. Numerical value (n) denotes the number of analyzed monazite grains.

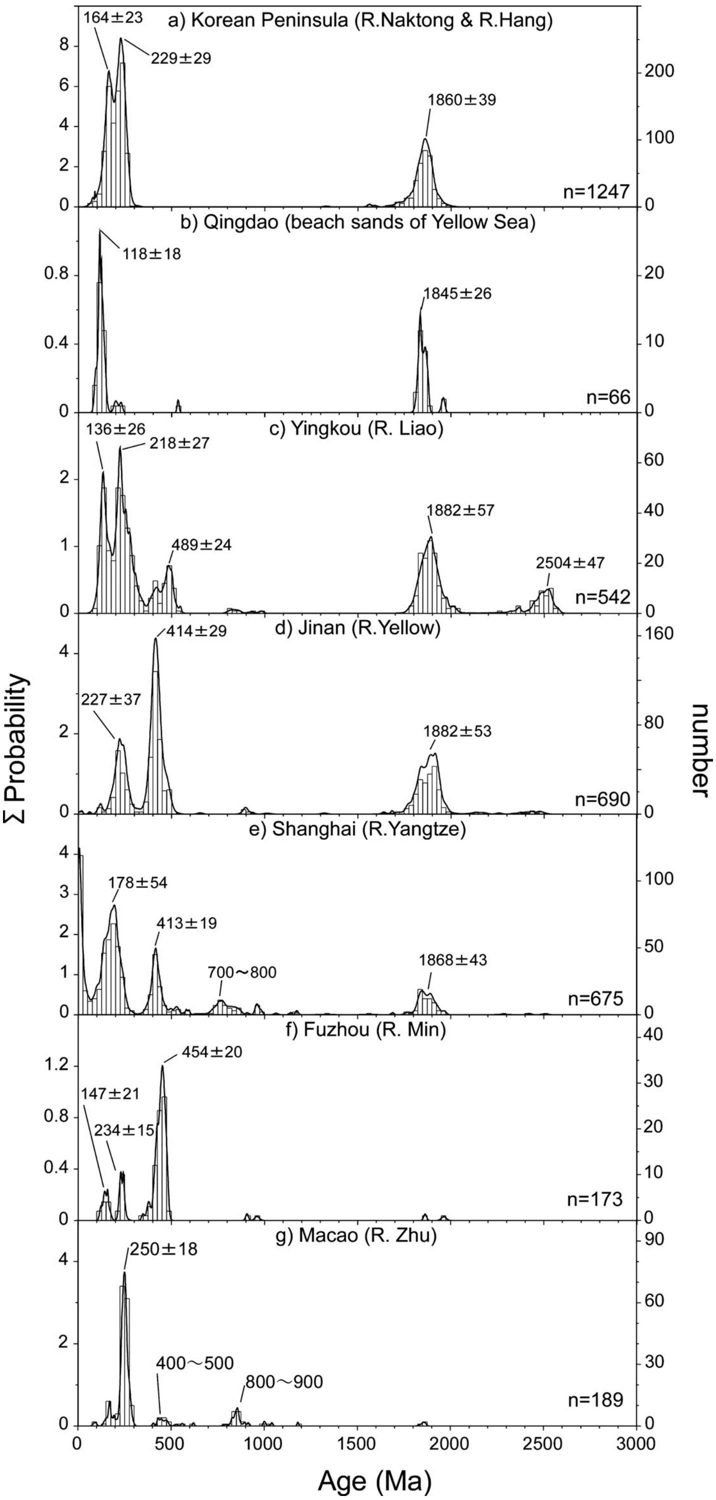


Fig. 7. Frequency and probability distribution diagrams of monazite ages in the sands collected along the East Asian continental margin. Numerical value (n) denotes the number of analyzed monazite grains.

Tertiary sandstones in Taiwan. Hence in this study we have determined the ages of detrital monazites in the sediments and compared the data with equivalent data for sands collected from the Asian continental margin in order to deduce the provenance of monazites in the Tertiary sandstones in Taiwan.

The drainage systems of rivers in the East Asia region have changed with geological time as evidenced by the occurrence of young monazites sourced in the Himalayan region which were supplied into the paleo-Yangtze River from the Early Pleistocene and small drifts of peaks suggesting a similar origin occurring since Late Tertiary (Fan *et al.*, 2004). This fact needs to be taken into account when comparing the monazites of modern river and beach sands with those in the Tertiary sandstones of Taiwan. The East Asian continent has been stable at least since the end of the Cretaceous (cf. Lee and Lawver, 1994) and the Tertiary sediments in Taiwan have been derived from the Asian continent. Thus it is useful to consider monazite age distribution data from modern river systems as an analogue for those in the Tertiary sandstones of Taiwan.

Western Foothills: Sandstones, except for Shangfuchi Sandstone in the central part of the Western Foothills, have strong monazite age peaks at ca. 150 Ma, 230–250 Ma, 430–450 Ma and ca. 1900 Ma (Fig. 5). Sediments of the Toukoshan and Cholan formations (i.e. Late Pliocene to Late Pleistocene) were derived from the central part of Taiwan, including the metasedimentary terrane of the Central Range (Chou, 1974; Chen *et al.*, 1992). The older sediments have paleo-current directions that indicate they were derived from the west of Taiwan. Thus it is reasonable that the monazite age patterns of the Toukoshan Formation should be different from those of the Early Miocene to Early Pliocene sequence, i.e. the Chuhuangkeng to Kueichulin formations. A study of sedimentary lithic fragments in the Late Pliocene to Early Pleistocene sediments of the Cholan Formation has shown that they were derived from central Taiwan (Chen *et al.*, 1992). Since the Cholan Formation has a similar monazite age pattern to the Miocene sediments, with a strong peak at 1900 Ma and subordinate peaks at 120–300 Ma and 430–450 Ma, it is probable that the detrital monazites were derived from erosion of the Miocene sediments in the Western Foothills as central Taiwan was uplifted by the collision of the Coastal Range with the Neogene volcanic arc (Suppe, 1981; Huang *et al.*, 1997).

None of the Recent sands collected from the Asian continent showed age patterns similar to those observed in the Chuhuangkeng to Kueichulin formations. However, it is possible to conclude that, with the exception of the Shangfuchi Sandstone, the Miocene to Early Pliocene age patterns could be formed by mixing of sands from the Korean Peninsula and the drainage basins of both the paleo-Yangtze and Yellow Rivers (Figs 5, 6 & 7). The strongest peak at 1900 Ma indicates that the present-day drainage basins of the Min and Zhu Rivers could not have been the provenance area for most of the Miocene sandstones in the central part of the Western Foothills. A relatively low peak at 450 Ma against 1900 Ma suggests that the major provenance for the Miocene sediments in the Western Foothills was the Korean Peninsula and areas around Qingdao on the southern side of the Shandong Peninsula.

In contrast, the Late Miocene Shangfuchi Sandstones have an age pattern with strong peaks at 230–250 Ma and 430–450 Ma, and a negligible peak at 1900 Ma (Fig. 5d). This age pattern is also consistently observed for the sands from the Min River cutting through the Fujian Province, which is the closest province to Taiwan (Fig. 1). The peak positions in the Shangfuchi Sandstones and the Min River sand patterns are coincident even in detail as shown in Fig. 8. Hence, it is reasonable to conclude that sediments in the Shangfuchi Sandstones were derived mostly from the Fujian Province, with a minor contribution from the northern areas which have 1900 Ma monazite. The close coincidence also suggests that the drainage system in the Fujian Province has not changed significantly since the Late Miocene.

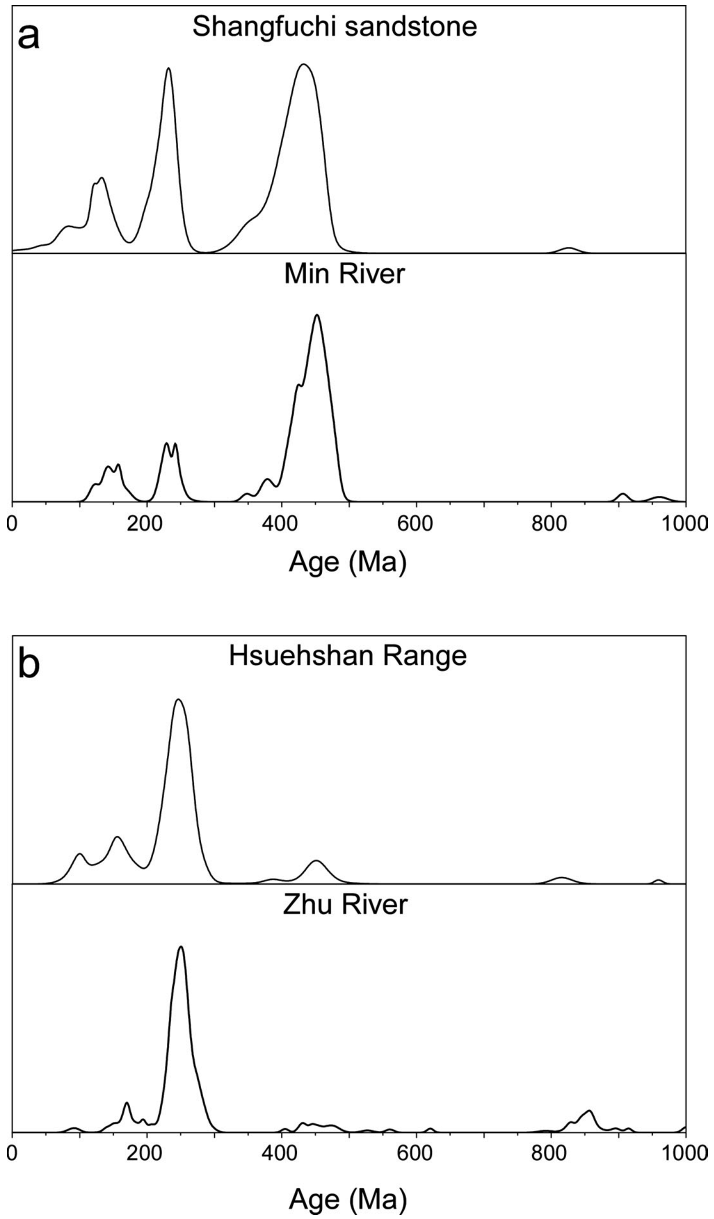


Fig. 8. Detailed comparison of monazite ages younger than 1000 Ma.
a: probability diagram of monazite ages in the Shangfuchi Sandstone and Recent sands from the Min River, Fujian Province. b: Oligocene-Eocene sandstones in the Hsuehshan Range and Recent sands from the Zhu River, Guangxi and Guangdong provinces.

In the northern end of the Taiwan, sandstones were collected from the Late Oligocene to Early Miocene formations in the Western Foothills. These sandstones have slightly different age patterns (Fig. 6). The age distribution of the Late Oligocene Wuchihshan Formation (Fig. 6d) has strong peaks at 230 Ma, 430 Ma and ca. 150 Ma. As such it is different from the pattern observed in the other three sandstones which have strong peaks at 1900 Ma (Figs 6a–c), but it is similar to the age pattern of the Shangfuchi Sandstone and Recent sands from the Min River. Thus it is concluded that the Fujian Province was the major area of provenance for the sandstones of the Wuchihshan Formation.

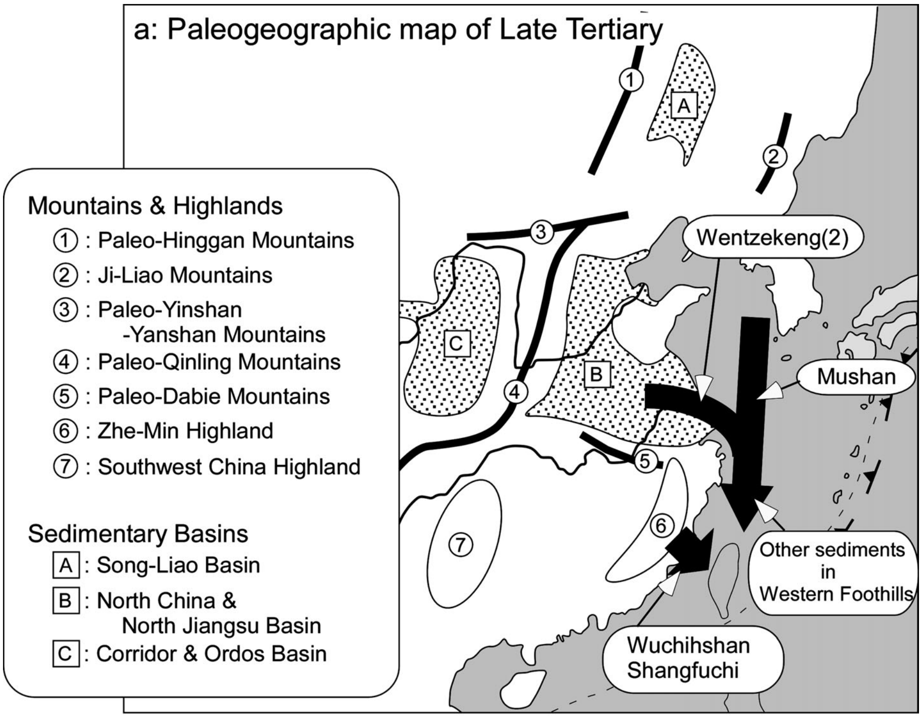
The Early Miocene Mushan Formation (Fig. 6a) has two major populations at 100–300 Ma and 1800–2000 Ma with a very minor peak at around 450 Ma. This pattern suggests that the sandstone was sourced from the Korean Peninsula and Quingdao area with a small contribution from the drainage basins of the paleo-Yangtze and paleo-Yellow rivers.

One of the Late Oligocene sandstones of the Wentzekeng Formation (Fig. 6b) has a monazite age distribution pattern that is similar to those of the Miocene sandstones in the central part of the Western Foothills. However, the other sandstone (Fig. 6c) has two major peaks at 100–300 Ma and 430–450 Ma and a subordinate peak at 1900 Ma, a pattern that is similar to that of the sands from the paleo-Yangtze River; this pattern, together with a characteristic peak at ca. 750 Ma, suggests that the sandstone has been sourced in the drainage basin of the Yangtze River.

According to the paleogeographic map for the Late Tertiary of China compiled by Wang (1985), a huge drainage basin was developed in the lower parts of the Yellow and Yangtze Rivers and the Ordos basin existed in the upper reaches of the Yellow River (Fig. 9a). Thus it seems probable that no sediment was transported from drainage basins in the upper sections of the present Yangtze and Yellow rivers into the lower parts of these rivers and thence to Taiwan. Furthermore, the paleogeographic map suggests that the paleo-Yellow River ran through the Shanghai area towards the East China Sea rather than into the Yellow Sea as did the palaeo-Yangtze River. This may explain why there is a negligible contribution from the Liao River, with a 2500 Ma peak (Fig. 7c), into the Tertiary sediments of Taiwan.

Probable drainage systems feeding the Tertiary sediments of the Western Foothills are summarized in Figure 9a. This reconstruction takes into account the crustal shortening of ca. 60 km that occurred in the Western Foothills after collision with the Neogene volcanic arc (Suppe, 1981). The major source of material for these Tertiary sediments was the Korean Peninsula and the southern side of the Shandon Peninsula as evidenced by the presence of a strong peak at 1900 Ma. Many sandstones have a moderate peak at 400–500 Ma. Such rocks indicate a subordinate contribution from the paleo-Yangtze River. In both the Shangfuchi and Wuchihshan sandstones, monazite with a 1900 Ma age is minor in amount and these sands have major peaks at ca. 230 Ma and ca. 430 Ma. This pattern is similar to that of sand collected from the Min River which runs through the nearby Fujian Province and has negligible contribution either from the Korean Peninsula or from the drainage basin of the paleo-Yangtze River.

Hsuehshan Range: In contrast to the sandstones in the Western Foothills, monazite is not well preserved in the sandstones from the Central Range monazite. Although a comparison of monazite ages from the Late Oligocene to Middle Miocene sandstones in the Western Foothills and Central Range was a major focus for this study, detrital monazite was not observed in the Late Oligocene to Middle Miocene sandstones collected from either the Hsuehshan or Backbone Ranges. However, about 200 detrital monazites were found in seven samples from the Eocene and Early Oligocene sandstones of the Hsuehshan Range. The age profiles of monazites from these sandstones have a strong peak at 250 Ma and minor peaks at 160 Ma and 450 Ma (Fig. 6e). This distribution pattern is quite different from that observed in sands from the Western



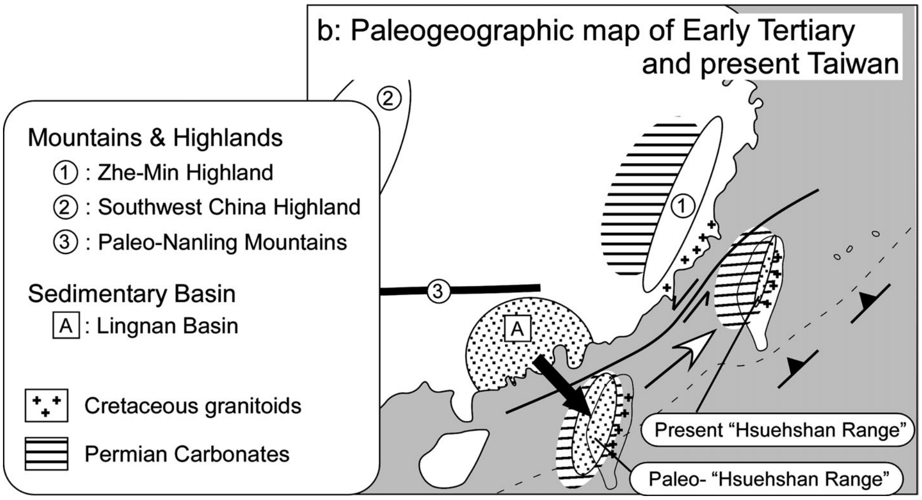


Fig. 9. Schematic diagrams. a: Inferred paleo-currents for the Tertiary sediments in the Western Foothills. b: probable paleogeographic position for the Paleogene sediments in the Hsuehshan Range. Strike-slip fault and arrangement of Permian carbonates, and Cretaceous granitoids were proposed by Jahn *et al*. (1992). Paleo-maps of China showing sedimentary basins and mountain ranges in the late and early Tertiary are after Wang (1985).

Foothills but the pattern is similar to that obtained from sands in the Zhu River which flows through the Guangxi and Guangdong provinces (Figs 6e & 7g). A detailed comparison over a restricted time range indicates only minor dissimilarities between them (Fig. 8b). Hence, it is concluded that the Eocene and Oligocene sediments of the Hsuehshan Range were sourced from an area that was within the drainage basin of the present-day Zhu River.

Paleo-current analysis of the Eocene to Oligocene sandstones in the Hsuehshan Range has shown that the sediments were derived from the northwest of its present position, that is, from the Fujian Province (Tan & Youh, 1978). If we assume that the sedimentary basin in which the sandstones were deposited was in or near its present position, then the monazite age data suggests that the Hsuehshan Range must have rotated clockwise after deposition; this scenario allows the Paleogene Hsuehshan Range sediments to be supplied only from the Guangxi and Guangdong provinces without any contribution from the nearby Fujian Province. The most probable alternative model, which also takes into account the age data presented in this study, is that the Eocene to Oligocene Hsuehshan Range sediments were deposited on the continental margin near the mouth of the Zhu River running through the Guangxi and Guangdong provinces and has been moved about 500 km northeastward by left lateral faulting (Fig. 9b).

In the Tertiary tectonic reconstructions of Taiwan, the Hsuehshan Range has always been sited near its present position (e.g. Lee & Lawver, 1994; Huang *et al*., 1997). However, the data presented in this study cannot explain the juxtaposition of the Western Foothills and Hsuehshan Range, which both include Late Oligocene and Middle Miocene sediments, without major transcurrent movement. A comparative study of Permian carbonate and Cretaceous granitoids in the Fujian Province and Taiwan has also proposed that Taiwan has been displaced from a position near the Zhu River after the intrusion of the Late Mesozoic granitoids which have ages of 80–90 Ma (Jahn, Chi & Yui, 1992; Fig. 9b). This timing is not in conflict with our model which suggests that the displacement occurred after the Early Oligocene.

Tectonic reconstructions of the South China Sea area are very complex since collision and rotation of small blocks were common in the Tertiary and subduction and opening of back-arc basins also occurred (Lee & Lawver, 1994). While many faults have been described along the continental margin of South China, except for the Red River Fault, which runs between the South China and Indochina blocks and has at least 500 km of displacement during the Early Miocene (Tapponnier *et al.*, 1990), no large left-lateral fault has been reported. Although we have failed to determine the provenances of the Late Oligocene to Middle Miocene sandstones in the Hsuehshan Range and the Middle Miocene sandstones in the Backbone Range, our data and model for the Eocene and Oligocene sandstones place important constraints on any tectonic models for the East Asia region.

Conclusions

Our studies and comparison of monazite age data from the Tertiary sandstones of Taiwan and the Recent sands from the East Asian continent have led us to the following conclusions:

Sandstones from the Western Foothills have strong monazite age peaks at ca. 150 Ma, 230–250 Ma, 430–450 Ma and ca. 1900 Ma. These monazite age patterns indicate that the Tertiary sediments in the Western Foothills were derived mainly from the Korean Peninsula and adjacent areas with a subordinate contribution from the drainage basin of the paleo-Yangtze River. Some sediments with a negligible peak at 1900 Ma were supplied sporadically to the Western Foothills basin from another provenance area. The Late Miocene Shangfuchi and Late Oligocene Wuchihshan sandstones were derived mainly from the Fujian Province. There is no systematic correlation between the depositional age and drainage basin for the sandstones in the

Western Foothills.

The Eocene to Early Oligocene sandstones in the Hsuehshan Range have monazite age patterns that differ from those observed in sands from the Western Foothills. They have predominant monazite populations with ages of 250 Ma with a few small concentrations at around 150 Ma and 450 Ma. The age distribution of the Paleogene sandstones is very similar to that obtained from sands of the Zhu River which flows through the Guangxi and Guangdong provinces. Based on our monazite age analyses and available paleocurrent directions, we propose that the Paleogene terrane of the Hsuehshan Range was deposited at the continental margin near the mouth of the Zhu River and was juxtaposed against the Western Foothills by left-lateral faults after the Early Oligocene. Our model, based on sand provenance studies, is essentially the same as the model proposed by Jahn, Chi & Yui (1992) to explain the distribution of Permian carbonates and Cretaceous granitoids in the Fujian Province and Taiwan.

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