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Thermal event records in SE China coastal areas: Constraints from Monazite Ages of Beach Sands from two sides of the Taiwan Strait

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Abstract

CHIME ages of >460 detrital monazites from beach sands from SE China (Chinmen Island) and W Taiwan were determined in order to deduce the major tectonothermal events affecting the coastal areas of SE China. Additional 360 monazites from estuarine sediments of the Minjiang River (eastern China), metamorphic rocks from Chinmen Island and sedimentary rocks from W Taiwan were also dated. Ages of the Chinmen beach monazites (245–80 Ma) reveal that they are derived from adjacent gneisses and mixed with sediment from the Jiulongjiang River (SE China). Some large, euhedral monazites contain older cores (~220 Ma) and younger rims (137–124 Ma), demonstrating that overgrowth on inherited Indosinian grains occurred at the time of gneiss formation (137 Ma). Monazites of W Taiwan fall into two age groups, one in the Paleoproterozoic (1900–1650 Ma) and the other spanning the Phanerozoic (530–120 Ma). Based on similar ages of Phanerozoic monazites from the Minjiang River and W Taiwan, monazites of the latter group are inferred to be derived mainly from this river, hence the Paleoproterozoic monazites are most probably derived from Cathaysia basement exposed in the drainage basin of the Wuyishan (NW Fujian). Along with monazite ages of the two-mica schist, sediments from the uplifted Changle–Nanao shear zone (CNSZ) constitute only a minor component of deposits in W Taiwan. The age frequency distribution of Phanerozoic monazites from W Taiwan, which shows peaks at 450–430, 360–350, ~275 and ~245 Ma suggests the existence of Caledonian, Hercynian and Indosinian crust beneath the immense Yanshanian cover of the SE China coastal area.

Keywords: CHIME monazite age; Cathaysia Block; SE China; W Taiwan

1. Introduction

Precise dating of igneous and metamorphic rocks has long been the target for geologists to unravel the nature of thermal events on earth. The U–Pb zircon and monazite isotopic ages are by far the most widely adopted method to constrain the time of magma emplacement or high-grade metamorphism. A less precise but more easily accessible dating technique, the chemical Th–U-total Pb isochron method (CHIME), has been applied by using a more common device—the electron microprobe (e.g., Suzuki and Adachi, 1994). Due to its high concentration of Th and U and low common Pb contents, monazite is ideal for such geochronology (e.g., Parrish, 1990; Montel et al.,

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1996; Cocherie et al., 2005). Generally speaking, CHIME monazite method is capable of dating rocks older than 100 Ma (Rhede et al., 1996), and may be applied to younger (~80 Ma) rocks as well (Suzuki et al., 1996; Tsuboi and Suzuki, 2003).

The SE China coastal area is basically a terrain consisting of the Late Mesozoic intrusive and volcanic rocks on the eastern margin of the South China continent. Since the beginning of the Cenozoic, evolution of the continental slope off SE China, now the Taiwan Strait and Taiwan island, involved two major stages of rifting associated with subsidence in the Eocene–Oligocene and Miocene, respectively, that resulted in a thick sequence (>10 km) in rifted basins (Lin and Watts, 2002). Ages of detrital minerals in large river systems have been demonstrated to be able to provide important information about regional tectonothermal events and erosion–deposition relation (e.g., Indochina; Bodet and Scharer, 2000). Beach placers on the coast of W Taiwan contain abundant black and yellow monazites (Overstreet, 1971). Aside from the black variety that is suggested to be authigenic in origin (Matzko and Overstreet, 1977), CHIME monazite ages (hereafter referred to as monazite ages) of the yellow variety are able to shed the light for the source to sink relation of these recycled sediments.

The purpose of this study is to know the main phases of thermal event of the SE China coastal area revealed from the monazite ages of beach sediments in W Taiwan. To constrain the contribution of possible supplying components, estuarine sediments of the most potential river system as well as the beach sands and metamorphic rocks of the SE China coastal area and one sedimentary rock in W Taiwan are examined in a similar way. With the insight of these ages, the provenance of sediments in W Taiwan, which has long been a debate (Bien, 1971; Chen et al., 1990, 2000), are also evaluated.

2. Geological background

The South China Block is one of the old cratons of the east Eurasia continent, surrounded by the North China Block in the north, the Songpan Ganzi terrain in the west and the Indochina Block in the southwest (Fig. 1). It is subdivided into the Yangtze Block and the Cathaysia Block that amalgamated in the Neoproterozoic (Li et al.,

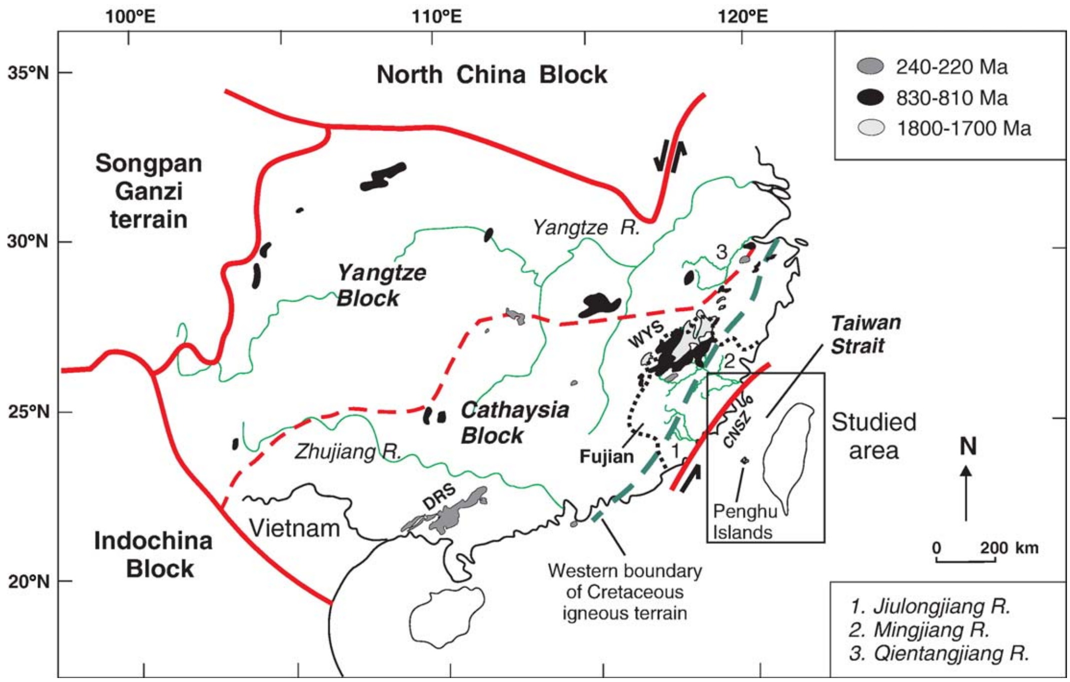

Fig. 1. Position of the Taiwan Strait relative to the Cathaysia Block, including distributions of the Paleoproterozoic (1800–1700 Ma), Late Jinning (830–810 Ma) and Indosinian (~220 Ma) granitoids, and drainage systems of the Yangtze, Qientangjiang, Mingjiang and Jiulongjiang Rivers. The light dashed line is the boundary of the Yangtze and Cathaysia Blocks and the heavy dashed line is the boundary of the Cretaceous and Jurassic igneous terrains in the Cathaysia Block. WYS and DRS denote the Wuyishan and Darongshan areas, and CNSZ, the Changle–Nanao shear zone. Note that the Mingjiang River system originates at the Wuyishan.

2003). The age of the Cathaysia basement is considered as Paleoproterozoic (e.g., Chen and Jahn, 1998), evidenced by the well-known exposures in Wuyishan, NW Fujian. This block has been subjected to various stages of granitic intrusions (± metamorphism) during the Neoproterozoic and Early Phanerozoic (Shen and Lin, 2002).

Principal Phanerozoic orogenies in the South China Block have been broadly related to the Caledonian, Hercynian, Indosinian (Triassic) and Yanshanian thermal events (Chen and Jahn, 1998). So far, only temporal and spatial variations of Yanshanian magmatic activities are better understood: Early Yanshanian (EY; Jurassic) rocks occur in large parts of the Cathaysia Block and Late Yanshanian (LY; Cretaceous) rocks cover the SE China coastal area (Fig. 1). Further southeast is a narrow belt of the Changle–Nanao shear zone (CNSZ), or the LY metamorphic core complex composed mainly of gneissic, migmatitic and granitic rocks dated about 140–110 Ma (Chen et al., 2004). There are also metasedimentary rocks with unknown ages, which have been regarded as the country rocks for these intrusives (Chen et al., 2002).

The influence of Early Phanerozoic orogenesis in the SE China coastal area is obscure because its surface is heavily covered by EY and LY granitoids. Major rivers running on the Cathaysia Block like Yangtze, Minjiang and Jiulongjiang, may be able to bring washouts of the underlain rocks to reside in their river mouths and further deposit in the subsided continental margin. Situated in the river channel of the paleo-Jiulongjiang River, Chinmen was deposited with Oligocene–Miocene sediments of this river known as the Chinmen Formation. Also situated in the middle of the CNSZ (Fig. 2), Chinmen is an ideal place for revealing the ages of different components in this zone.

The island of Taiwan was formed by thickening of the crust in the continental slope due to the collision between the Eurasian and the Philippine Sea plate since the Late Miocene (Teng and Lin, 2004). Sedimentary sequences of W Taiwan, mainly alternating sandstones and shale, are distributed with the N–S trending Neogene strata in the foothills and Paleogene strata in the Central Range (Fig. 2a). Because of the drainage patterns in W Taiwan, beach sands in the northwest are mostly derived from the Neogene, whereas those in the

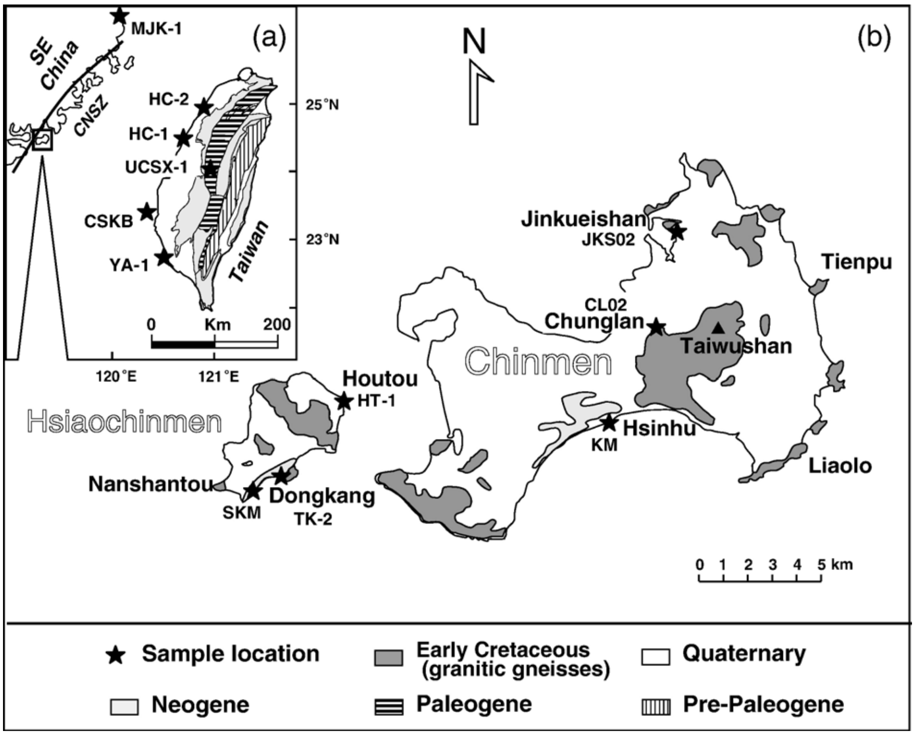

Fig. 2. Simplified geological maps of the studied area (Fig. 1) with sample localities: (a) Miaoli (HC-1), Hsinchu (HC-2), Chiayi (CSKB), Tainan (YA-1) and the Paleogene strata (UCSX-1) in W Taiwan, and Minjiang River mouth (MJK-1) in E Fujian; (b) Hsinhu (KM) in Chinmen, and Nanshantou (SKM), Houtou (HT-1) and Dongkang (TK-2) in Hsiaochinmen. Moreover, the Chunglan gneiss (CL02) and Jinkueishan two-mica schist (JKS02) are also included. The Neogene in the Chinmen area is the Chinmen Formation, and beach sands from KM and SKM are designated to know the influence of this formation.

southwest from both the Paleogene and Neogene strata (Chen et al., 2000).

Phanerozoic thermal events were suggested to have involved either metamorphism of the Proterozoic basement (the Caledonian metamorphic belt; Shen and Lin, 2002) or extensive remelting of crustal materials (the Indosinian and EY overprints; Xu et al., 2005). Therefore, rocks related to these events are potential sources for generating monazites (Parrish, 1990). On this basis, the monazite age spectra of the sediments contributed from the SE China coastal area in the Cenozoic depositional cycle can be used for tracing Phanerozoic thermal events.

3. Sample preparation

Samples were collected from four localities in the Chinmen area (HT-1, TK-2, SKM, and KM) and five in W Taiwan (HC-1, HC-2, CSKB, YA-1 and UCSX-1). In addition, river mouth sediments of Minjiang (MJK-1) were also included. For better constraining various sources of monazite, two rock samples in Chinmen, including the gneiss at Chunglan (CL02) and the two-mica schist at Jinkueishan (JKS02), were crushed for collecting monazites (Fig. 2b). In sample CL02, we found that the coexisting cheralite, the Ca- and Th-rich variety of the monazite group or (Ce, Ca, Th)(P, Si)O4, is able to provide CHIME ages as well.

Samples (5–50 kg) were cleaned and subjected to magnetic removal of magnetite, and then run through a rocking table for collecting the heaviest portion. From these heavy sands, monazites (generally occupying 1–2 vol.%) were either hand-picked under the stereo microscope or gravitationally separated with a heavy liquid. It is noted that monazites of samples KM, SKM, HC-1 and CSKB are taken from concentrates for mining purpose, and thus represent mixtures covering a large sampling area up to several km^2 rather than one small site like others.

Monazite generally forms rounded grains in the beach sands except at Houtou (HT-1) where it keeps prismatic outlines and even double pyramids (500 × 400 μm). Oval shapes with long axis in ~400 μm and short axis in ~300 μm are common for TK-2 and SKM, and smaller sizes for others: ~200 × 100 μm (KM and HC-1), 100 × 80 μm (HC-2 and UCSX-1), 80 × 60 μm (CSKB, YA-1 and CL02) and ~50 μm (JKS02). We mainly focus on dating the core ages to reveal the main populations of the presumed formation time for these monazites. A simple reconnaissance on the age difference between the core and rim is carried out for some large euhedral monazites (>350 μm).

4. Analytical methods

The instrument used is a Shimadzu-ARL electron microprobe model EMX-SM equipped with 4 channels of wavelength-dispersive spectrometers. The acceleration potential of 15 kV, sample current of 20 nA and smaller beam size of ~5 μm is adopted to allow a better spatial resolution (Montel et al., 1996; Crowley and Ghent, 1999). Epoxy-mounted monazites are measured for Th, U, Pb and Y contents simultaneously, and standards are synthetic ThO_2, UO_2, PbS and YAG (Y–Al-garnet with Y_2O_3 = 57.1 wt.%). These standards are basically similar to those described by Cocherie and Albarede (2001). Counting times are total 180 s (3 × 60 s) on characteristic X-ray lines and 360 s (6 × 60 s) on backgrounds.

X-ray lines adopted are M_α for Th and Pb, and M_β for U and L_α for Y to avoid interferences of ThM_β on UM_α and crystals used are ADP and PET. Correction for the interference of YLã on PbM_α is made on the YAG standard as well. Moreover, the data reduction for ZAF corrections (Chen and Tung, 1984) is based on fixed weight mode of P and REE (Pyle et al., 2005). With our apparatus, detection limits of PbO and UO_2 at 1σ confidence level are 0.018 and 0.016 wt.%, respectively, and the relative error is 12% in Pb and U. A systematic error of 2% is considered for ThO_2, and also for PbO and UO_2, above 1 wt.%.

Apparent ages calculated from the analysis for all the studied monazite grains are listed in Appendix A (available on the web). Single grain analysis and discrete grains of monazite that define a significant linear trend in the PbO versus ThO_2^* (ThO_2 incorporating UO_2 equivalents) plot are used to calculate an age isochron and the mean square of weighted deviates (MSWD) by adopting the best fitting slope of linear regression model (Kato et al., 1999). Although no common Pb correction has been considered (Cocherie et al., 2005), the isochron thus obtained can also provide a simple assessment for the common Pb effect on cogenetic detrital grains (Suzuki and Adachi, 1998). For the total age population of beach sand monazites in certain areas, the ISOPLOT3 program (Ludwig, 2003) is used to construct the age frequency curve. Test of the methodology for present analytical conditions is made by determining monazite ages in a medium-grained, almandine- and cordierite-bearing granite of the Darongshan Complex, S China (Fig. 1). The isochron age obtained (224 ± 13 Ma based on 17 grains, Fig. 3a) is in agreement with the in situ monazite age (213 ± 23 Ma on 14 measurements, Montel et al., 1996) and the SHRIMP U–Pb zircon

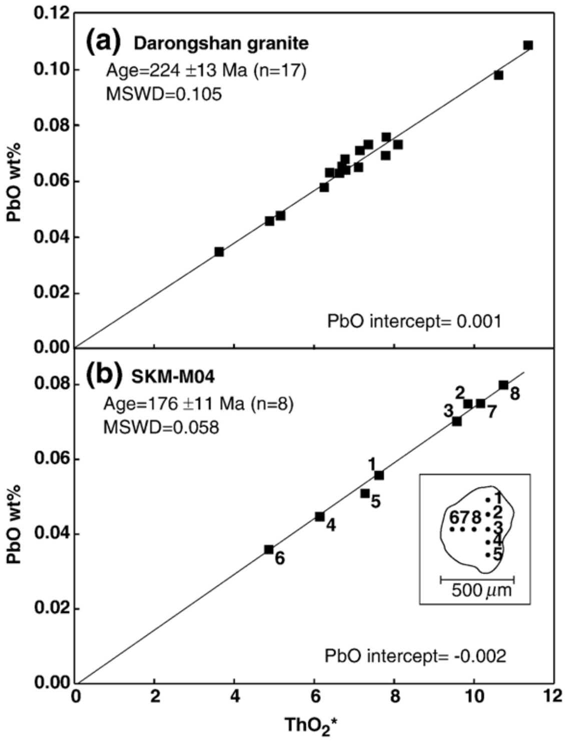

Fig. 3. PbO vs. ThO_2^* plots for revealing monazite age isochrons of (a) the Darongshan granite, S Guanxi (for self-test of the methodology), and (b) a single-grain spot analysis (SKM-M04 from Hsiaochinmen). Ages and uncertainties (2σ) are calculated using the method of Kato et al. (1999). The latter case shows the consistency of apparent ages despite a large variation of ThO_2 and PbO contents in this monazite (Appendix).

age (230±4 Ma on 13 measurements, Deng et al., 2004).

5. Results

5.1. Ages of Chinmen monazites

The great majority of beach sands monazites exhibit a small range of apparent ages irrespective of the ThO_2, UO_2 and PbO variations in the grain. This can be exemplified by the result of a large subrounded monazite grain SKM-M04 that yields an isochron age of 176±11 Ma based on 8 spot analyses (Fig. 3b). However, multi-stage development of monazites has been observed for large euhedral grains. In sample HT-1, rims of euhedral grains generally yield younger apparent ages, by which an isochron age of 124±8 Ma can be calculated when incorporated with ages of the youngest group of monazites. On the other hand, their cores and other monazites display two older ages of 159±8 and 219±12 Ma (Fig. 4a). Similarly, two groups of age can be distinguished in sample TK-2: a large number of monazites result in a younger isochron age of 137±5 Ma, and the rest yields an older isochron age of 223±27 Ma (Fig. 4b). A monazite core age of ~220 Ma seems to be a common feature for samples HT-1 and TK-2.

Apparent ages of monazites in sample SKM (n=107) basically fall in the Mesozoic ranging from 245 to 80 Ma (n=98), with few in the Paleoproterozoic (~1860 Ma, n=1) and Paleozoic (470–265 Ma, n=8) (Fig. 4c). Among the Mesozoic monazites, the age groups of 146–121 Ma (n=23) and 90–80 Ma (n=16) coincide well with the time of gneiss formation and rhyolite eruptions, respectively, in the SE China coastal area (Chen et al., 2004). Others reveal a continuous age spectrum in the Early Mesozoic. The scarcity of 120–90 Ma monazites is due to the large exposure of monazite-free I-type hornblende-bearing granites in the studied area that emplaced at this time. Monazites of sample KM, with an age span of 215–83 Ma (n=20), are similar to the essential group obtained from sample SKM. More than half of the data set (n=11) can reveal a significant isochron age of 139±5 Ma (Fig. 4d), reflecting the influence of adjacent gneissic body (Taiwushan; Fig. 2b; see later section).

Apparent ages obtained from monazites in the Chunglan gneiss (CL02) can be divided into two groups: the older group of 485–208 Ma (n=16) and the younger group of 144–133 Ma (n=17). Most monazites in the older group are confined to a narrow time span (234–212 Ma, n=10) leading to an isochron age of 223±23 Ma (Fig. 4e). Cheralites (ThO_2=36.8–48.5 wt.%, UO_2=2.3–7.4 wt.% and PbO=0.26–0.39 wt.% on 17 grains) show a small range of apparent ages from 143 to 132 Ma. By combining cheralites and the younger group of monazites based on the similarity of age ranges, an isochron age of 137±5 Ma is obtained (Fig. 4e), which is in good accord with the U–Pb zircon age of the Taiwushan gneiss (139.4±0.4 Ma; Yui et al., 1996)—the same unit as the Chunglan gneiss (Fig. 2b). Coexistence of the 223 and 137 Ma monazites in Chunglan gneiss coincides very well with the case of beach sands in sample TK-2 that shows two groups of monazite ages: 221 and 137 Ma (Fig. 4b). This indicates that the beach sand monazites here are basically derivatives of a gneissic body equivalent to Chunglan or Taiwushan.

Monazites in the Jinkueishan two-mica schist (JKS02) are mostly the Paleozoic and Mesozoic ages (Fig. 4f). Except one Paleoproterozoic age (1797 Ma) preserving in the core of a grain with the rim age of 385 Ma, there is no other Precambrian age among 70 analyses. Without counting the particularly old grain of

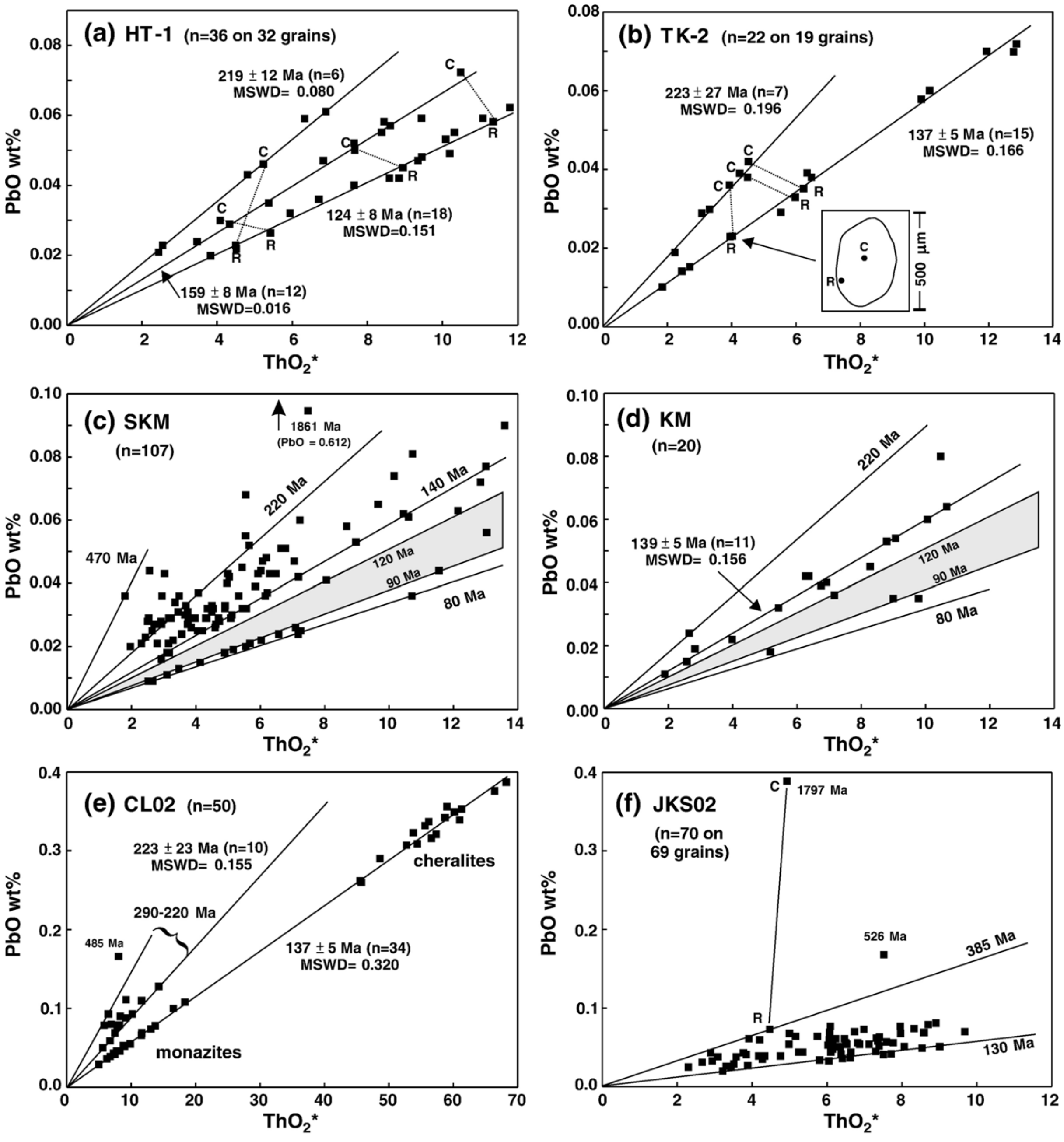

Fig. 4. PbO vs. ThO_2^* plots for monazites from (a) Houtou (HT-1), (b) Dongkang (TK-2) and (c) Nanshantou (SKM) in Hsiaochinmen, (d) Hsinhu (KM), (e) Chunglan (CL02), and (f) Jinkueishan (JKS02) in Chinmen (Fig. 2b). Samples HT-1 and TK-2 contain many large euhedral monazites and the tie lines connect core (C) and rim (R) compositions. Lack of ages pertaining to the range of 120–90 Ma (shaded in SKM and KM) is noted (see text for explanation). Few isochrons (with uncertainties) are constructed for representing the age of monazite hosts or adjacent igneous bodies; and age reference lines (without uncertainties) are shown for comparison.

526 Ma, Paleozoic ages spread between 385 and 250 Ma ($n = 19$) and Mesozoic ages are nearly a continuous spectrum ranging from 234 to 129 Ma ($n = 49$). These results provide a maximum age for the sediment deposition of ~130 Ma.

5.2. Ages of the river mouth monazites from Minjiang (MJK-1)

River mouth sediments here represent samples unaffected by the major LY shear movement in the

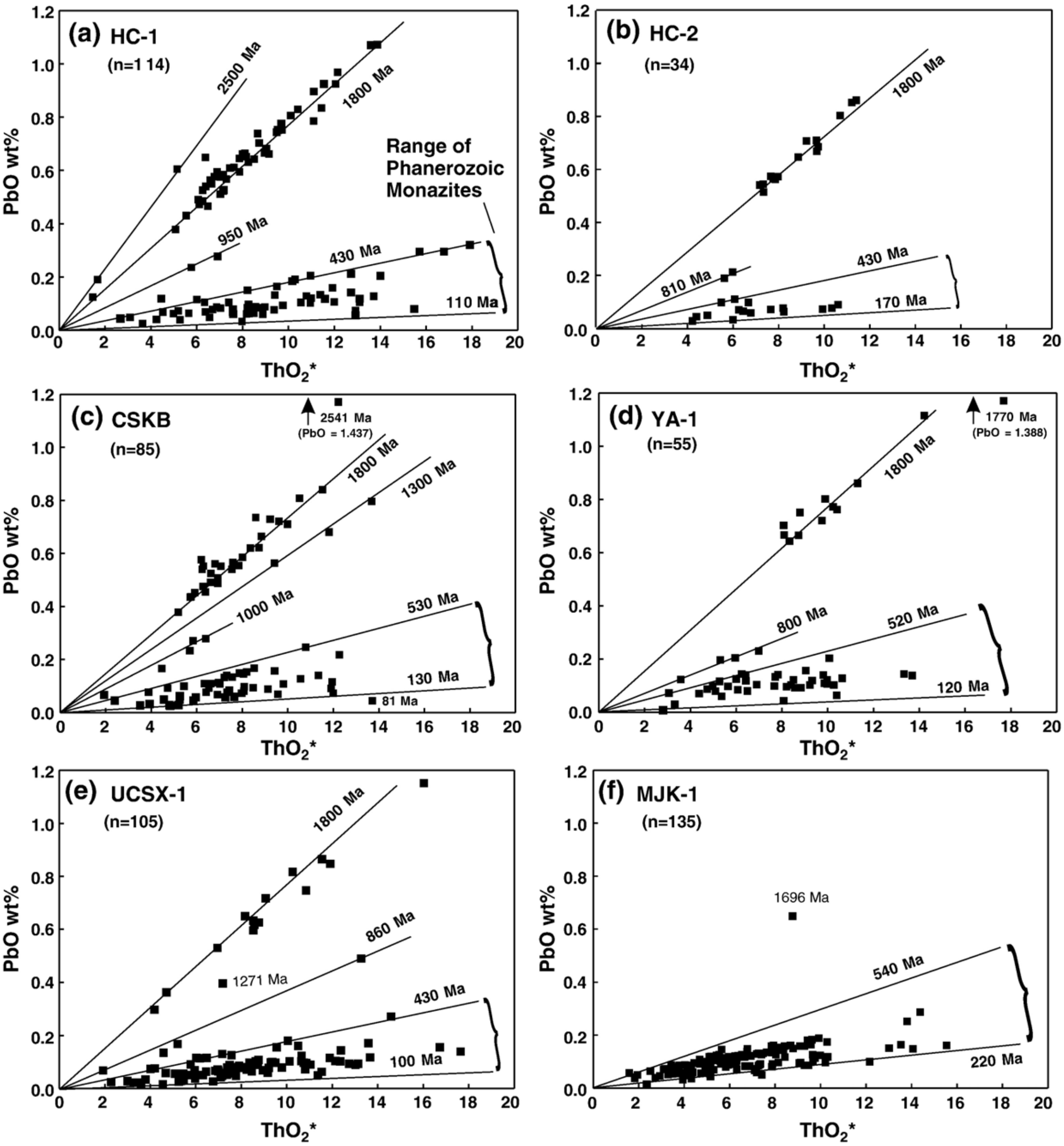

Fig. 5. PbO vs. ThO_2^* plots for monazites from (a) Miaoli (HC-1), (b) Hsinchu (HC-2), (c) Chiayi (CSKB), (d) Tainan (YA-1) and (e) the Paleogene strata (UCSX-1) in W Taiwan, and (f) Minjiang River mouth (MJK-1) in E Fujian (Fig. 2a). Only age reference lines are shown.

coastal area as sampling sites are west to the CNSZ. Monazites in sample MJK-1 are mostly angular to subangular and large in grain size (200–300 μm), indicative of short distance of transportation. The great majority falls in the range between 540 and 220 Ma (n = 109 out of 135; Fig. 5f) despite that the sampling site is close to a large Cretaceous igneous terrain (Fig. 1). Major age groups are 540–510 Ma (n = 13), 480–405 Ma (n = 55), 380–330 Ma (n = 22), 295–270 Ma (n = 17) and 250–220 Ma (n = 12). The most significant group of 480–405 Ma matches the Caledonian thermal event of 470–425 Ma in the Cathaysia interior (Xu et al., 2005). Precambrian populations are rather small, containing only few ages of 1700 Ma (n = 1), ∼840 Ma (n = 1) and 610–600 Ma (n = 3).

5.3. Ages of W Taiwan monazites

Miaoli and Hsinchu (HC-1 and HC-2) and Chiayi and Tainan (CSKB and YA-1) areas in the NW and SW Taiwan, respectively, are designated for distinguishing monazites preserved in the Neogene and Paleogene sedimentary rocks. In addition, sample UCSX-1 is used to constrain monazites derived from the Paleogene strata in W Taiwan. Overall monazite ages obtained from sample HC-1 are of two main groups: one can be regarded as pertaining to a cluster of ~1800 Ma, and the other spreads between 430 and 110 Ma (Fig. 5a). Sample HC-2 displays coherent age patterns with an age population of ~1800 Ma and random distributions of data spreading between 430 and 170 Ma (Fig. 5b). Consistency of age patterns from these two samples reflects the generality of same monazite sources. Altogether (n=148), ages beyond these two main groups, i.e., ~1800 and 430–110 Ma, are very few and present at 2600–2300 Ma (n=3), 950–790 Ma (n=4), and ~620 Ma (n=1).

For samples of SW Taiwan (CSKB and YA-1), again, two monazite age clusters are observed: an older group of ~1800 Ma and a younger group spreading between 530 and 130 Ma (Fig. 5c) or 520–120 Ma (Fig. 5d). Put together all these data (n=140), other ages include ~2500 Ma (n=1), ~2000 Ma (n=6), ~1300 Ma (n=3) and 1100–800 Ma (n=9). As compared with the Miaoli–Hsinchu samples, the age of 530–510 Ma is characteristic and contributions of the Neoproterozoic monazites seem to be more abundant in these two samples. Moreover, monazite ages of sample UCSX-1 (n=105) mostly belong to the Phanerozoic (430–84 Ma) and the rest to the Proterozoic, including 1800–1600 Ma (n=14), ~1300 Ma (n=1), and 900–700 Ma (n=3) (Fig. 5e). The relative proportion of the Paleoproterozoic monazites is significantly smaller than the beach sand samples.

6. Discussion

6.1. Applicability of monazite ages

In the application of CHIME geochronology for metamorphic rocks, the age and zoning pattern of cores are sometimes different from grain to grain even within a rock sample when older cores are mantled by younger rims (Suzuki and Adachi, 1994; Cocherie et al., 1998; Crowley and Ghent, 1999; Williams and Jercinovic, 2002). It has been suggested that Pb diffusion loss from monazites is generally insignificant for metamorphism of upper amphibolite facies or even granulite facies up to 900 °C if no fluid is involved (Braun et al., 1998; Montel et al., 2000; Cherniak et al., 2004). Hence, core monazite ages can retain the record of pre-metamorphic thermal events. On the other hand, new monazites may be generated from the breakdown of REE-bearing minerals during high T/low P amphibolite facies (e.g., Dunning et al., 1995; Cherniak et al., 2004) or high T/P granulite facies metamorphism (e.g., Bingen et al., 1996).

6.2. Thermal records reflected by gneisses

The younger isochron ages of 124±8 Ma (HT-1), 137±5 Ma (TK-2) and 139±5 Ma (KM) obtained from detrital samples in the Chinmen area (Fig. 4a, b and d) can be related to the main-phase thermal event for the formation of gneisses in the CNSZ (Chen et al., 2004). This is supported by the younger isochron age of 137±5 Ma shown in the gneissic rock sample CL02 (Fig. 4e). Therefore, one important source for Chinmen monazites is the gneissic rock. In dealing with the tectonic evolution in SE China, Jahn et al. (1976) and Yui et al. (1996) have drawn attentions for the age of ~160 Ma in Chinmen rocks as a stage of large-scale anatexis. In fact, inherited zircons of ~160 Ma are commonly present in many gneissic bodies in Chinmen (our unpublished data). However, the thought that precedent rocks for gneisses are the EY magmatic product before metamorphism (Chen et al., 2004) can only be reflected by a loosely defined monazite core age of 159±8 Ma in sample HT-1 (Fig. 4a).

Tectonothermal events pertaining to the Indosinian orogeny has rarely been mentioned in the SE China coastal area, thus, the presence of ~220 Ma monazite grain and core ages in Chinmen samples appears to be a new finding. Monazites of sample CL02 provide useful information: in addition to the well-defined metamorphism age of 137 Ma, there exists another isochron age of 223 Ma and a group of older age ranging from 485 to 256 Ma (Fig. 4e). Monazites older than ~220 Ma are explained as xenocrysts due to wall rock contamination and/or inherited grains derived from older rocks at the site of melt generation. Dominance of ~220 Ma monazites in this group, along with the common existence of monazites with same ages in beach sands, favors the origin of Paleozoic contaminants during ascend of magmas plus residues after remelting of Indosinian crusts. Such crusts have endured extensive LY (±EY) overprints with thermal conditions lower than the Pb closure temperature (>900 °C) allowing inherited monazites to survive (Cherniak et al., 2004; Seydoux-Guillaume et al., 2002).

6.3. Metasedimentary rocks and sediment sources of Chinmen samples

The CNSZ was active during the Late Mesozoic. Using amphibole geobarometry, granitic gneisses in this zone were suggested to have emplaced at depths of 18–24 km (Chen et al., 2004). Because metasedimentary rocks have been found in direct contact with gneissic rocks in few localities of the CNSZ and the maximum age of sediment deposition is ~130 Ma (Fig. 4f), they should have deposited in this shear zone at the expose of gneissic rocks (110 Ma; Yang et al., 1997). This rules out the possibility that they represent the Paleozoic sedimentary wall rocks of these gneisses (Chen et al., 2002). The lack of monazites of 90–80 Ma is a sign that deposition of sediments ended before onset of anorogenic rhyolitic volcanism. Therefore, the post-orogenic subsidence in the CNSZ can be confined in a time span of 110–90 Ma to receive large volumes of such sediments. Probably until Early Cenozoic (the time of major stratigraphic hiatus in Taiwan Strait), the CNSZ was tectonically uplifted again.

The age spectrum of these metasediments (JKS02) shows the highest peak at 195 Ma and two moderate peaks at 260 and 135 Ma, whereas the Chinmen beach monazites (SKM plus KM) reveal three major age peaks at 160, 140 and 85 Ma and one minor peak at 215 Ma on the age frequency curve (Fig. 6a and b). Therefore, contribution from the metasedimentary rocks to the

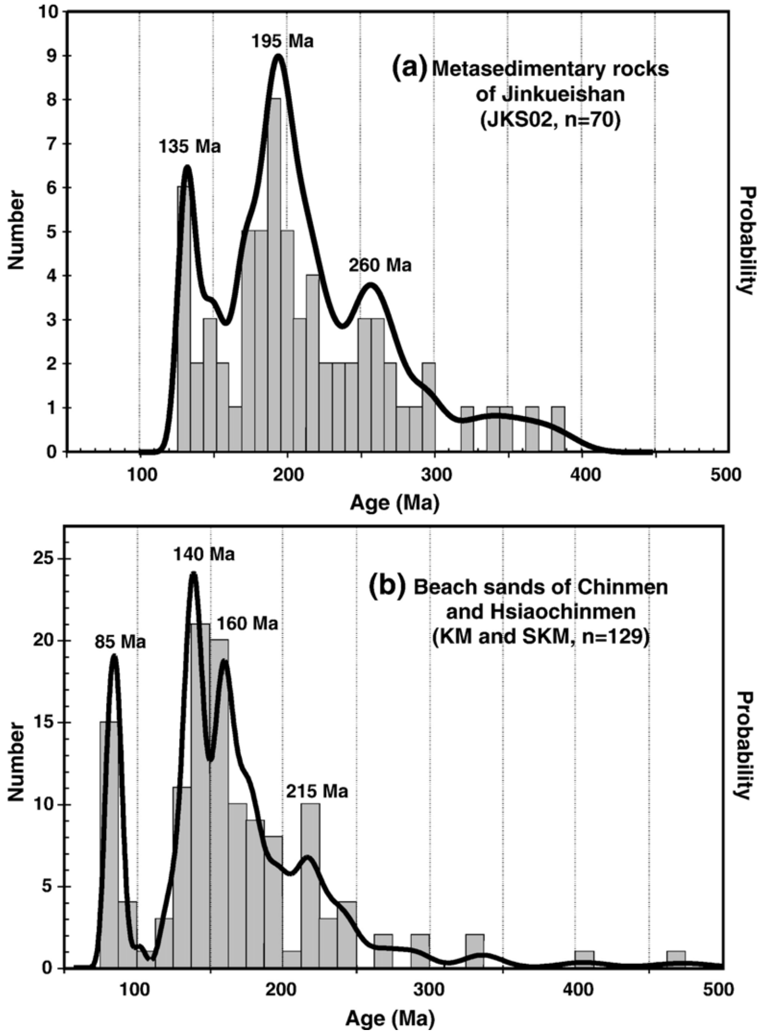

Fig. 6. Age frequency curves of monazites for (a) metasedimentary rocks (represented by the Jinkueishan two-mica schist), and (b) beach sands from Chinmen areas.

beach sands is minor. They are rather a mixture of the disintegrated Chinmen Formation and the decomposed gneissic bodies. Incision of the Jiulongjiang river system on the EY granitic plutons can certainly bring up eroded materials from pluton sites to deposit as the Chinmen Formation during the Neogene. However, whether there are Indosinian plutons sitting on the pathway of this river remain unsolved.

6.4. Comparison between NW and SW Taiwan

Differences for the age population of monazites between the NW (Miaoli–Hsinchu) and SW (Chiayi–Tainan) Taiwan can somewhat shed the light for sediments deposited during the Neogene and Paleogene. The relative proportion of monazite age population between Phanerozoic and Paleoproterozoic is 52% vs. 43% in the north and 61% vs. 27% in the south of W Taiwan, i.e., a less influence of the Paleoproterozoic source as beach sands spread further south (Fig. 7a and b). Reversely, Meso- and Neoproterozoic monazites are more influential in the south (12%) than the north (3%). Monazites in the Paleogene strata show an even larger contrast, 83% vs. 13%, between Phanerozoic and Paleoproterozoic ages (Fig. 7c). This suggests that the Paleoproterozoic provenance becomes more influential in the later stage of the Cenozoic depositional cycle on this continental margin.

A striking feature for Phanerozoic age populations in the beach sand monazites is that there are strong reflections from relicts of Caledonian, Hercynian and Indosinian events, despite that the SE China coastal area is largely covered by the Yanshanian igneous rocks. In the Paleogene strata (Fig. 7c), the Yanshanian (34%) and Indosinian (38.5%) predominate over the Hercynian (17.5%) and Caledonian (10%). However, Hercynian and Caledonian ages are more widespread in the beach sand monazites, occupying 26% and 18% in the north and 36% and 30% in the south. Therefore, exposes of the Paleozoic provenances are in concurrence with the Paleoproterozoic effect. Here we also stress the importance of the Indosinian age group within the beach sand monazites: 31% in the Miaoli–Hsinchu and 16% in the Chiayi–Tainan areas.

6.5. Role of the Wuyishan basement

Because there are abundant Paleoproterozoic monazites in the W Taiwan sediments, the only well-exposed Precambrian basement in SE China, i.e., the Wuyishan area, must be taken into consideration. The center part of this area, where the Mingjiang River originates (Fig. 1), is a terrain of Paleoproterozoic peraluminous granitoids and amphibolites as revealed from few U–Pb zircon ages of amphibolites (1766±19 Ma), tonalites (1800 ±44 Ma) and monzogranites (1870±36 to 1975±80 Ma) (Li, 1997; Wang et al., 1998b).

Most recently, Wuyishan is known for the existence of Neoproterozoic rocks surrounding its center in an area greater than those suggested previously (Fig. 1). They are considered as equivalents to the granites with ages of 830–810 Ma that are widespread around the Yangtze craton margin as a consequence of the Late Jinning orogeny (e.g., Wang and Qiao, 1984; Li et al., 2003). For instance, the Mamianshan rhyolite, a member of the bimodal volcanics in the Neoproterozoic sedimentary sequences, exhibits a U–Pb zircon age of 818±9 Ma (Li et al., 2005).

To the southeast of the Wuyishan area, rocks pertaining to the Caledonian thermal events are widespread (FBGMR, 1985). Regional metamorphism up to amphibolite facies and associated plutonism (500–380 Ma) have been mentioned, however, no precise ages can be referred. Hercynian and Indosinian rocks are seldom recognized in this area and reliable ages so far are only the small Yangfang syenitic body (242±4 Ma; Wang et al., 2005) and the Dashuang granite (240 ±1 Ma; Wang et al., 1998a). Therefore, Wuyishan as a whole is a potential area to supply the Paleo- and Neoproterozoic as well as the Caledonian monazites. Sources for Hercynian and Indosinian monazites are uncertain.

6.6. Influence of river systems in SE China

Major rivers in SE China coastal area that have been mentioned as potential contributors for supplying sediments to Taiwan are the Yangtze River (Chen et al., 1990) and the Minjiang River (Bien, 1971; Chen et al., 2000). Drainage systems of rivers in relevance are shown in Fig. 1.

Cored sediments from Yangtze River mouth have been studied for the CHIME monazite age population in different layers (Yokoyama and Zou, 2002). Ages of monazite are marked by the essential Phanerozoic population (81%), in which nearly 25% of these grains are of the Early Miocene. Besides, source of these sediments has changed with time: monazites with ages of 500–350 Ma are dominant in the Pliocene layers and those of 275–100 Ma are more abundant in the Quaternary layers (Fan et al., 2004). Put together all these monazite ages, scarcity of the Paleoproterozoic and the Phanerozoic population for 350–275 Ma in

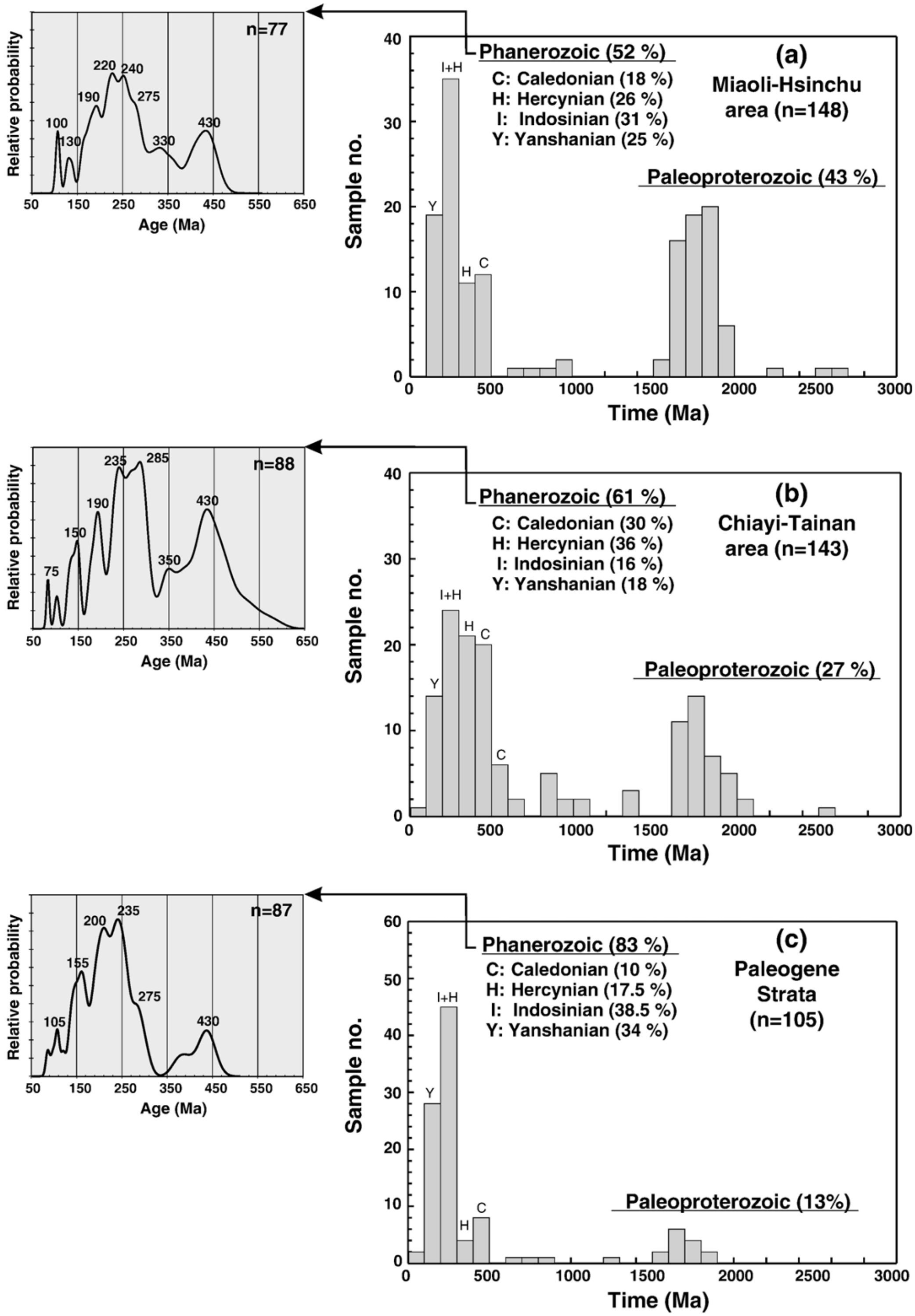

Fig. 7. Histograms of monazite ages of (a) NW and (b) SW Taiwan sediments, and (c) the Paleogene strata in W Taiwan. Age frequency curves for the Phanerozoic population in each area are also depicted.

sediments from the Yangtze River mouth minimizes its influence on W Taiwan.

The Minjiang system, on the other hand, delivers abundant Paleozoic and Early Mesozoic sediments to the river mouth. When the Phanerozoic total age frequencies of W Taiwan and Minjiang river mouth monazites are compared, they match within the analytical errors for major peaks in the entire age spectra although the relative proportion of each peak may be different (Fig. 8a and b). The only difference for ages >180 Ma is the lack of a minor 530 Ma peak in the W Taiwan sediments. The cogenetic relationship can also be supported by the fact that monazites with ages < 180 Ma are relatively in a small proportion for both populations. Short distances of sediment transport suggest that potential sources of Early Phanerozoic monazites are the Wuyishan peripheral beyond the Yanshanian terrain (Fig. 1). Scarcity of Proterozoic monazites in recent sediments of the Minjiang River mouth is puzzling, but may be ascribed to the human construction of some reservoirs and dams in this river (e.g., the Shuikuo Dam in the Minchin County).

6.7. Supply of W Taiwan sediments through time

Supply of W Taiwan (including Taiwan Strait) sediments is closely related to the tectonic evolution of the SE China coastal area. In the Early Cretaceous, due to the compressional force caused by the paleo-Pacific plate subduction, a west-bounding thrust system would cause the CNSZ to expose with the deep-seated gneissic rocks. Exhumation rates were estimated to vary

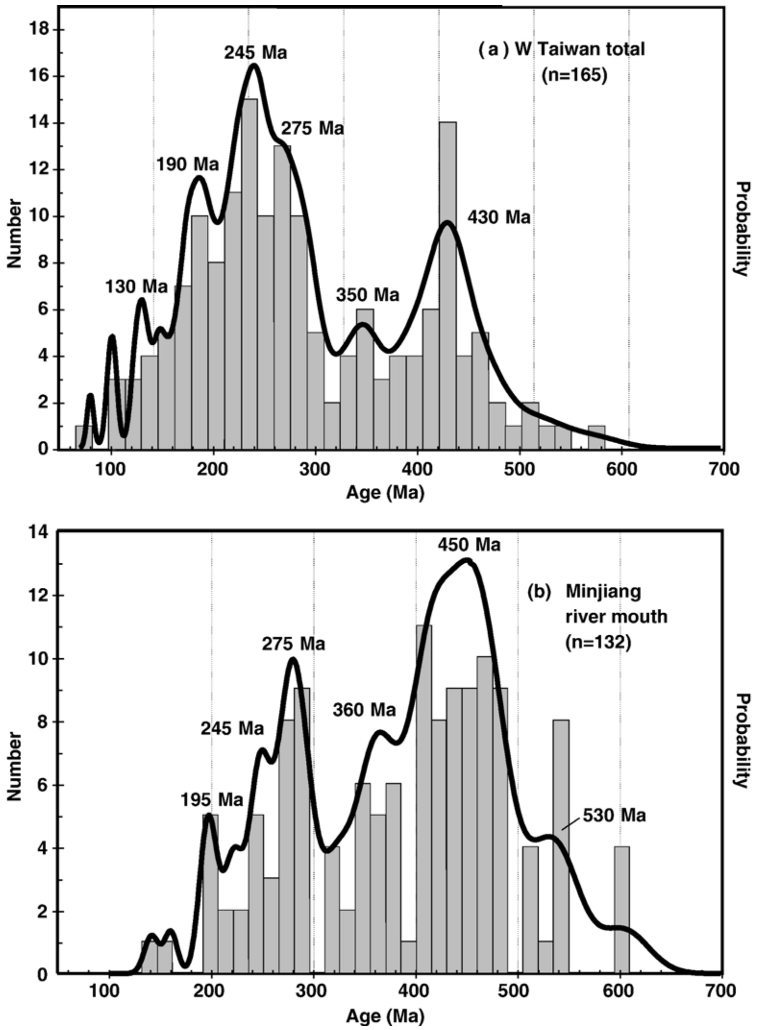

Fig. 8. Age frequency curves of the Phanerozoic monazites for (a) Minjiang River mouth, and (b) W Taiwan sediments. Note that peak ages of two curves are very similar, although relative intensities of the corresponding peaks are different.

from 1.3 to 0.8 km/Myr in different sections of this zone between 130–110 Ma (Chen et al., 2002). With the cover of >18 km being deprived, materials eroded from the CNSZ were then transported to build up the Cretaceous sedimentary sequences (120–100 Ma) in the Taiwan Strait (Teng and Lin, 2004).

In the Late Cretaceous, the coastal Fujian turned to an extensional tectonism and became invaded by shallow intrusives and rhyolites (Chen et al., 2004). Therefore, materials delivered to the continental slope were largely the rhyolites from highlands in the LY magmatic belt. Probably until the time when the foreland basin in the continental margin started to form (Lin and Watts, 2002), the CNSZ was eroded with the infilled sediments to redeposit in W Taiwan. This can explain the phenomenon that only the Paleogene sedimentary sequences in W Taiwan contain more abundant rhyolite fragments (Chen, 1964) and exhibit higher ε Nd(T) values (Lan et al., 2002).

During the Cenozoic, the extensional tectonics continued (Lin and Watts, 2002). In the Paleogene, Minjiang River played a more important role in bringing the Caledonian to Indosinian monazites to W Taiwan. In the Neogene, incision of the Minjiang River had reached a more mature stage to bring greater amounts of eroded materials from the center part of Wuyishan. Thus, Paleoproterozoic monazites can occupy 43% of the age population of the NW Taiwan sediments (Fig. 7a).

7. Inferred Cathaysia crust in the SE China coastal area

7.1. Precambrian crust

Main stages for the Precambrian accretion of the Cathaysia crust have been suggested to be 2.5, 2.1, 1.8, 1.4–1.2 and ~1.0 Ga as deduced from zircon inheritance ages of the Phanerozoic granitoids in SE China and NE Taiwan (Jahn et al., 1986; Li et al., 1992; Yui et al., 1996). Basements exposed in SE China that can support these events are mainly the highly metamorphosed Paleoproterozoic and less extensively metamorphosed Neoproterozoic rocks (Shen and Lin, 2002). Combining all these data, five Precambrian stages of crustal growth (I to V) in the Cathaysia Block, namely, ~2.5, 2.1, 1.9–1.7, 1.4–1.2 and 1.1–0.8 Ga, are suggested (Fig. 9a). Such age distributions are similar to those reported for sediments of major rivers in the Indochina continent (Bodet and Scharer, 2000). In this study we found that monazite ages of W Taiwan sediments generally match these five characteristic stages (Table 1).

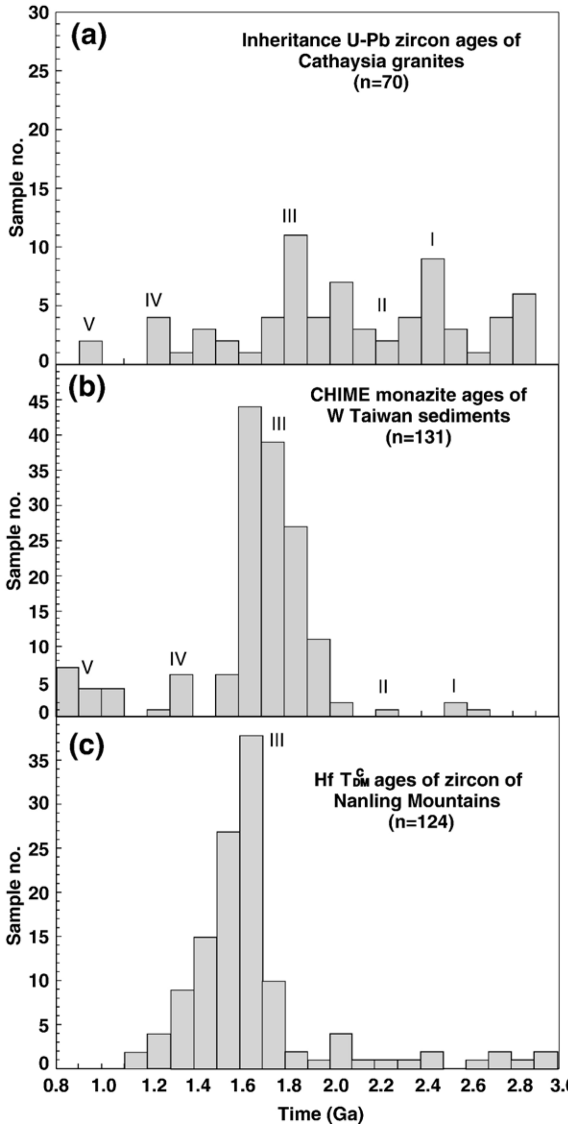

Fig. 9. Precambrian age histograms for (a) zircon inheritance ages of granites in the Cathaysia Block (Shen and Lin, 2002; Yui et al., 1996; Jahn et al., 1986), (b) monazite ages of W Taiwan sediments (this study), and (c) mean Hf isotope model ages (Hf T_{DM}^{C}) of zircons of the Nanling Mountains, S China (Xu et al., 2005).

Since early accretions in the SE China continent reflected by the inherited zircons are multi-stage and developed from the Late Archean to Neoproterozoic, the W Taiwan monazites dominated in the stage III (Fig. 9b) most probably indicate derivatives of a single source on this continent or the restriction of monazites in specific rock types. Although zircon inheritance ages of 1.9–1.7 Ga are commonly obtained from Yanshanian granitoids in SE China, Chinmen and NE Taiwan (Table 1), our data of Chinmen samples indicate that the Paleoproterozoic ages are, in principle, unlikely

Table 1
Precambrian age records (Ga) in SE China, Indochina, and Taiwan

Age stage	I	II	III	IV	V	References
1. U–Pb zircon inheritance ages of granitoids						
Cathaysia granites,	2.5		1.8	1.4–1.2		Li et al. (1992)
SE China*	2.5–2.4		1.9–1.7		1.1–0.9	Shen and Lin (2002)
Chinmen granites and gneiss			1.8–1.7			Yui et al. (1996)
NE Taiwan granites			1.7		1.0	Jahn et al. (1986)
and gneisses		2.1				Yui et al. (1996)
2. U–Pb zircon ages						
Wuyishan			1.8–1.7			Li (1997);
metamorphic rocks					0.8	Li et al. (2005)
Indochina river sediments	2.5	2.3	1.9	1.1	0.8	Bodet and Scharer (2000)
3. CHIME monazite ages						
Yangtze river mouth sediments			1.9–1.8		0.8	Yokoyama and Zou (2002)
Minjiang river mouth sediments			1.7		0.8	This study
W Taiwan sediments	2.6–2.5	2.3	1.8–1.6	1.3	1.0–0.8	This study

*The inheritance age of 2.8 Ga for Cathaysia granites reported by Shen and Lin (2002) is not included.

inherited from the rounded monazite nuclei being incorporated in these granitoids.

Most recently, Xu et al. (2005) reported the mean Hf isotope model ages (Hf T_{DM}^{C}) of zircons of the Nanling Mountains in the Cathaysia interior, indicating the mono-peak age of 1.8–1.6 Ga (Fig. 9c). Therefore, the Paleoproterozoic event is a common feature for both the Cathaysia interior and coastal area. In addition, based on the presence of Archean zircons (2.7–2.5 Ga) in the Mesoproterozoic basement (~1.4 Ga), they envisaged that the Cathaysia Block may include Archean micro-continent fragment. Due to very small number of Archean monazite ages in W Taiwan, the proposition that the eastern part of Cathaysia (1.9–1.7 Ga) had accreted along the ~2.5 Ga Archean nucleus (Zhu, 1999; Xu et al., 2005) needs further verifications.

7.2. Phanerozoic crust

Some Phanerozoic thermal events in the SE China can be reflected by the monazite age frequency curves of the W Taiwan and Minjiang samples (Fig. 8a and b). Particularly, peak ages corresponding to the Caledonian (450–430 Ma), Early and Late Hercynian (360–350 and ~275 Ma), and Indosinian (~245 Ma) orogenies are noted. This infers the existence or concealing of such crusts in the SE China coastal area although many local geologists advocate that there are no Hercynian granitoids in S China (e.g., Xu et al., 2005). It is also noted that the Indosinian peak age here is slightly older than that in Chinmen (~220 Ma), indicating two stages of Indosinian thermal events in the SE China coastal area and the CNSZ. The Cambrian age group of 540–510 Ma appeared in sediments of the Minjiang river mouth and SW Taiwan is similar to those obtained from sediments in the Permian to Early Mesozoic Shiwandashan Basin, S China (X.H. Li, 2005; personal communication). However, like the case of the Hercynian ages, no any igneous/metamorphic event and/or provenances in S China are known.

The Yanshanian thermal activities seem to have reactivated cyclically. Ages of the Early Jurassic monazite are peaked at 195 Ma in Minjiang and 190 Ma in W Taiwan sediments (Fig. 8). They are similar to the highest age peak for the metasedimentary rocks in Chinmen (Fig. 6a), indicating the common existence of 195–190 Ma rocks in the inner Fujian. This probably marks the initiation of the EY orogeny in the SE China coastal area. Late Jurassic thermal activities at ~160 Ma that prevailed in the Cathaysia interior (Chen and Jahn, 1998) show a strong sign in Chinmen (Fig. 6b) but leave insignificant traces in W Taiwan (Fig. 7). We suggest that the shear stress in the CNSZ had caused remelting of the pre-existing igneous rocks (~220 Ma) and formed the ~140 Ma gneissic rocks in the beginning of the LY syn-orogenic stage. The 120–80 Ma intrusive and volcanic rocks in the SE China coastal area were mainly controlled by the subduction-related magmatism in the LY post- and an-orogenic stages, in which only the 90–80 Ma rhyolites involve large degree of crust melting to account for the monazite ages of this group (Fig. 6b).

8. Conclusions

Beach sands of the W Taiwan contain significant populations of Paleoproterozoic (~1.8 Ga) monazites.

Sediments from the Minjiang River in N Fujian, China, are considered the most likely source of these monazites through the transport of sediments from the Wuyishan area. Because monazite occurrence in igneous and metamorphic rocks is restricted to peraluminous bulk compositions, contribution from the metaluminous Mesoproterozoic rocks like the Nanling Mountains (~1.3 Ga, Xu et al., 2005) is uncertain. However, coastal area of the Cathaysia Block has been repeatedly overprinted by the Caledonian, Hercynian and Indosinian (±Early Yanshanian) thermal events before being covered by the Late Yanshanian intrusive and volcanic rocks.

The provenance of some Phanerozoic monazites, which may be related to orogenies in SE China, is still unknown. These include: (1) the classical Caledonian orogeny has been widely accepted for the early Paleozoic thermal pulses, particularly in Ordovician and Silurian time. Here we found one additional thermal record in the Cambrian, at 540–510 Ma. (2) Traditionally, Hercynian orogeny includes the Late Paleozoic orogenic era extending through the Carboniferous and Permian. Our data suggest that a large number of Hercynian monazites exist in the sediments of W Taiwan and the Minjiang River, peaking at 360–350 Ma (Early Carboniferous) and ~275 Ma (Early Permian), respectively.

The Indosinian orogeny is a well-known thermal event responsible for the generation of the Darongshan S-type granitoids in southern China. Our data suggest that Indosinian activities could be equally important in SE China coastal area and there might be two stages in this orogenic event, i.e., ~245 and ~220 Ma. The latter group is particularly obvious in the cores of monazite from Chinmen. The Early Yanshanian movement (~160 Ma) that prevailed in the Cathaysia interior does not show a strong sign to extend to the coastal area. Severe Late Yanshanian overprints of the Indosinian (±Early Yanshanian) crusts, mainly occurred at ~140 Ma, are clearly represented in gneissic rocks of the CNSZ and are regarded as the onset of the Late Yanshanian magmatism.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.chemgeo.2006.01.023.

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