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Tectonophysics 320 (2000) 69–82

TECTONOPHYSICS

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Rates of cooling and denudation of the Early Penglai Orogeny, Taiwan, as assessed by fission-track constraints

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Received 15 June 1998; accepted for publication 14 January 2000

Abstract

As an attempt to define the timing of the peak temperature of the Penglai Orogeny and estimate the early cooling and denudation rates of the Taiwan mountain belt, fission-track dating of zircon and apatite was conducted on several key metamorphic rock samples. The zircon fission-track ages for the metasandstone clasts, collected from the central and northern parts of the Coastal Range, were determined as 4.0 ± 0.5 and 3.6 ± 0.3 Ma, respectively. Both of the clasts were identified as from the ancient Central Range which was metamorphosed at temperatures high enough to cause a complete reset of the zircon fission-track system. During 1–2 Ma, they were exhumed and deposited in the Coastal Range basin due to the later Penglai Orogeny of Taiwan. Obviously, they have not further been annealed since their deposition in the Coastal Range. The difference between the above fission-track ages and the stratigraphical age of the host sedimentary formation represent the ancient cooling ages when they were exposed on the early Central Range. These ancient cooling ages are comparable with the zircon fission-track age of a present-day outcrop of the Tananao Schist, 1.8 ± 0.2 Ma. This accordance implies that at ca. 5 Ma the northern and central parts of the Central Range achieved the peak temperature of the Penglai Orogeny and then they began to emerge above sea level. Accepting this scenario, we calculate the rates of denudation and cooling of the Central Range to be ca. 2.5–4.6 mm yr^{-1} and ~ 120°C $\mathrm{m.y.}^{-1}$, respectively, for the last 4 Ma.

Keywords: arc–continent collision; cooling rate; fission-track dating; Taiwan

1. Introduction

The mountain belt of Taiwan is one of the best examples in the world of active arc–continent collision (e.g. Biq, 1972, 1973; Chi et al., 1981; Suppe, 1981; Lo and Onstott, 1995). The Longitudinal Valley marks a portion of the suture between the Eurasian plate and the Philippine Sea plate (Fig. 1). The tectonostratigraphic belts from west to east are: the Coastal Plain; the Western Foothills; the western Central Range (including the Hsueshan Range and the Slate belt); and the eastern Central Range (the Tananao Schist) to the west of the Longitudinal Valley and the Coastal Range to the east. The first three belts comprise the Cenozoic cover strata and the fourth one, the Tananao Schist, is the underlying pre-Tertiary metamorphic basement. These all lie on the Asiatic continental margin. The Coastal Range is a Neogene magmatic arc with overlying sediments derived from the arc itself and the continental side.

The eastern Central Range is nearly 250 km in

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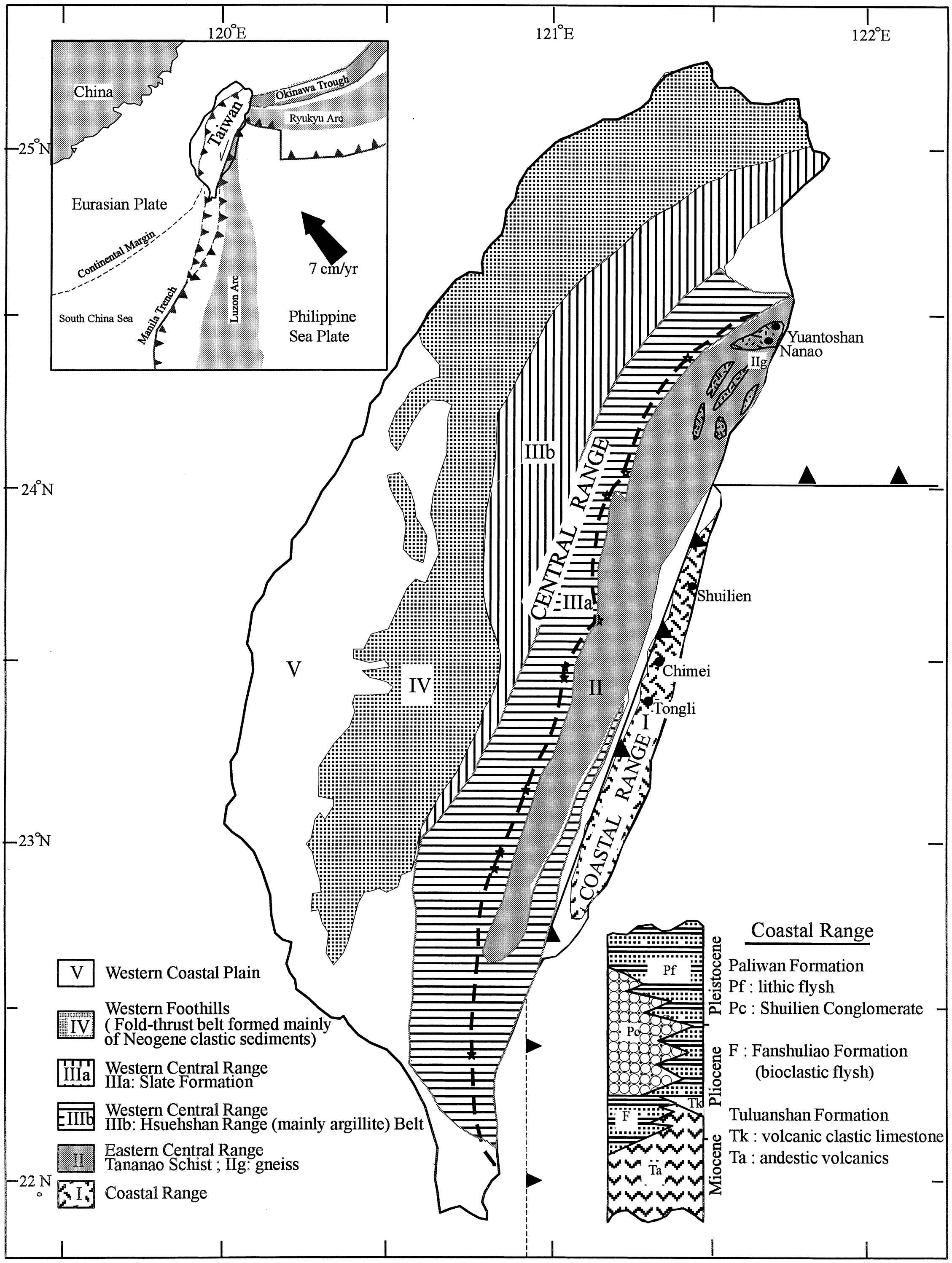
PII: S0040-1951(00)00028-7


120°E
121°E
122°E
25°N
24°N
23°N
22 N
China
Okinawa Trough
Ryukyu Arc
Taiwan
Eurasian Plate
Continental Margin
7 cm/yr
South China Sea
Manila Trench
Luzon Arc
Philippine
Sea Plate
Yuantoshan
Nanao
IIg
IIIb
CENTRAL RANGE
IIIa
II
Shuilien
Chimei
Tongli
I
COASTAL RANGE
V
IV
V Western Coastal Plain
IV Western Foothills (Fold-thrust belt formed mainly of Neogene clastic sediments)
IIIa Western Central Range IIIa: Slate Formation
IIIb Western Central Range IIIb: Hsuehshan Range (mainly argillite) Belt
II Eastern Central Range Tananao Schist ; IIg: gneiss
I Coastal Range
Coastal Range
Pleistocene
Pliocene
Miocene
Pf
Pc
Tk
F
Ta
Paliwan Formation
Pf : lithic flysh
Pc : Shuilien Conglomerate
F : Fanshuliao Formation
(bioclastic flysh)
Tuluanshan Formation
Tk : volcanic clastic limestone
Ta : andestic volcanics

length and from 10 to 30 km in width. The metamorphic complex is made up mostly of schists, metamorphosed limestone or marble, and scattered gneiss and amphibolite bodies exposed mainly in the northern part. All these metamorphic rocks are grouped under the general stratigraphic term 'Tananao Schist'. The overall metamorphic grade of the rocks is mainly greenschist facies and partly amphibolite facies. Some glaucophane schist bodies have been found on the southeastern part of this belt. Only a few deformed Permian fusulinids have been found in the limestone (Yen et al., 1951). The Tananao Schist have been subjected to several major or minor phases of deformation or metamorphism (Liou and Ernst, 1984). Two major episodes of metamorphism have been recognized. They are: (1) formation of late Mesozoic paired metamorphic belts (approximately 90 Ma); and (2) Plio-Pleistocene greenschist to amphibolite facies metamorphism. The metamorphic grade decreases westward from the Tananao Schist. It is the second and most important orogenic episode, called Penglai Orogeny, which affected the whole island and is responsible for the deformation, metamorphism and uplift of the Taiwan Island.

The sediments that were eroded in the early stages of the Penglai orogeny from the eastern flank of the uplifting Central Range were deposited in basins to the east. They were deformed and squeezed up along with the underlying volcanic basement by the collision to form the Coastal Range. Previous apatite and zircon fission-track studies on the samples collected from the present-day outcrops of the eastern Central Range have shown completely reset apatite ages ranging from 0.3 to 0.6 Ma and zircon ages from 0.9 to 2.0 Ma (Liu, 1982, 1986). According to the above literature, the effective track retention temperatures can be estimated as 135 ± 20 and 235 ± 20°C for apatite and zircon, respectively. Further, assuming a geothermal gradient of 30°C km^{-1} for the last 2 Ma, cooling rates of ~130–260°C $\mathrm{m.y.}^{-1}$, corresponding to an uplift of 4.9–8.9 mm yr^{-1}, have also been calculated.

In spite of a large number of K–Ar, Rb–Sr and $^{40}\mathrm{Ar}/^{39}\mathrm{Ar}$ ages for the metamorphic rocks (Yen and Rosenblum, 1964; Juan et al., 1972; Juang and Bellon, 1986; Jahn et al., 1986; Lan et al., 1990; Lo and Onstott, 1987, 1995), the timing of peak temperature and the early cooling rate of the Penglai Orogeny remained poorly known. The major reason is that these isotopic systems commonly exhibit complicated ages due to mixing or partial resetting by the late Tertiary–Quaternary Penglai Orogeny which followed the main metamorphic event during the late Mesozoic Nanao Orogeny (Lo and Onstott, 1995). For example, in the lower greenschist facies area, hornblendes and coarse-grained muscovites still retain most of their radiogenic argon and display fairly flat $^{40}\mathrm{Ar}/^{39}\mathrm{Ar}$ age spectra with plateau dates of 82–95 Ma which record a cooling during the late Mesozoic tectonothermal event of the Nanao Orogeny. In contrast, all microclines which has $^{40}\mathrm{Ar}/^{39}\mathrm{Ar}$ closure temperature at ca. 240–250 °C are completely reset and yield young plateau dates of 1.6–1.7 Ma. Most of the partially reset minerals (e.g. muscovite from the upper greenschist facies area and biotite from the lower greenschist facies area) yield geologically meaningless $^{40}\mathrm{Ar}/^{39}\mathrm{Ar}$ integrated dates that fall between the ages of the two tectonothermal events.

On the other hand, the fission tracks in the zircons separated from submetamorphosed Paleogene sandstones of the western Central Range (i.e. the Hsueshan Range) have undergone varying degrees of annealing during the Penglai Orogeny as was indicated by fission-track grain age distribution relative to their respective stratigraphic ages (Liu, 1988). Zircon grains from each completely reset sample show a restricted range of ages, the mean of which can be used to define a cooling age for each individual sample. The cooling ages obtained fell in the range of 4–5 Ma, implying much lower cooling (~50°C $\mathrm{m.y.}^{-1}$) and erosion

Fig. 1. General tectonic and geological map of Taiwan showing geologic provinces (after Ho, 1975), stratigraphic column of the Coastal Range (after Teng, 1982 lower left inset) and sample localities. The line connecting the star symbols, which represent the main summits, denotes the major divide of the island.

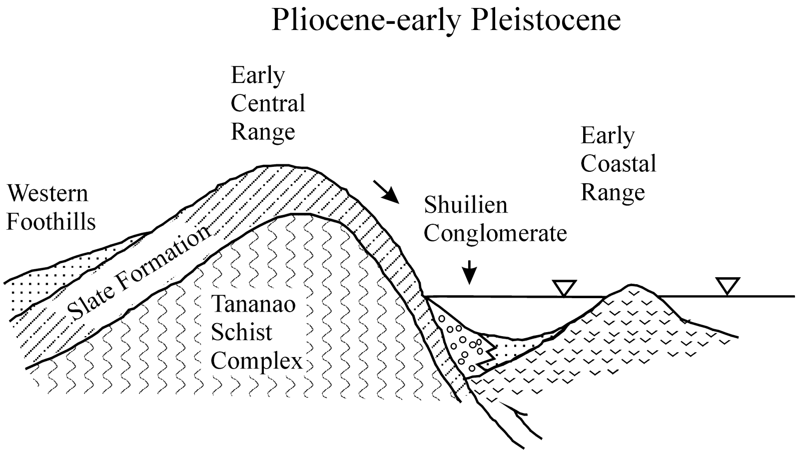


Fig. 2. Schematic diagram of the deposition of the Shuilien Conglomerate and the geologic configuration of its source terrain (modified from Teng, 1982).

rates (~1.7 mm yr^{-1}) than the eastern Central Range. For the samples collected from the lower temperature margin of the completely reset terrain, their cooling ages can also be regarded as the timing for the peak metamorphic temperature attained.

The Shuilien Conglomerate (Chi et al., 1981; Teng, 1982) is a lithologically distinct stratigraphic unit exposed in the northern Coastal Range. Its framework clasts are mainly composed of metasandstone, slate, and vein quartz, with minor ophiolitic rocks. Some clasts reach >1 m in diameter, implying that the adjacent early Central Range (eastern flank) was the principal source terrain (Fig. 2). The Conglomerate started to deposit at about the base of NN16 (Chi et al., 1981) which is chronologically equivalent to 3.0 ± 0.5 Ma as inferred by paleomagnetic results (Lee et al., 1991). This paper will demonstrate that this formation has not been heated to a high temperature and the zircon fission-track ages of its constituent metasandstone clasts provide constraints on the early history of the orogeny.

2. Samples and experimental methods

For the purpose of understanding recent tectonic activity of the Central Range, rock sample were collected from the Yuantoshan gneiss body of the Tananao Schist (Fig. 1), and from metasandstone boulders in the Shuilien Conglomerate. The boulders themselves were well recrystallized as indicated by quartz veinlets, interlocking grain boundaries, and the preferred orientation of mineral grains observed under the microscope. In order to detect the thermal influence induced by the Penglai Orogeny for the Coastal Range, a sample rich in apatite was also collected from a large exotic amphibolite block in the Lichi mélange of the Coastal Range.

Zircons were separated in the usual manner. Euhedral to subhedral grains were selected and aligned with one of their flat prismatic external surfaces of each individual sitting on glass slides under a binocular reflective microscope. They were then mounted parallel to their c-axis in PFA (perfluoralkoxyethylene) teflon sheets, which in turn were carefully ground with fine calcite powders until a natural external prismatic surface of each crystal was exposed and the two pyramid ends of crystals were still embedded in the PFA sheets. Because the hardness of calcite (Mohs scale = 3) is greater than that of PFA teflon but much less than that of zircon (Mohs scale = 7.5), this method can render a flush contact between zircon prismatic surfaces and mica detectors and give a 2π geometry for fossil track densities. There are two additional advantages as compared with the conventional '4π' method. (1) The '2π' method is better in preventing zircon grains from falling off the PFA sheets; and (2) the spontaneous and the induced track densities were measured in the same 2π geometry and for the same uranium contents. Common rock-forming minerals are very low in uranium content as compared with zircon. Hence the number of tracks registered on the external surfaces of zircon due to neighboring common rock-forming minerals is negligible. Zircons were etched with a mixture of NaOH, KOH, and $\mathrm{LiOH \cdot CH_2O}$ (6:14:1 mol%; Zaun and Wagner, 1985) at 200±5°C for 30±5 h until the weakest tracks, usually those parallel to the c-axis (Gleadow, 1981), were clearly revealed. Track counting was conducted using a magnification of 2500 under oil immersion. 'Grain-by-grain' and mica external detector techniques were adopted to obtain individual grain ages.

Apatites were dated by the commonly used 'population method' (Naeser, 1967) whereby apatite concentrates were divided into two parts, one was mounted in epoxy disc and polished to expose internal grain surfaces (i.e. 4π geometry) for measuring fossil track density (ρ_s). The other was annealed at 550°C for 2 h (Fleisher et al., 1975), mounted, irradiated, polished, and etched for induced track density (ρ_i). At least two pieces of standard glass NBS SRM-610 or SRM-612, which have been calibrated against the proposed fission-track age standard — Fish Canyon Tuff (Naeser et al., 1981) were wrapped tightly and irradiated with samples. The zeta (ζ) values (Hurford and Green, 1983) for the standard glass SRM-612 and SRM-610 were evaluated to be 340±12 (1σ) and 27.5±1.0 (1σ), respectively. The former is comparable to the value of 339±10 (2σ) by Hurford and Green (1983) and 342.1±6.2 (2σ) by Tagami (1987).

Fission-track grain ages were calculated using the equation:

$$T_{\mathrm{unk}} = \frac{1}{\lambda_d} \ln\left[1 + \left(\frac{\rho_s}{\rho_i}\right)\lambda_d \rho_d \zeta\right]$$

where λ_d is the total decay constant of uranium ($1.551 \times 10^{-10}\ \mathrm{yr}^{-1}$), and ρ_d is the detector track density from the standard glass dosimeter (tracks per cm^2). Uncertainties in ages were calculated from the Poisson uncertainties in N_s, N_i, N_d and ζ value in the manner described by Green (1981). The final fractional uncertainty in grain age T is:

$$\frac{\sigma(T)}{T} = \left\{\left[\frac{\sigma(N_s)}{N_s}\right]^2 + \left[\frac{\sigma(N_i)}{N_i}\right]^2 + \left[\frac{\sigma(N_d)}{N_d}\right]^2 + \left[\frac{\sigma(\zeta)}{\zeta}\right]^2\right\}^{\frac{1}{2}}$$

where N_s and N_i denote the number of counts of spontaneous and induced tracks, respectively, in each crystal and N_d is the count induced by the standard glass dosimeter and registered on a mica detector.

3. Results and tectonic implications

The fission track data are presented in Tables 1–4. The radial plots as described by Galbraith (1990) and histograms for the zircon grain ages were displayed in Fig. 3. The positive correlation between fossil track densities (ρ_s) and induced track densities (ρ_i) implies that variations in the grain-age population for each rock sample are mainly due to the variations in the uranium content between different grains. All sample ages are calculated using the ZETAAGE program v. 4.5 (Brandon, 1996). Both the Yuantoshan gneiss from the Tananao Schist Complex and the metasandstone clast from Shuilien pass the χ^2-test at 5% and each is judged to define a single population. The mean ages (1.8±0.2 and 4.2±0.5 Ma, respectively) were assigned as representative ages for the two samples. On the other hand, the statistical parameters of the metasandstone clast from Chimei slightly fail in the χ^2-test at 5%. In this case, the central age was calculated from the logarithmic mean of the individual fission-track density log (ρ_s/ρ_i) (Galbraith and Laslett, 1993; Andriessen and Zeck, 1996), and 3.6±0.3 Ma is assigned instead of the mean age (3.8±0.5 Ma). Actually, all the mean ages of the three samples are not that different from their respective central ages.

The stratigraphic ages of the low-grade metamorphosed sedimentary rocks in the Central Range are Paleocene–Miocene, that is, 65 to 7 Ma. Their constituent detrital sediments were derived

Table 1
Results of fission track dating for detrital zircon grains extracted from a metasandstone boulder of the Shuilien Conglomerate at the Shuilien village[a]

Crystal	$\rho_s/10^6$ (tracks cm^{-2})	N_s	G_s ($=G_i$)	$\rho_i/10^6$ (tracks cm^{-2})	N_i	$\rho_d/10^5$ (tracks cm^{-2})	N_d	Age ± 1σ (Ma)	U ± 1σ (ppm)
1	0.044	7	360	1.42	227	1.32	3741	1.4 ± 0.5	132 ± 9
2	0.282	10	80	3.04	108	1.32	3741	4.1 ± 1.4	283 ± 28
3	0.386	12	70	5.18	161	1.32	3741	3.3 ± 1.0	482 ± 39
4	0.809	14	39	7.39	128	1.32	3741	4.9 ± 1.4	688 ± 62
5	0.196	6	69	2.64	81	1.32	3741	3.3 ± 1.4	246 ± 27
6	0.788	21	60	6.12	163	1.32	3741	5.8 ± 1.3	570 ± 46
7	0.631	14	50	4.46	99	1.32	3741	6.3 ± 1.8	415 ± 43
8	0.601	8	30	5.86	78	1.32	3741	4.6 ± 1.7	545 ± 63
9	0.135	3	50	3.02	67	1.32	3741	2.0 ± 1.2	281 ± 35
10	0.451	10	50	5.59	124	1.32	3741	3.6 ± 1.2	520 ± 48
11	0.413	11	60	6.19	165	1.32	3741	3.1 ± 0.9	577 ± 46
12	0.135	3	50	1.13	25	1.32	3741	5.4 ± 3.3	105 ± 21
13	0.225	5	50	1.35	30	1.32	3741	7.5 ± 3.6	126 ± 23
Mean age								4.2 ± 0.4	
Central age								4.0 ± 0.5	
Age dispersion								24	
Pooled age								3.8 ± 0.4	
χ^2								18	
P (χ^2)								11	
Degree of freedom (df)								12	
Stratigraphic age of the clast in the Coastal Range								2.5–3.4	
Inferred ancient cooling age when the sample was exposed on the Central Range								1.8–0.9	

[a] ρ_s, spontaneous track density; N_s, N_i and N_d, number of tracks actually counted to determine the reported track density (2π geometry); ρ_i, induced track density from sample zircon grain; ρ_d, detector track density from the standard glass dosimeter NBS SRM-612; G_s and G_i, number of grids counted for fossil and induced tracks, respectively; 1 grid $= 4.44 \times 10^{-7}$ cm^2.

from the pre-Tertiary (>65 Ma) source rocks in southeastern China (Jahn et al., 1976). All the fission-track ages for detrital zircons from the unmetamorphosed stratigraphically equivalent strata in the Western Foothills are also greater than 65 Ma (Liu, 1988). Fig. 3 shows the measured temporal relationship among the fission-track grain ages, the possible depositional ages and the minimum cooling ages of pre-metamorphic source rocks for the detrital zircon grains. All the zircon fission-track ages for the Yuantoshan gneiss and the two clast samples from the Shuilien Conglomerate are very young and have a narrow range in grain ages as compared with their pre-metamorphic provenence rock ages. Evidently, the zircon fission-track clock for the metasandstones was completely reset by the Penglai Orogeny before the metasandstones were eroded from the Central Range and deposited as the Shuilien Conglomerate.

In contrast, the clastic sedimentary rocks of the Fanshuliao Formation, Shuilien Conglomerate and Paliwan Formation overlying the volcanic basement of the Tuluanshan Formation (Fig. 1) of the Coastal Range terrain were not subjected to a temperature high enough to cause partial annealing of the fission tracks in zircon after deposition. This conclusion is supported by fission-track thermochronological studies on apatites from the Coastal Range. The oldest core of the Coastal Range is formed of Miocene andesitic rock complex (the Tuluanshan Formation) which is composed of lava flows, agglomerates, tuffs and associated volcanogenic sediments. Apatite fission-track ages for the hydrothermally altered andesitic complex at Chimei fall in the range from 15 to

Table 2
Results of fission track dating for detrital zircon grains extracted from a metasandstone sample of the Shuilien Conglomerate at Chimei village[a]

Crystal	$\rho_s/10^6$ (tracks cm^{-2})	N_s	G_s $(=G_i)$	$\rho_i/10^6$ (tracks cm^{-2})	N_i	$\rho_d/10^5$ (tracks cm^{-2})	N_d	Age ± 1σ (Ma)	U ± 1σ (ppm)
1	0.48	38	178	5.88	465	0.132	3741	3.7 ± 0.6	548 ± 27
2	0.48	25	118	5.67	297	0.132	3741	3.7 ± 0.8	528 ± 33
3	0.29	36	280	4.84	602	0.132	3741	2.7 ± 0.5	451 ± 20
4	0.42	26	138	4.06	249	0.132	3741	4.7 ± 1.0	378 ± 25
5	0.05	1	50	1.31	29	0.132	3741	1.5 ± 1.6	122 ± 23
6	0.55	19	78	7.57	262	0.132	3741	3.2 ± 0.8	704 ± 45
7	0.71	22	70	8.11	252	0.132	3741	3.9 ± 0.9	755 ± 50
8	0.20	9	100	1.62	72	0.132	3741	2.8 ± 0.9	151 ± 18
9	0.39	7	40	2.76	49	0.132	3741	6.4 ± 2.6	257 ± 37
10	0.38	10	60	5.63	150	0.132	3741	3.0 ± 0.9	524 ± 44
11	0.23	3	30	1.73	23	0.132	3741	5.8 ± 3.6	161 ± 33
12	0.23	5	49	5.61	122	0.132	3741	1.8 ± 0.8	522 ± 49
13	0.09	2	52	2.56	59	0.132	3741	1.5 ± 1.1	238 ± 31
14	0.49	13	60	7.39	197	0.132	3741	3.0 ± 0.8	688 ± 51
15	0.47	5	24	5.16	55	0.132	3741	4.1 ± 1.9	481 ± 65
16	0.23	5	50	5.86	130	0.132	3741	1.7 ± 0.8	545 ± 49
17	0.23	4	40	1.18	21	0.132	3741	8.5 ± 4.6	110 ± 24
18	0.45	14	70	4.31	134	0.132	3741	4.7 ± 1.3	401 ± 35
19	0.83	7	19	7.11	60	0.132	3741	5.2 ± 2.1	562 ± 86
Mean age								3.8 ± 0.5	
Central age								3.4 ± 0.3	
Age dispersion								21	
Pooled age								3.3 ± 0.3	
χ^2								30	
P (χ^2)								3.8	
Degree of freedom (df)								18	
Stratigraphic age of the clast in the Coastal Range								1.0–1.7	
Inferred ancient cooling age when the sample was exposed on the Central Range								2.8–2.1	

[a] See footnote to Table 1.

17 Ma (Yang et al., 1988). Overlying the volcanic rocks is a series of clastic sedimentary units including the Lichi Formation. This formation is a chaotic and non-stratified, muddy to clayey formation containing many exotic blocks of different sizes, ages and lithologies (Hsu, 1976) emplaced during the Penglai Orogeny. Two of the exotic amphibolite blocks of ophiolitic clan yield apatite fission-track ages of ca. 11 Ma (Table 4). All the above-mentioned apatite ages are much older than the timing (~5 Ma) of the peak temperature induced by the Penglai Orogeny. This implies that

Table 3
Results of fission track dating for apatite extracted from two large exotic amphibolite blocks of the Lichi Melange at Tongli[a]

Sample No.	ρ_s(tracks cm^{-2})	N_s	G_s	ρ_i (tracks cm^{-2})	N_i	G_i	ρ_d (tracks cm^{-2})	N_d	Age ± 1σ(Ma)
CLW-12	4.56×10^3	126	1079	2.46×10^5	501	154	1.64×10^6	5556	11.2 ± 1.5
CLT-50	1.31×10^4	190	594	7.40×10^5	1391	66	1.64×10^6	5556	10.8 ± 1.3

[a] See footnote to Table 1; standard glass dosimeter used was NBS SRM-612.

Table 4
Zircon fission track analytical data for Yuantoshan geniss from the Tananao Schist Complex of the Central Range[a]

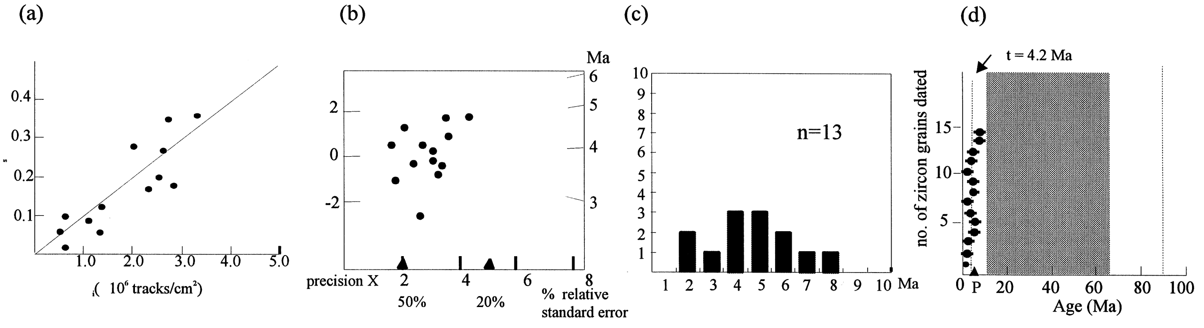
Grain No.	$\rho_s/10^5$ (tracks cm^{-2})	N_s	$G_s(=G_i)$	$\rho_i/10^6$ (tracks cm^{-2})	N_i	$\rho_d/10^6$ (tracks cm^{-2})	Age ± 1σ (Ma)	U ± 1σ (ppm)
1	3.2	58	408	9.93	1801	2.47	2.2 ± 0.3	605 ± 18
2	3.51	49	315	11.4	1602	2.47	2.1 ± 0.3	697 ± 24
3	2.97	37	280	11.7	1450	2.47	1.7 ± 0.3	710 ± 23
4	7.45	129	390	20.9	3620	2.47	2.4 ± 0.3	1272 ± 33
5	2.48	16	146	14.1	313	2.47	1.2 ± 0.3	146 ± 33
6	1.98	17	194	8.53	379	2.47	1.6 ± 0.4	194 ± 22
7	2.25	33	329	9.38	417	2.47	1.6 ± 0.4	571 ± 19
8	2.25	33	329	9.05	893	2.47	1.7 ± 0.3	551 ± 19
9	1.98	15	140	11.3	504	2.47	1.2 ± 0.3	170 ± 27
10	1.98	15	140	10.9	871	2.47	1.2 ± 0.3	170 ± 26
11	3.08	39	285	9.77	781	2.47	2.2 ± 0.4	595 ± 20
12	1.17	17	326	6.43	571	2.47	1.3 ± 0.4	326 ± 15
13	6.98	62	200	24.3	270	2.47	2.0 ± 0.3	1480 ± 43
14	1.94	31	360	13.5	567	2.47	1.8 ± 0.3	823 ± 29
15	2.09	28	300	7.23	546	2.47	2.0 ± 0.4	300 ± 16
16	3.67	18	110	14.8	329	2.47	1.7 ± 0.5	110 ± 38
17	2.34	27	260	8.66	462	2.47	1.8 ± 0.4	527 ± 20
18	5.47	101	415	17.9	915	2.47	2.1 ± 0.2	1090 ± 29
Mean age							1.8 ± 0.2	
Central age							1.8 ± 0.2	
Age dispersion (%)							15.9	
χ^2 age							1.8 ± 0.2	
Pooled age							1.9 ± 0.2	
χ^2							5.0	
Degree of freedom (df)							17	
Stratigraphic age of the pre-metamorphic rock							> 90	

[a] See footnote to Table 1; standard glass dosimeter used was NBS SRM-610.

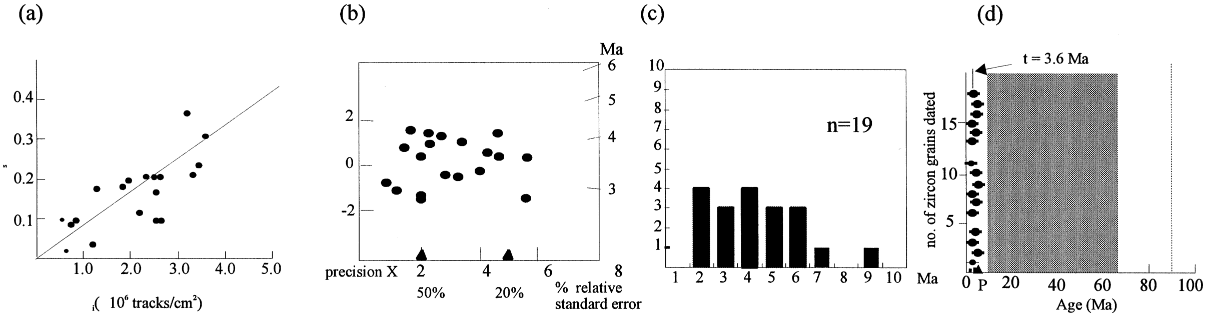
the clastic sediments of the Coastal Range have not experienced a temperature which can completely reset the apatite fission-track system, not to say a temperature for the resetting of zircon. The zircon fission-track ages obtained thus undoubtedly represent the total time elapsed since they passed effective closure temperature during their exhumation.

The depositional age of the Shuilien Conglomerate has been well documented by paleontological and paleomagnetic studies (Chang, 1968; Chi et al., 1980, 1981; Lee and Chi, 1990; Lee et al., 1991). Nannofossils indicative of NN 16–18 and formanifera of N21 from Shuilien and of middle NN19 from Chimei correspond to depositional ages of 3.0 ± 0.1 and 1.0 ± 0.1 Ma, respectively. The amount of time needed to exhume the metasandstones from the Central Range can be estimated by substracting their depositional ages mentioned above in the Coastal Range from respective zircon fission track ages, that is, 4.2 ± 0.5 and 3.6 ± 0.3 Ma measured today. The resulting time is ca. 1.2–2.6 m.y., both of which are close to the zircon fission-track ages 1.0 ~ 2.0 Ma of the present Tananao Schist in the eastern flank of the Central Range. The consistence of the ancient and the present zircon fission-track dates implies steady exhumation and cooling rates since ~4Ma, suggesting that the Central Range achieved its steady-state form shortly after initial emergence above sea level ca. 5 Ma. This inferrence is in good agreement with the conclusion obtained from the analysis of the mechanics of mountain building in Taiwan (Suppe, 1981). Due to the continued

(A) Shuilien



(B) Chimei



(C) Nanao

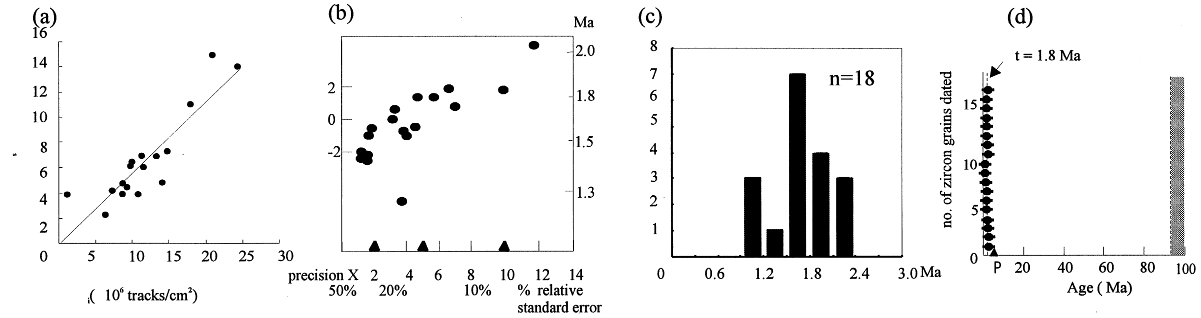


Fig. 3. Graphic presentations of the analytical results for the zircon samples from the Shuilien Conglomerate at (A) Shuilien village and (B) Chimei village, and from (C) Yuantoshan gneiss at Nanao. (a) ρ_s versus ρ_i plot, (b) radial plot, (c) single-grain age histogram, (d) relationship between fission-track zircon grain ages (bold dots with 1σ bars), stratigraphic age range (shaded area) of the pre-metamorphic parental sandstones, and the lower age limit (dotted line) of provenance rocks for the detrital zircons.

oblique arc–continent collision, the mountain belt grows steadily wider and higher until the central part (i.e. the segment of the Tananao Schist) has been a region of constant and steady state topography. The rate of the growth of the Taiwan mountain belt due to plate-boundary compression equal the rate of erosion. It has been shown by Suppe (1981) that the Tananao Schist attained steady-state topographic form in ca. 1 and 1/3 m.y. after initial emergency of the Taiwan mountains. In other words, the erosion and cooling rates of the Tananao Schist had been the same as present at ca. 3 and 2/3 Ma. This inference is in good agreement with that obtained from zircon fission-track ages stated above.

In the northern Tananao Schist, the cooling rate estimated from the pair of zircon and apatite fission-track ages (0.9 and 0.3 Ma, respectively; Liu, 1982) and their general closure temperatures (~220–235 and ~110–135°C, respectively) was ca. 160°C m.y.$^{-1}$ Accordingly, the closure temperature of ~240°C can be adopted for zircons from the Tananao Schist as compared with the values given by Wagner and Reimen (1972), Haack (1977), Gleadow and Brooks (1979), Zaun and Wagner (1985), Hurford (1986) and Brandon and Vance (1992).

Brandon et al. (1998) pointed out that a rapid erosion rate causes isotherms to move towards the surface but also induces a faster rate of cooling so that closure occurs at a higher temperature. The average exhumation rate is determined by dividing the closure depth by the fission-track age. Here we take a simplified way to estimate average exhumation rate of the Tananao Schist. Present-day local thermal gradients measured in geothermal wells in the northern Tananao Schist area are ca. 55°C km^{-1} (Lee and Cheng, 1986), which can be taken as the upper limit of the regional thermal gradients for the Tananao Schist. On the other

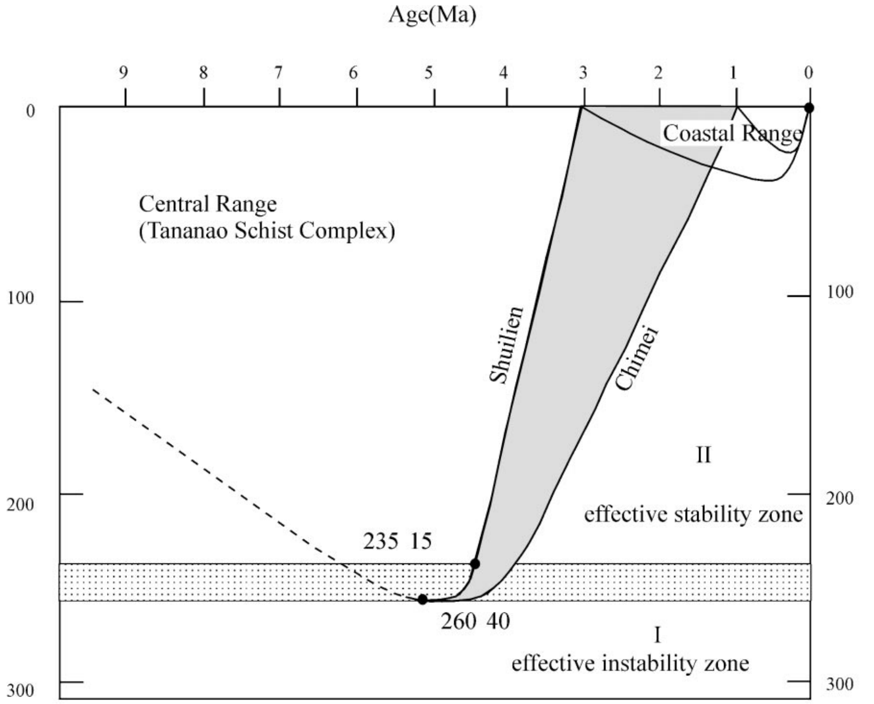


Fig. 4. Schematic thermal history of metasandstone boulders in the Shuilien Conglomerate. The temperature axis is divided into two zones according to the stability of the fission-tracks in zircon. The lightly shaded area show the transitional temperature range between the zones. The heavily shaded area represent the *T–t* paths for the present metasandstone samples in the Shuilien Conglomerate.

hand, the thermal gradient of 30°C km^{-1} for the Western Foothills (Suppe and Witte, 1977) can be considered as the lower limit. The average thermal gradient for this area as a whole is thus estimated at 42°C km^{-1} by interpolation. With the above-mentioned closure temperature (~240°C) and the thermal gradient (~42°C km^{-1}), the zircon ages of 1.0-2.6 Ma for the Tananao Schist suggest erosion rates of ca. 2.3~6.0 mm yr^{-1}. The upper bound of this range is close to the modern erosion rate (5.5 mm yr^{-1}) determined by sediment yield data (Li, 1976), while the lower bound equals approximately to the value (2.5–3.5 mm yr^{-1}) calculated by the method described by Brandon et al. (1998).

Based on fluid inclusion studies of quartz from similar rock types, the peak temperature attending the metamorphism of the metasandstones was estimated to be 260±40°C (Tan and Wang-Lee, 1977). The approximation of zircon fission-track closure temperature to the peak metamorphic temperature implies that the timing of peak temperature of the Penglai Orogen was only slightly older than 4.3 Ma and agrees well with the inference of 5 Ma from fission track studies on the Hsuehshan Range (Liu, 1988). If regional cooling could be

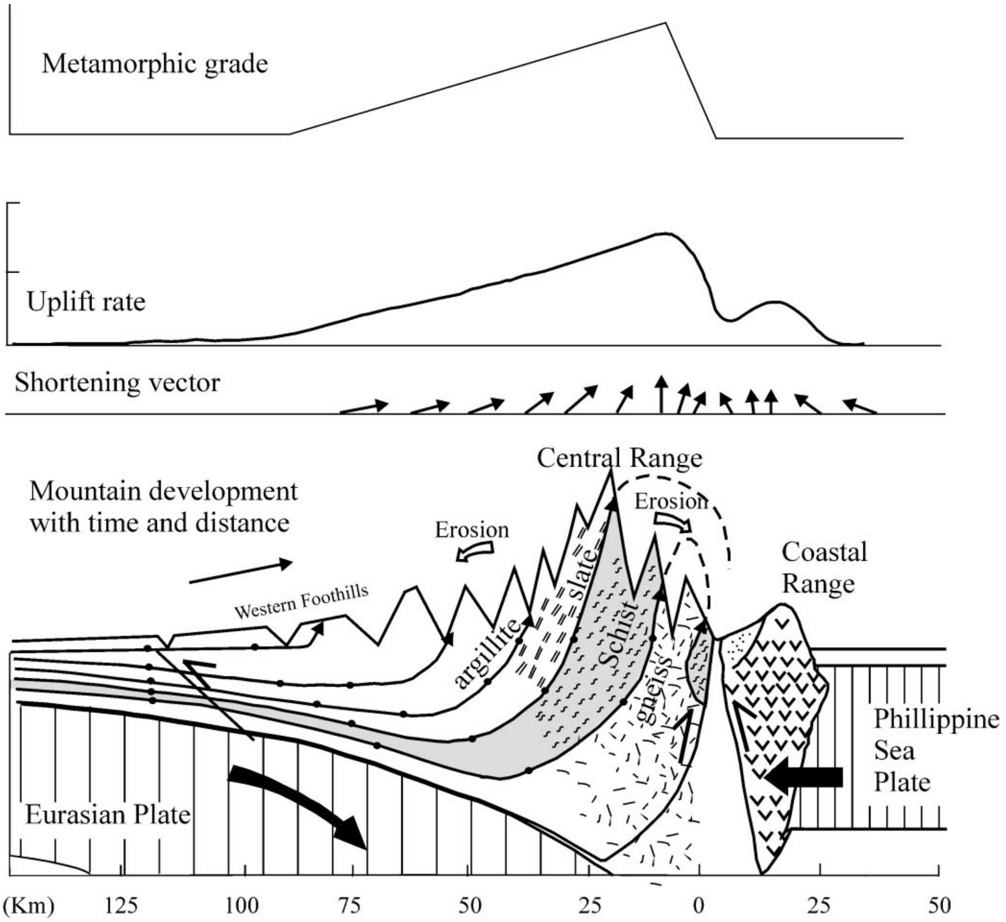


Fig. 5. Schematic geologic cross-section of present-day central Taiwan. The lines connecting the dots (●), which denote progressive equal-time positions of points initially aligned vertically are material trajectories (travelling paths) of rocks now occurring on the surface.

attributed to large-scale erosion, then the age of ca. 5 Ma could also mark the timing when the Taiwan Mountain belt began to emerge above sea level. Fig. 4 shows the entire thermal history of the metasandstone clasts found in the Shuilien Conglomerate.

It is worthy mentioning that the zircon fission-track ages obtained previously for the present metasandstone outcrops of the Hsueshan Range are ca. two to five times of the zircon cooling ages of the early or present eastern Central Range. This implies that the rates of uplift-exhumation-cooling for the rear (eastern) and frontal (western) flanks of the Taiwan accretionary wedge have been distinctly asymmetrical since the beginning of the Penglai Orogeny. Fig. 5 shows schematic illustrations of the present-day geological profile and associated metamorphic grade and uplift rate. Two points are worthy to mention. First, the suture of the two converging plates, that is, the Longitudinal Valley, is bounded by two high- angle thrust faults. Second, the metamorphic grade of surface rocks generally increases eastward but the highest grade rocks are exhumed in the orogen interior at high elevation of the rear flank (retro-wedge) instead of the frontal flank (pro-wedge) as considered by Willett et al. (1993). Actually, there is no remarkable difference in modern annual mean precipitation (2700–2900 mm yr^{-1}) between both flanks of the Taiwan Orogen (WRPC, 1995). In the sense of orographically controlled precipitation and its effect on the exhumation rate, the Taiwan Orogen can be considered as transitional between the two extreme models proposed by Willett et al. (1993), which result from a wet, rapidly denuded, windward side and a dry side with little erosional denudation.

4. Conclusions

The fission tracks in the detrital zircons extracted from metasandstone boulders in the Shuilien Conglomerate had been completely reset before the rocks were exposed on the Central Range during the early stage of the Penglai Orogeny. After having been deposited in the basin of the Coastal Range, they have remained at temperatures less than the annealing temperature of apatite. The zircon fission-track ages obtained at present are ~4.2–3.6 Ma. Their zircon cooling ages at the time of deposition of the Shuilien Conglomerate (1.2–2.6 m.y.) are basically the same as that determined for the Tananao Schist (1–2 Ma) presently exposed on the eastern flank of the Central Range. Both results demonstrate rapid erosion associated with the Penglai Orogeny. The Central Range, at least its central and northern parts, had already reached the peak metamorphic temperature of the Penglai Orogeny at ca. 5 Ma. Subsequent cooling of the rear flank at an average rate of ~120 °C $\mathrm{m.y.}^{-1}$ for the last 4 m.y. is attributed to rapid large-scale erosional exhumation.

Acknowledgements

The authors are grateful to Professor Y. Wang for comments on early version of the manuscript. Critical reviews by Drs M.T. Brandon and P.A.M. Andriessen helped sharpen the presentation and focus of this paper. This study was supported by the National Science Council of the Republic of China under Grant No. NSC72-0202-M02-03.

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