Available online at www.sciencedirect.com
ScienceDirect

ELSEVIER

Earth and Planetary Science Letters 252 (2006) 413–422

EPSL

www.elsevier.com/locate/epsl

Mountain building mechanisms in the Southern Central Range of the Taiwan Orogenic Belt — From accretionary wedge deformation to arc–continental collision

Yuan-Hsi Lee [a,*], Chien-Chi Chen [a], Tsung-Kwei Liu [b], Hsin-Cheng Ho [c], Hsueh-Yu Lu [a], Wei Lo [d]

[a] *Department of Earth and Environment Sciences, National Chung-Cheng University, 168 University RD. San-Hsing, Min-Hsiung Chia-Yi ,Taiwan, ROC*
[b] *Department of Geoscience, National Taiwan University, P.O. Box 13-318, Taipei 106, Taiwan, ROC*
[c] *Central Geological Survey, MOEA, P.O. BOX 968, Taipei, Taiwan, ROC*
[d] *Department of Materials and Mineral Resources Engineering, Taipei, National Taipei University of Technology, 1, Sec. 3, Chung-Hsiao E. Rd. Taipei 106, Taiwan, ROC*

Received 31 May 2006; received in revised form 29 September 2006; accepted 30 September 2006
Available online 15 November 2006
Editor: R.W. Carlson

Abstract

Most researches consider the Taiwan Orogeny to be the result of an oblique arc–continental collision between the Philippine Sea Plate and Eurasia Plate. According to kinematic modeling, the mountains started to build from the north and progressively propagated southward at a rate of 60–90 km/my. Because of the oblique nature of the collision, the influence of the collision on mountain building resulted in the southern Central Range experiencing orogenic processes more recently than in the north. In order to test this model, we studied a critical area using zircon and apatite fission-track data to reveal the early exhumation history of the southern Central Range. We find that exhumation started about 6 Ma, which is earlier than the previously predicted timing of mountain building. We also find that the exhumation history can be separated into two stages: an initial stage starting at ca. 6 Ma and continuing to ca. 1 Ma with a slow uplift rate of <1 mm/yr; and a second stage starting at ca. 1 Ma until the present with a high uplift rate of 4–10 mm/yr. The initial stage of mountain building is considered to be related to accretionary wedge deformation as the South China Sea Plate subducted beneath the Philippine Sea Plate whereas the second stage mountain building resulted from the arc–continental collision. Combining the ages of isotopic dating and fission-track dating in the northern Central Range, we find that the northern Central Range also could start exhumation at ca. 6 Ma and that its exhumation history can also be separated into two stages with similar exhumation patterns and mechanisms to that of the southern Central Range. The most notable difference between the exhumation history of the northern and southern areas of the range is the more extensive degree of exhumation in the north; this could be attributed to the northern Central Range having experienced a longer collision history.

Keywords: Taiwan orogeny belt; Fission-track dating; Arc–continental collision; Accretionary wedge deformation

---

[*] Corresponding author.
E-mail address: seilee@eq.ccu.edu.tw (Y.-H. Lee).

doi:10.1016/j.epsl.2006.09.047

1. Introduction

Most researches consider Taiwan Orogeny to be the result of an oblique collision between the Luzon arc and the passive continental margin of the Eurasia plate. The Luzon arc trends N–S on the Philippine Sea plate and the Eurasia continental margin is NE trending. The Philippine Sea plate moves NW at 7–8 cm/yr (e.g., [1]) resulting in a collision starting in the north and progressively propagating southward (e.g., [2–5]). According to different geometric boundary conditions, different researches have concluded varying rates of southern propagation from 60–90 km/my (e.g., [2,6,7]) (Fig. 1). In addition, different kinematic modeling has given different estimates of the timing of the arc–continental collision; these are as follows: 2–3 Ma for Malavieille et al., (e.g., [8]), 4 Ma for Suppe (e.g., [3]), 5–3 Ma for Teng (e.g., [9]), 6–4 Ma for Barrier and Angelier (e.g., [10]) and Hwang et al., (e.g., [5]). However, regardless of the variety of estimates in the southern propagation rate and timing of the collision all these models indicate the southern Central Range of Taiwan starting its collision and mountain building more recently than the northern range. The seismological data show the collision occurring to the north of Taitung and the South China Sea Plate subducting the Philippine Sea Plate to the south of Taitung (e.g., [11,12]) (Fig. 1). By contrast, Lin and Watts (e.g., [13]) found the initial timing of the foreland basin's development to be ca. 6.5 Ma from the north to south of Taiwan. The development of the foreland basin results from the load on the orogenic belt. Consequently, the age of the foreland basin can also indicate the timing of mountain building. Their study shows the initial timing of mountain building is roughly the same from north to south.

In order to reveal the cooling and exhumation history, we use a low temperature thermochronometry method, zircon fission-track dating, to reveal the initial timing of mountain belt formation. Whilst a good deal of zircon fission-track dating has been done previously on Taiwan orogenic belt, most of the dating has concentrated on the mid-part of the Central Range (e.g., [7,14]). The mid-part of the Central Range is in a steady-state of exhumation, and hence zircon fission-track-data ages range from 1.5–3 Ma (e.g., [15,16]) and the initial timing of mountain building cannot be inferred from this data (e.g., [17]). In the southernmost region of the Central Range, the metamorphic grade progressively decreases from north to south, from green-schist facies to prehnite–pumpellyite facies, and then to zeolite facies and the strata are also progressively younger from north to south (e.g., [18]) (Figs. 2 and 5). In order to conduct our study an appropriate study area, where zircon fission tracks had been totally reset, needed to be determined; and this area would be near the boundary of total reset and partial reset of zircon fission tracks. For such an area, the total exhumation amount should not be too large and zircon fission-track aging could record the oldest reset ages and reflect closely the timing of initial uplift. As a result, we chose the transect from Sandiman to Taimali, an expanse located near the southern boundary of the total reset area for zircon and where metamorphic grade is of low green-schist face, which is only slight higher than the reset temperature of zircon, 235±20°(e.g., [18]).

2. Geological background, samples, and experimental methods

In the Central Range of Taiwan, the strata are composed of a Pre-Tertiary metamorphic complex (Tananao Schist), which experienced its first metamorphism to amphibolite facies ca. 90 Ma, and a thick cover sequence of Cenozoic clastic sediments derived from pre-Tertiary granitic rocks in southeast China (e.g., [19]). During the Penglai Orogeny, these basement rocks and overlying sediments were metamorphosed, with metamorphic grade decreasing progressively westward from the upper green-schist facies, through prehnite–pumpellite facies in slate formation, to unmetamorphosed sediments in the Western Foothills Belt. Lithostratigraphic units and metamorphic isogrades are generally aligned parallel to plate suture (e.g., [18]).

In the mid-part of the Central Range, mountain building is in a steady-state of exhumation and with a great deal of material having been eroded (e.g., [16]); and consequently, the eastern part of the Central Range is only composed of Pre-Tertiary metamorphic complex. By contrast, the southern Central Range shows a lower degree of exhumation with Tertiary Miocene strata still exposed on the eastern side of the range. This results in a dome structure with a core of Pre-Tertiary metamorphic rocks and outer areas of Tertiary strata (Figs. 1 and 2).

For this study, a total of 313-zircon grain ages were obtained from 13 sandstone samples collected from the southernmost Central Range transect, Sandiman to Taimali, almost perpendicular to the plate suture (Longitudinal Valley; Fig. 1). 3 samples were collected from Pre-Tertiary Tanano Schist with the remaining 10 samples collected from Miocene Lushan formation (Fig. 2). Sample processing and age calculations followed the procedures of Liu et al. (e.g., [7,15]).

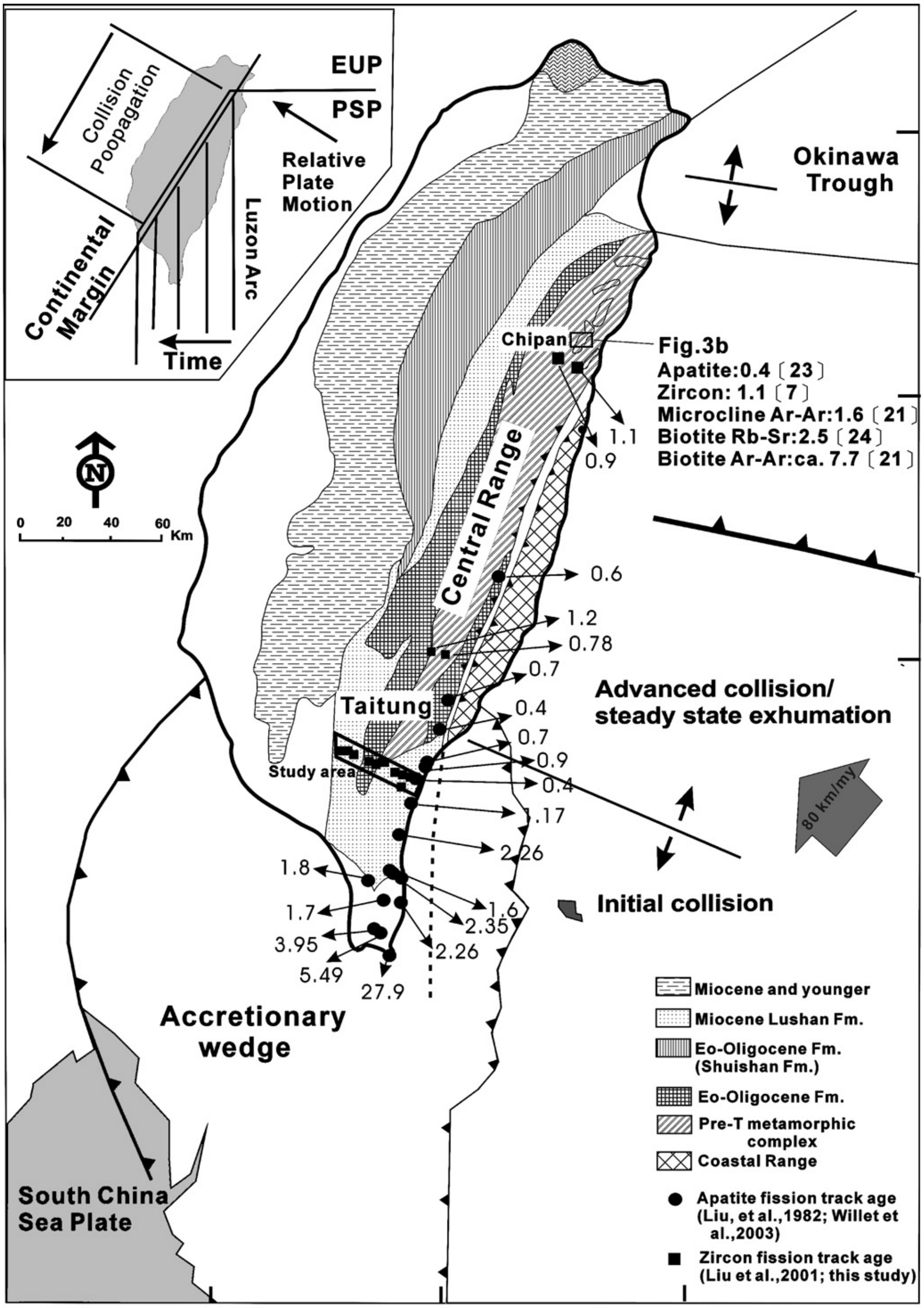

Fig. 1. Generalized geologic and tectonic map of Taiwan with apatite fission-track ages and study area [21,14]. The boundary between the advanced collision and initial collision is around Taitung. South of Taitung, a clear Waddi–Beneiff zone can be identified. The study area is located at the initial collision area. Inset shows plate configuration for the collision between the Luzon arc of the Philippine Sea plate (PSP) and the Asian passive margin of the Eurasian plate (EUP). Apatite and zircon ages are pooled ages in Ma.

3. Thermochronometry

The age data is shown in Table 1 and Fig. 2. West of the Chiaokolatsi fault, pooled ages progressively decrease from west to east and range from 22–43 Ma. These ages show to be bimodal with grain ages being generally larger and showing greater variation than the strata age, indicating a partial reset area (e.g., [20]) (Fig. 2b and Table 1). For instance, for sample 071401, taken from the most western side of the partial reset area, the pooled age is 48.9 Ma and grain ages range from ca. 20 Ma to 80 Ma with a bimodal distribution (Fig. 2b and

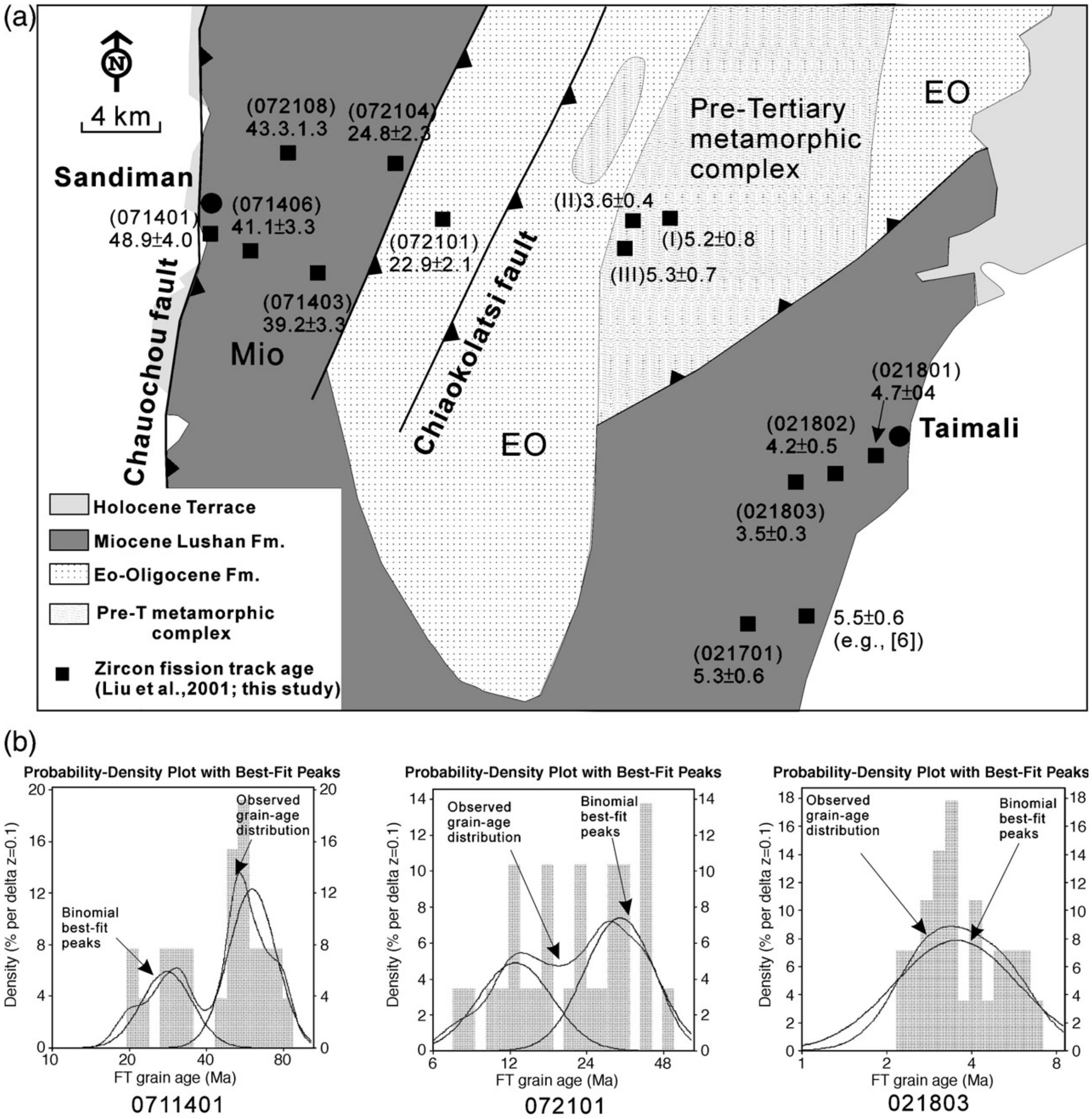

Fig. 2. Study area and pooled ages of zircon fission-tracks in Ma. Location shows in Fig. 1. West of the Chiaokolatsi fault all samples are partially annealed. East of the Chiaokolatsi fault, the ages range from 3.5–5.5 Ma. Details of new zircon ages are given in Table 1. Histogram and curves of observed grain–age distribution and binomial best-fit peaks for the samples of 0711401, 072101, and 021803. Both samples 0711401 and 072101 are partial reset but the ages of 072101 is younger. Sample 021803 are total reset and all the grain ages are less than the strata age. We plot these figures using BINOMIT from Brandon (e.g., [20]).

Table 1
Zircon fission-track (FT) analytical data

Sample no.	Rock type	No. of grains counted	$\rho_s \times 10^6$ (Ns)	$\rho_i \times 10^6$ (Ni)	$\rho_s \times 10^5$ (N_Φ)	Grain age (±1σ)	Pooled age (Ma) (±1σ)	Mean age (Ma±1σ)	Central age (Ma±1σ)
			▲Youngest grain ▼Oldest grain			Youngest grain Oldest grain			
071401	Tertiary Lushan Fm.	26	1.6	2.05					
			▲(32)	▲(41)	0.74	19.6±4.7	48.9±4.0	49.8±3.7	44.5±5.0
			7.4	2.32	(243)	79.8±12.7			
			▼(185)	▼(58)					
071406	Tertiary Lushan Fm.	26	1.08	1.54					
			▲(38)	▲(27)	0.74	17.7±5.3	41.1±3.3	44.3±3.7	39.1±4.3
			5.64	1.69	(243)	83.6±14.7			
			▼(127)	▼(38)					
071403	Tertiary Lushan Fm.	25	1.15	1.8					
			▲(23)	▲(36)	0.74	16.1±4.3	39.2±3.3	42.1±3.9	36.7±4.4
			3.72	1.04	(243)	89.4±17.8			
			▼(93)	▼(26)					
072108	Tertiary Lushan Fm.	22	0.50	0.65					
			▲(10)	▲(13)	0.74	19.1±8.2	43.2±3.1	43.4±3.2	42.9±3.3
			1.75	0.60	(243)	70.6±25.0			
			▼(35)	▼(12)					
072104	Tertiary Lushan Fm.	31	0.44	1.28					
			▲(11)	▲(32)	0.74	8.6±3.0	24.9±1.6	26.8±2.3	23.6±2.4
			1.32	0.68	(243)	48.7±14.4			
			▼(33)	▼(17)					
072101	Tertiary Lushan Fm.	29	0.28	0.96					
			▲(7)	▲(24)	0.74	7.4±3.1	23.0±1.2	24.6±2.3	21.4±2.1
			1.32	0.64	(243)	50.5±16.2			
			▼(33)	▼(16)					
III	Pre-Tertiary Tananao Schist	14	0.10	0.90					
			▲(2)	▲(18)	0.74	2.8±2.1	5.3±0.7	5.6±0.6	5.3±0.7
			0.34	0.97	(243)	8.8±4.2			
			▼(6)	▼(17)					
II	Pre-Tertiary Tananao Schist	17	0.08	0.96					
			▲(2)	▲(24)	0.74	2.1±1.5	3.6±0.4	3.9±0.4	3.6±0.4
			0.09	0.31	(243)	7.2±5.8			
			▼(2)	▼(7)					
I	Pre-Tertiary Tananao Schist	14	0.13	1.96					
			▲(2)	▲(31)	0.74	1.6±1.2	5.2±0.8	5.9±0.5	5.2±0.8
			0.11	0.33	(243)	8.4±6.8			
			▼(2)	▼(6)					
021701	Tertiary Lushan Fm.	29	0.08	0.88					
			▲(2)	▲(22)	0.74	2.3±1.7	5.4±0.6	5.4±0.4	5.3±0.6
			0.40	1.04	(243)	9.7±3.6			
			▼(10)	▼(26)					
021801	Tertiary Lushan Fm.	29	0.16	1.60					
			▲(4)	▲(40)	0.74	2.5±1.3	4.7±0.4	4.8±0.4	4.7±0.4
			0.32	0.88	(243)	9.2±5.3			
			▼(4)	▼(11)					
021802	Tertiary Lushan Fm.	23	0.12	1.36					
			▲(3)	▲(34)	0.74	2.2±1.3	4.2±0.5	5.2±0.4	4.2±0.5
			0.25	0.75	(243)	8.4±4.4			
			▼(5)	▼(15)					
021803	Tertiary Lushan Fm.	28	0.08	0.96					
			▲(2)	▲(24)	0.74	2.1±1.6	3.5±0.3	3.7±0.2	3.5±0.3
			0.08	0.32	(243)	6.3±4.0			
			▼(2)	▼(8)					

Table 1). Toward the eastern boundary of the partial-reset-of-zircon-fission-track area, the pooled age of sample 072101 decreases to 22.9 Ma and grain ages ranges from ca. 7.4 to 50.5 Ma with a bimodal distribution (Fig. 2b and Table 1). The pooled ages progressively decrease from west to east, coinciding with metamorphic grade progressively increasing from west to east (Fig. 2) (e.g., [18]). East of the Chiaokolaitsi fault, pooled ages range from 3.5–5.4 Ma and individual grain ages are less than the strata age, indicating total annealing of zircon fission tracks for these samples (Fig. 2b and Table 1). Further east, near Taimali and where younger strata are exposed, Willet et al. (e.g., [14]) report partially annealed zircons with an age of 73 Ma. Our samples are from strata exposed west of the sample locations of Willet et al. (e.g., [14]) and indicate a region of totally annealed zircon fission tracks.

4. The mechanism for mountain building in southern central range

Assuming a 30 °C/km thermal gradient, 15 °C surface temperature, and combining the ages of zircon and apatite fission tracks (e.g., [14]), we can calculate the cooling and exhumation rate of the southern Central Range at different stages. We found that the cooling and exhumation history could be separated into two stages. The first stage started ca. 6 Ma and continued to ca. 1 Ma with a slow exhumation rate, 0.89 mm/yr and the second stage started from ca. 1 Ma to present with a high exhumation rate, ca. 4–10 mm/yr. (Fig. 3). A high uplift rate could result in vertical advection of heat, raising the geogradient near the surface. Thus apatite may be being cooled by exhumation down a 40°/km gradient, whereas zircon might be cooling by exhumation with a 25°/km. We consider the total-reset-of-zircon-fission-track sample, 021701, which was taken near the southernmost boundary for total reset of zircon fission tracks, and one of the apatite-fission-track samples of Willet (2001) taken from near the same place (e.g., [14]). The ages of zircon and apatite fission tracks are ca. 5.4 Ma and 0.4 Ma, respectively. Considering a 25°/km geogradient for zircon and 40°/km geogradient for apatite, uplift occurs at about 1.2 mm/yr from 5.3 to 0.4 Ma and ca. 7.5 mm/yr from 0.4 Ma to now. Even when one considers the vertical advection of heat, the uplift rate still accelerates from 0.4 Ma to now. The initial age of exhumation may have occurred slightly prior to peak metamorphic conditions reflected in zircon-fission-track aging. In this area the metamorphic grade is prehnite–pumpellyite facies with a metamorphic range from 190–300 °C, which is slightly higher than the reset temperature 235 °C for zircon, therefore we consider the initial age of exhumation could be slightly older than 5 Ma, perhaps ca. 6 Ma. Prior to 6 Ma, collision had either just started or not yet started at the northern Central Range (e.g., [2,3,5]), hence the arc–continental collision cannot be the mechanism of first-stage exhumation in the southern Central Range and the only tectonic process of consequence at that time was the South China Sea Plate's westwards subduction of the Philippine Sea Plate. Therefore, the only possible mechanism of first-stage mountain building was the deformation of an accretionary prism during this subduction process. (Fig. 4) However, the second-stage-exhumation mechanism in the southern Central Range, commencing ca. 1 Ma, can be described by the arc–continental collision.

The above discussion, of a two-stage mechanism describing the initial exhumation as a consequence of an accretionary wedge and second-stage exhumation as a result of the arc–continental collision, is different from previous models, which consider mountain building in the southern Central Range to have occurred as a result of the more recent arc–continental collision and uplift.

The foreland basin is developed by the loading of the mountain belt. Therefore the initial timing of development of the foreland basin records the starting time of mountain building. Lin and Watts (e.g., [13]) show the foreland basin starting to develop at ca. 6.5 Ma, which is similar to our result.

Willett et al., (e.g., [14]) conducted apatite fission-track analysis south of the study area and although many of their apatite fission-track ages were younger than the age of the strata, they considered all of the ages as effectively unreset. They suggested that the zircon were reset by sedimentary burial on the ocean floor and a high geothermal gradient rather than tectonic burial during accretion. They interpret ages as reflecting the time of accretion into a submarine accretionary structure where subsequent underthrusting and hanging wall 'refrigeration' locked in the age. In contrast to Willett's discussion, we consider the possibility that the ages, ranging from 5.39 to 1.17 Ma, were totally reset ages as a consequence of tectonic processes. In the southern Central Range, metamorphic grade progressively decreases from green-schist facies to prehnite–pumpellyite facies, then to zeolite facies from north to south (Fig. 5) (e.g., [19]). The deformational intensity also progressively decreases from north to south, from schist to slate, and then to argillite. We plot total reset age, showing ages roughly progressively increasing from north to south, a phenomenon that suggests a progressively decreasing rate of exhumation from north to south, which

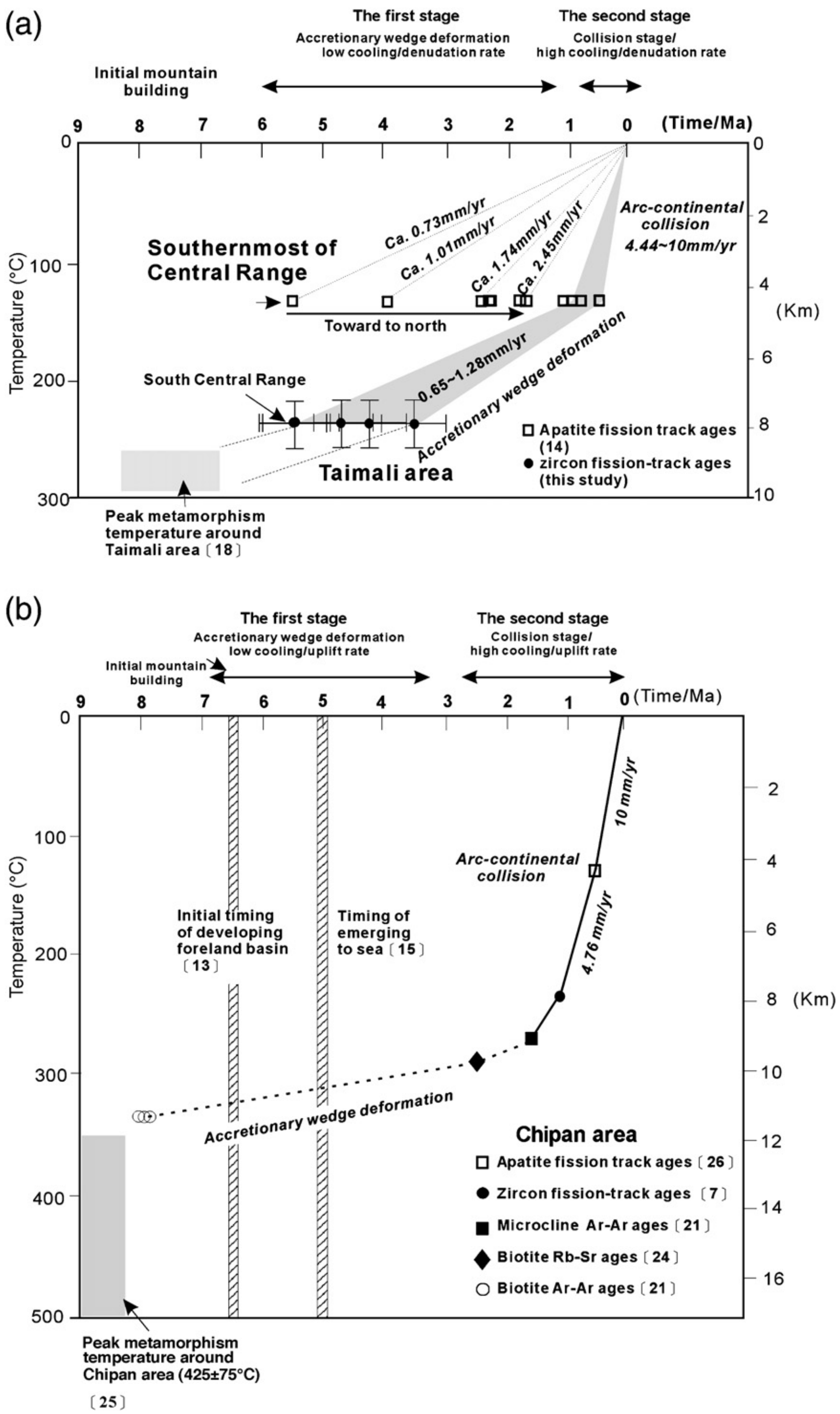

Fig. 3. (a) Cooling and exhumation rates of the southern Central Range. The first stage mountain building results from the accretionary wedge deformation with a slow denudation rate. The second stage mountain building results from the arc–continental collision with a high denudation rate. (b) Cooling and exhumation rates of the northern Central Range in Chipan area. Study location is shown in Fig. 1. The exhumation rate also shows a slow exhumation rate in the early stage and progressively accelerates to present.

is consistent with the deformation and metamorphism patterns (Fig. 3). Considering these conditions, we conclude that the strata were metamorphic and deformed by tectonic deformation rather than buried metamorphism. The progressive decrease in exhumation rate from north to south could reflect some decreasing

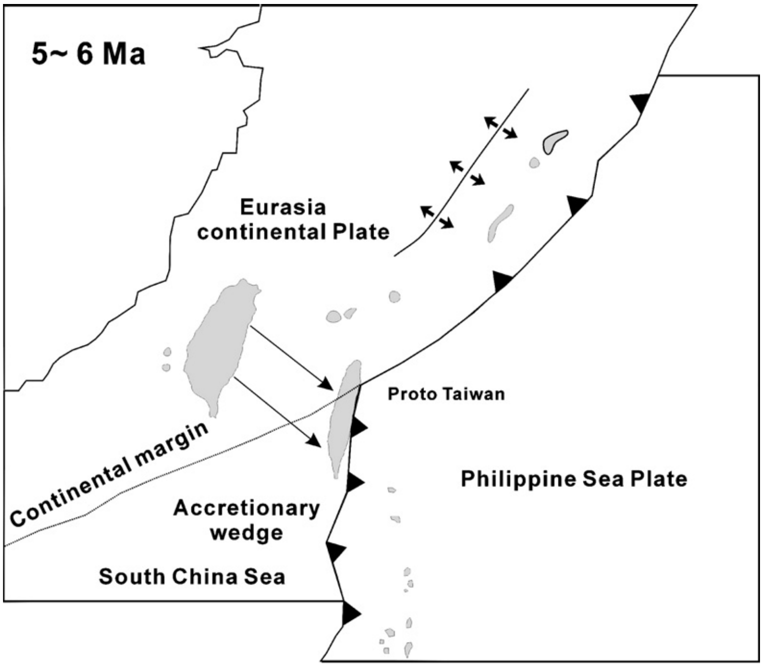

Fig. 4. Schematic tectonic map of Taiwan Orogeny at 5–6 Ma. The mechanism of mountain building at 5–6 Ma was caused by the accretionary wedge deformation while the South China Sea Plate subducted the Philippine Sea Plate.

influence of the arc–continental collision from north to south. Toward the southern tip of the Central Range the major mechanism for mountain building was deformation caused by an accretionary wedge deformation rather than the collision; this conclusion is supported by seismological data (e.g., [12]). In addition, according to our results, the southern Central Range started to uplift ca. 6 Ma. In this area the metamorphic grade is zeolite facies and the metamorphism temperature (<190 °C) is only slightly larger than the reset temperature of apatite

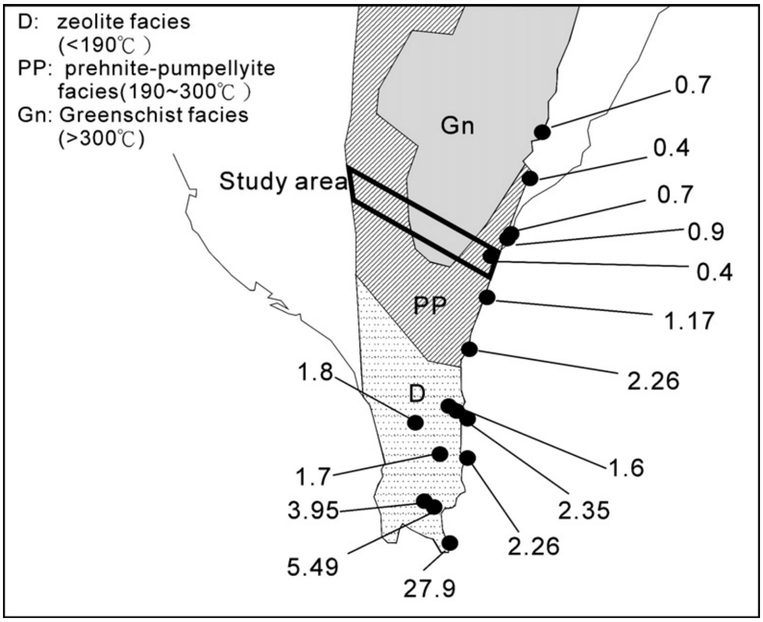

Fig. 5. Metamorphic grade map and relative metamorphic temperature around the southern Central Range (e.g., [18]). The numbers show the apatite fission-track ages in Ma. (e.g., [14]).

(ca. 120 °C) (e.g., [18]). The reset age of apatite fission-track dating in the southernmost Central Range is 3.95–5.39 Ma, which indicates that the initial timing of uplift should be earlier than 3.95–5.39 Ma and could be closer to 6 Ma, a result in keeping with our study.

A question worth examining is whether we can apply this two-stage mountain building model to the northern Central Range. Liu et al., (e.g., [15]) dated sandstone samples from the forarc basin of the Coastal Range by zircon fission-track dating. The meta-sandstones were eroded from the old Central Range and the reset ages indicate when the Central Range started to emerge above the plane of the sea. The implications of their dating were that at ca. 5 Ma the northern and central parts of the Central Range began to emerge above sea level. Given this age of 5 Ma, the initial uplift age should be earlier than 5 Ma and may well be ca. 6 Ma, which is similar to the age of initial exhumation at the southern Central Range. Previous studies have shown that the exhumation or cooling rate accelerates from ca. 3 Ma to present in northern Central Range (e.g., [6,7,22,23]). For instance, in Chipan area according to the ages of Biotite Ar–Ar, Biotite Rb–Sr, K–feldspar Ar–Ar, zircon fission-track, and apatite fission-track analyses and considering that the Central Range emerged about 5 Ma (e.g., [6]) with initial timing for the development of the foreland basin being ca. 6.5 Ma (e.g., [12]) and metamorphic temperature for recent events being ca. 425 °C±75 °C (e.g., [25]), the exhumation rate is slow from ca. 8 Ma to 2.5 Ma and accelerates from ca. 2.5 Ma to present (e.g., [6,21,23,24]) (Fig. 3b).

On the other side, in northern and western side of the Hsiehshan Range, the ages of total reset zircon fission tracks are ca. 5 Ma (e.g., [26]). In these areas the metamorphic grade and amount of denudation are rather lower than on the eastern side of Hsiehshan and the Central Range. These observations also potentially record an early denudation history and indicate that the western side of the Hsiehshan Range started to uplift earlier than 5 Ma, perhaps at ca. 6 Ma too. The rather slow denudation rate of the early stage might also result from the Eurasian Plate subducting the Philippine Sea Plate. In combination, these inferred ages from the foreland basin and zircon fission-track analysis all show potential for the initial timing of uplift being ca. 6 Ma for the entire mountain range.

This raises the question as to there being any difference between the exhumation history of the northern and southern Central Range. It seems the same model can describe mountain building in the northern Central Range as it does in the south, i.e., an initial stage resulting from accretionary wedge deformation by the Eurasian Plate subducting the Philippine Sea Plate, and a later stage resulting from the arc–continental collision, the major differences being the northern Central Range having exposed higher metamorphic grade strata and a greater degree of exhumation. Although the initial timing of exhumation may be the same, perhaps the timing of the collision is different. Taiwan orogeny results form an oblique collision; therefore, the northern Central Range could have experienced collision for longer, explaining the higher degree of exhumation over the southern Central Range, which began experiencing the collision later, explaining the lower degree of exhumation.

5. Conclusion

1. To the west of the Chiaukolatsi fault, all samples exhibit partial annealing of zircon fission tracks. Pooled ages progressively decrease from west to east and range from 43–22 Ma indicating a progressively increasing metamorphic grade of strata from west to east. To the west of the Chiaukolatsi fault, all samples exhibit total annealing of zircon fission tracks and pooled ages range from 3.5 to 5.4 Ma.
2. The exhumation history of the southern Central Range can be separated into two stages. The first stage is from ca. 6–1 Ma with a slow uplift rate, <1 mm/yr and the second stage is from 1 Ma to present with a high exhumation rate, ca. 4–10 mm/yr. The first stage of exhumation results from accretionary wedge deformation during the South China Sea Plates eastward subduction of the Philippine Sea Plate. The second stage was caused by the arc–continental collision.
3. The initial timing of mountain building is roughly the same ca. 6 Ma from north to south of the Central Range. The northern Central Range also shows similar two-stage mountain building. The difference between the north and south is that the northern Central Range has experienced a longer history of collision resulting in exposing high metamorphic grade strata.

Acknowledgements

The authors thank two reviewers Dr. Tim Byrne and Dr. Sean D. Willet. Their reviews and comments helped improve the presentation and focus of this paper. Special thanks to Dr. Tim Byrne for his kind revisions that made the final version of this paper more complete. This project has been fully supported by the National Science Council, Taiwan, ROC, under Grant NSC 93-2119-M-94-002.

References

[1] S.B. Yu, H.Y. Chen, L.C. Kuo, Velocity of GPS stations in the Taiwan area, Tectonophysics 274 (1997) 41–59.

[2] J. Suppe, Mechanics of mountain-building and metamorphism in Taiwan, Mem. Geol. Soc. China 4 (1981) 67–89.

[3] J. Suppe, Kinematics of arc–continent collision, flipping of subduction, and back-arc spreading near Taiwan, Mem. Geol. Soc. China 6 (1984) 21–33.

[4] L.S. Teng, Geotectonic evolution of late Cenozoic arc continent collision in Taiwan, Tectonophysics 183 (1990) 57–76.

[5] C.Y. Huang, W.Y. Wu, C.P. Chang, S. Tsao, P.B. Yuan, C.W. Lin, K.Y. Xia, Tectonic evolution of accretionary prism in the arc–continent collision terrane of Taiwan, Tectonophysics 281 (1997) 31–51.

[6] N. Lundberg, R.J. Dorsey, Rapid Quaternary emergence, uplift, and denudation of the Coastal Range, eastern Taiwan, Geology 18 (1990) 638–641.

[7] T.K. Liu, S. Hseih, Y.G. Chen, W.S. Chen, Thermo-kinematic evolution of the Taiwan oblique-collision mountain belt as revealed by zircon fission track dating, Earth Planet. Sci. Lett. 186 (2001) 45–56.

[8] J. Malavieille, S.E. Lallemand, S. Dominguez, A. Deschamps, C.Y. Lu, C.S. Liu, P. Schnurle, The ACT scientific crew, 2001, Geology of the arc–contiental collision in Taiwan: marine observations and geodynamic model, Geol. Soc. Am. Spec. Pap. 358 (2002) 187–211.

[9] L.S. Teng, Extension collapse of the northern Taiwan mountain belt, Geology 24 (10) (1996) 949–952.

[10] E. Barrier, J. Angelier, Active collision in eastern Taiwan: the coastal range, Tectonophysics 125 (1986) 39–72.

[11] F. Wu, R.J. Rau, D. Salzberg, Taiwan orogeny: thin-skinned or lithospheric collision? Tectonophysics 274 (1997) 191–220.

[12] H. Kao, G.C. Huang, C.S. Liu, Transition from oblique subduction to collision in the northern Luzon arc–Taiwan region: constraints from bathymetry and seismic observations, J. Geophys. 105 (2000) 3059–3079.

[13] A.T. Lin, A.B. Watts, Origin of the West Taiwan Basin by orogenic loading and flexure of a rifted continental margin, J. Geophys. 107 (2002) 2–19 (ETG2-1).

[14] S.D. Willett, D. Fisher, C. Fuller, E.C. Yeh, C.Y. Lu, Erosion Rates and Orogenic Wedge Kinematics in Taiwan Inferred from Fission Track, 2003.

[15] T.K. Liu, Y.G. Chen, W.S. Chen, S.H. Jiang, Rates of cooling and denudation of the early Penglai Orogeny, Taiwan, as assessed by fission-track constraints, Tectonophysics 320 (2000) 69–82.

[16] S.D. Willett, M.T. Brandon, On steady states in mountain belts, Geology 30 (2002) 175–178.

[17] G.A. Wagner, G.M. Reimer, Fission track tectonics: the tectonic interpretation of fission track apatite age, Earth Planet. Sci. Lett. 14 (1972) 263–268.

[18] C.H. Chen, Metamorphic Rock of Taiwan, Central Geological Survey, Taiwan, 1998, p. 365.

[19] C.S. Ho, An Introduction to the Geology of Taiwan: Explanatory Text of the Geologic Map of Taiwan, Central Geological Survey, Taiwan, 1986, p. 163.

[20] MT. Brandon, Probability density plot for fission track grain-age samples, Radiat. Meas. 26 (1996) 663–670.

[21] C.H. Lo, T.C. Onstott, Rejuvenation of K–Ar systems for minerals in the Taiwan Mountain belt, Earth Planet. Sci. Lett. 131 (1995) 71–98.

[22] C.Y. Lan, T. Lee, C.L. Wang, The Rb–Sr isotopic record in Taiwan gneisses and its tectonic implication, Tectonophysics 183 (1990) 129–143.

[23] T.K. Liu, Tectonic implication of fission-track ages from the Central Range, Taiwan, Proc. Geol. Soc. China 25 (1982) 22–37.

[24] B.M. Jahn, F. Martineau, J.J. Peuca, J. Cornichet, Geochronology of the Tananao Schist complex and crustal evolution of Taiwan, Mem. Geol. Soc. China 7 (1986) 383–404.

[25] J.G.. Liou, W.G. Ernst, D.E. Moore, Geology and petrology of some polymetamorphosed amphibolites and associated of some polymetamorphosed amphibolites and associated rocks in northeastern Taiwan, Bull. Geol. Soc. Am. 92 (1981) 219–224.

[26] T.K. Liu, Fission track dating of the Hsueshan Range: thermal record due to arc–continent collision in Taiwan, Acta Geol. Taiwan 26 (1988) 279–290.