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POSSIBLE FACTORS AFFECTING THE TOPOGRAPHY OF THE BACKBONE RANGE OF TAIWAN

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ABSTRACT

Topography of an active mountain range is a reflection of perplexed interactions between bedrock uplift and denudation and consequently can provide valuable information on the responsible processes. The topographic architecture of the Backbone Range of Taiwan is asymmetric in the E-W profile. The highest elevation of the range developed where low-grade metamorphic rocks outcrop and is skewed to the west. Analyses of the available fission-track and structural data suggest that synorogenic extensional structures contributed significantly to the development of the asymmetric topographic profile, although differential erosion across the mountain range may also have played a role. On the other hand, decreasing extrusion velocity or decreasing strike-slip extrusion component westward across the mountain range during the upward extrusion of the Backbone Range caused by oblique convergence, and the "space" problem induced by the presence of the Hsuehshan Range in the west hampering the westward rock movement of the uprising Backbone Range in the east, might also be important factors.

Key words: uplift, denudation, topography, Taiwan

INTRODUCTION

Grand scale topography is an integrated result of natural processes. For a tectonically active orogenic belt, its topography is dictated by a complicated competition between processes that lead to the accumulation of energy (such as crustal thickening and bedrock uplift) and processes that lead to the dissipation of energy (such as tectonic and erosional denudation). The shapes of mountains therefore contain valuable information on the relative contributions of uplift and denudation across the mountain ranges. To understand the controlling factors for the observed topographic profile of an evolving mountain range is hence not only crucial in delineating the topographic effects of various processes but also of prime importance in identifying boundary conditions for further simulation modeling (e.g., see Koons, 1995).

The Backbone Range of Taiwan is located at the eastern part of the active Taiwan Mountain Belt. Its present topography has largely been fabricated during the Cenozoic arc-continent collision. The Hsuehshan Range, which runs parallel to the Backbone Range and is also a component of the Taiwan Mountain Belt, lies to the west. The Longitudinal Valley, which marks the boundary between the Eurasian and the Philippine Sea plates, lies to the east (Fig. 1). The surface of the Backbone Range is now composed mainly of prehnite-pumpellyite facies (~200-300^{o}C/2-3 kbar) to greenschist facies (~300-450^{o}C/3-5 kbar) metamorphic rocks (see Chen and Wang, 1995), suggesting that the cover strata with a maximum 7-15 km thickness were removed from across the mountain range since the collision. The topography of the Backbone Range (Fig. 2) shows that the elevation decreases both north- and south-ward, probably resulting from the opening of the Okinawa trough in the north and the commencement of the arc-continent collision in the south. The central part, from latitude 23^{o} to 24.5^{o} north, may have a steady-state topography (Suppe, 1981; Liu *et al*., 2000) and will be the main subject of the present study. In this central part of the Backbone Range, the E-W topographic profile, however, is not symmetrical. Characteristically, the highest elevation (about 3000 m) of the mountain range, where prehnite-pumpellyite facies metamorphic rocks outcrop, is skewed to the west, while the metamorphic rocks recording the highest metamorphic conditions in this mountain range crop out at the eastern part with lower elevations (Fig. 1B). The purpose of the present paper is, based on the available data, trying to analyze the possible processes contributing to this characteristic profile of the Backbone Range. With all these controlling factors in mind, more quantitative studies could be formulated in the future.

GEOLOGICAL BACKGROUND

The island of Taiwan is located at the boundary between the Asian Plate and the Philippine Sea Plate. Its formation is due to the Luzon arc-Asian continent collision from the Plio-Pleistocene to the present (Suppe, 1984). The Philippine Sea Plate is now subducting northward beneath and overriding westward on top of the Asian Plate at the Ryukyu and the Manila Trench, respectively (Fig. 1A). Geologically, the island can be divided into five major tectonostratigraphic units. From west to east, they are the Coastal Plain, the Western Foothills, the Hsuehshan Range, the Backbone Range and the Coastal Range (Ho, 1988) (Fig. 1A).

Structural and Metamorphic Characteristics of the Backbone Range

The Backbone Range is composed of the prehnite-pumpellyite-facies Lushan Formation of Miocene age, the prehnite-pumpellyite-facies to greenschist-facies Pilushan Formation of Eocene age and the greenschist-facies to amphibolite-facies Tananao Metamorphic Complex of pre-Tertiary age. The metamorphic grade correlates roughly with the age of the rock units. The Lushan and the Pilushan Formations are collectively known as the slate belt. The Tananao Metamorphic Complex is the basement rock of Taiwan and was interpreted as an ancient accretionary complex that has experienced several stages of tectonic processes during the Mesozoic in addition to the most recent arc-continent collision (Yui *et al*., 1990a, 1990b). The Backbone Range has been extensively studies in the past two decades. Three conspicuous features on structural and metamorphic observations, which can be best illustrated in the transect across the central part of the mountain range as shown in Figure 1B, are summarized as follows:

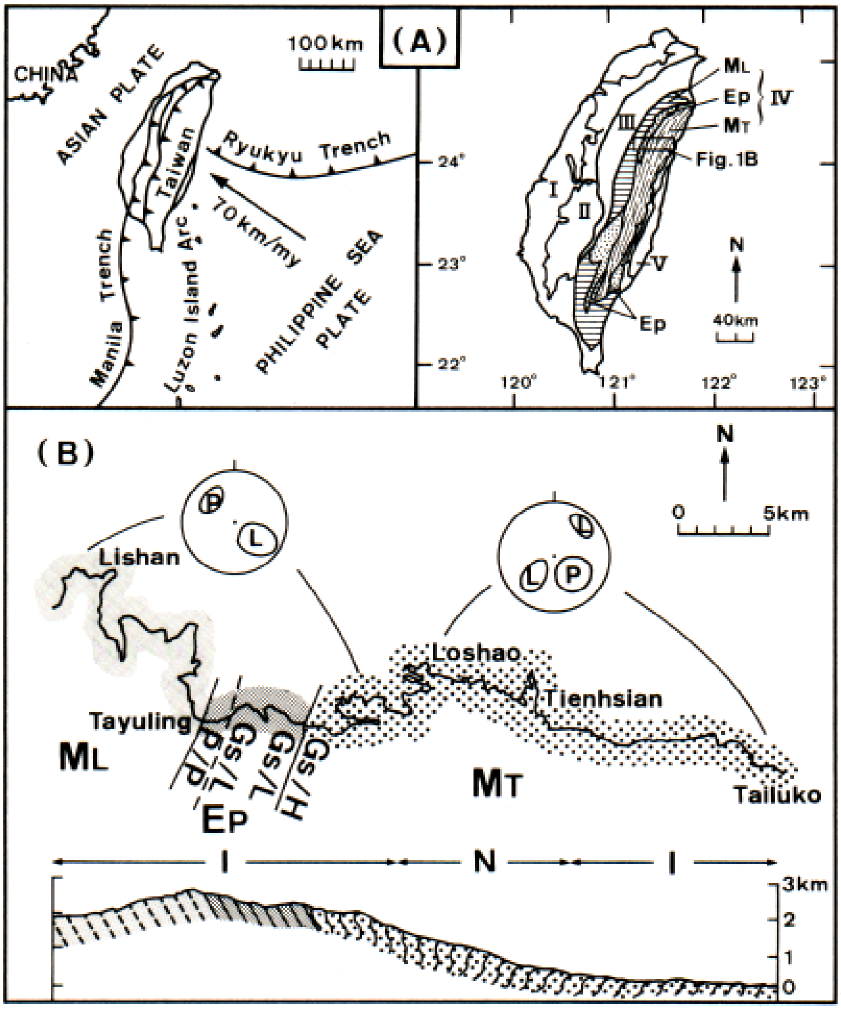

Figure 1. (A) Simplified tectonic and geologic map of Taiwan showing the present tectonic setting around Taiwan and the 5 major tectonostratigraphic units: the Coastal Plain (I), the Western Foothills (II), the Hsuehshan Range (III), the Backbone Range (IV), (which includes the Lushan Formation (ML), the Pilushan Formation (EP) and the Tananao metamorphic Complex (MT)), and the Coast Range (V). The Longitudinal Valley is located between units IV and V. (B) A geologic transect/ profile across the central part of the Backbone Range showing characteristic metamorphic and structural features. See text for details. P/P: prehnite-pumpellyite facies; Gs/L: lower greenschist facies; Gs/H: higher greenschist facies; I: inverted metamorphic zonation; and N: normal metamorphic zonation. The lower hemisphere stereographic projections show the poles of the cleavage (P) and projections of stretching lineation (L). (Data compiled after Yen *et al*. (1984), Faure *et al*. (1991) and Lee(1997).)

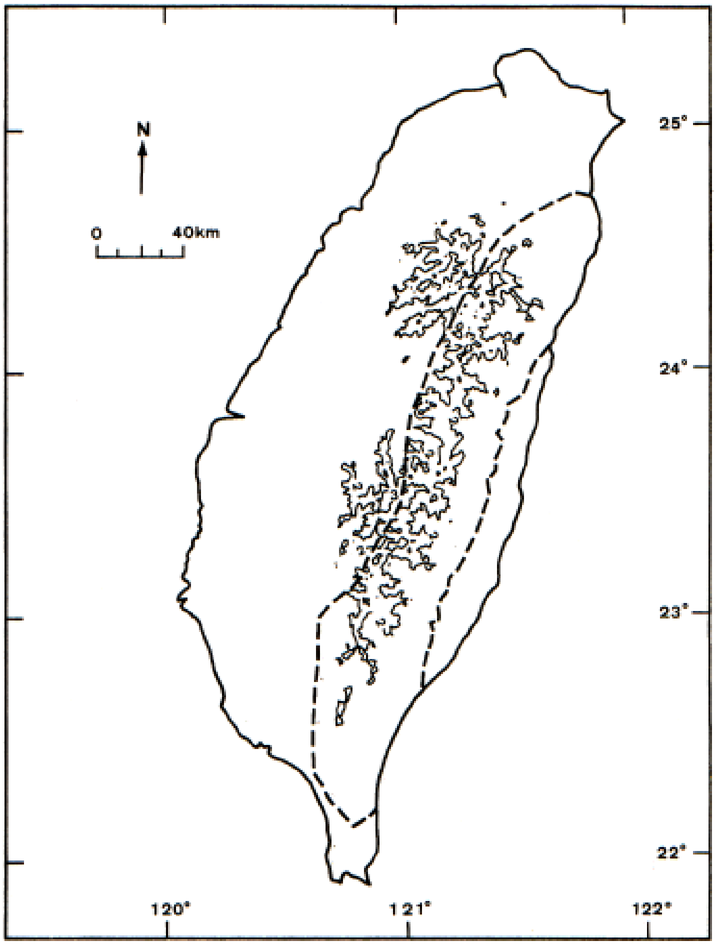

Figure 2. Simplified topographic map of Taiwan. Elevation contours of 2000 m (labeled as 2) and 3000 m (labeled as 3) are shown. Bold-dash line outlines the geographic area of the Backbone Range shown in Figure 1.

(1) The strike of the dominant cleavage of the metamorphic rocks is in the NNE direction, roughly parallel to the main trend of the island. The dip of the cleavage, however, shows a fanning orientation, i.e., the strata's cleavage gradually changes from dipping to the east for rocks in the western part to dipping to the west for rocks in the eastern part of the mountain range (Fig. 1B). The rocks at the westernmost part of the Tananao Metamorphic Complex show an almost vertical cleavage, albeit in the southern part of the mountain range rocks with vertical cleavage are located at the easternmost part of the Pilushan Formation. Although part of the metamorphic rocks (such as the basement complex) may have a complicated tectonic history, this dominant cleavage was suggested to have been formed during the Cenozoic arc-continent collision (Stanley, *et al*., 1981; Yen *et al*., 1984; Faure *et al*., 1991; Clark and Fisher, 1995; Crespi *et al*., 1996; Lee, 1997).

(2) Down-dip stretching lineation with top-to-the-northwest shear sense was recorded in the east-dipping metamorphic rocks. This lineation direction is approximately perpendicular to the trend of orogen. On the other hand, the stretching lineation is roughly parallel to the strike of the cleavage (or to the trend of orogen) and exhibits a left-lateral sense of shear in the west-dipping rocks. The change between these two sets of lineations is gradual (Fig. 1B) (Faure *et al*., 1991; Lee, 1997; Byrne *et al*., 1999).

(3) The amphibolite-facies mineral assemblages of limited occurrence in the Tananao Metamorphic Complex were largely formed during the Mesozoic tectonic events. The collision-induced metamorphism during the arc-continent collision generally yielded greenschist facies and prehnite-pumpellyite facies minerals in rocks from the Backbone Range (e.g., Ernst, 1983a). Across the transect in Figure 1B, the metamorphic grade increases from west to east, and then decreases further east. The highest metamorphic condition (i.e., 450^{o}C and 3-4 kbar) was recorded in the Tananao Metamorphic Complex (e.g., Ernst, 1983a; Yui, 1994). It was also noted that there is no prominent break in metamorphic grade across the Backbone Range (Ernst, 1983a, 1983b, 1984; Warneke and Ernst, 1984, Yui *et al*., 1996) and the isograde is roughly parallel to the strata's cleavage (Chen and Wang, 1995). Considering the rock attitude mentioned above, the rock strata along the transect can be divided into three parts. The eastern and western parts show an inverted metamorphic zonation while the central part gives a normal metamorphic zonation (Fig. 1B). Because the metamorphic grade roughly correlates with the age of rock unit in the Backbone Range, the inverted metamorphic zonation also denotes a stratigraphic inversion in terms of the Lushan Formation, the Pilushan Formation and the Tananao Metamorphic Complex.

Upward Extrusion of the Backbone Range

To explain the above mentioned structural and metamorphic characteristics, Yui and Chu (2000), based on the stable isotope profiles of thin marble layers, postulated an upward extrusion model to account for the exhumation of the Backbone Range during arc-continent collision. Their model can be conceptually summarized in Figure 3.

The Backbone Range of Taiwan represents the southeastern margin of the Eurasian continent. During the Miocene, this part of the continental margin was preceded by the South China Sea plate, which was subducting beneath the Philippine Sea plate to form the Luzon Arc (Biq, 1972). When the South China Sea plate was completely consumed through subduction, the leading edge of the continental margin was dragged down beneath the Philippine Sea plate that marked the beginning of the so-called arc-continent collision. This continental subduction did not last long because the resistive buoyancy of the lighter material would have soon increased to the point where decoupling occurred and the subducted crust exhumed back to the surface through the combined effects of buoyancy, compression and erosion (Angelier, 1986; Ho, 1988; Lin and Roecker, 1998; Lin *et al*., 1998).

When it was dragged down beneath the Philippine Sea plate, the southeastern margin of the Eurasian continental crust was thickened and heated. It is likely that not only the younger covers but also the continent basement were subjected to the metamorphism/deformation induced by this continental subduction. New metamorphic minerals were formed and new cleavage planes developed accommodating the subduction shear stress. The inclined lines in Figure 3A depict metamorphic isotherms parallel to the subduction plane of this leading edge (Lin and Roecker, 1998). These lines may also roughly represent separations of the cover (incipiently metamorphosed) strata, slate and schist, as well as approximate the newly developed strata's cleavage planes. The thick black line at the bottom of the schist denotes the highest metamorphic grade rock currently outcropping along the transect of the Backbone Range shown in Figure 1B.

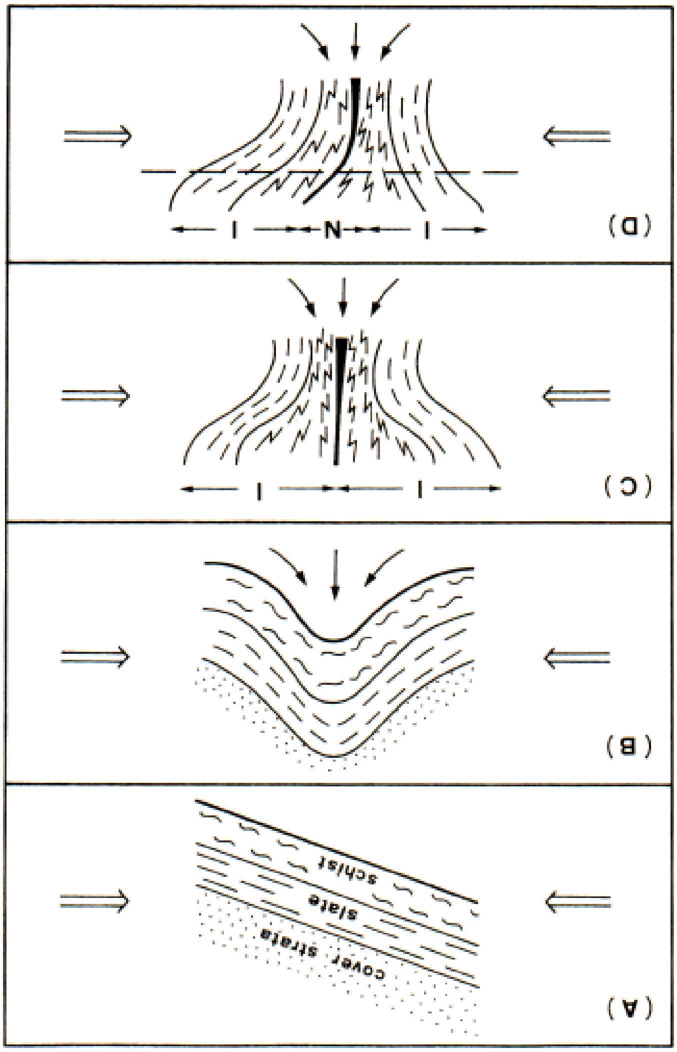

Figure 3. Simplified conceptual diagrams showing the cross section of upward extrusion exhumation model of the Backbone Range (taken from Yui and Chu, 2000). (A) Continental crust was metamorphosed/deformed when it was dragged down beneath the Philippine Sea plate. Inclined lines are metamorphic isotherms, as well as approximate newly developed rock cleavage planes. (B) Hot mid-crust was extruded upward due to buoyancy and compression after continental crust decoupled from the subducting oceanic plate. (C) Extrusion exhumation resulted in an orogen-scale antiform and ultimately led to a fanning orientation of the rock cleavage as well as inverted metamorphic zonations. (D) The crust might have been twisted from the ideal geometry due to the shape and dip angle of the rigid indenter. The dashed line roughly represents the structural level of rock section currently outcrops in the central part of the Backbone Range shown in Figure 1B.

As the continental crust decoupled from the subducting oceanic plate, both buoyancy and compressive force caused the exhumation. In addition to the bulk exhumation of the continent along the subduction plane (Lin and Roecker, 1998; Lin *et al*., 1998), differential movement within the exhumed crust is also anticipated. It is conceivable that through continuous convergence the heated mid-crust might have behaved plastically and could have been extruded upward like toothpaste in a tube (Fig. 3B). This mid-crust upward extrusion might have occurred close to the point where the continent started to subduct. When extruded material pops up forming a huge antiform above the zone of lateral shortening, the upper parts would start an orogen-normal horizontal escape by gravity spreading (Merle and Guillier, 1989; Bonini *et al*., 1999). That would result in a mushroom-like cross section (Fig. 3C). The upper part of Figure 3C displays the stratigraphic inversion, inverted metamorphic zonation and fanning orientation of rock strata. In the ideal situation, the highest metamorphic grade rock would occur at the extrusion center and exhibit a vertical attitude as shown by the thick black line in Figure 3C. However, the real geometry would be highly influenced by the shape and dip of the frontal face of the rigid indenter (i.e., the Luzon Arc and the Philippine Sea plate) (Bonini *et al*., 1999). It is quite probable that the mushroom-like cross section was twisted a little and yielded the final result as in Figure 3D. The dashed line in Figure 3D represents the approximate structure level that would exhibit the same cleavage and metamorphic characteristics as the transect of the Backbone Range shown in Figure 1B

Stretching Lineation: Secondary

In the above extrusion model (see Figs. 3C and D), the sense of shear of stretching lineation should be reversed across the extrusion center (i.e., the highest metamorphic grade rock). Such a reversal of shear sense of stretching lineation, however, was not observed in the high-grade metamorphic rocks of the Backbone Range. In the Tananao Metamorphic Complex, the shear sense of stretching lineation is mostly left-lateral (Fig. 1B). This shear sense can be interpreted as a result of transpression due to the northwest oblique collision between two plates (Fig. 1A), but it does not agree with that predicted by the extrusion exhumation model. The observed stretching lineation in metamorphic rocks of the Backbone Range was therefore treated as "secondary" in nature to reconcile this discrepancy (Yui and Chu, 2000). This means after exhumation folding, the overturned strata still behaved plastically, but due to rheologic change induced by temperature decrease and/or due to the overburden loading, the strata responded to the convergence stress differently from that during the initial stage of exhumation folding. During this stage, the strain would have been partitioned into orogen-parallel and orogen-normal directions as a function of distance from the indenter (e.g., Fitch, 1972; Pinet and Cobbold, 1992), as recorded in the west-dipping and east-dipping strata, respectively. That the angle between the Eurasia/Philippine Sea plate boundary and the plate motion before 3-4 Ma was much smaller than the present tectonic configuration (e.g., Angelier *et al*., 1986) would substantiate this suggested strain partitioning. Because the "primary" stretching lineation was largely obliterated, the exact direction of material movement in response to oblique collision during the initial stage of rock exhumation is difficult to determine.

FACTORS AFFECTING THE TOPOGRAPHY OF THE BACKBONE RANGE

As mentioned previously, the E-W topographic profile of the Backbone Range is not symmetrical. The highest elevation of the range is not located near the extrusion center, but is skewed about 20 km to the west as exemplified by the transect/profile in Figure 1B. The Tananao basement has a lower elevation than the slate belt to the west in spite of its being the extrusion center and its higher metamorphic grade. Since the topography of a mountain range is mainly a result of interaction between uplifting and denudation, possible factors relating to this interaction will be discussed separately.

Denudation Factors

In a fission-track study across the Backbone Range, Tsao *et al.*, (1992) showed that during the arc-continent collision the metamorphic temperature of the Lushan Formation was not high enough to totally reset the detrital zircons and that zircons from the Pilushan Formation and the Tananao Metamorphic Complex were completely annealed. The fission-track age of zircon for the Pilushan Formation ranges from 1.5 to 3.0 Ma and that for the Tananao basement, from 1.0 to 2.0 Ma (Shieh, 1990; Taso *et al.*, 1992). The exhumation rate for the latter was therefore suggested to be higher than that of the former, if the paleo-geothermal gradient of the two areas did not differ significantly. Liu (1982) also showed that the exhumation rate of the Tananao basement increased significantly especially during the past 0.6 Ma chiefly based on fission-track data of apatite (0.3 - 0.6 Ma) and zircon (0.9 - 1.3 Ma). The blocking temperatures of fission-track dating for apatite and zircon in the Backbone Range were suggested to be 135^{o}C and 235^{o}C, respectively (Liu, 1982). Pelitic rocks under these temperature conditions mainly behave elastically. This is also evidenced by the suggestion that extensional joints (i.e., brittle deformation) in the Tananao Metamorphic Complex at the Hoping area might have developed before 1.5 Ma (Wang, 1997). That would mean the higher exhumation rate of the Tananao basement derived from fission-track data could not be due to faster transport of rocks through the cover strata, but most likely resulted from more intense normal faulting or higher erosion rate to remove the overburden. It should be noted that both normal faulting and erosion are two major denudation processes that can effectively reduce the surface elevation. Assuming a 40-50^{o}C/km paleo-geothermal gradient due to the fast exhumation, the zircon fission track data mentioned above would suggest at least a ~2 km difference in denudation thickness between the Tananao basement and the slate belt during the past 2.0 Ma.

Recent GPS surveys of Taiwan showed that while Taiwan is in general under horizontal contraction, the Backbone Range is extending (Yu and Chen, 1996). The above mentioned extrusion exhumation model for the Backbone Range (Yui and Chu, 2000) seems to be consistent with this observation. In addition, in agreement with the GPS data, synorogenic normal fault has been observed both in the slate belt and in the Tananao basement of the Backbone Range (Crespi *et al.*, 1996; Lee, 1997). Semi-brittle to ductile normal-displacement shear zones were also reported to have developed locally in the basement rocks (Crespi *et al.*, 1996). These extensional structures were reported cutting across the compressional ones and were therefore interpreted to have taken place later (Crespi *et al.*, 1996; Lee, 1997). Seismic studies further showed that shallow microearthquakes (<30 km) with normal-type fault plane solutions occur only beneath the basement rocks (Lin *et al.*, 1998). Such extensional features at the rear part of a mountain range are not uncommon worldwide and can be accounted for by crustal thickening (Platt, 1993), although the obliqueness of the shear convergence may also have played a role (McCaffrey and Nabelek, 1996). These observations, therefore, may suggest that normal-sense rock movement might have recently been occurring more intensively within the Tananao basement than in the slate belt and could, at least partly, contribute to the observed topographic characteristics.

It should be noted, however, that semi-brittle to ductile normal-displacement shear zones can lower the surface elevation but can not help exhume rock strata at shallower depths dominated by brittle deformation. Normal-faulting effect should be more pronounced in the Tananao basement than in the slate belt, if the different exhumation rate between the Tananao Basement and the Pilushan Formation derived from fission-track data were solely attributed to the extensional processes. The available data, however, cannot yield any quantitative assessments at the moment supporting such a difference (Crespi *et al*., 1996; Lee, 1997). This leads to the possibility that differential erosion may also have played a role in causing the higher exhumation rate of the Tananao basement during the past 2.0 Ma compared with that of the slate belt, and may have also contributed in part to the observed asymmetric topography.

Erosion rate is related to the physical/chemical properties of bedrocks, the relief of mountain ranges, the climatic temperature (range), as well as the meteoric precipitation (or the runoff). The average erosion rate of the Taiwan Mountain Belt since the Pliocene is rather high (i.e., 5. 5 mm/yr, Li, 1975), but there is no available data showing rate variations across the mountain belt. Although differential erosion across a mountain range during orogenic processes may not be uncommon, its exact effect is difficult to assess. Koons (1989, 1990, 1995), based on numerical modeling, presented the effects of collision-erosion interplay to demonstrate the topographic evolution of the Southern Alps of New Zealand. He showed that if precipitation, and therefore erosion, was concentrated at the toe of the wedge facing the indenter, it would cause low elevation, rapid uplift, exposure of deep crustal rocks at the wedge side near the indenter and consequently the asymmetric topography of the Southern Alps. He also demonstrated that the relationship among uplift rate, total amount of uplift and elevation across a mountain range is not straightforward and is highly influenced by the erosion rate. Similar results could also be derived for the Himalayas and the Western European Alps (Koons, 1990). Note that the shape profiles of these mountains (see Figure 2 of Koons, 1990) seem to be comparable to the topographic characteristics of the Backbone Range. However, the present precipitation across the Backbone Range (Fig. 4) does not show the same marked difference as that seen across the Southern Alps. Koons' model could therefore not be applied in such a straightforward way. Noteworthily, Koons (1989) also showed that temporal variation in precipitation with a period of about 50 ka could effectively perturb the uplift-elevation relation for about 200 ka. If the climatic variations, which may change the precipitation pattern, in such a time scale did occur during the past 2.0 Ma, Koons' model of differential erosion could be an appropriate one to account for the topographic characteristics of the Backbone Range. Quantitative estimations on erosion rates across the Backbone Range, as well as through geologic time, are needed to substantiate the possibility. It is, however, worth mentioning that the collisional uplift mechanism employed by Koons' numerical modeling (1990) was a modified bulldozer accretionary prism rather than an upward extrusion exhumation.

Uplifting Factors

Based on the available age data, extrusion exhumation of the highest metamorphic grade rock in the Backbone Range might have started at ~8 Ma (Lo and Onstott, 1995). Considering the depth of metamorphism of the highest-metamorphic-grade rock before uplifting (i.e., ~15 km), a simple estimate of its average (rock) uplifting rate would be ~2 mm/yr during the time period. This estimate is a lower limit because it has not considered the surface uplift. Note that the uplifting rate of a mountain range might not be the same temporally. The uplifting rate may also not be equal to the exhumation rate. In this regard, the real uplifting rate of the Tananao Metamorphic Complex might have been higher than, equal to, or lower than its exhumation rate during the past 2.0 Ma (which might be as high as 6-9 mm/yr (Liu, 1982; Liu *et al*., 2000)), depending on whether the surface elevation of the area has increased, been constant, or decreased during the time period considered.

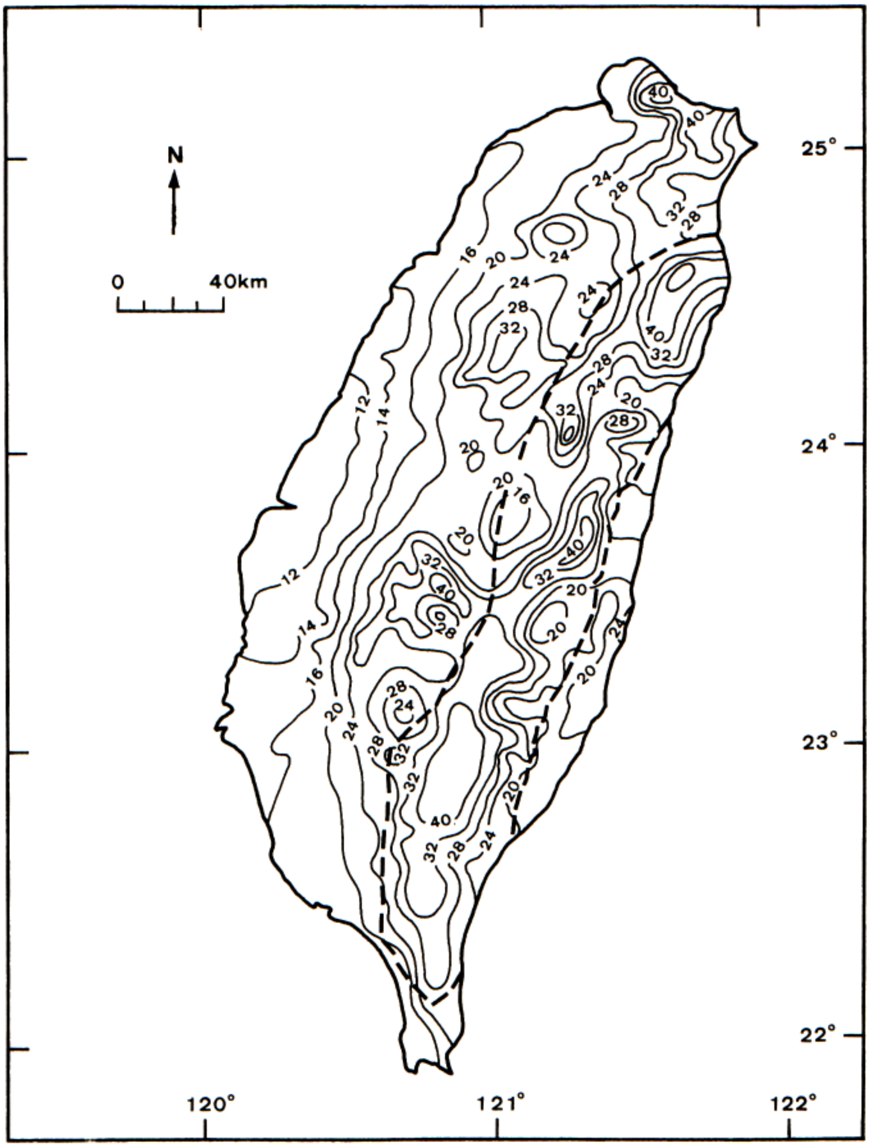

Figure 4. Normal annual total precipitation map of Taiwan (CWB, 1990). The labeled number near an isoline times 100 giving the normal annual total precipitation in mm. Bold-dash line outlines the geographic area of the Backbone Range shown in Figure 1.

Although it was suggested that the Backbone Range might have been uplifted as an integral body during arc-continent collision (Lee, 1997; Lin and Roecker, 1998; Lin *et al*., 1998), differential uplifting across the central part of the Backbone Range was also noted by Tsao *et al*., (1992) and Liu (1995). This differential uplifting would especially have played a role in shaping the topography of the mountain range.

As mentioned previously, the attitude of rock movement during the initial stage of rock exhumation can not be deduced from the available lineation information. Its exact effect on topography is therefore difficult to evaluate. However, thermal modeling of extrusion exhumation did reveal differential uplifting rates, and hence probably different elevations, across the mountain ranges if the strike-slip component of the rock movement had a systematical spatial variation due to oblique convergence (Thompson *et al*., 1997). From the relative geographic position, it is quite probable that the Tananao Metamorphic Complex might well have had a larger strike-slip component than the slate belt during the initial exhumation stage caused by oblique arc-continent collision. In such a case, the mountain range would develop an asymmetric topographic profile. On the other hand, different extrusion velocities across the mountain range due to arc-continent collision could mitigate the above proposition. Note that based on fission track data, Tsao *et al*. (1992) showed that the Tananao Metamorphic Complex had a higher uplifting rate than the slate belt during the past 2 Ma.

Before exhuming to shallow depths dominated by brittle deformation, it has been shown that the west-dipping strata of the Tananao basement moved roughly in an along-strike direction with a small vertical component as indicated by the recorded stretching lineation with left-lateral sense of shear (Fig. 1B). On the other hand, the east-dipping slates moved northwestward with a larger vertical component (Fig. 1B). This inferred difference in vertical component is qualitatively consistent with the present differential vertical crustal movement across the central part of the Backbone Range (Liu, 1995 and personal communication). Although different vertical components may yield different uplifting rates (and hence different topographic elevation), it is difficult to make a firm conclusion without knowledge of the velocity as well as the time of such a movement. However, it should be noted that there are two mountain ranges running side by side in the Taiwan Mountain Belt, i.e., the Backbone Range in the east and the Hsuehshan Range in the west (Fig. 1). The Hsuehshan Range was shown to have slightly older zircon fission-track ages (i.e., 3.0 to 6.5 Ma) (Liu, 1988; Shieh, 1990). This Range was envisaged as a pop-up structure internally deformed by upright symmetrical folds/subvertical cleavage and was interpreted as genetically related to the pre-collisional half-graben structure (Clark *et al*., 1993; Tillman and Byrne, 1995). While the along-strike-moving strata of the Tananao basement in the Backbone Range may have moved voluntarily along the convergent boundary, the west-moving strata of the slate belt might have been hindered by the existing "pop-up" Hsuehshan Range. The latter may lead to a "space" problem, which could be compensated by an increase in surface elevation and may therefore partly account for the asymmetric topography of the Backbone Range shown in Figure 1B.

Lastly, it should be pointed out that the differential uplifting across the central part of the Backbone Range reported by Tsao *et al*., (1992) and Liu (1995) is different in trending. Tsao *et al*., (1992) suggested an increasing uplifting rate eastward during the past 2 Ma based on fissure track data, while Liu (1995) demonstrated westward increase in uplifting rate in recent decades through leveling measurements. Although this apparent discrepancy might be due to different definitions of "uplifting rate" in different studies, to different observation timescales or to temporal variations of uplifting rate, the reasons, as well as the responsible mechanisms, are not yet clear. One possible explanation is that the extensional displacement deep within the Tananao Metamorphic Complex may play a more important role with time.Alternatively, the crust may deform differently on different timescales (e.g., Liu *et al*., 2000). In any case, this difference certainly elucidates the complex interactions between denudation and uplifting through time, as well as the possibility of temporal variation of topographic shape of a mountain range.

CONCLUSIONS

The Backbone Range exhibits an asymmetric topography in the E-W profile, i.e., its highest elevation developed where low-grade metamorphic rocks outcrop and the highest elevation is skewed to the west. The available fission-track data and structural observations demonstrate that synorogenic extensional structures and, possibly, differential erosion across the mountain range were two important factors. However, different extrusion velocities and/or different strike-slip components of rock movement across the mountain range during the upward extrusion exhumation caused by oblique convergence, as well as the "space" problem induced by the retarding of westward rock movement due to the presence of the Hsuehshan Range, may also have played a role.

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REFERENCES

Angelier, J. (1986) Preface to the special issue on "Geodynamics of the Eurasian-Philippine Sea Plate Boundary": *Tectonophysics*, **125**, IX-X.

Angelier, J., Barrier, E. and Chu, H.T. (1986) Plate collision and paleostress trajectories in a fold-thrust belt: the foothills of Taiwan: *Tectonophysics*, **125**, 161-178.

Biq, C. (1972) Dual-trench in the Taiwan-Luzon region: *Porc Geol. Soc. China*, **15**, 65-75.

Bonini, M., Sokoutis, D., Talbot, C.J., Boccaletti, M. and Milnes, A.G. (1999) Indenter growth in analogue models of Alpine-type deformation: *Tectonics*, **18**, 119-128.

Byrne, T., Crespi, J., Pulver, M. and Spiker, E. (1999) Deformation of the Taiwan hinterland: Strike-slip faulting, extrusion or both? *International Conference and 4th French-Taiwan Symposium "Active Subduction and Collision in Southeast Asia: Data and Models", Program and Extended Abstract*, 145-147.

Chen, C.H. and Wang, C.H. (1995) Explanatory notes for the metamorphic facies map of Taiwan (2nd ed.): *Special Pub. Central Geol. Surv*., **2**, 51. (in Chinese)

Clark, M.B. and Fisher, D. (1995) Strain partitioning and crack-seal growth of chlorite-muscovite aggregates during progressive noncoaxial strain: an example from the slate belt of Taiwan: *Jour. Struct. Geol*., **17**, 461-474.

Clark, M.B., Fisher, D.M., Lu, C.Y., and Chen, C.H. (1993) Kinematic analyses of the Hsuehshan Range, Taiwan: a large-scale pop-up structure: *Tectonics*, **12**, 205-217.

Crespi, J.M., Chan, Y.C. and Swaim, M.S. (1996) Synorogenic extension and exhumation of the Taiwan hinterland: *Geology*, **24**, 247-250.

CWB (Central Weather Bureau) (1990) *Climatic Atlas of Taiwan, Republic of China (I)*: Central Weather Bureau, Ministry of Communications, ROC. 96.

Ernst, W.G. (1983a) Mountain building and metamorphism: a case history from Taiwan. In: K.J. Hsu (Editor), *Mountain Building*, London, Academic Press, 247-256.

Ernst, W.G. (1983b) Mineral parageneses in metamorphic rocks exposed along Tailuko Gorge, Central Mountain Range, Taiwan: *J. Metamorphic Geol*., **1**, 305-329.

Ernst, W.G. (1984) The nature of biotite isograde in the Tailuko Gorge transect, Central Mountain Range, Taiwan: *Proc. Geol. Soc. China*, **27**, 25-40.

Faure, M., Lu, C.Y. and Chu, H.T. (1991) Ductile deformation and Miocene nappe-stacking in Taiwan related to motion of the Philippine Sea Plate: *Tectonophysics*, **198**, 95-105.

Fitch, T.J. (1972) Plate convergence, transcurrent faults, and internal deformation adjacent to southeast Asia and the western Pacific: *J. Geophys. Res*., **77**, 4432-4460.

Ho, C.S. (1988) An Introduction to the Geology of Taiwan: *Explanatory Text of the Geologic Map of Taiwan*: Ministry of Economic affairs, Taipei, Taiwan, 192.

Koons, P.O. (1989) The topographic evolution of collisional mountain belts: a numerical look at the Southern Alps, New Zealand: *Am. J. Sci*., **289**, 1041-1069.

Koons, P.O. (1990) Two-sided orogen: Collision and erosion from the sandbox to the Southern Alps, New Zealand: *Geology*, **18**, 679-682.

Koons, P.O. (1995) Modeling the topographic evolution of collisional belts: *Annu. Rev. Earth Planet. Sci*., **23**, 375-408.

Lee, Y.H. (1997) *Structural evolution of the middle Central Range during the Penglai Orogeny, Taiwan*: Ph.D. Dissertation, Inst. of Geology, Nat'l. Taiwan University, Taipei, Taiwan, 202. (in Chinese)

Li, Y.H. (1975) Denudation of Taiwan Island since the Pliocene Epoch: *Geology*, **4**, 105-107.

Lin, C.H. and Roecker, S.W. (1998) Active crustal subduction and exhumation in Taiwan. In: B.P. Hacker and J.G. Liou (Editors), *When Continents Collide: Geodynamics and Geochemistry of Ultrahigh-Pressure Rocks*, Kluwer Academic Publishers, Dordrecht, The Netherlands, 1-25.

Lin, C.H., Yeh, Y.H., Yen, H.Y., Chen, K.C., Huang, B.S., Roecker, S.W. and Chiu, J.M. (1998) Three-dimensional elastic wave velocity structure of the Hualien region of Taiwan: Evidence of active crustal exhumation: *Tectonics*, **17**, 89-103.

Liu, C.C. (1995) Geodetic monitoring of mountain building in Taiwan: *EOS Trans. AGU*, **76(46)**, 636.

Liu, M., Yang, Y., Stein, S., Zhu, Y. and Engeln, J. (2000) Crustal shortening in the Andes: Why do GPS rates differ from geological rates? *Geophys. Res. Lett*., **27**, 3005-3008.

Liu, T.K. (1982) Tectonics implication of fission track ages from the Central Range, Taiwan: *Proc. Geol. Soc. China*, **25**, 22-37.

Liu, T.K. (1988) Fission track dating of the Hsuehshan Range: thermal record due to arc-contitnent collision in Taiwan: *Acta Geol. Taiwanica*, **26**, 279-290.

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

Lo, C.H. and Onstott, T.C. (1995) Rejuvenation of K-Ar systems for minerals in the Taiwan mountain belt: *Earth Planet. Sci. Lett.*, **131**, 71-98.

Lu, C.Y. and Malavieille, J. (1994) Oblique convergence, indentation and rotation tectonics in the Taiwan Mountain Belt: Insights from experimental modeling: *Earth Planet. Sci. Lett.*, **121**, 477-494.

McCaffrey, R. and Nabelek, J. (1996) Role of oblique convergence in the active deformation of the Himalayas and southern Tibet plateau: *Geology*, **26**, 691-694.

Merle, O. and Guillier, B. (1989) The building of the Central Swiss Alps: and experimental approach: *Tectonophysics*, **165**, 41-56.

Pinet, N. and Cobbold, P.R. (1992) Experimental insights into the partitioning of motion within zones of oblique subduction: *Tectonophysics*, **206**, 371-388.

Platt, J.P. (1993) Exhumation of high-pressure rocks: a review of concepts and processes: *Terra Nova*, **5**, 119-133.

Shieh, S.L. (1990) *Fission-track dating of zircons from several east-west cross sections of Taiwan island*: Ms. Thesis, Inst. of Geology, Nat'l. Taiwan University, Taipei, Taiwan, 134. (in Chinese)

Stanley, R.S., Hill, L.B., Chang, H.C. and Hu, H.N. (1981) A transect through metamorphic core of the Central Mountains, southern Taiwan: *Mem. Geol. Soc. China*, **4**, 443-474.

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

Thompson, A.B., Schulmann, K. and Jezek, J. (1997) Thermal evolution and exhumation in obliquely convergent (transpressive) orogens: *Tectonophysics*, **280**, 171-184.

Tillman, K.S. and Byrne, T.B. (1995) Kinematic analysis of the Taiwan slate belt: *Tectonics*, **14**, 322-341.

Tsao, S., Li, T.C., Tien, J.L., Chen, C.H. and Liu, T.K. (1992) Illite crystallinity and fission-track ages along the east central Cross-Island Highway of Taiwan: *Acta Geol. Taiwanica*, **30**, 45-64.

Wang, P.L. (1997) K-feldspar $^{40}Ar/^{39}Ar$ *Thermochronology and its Applications*: Ph.D. Dissertation, Inst. of Geology, Nat'l. Taiwan University, Taipei, Taiwan, 198. (in Chinese)

Warneke, L.A. and Ernst, W.G. (1984) Progressive Cenozoic metamorphism of rocks cropping out along the Southern East-West Cross-Island Highway, Taiwan: *Mem. Geol. Soc. China*, **6**, 105-132.

Yen, T.P., Wu, C.H. and Chuang, T.Y. (1984) Geology along the southern Taiwan East-West Cross-Mountain Highway: *Special Pub. Central Geol. Surv.*, **3**, 11-24 (in Chinese).

Yu, S.B. and Chen, H.Y. (1996) Spatial variations of crustal strain in the Taiwan area: *The 6th Taiwan Symposium on Geophysics*, Chiayi, Taiwan, 659-668.

Yui, T.F. (1994) Carbon isotope composition of metamorphic rocks of Taiwan: *Program with Abstracts, Geol. Soc. China Annual Meeting*, 274-277.

Yui, T.F., Lu, C.Y. and Lo, C.H. (1990a) Tectonic evolution of the Tananao Schist Complex of Taiwan. In: J. Aubouin and J. Bourgois (Editors), *Tectonics of Circum-Pacific Continental Margins*, VSP, Uttrecht, 193-209.

Yui, T.F., Wu, T.W. and Jahn, B.M. (1990b) Geochemistry and plate-tectonic significance of the metabasites from the Tananao Schist Complex of Taiwan: *J. Southeast Asian Earth Sci.*, **4**, 357-368.

Yui, T.F., Huang, E. and Xu, J. (1996) Raman spectrum of carbonaceous material: a possible metamorphic grade indicator for low-grade metamorphic rocks: *J. Metamorphic Geol.*, **14**, 115-124.

Yui, T.F. and Chu, H.T. (2000) "Overturned" marble layers: Evidence for upward extrusion of the Backbone Range of Taiwan: *Earth Planet. Sci. Lett.*, **179**, 351-361.