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Nappe structure revealed by thermal constraints in the Taiwan metamorphic belt

Chih-Tung Chen,[1] Yu-Chang Chan,[2] Chia-Yu Lu,[1] Martine Simoes[3] and Olivier Beyssac[4]

[1]*Department of Geosciences, National Taiwan University, Taipei, Taiwan;* [2]*Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan;* [3]*Institut de Physique du Globe de Paris, Sorbonne Paris Cité, UMR 7154 CNRS, F-75005, Paris, France;* [4]*Institut de Minéralogie et de Physique des Milieux Condensés, Universite Pierre et Marie Curie, CNRS UMR7590, Paris, France*

ABSTRACT

Vitrinite reflectance and Raman spectroscopy of carbonaceous material data are used to better resolve the thermal history of the Hsuehshan Range, which is accreted between the foreland fold–thrust belt and bulldozer hinterland units in the Taiwan mountain belt. The observed thermal data indicate that the strata in the northern Hsuehshan Range underwent dynamic metamorphism during the Neogene orogeny, while the strata in the southern Hsuehshan Range may have predominantly experienced burial metamorphism during Palaeogene sedimentation. Based on the thermal constraints, the Hsuehshan Range is interpreted to consist of nappe stacks, originating from the rifted Eurasian continental margin. This interpretation is consistent with well-documented cases in the European Alps and the Himalayas and is also shown in physical modelling and thermo-kinematic studies invoking underplating and erosion processes.

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Introduction

The island of Taiwan was created by active convergence between the Luzon arc of the Philippine Sea Plate and the Eurasian continental margin in the late Miocene and early Pliocene (Suppe, 1981; Teng, 1990). In the Taiwanese mountains, underplating (i.e. basal accretion) has been proposed to contribute <25% (e.g. Dahlen and Barr, 1989), approximately 50% (Fuller *et al*., 2006) or more than 90% (Simoes *et al*., 2007) of the influx of material into the orogenic wedge. The underplating process substantially compensates for materials removed by surface erosion based on previous studies on the central part of Taiwan (Fuller *et al*., 2006; Simoes and Avouac, 2006; Simoes *et al*., 2007, and references therein). However, little attention has been paid to the northern part of the island, where the collision process is waning, if not at a total halt. As the northern part records a longer history of mountain growth, it provides better opportunities for studying the *P*–*T* paths and dynamic processes during the Neogene orogeny.

In this article, the thermal metamorphism of the Hsuehshan Range in Taiwan is investigated through a new compilation of vitrinite reflectance (VR) data (Chiu and Chou, 1988; Lin and Kuo, 1996; Lin *et al*., 2001) and the published Raman spectroscopy of carbonaceous materials (RSCM) measurements of Beyssac *et al*. (2007). The Hsuehshan Range is a prominent physiogeographic division accreted between the foreland fold–thrust belt and hinterland units in the Taiwan mountain belt (Lu and Hsu, 1992; Clark *et al*., 1993; Chan *et al*., 2005; Shyu *et al*., 2005). The pattern of observed peak metamorphic temperatures provides new perspectives on the structural evolution of the Hsuehshan Range and, at the same time, highlights the important roles of underplating and surface erosion on the present mountain structure, as also shown in recent physical modelling and thermo-kinematic studies (Bonnet *et al*., 2007; Simoes *et al*., 2007; Malavieille, 2010).

Correspondence: Dr Yu-Chang Chan, Institute of Earth Sciences, Academia Sinica, 128 Sec. II Academia Road, Nankang, Taipei 115, Taiwan. Tel.: +886 2 27839910; fax: +886 2 27839871; e-mail: yuchang@earth.sinica.edu.tw

Regional background

The Hsuehshan Range, bounded by the Chuchih Fault and the Lishan Fault (Lee *et al*., 1997), is composed of metamorphosed and exhumed continental margin sediments, which were deposited in then-subsiding grabens related to the Palaeogene opening of the South China Sea (Teng, 1992) (Fig. 1). The meta-sediments in the northern Hsuehshan Range are divided into the following stratigraphic units: the Eocene Hsitsun Formation, the Oligo-Eocene Szeleng Sandstone, the Oligocene Kankou Formation, the Oligocene Tsuku Sandstone, the late-Oligocene Tatungshan Formation and the early–middle Miocene Sule Formation. In the eastern part of the northern Hsuehshan Range, the Tatungshan, Tsuku and Kankou Formations become indistinguishable and are pooled into the Paling Formation

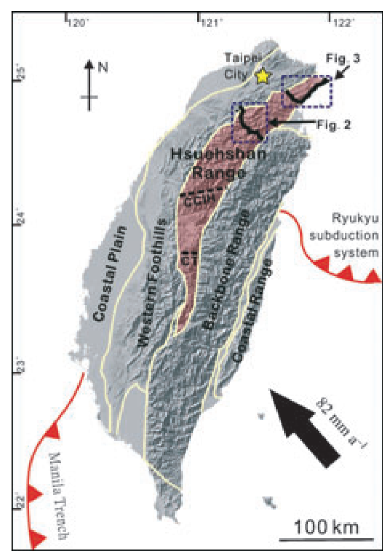

Fig. 1 Simplified geologic divisions of Taiwan with the Hsuehshan Range highlighted. The region along the Northern Cross-Island Highway is presented in Fig. 2, and the region along the Taipei-Ilan Highway and the North Coast Highway is presented in Fig. 3. CCIH, Central Cross-Island Highway; CT, Choshui Transect. Plate convergence rate and direction are from Yu *et al*. (1997).

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(Fig. 2). In contrast, the central and southern Hsuehshan Range is composed of another set of stratigraphic units: the Eocene Tachien Sandstone, the Oligocene Paileng Formation, the Oligocene Chiayang Formation and the late-Oligocene Shuichangliu Formation. All of the formations were deformed during the Neogene orogeny and have traditionally been assigned to the prehnite–pumpellyite metamorphic facies with a core of lower greenschist facies in the eastern part of the range (Chen and Wang, 1995; Beyssac *et al.*, 2007).

Metamorphic temperature constraints from RSCM data

The RSCM method, a novel geothermometer recording the maximum metamorphic temperature of carbonaceous materials (Beyssac *et al.*, 2002), was applied to the slates in the Hsuehshan Range on the Central Cross-Island Highway (CCIH) and the Choshui Transect (CT) (Fig. 1). The RSCM temperatures range from 350 to 475 °C along the CCIH in the Chiayang Formation, exhibiting a reasonable geothermal gradient of ~30 °C km^{-1}. The RSCM temperatures are below 330 °C in the Paileng

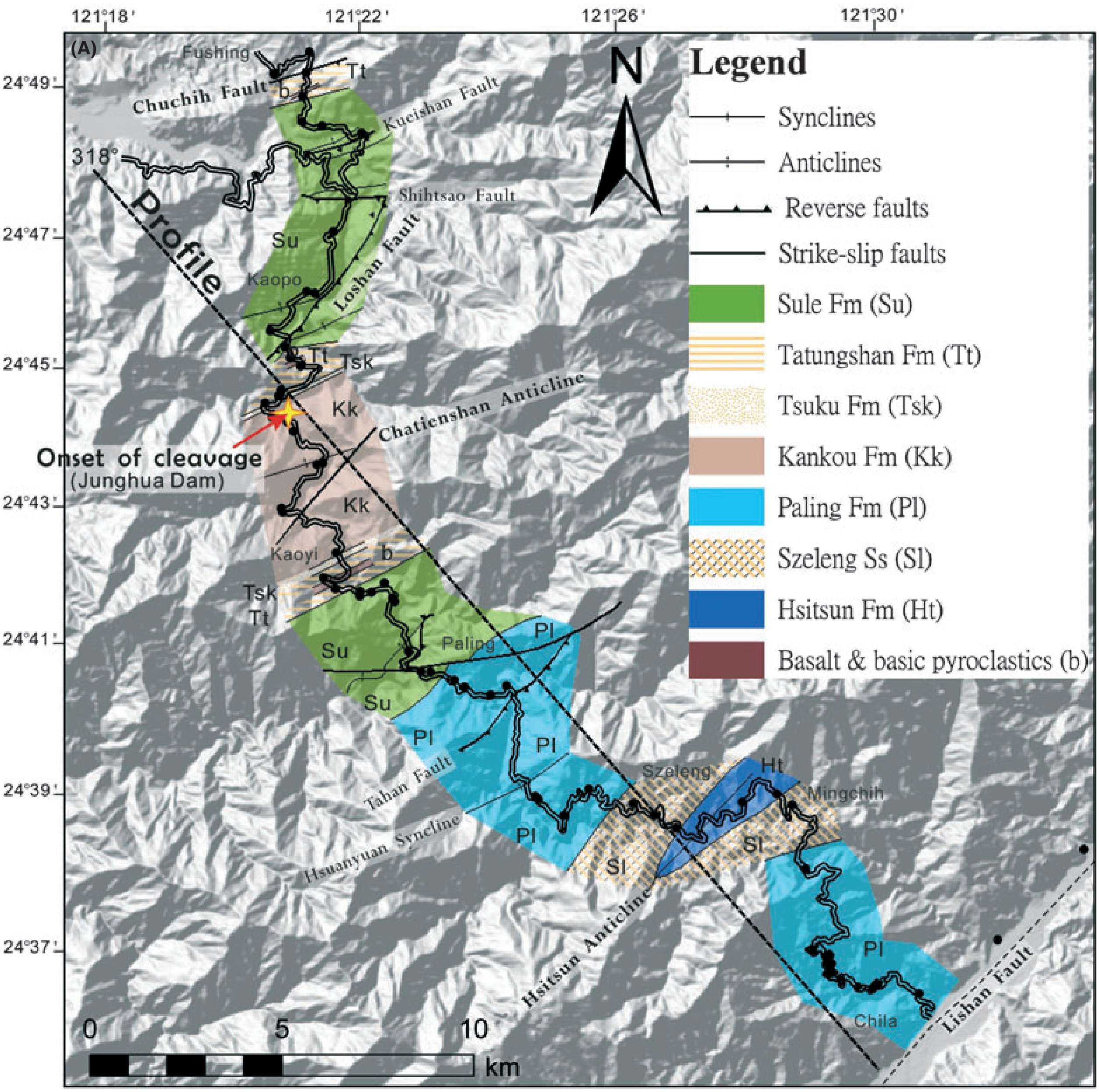

Fig. 2 (A) Geologic strip map of the Northern Cross-Island Highway transect. Vitrinite reflectance sampling sites from Lin and Kuo (1996) and Chiu and Chou (1988) are marked as black dots. (B) Sketch of the geologic structures along the transect shown in (A), with projected sampling sites of vitrinite reflectance measurements. (C) The profile of vitrinite reflectance values along the transect. (D) Derived maximum temperature profile of the transect.

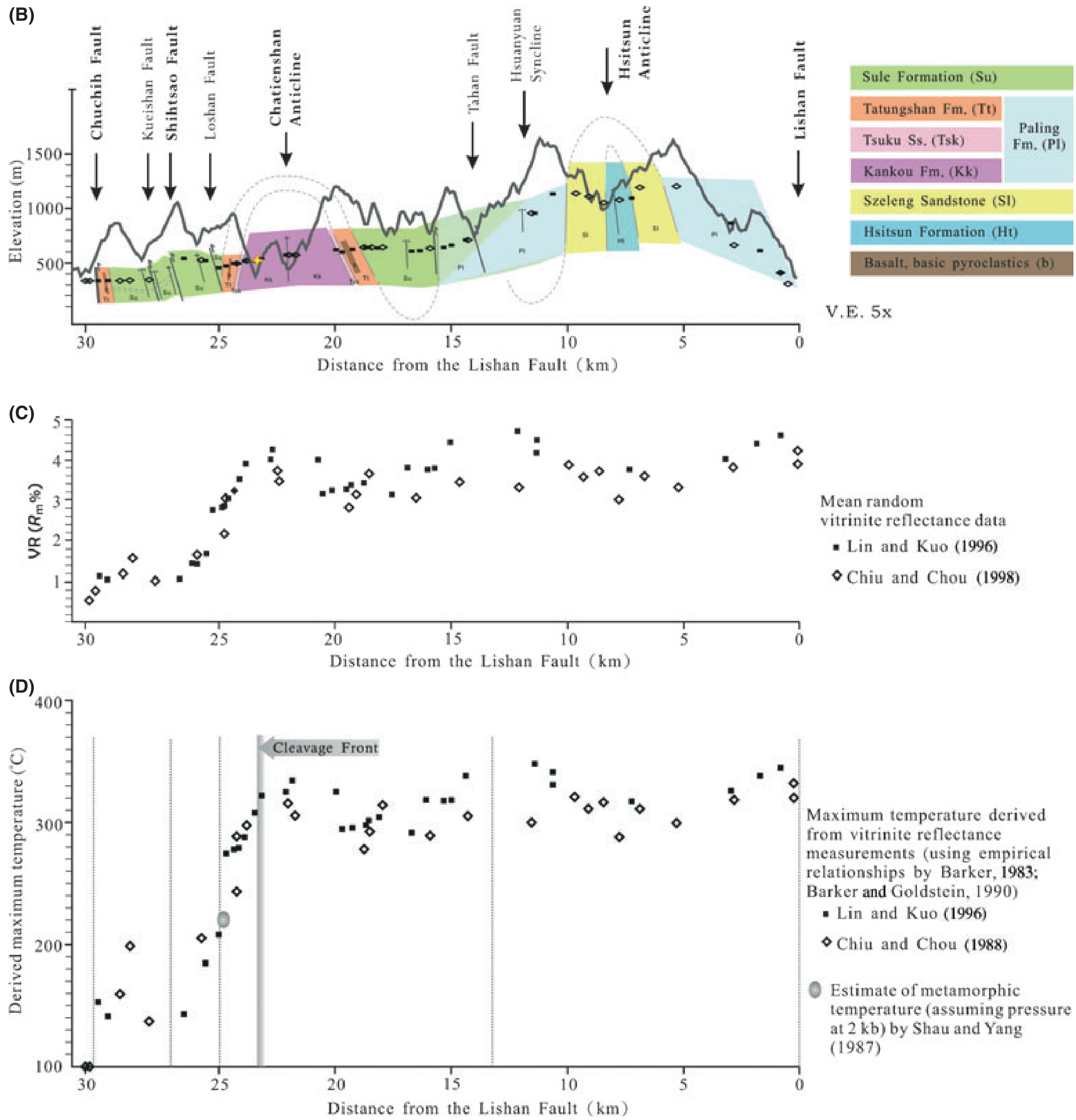

Fig. 2 Continued

Formation. Thermochronological data including zircon fission track and (U–Th)/He and apatite fission track dating are totally reset to Plio-Pleistocene ages in the Chiayang Formation/Tachien Sandstone and partially reset in the Paileng Formation (Liu *et al.*, 2001; Fuller *et al.*, 2006; Beyssac *et al.*, 2007). Along the CT transect, the RSCM temperatures remain between 345 and 375 °C in the Chiayang Formation and below 330 °C in the Paileng Formation, while the Tachien Sandstone is thermochronologically reset (Beyssac *et al.*, 2007).

Since all the rocks were deposited during the Palaeogene, post-dating the previous Cretaceous orogeny (Yui *et al.*, 1988), the observed metamorphic records are all associated with the Cenozoic sedimentation and orogenic processes. Three lines of evidence indicate that the metamorphism of the central–southern part of the Hsuehshan Range is predominantly static or burial metamorphism. First, the uppermost Paileng Formation is associated with low temperatures (below 330 °C), and zircon fission track and (U–Th)/He dates are not reset or partially reset; secondly, the Chiayang Formation is associated with higher temperatures (from 330 to 475 °C) down-section and eastward, i.e. deeper in the half-graben deposition basin; and, thirdly, the lowermost Tachien Sandstone is thermochronologically reset, as shown by existing zircon fission track and (U–Th)/He dates. The meta-sediments were then heated in the basins on the rifted Eurasian continental margin, which can be over 10 km deep (Lin *et al.*, 2003), and subsequently transported to the surface during the Neogene orogeny (Beyssac *et al.*, 2007; Simoes *et al.*, 2007).

Metamorphic temperature constraints from VR data

Vitrinite reflectance measures irreversible coalification, which sensitively reflects the diagenesis and metamorphic conditions of the host rock (Teichmüller, 1987). Its value is affected by several kinetic factors, but for heating durations over 10 000 years the maximum temperature is the major control (Barker, 1983). Therefore, VR is considered a reliable geothermometer in diagenetic to lower greenschist facies rocks for peak temperatures not exceeding 400 °C (Barker and Goldstein, 1990). The mean random VR as a percentage (R_m) and the maximum temperature (T_M) have an empirical logarithmic relation:

$$T_M = \frac{\ln(R_m) + 0.832}{0.00683} \text{ (Barker, 1983).}$$

$$T_M = \frac{\ln(R_m) + 1.26}{0.00811} \text{ (Barker and Goldstein, 1990).}$$

The rocks of the Hsuehshan Range contain abundant organic material and have been heated during deep burial and/or metamorphism over million-year time-scales. They are thus suitable for VR studies. Here, we integrate VR measurements along the Northern Cross-Island Highway (NCIH) (Chiu and Chou, 1988; Lin and Kuo, 1996), the Ilan-Taipei Highway and the North Coast Highway (Lin *et al.*, 2001) in northern Taiwan. The VR data are converted to peak metamorphic temperatures using the empirical equations above. We then mapped the derived temperatures to reveal the pattern and spatial variation of metamorphism.

VR results in the north-central part of the range

A geologic map and the distribution of maximum metamorphic temperatures along the NCIH are presented in Fig. 2. The area comprises a series of NNE-trending folds and reverse faults, with depositional ages spanning from late Eocene to middle Miocene (Fig. 2A,B). The combined VR datasets from Chiu and Chou (1988) and Lin and Kuo (1996) provide exceptionally detailed sampling, with 58 measurements along the 30 km long transect. The VR values (Fig. 2C) and the derived peak tem-

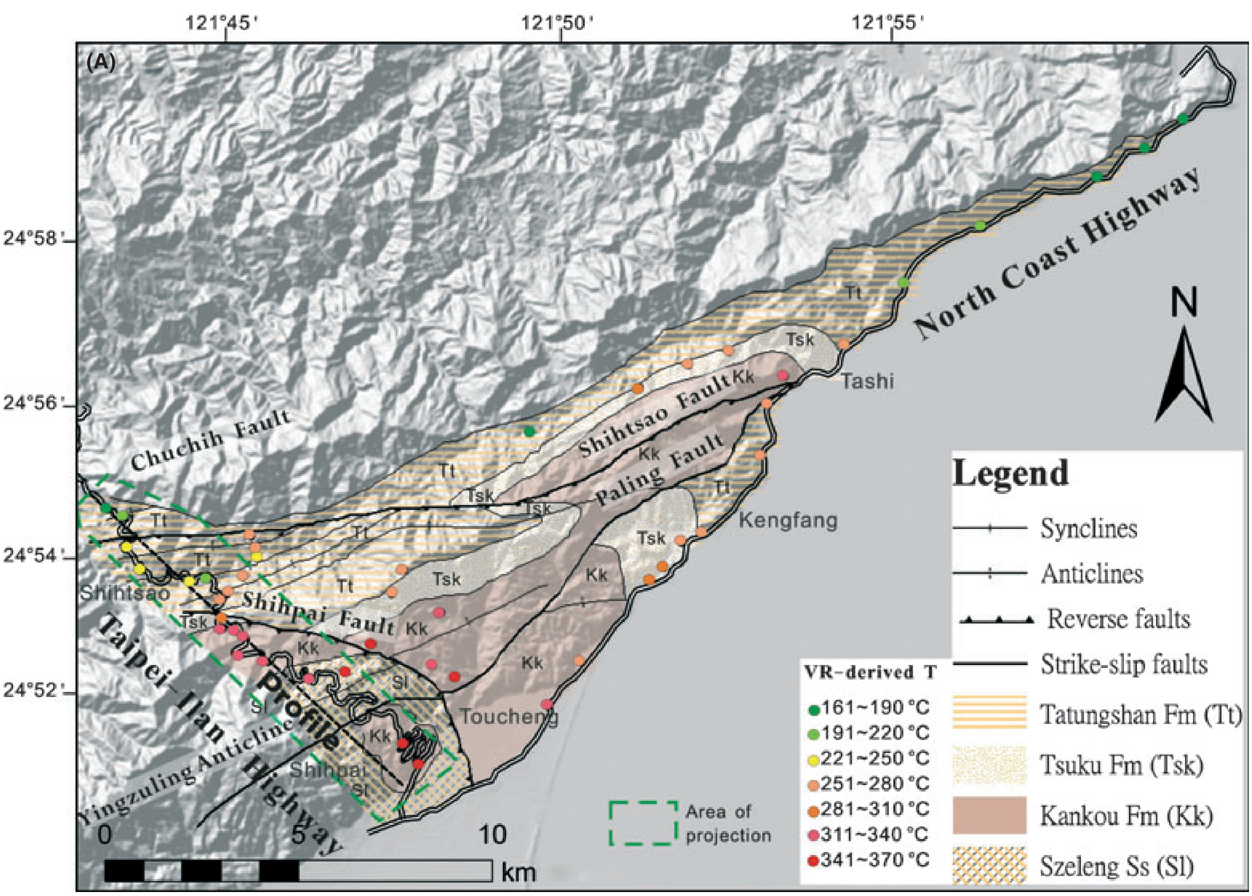

Fig. 3 (A) Geology of the northernmost part of the Hsuehshan Range. Vitrinite reflectance sampling sites and the maximum temperatures derived from vitrinite reflectance data from Lin *et al.* (2001) are marked by coloured dots. Data and area incorporated into the Taipei-Ilan Highway transect are indicated. (B) Geologic structures along the Taipei-Ilan Highway transect with projected sampling sites of vitrinite reflectance measurements. (C) Derived maximum temperature profile along the transect.

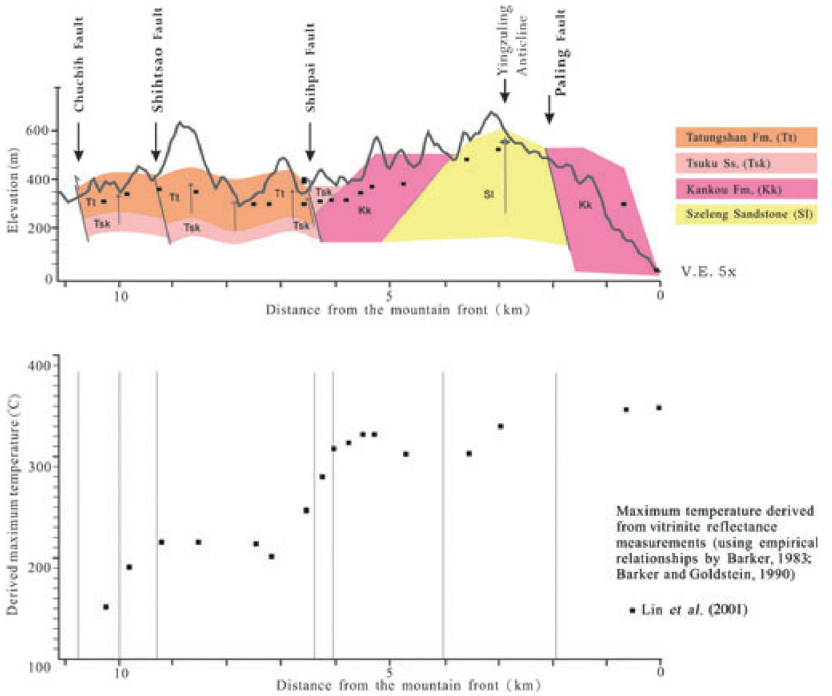

Fig. 3 Continued

peratures (Fig. 2D) exhibit a relatively simple pattern. Across the Chuchih Fault the VR value increases abruptly and the T_M ascends above 100 °C from the Western Foothills to the Hsuehshan Range. The T_M remains stable at around 150 °C between the Chuchih and Shihtsao Faults. Southeastward from the Shihtsao Fault, the T_M rises rather linearly from 150 °C to over 300 °C at the core of the Chatienshan Anticline. The pattern of derived temperatures agrees with the petrology of meta-basalts proposed by Shau and Yang (1987).

For the rest of the NCIH transect, starting at the Junghua Dam, where slaty cleavage becomes visible, the T_M values cluster mostly between 300 and 350 °C without significant variation and are almost totally unrelated to the stratigraphic position and structures. The VR data indicate that the Eocene to Miocene rocks between the Chatienshan Anticline and the Lishan Fault have been subjected to similar peak metamorphic temperatures, equivalent to 10–20 km depth assuming a geothermal gradient of 15–30 °C km^{-1}. The fact that the VR-derived temperatures do not correlate with stratigraphy suggests that dynamic metamorphism overprinted the original burial metamorphism along the NCIH transect.

VR results in the northern-most part of the range

At the northern tip of the Hsuehshan Range, Oligocene meta-sediments of the Szeleng, Kankou, Tsuku and Tatungshan Formations crop out and are deformed into a series of NE-trending folds and reverse faults (Fig. 3A). By plotting the VR data of Lin *et al.* (2001) and their derived T_M values (Fig. 3A), two different patterns of metamorphic grade can be observed. In the southern part of the area, along the Taipei-Ilan Highway, the documented metamorphic temperatures are clearly decoupled from stratigraphy, as observed along the NCIH. Figure 3B shows the geologic cross-section of the Taipei-Ilan Highway transect, where the Chuchih, Shihtsao and Shihpai Faults seem to affect the R_m and derived T_M values (Fig. 3C). Between the Shihtsao and Shihpai Faults, despite the presence of several mappable folds and possible Miocene strata, peak metamorphic temperatures are almost constant at 230–240 °C.

At the Shihpai Fault the T_M profile exhibits a remarkably steep and continuous rise within the area of the Tsuku Sandstone, reaching about 330 °C, resembling what is observed on the western limb of the Chatienshan Anticline in the NCIH transect. At the southeastern end of the profile lies a major south-dipping normal fault bounding the Ilan Plain. The Ilan Plain is connected to the actively rifting Okinawa Trough and may have enhanced exhumation of the Hsuehshan Range rocks (Clift *et al.*, 2008). In the rest of the region, particularly north of the Shihpai Fault, R_m and T_M are closely associated with stratigraphy: 130–230 °C for the Tatungshan Formation, 230–300 °C for the Tsuku Formation and 300–330 °C for the Kankou Formation.

Discussion

According to the thermal data from VR and RSCM measurements, three distinct metamorphic regimes can be distinguished in the Hsuehshan Range (Fig. 4). (1) In the central to southern part of the range (viewed as an upper nappe unit) peak temperatures correspond to 20 km deep stratigraphic levels in the original sedimentary basin settings with a reasonable geothermal gradient (Beyssac *et al.*, 2007) and an eastward deepening of sedimentary levels matching the half-graben structures during the Eo-Oligocene opening of the South China Sea (Teng, 1992). (2) In the internal portion of the northern part of the range (viewed as a lower nappe unit), located east of the Shihtsao Fault along the NCIH and south of the Shihpai Fault on the Taipei-Ilan Highway, meta-sediments have lost their burial diagenetic signatures and are dynamically metamorphosed. (3) In the external portion of the northern part of the range (viewed as a shallow duplex unit), the strata preserve their rather high and SE-increasing diagenetic temperatures, with closely spaced fold-and-thrust structures.

We propose that the upper nappe unit and the shallow duplex unit acquired their peak metamorphism during the Palaeogene as a result of diagenesis and that they were later transported upward and deformed at lower temperatures during the Neogene orogeny (Simoes *et al.*, 2007) without prograde metamorphic overprinting. In contrast, the lower nappe unit was tectonically buried to levels

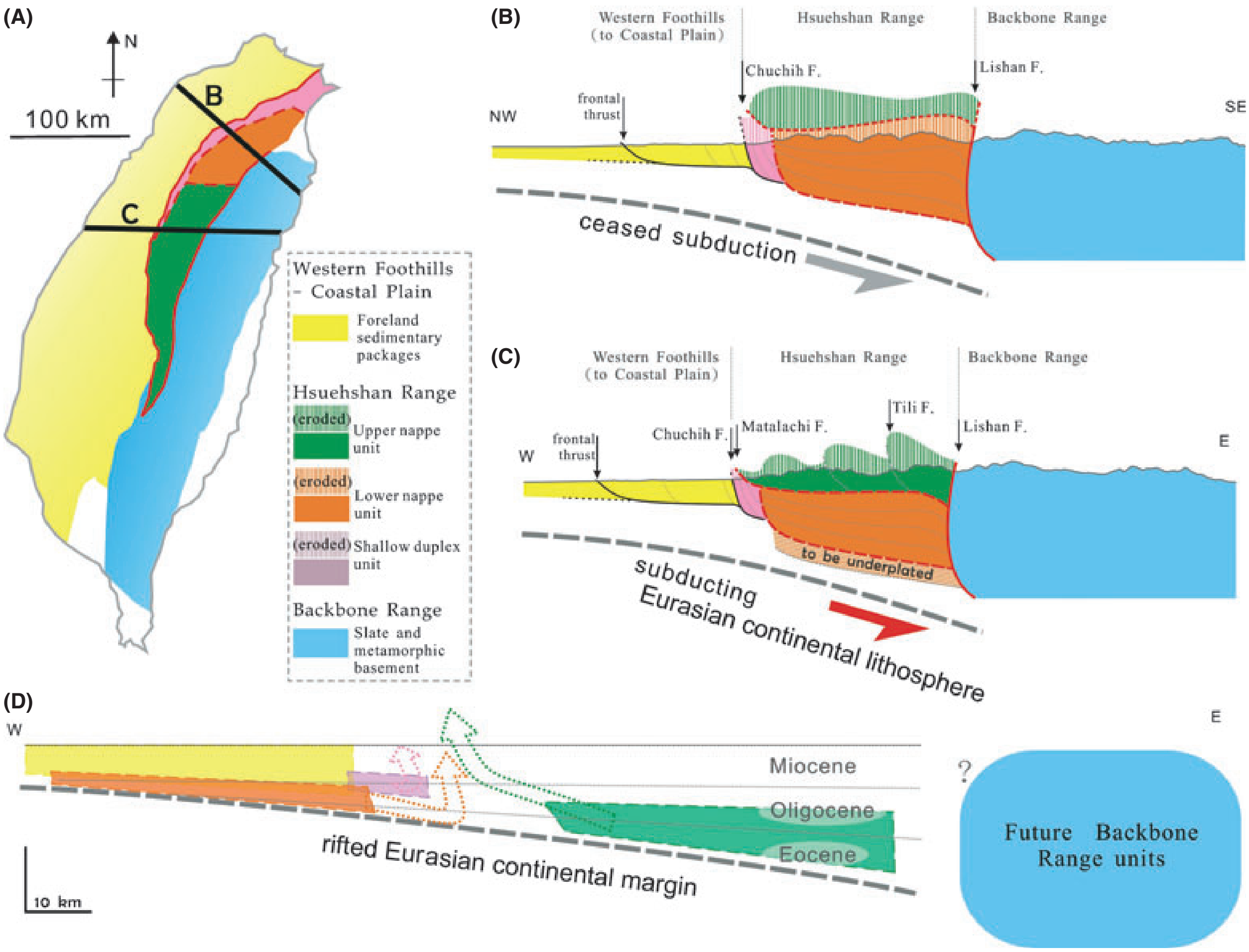

Fig. 4 Proposed tectonic model of the Hsuehshan Range with nappe structures. (A) Simplified geologic map and the studied transects. (B) Structural profile across the northern part of the range, where underplated lower nappes are exposed. (C) Structural profile across the central part of the range, where the upper nappe unit is above the Matalachi Fault. (D) Depositional configurations on the original rifted Eurasian continental margin and inferred transport paths of the depositional units (after Lin *et al.*, 2003; Simoes *et al.*, 2007).

deeper than the previously deposited levels and thermally overprinted during the Neogene orogeny. The observed thermal data suggest that the lower nappes were first subducted and then underplated into the orogenic wedge, probably at 10–20 km depth assuming a 15–30 °C km^{-1} geothermal gradient. The peak temperatures experienced by the lower nappes, ranging from about 300 to 350 °C, can be interpreted as temperatures at the detachment level during underplating of the lower nappes. This interpretation was similarly stated in the wedge kinematics as modelled by Simoes *et al.* (2007) where the underplating mechanism was mentioned.

To bring together the above observations and arguments, a tentative tectonic model of the Hsuehshan Range is proposed (Fig. 4). Along the profile of the CCIH (Fig. 4C), the continental margin sediments were accreted into the orogenic wedge, driven by the bulldozer of the Backbone Range (Lu and Hsu, 1992; Shyu *et al.*, 2005). The accretion process formed a thin-skinned fold-and-thrust belt, i.e. the Western Foothills, and the complex Hsuehshan Range capped by the upper nappe unit, which was uplifted by underplating. Nappe stacks resulting from underplating are commonly observed in orogenic belts. Underplating may occur simultaneously with frontal accretion, exerting significant controls on wedge development (Fuller *et al.*, 2006; Simoes and Avouac, 2006; Beyssac *et al.*, 2007; Bonnet *et al.*, 2007; Simoes *et al.*, 2007; Malavieille, 2010). Further north along the NCIH (Fig. 4B), the upper nappe unit has been eroded in windows that expose the underplated lower nappes. The Matalachi Fault, a formerly well-recognized boundary fault in the Hsuehshan Range (Biq, 1989), is considered to be the main detachment between the upper and lower nappes. The original sedimentary configuration of the Eurasian continental margin before the Neogene orogeny is schematically reconstructed in Fig. 4D. The figure shows that the Eo-Oligocene sedimentary boundary is tilted, reflecting the Palaeogene rifting, and the tectonic transport paths for the upper and lower nappes and shallow duplex unit.

Conclusion

We interpret the southern Hsuehshan Range in Taiwan as a detached nappe originating from the deep portion of the rifted Eurasian continental margin, based on the observed thermal data. The Eo-Oligocene nappe strata were transported in the foreland direction and subsequently uplifted by the stacking of underplated materials during the Neogene orogeny. A portion of the allochthonous nappe has been eroded, exposing the underplated nappes in the northern Hsuehshan Range. The interpreted nappe stack in Taiwan further supports the essential processes, such as basal accretion and surface erosion (e.g. Simoes and Avouac, 2006; Simoes *et al.*, 2007; Malavieille, 2010), simultaneously acting upon the Taiwan accretionary orogen.

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