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The Thermal- Mechanical Evolution of Mid-Hsuehshan Range, Taiwan: Through Numerical Modeling and ZFT Ages

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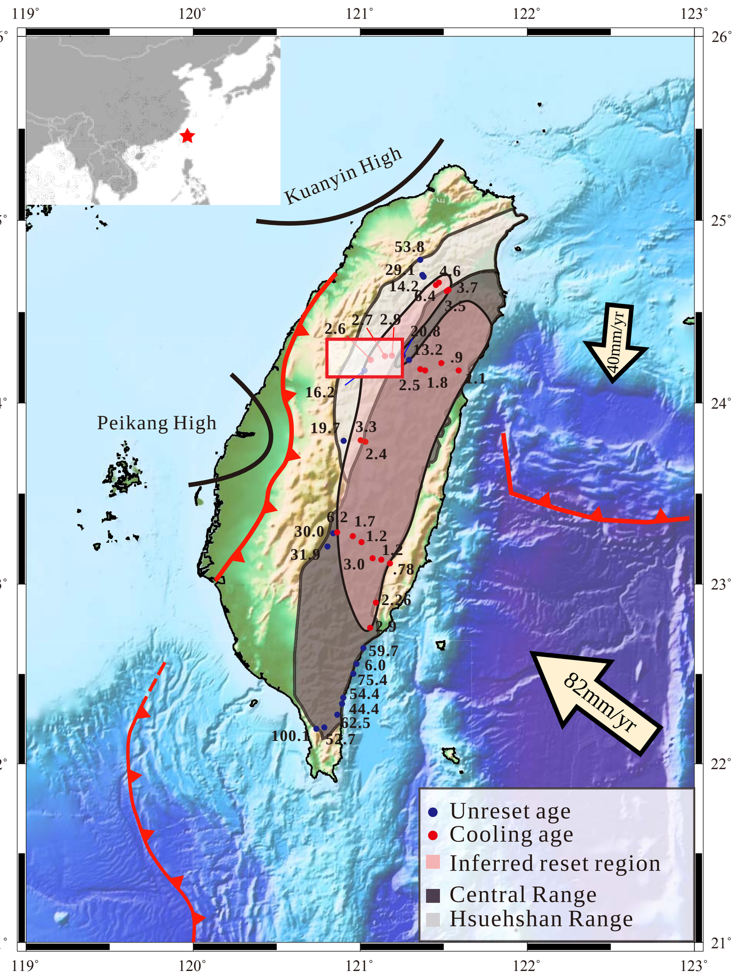

Figure 1. The tectonic setting of Taiwan (Modified after [2~3]). The inferred totally reset region of zircon fission track is located in the mountain area of Taiwan, however it splits into two zones to the north. The red rectangle is the study area (Fig. 2).

Introduction

Taiwan (Fig. 1), situated on the boundary between the Philippine Sea plate and the Eurasia plate, is one of the youngest orogenies in the world. Located in central Taiwan with high denudation rates, the NNE-SSW trending Hsuehshan Range (HR) is the second largest range (another one is Central Range). In most previous studies, the forward modeling results cannot simulate this second mountain peak except one study [1]. This phenomenon is working only by assuming two underplating windows in the numerical model.

In this study, we discuss local uplifts rate in mid-HR (Fig. 2) using six newly reported zircon fission track (ZFT) ages together with previously published data regarding the non-steady state one dimension thermal advection-diffusion model. Furthermore, for the purpose of testing the assumption of the tectonic framework, we simulate the formation of Hsuehshan range by introducing the thermal-mechanical model and then by comparison between the mode predicted results and real ZFT ages.

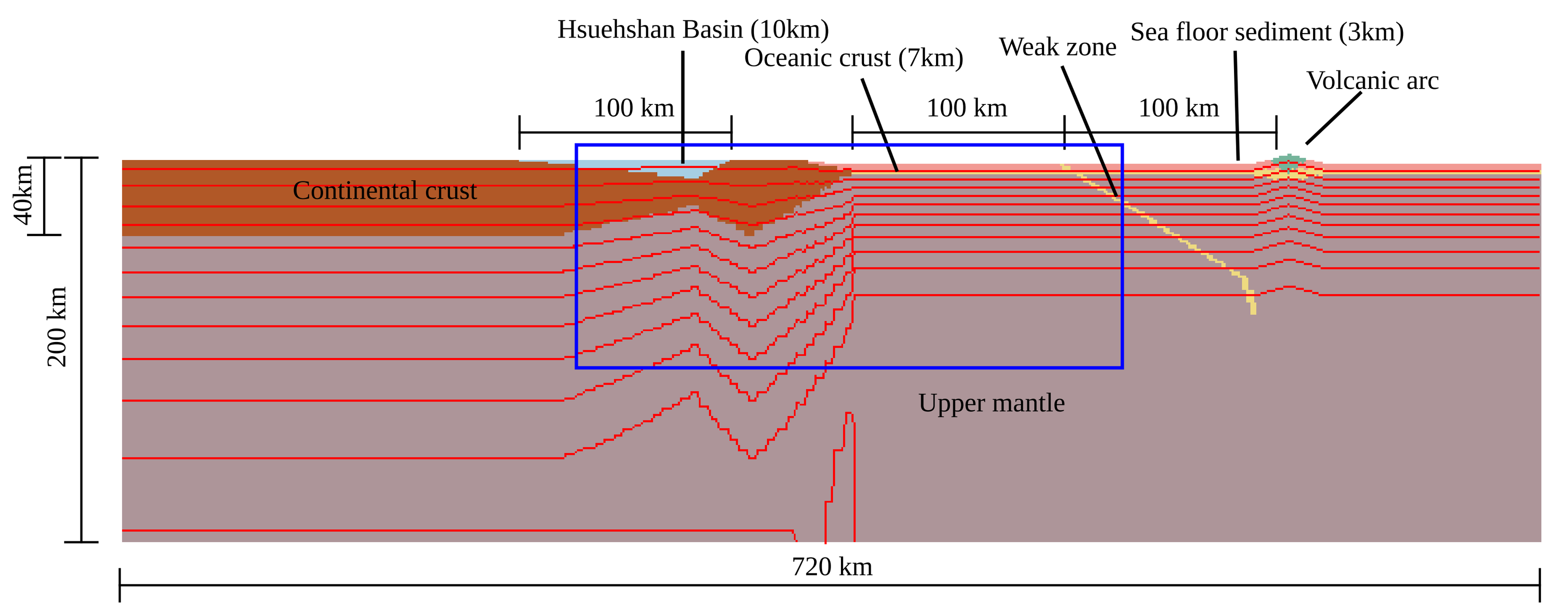

Figure 4. The initial setting of thermal-mechanical model.
The dimension of mesh is 419 × 63. The highest resolution is 1.5 km × 1.5 km. Surface and bottom temperature are 10°C and 1200°C respectively. The interval of isotherm (red line) is 100°C. The dip of weak zone is ~37°. The result in blue frame is Fig. 9.

Methods

1. Thermochronometry

Thermochronometer is a counter that records the elapsed time when the target mineral cools down below its own closure temperature. The closure temperature of ZFT is generally around 220-260°C, depending on cooling rates [11]. A total of 149 ZFT grain ages are obtained from 6 sandstone samples collected from mid-Hsuehshan Range. The Zeta value for the standard glass NBS-610 was evaluated to be 36.11 ± 6.1 (1σ) in experiments.

2. Modeling

a) 1D thermal advection-diffusion (A-D) model

A finite difference one-dimension thermal advection-diffusion code has been developed, in FORTRAN 95, to solve cooling history of thermochronometers. The kernel is based on Fourier's Law and conservation of energy in 1D (Table 1a). The values of thermochronometer closure temperature are based on cooling rate of ZFT [11] and (U-Th)/He zircon (ZHe, closure temperature is ~ 180°C) [12] respectively. Assuming the temperature at the surface and bottom of lithosphere is constant 0°C and 1200°C, the thickness is 100 km. Thermal conductivity is 4 mWm^{-1}k^{-1}. Mesh resolution is 50 m.

b) Thermal-mechanical model

Previous studies have suggested that the strata deformation in mid-HR are mainly ductile [4], we deliberately picked up appropriate numerical and rheological approximations relevant to the thermal-mechanical processes occurring in the lithosphere in order to model the formation of HR. We use the Fast Lagrangian Analysis of Continua (FLAC) technique improved by Tan et al. [13]. We add a subroutine to compute the cooling ages of thermochronometers following the cooling-rate-closure-temperature-dependent relationship. To better constrain the predicted model, we also evaluated the surface processes, such as erosion by stream power law and deposition by distance to the coastline (Table 1b, 1c). The tectonic settings of initial model (Fig. 4) are based on previous studies [14-15] and the rocks have own properties (Table 2).

Table 1. Formulae.

a. Fourier's Law for hear transfer.

$$\vec{q} = k\nabla T$$

q: Heat flow(W t^{-1}m^{-2})
k: Thermal conductivity (W m^{-1}k^{-1})
T: Temperature (°C)

b. Stream power law for erosion.

$$e = k_{sn} \times s^m \times a^n$$

e: Erosion rate (km/myr)
k_{sn}: Erosion constant (5×10^{-2})
s: Slope
a: Drainage area (km; distance to the divide in 2D)
m: 0.4; n: 0.3

c. Testing equastion for deposition.

$$d = k_{dp} \times x^i \times y^j$$

d: Deposition rate (km/myr)
k_{dp}: Deposit constant
x: Distance to nearest coast (km)
y: The depth to the erosion base line (km).
i: -1; j: 0.3

Table 2. Phase properties [16].

	Density (g m^{-3})	Friction angle (°)	Thermal conductivity (mW m^{-1}k^{-1})	Heat capacity (J kg^{-1} °C^{-1})
Granite (continental crust)	2800	30	3.05	958
Basalt/Dunite (oceanic crust)	3000	30	3.01	1230
Olivine (upper mantle)	3300	30	2.00	960
Meta-sandstone (Hsuehshan Basin)	2650	20.3	5.26	991
Andesite (volcanic arc)	2850	30	2.26	1136
Shale (sea flood sediment)	2800	7	2.07	1180

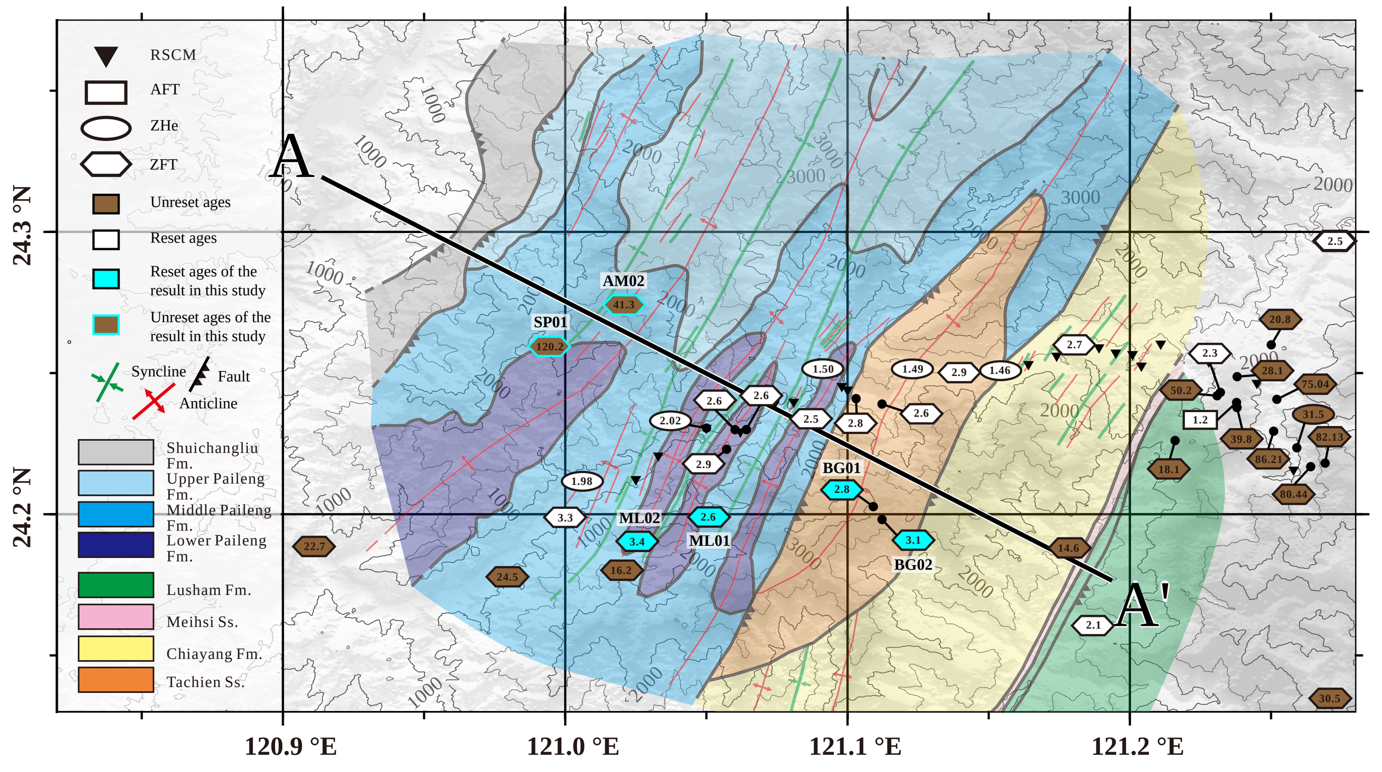

Figure 2. Study area in mid-Hsuehshan Range (Modified after [4]).
The map shows the structure framework in study area. In this area, the strata are composed mainly of meta-sandstone and slate is minor. Ductile deformation (buckling type) is widely distributed and the strain of strata is around ~0.3 [5]. The numbers are the ages of published thermochronological data form [6-10]. RSCM: raman spectrum carbonaceous material. AFT: apatite fission track. ZHe: (U-Th)/He zircon. ZFT: zircon fission track.

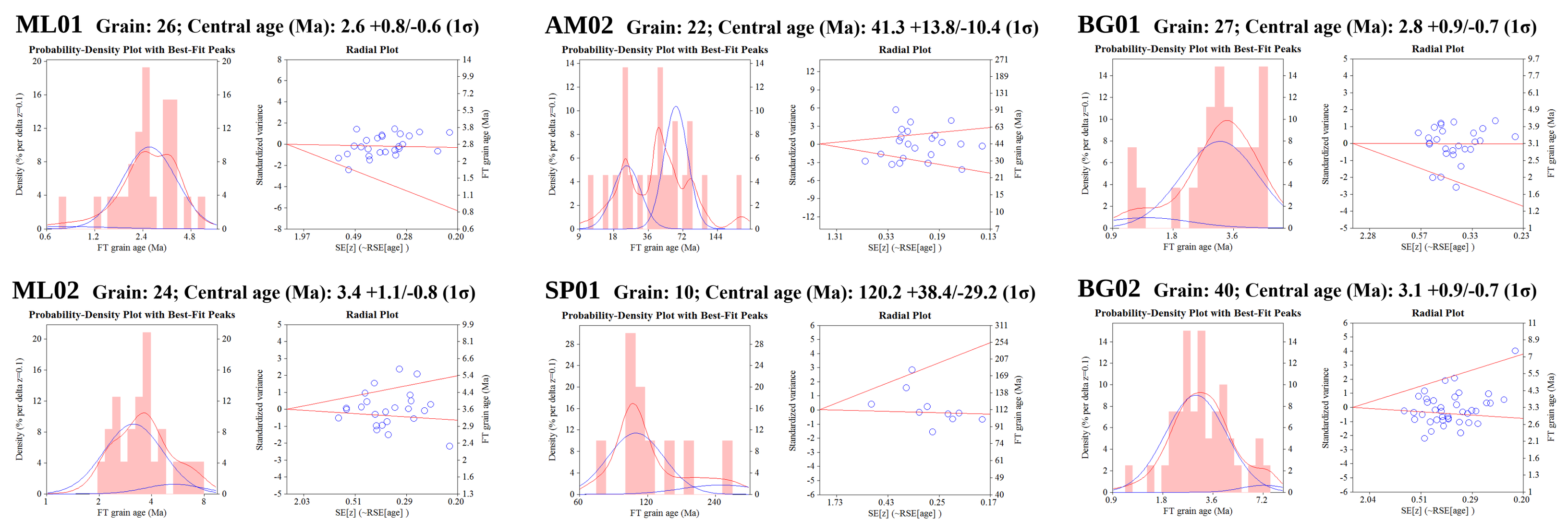

Figure 3. Probability density plot with best-fit peaks and radial plot of six ZFT samples.

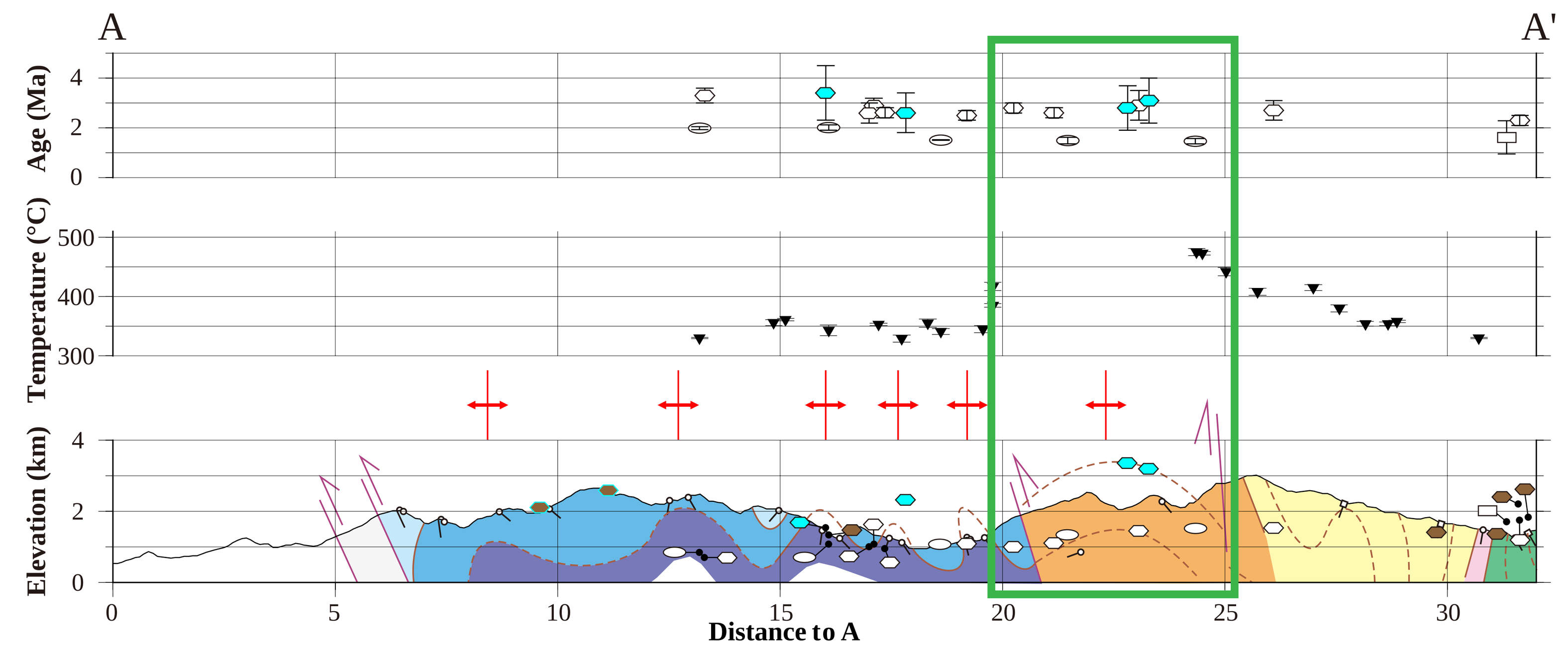

Figure 5. A-A' profile in study area [4].
The legends are the same as in Fig 2. The thermochronological data in green frame are used to compare with 1D A-D model.

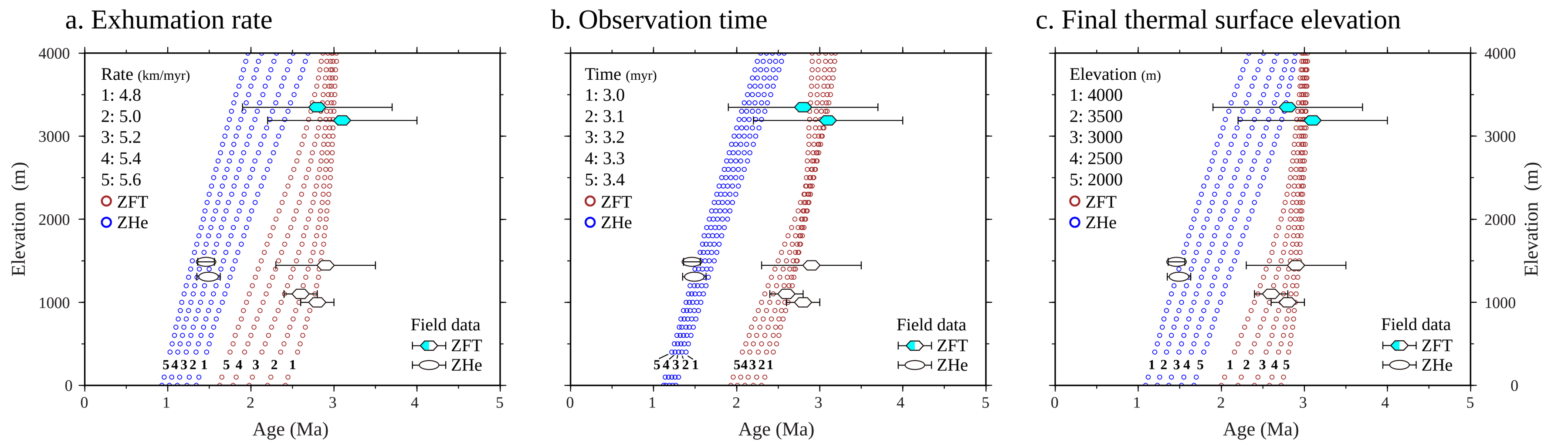

Figure 7. The sensitivity tests of 1D advection-diffusion model.
The brown and blue circles represent age elevation relationship of ZFT and ZHe in 1D model respectively. The symbols with error bars are the thermochronological data in green frame, Fig. 5. The parameters of three models are: 1) Lithosphere thickness, 100km. 2) Geotherm, 13°C/km. 3) Thermal conductivity, 4 mWm^{-1}k^{-1}. 4) Exhumation rate, 5 km/myr (changed in test a). 5) Observation time, 3.1 myr (changed in test b). 6) Final thermal surface elevation, 3500 m (changed in test c).

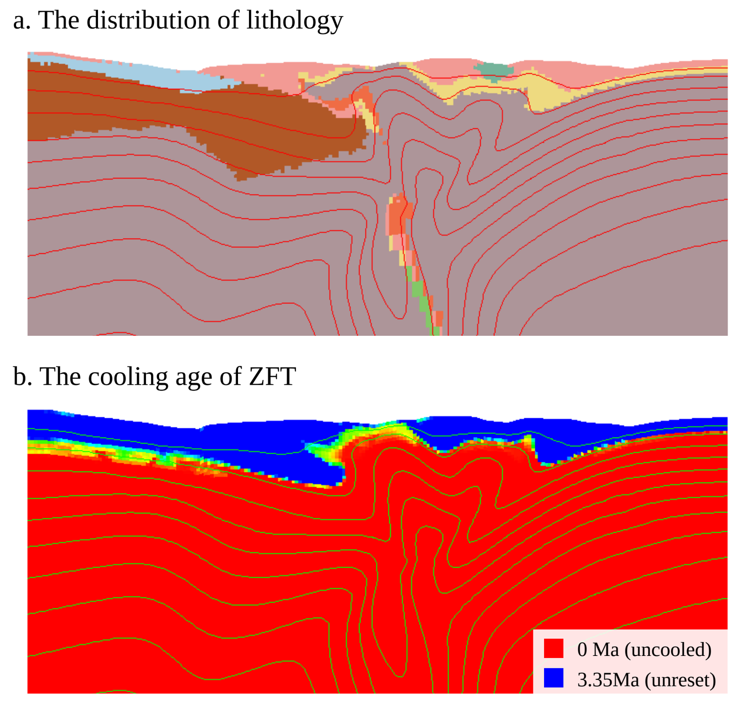

Figure 9. The feasibility test result of thermal-mechanical model. The figure represents the snapshot at 3.35 myr around subduction zone.

Result & Discussion

1. Zircon fission track ages

All of the experimental ages are shown in Fig. 3. Taking the horizontal lithology variation of mid-Hsuehshan Range into account, we choose a zone (Fig. 5, 20-25 km) with similar metamorphic degree to calculate local exhumation rate by ZFT ages in different elevations. We assume the isotherms around closure temperature of ZFT were horizontal between high- and low-elevation sample sites. The oldest ZFT age in mid-HR is only 3.4 Ma. With such a young age, the topography effects to high temperature isotherm would be insignificant. The sampling altitudes and ZFT ages are 1000 - 3300 m, and 2.7 - 3.0 Ma respectively. The apparent exhumation rate is 10 km/myr in average. But the apparent exhumation rate may not represent the true exhumation rate (see next section).

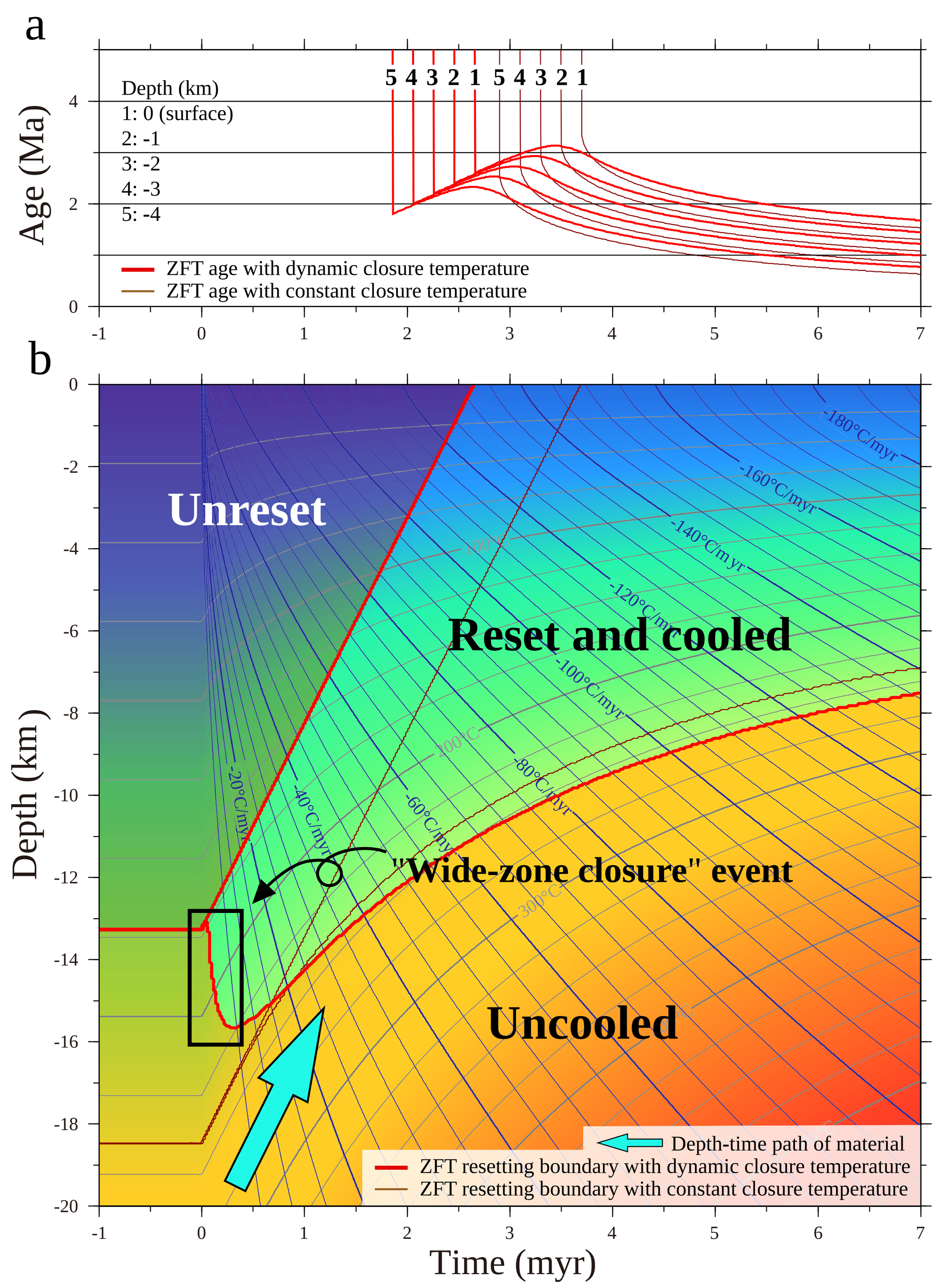

Figure 6. The cooling history of 1D advection-diffusion model.
a) The ages change at surface and different depth with time in model. b) The mesh pause 1 myr and start to exhume with 5 km/myr. Due to the cooling rate increase, the closure temperature raise rapidly, which cause the depth of closure line sinks about 2 km. The ZFT age in this 2 km would almost the same when we observe at the surface. We call it "wide-zone closure" event.

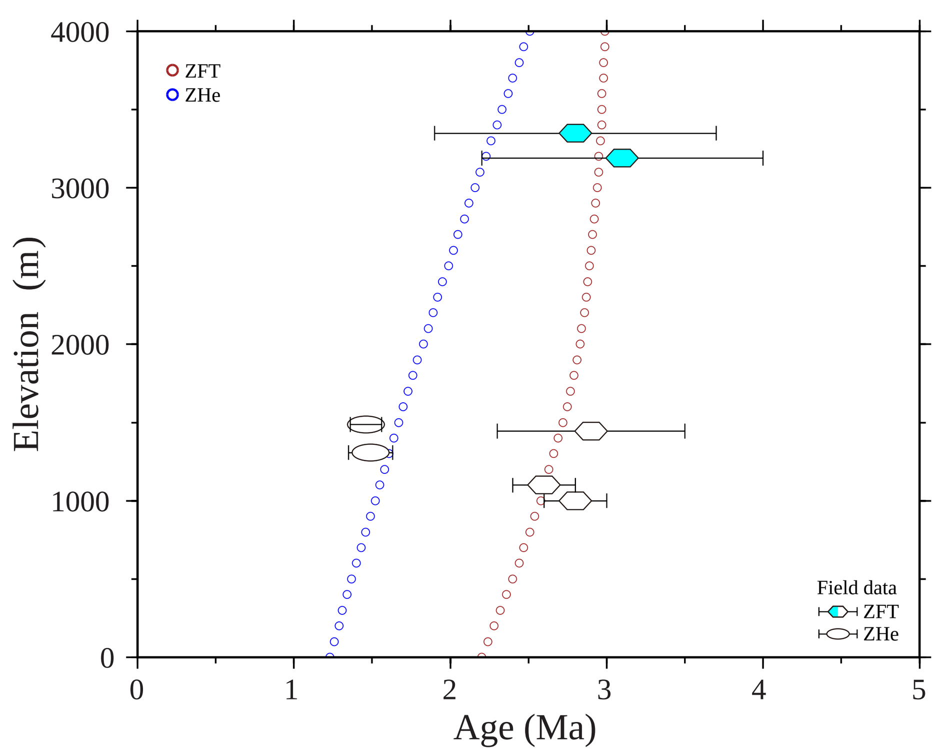

Figure 8. Best-fit 1D advection-diffusion modeling result.
The parameters are the same as common setting in Fig. 7. It shows that the mid-Hsuehshan Range begin to uplift since 3.1 Ma and with the constant rate 5 km/myr. The thermal surface is at 3500 m that's almost as same as the peak of topography, which means the closure isotherm will not be significantly affected by relief when the thermochrometer is under cooling.

2. 1D thermal advection-diffusion model

Following our 1D A-D model, the ZFT cooling history can be reconstructed in the Fig. 6 while sensitivity tests are shown in Fig. 7 and the best-fit model result in Fig. 8. The variation of cooling rate at the beginning of exhumation causes an abnormal pattern of ZFT closure (the black rectangle in Fig.6). The closure temperature within the rectangle increases rapidly, resulting to a zone at depths 13 - 16 km where minerals buried at these depths are closed almost at the same time. We call this event "wide-zone closure". The material in this zone will move upward and get eroded at the surface. Once the materials with unreset ZFT are all eroded, materials with reset ZFT ages will be exposed on the surface. The ZFT ages of surface material will increase linearly first and then decrease gradually to a constant age in steady state. We find that the ZFT age decreases slowly in the first 2 km depth around 2.5 to 3.5 myr in the model. The ages would be ~2.5 to ~3 Ma which are as same as the ZFT ages in mid-HR (also fit ZHe ages). It implies that the mid-HR may start uplifting with 5 km/myr exhumation rate around ~2.5 to ~3.5 million years ago. By contrast, if assuming the closure temperature is constant at 240°C, we will observe a single decreasing trend of the ages only. The age difference will be too large to fit the field data.It is why previous study could not calculate the exhumation rate by ages elevation relationship in mid-Hsuehshan Range.

3. Thermal-mechanical model

A feasibility test (Fig.9) shows the oceanic crust is deformed by collision with the continent. The exhumation occurs at the wedge, which is shown by ZFT age smoothly in model. However, we should note that the model didn't take into account the mass balance of erosion and deposition. Also, the Hsuehshan basin was not deformed because that the continental crust is too strong to absorb strain. We will continue to improve the model to better fit the observations.

Summary

1. The results of 1D advection-diffusion model shows that in the young orogeny, the wide-zone closure signature will occur and induce a spatial vertical zone with similar thermochronological ages.
2. The ZFT ages are almost the same between 1000 and 3300 meters above sea level in mid-Hsuehshan Range which suggests that this area started to uplift at 5 km/myr at ~3.1 Million years ago by combining experiment result and 1D thermal advection-diffusion non-steady state model.
3. The feasibility pilot test of thermal-mechanical model shows the potential to reflect the cooling variation of exhumation. Future modifications regarding the surface processes in our model are crucial to approach the physics of nature.

Reference