台灣增積造山楔的複雜生長機制－從板岩帶變質歷史出發

Growth kinematics of the Taiwan orogenic wedge: perspectives from the metamorphic history of the Slate Belt

陳致同 Chih-Tung Chen

台灣大學地質科學系

Department of Geosciences, National Taiwan University

My honored co-workers:

- Yu-Chang Chan (IESAS & NCU)
- Ching-Hua Lo (NTU)
- Chia-Yu Lu (NTU)
- Jacques Malavieille (UMontpellier)
- Sun-Lin Chung (IESAS & NTU)
- Jian-Cheng Lee (IESAS & NCU)
- Yuan-His Lee (NChungChengU)
- Yue-Gau Chen (NTU)

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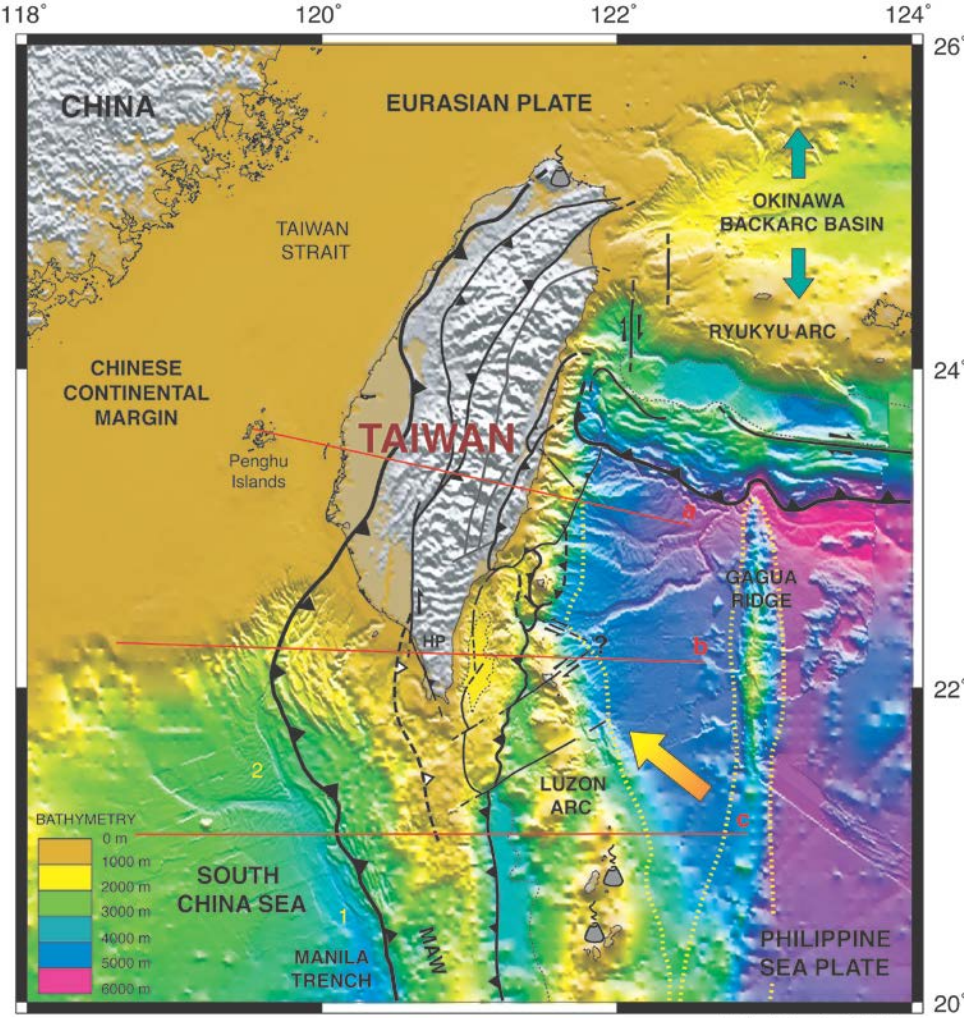
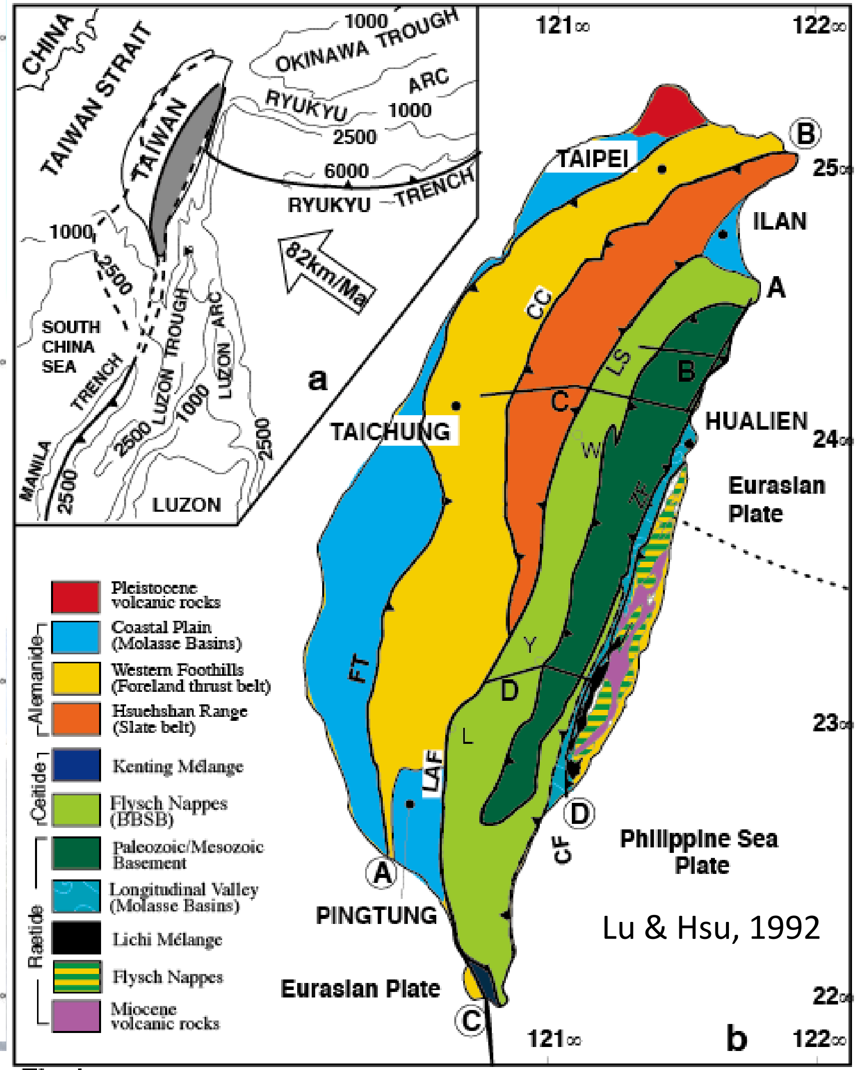
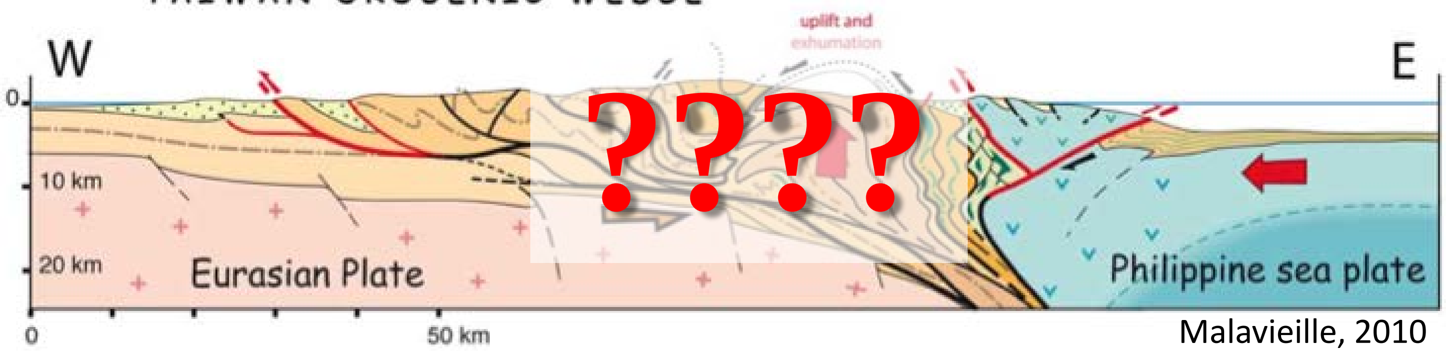


Malavieille et al., 2002



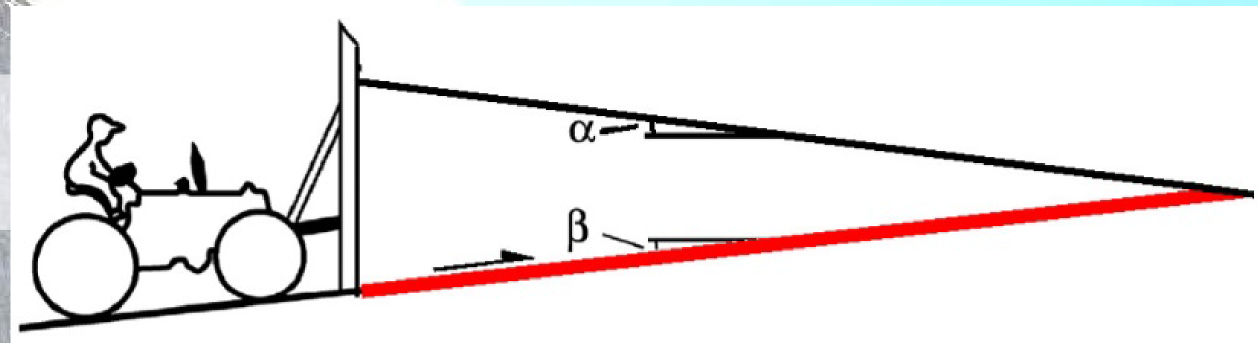
TAIWAN OROGENIC WEDGE



Malavieille, 2010

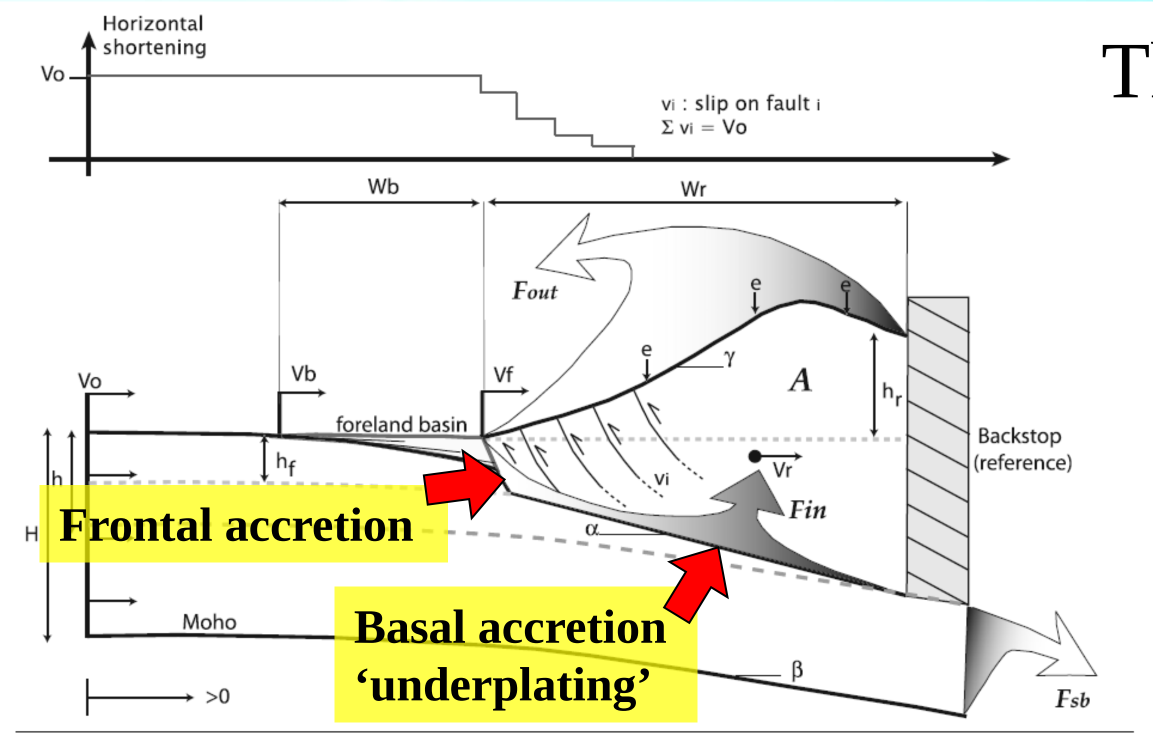
Orogenic accretionary wedges….

In classical theory,
we expect:



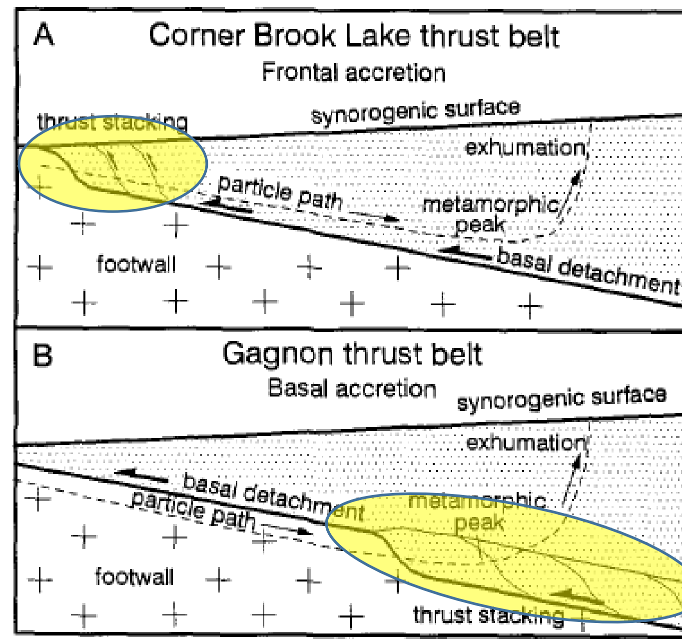
In reality,
we often encounter:

The orogenic wedge



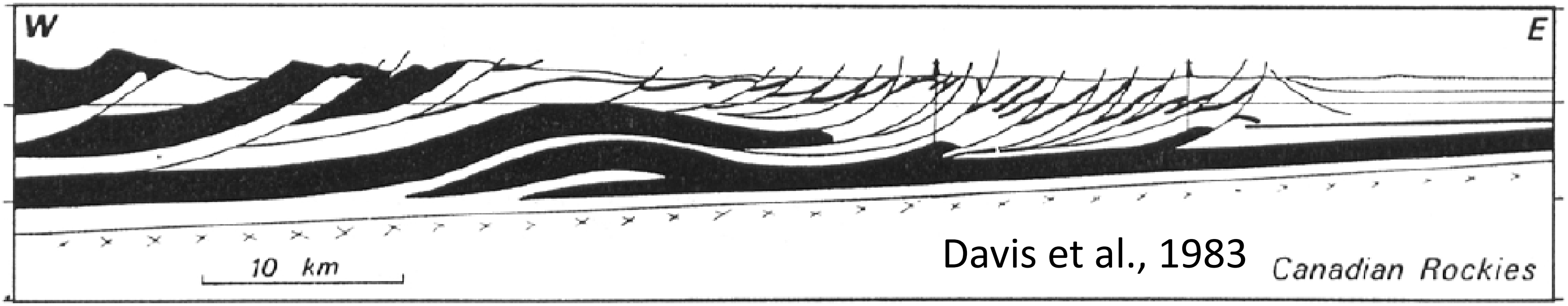
- angle $\delta = 2\beta - \alpha$
- Front migration: $Vf = -d(Wr)/dt$
- If barycenter of the range load is half way between front and backstop: $Vf \sim 2.\ Vr$
- Forebulge migration: $Vb = -d(Wr + Wb)/dt$
- h_f accreted at the front and $h - h_f$ underplated
- Incoming flux: $Fin = (Vo - Vf).\ h$
- Erosional flux: $Fout = Wr.\ e$
- Balance between fluxes: $dA/dt = Fin - Fout$
- Steady state regime for foreland-orogen system: $Vb = Vf = Vr = 0$

Figure 1. Schematic diagram defining the kinematic framework used for this study. All velocities are relative to the backstop and taken positive toward the backstop. See text for further details.

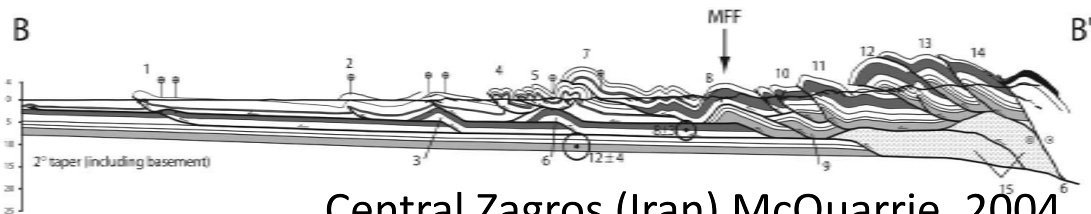


Van Gool & Cawood, 1994

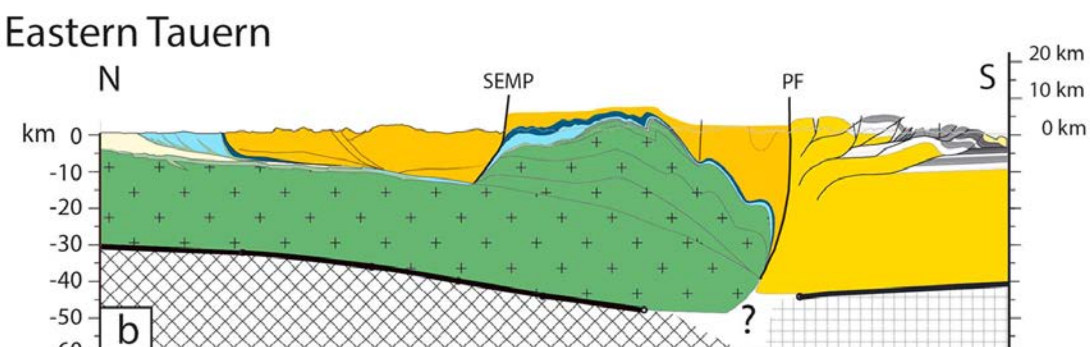
Simoes & Avouac, 2006



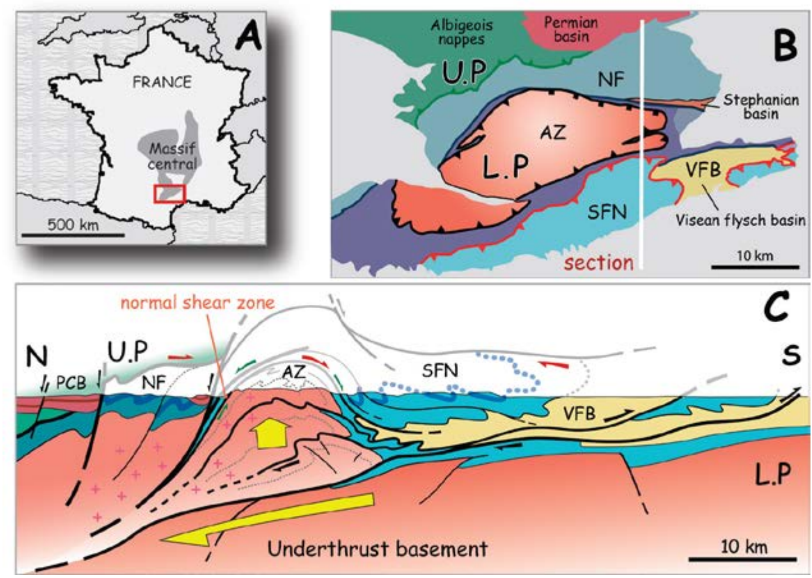
Davis et al., 1983



Central Zagros (Iran) McQuarrie, 2004

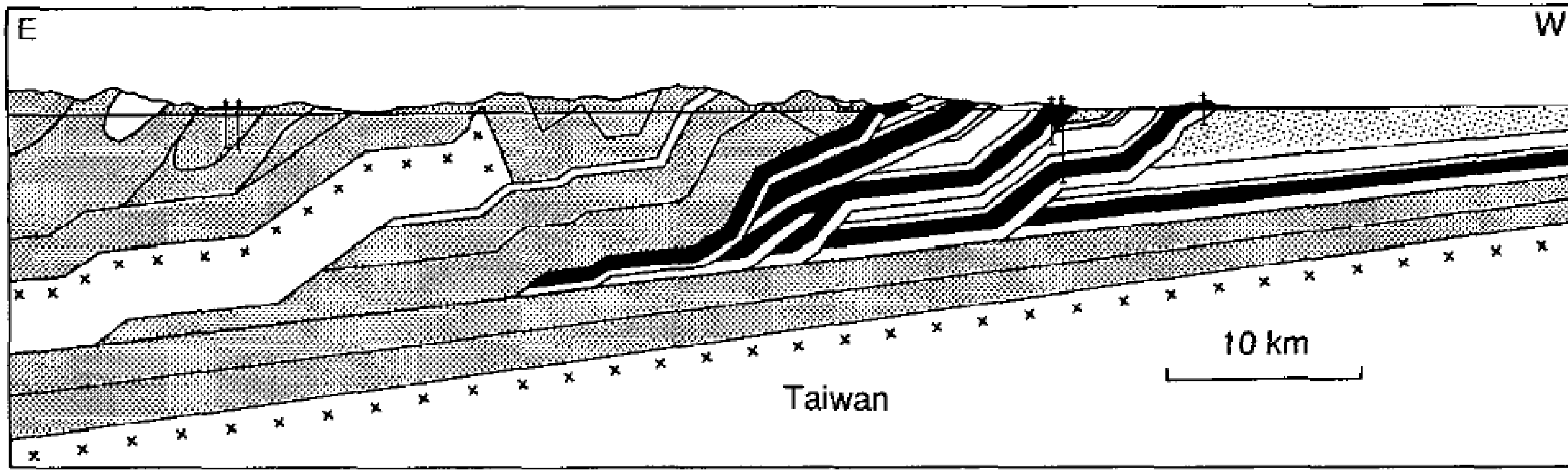


Rosenberg et al., 2015;
Schmid et al., 2004

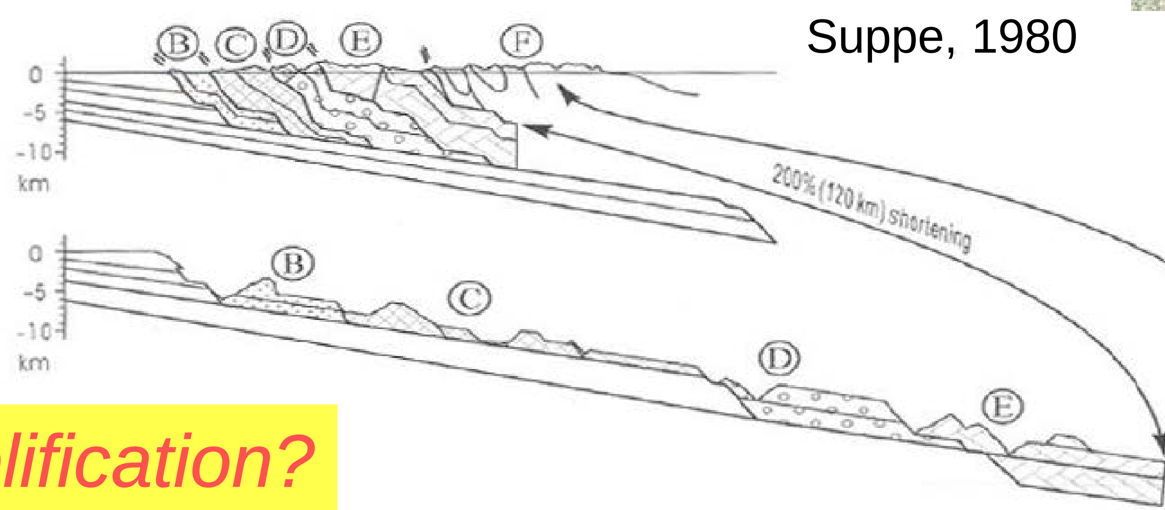


Malavieille, 2010

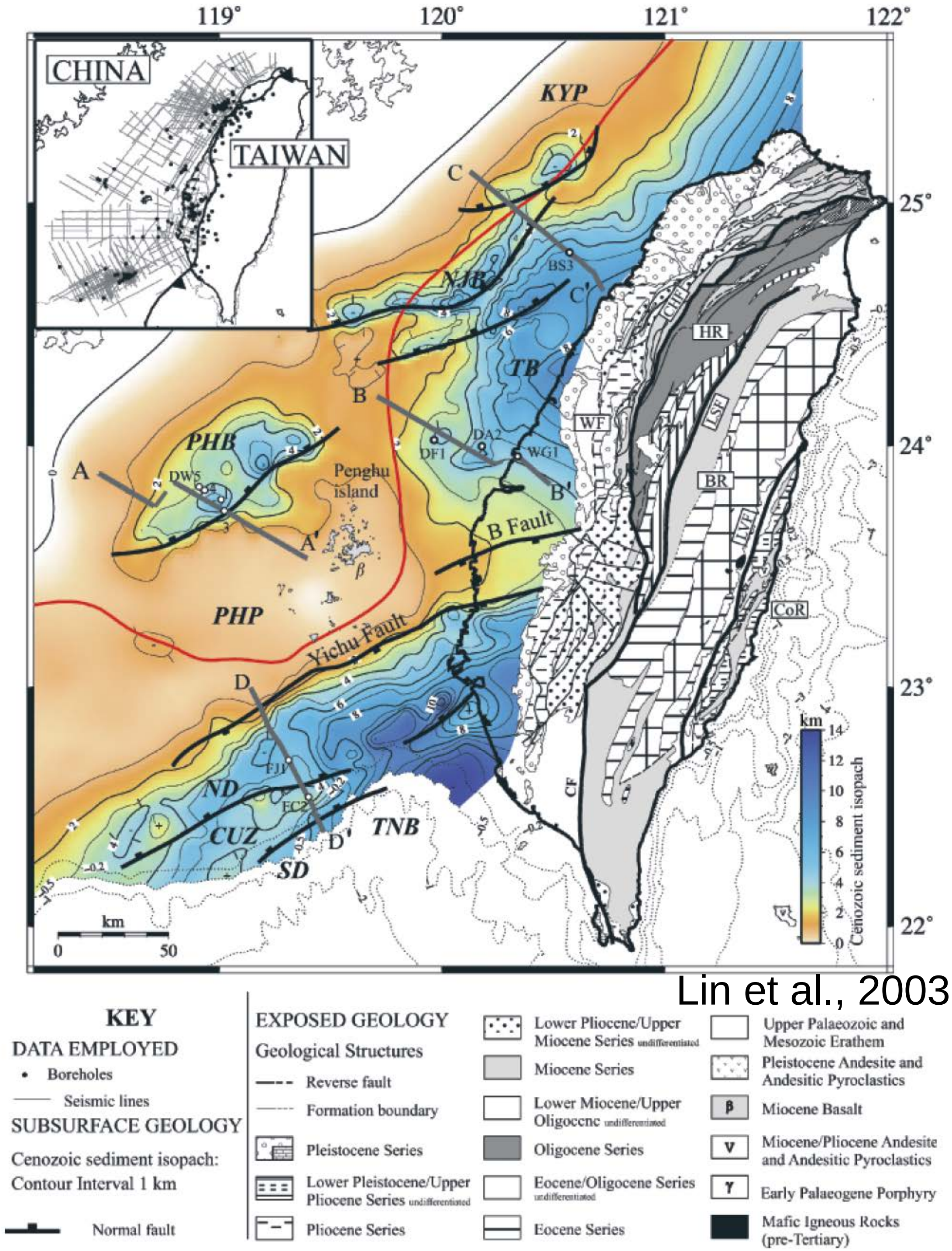
Classical style of structures observed in wedges grown by *frontal accretion*



Suppe, 1980



Validity of such simplification?

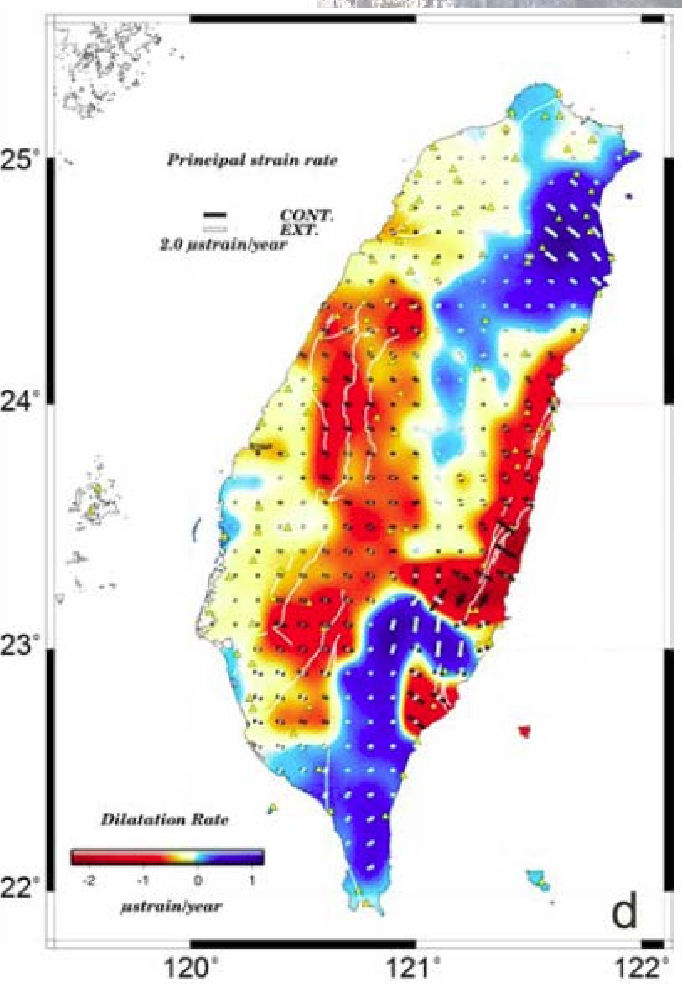


Lin et al., 2003

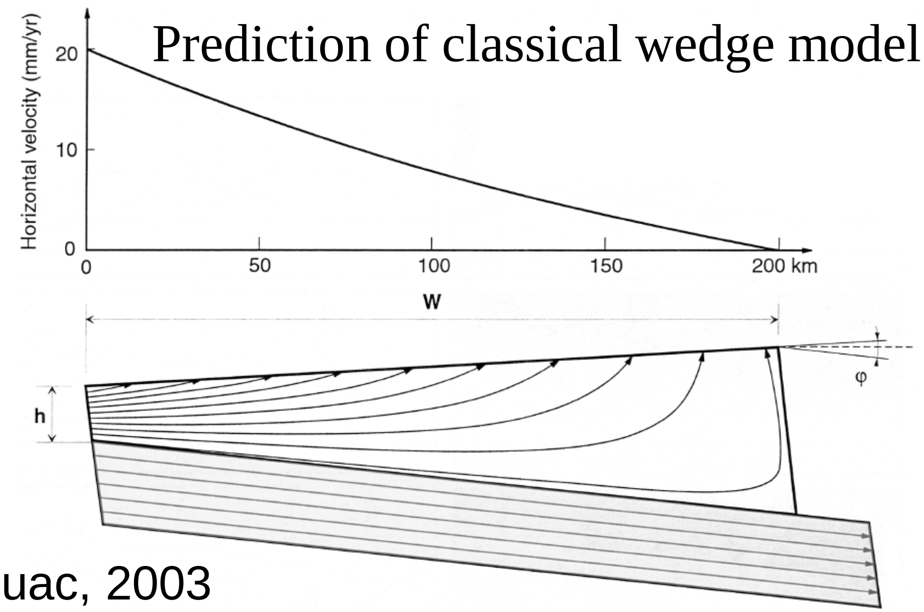
The subducting / incorporated Chinese Continental Margin is highly irregular, may preclude the monopoly of a single detachment

Active convergence is mostly taken up along wedge boundaries, other than been evenly distributed

Lin et al., 2010

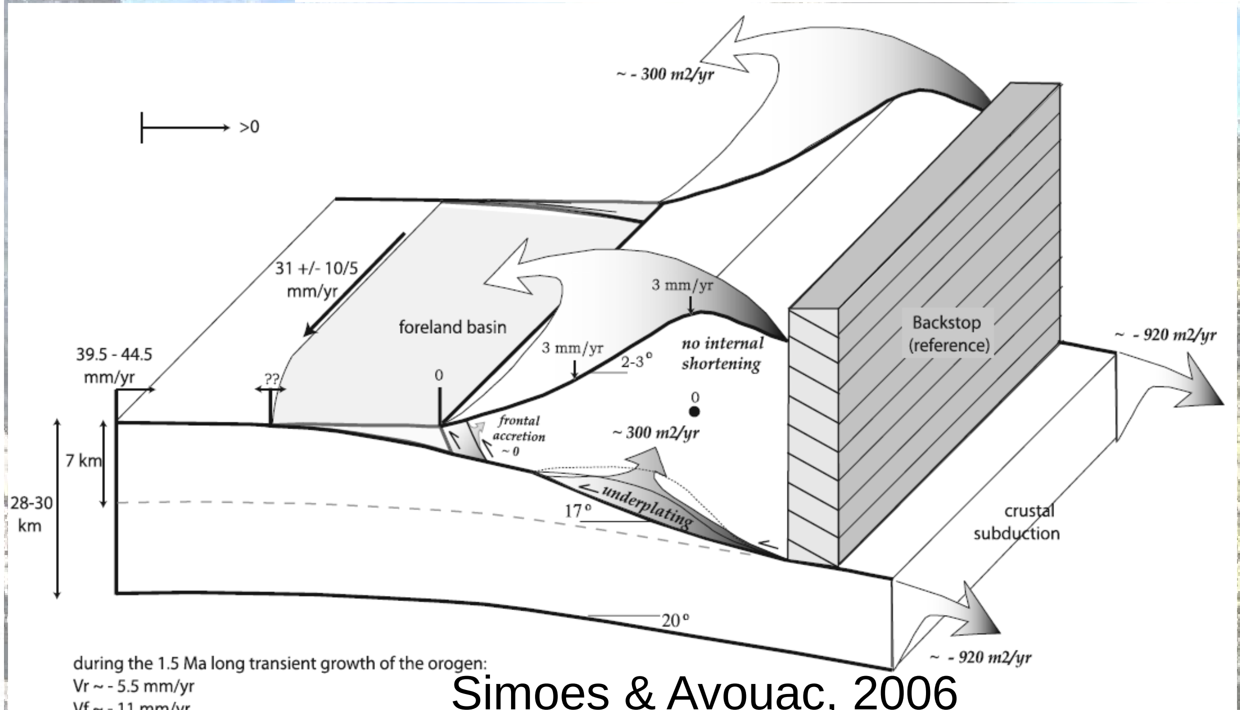


Prediction of classical wedge model



Avouac, 2003

FIG. 6. Particle trajectories in a steady-state critical accretionary prism subjected to erosion (Barr *et al.*, 1991). Horizontal surface velocities computed from Eq. (1) for $h = 15$ km, $W = 200$ km, $tg(\alpha + \beta) = 4\%$, and $V_0 = 20$ mm/year, and an erosion rate of 1.5 mm/year.



Simoes & Avouac, 2006

Wedge kinematics -role of underplating

- Exerts fundamental controls on **structural** and **metamorphic** configurations of the mountain belt

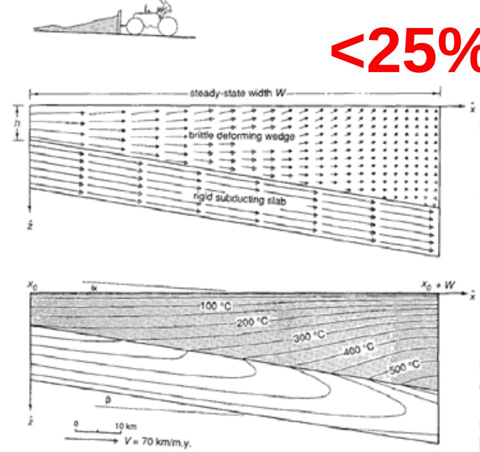


Figure 1. Top: Idealized cross section of Taiwan fold-and-thrust belt and underlying subducting plate (no vertical exaggeration). Arrows show theoretical steady-state velocity u (equation 5). Bottom: Theoretical steady-state temperature distribution for $\mu_b^* = 0.16$ and $\mu^* = 0.34$. Temperature is contoured at 50 °C intervals with 100 °C isotherms labeled. Shaded region denotes deforming fold-and-thrust belt.

<25%

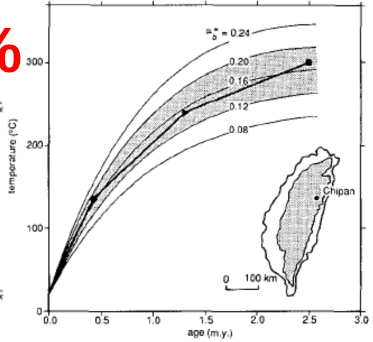
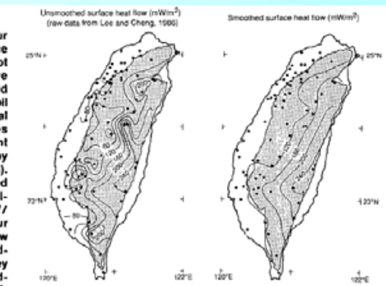


Figure 5. Comparison of fission-track and radiometric data from site near Chipan (Liu, 1982) with theoretical cooling histories for models with various effective coefficients of basal friction μ_b^*. For each value of μ_b^*, effective wedge strength μ^* is taken to be that consistent with critical taper. Thermal conductivity is assumed to be $k = 3.5$ W/(m · °C). Heavy line connects Chipan data; circle shows measured fission-track age for apatite (blocking temperature of 135 °C); triangle is fission-track age for zircon (235 °C); and square is Rb/Sr age for biotite (300 °C). Chipan is located about 80 km east of deformation front. Shaded area on plot denotes range of acceptable fits; best fit is obtained for $\mu_b^* = 0.16$.

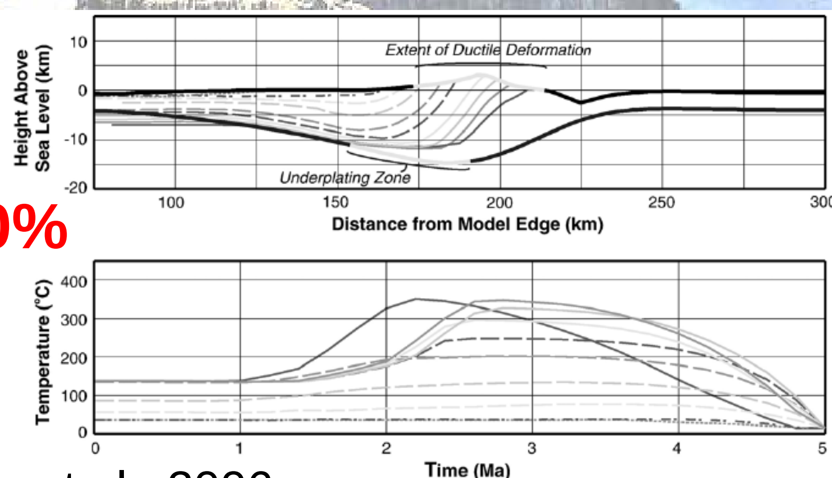
Figure 2. Left: Contour map of observed surface heat flow in Taiwan. Dot pattern denotes active fold-and-thrust belt. Solid circles show location of oil and gas wells, geothermal wells, and boreholes where thermal gradient has been measured by Lee and Cheng (1986). Data have been converted to nominal heat-flow values using $k = 3.5$ W/(m · °C). Right: Contour map of surface heat flow after application of head-banging smoother (Tukey and Tukey, 1981; Goodall and Hansen, 1989; Hansen, 1989). Anomaly caused by combination of brittle frictional heating and uplift is evident between lat 23°N and 24.75°N.



"Classic wedge model"

Barr & Dahlen, 1990

~50%



Fuller et al., 2006

Fig. 9. Particle paths and corresponding temperature histories for material exposed at the surface of the orogen at 5 Ma in our preferred model. (a) Particle paths are shown as fine lines, and the mechanical model boundary is in bold. The predicted surface region exposing material that has been ductilely deformed is indicated. (b) Temperature histories for particles in (a). The maximum temperature reached by any particle is ~350°, consistent with constraints provided by the $^{40}Ar/^{39}Ar$ dating of Lo and Onstott (1995). See Video 3 for additional detail.

Simoes et al., 2007

>90%

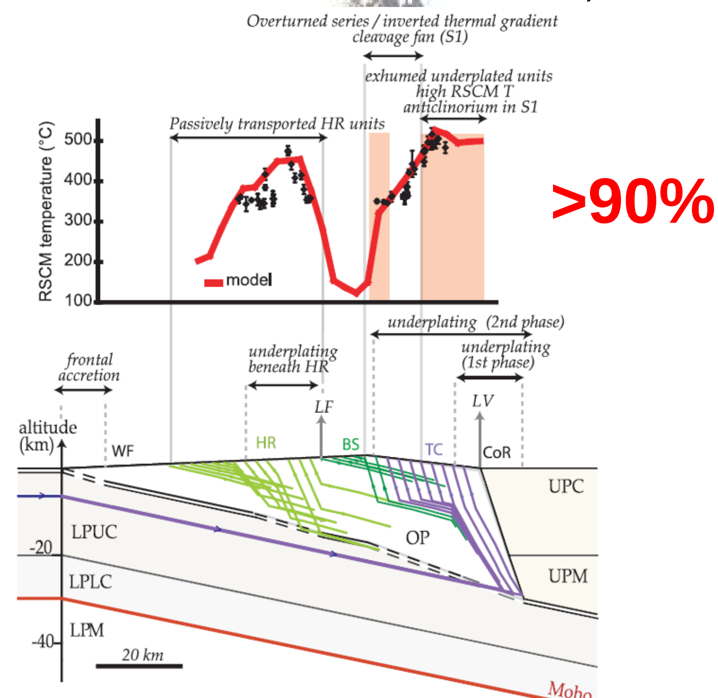
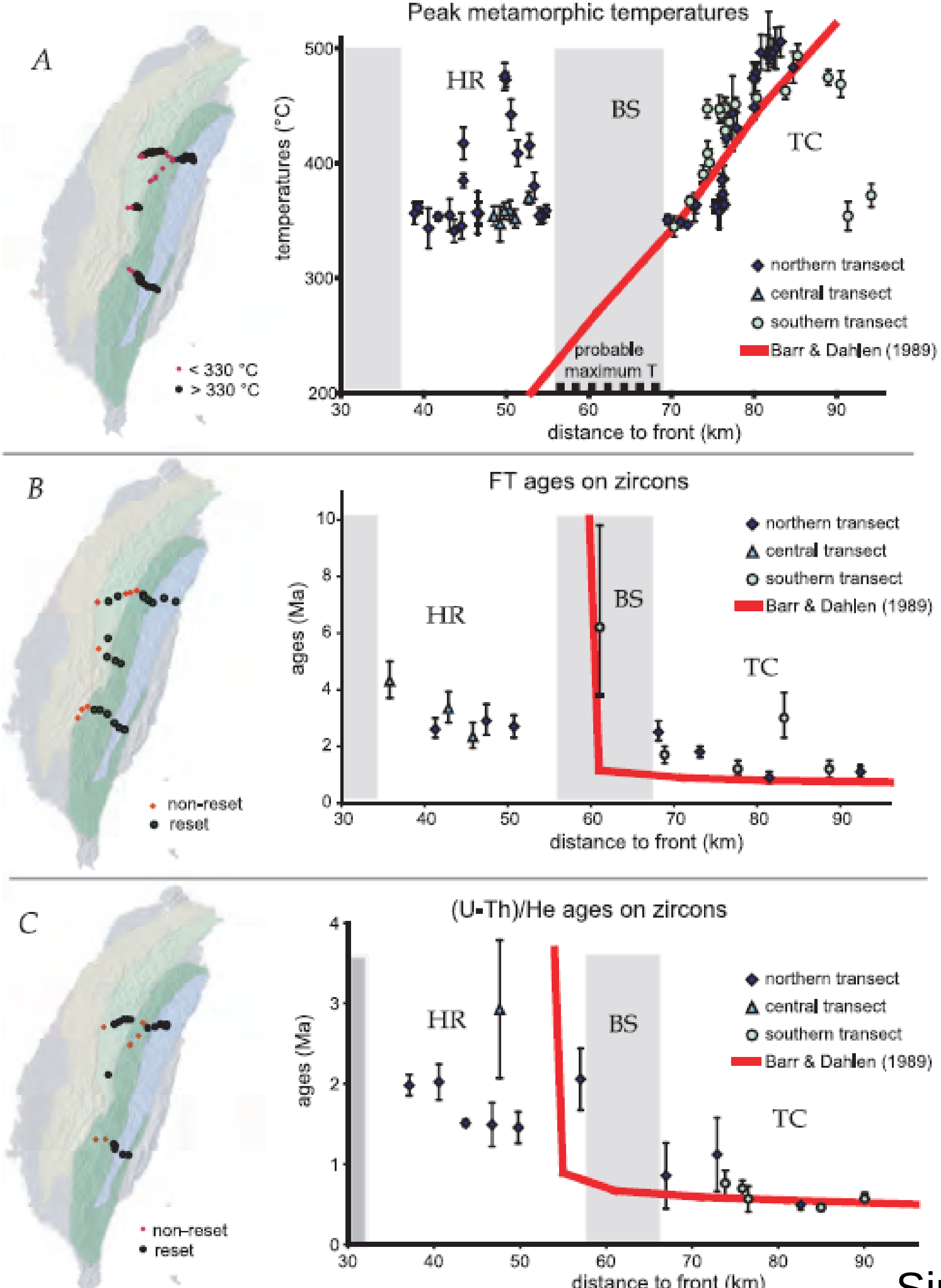


Figure 13. (bottom) Particle trajectories derived from our model for rocks presently at the surface along the northern transect. (top) Corresponding predicted and measured peak metamorphic temperatures with some of key structural observations. See Figure 7 for abbreviations.



Simoes et al., 2007

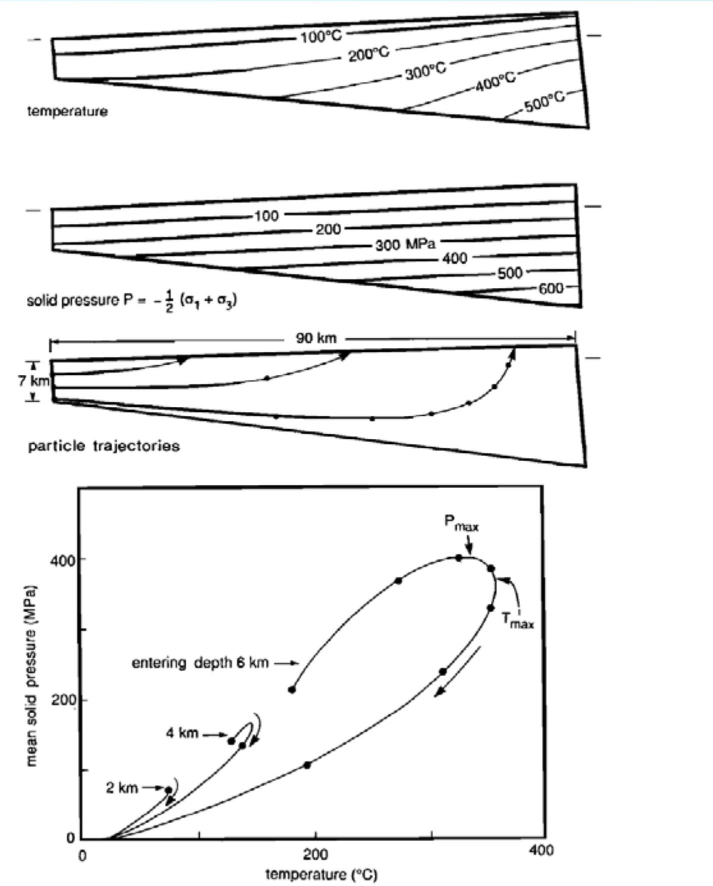


Fig. 9. (Top) Trajectories of three rocks moving through the steady state temperature and mean solid pressure fields in the Taiwan wedge. (Bottom) Corresponding pressure-temperature-time trajectories of the same three rocks, with entering depths of 2, 4, and 6 km. The dots on both the particle and P–T–t trajectories represent 1-m.y. intervals. The rock entering at 6 km depth attains its maximum pressure P_{max} approximately 2 m.y. after it is accreted, whereas it does not attain its maximum temperature T_{max} until 3 m.y. after it is accreted.

Barr & Dahlen, 1989

Great conflict between nature evidences and the classic wedge model in the pattern of metamorphic grade distribution, especially the ultra-hot Hsuehshan 雪山山脈 in the prowedge part

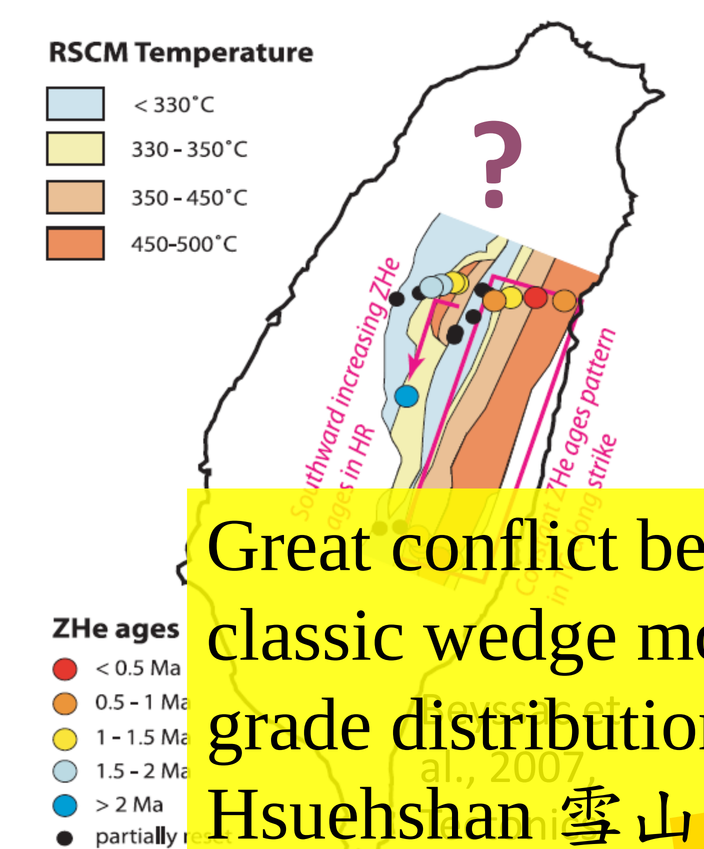
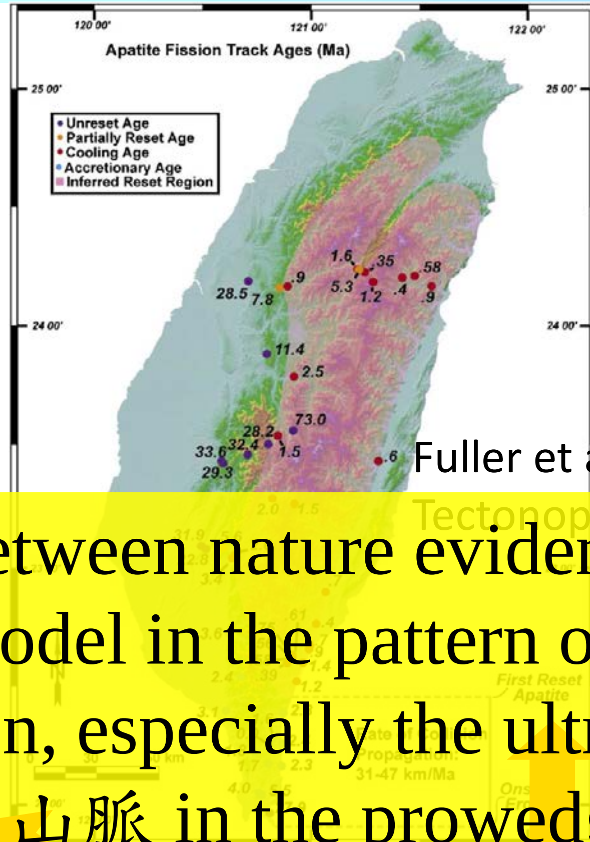
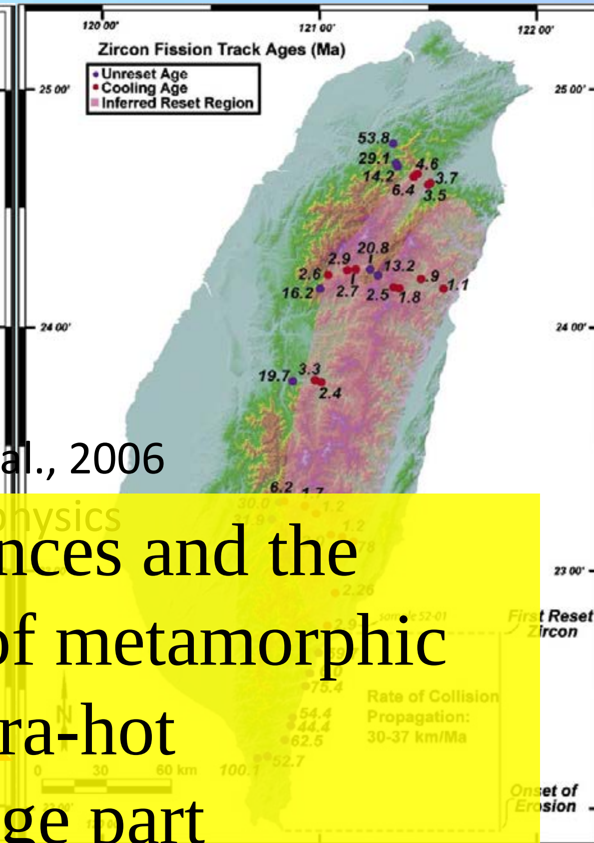


Figure 15. Schematic map showing thermal metamorphism (RSCM temperatures) and (U-Th)/He ages on zircon over central Taiwan. Contours were drawn by laterally extrapolating the results obtained on the three transects investigated in this study (Figure 1). Note the laterally constant pattern over the Tananao basement in opposition to the N-S progressive exhumation of the HR units.





Fuller et al., 2006

Tectonophysics

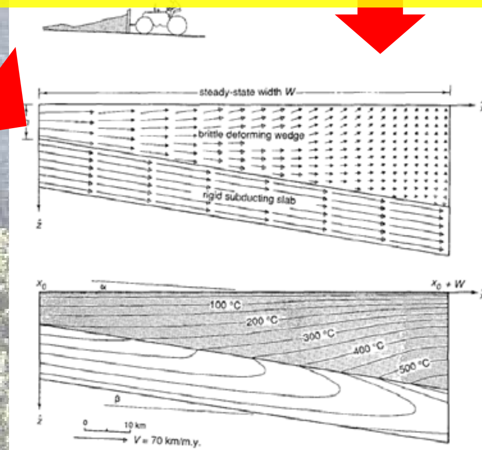
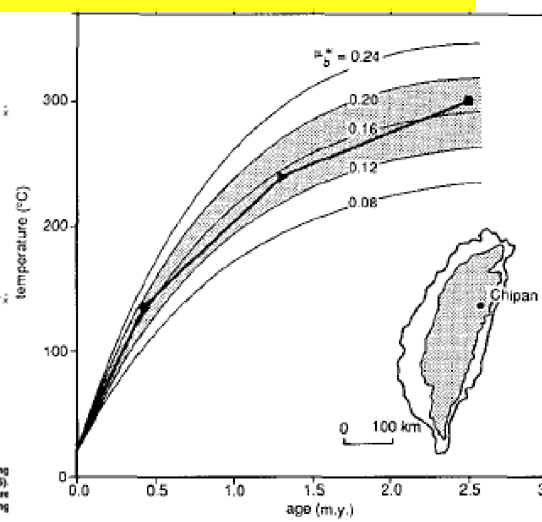


Figure 1. Top: Idealized cross section of Taiwan fold-and-thrust belt and underlying subducting plate (no vertical exaggeration). Arrows show theoretical steady-state velocity u (equation 5). Bottom: Theoretical steady-state temperature distribution for $\mu_b = 0.16$ and $\mu^* = 0.34$. Temperature is contoured at 50 °C intervals with 100 °C isotherms labeled. Shaded region denotes deforming fold-and-thrust belt.



Barr & Dahlen, 1990

The ***Basal Accretion*** issue of Taiwan orogen

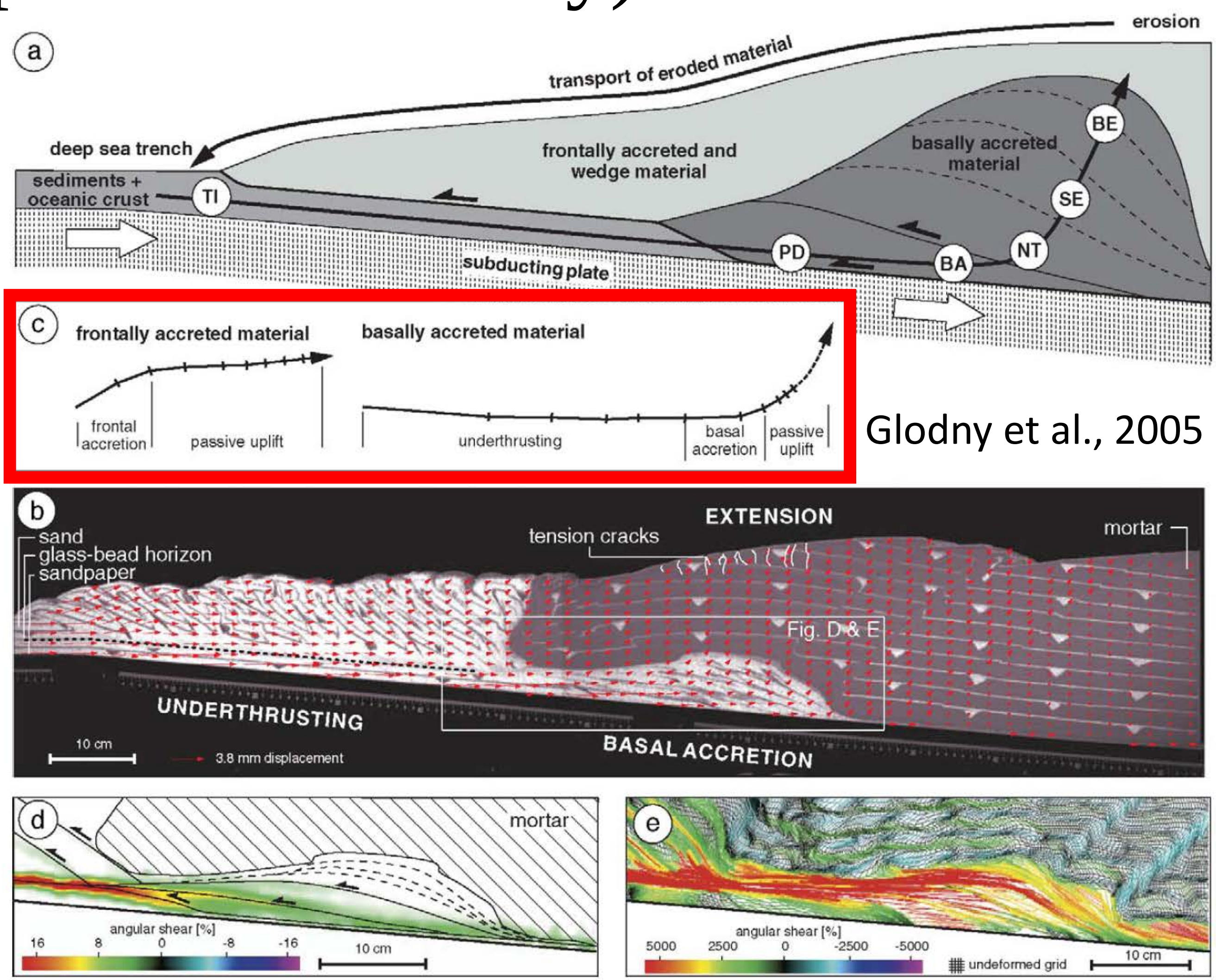
- ***Is it Present***? If **yes**, then: **Task 1**
  - **How** did material enter the wedge through basal accretion, i.e. what kind/style of structures is responsible for the process?
  - **Where** is the underplating window(s)? **Task 2**
  - **When** has the process started and operated? **Task 3**

- Target for the investigation: **Slate Belt of northern Taiwan**
  - ✓Cenozoic cover series of the continental margin, experienced definitely **only the recent Penglai Orogeny**
  - ✓Contains **complete orogen history** in its collisional phase considering the time-space equivalence due to the southward propagation of the orogeny (Suppe, 1984)

Task 1:
Is it **present**? & **How** it operated?

- Detailed thermal & metamorphic documentation across the northern Slate Belt
- Construction of rock kinematic history by incorporating stratal/sedimentary basin constraints

How to distinguish? (via particle path / P-T history)



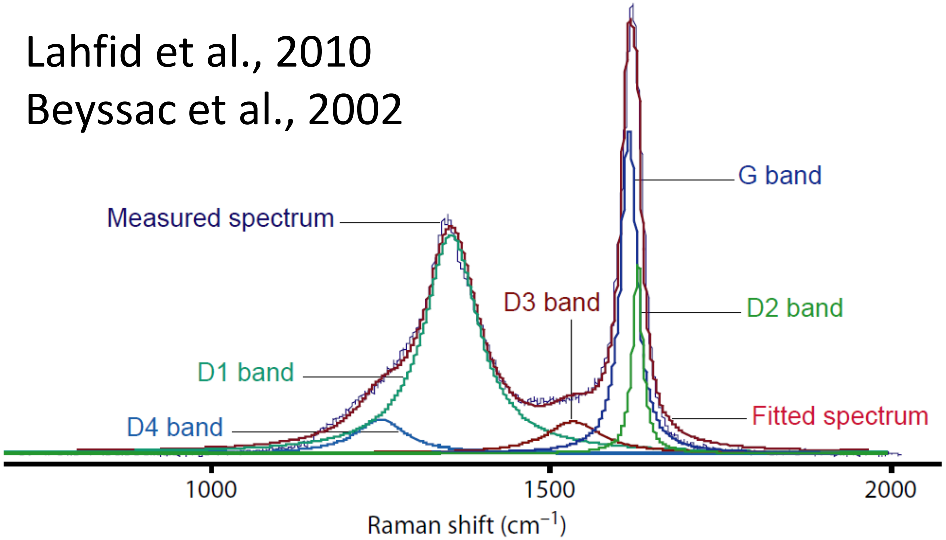
Glodny et al., 2005

The dramatically different P-T-t path and hence metamorphic history between frontally & basally accreted materials

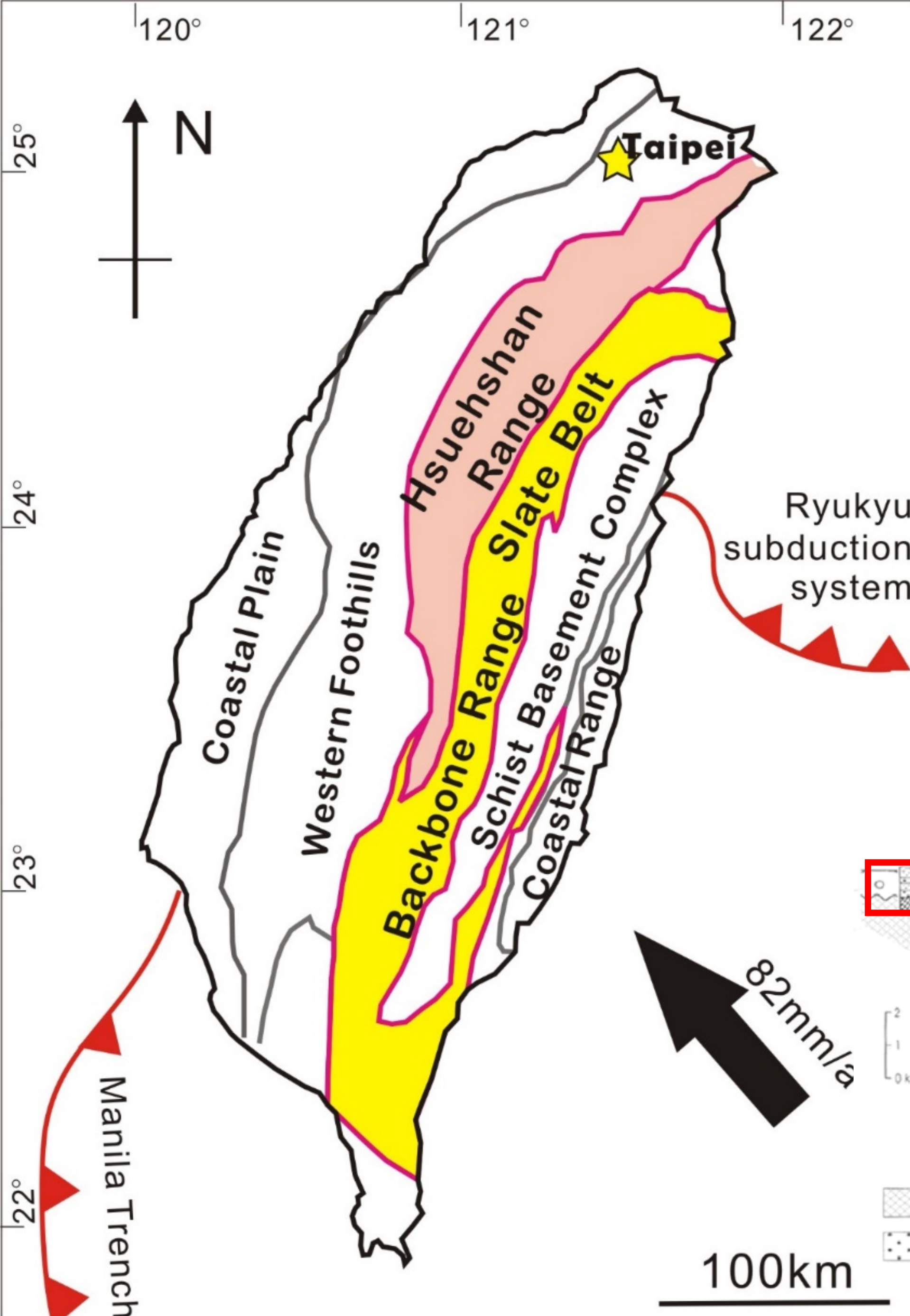
To resolve the detailed thermal structure within the meta-sediment regime… the carbonaceous detritus!

- Estimation of peak metamorphic temperature:
  - Vitrinite reflectance (VR), useful from diagenesis to ~ 250-300°C
  - Raman spectrum of carbonaceous materials (RSCM), quantitative estimates from ~200 to ~700°C
  - Both records the <u>irreversible graphitization</u> of carbonaceous matters

Lahfid et al., 2010
Beyssac et al., 2002

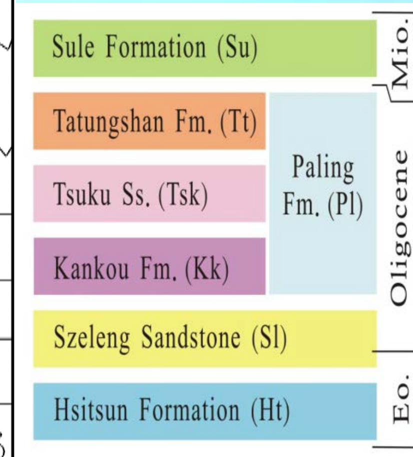


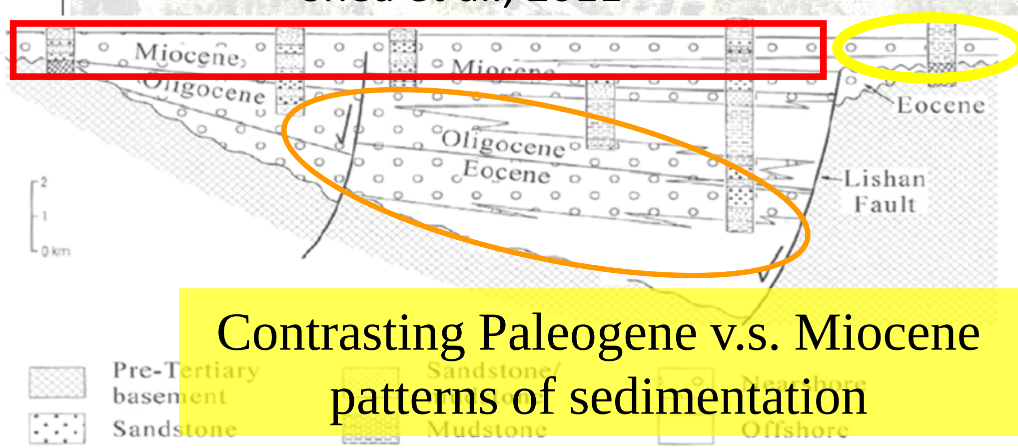
Task 1: structure



本							文
時代	雪山山脈北段		雪山山脈南段西翼（地利斷層以西）				雪山山脈南段東翼（地利斷層以東）
中新世							盧山層
	澳底層		十四股層				
漸新世	大桶山層 粗窟砂岩 乾溝層	巴陵層	水長流層				（假整合）
始新世	四稜砂岩		白冷層	H_2段	梅子林段	上段	眉溪砂岩
	西村層 中嶺層			H_1段	裡冷段	中段	佳陽層
	（未出露）				東卯段	下段	（玉山主山層）達見砂岩
			（未出露）				十八重溪層 （斷層截切）
地層資料參考Chen(1979), 陳肇夏(1992), Lee(1979), Huang(1986), 羅偉等(1999), 劉桓吉、高銘健(2010)							

Shea et al., 2011



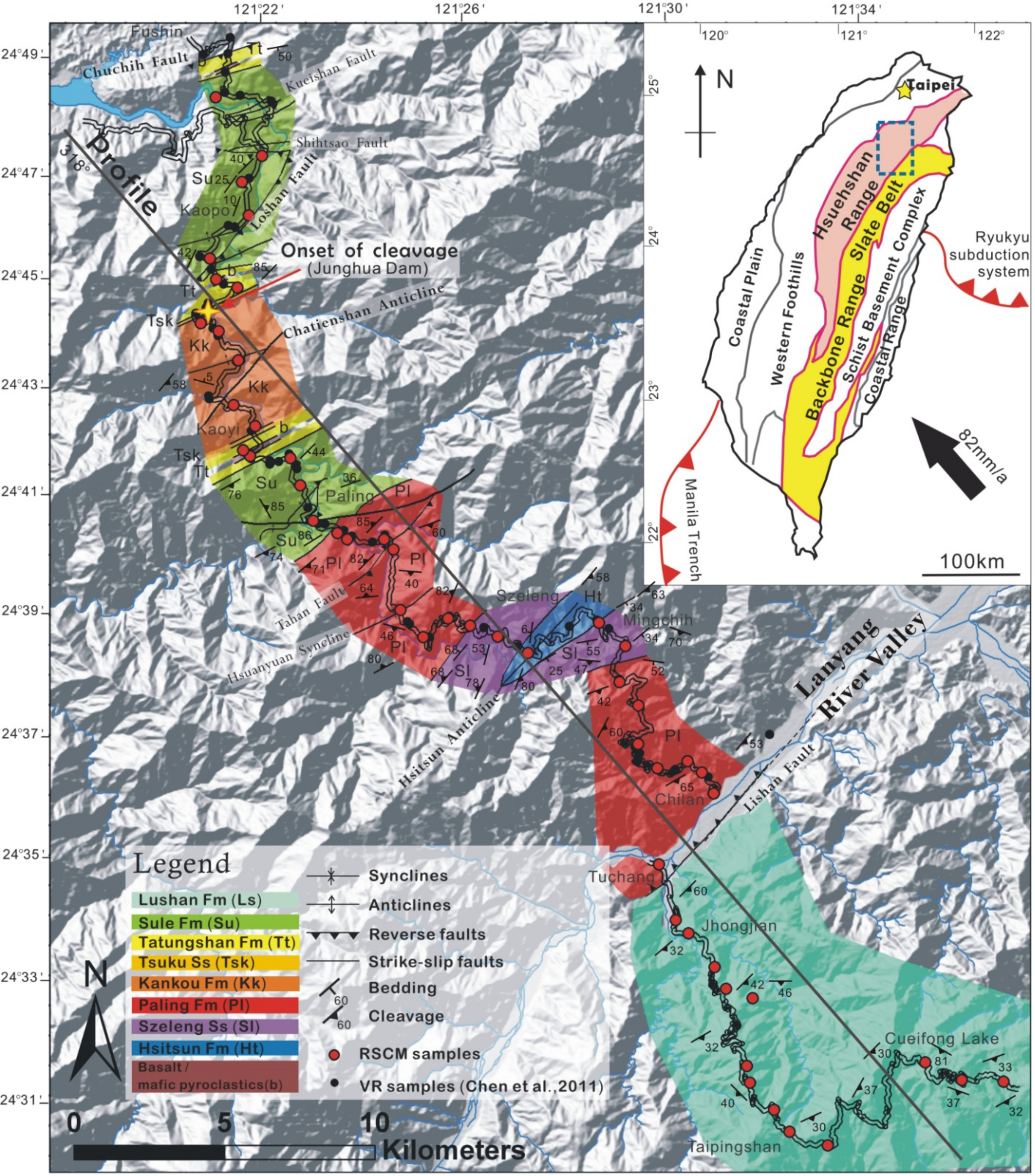


Contrasting Paleogene v.s. Miocene patterns of sedimentation

Teng et al., 1991

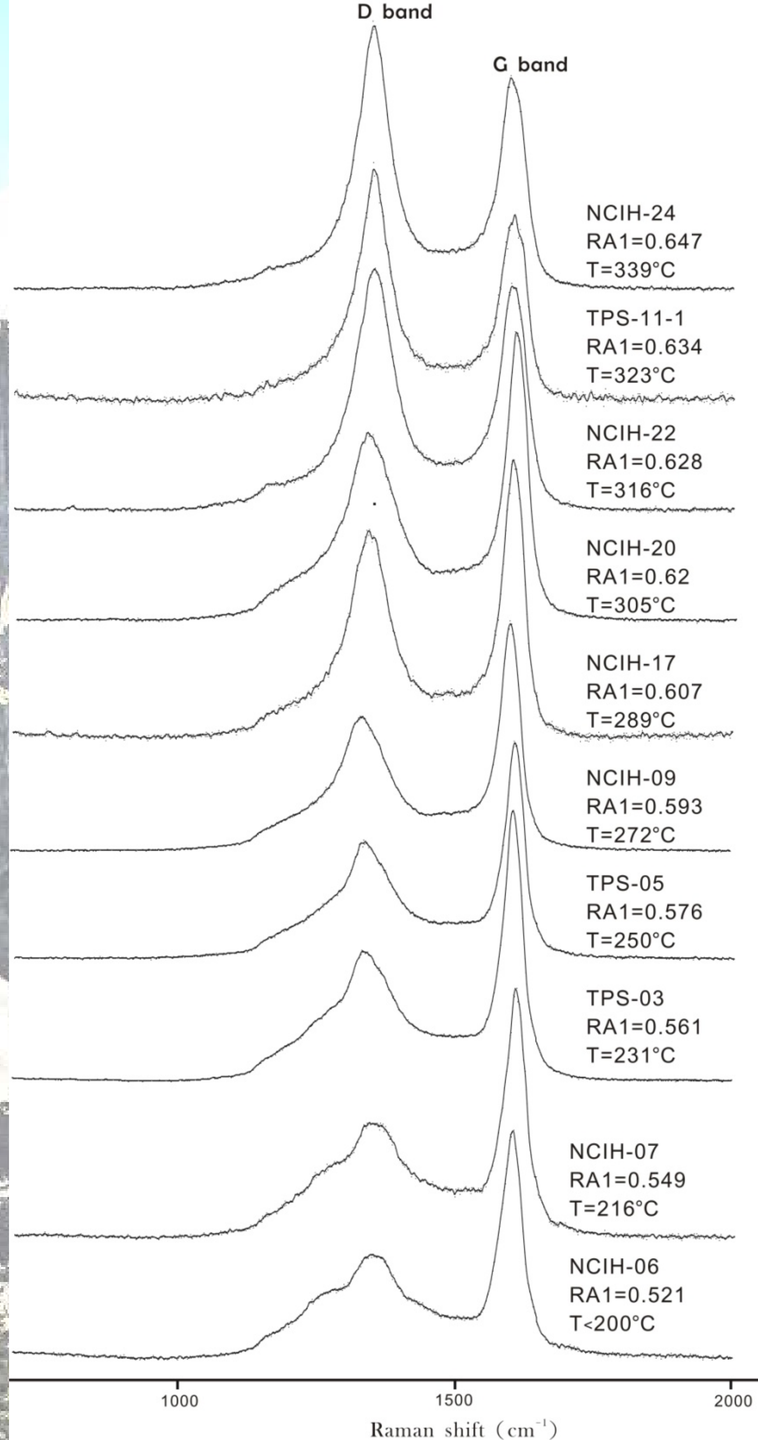
Task 1: structure

Northern Cross-Island Highway transect

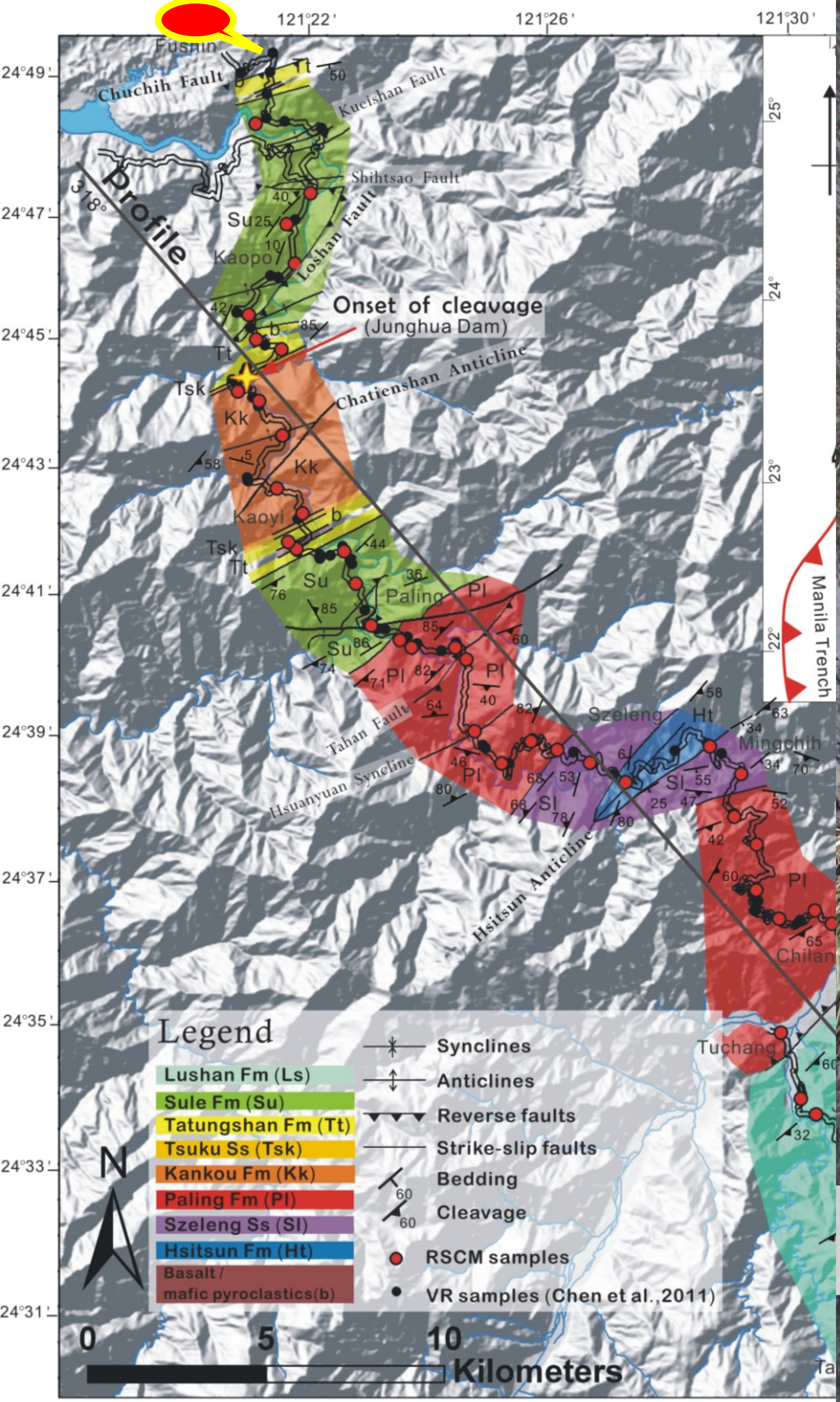


Task 1: structure

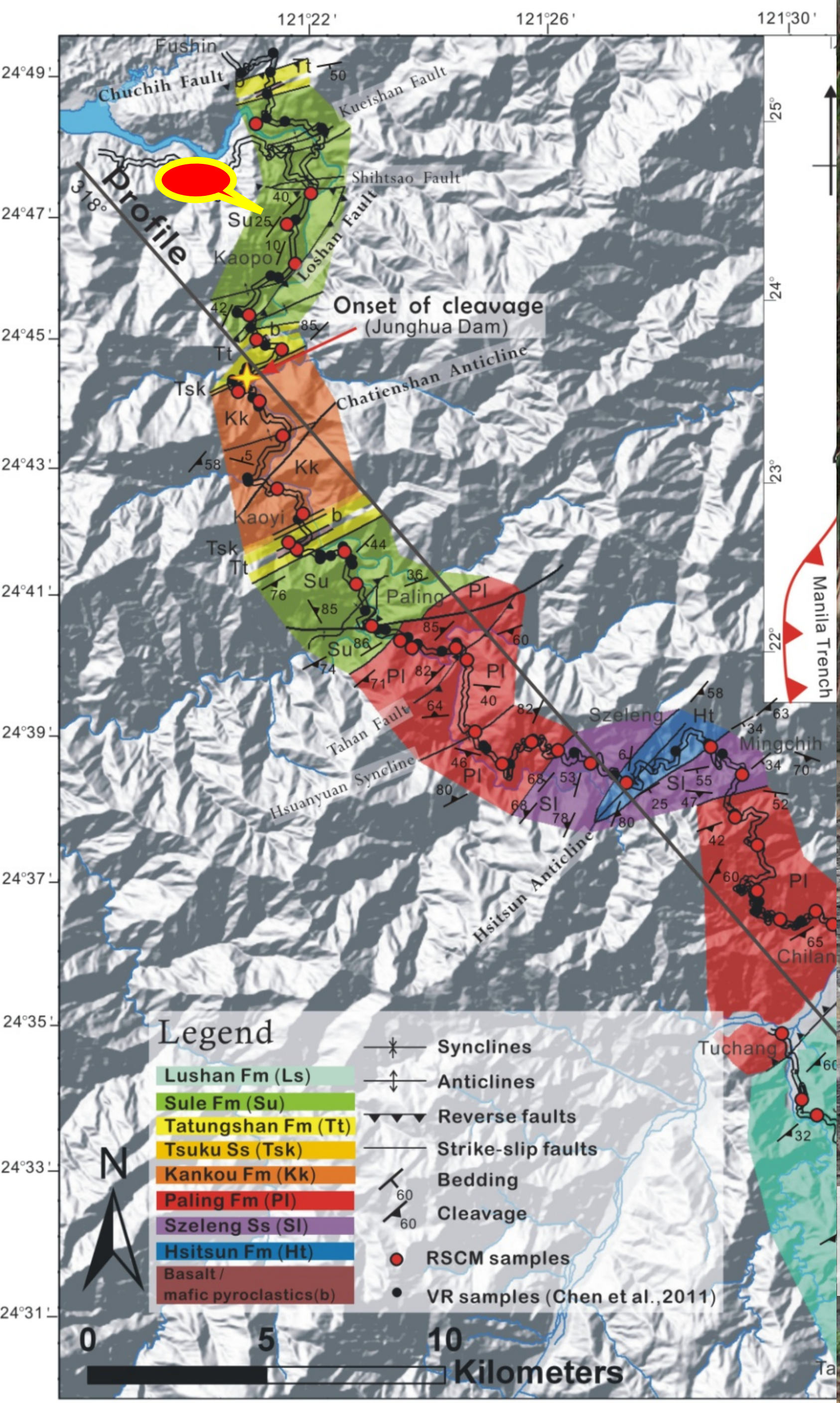
RSCM spectra

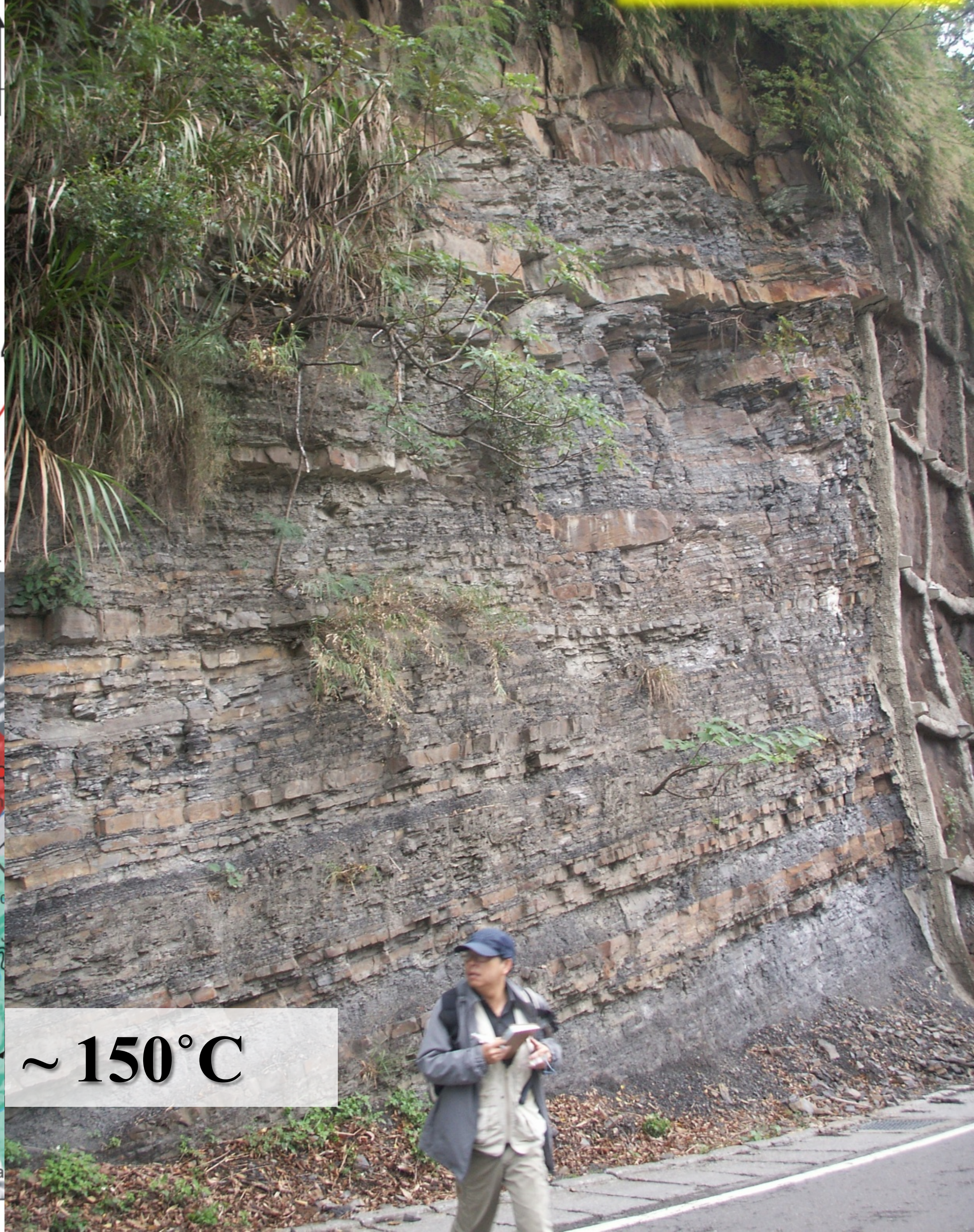


Task 1: structure



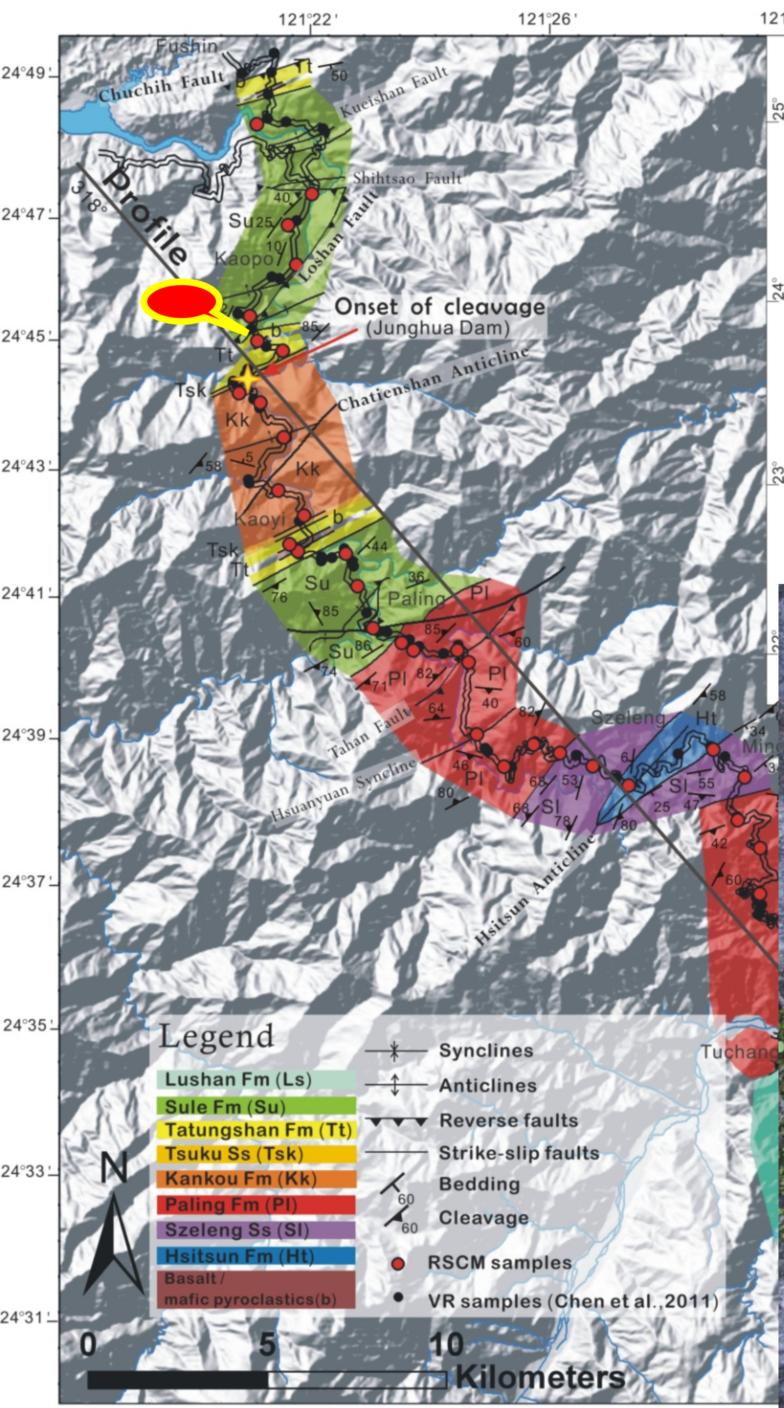
Task 1: structure

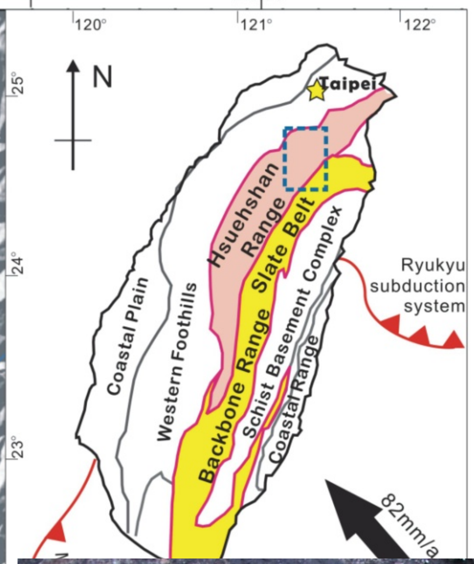




~ 150°C

Task 1: structure





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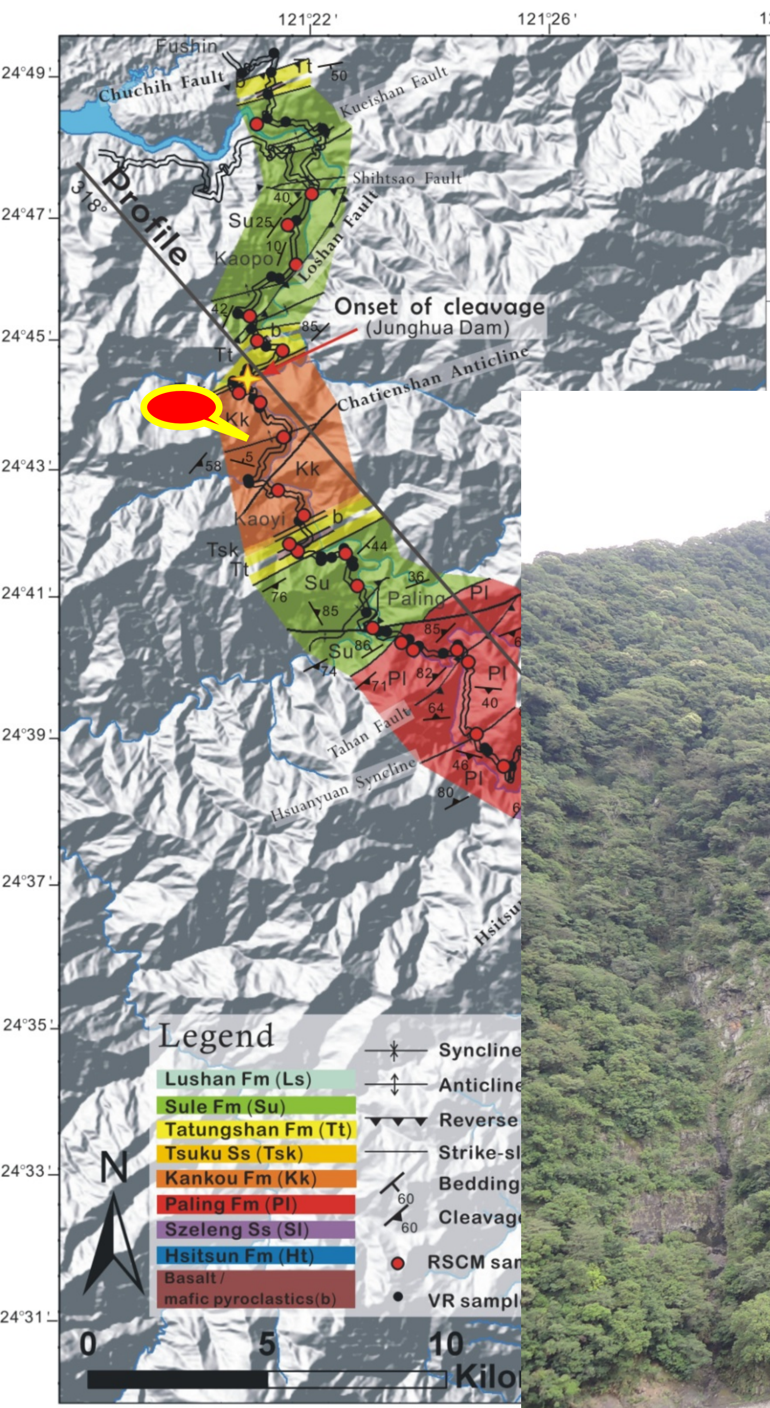
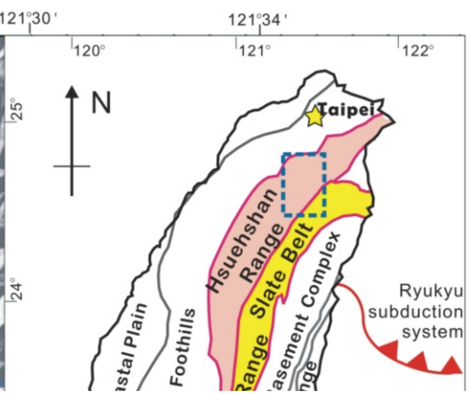
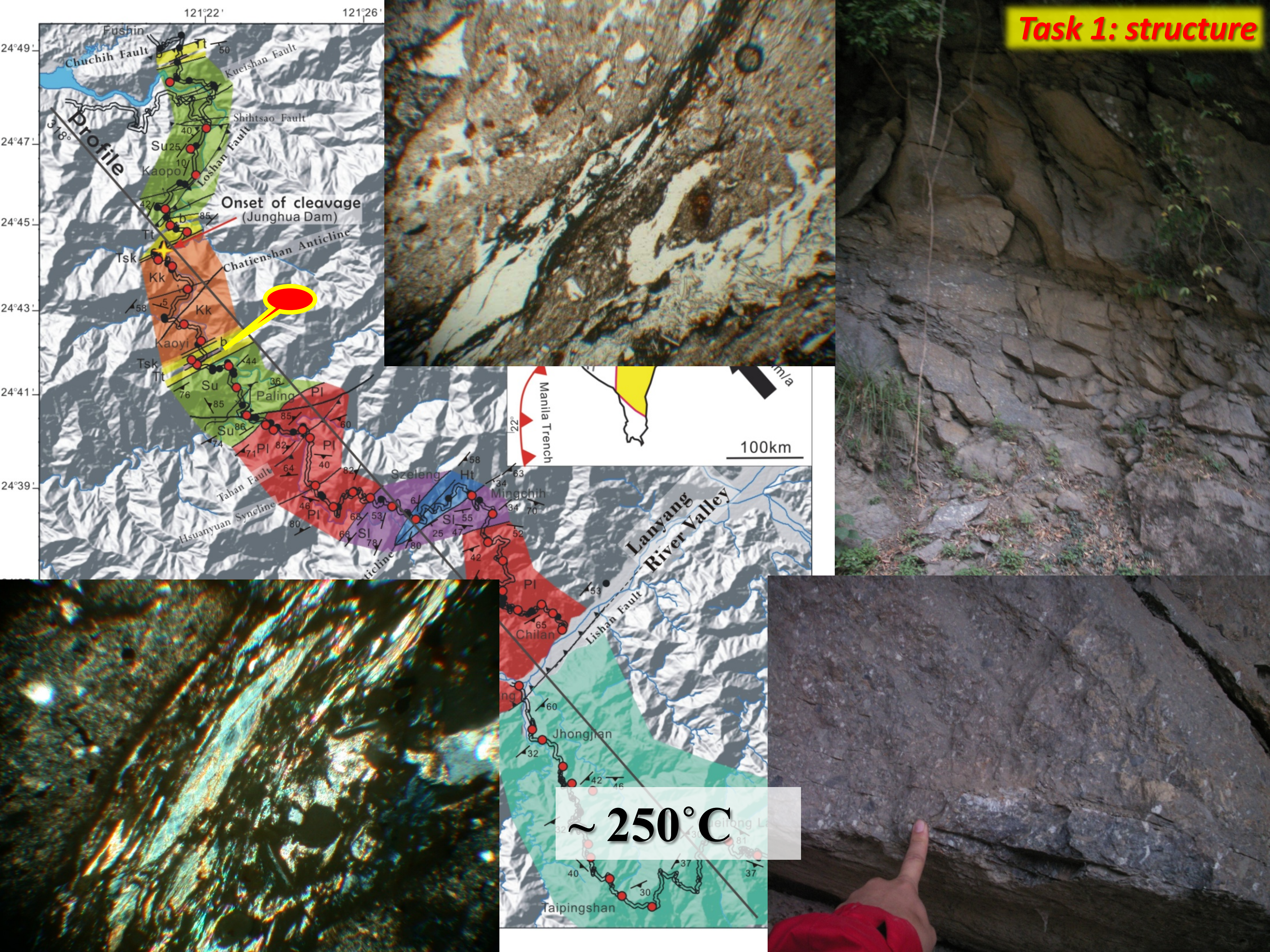
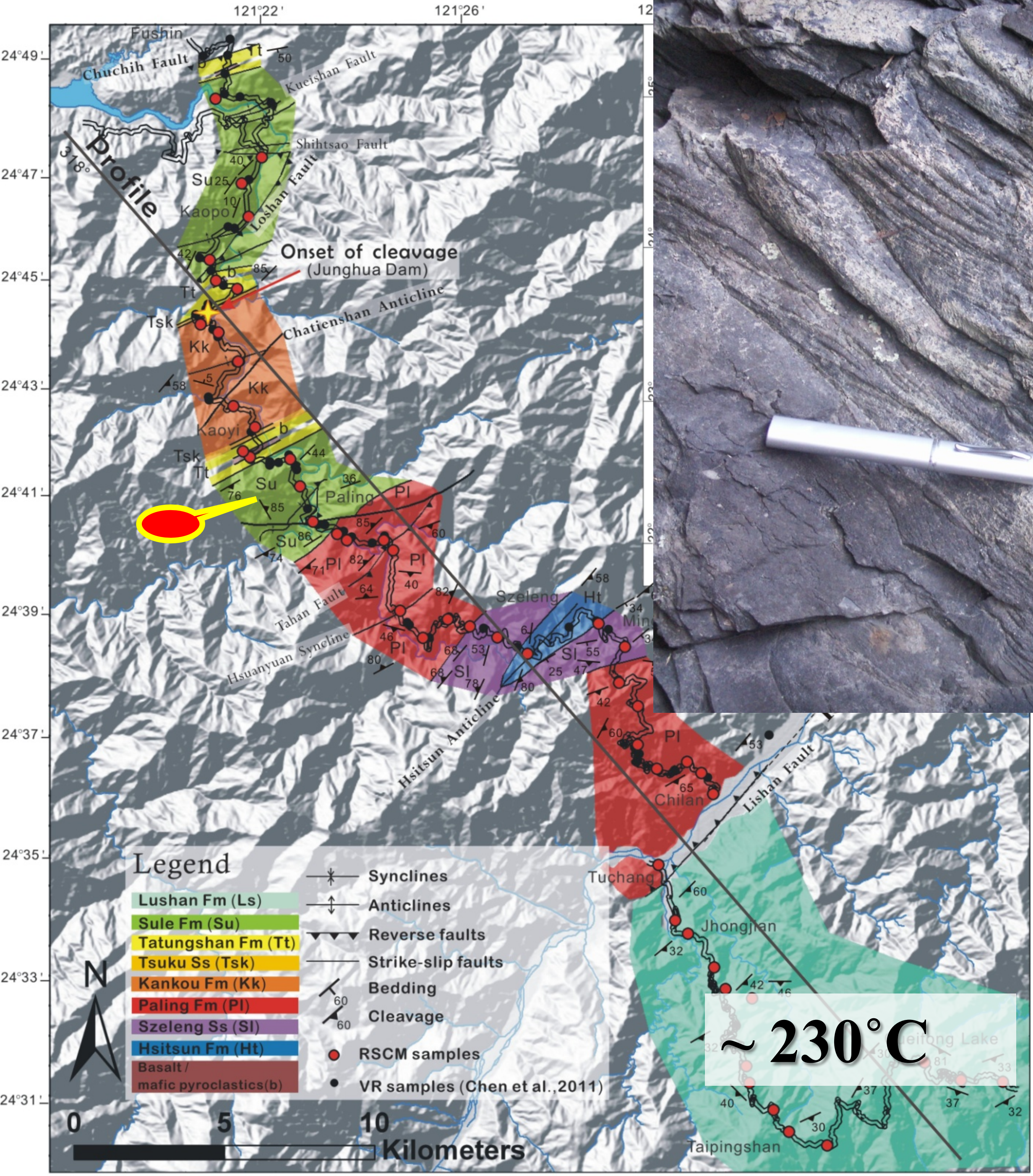




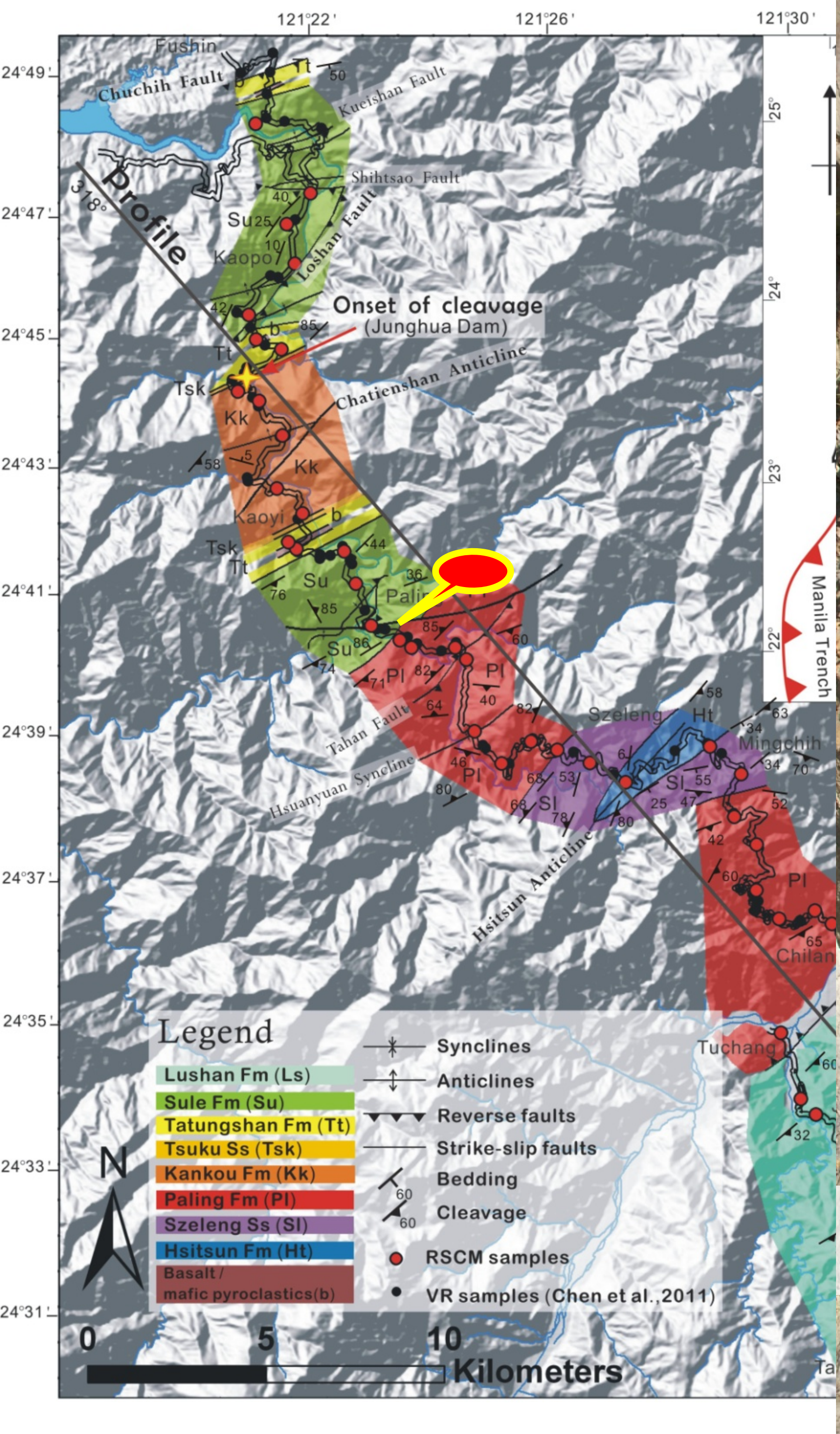

Task 1: structure
121°22'
121°26'
24°49'
24°47'
24°45'
24°43'
24°41'
24°39'
Fushin
Chuchih Fault
Kuetshan Fault
Shihtsao Fault
Loshan Fault
Profile
318°
Onset of cleavage
(Junghua Dam)
Chatienshan Anticline
Kaopo
Kaoyi
Paling
Tahan Fault
Hsuanyuan Syncline
Szeleng
Mingchih
Lanyang River Valley
Lishan Fault
Chilan
Jhongjian
Taipingshan
Manila Trench
100km
~ 250°C

Task 1: structure



~ 230°C

Task 1: structure



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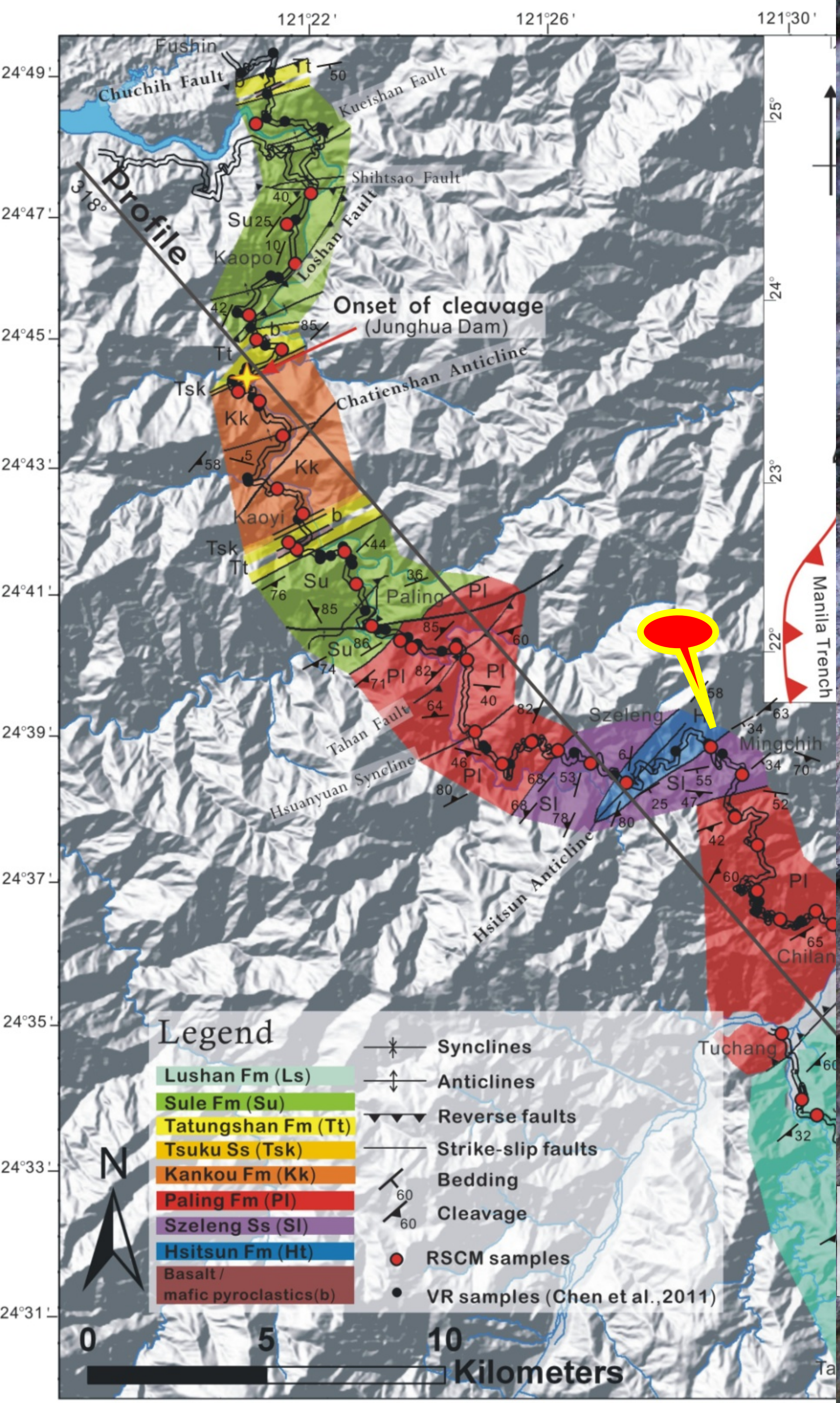
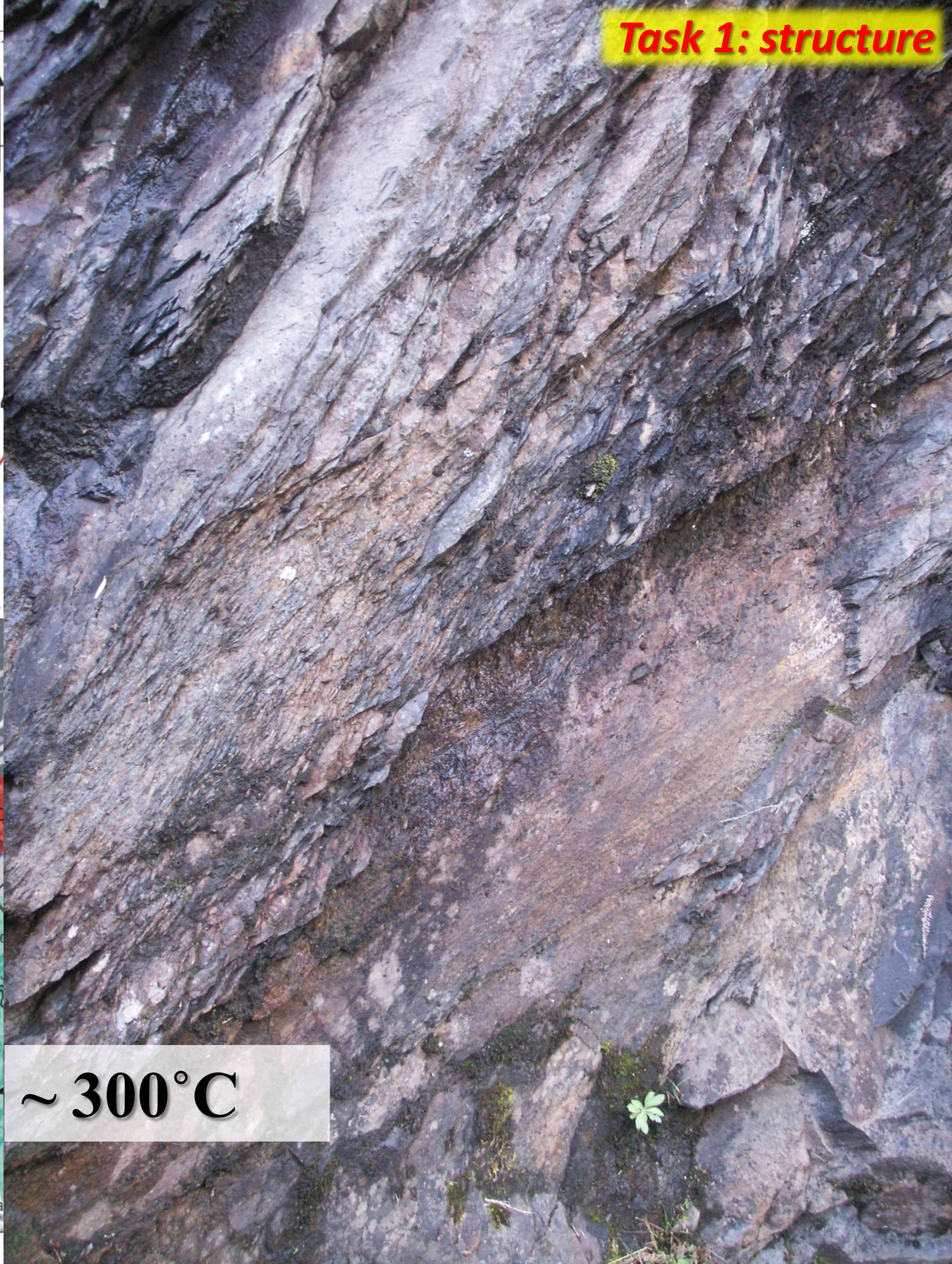
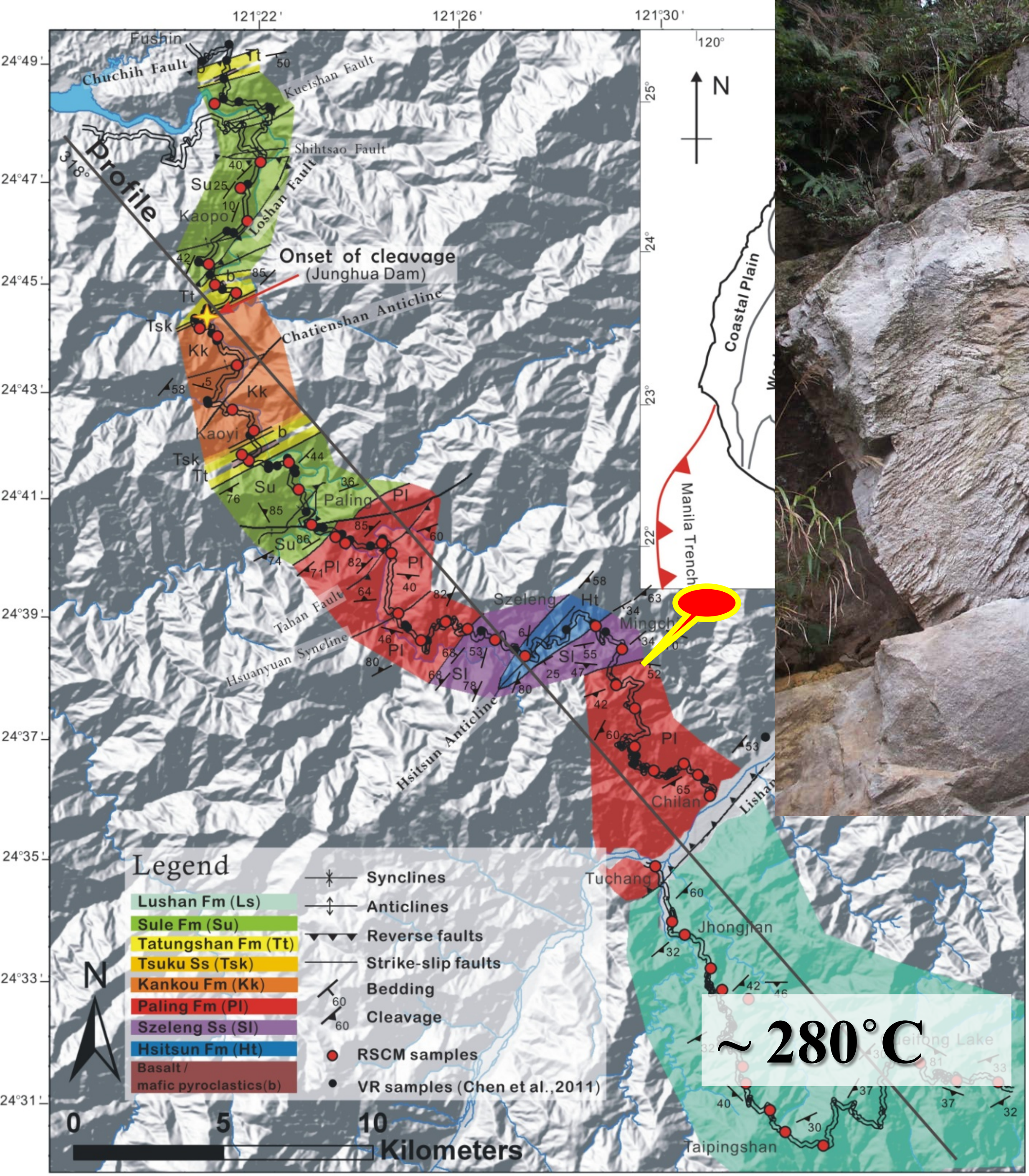




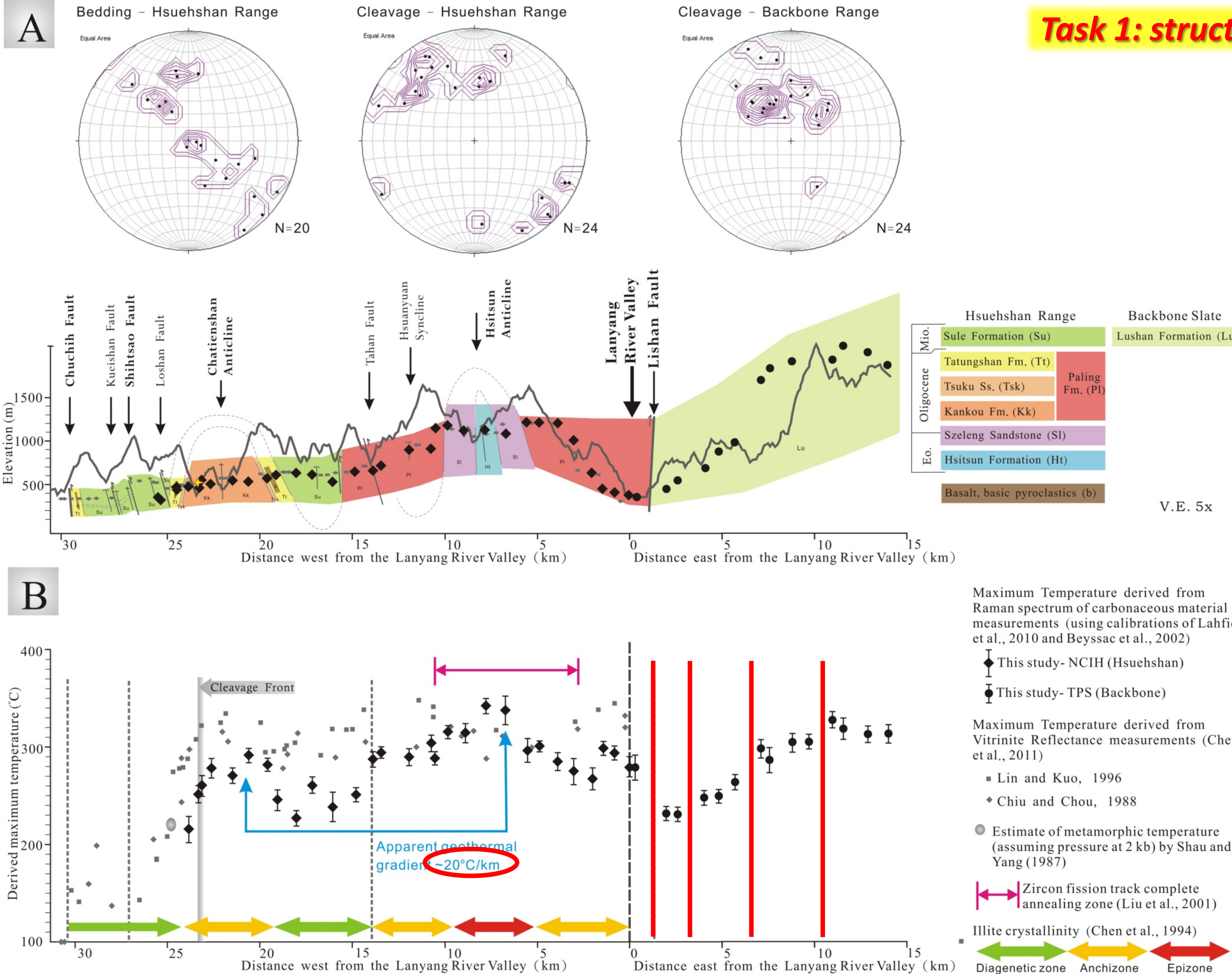
~ 300°C

Task 1: structure

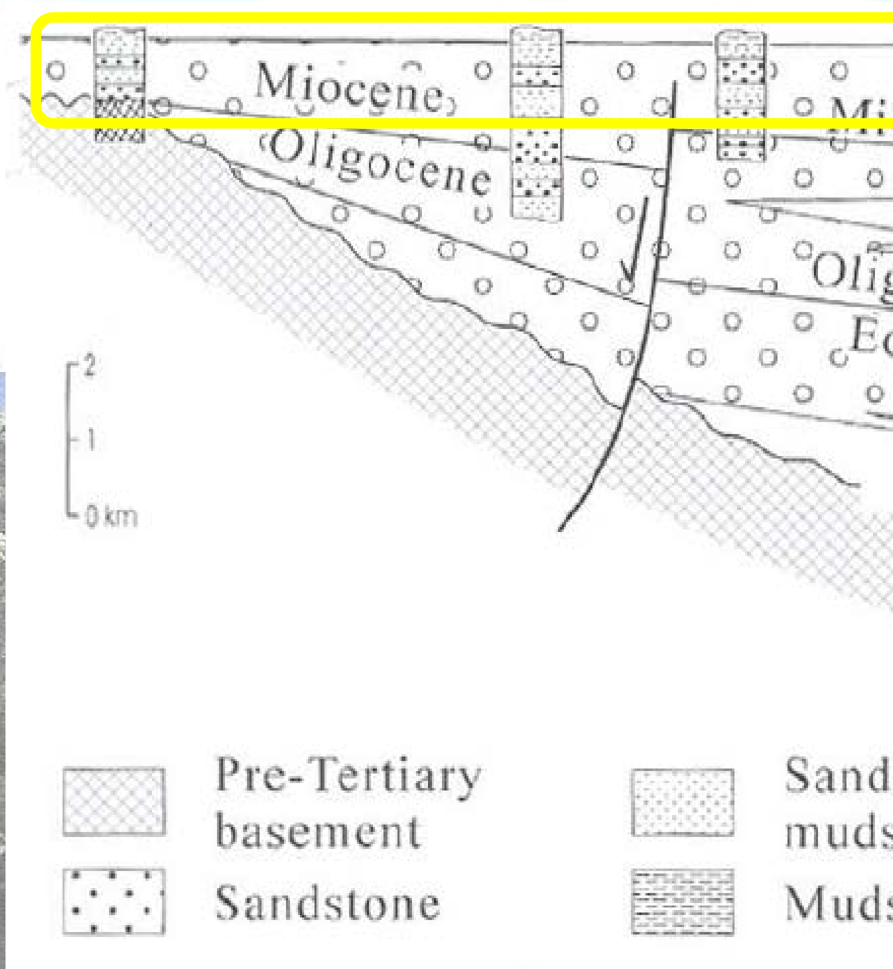


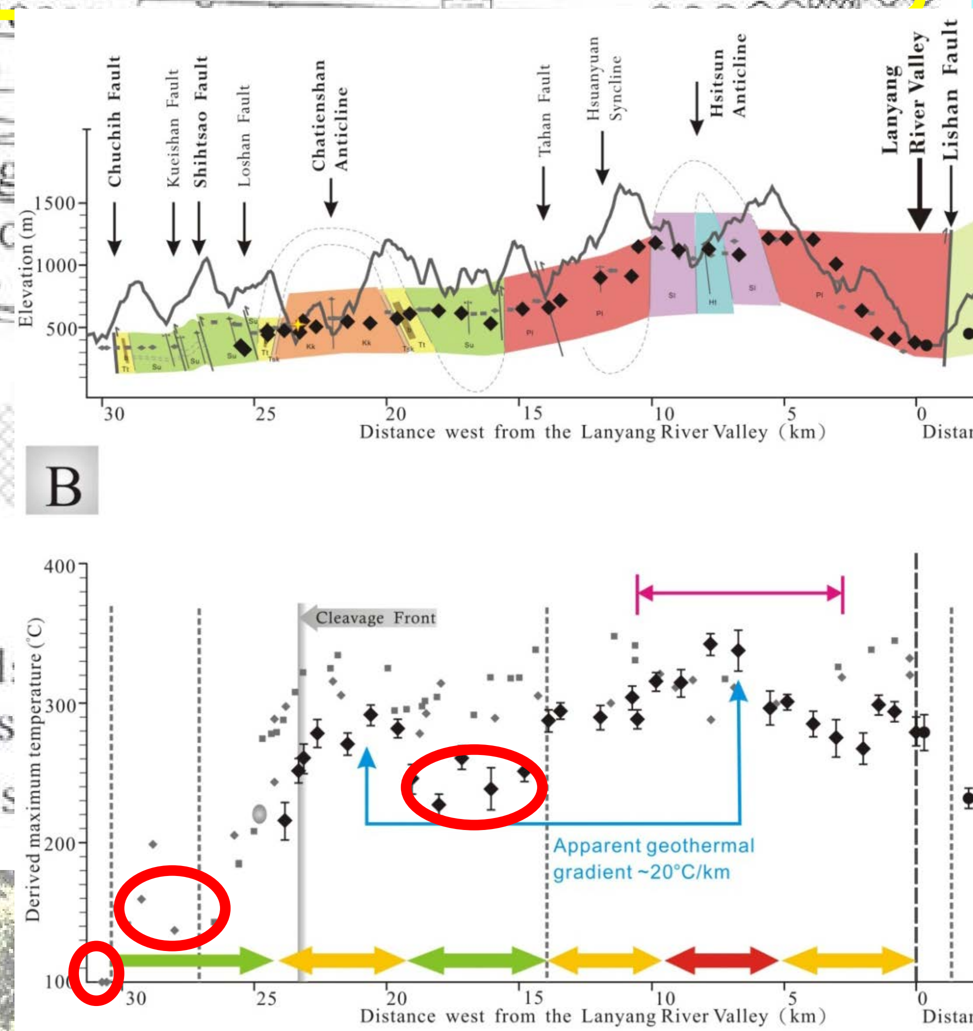
~ 280°C

Task 1: structure



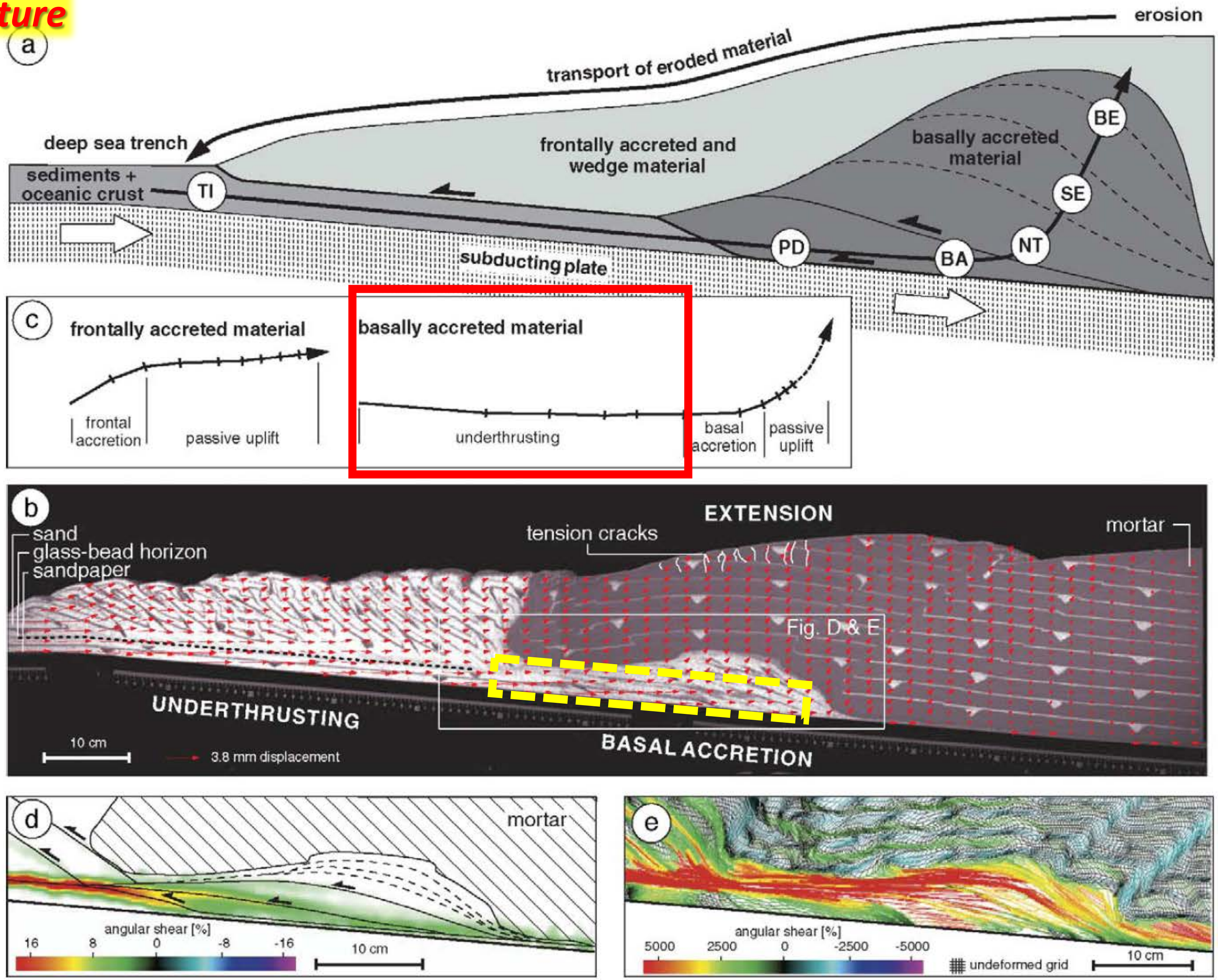
Passive margin configuration before convergence





Teng et al., 1991

Task 1: structure

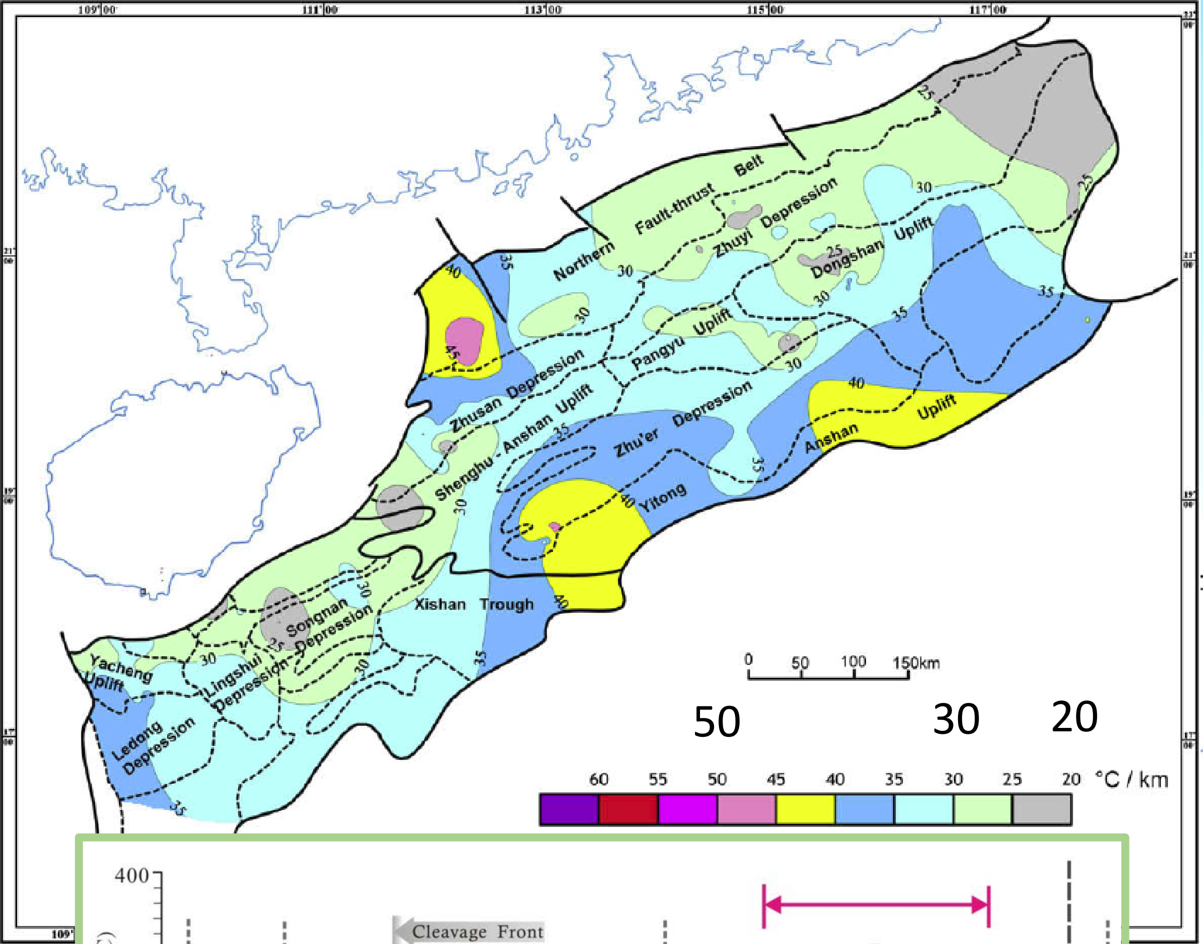


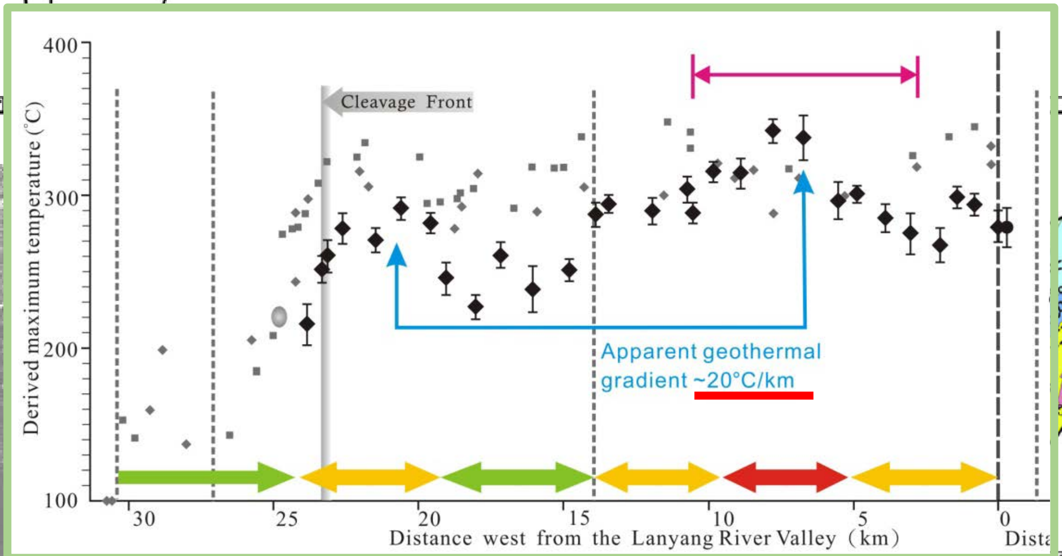
Glodny et al., 2005

Task 1: structure

Present-day geothermal gradient along the Chinese Continental Margin at Pearl River Mouth Delta

Yuan et al., 2009





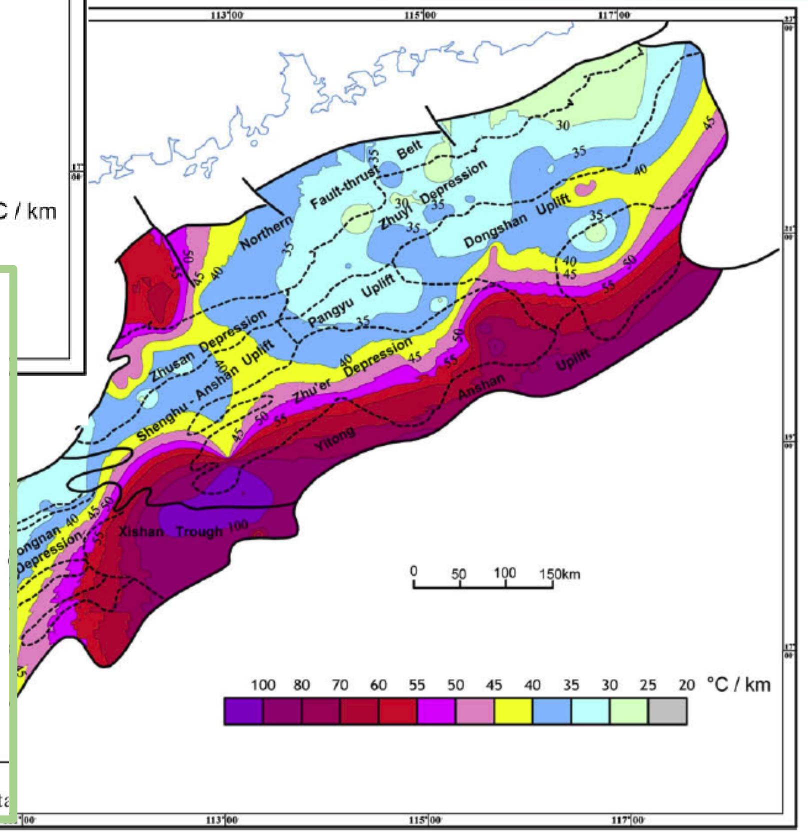
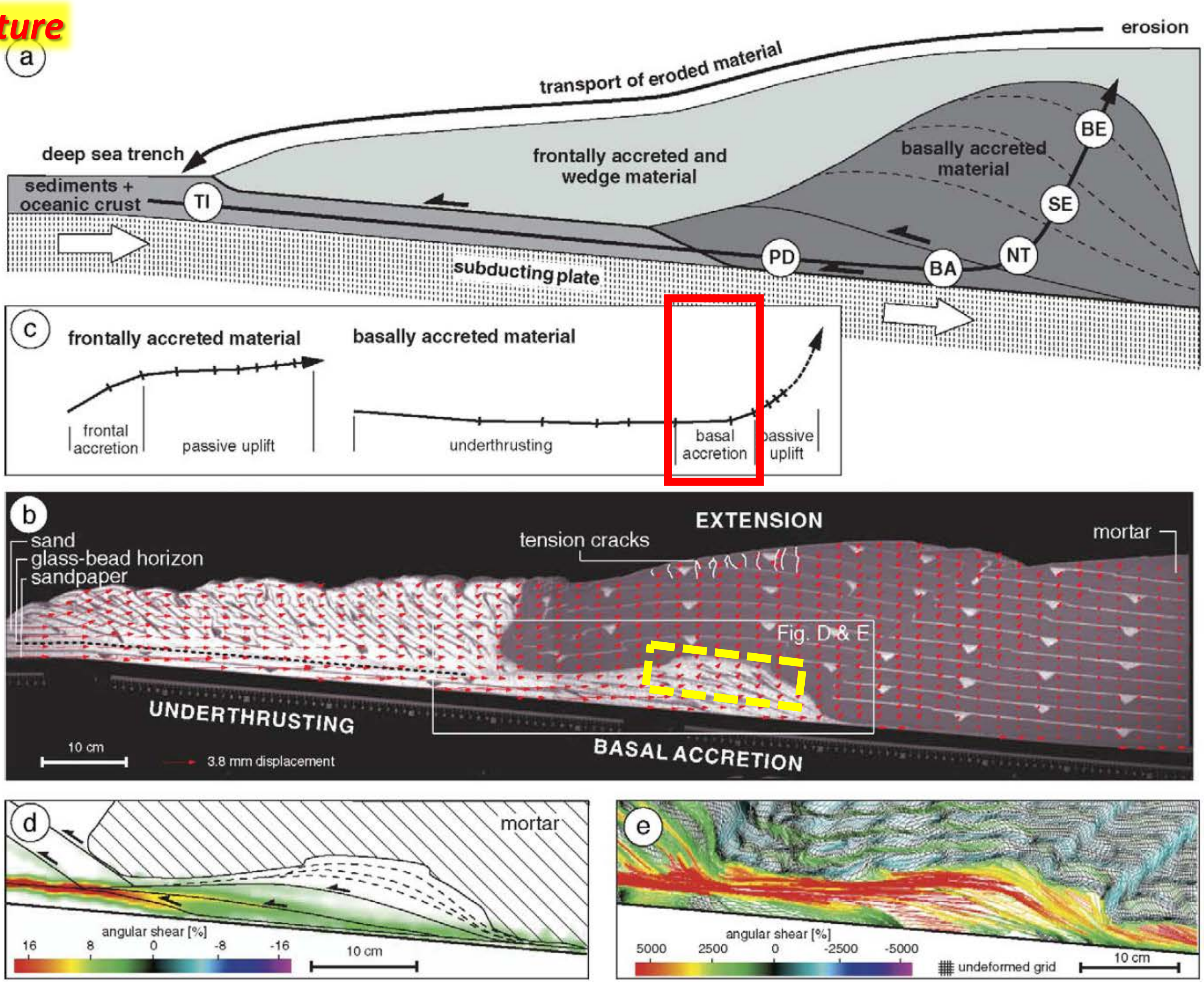


Fig. 4. Contour map of the measured geothermal gradient of the PRMB and QDNB.

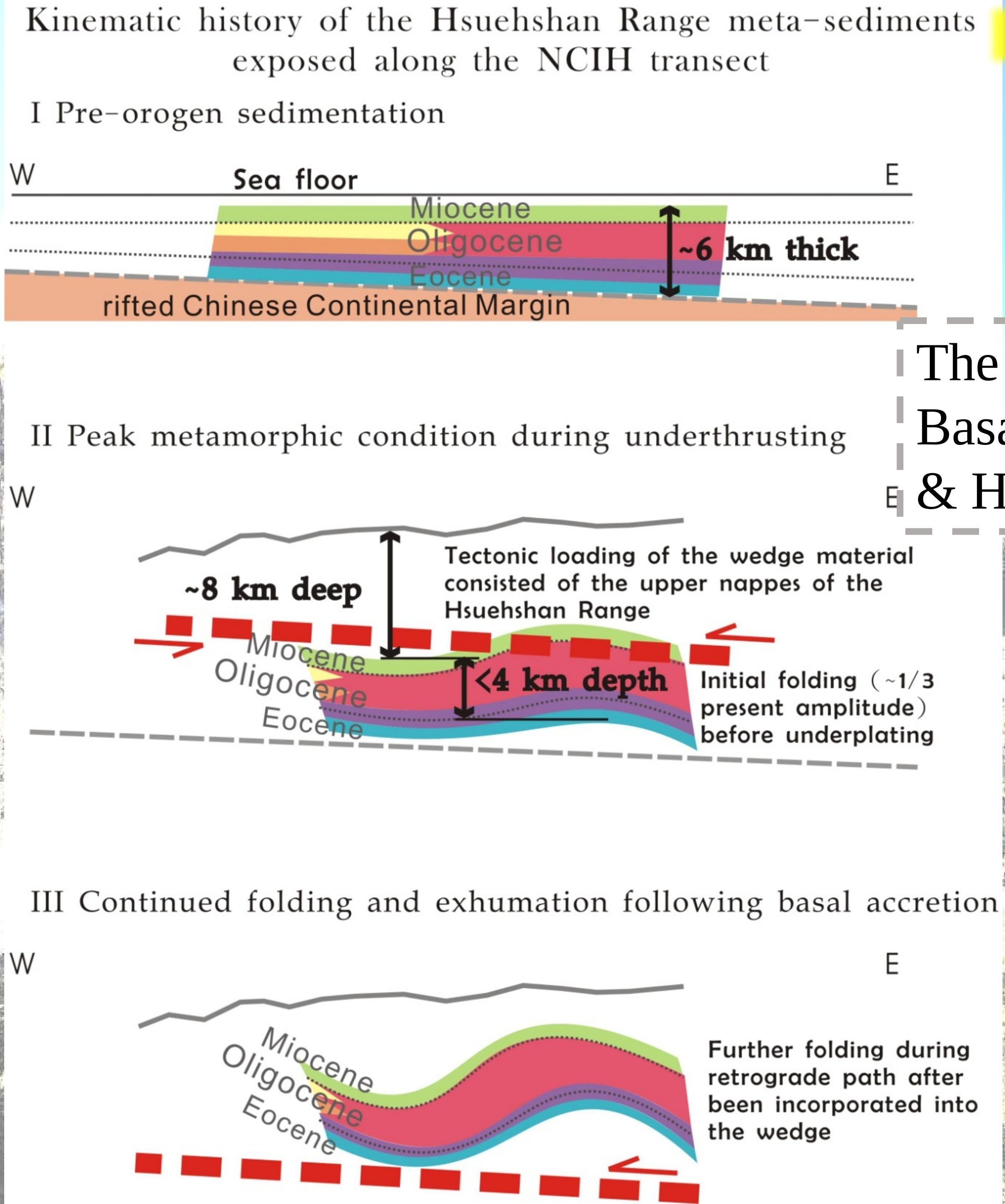
Task 1: structure



Glodny et al., 2005

Task 1: structure

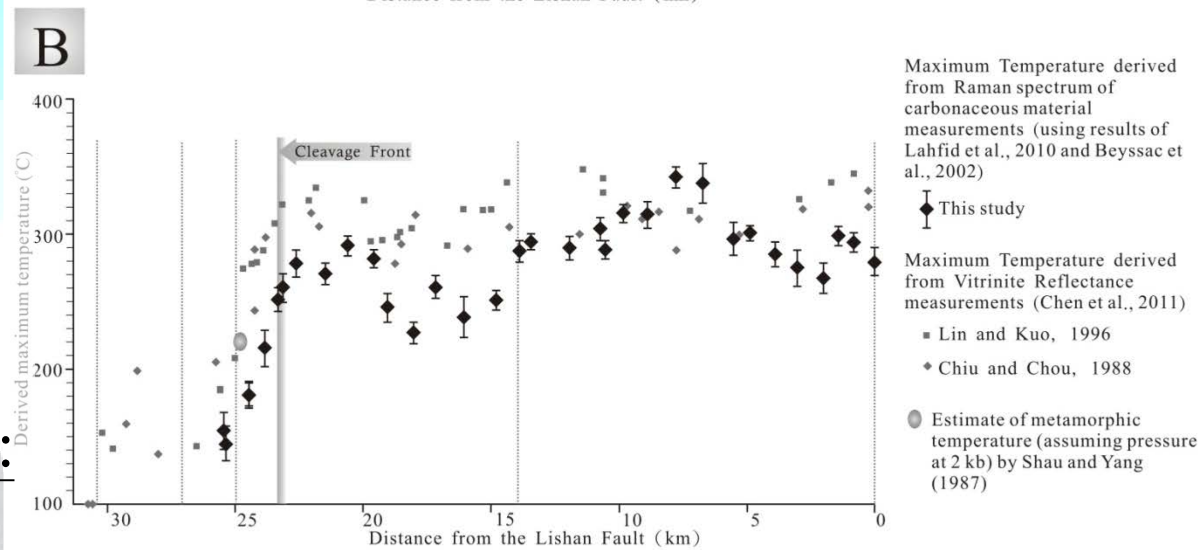
The Presence of Basal Accretion & How it worked

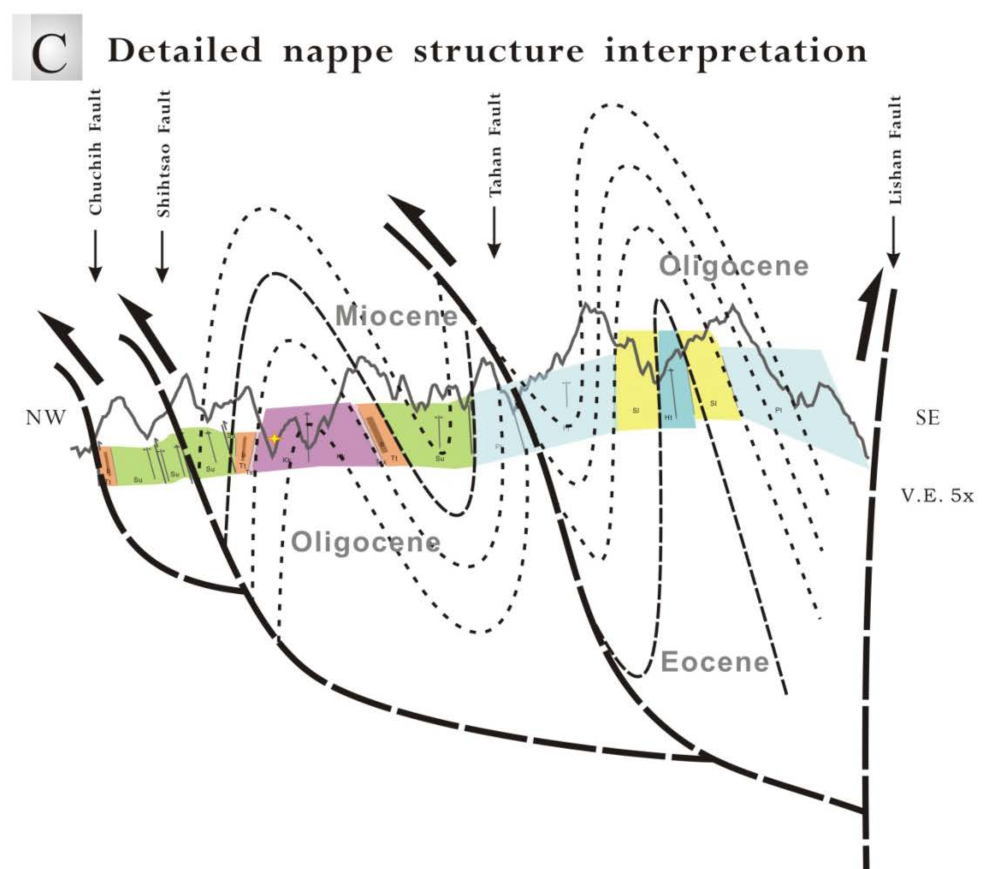


Task 1: structure

- **Fault-fold structure:** dominance of the Shihtsao and Tahan faults

- **Stratigraphic architecture:** correlation of Miocene strata from Foothills to the Hsuehshan Range; lateral facies changes within the Oligocene strata





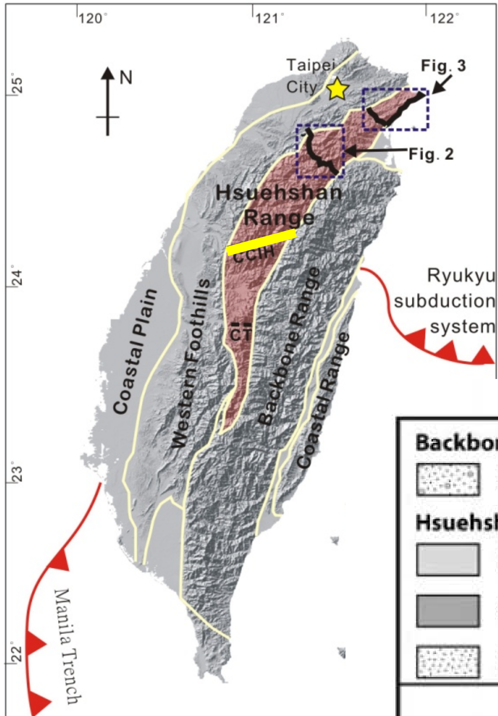
Task 2:

Where it operated?

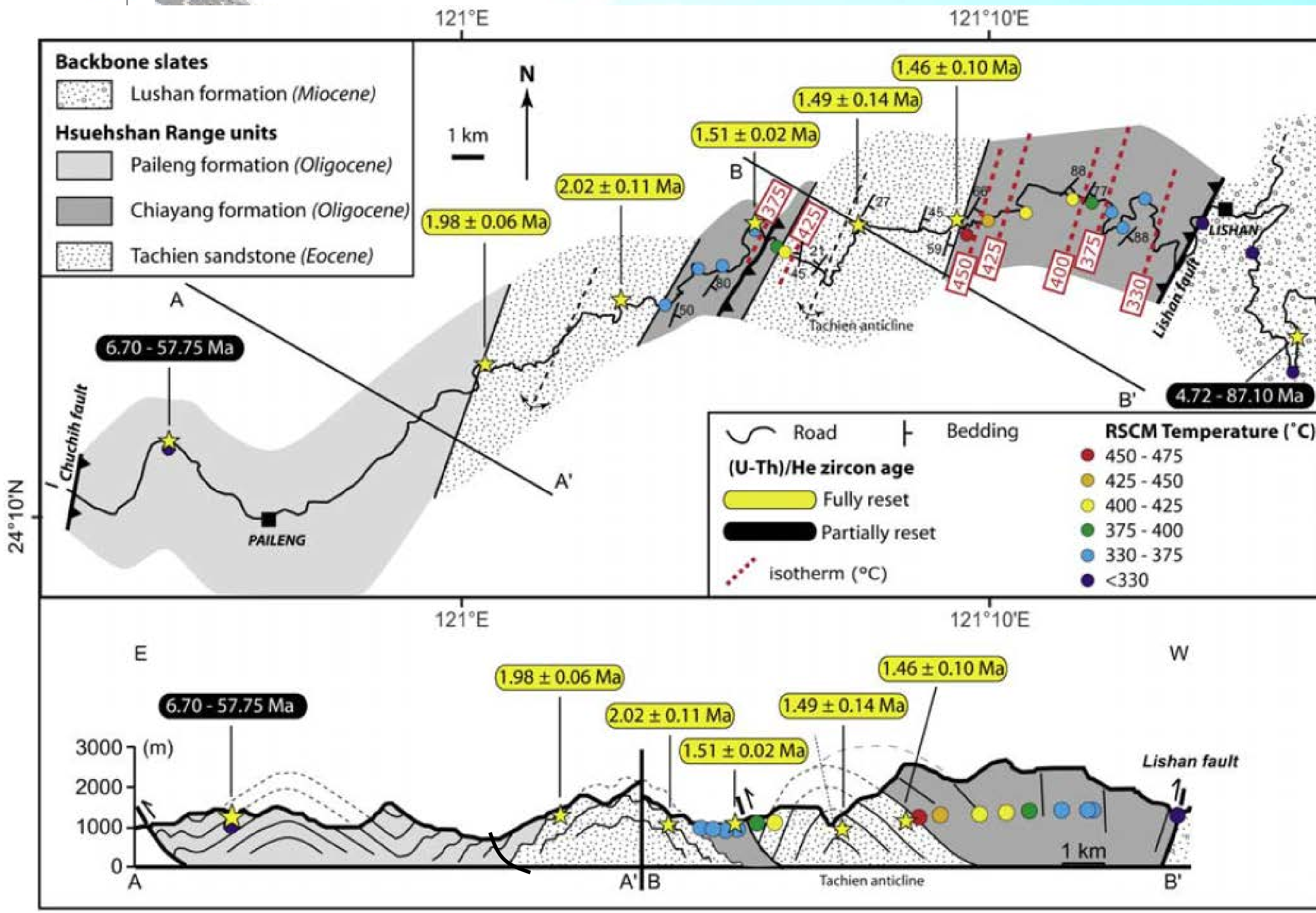
- Along-strike comparisons within the Hsuehshan Range under the space-time equivalence of the Taiwan orogeny:
  1. N-S thermal-metamorphic pattern contrasts,
  2. sedi. facies differences within the Hsuehshan Trough

Task 2: locality

Central Cross-Island Highway transect



Beyssac et al., 2007



Task 2: locality

RSCM

Peak T correlates to stratigraphic positions within graben basin with a reasonable (~30°C/km) geothermal gradient

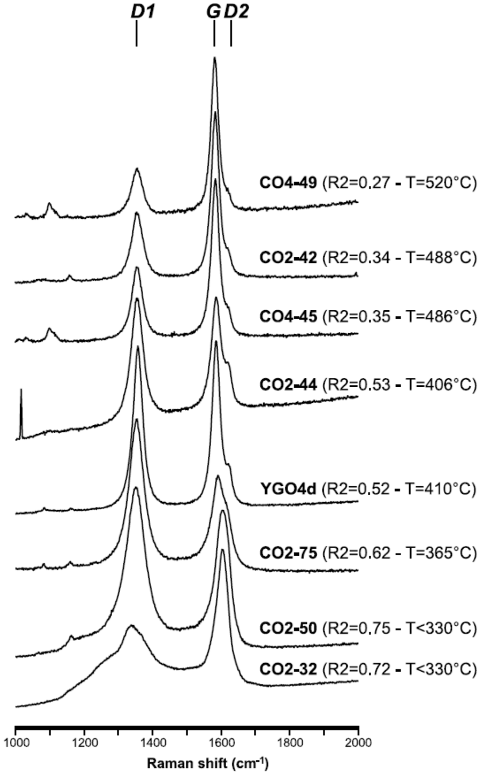
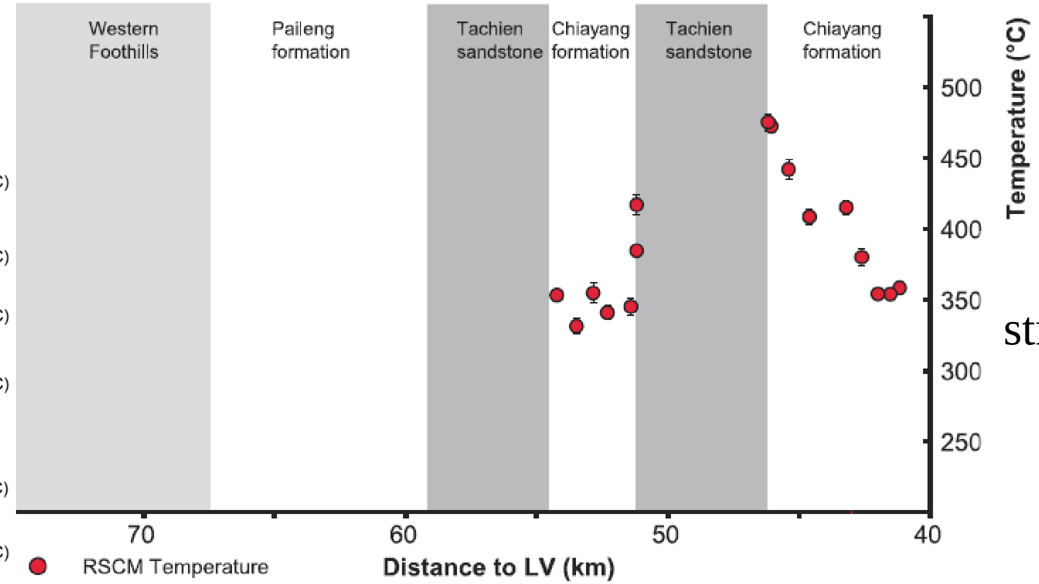
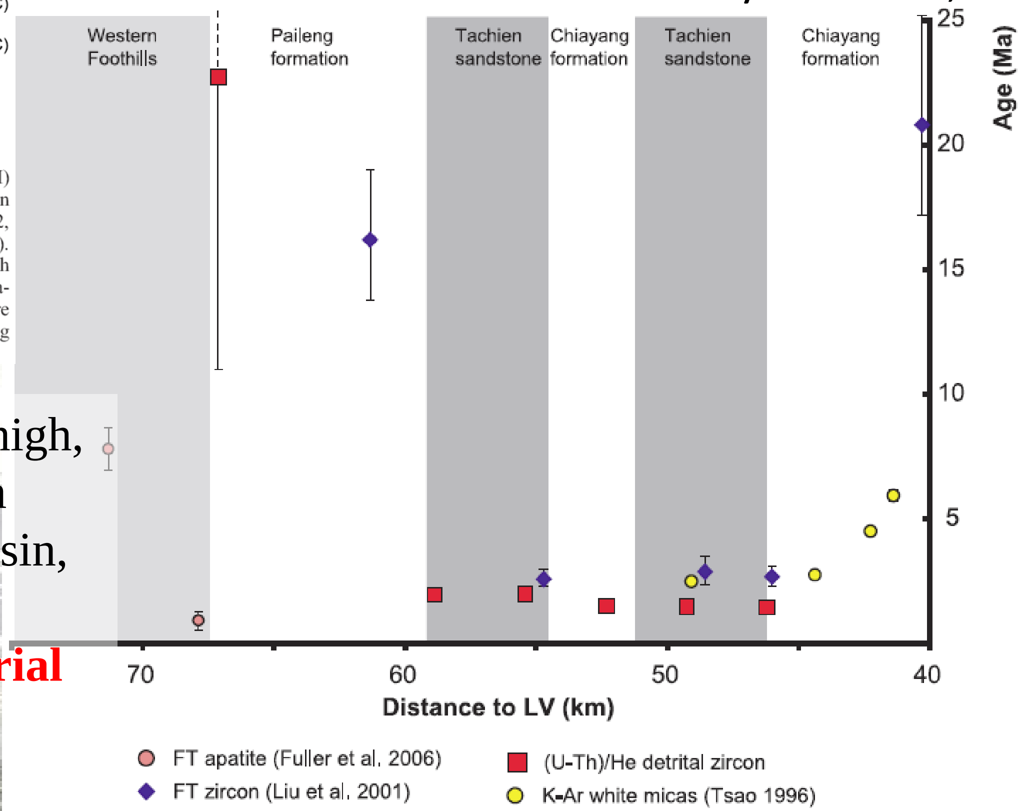


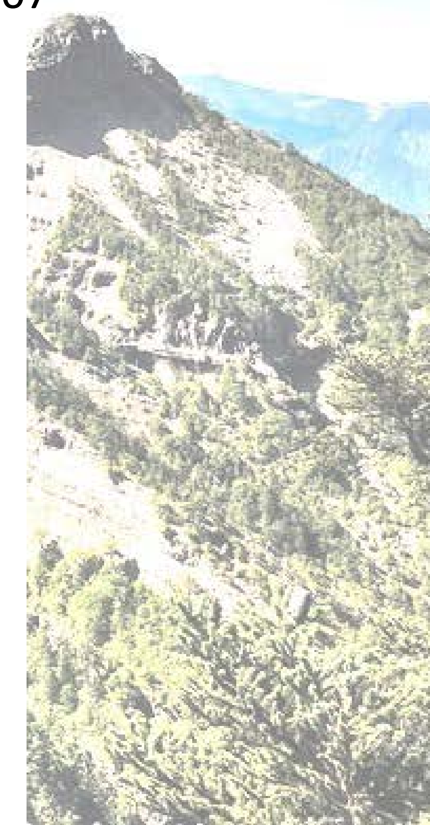
Figure 3. Raman spectra of carbonaceous material (CM) obtained along the central cross-island highway section from samples in the HR (C02-42, C0244), BS (C02-32, C02-50), and TC (C02-75, YG04d, C04-45, C04-49). Positions of G, D1, and D2 bands are indicated. For each spectrum, the R2 ratio and corresponding RSCM temperature calculated from the depicted CM spectrum are indicated. See *Beyssac et al.* [2002a] for details regarding RSCM thermometry.



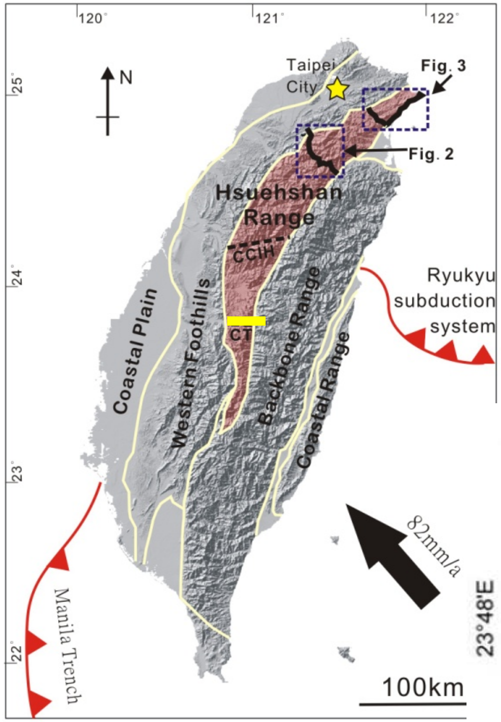
Beyssac et al., 2007



Though the T is pretty high, it retains signature from original sedimentary basin, therefore regarded as resulted from **static burial metamorphism**



Choshui River transect



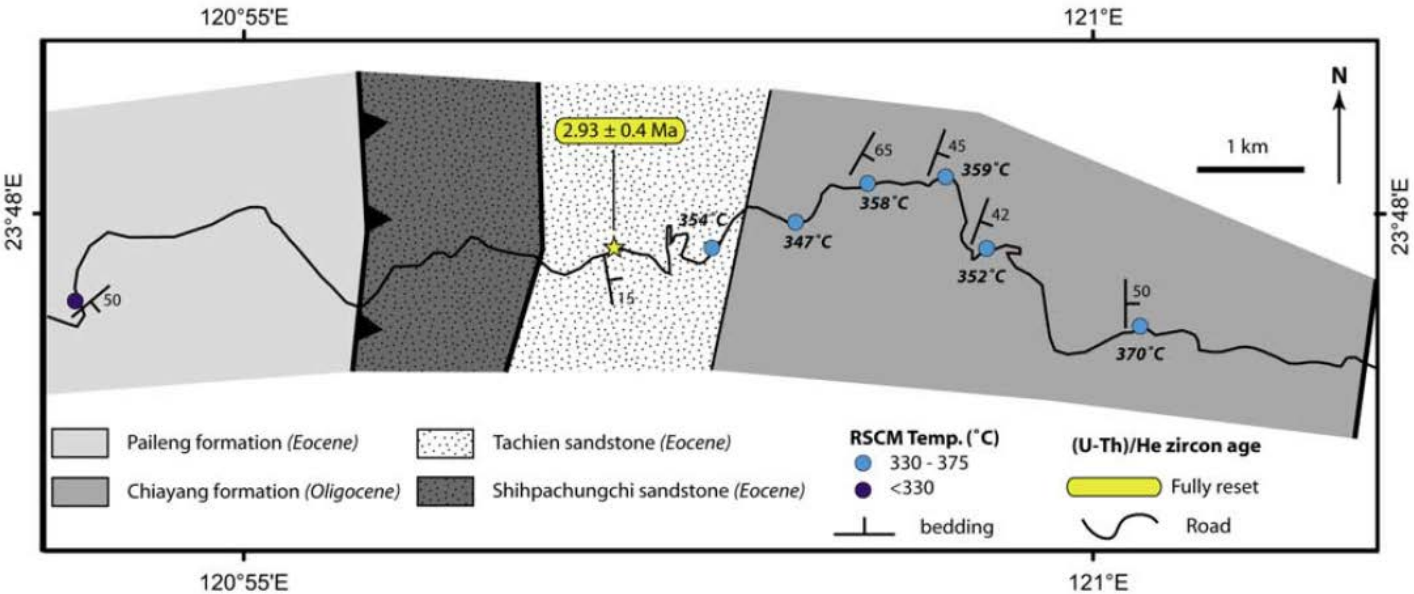


Figure 10. Geological map of the HR along the mid-Taiwan highway (Choushui river; see Figure 1 for location), modified from *Ho* [1988]. Structural data are from this study. RSCM temperatures are depicted by the blue to red circles. The unique zircon (U-Th)/He age (Tachien sandstone) obtained in this area is shown.

Beyssac et al., 2007

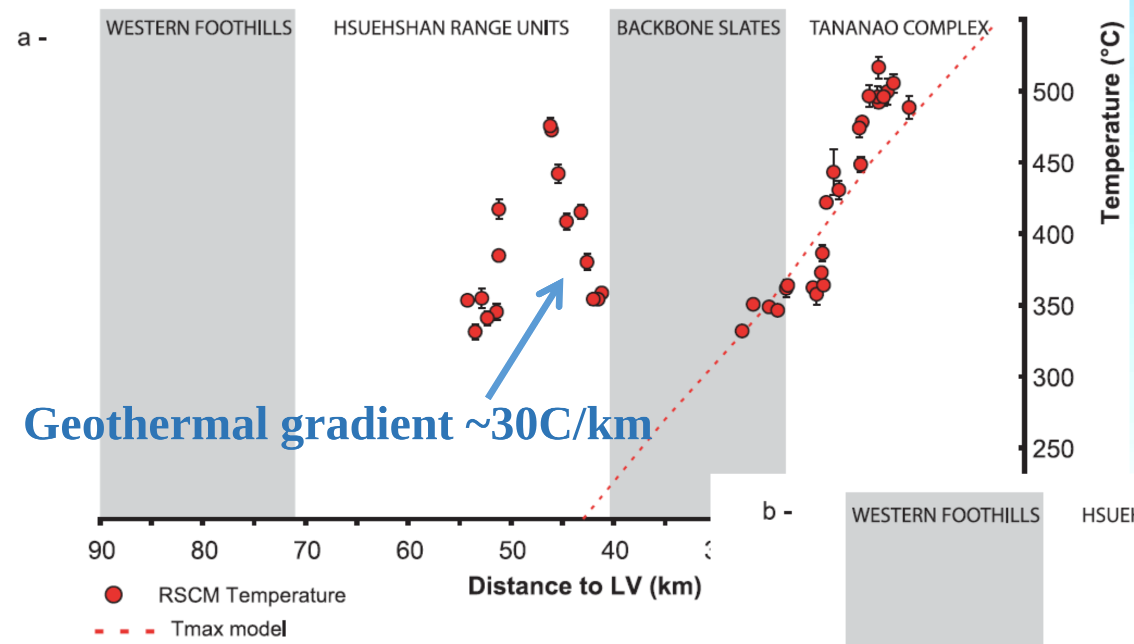
Relatively lower in T, equivalent to the outer folds in CCIH transect

Task 2: locality

N-S discrepancies in Hsuehshan Range

- Lesser peak T in northern Paleogene sediments
- Dramatic eastward increase of peak T of Miocene sediments in the north
- Significantly lower apparent geothermal gradient in the north

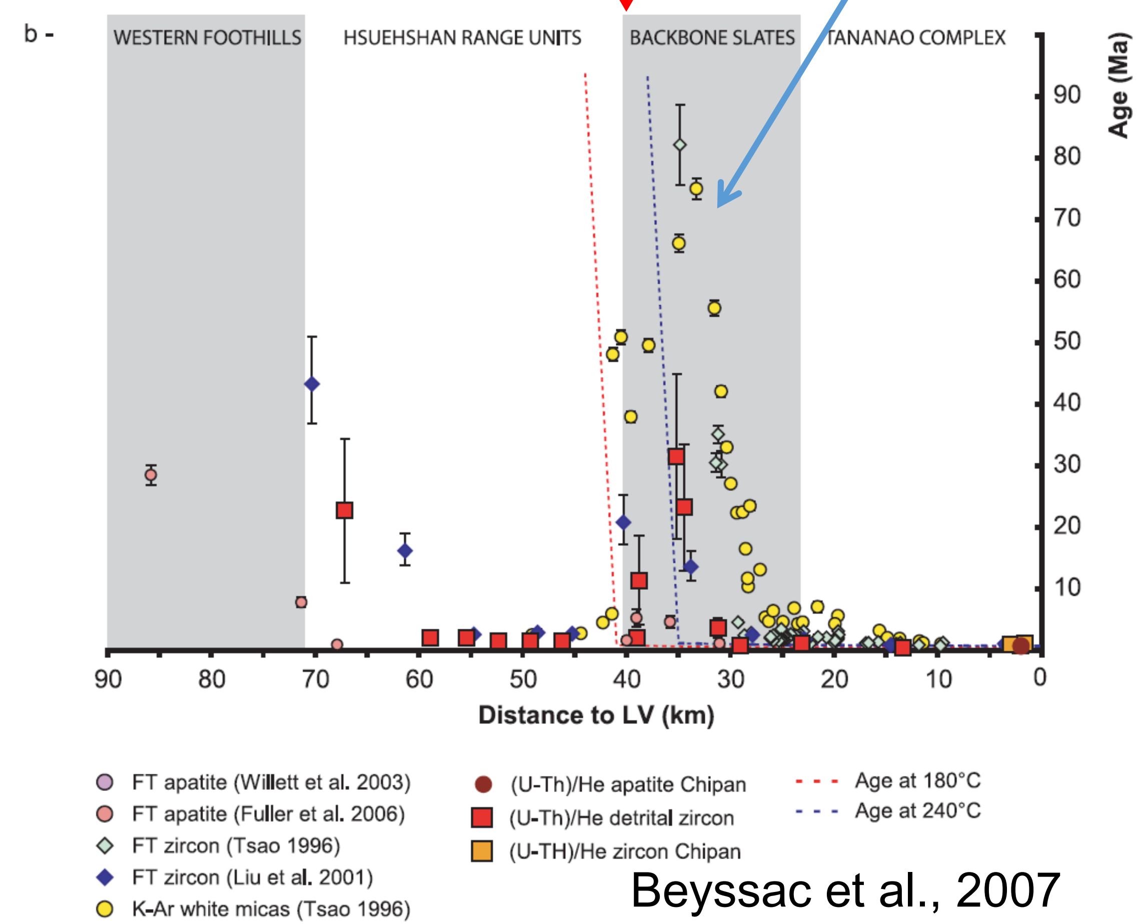
Task 2: locality

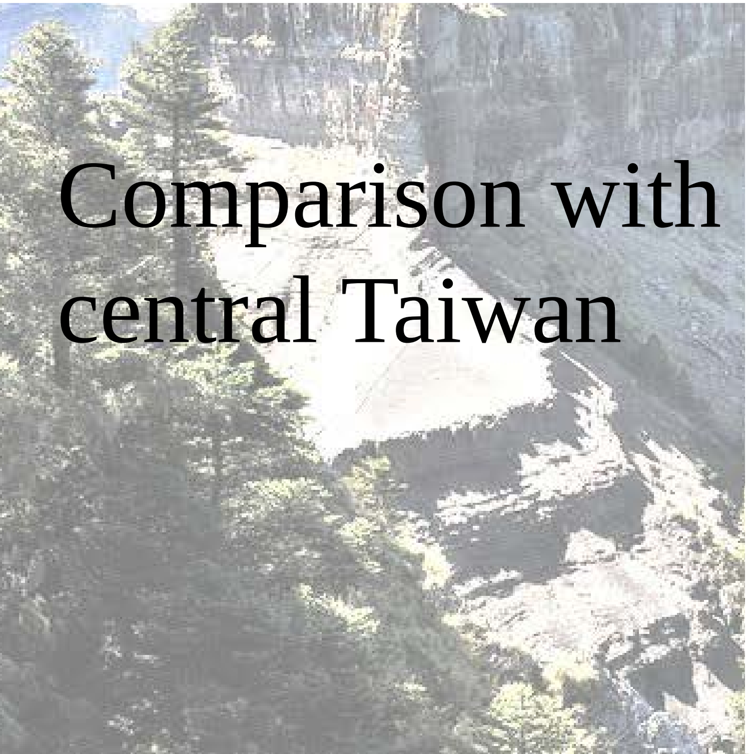


Geothermal gradient ~30C/km

Contrast in metamorphic degrees

Rapid E-ward increase of grade

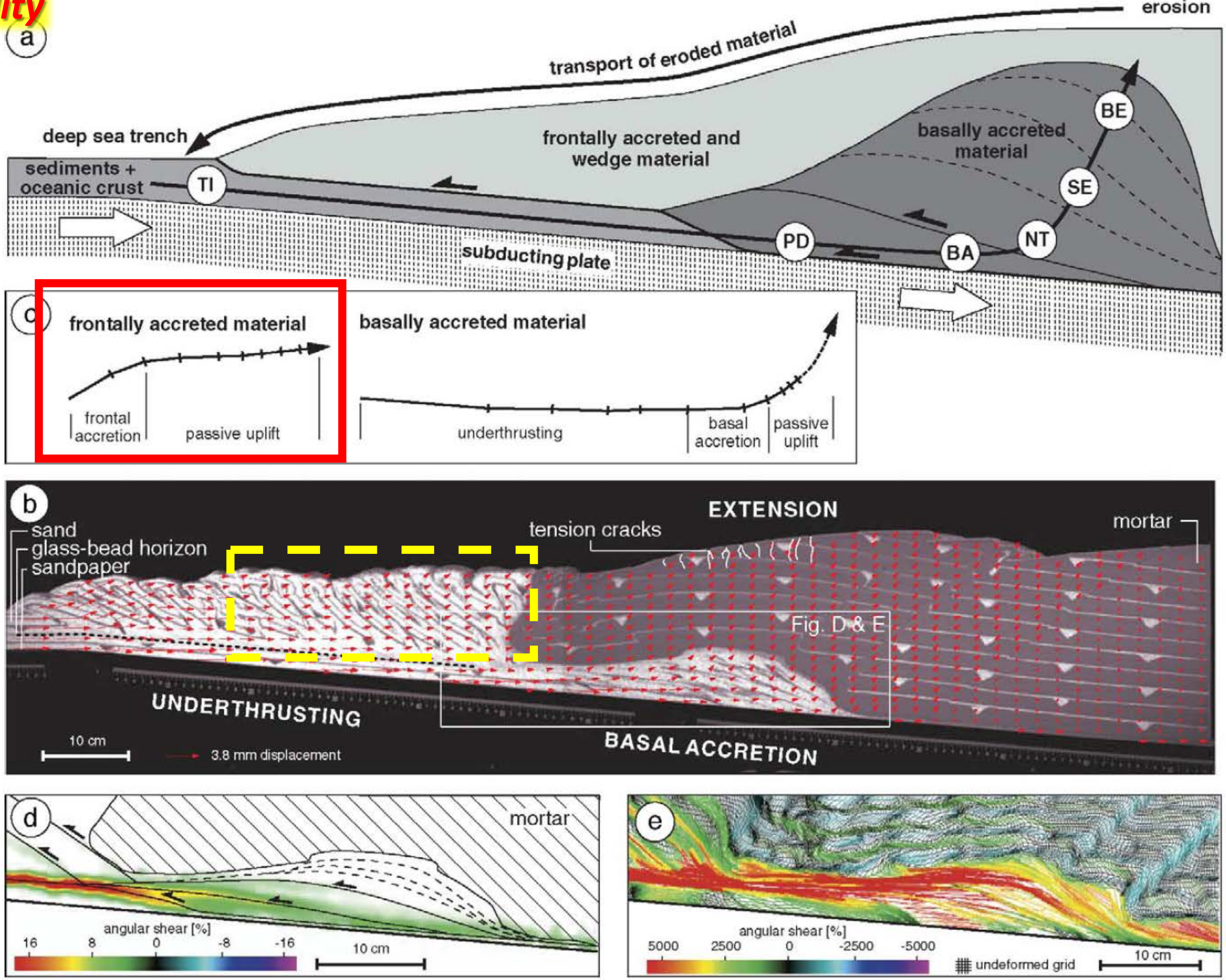




Comparison with central Taiwan

Beyssac et al., 2007

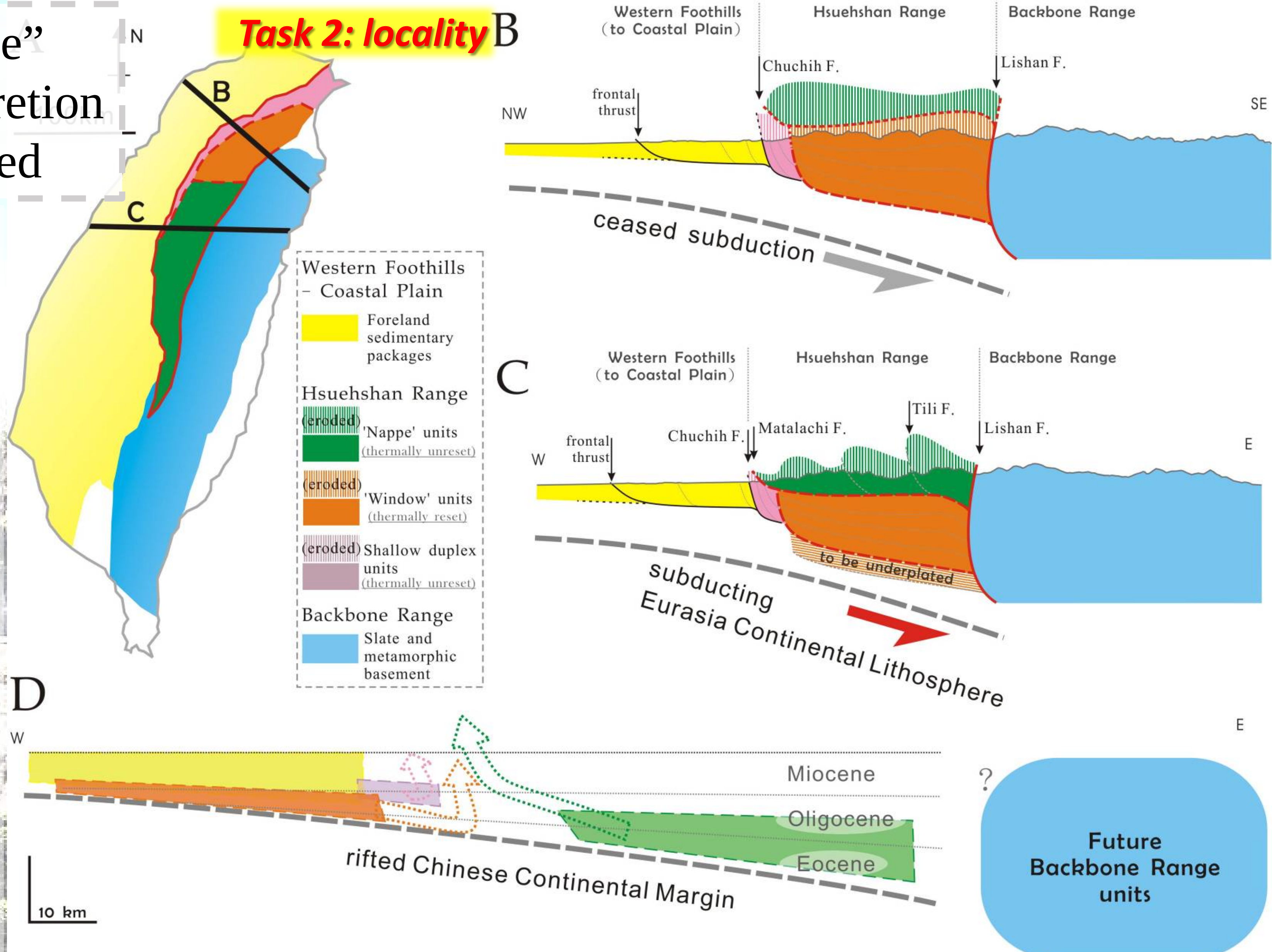
Task 2: locality



Glodny et al., 2005

“Where” basal accretion operated

Task 2: locality



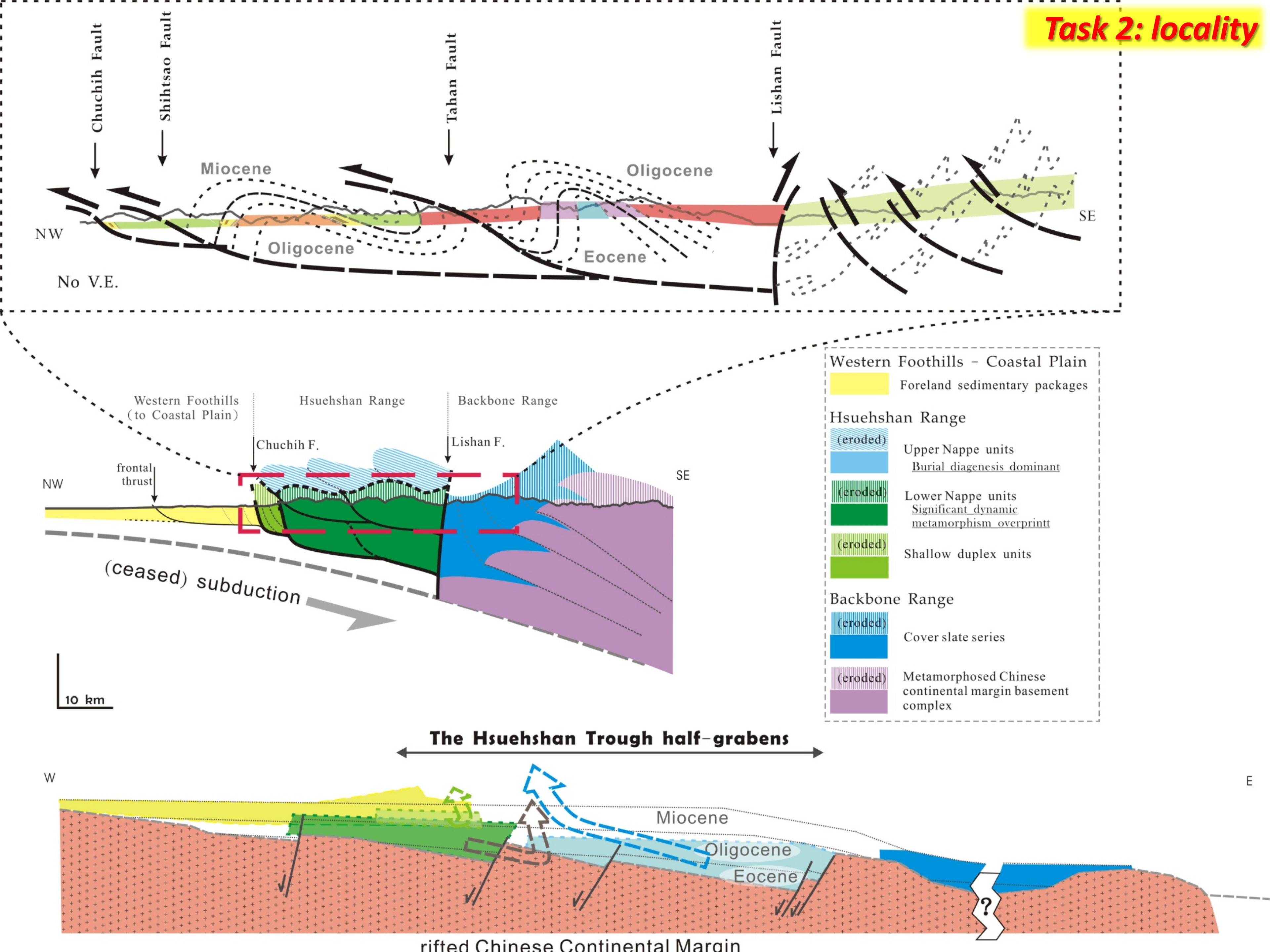
Conceptual model emphasizing the role of basal accretion in the pro-wedge part and the resulting nappe-window structure of the Taiwan Orogeny

Dominant role of tectonic-driven exhumation coupled with erosion

Northward progressive maturation of orogenesis and exhumation

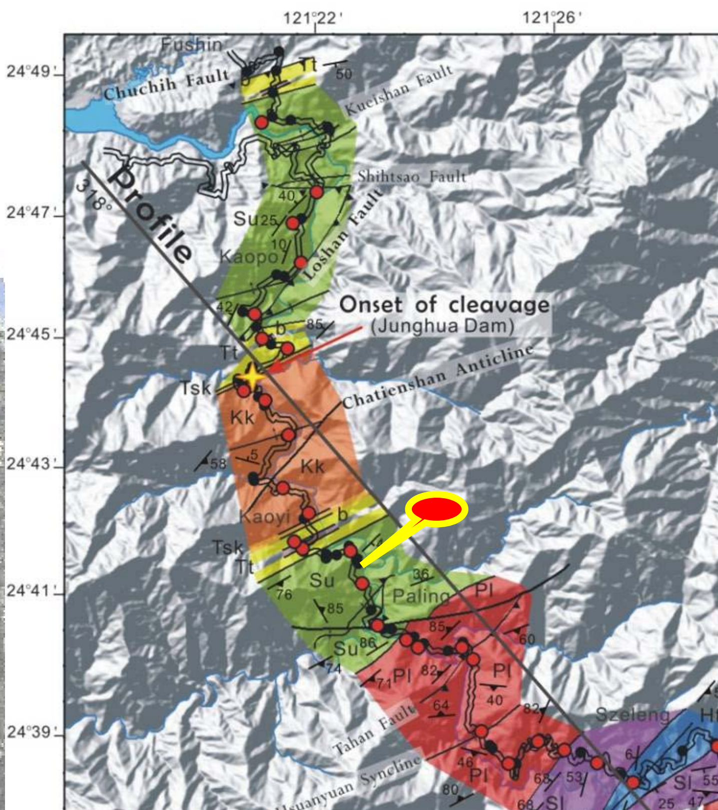
Chen et al., 2011, Terra Nova

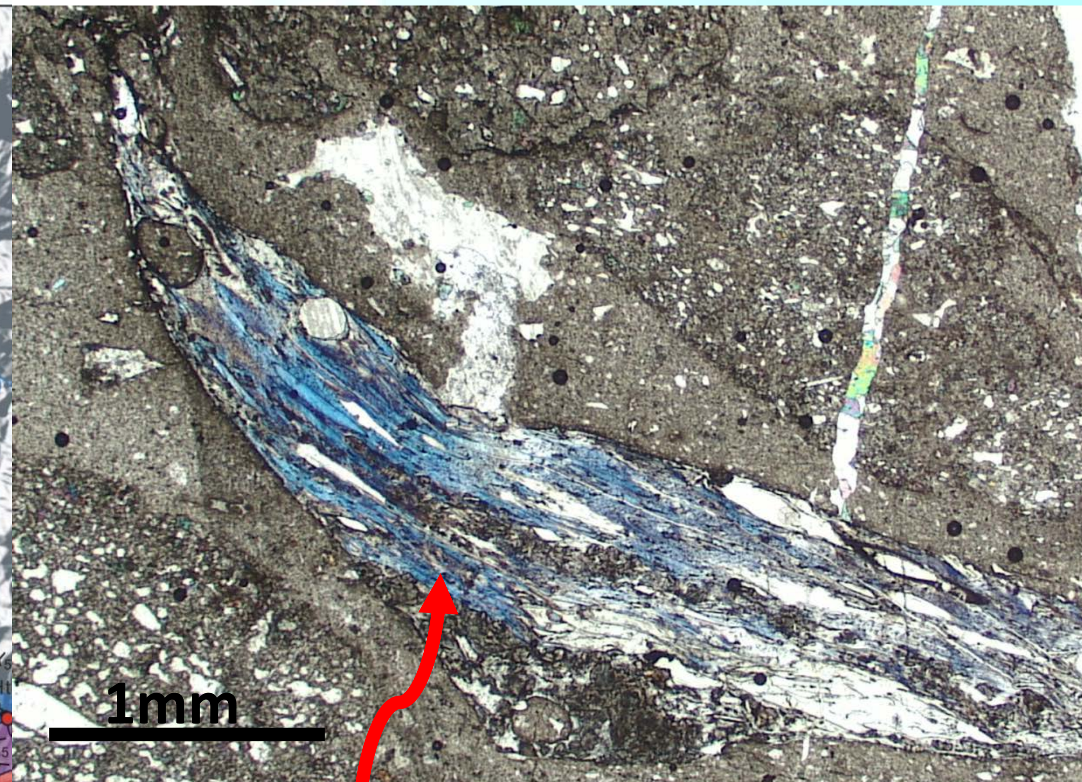
Task 2: locality



Task 3: when

- The **Presence**, **Sites**, and the **Responsible Structures** for Basal Accretion in Taiwan pro-wedge are pinpointed, but **When**…….





Syn-kinematic muscovite+corrensite growth aggregates along pressure solution seams in the meta-mafic-pyroclastics

Task 3: **When** it operated?

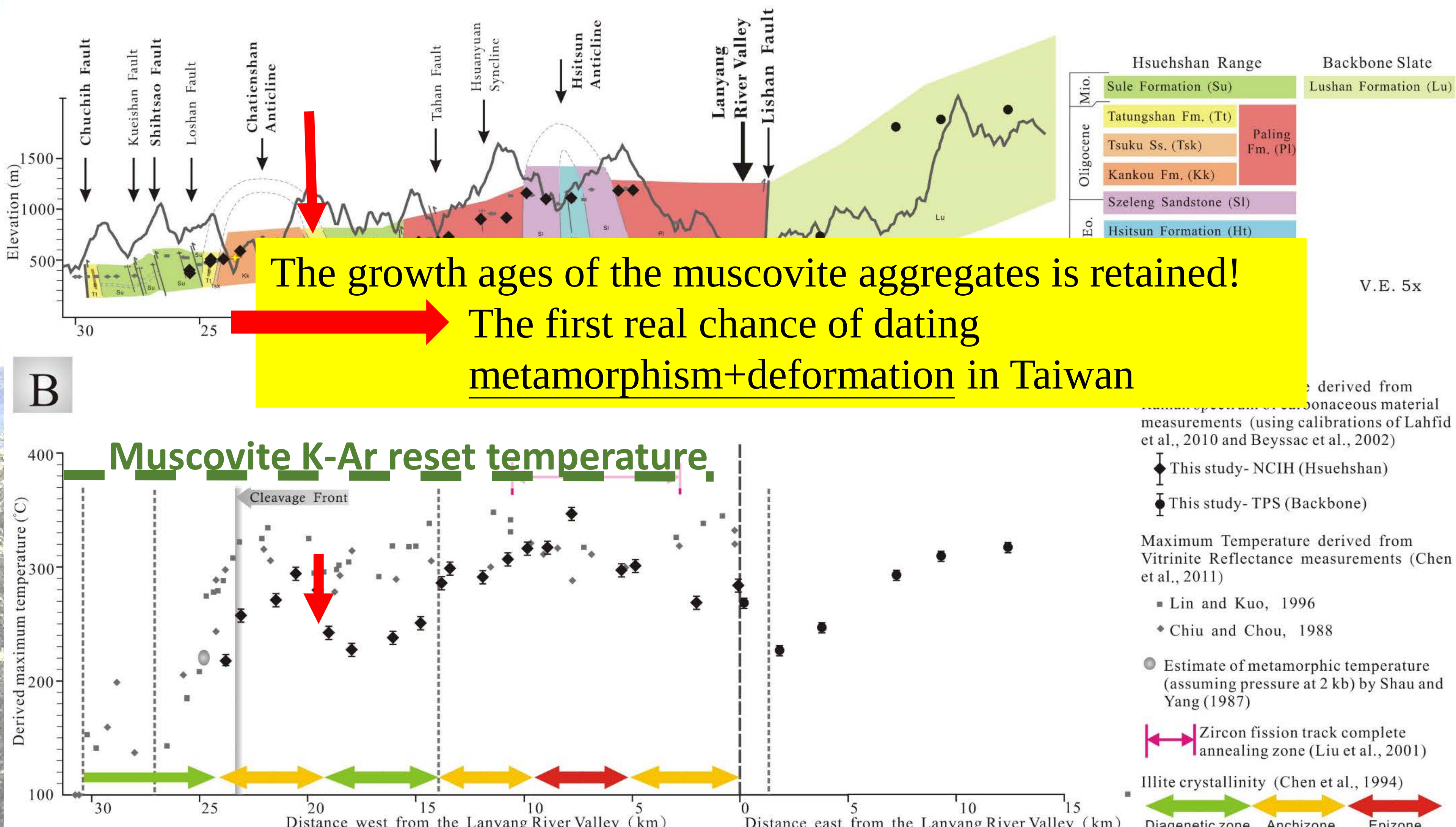
- In-situ dating of syn-kinematic mineral growth fibers under comprehensive thermo-metamorphic constraints

Task 3: when

The growth ages of the muscovite aggregates is retained!

The first real chance of dating <u>metamorphism+deformation</u> in Taiwan

Muscovite K-Ar reset temperature



Task 3: when

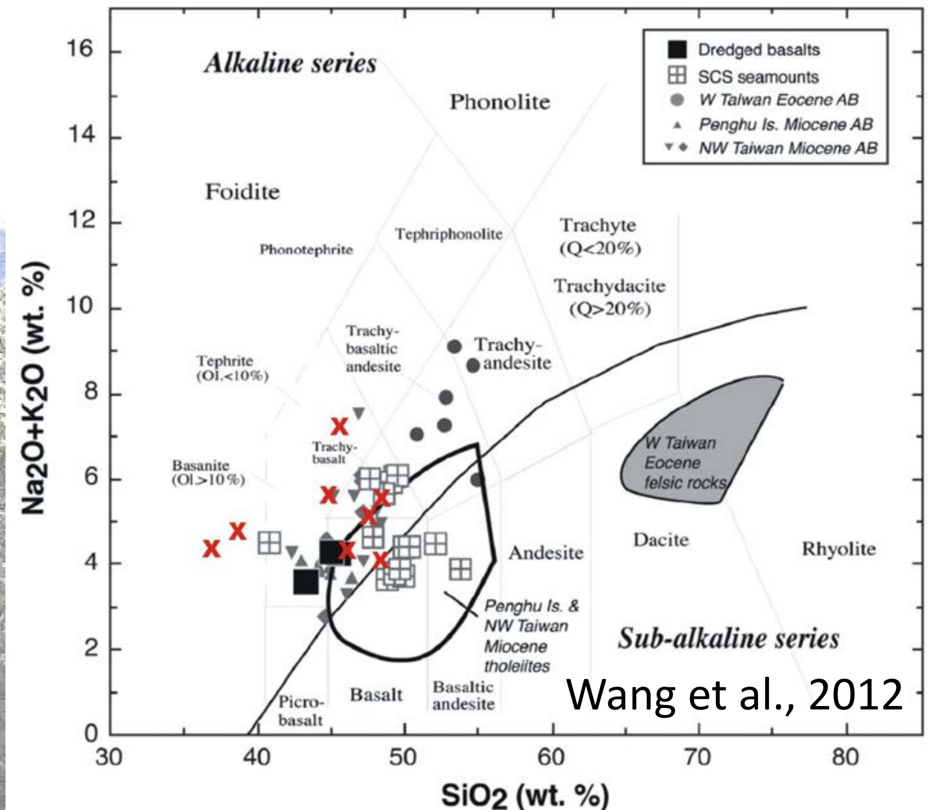
Multiple thermal-chronologic gears

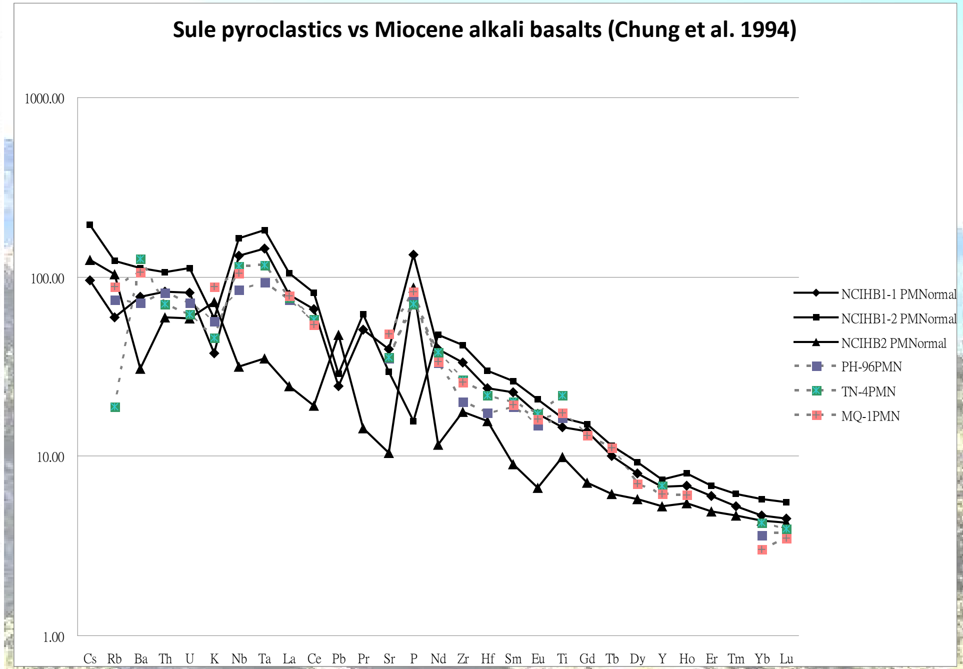
- RSCM (nearby sample): *peak thermal state*
- Whole-rock chemistry: *protolith*
- Zircon U-Pb dating: *deposition & provenance*
- Muscovite $^{40}Ar/^{39}Ar$ in-situ spot fusion dating: *deformation age*
- Zircon & Apatite fission track dating: *exhumation*

Task 3: when

Whole-rock chemistry

Sample Name	SiO2	TiO2	Al2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	P2O5	Total
NCIHB1-1	36.54	3.43	14.37	10.28	0.16	9.05	11.59	2.07	0.94	1.27	89.69
NCIHB1-2	40.99	3.90	17.11	12.62	0.17	7.62	6.13	1.79	1.82	0.83	92.98
NCIHB2	48.59	2.36	15.14	12.23	0.08	5.87	4.36	2.19	1.47	0.15	92.43

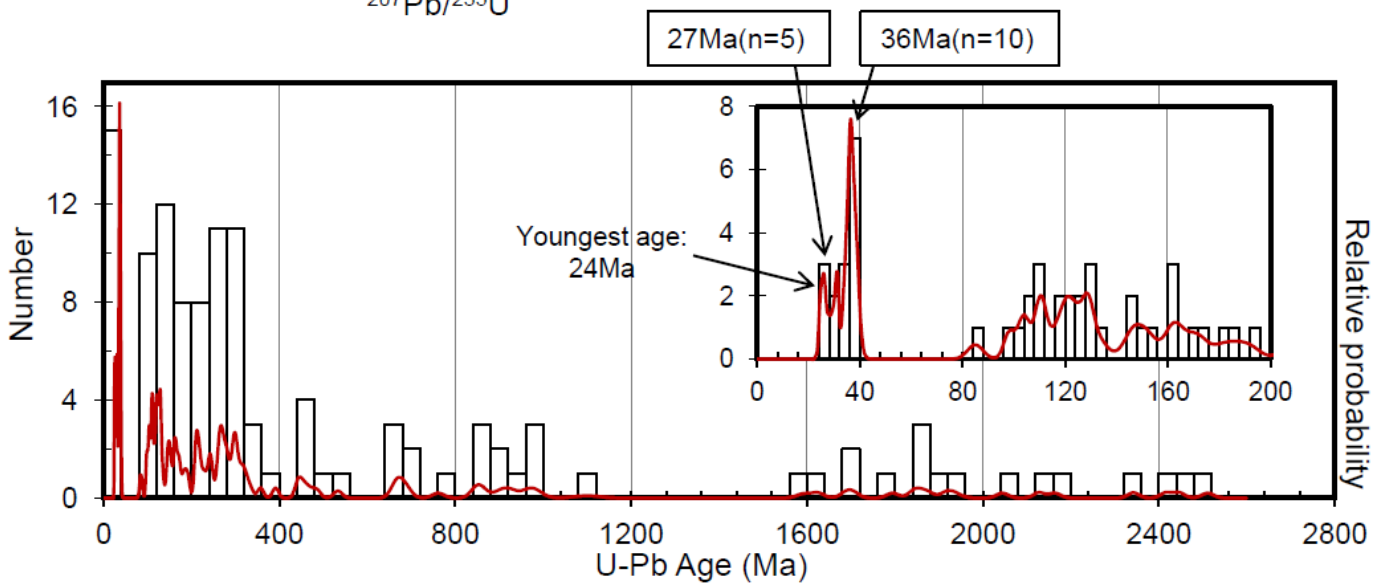


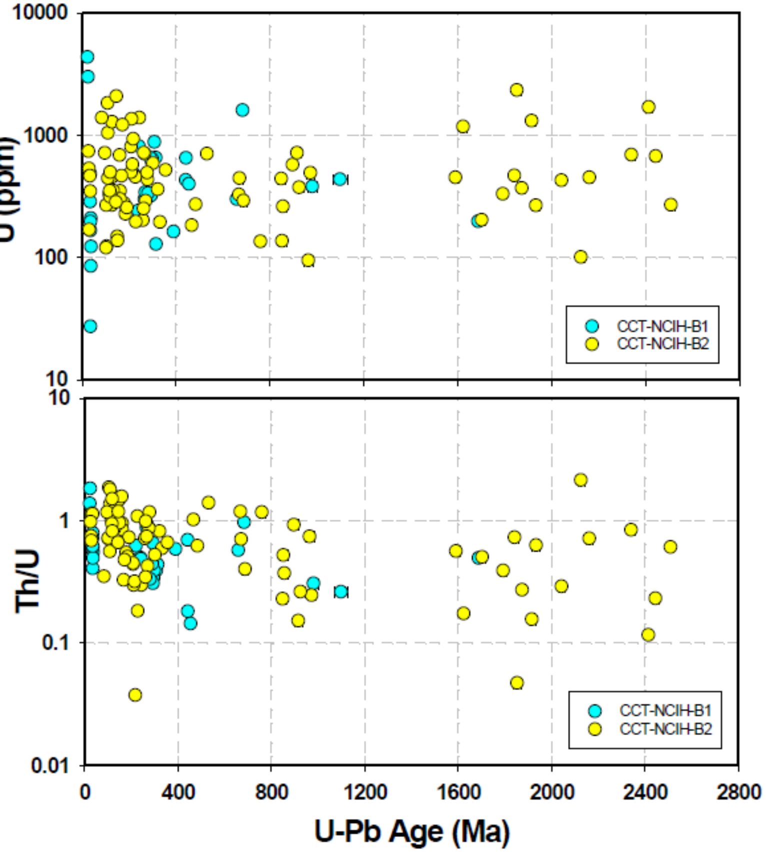


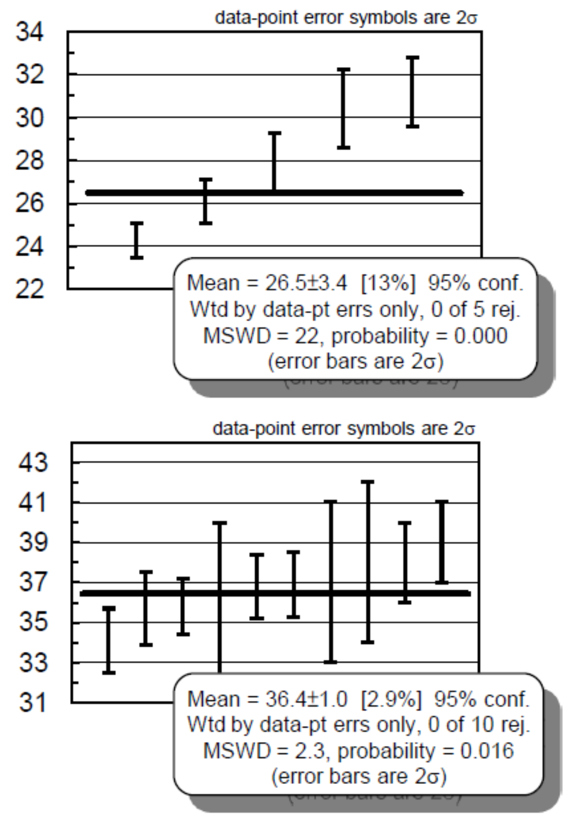
Characteristics of early Miocene alkali basalt 公館期

Task 3: when

Zircon U-Pb dates

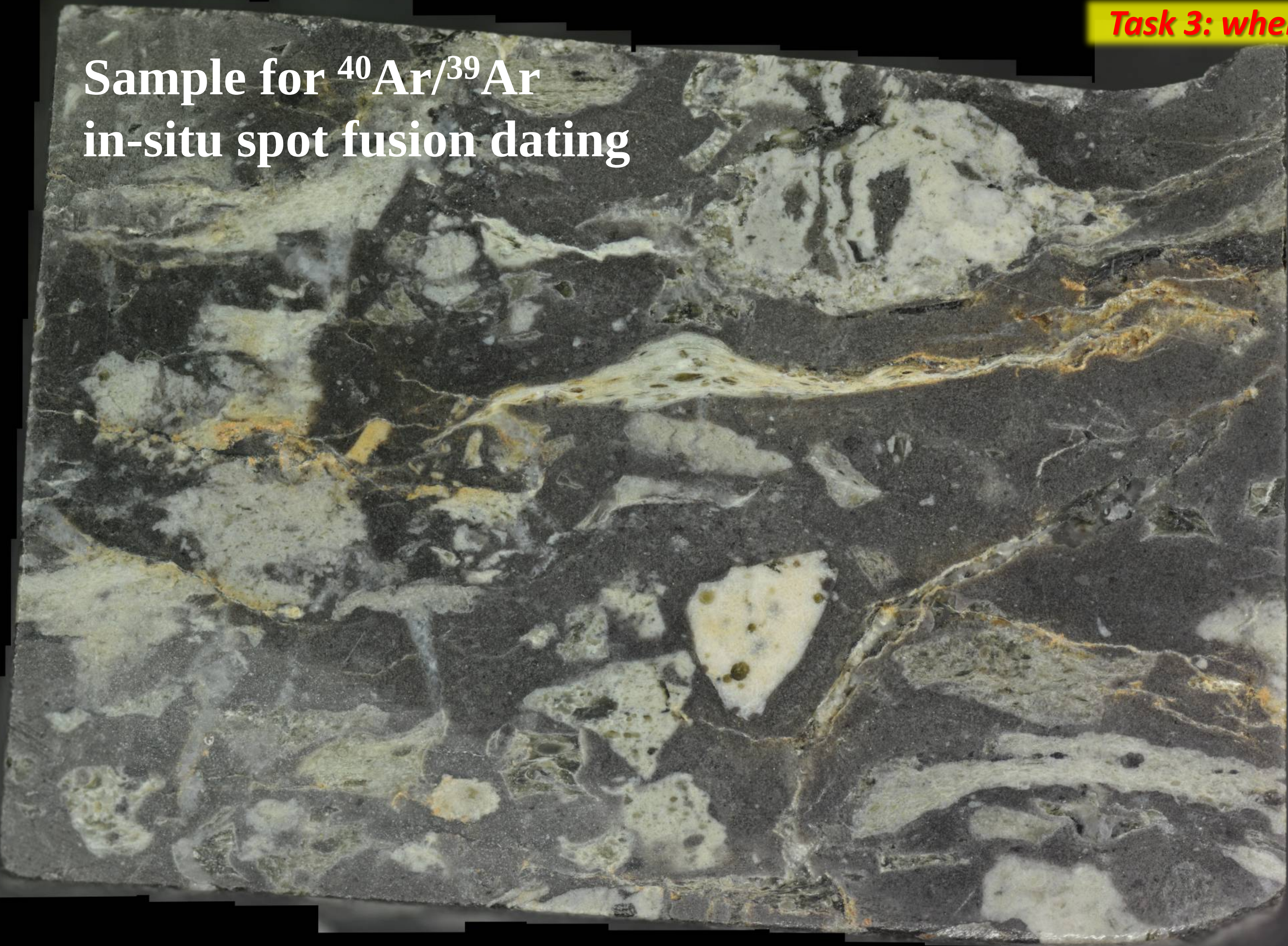




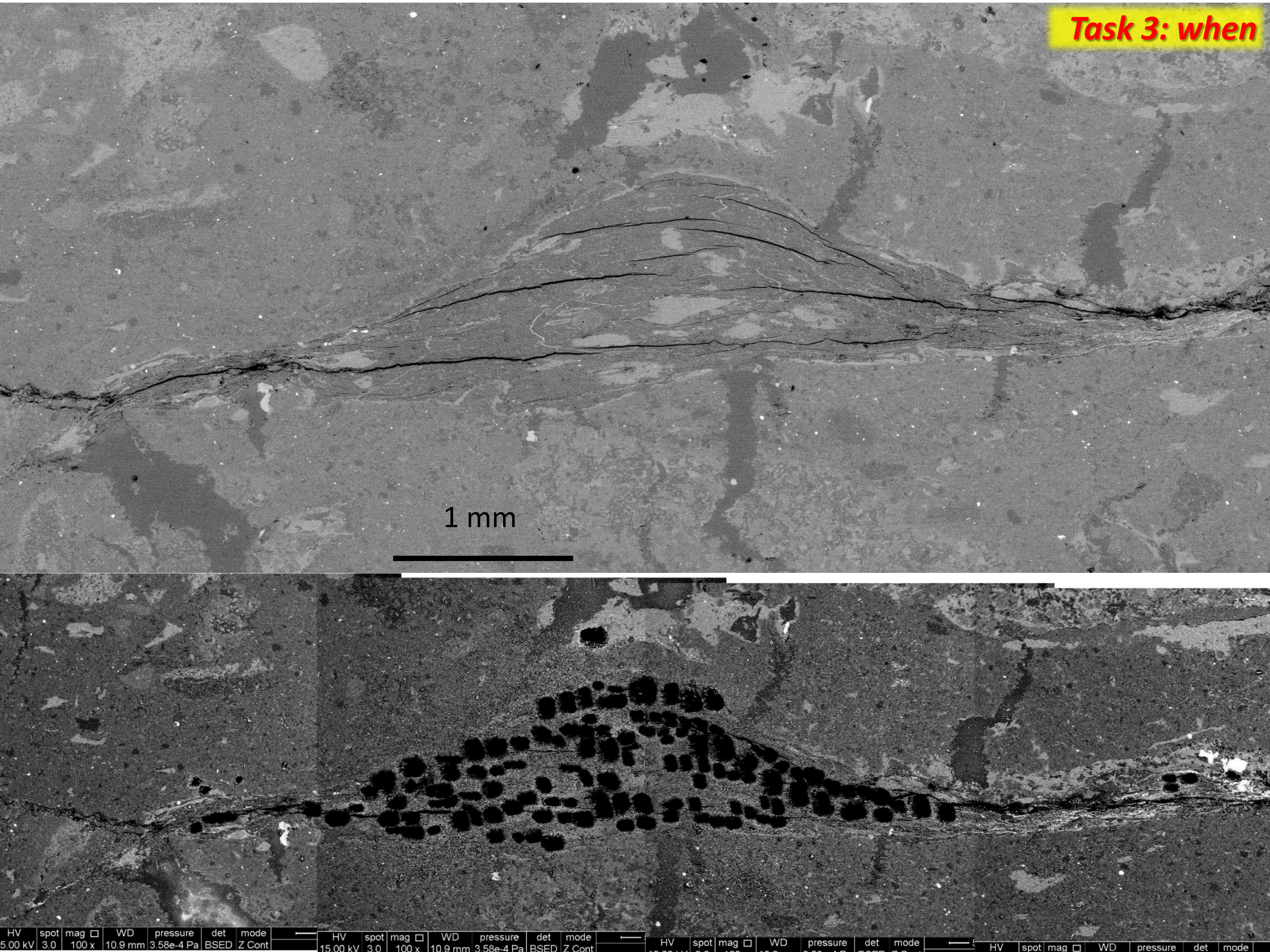


Formed on the Oligo-Miocene boundary

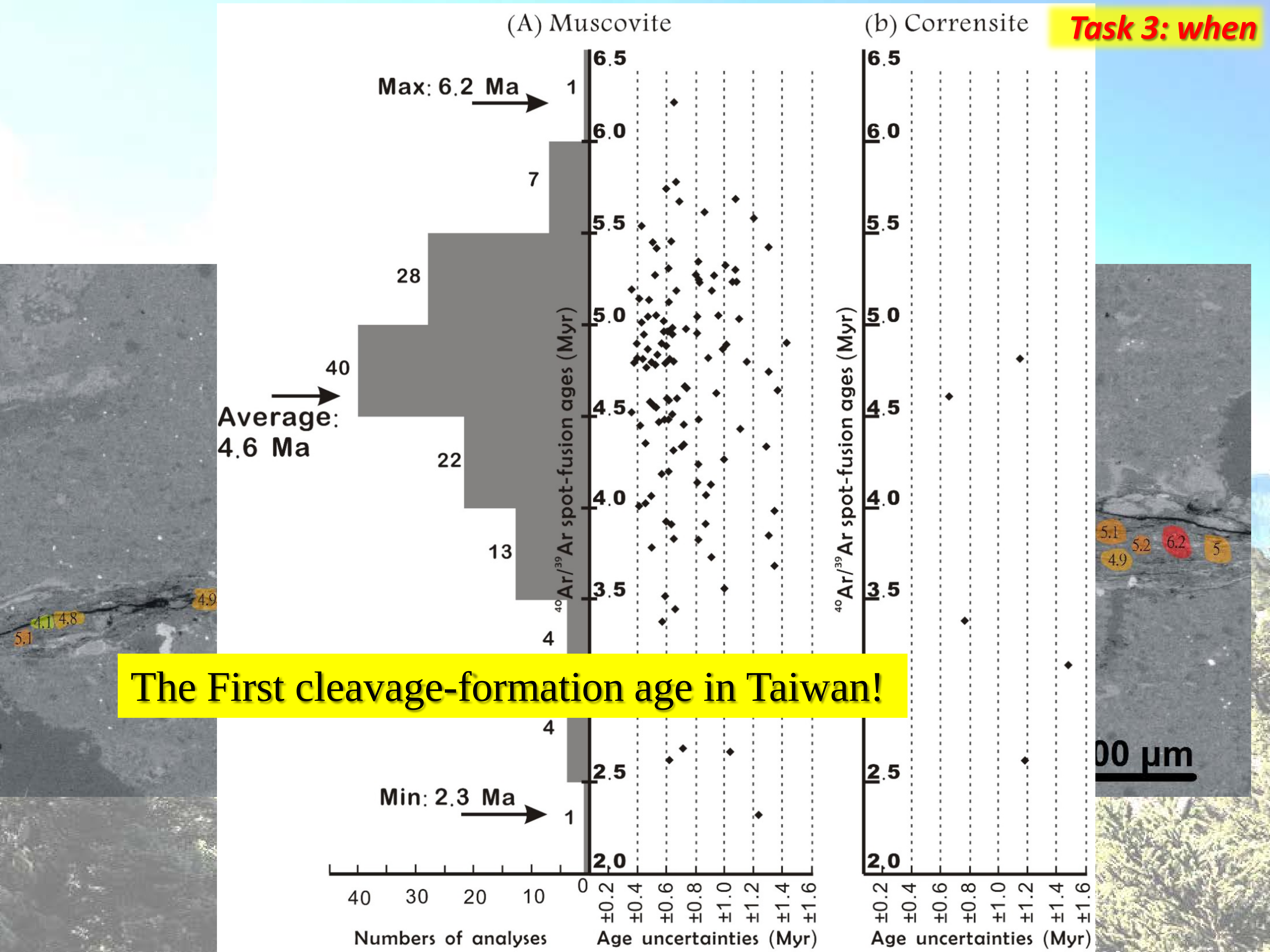
Task 3: when



Task 3: when

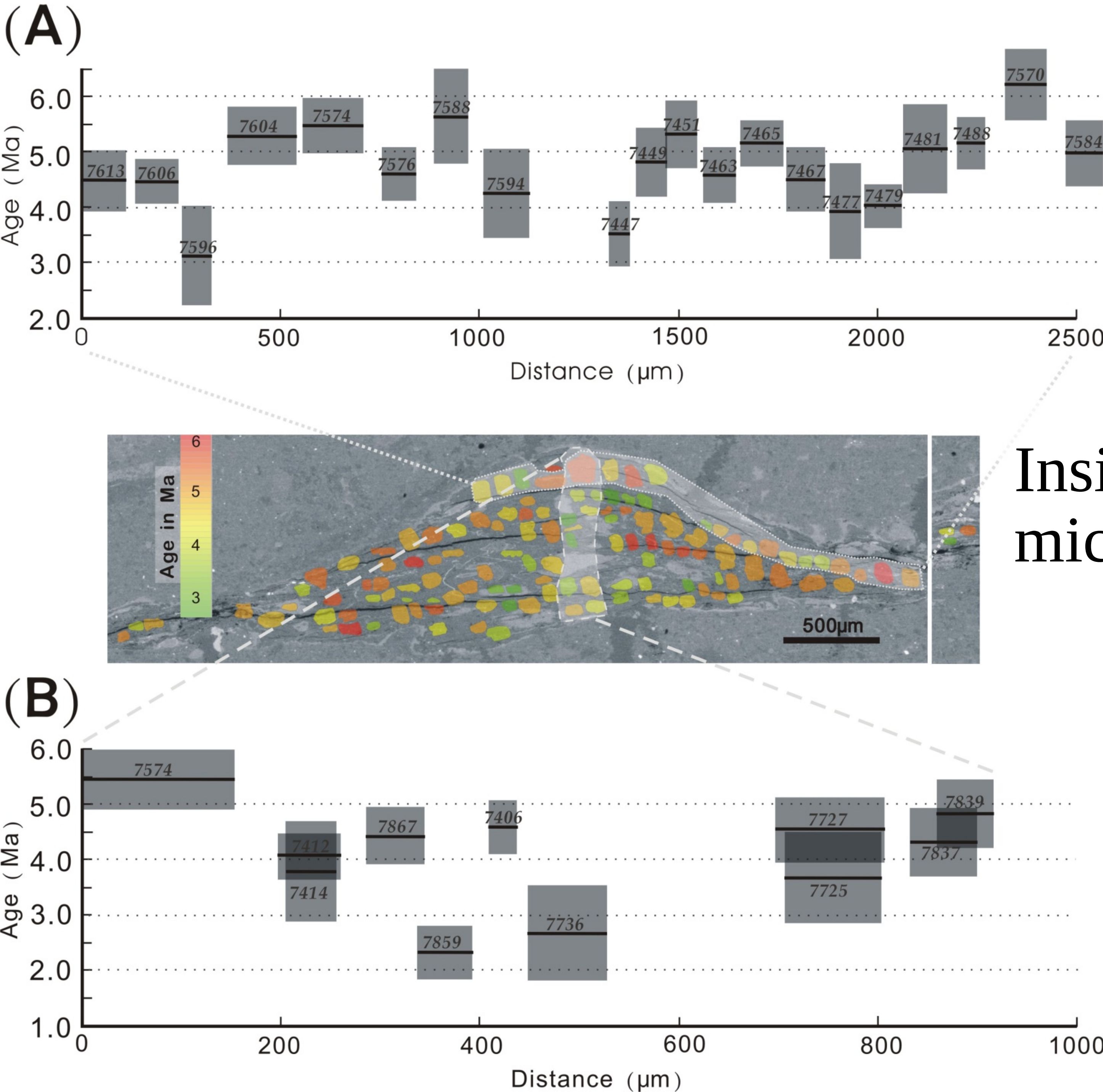

1 mm
HV | spot | mag | WD | pressure | det | mode
5.00 kV | 3.0 | 100 x | 10.9 mm | 3.58e-4 Pa | BSED | Z Cont
HV | spot | mag | WD | pressure | det | mode
15.00 kV | 3.0 | 100 x | 10.9 mm | 3.58e-4 Pa | BSED | Z Cont
HV | spot | mag | WD | pressure | det | mode
HV | spot | mag | WD | pressure | det | mode

Task 3: when



The First cleavage-formation age in Taiwan!

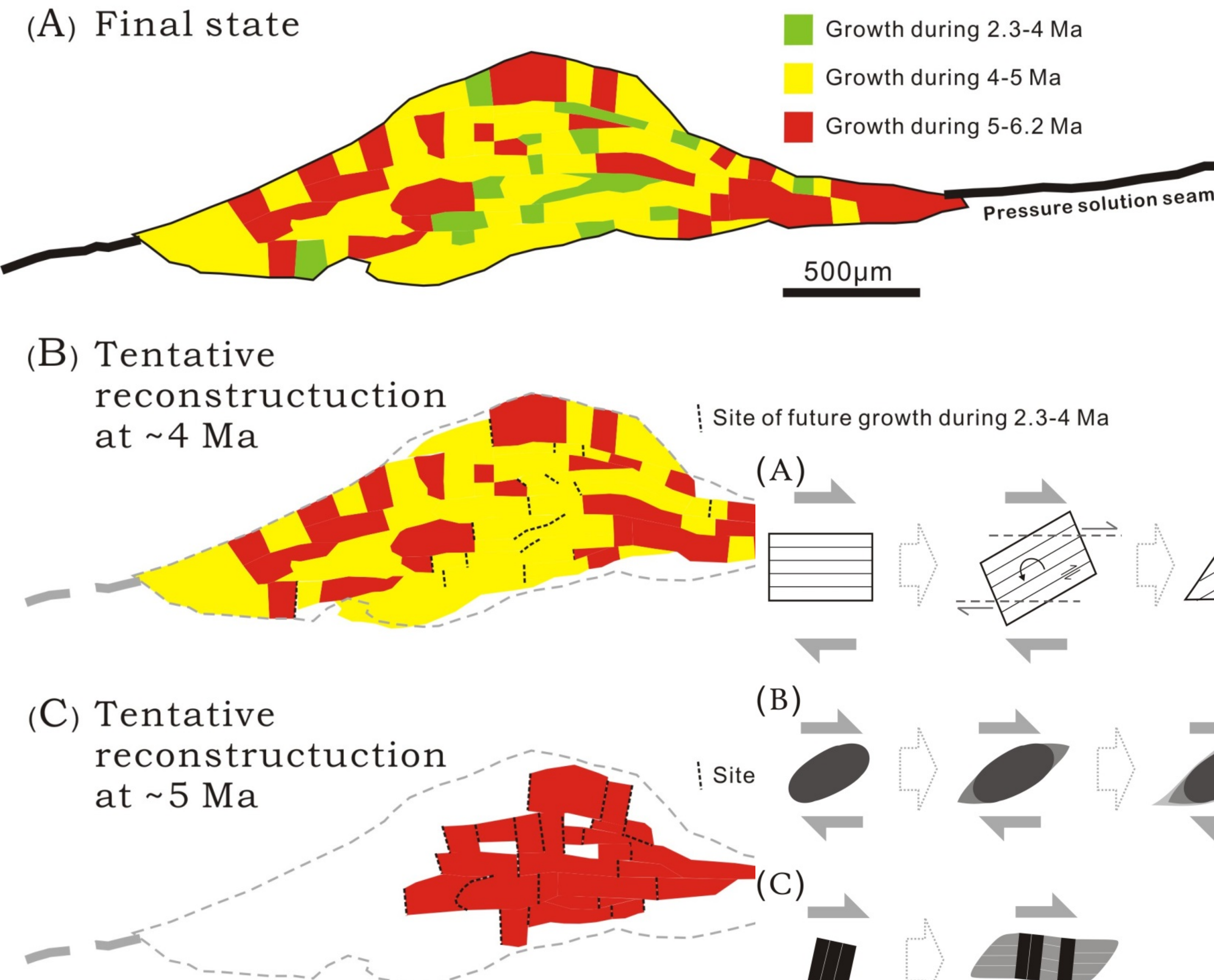
Task 3: when

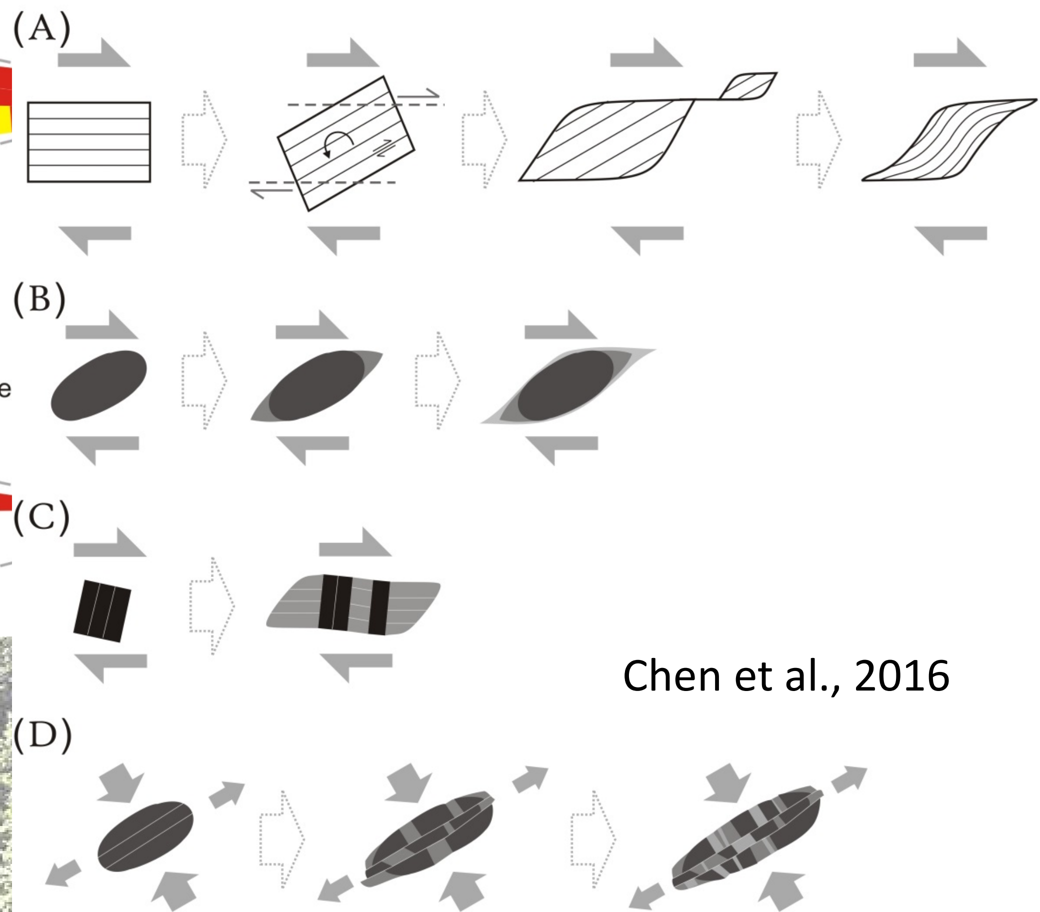


Insights on microstructures

Chen et al., 2016

Task 3: when

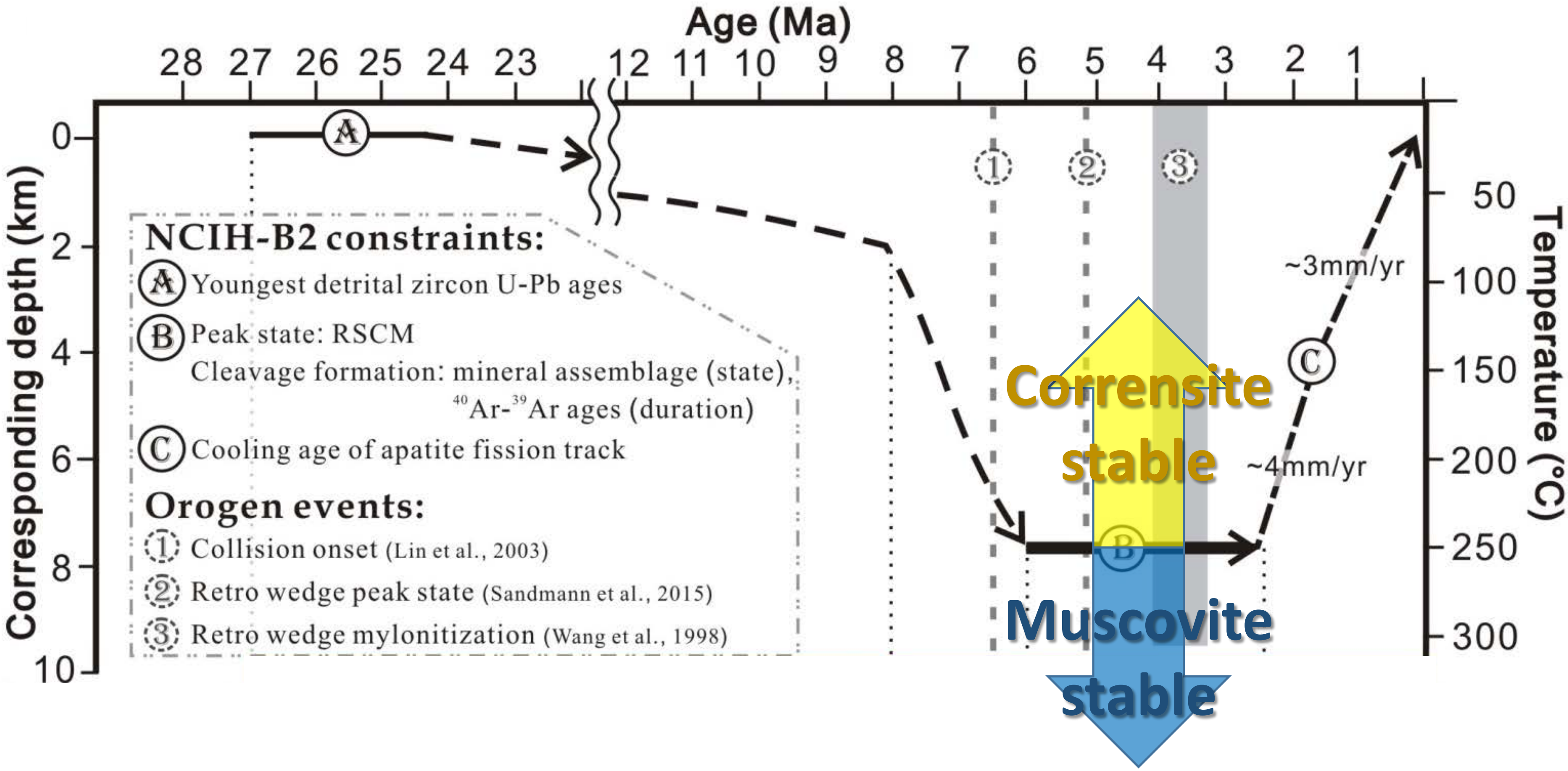




Chen et al., 2016

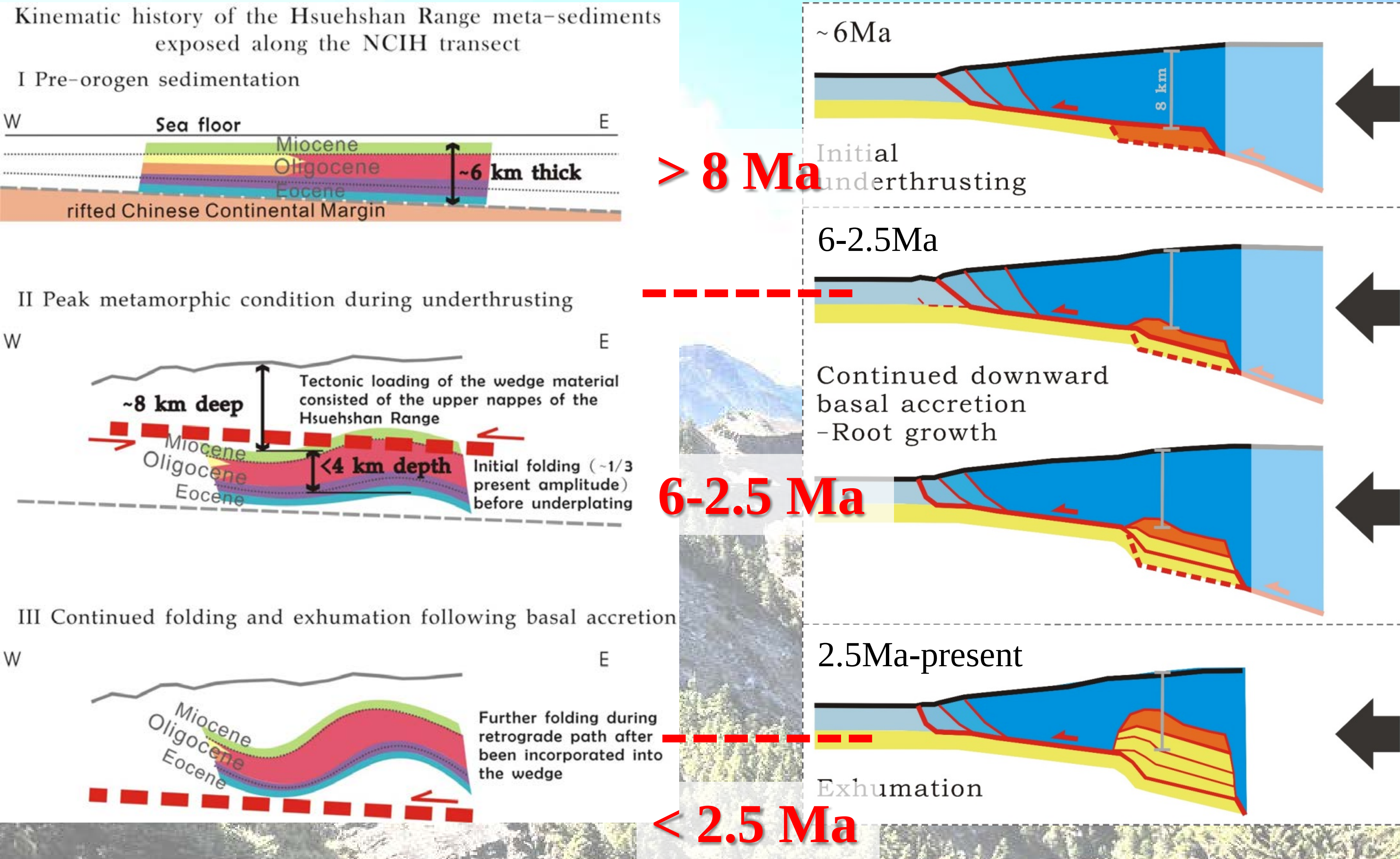
Task 3: when

Complete (P-)T-t history



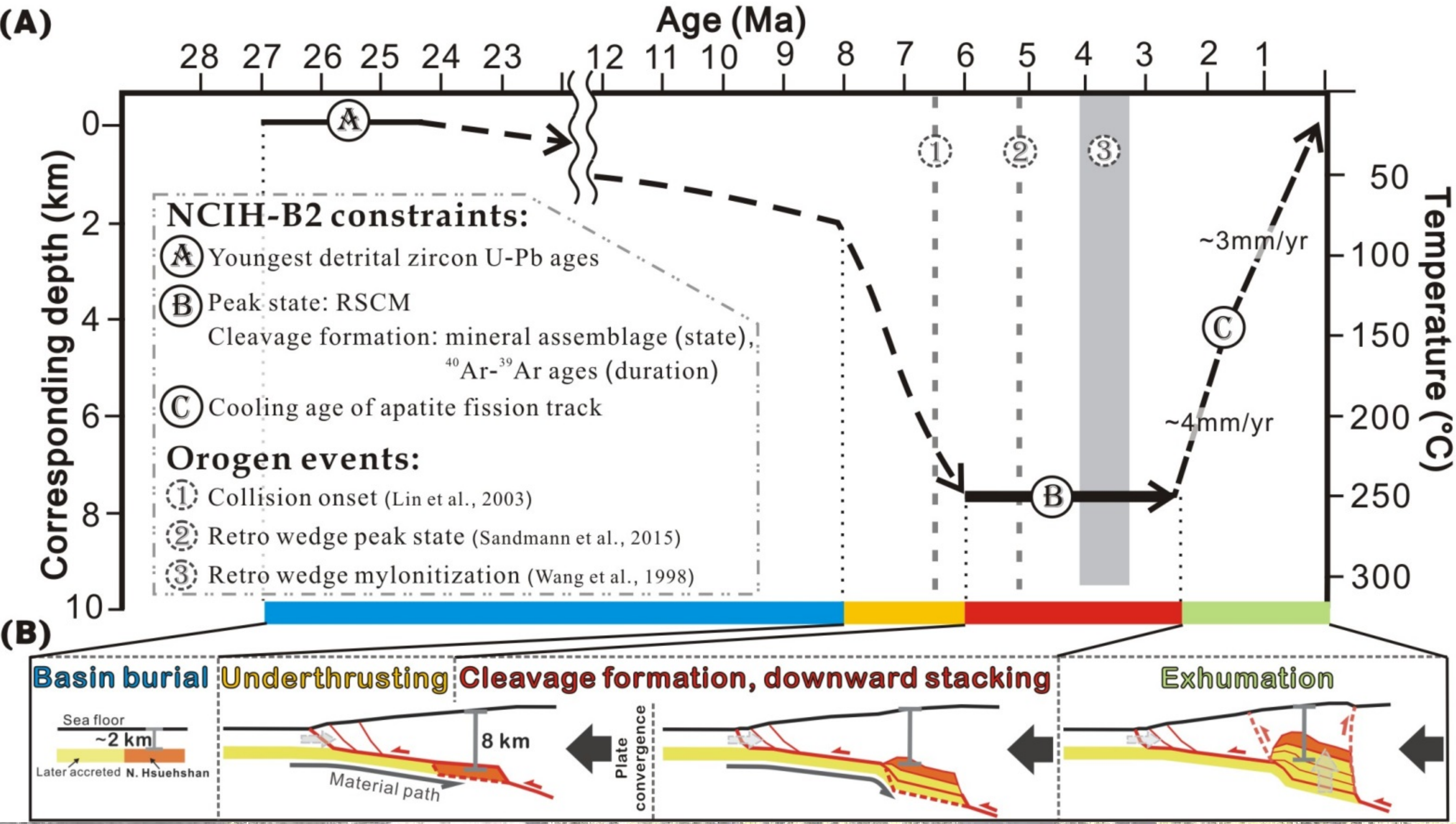
Link between thermal history and tectonic deformation?

Task 3: when



Kinematic history of the Hsuehshan Range meta-sediments exposed along the NCIH transect
I Pre-orogen sedimentation
W
Sea floor
E
Miocene
Oligocene
Eocene
~6 km thick
rifted Chinese Continental Margin
II Peak metamorphic condition during underthrusting
W
E
~8 km deep
Tectonic loading of the wedge material consisted of the upper nappes of the Hsuehshan Range
Miocene
Oligocene
Eocene
<4 km depth
Initial folding (~1/3 present amplitude) before underplating
III Continued folding and exhumation following basal accretion
W
E
Miocene
Oligocene
Eocene
Further folding during retrograde path after been incorporated into the wedge
~6Ma
8 km
Initial underthrusting
6-2.5Ma
Continued downward basal accretion
-Root growth
2.5Ma-present
Exhumation
> 8 Ma
6-2.5 Ma
< 2.5 Ma

Tectonic synthesis



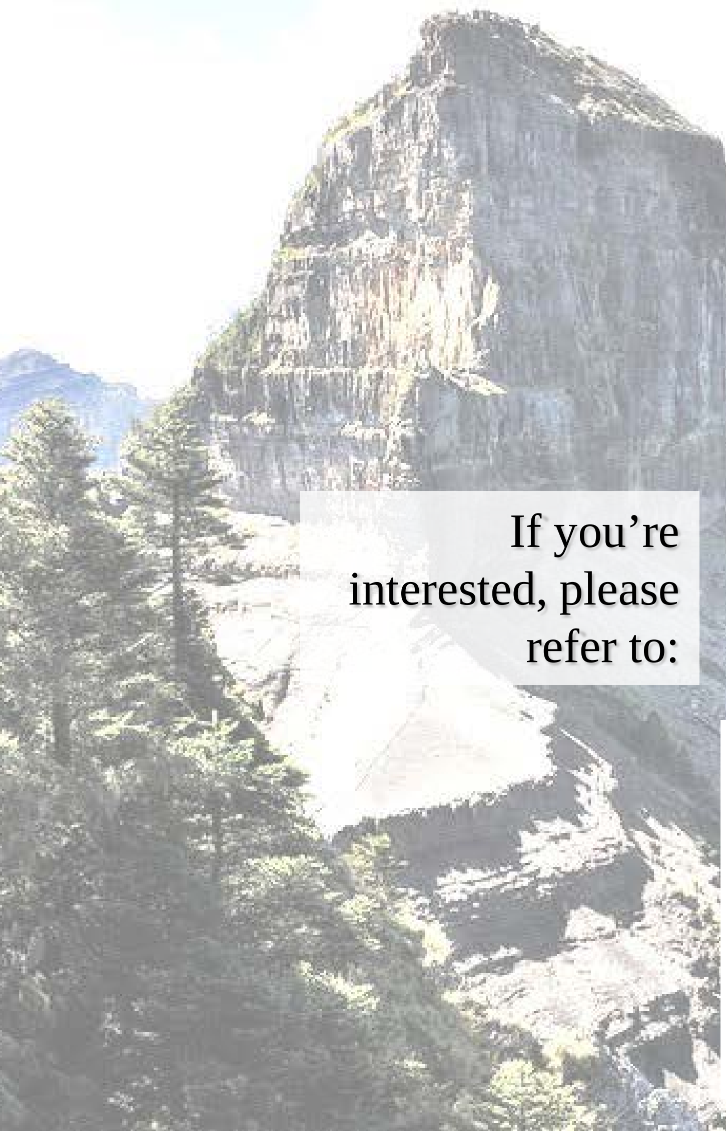
To summarize….

- Basal accretion is the major mechanism of material influx in the Taiwanese orogenic wedge, with 1 underplating window under the Hsuehshan Range in prowedge side (another in E Central Range)

- Basal accretion started immediately after onset of collision, and continued to operate

- The Hsuehshan Range consists of nappes originated from various portions of the subducted/incorporated Chinese Continental Margin with different initial stratigraphic positions, burial-exhumation history, and grade of metamorphism

Thank you for your attention!



If you're interested, please refer to:

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Growth of mica porphyroblasts under low-grade metamorphism – A Taiwanese case using *in-situ* $^{40}Ar/^{39}Ar$ laser microprobe dating

Chih-Tung Chen [a,*], Yu-Chang Chan [b], Ching-Hua Lo [a], Chia-Yu Lu [a]

[a] *Department of Geosciences, National Taiwan University, No. 1, Sec. 4, Roosevelt Road, Taipei, Taiwan, ROC*
[b] *Institute of Earth Sciences, Academia Sinica, No. 128, Sec. 2, Academia Road, Nangang, Taipei, Taiwan, ROC*

Terra Nova

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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*

Terra Nova

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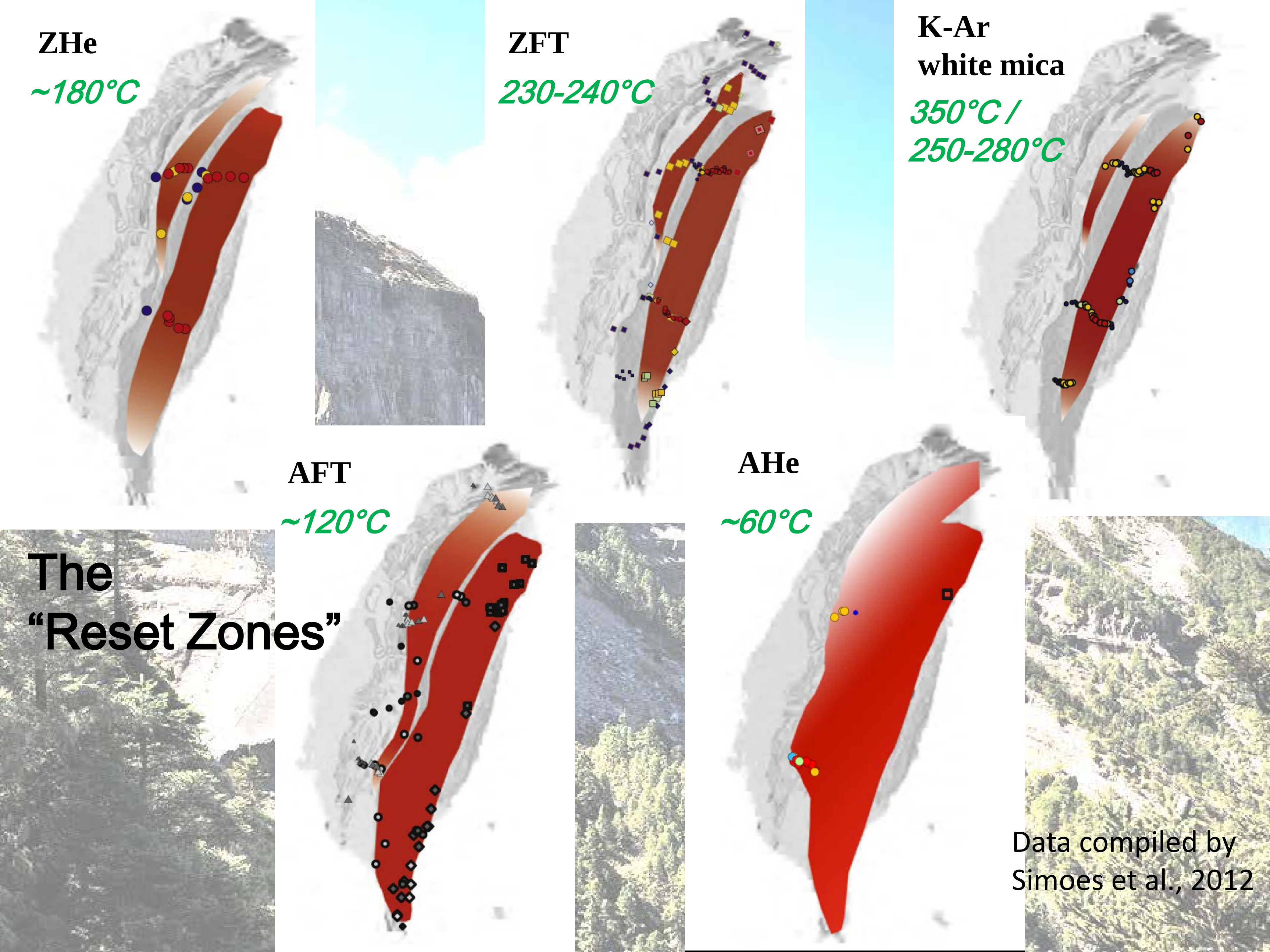
[1]*Department of Geosciences, National Taiwan University, Taipei, Taiwan;* [2]*Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan;* [3]*Institut de Physique du Globe de Paris, Sorbonne Paris Cité, UMR 7154 CNRS, F-75005, Paris, France;* [4]*Institut de Minéralogie et de Physique des Milieux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

ABSTRACT

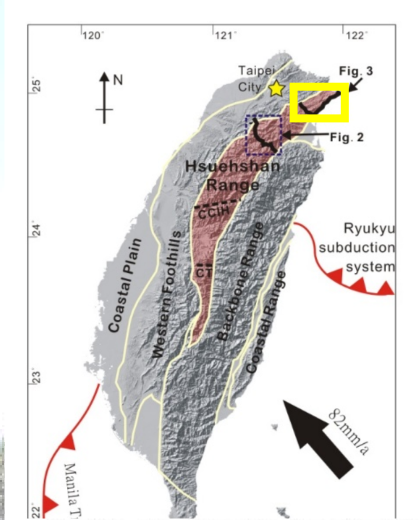
Vitrinite reflectance and Raman spectroscopy of carbonaceous material data are used to better resolve the thermal history of the Hsuehshan Range, which is accreted between the foreland fold–thrust belt and bulldozer hinterland units in the Taiwan mountain belt. The observed thermal data indicate that 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.

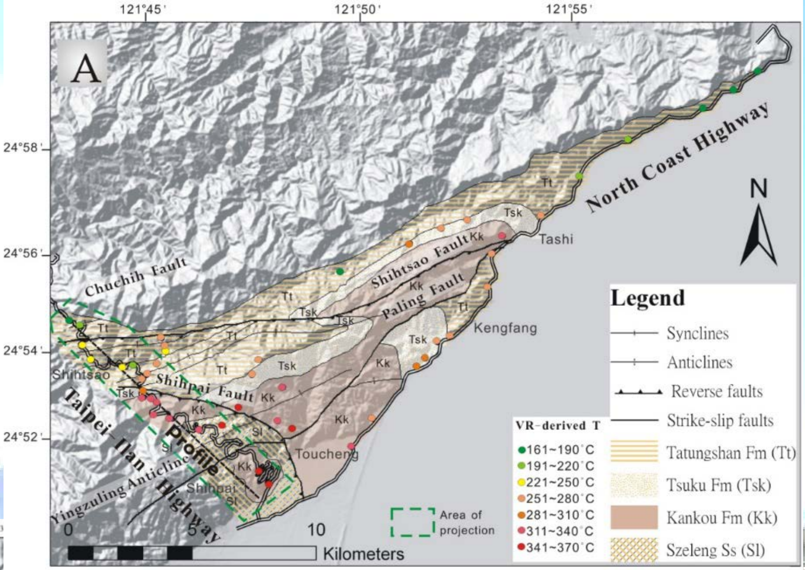
Terra Nova, 23, 85–91, 2011

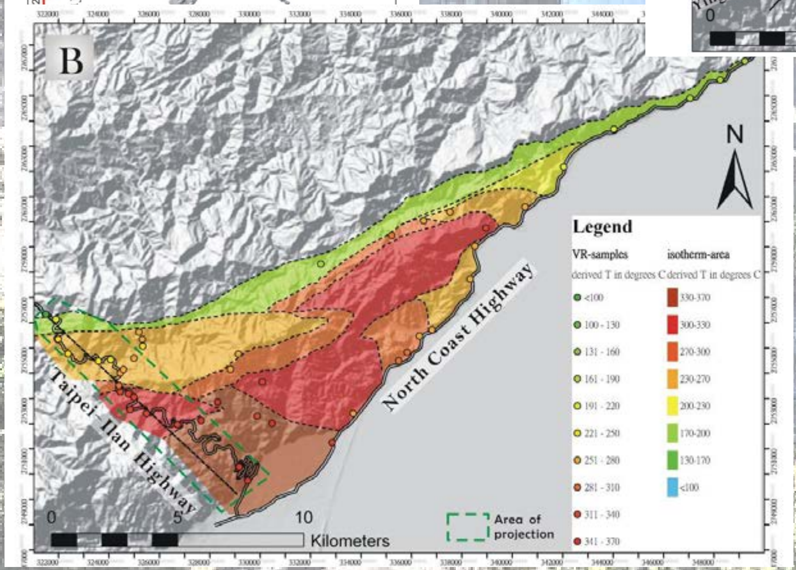
The "Reset Zones"



Data compiled by Simoes et al., 2012



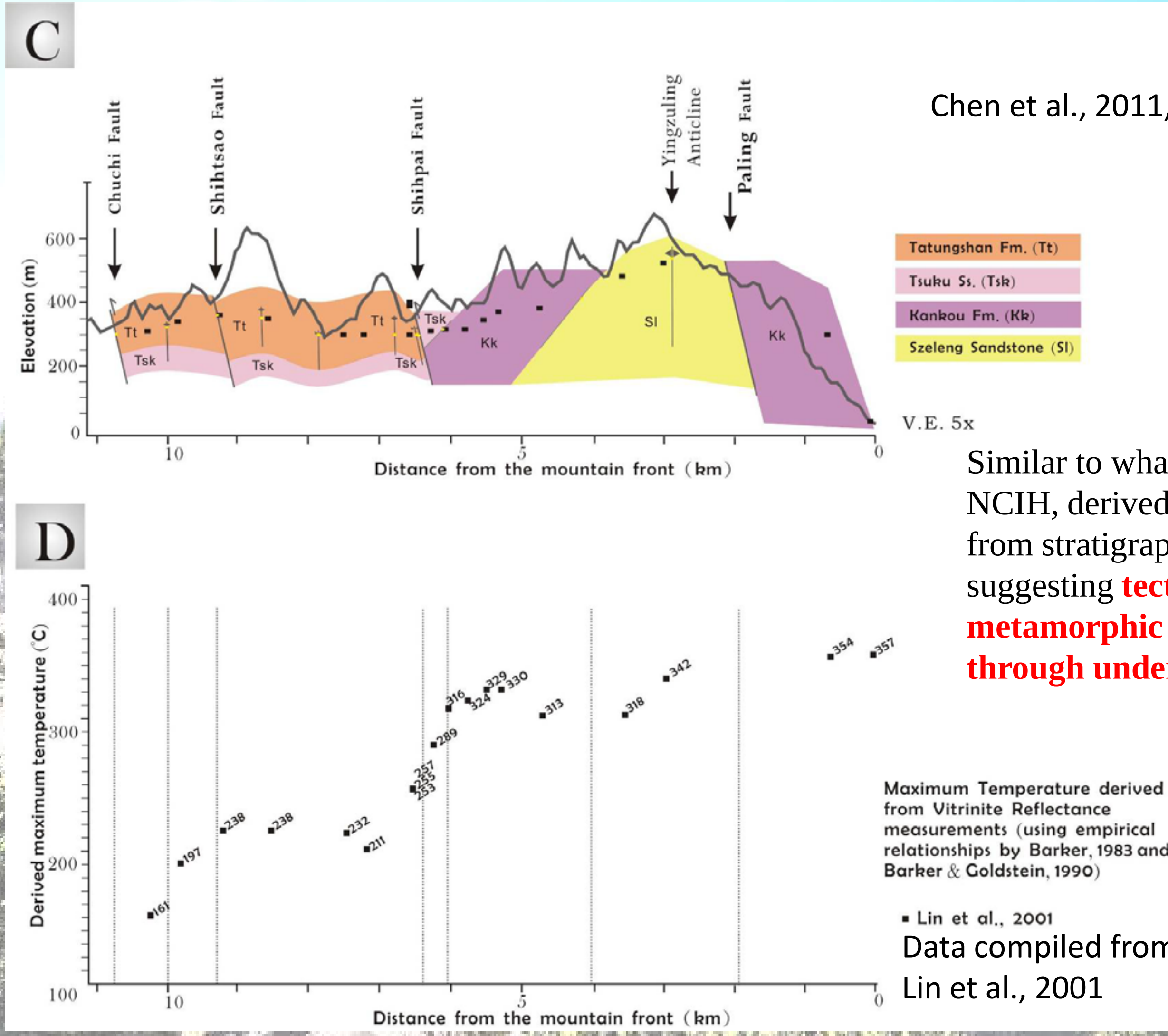




North-east Coast

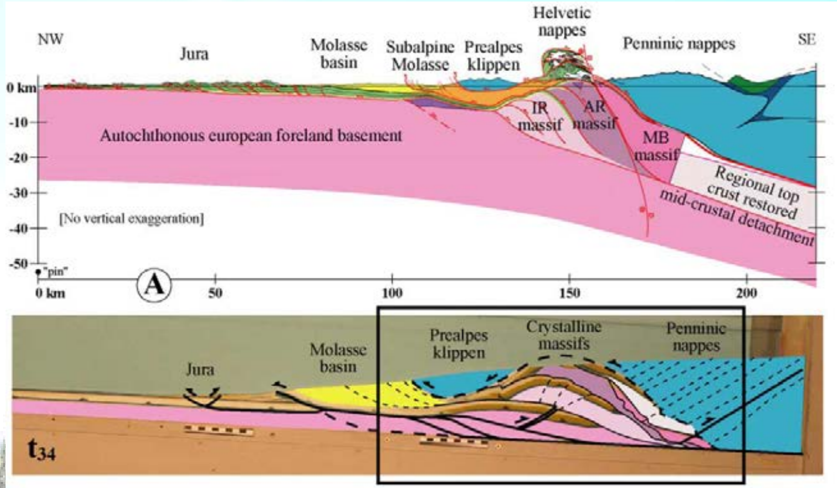
Chen et al., 2011, Terra Nova

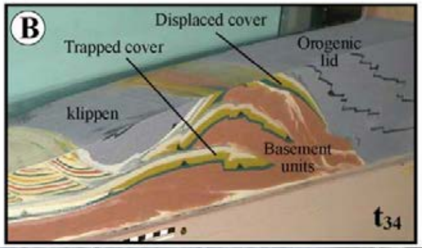
Chen et al., 2011, Terra Nova



Similar to what observed in NCIH, derived T decoupled from stratigraphy, suggesting **tectonic metamorphic overprint through underplating**

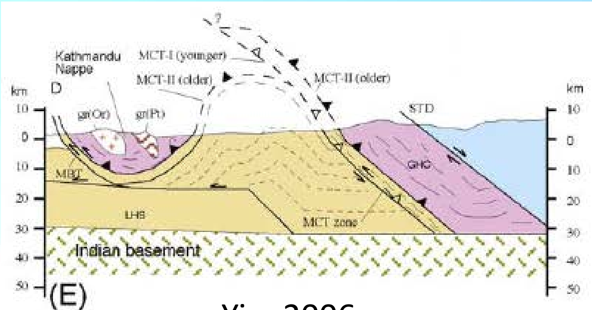
Data compiled from Lin et al., 2001



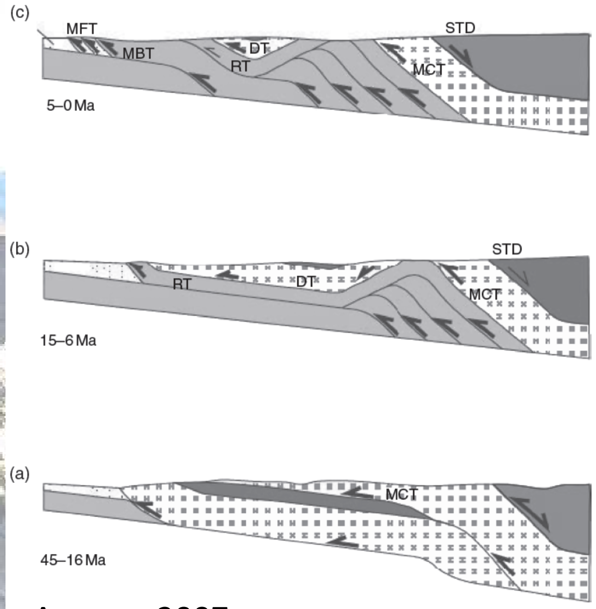


Bonnet et al., 2007

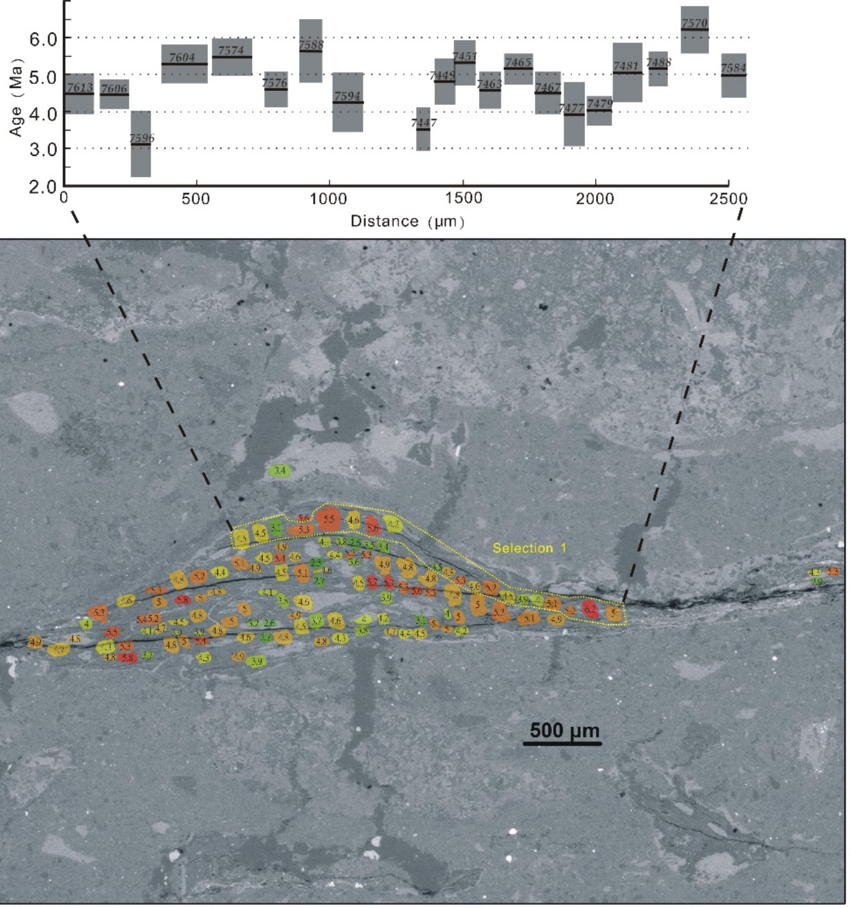
The European Alps and Himalaya cases

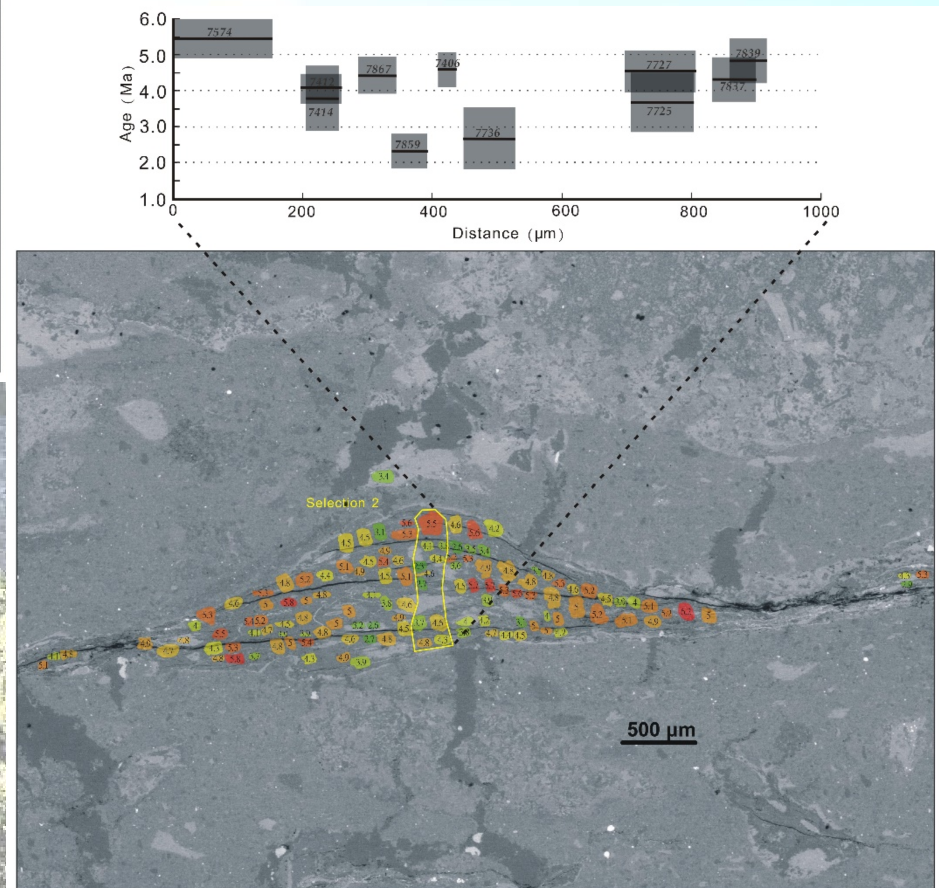


Yin. 2006



Avouac, 2007


Age (Ma)
Distance (μm)
7613
7606
7596
7604
7574
7576
7588
7594
7447
7445
7451
7463
7465
7467
7477
7479
7481
7488
7570
7584
Selection 1
500 μm


Age (Ma)
Distance (μm)
7574
7414
7867
7406
7859
7736
7727
7725
7839
7837
Selection 2
500 μm

Few concluding thoughts

- The Hsuehshan Range consists of nappes originated from various portions of the subducted/incorporated Chinese Continental Margin with different initial stratigraphic positions, burial-exhumation history, and grade of metamorphism
- The resultant nappe stacking structure of the range highlights the significance of underplating/basal accretion in the dynamics of the Taiwanese orogenic wedge, which shapes the mountain belt simultaneously with surface erosion and frontal accretion
- Deformation of the underplated material occurred both before and after basal accretion, suggesting continued shortening in the interior part of the wedge
- Carbon geothermometers can be useful tools in understanding kinematics within orogenic belts, as the VR is more suitable for diagenetic-grade rocks and RSCM for slaty and schistose rocks