Geomorphology and Thermochronology
地殼形變量測與熱定年

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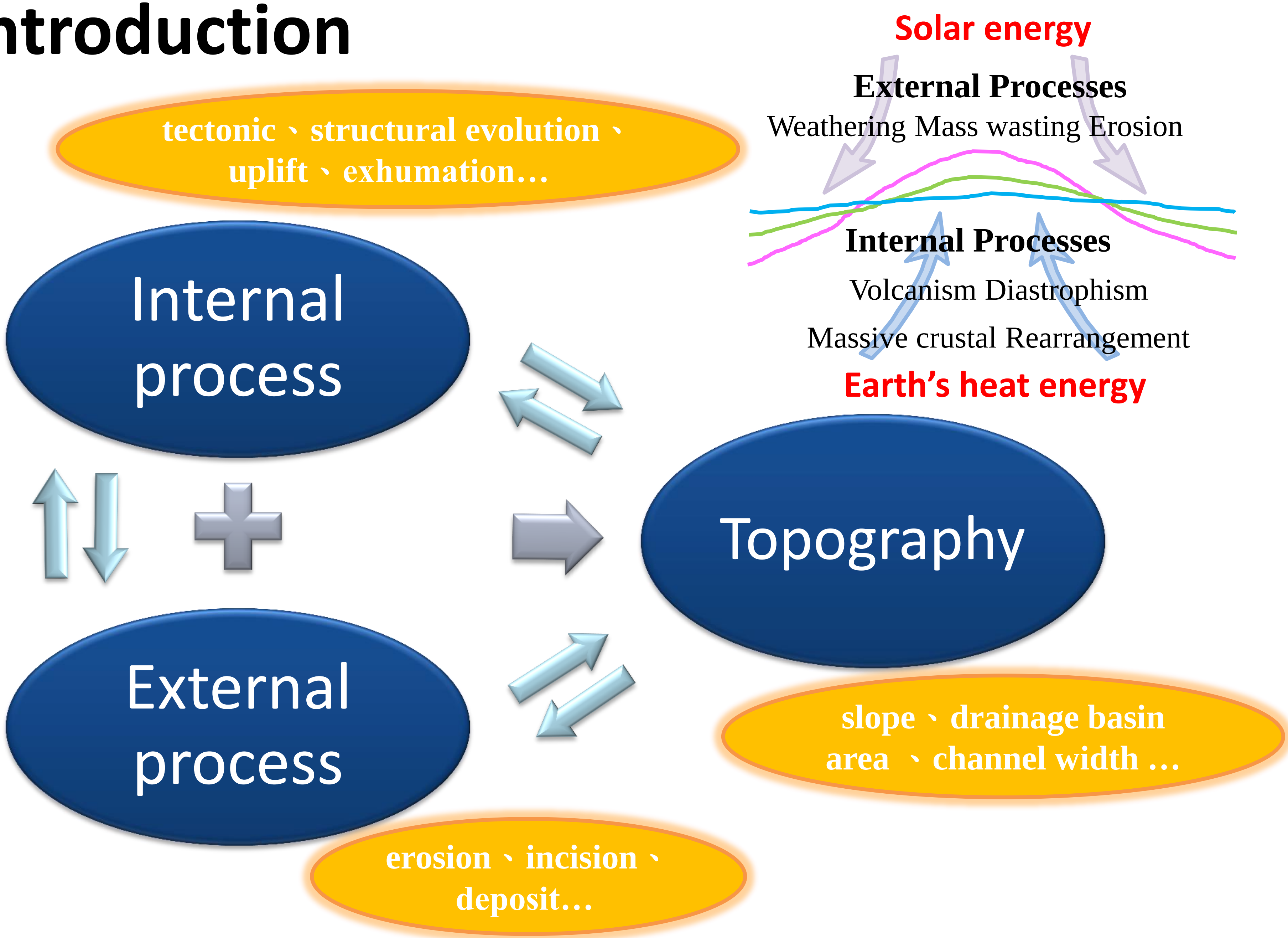
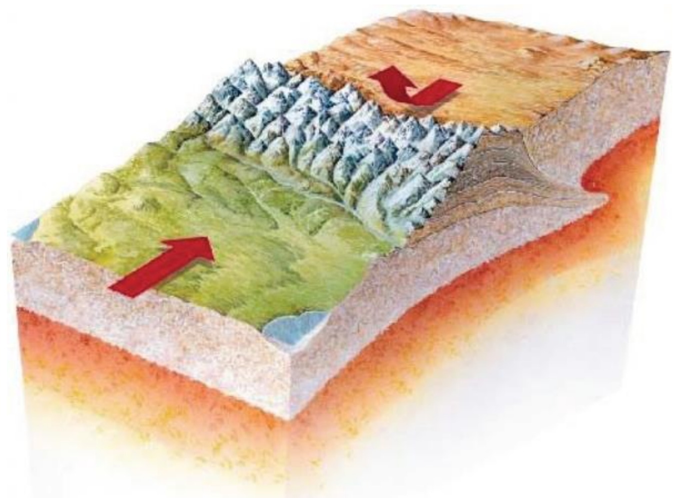
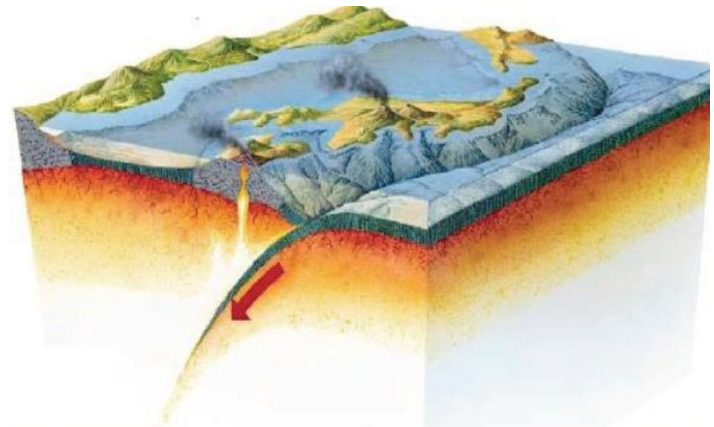
郭力維

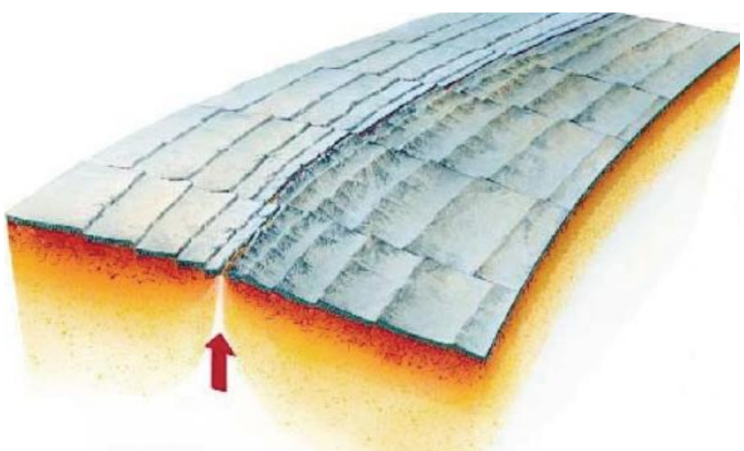
Introduction

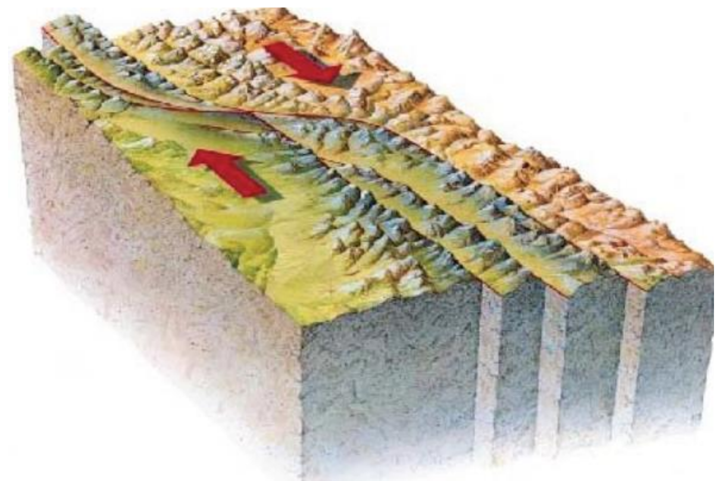


- **Internal process: *Uplift* is tied to plate tectonics and involves the deformation of lithosphere.**



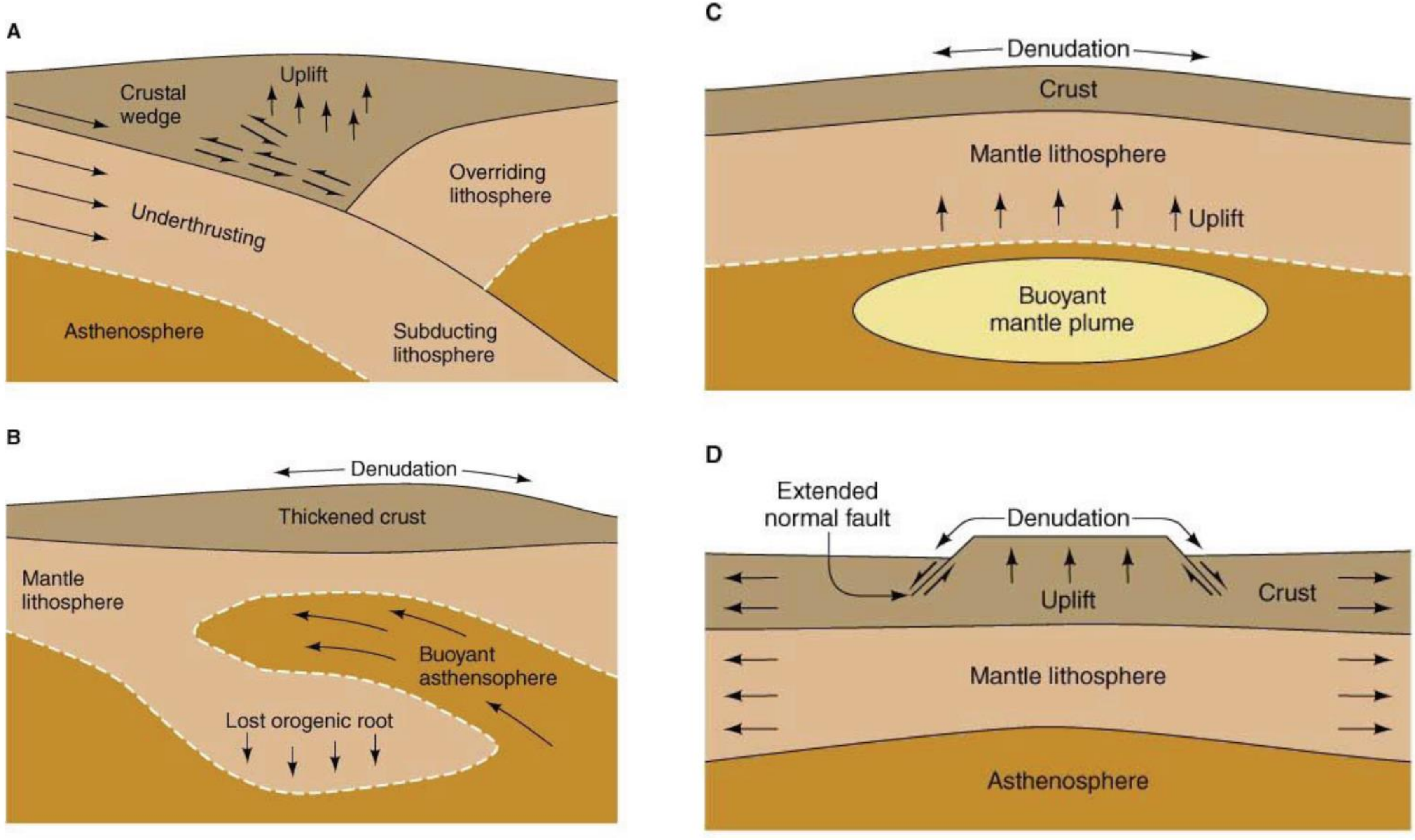






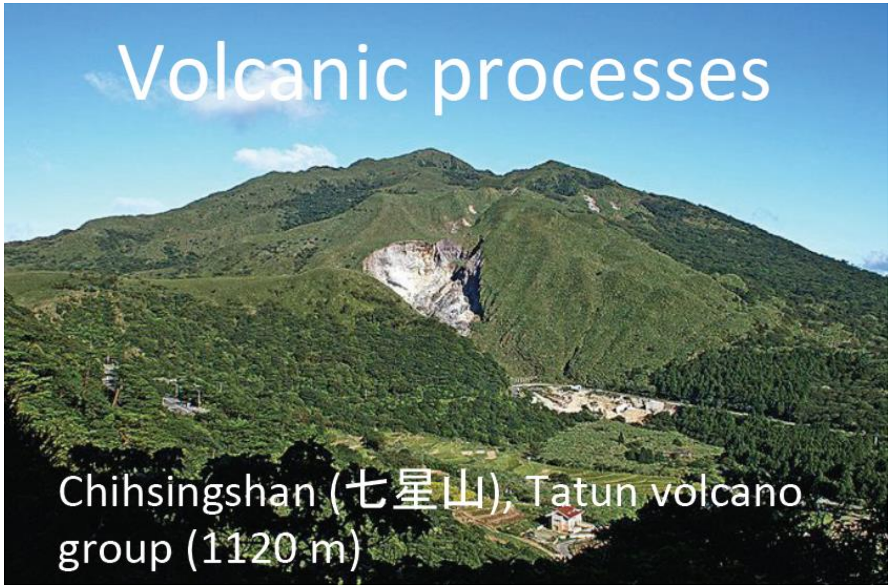
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

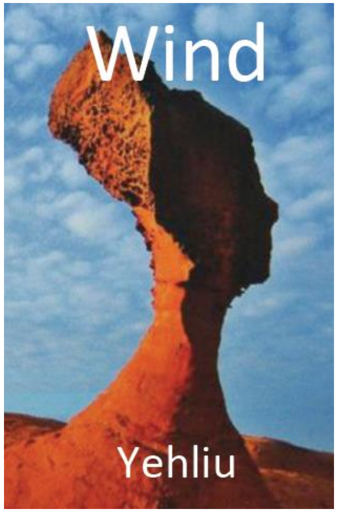
- **Internal process: *Uplift* can occur from collisional, isostatic and extensional mechanism.**



The dynamic Earth: An Introduction to Physical Geology, 5th Edition- B.J.Skinner abd S.C.Porter. 2004 Wilet Ed.

➢ Internal versus External processes





Topographic control on landscapes

Relief exerts a strong influence on denudation rates.

Tectonically active regions with high rates of uplift generate rapid erosion.

In areas far from active tectonism, relief typically is low, erosion rates are much slower, and landscape changes are more gradual.

Chingshui cliffs, Eastern Taiwan

Summary

- Changes in the landscape are generated by the competing processes of uplift, exhumation and denudation.
- Each of these processes can change the relief of the landscape.
- Geomorphology is the study of landforms and their evolution.

Key Concept

- Rate of denudation and surface uplift is functions of both time and space (local such as drainage basin or regional ~ 1000 km^2)
- Regional parameters: Isostatical loading and unloading
- Local: geomorphic events such as landslides, rapid incision rivers
- Rate varies at any given point, such as summits or river valleys

Key Terminology

- (Geomorphic) Erosion rate（侵蝕速率）: Surficial mechanical (landslide) and chemical weathering and removal of debris
- Denudation rate (剝蝕速率): erosion + tectonic denudation (extension and normal faulting) rate
- Uplift rate (抬昇速率): surface uplift = rock uplift - exhumation
- Exhumation rate (裸露速率): similar to erosion but refer to preexisting surface, landscape or feature
- River incision rate（河流下切速率）
- Steady-state topography（穩定狀態地形), denudation (exhumation) rate, thermal

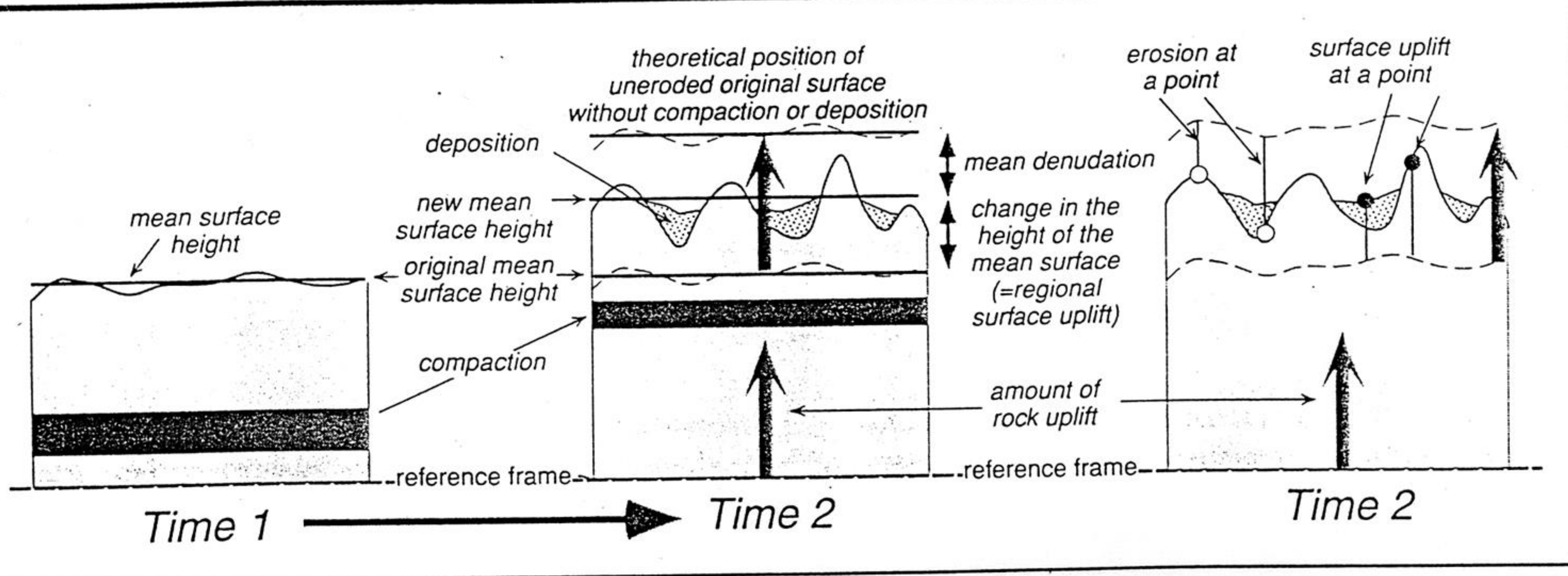
Reference:

Tectonic Geomorphology, Burbank and Anderson, 2012, Ch. 7. Blackwell Pub.

岩盤抬昇、沈積作用、壓密及侵蝕作用交互影響地表地形

地表抬昇＝岩盤抬昇＋沈積-壓密-侵蝕
(surface uplift= bedrock uplift + deposition -compaction-erosion)

FIGURE 7.1. Schematic of factors controlling position of the land surface: bedrock uplift, denudation, compaction, and deposition. Note that denudation can be erosional or tectonic.



Rates of Erosion and Uplift

1. Determining rates of erosion.
（計算侵蝕速率）
2. Determining rates of uplift.
（計算抬昇速率）
3. Calculating mass balances and material fluxes.
（計算物質進出和面積守恆）
4. Reconstructing the past geometry of tectonically active landscape.
（重新建構過去地質構造活動的規模）

參考書: Tectonic Geomorphology, Burbank and Anderson, 2001, Ch. 7. Blackwell Pub.

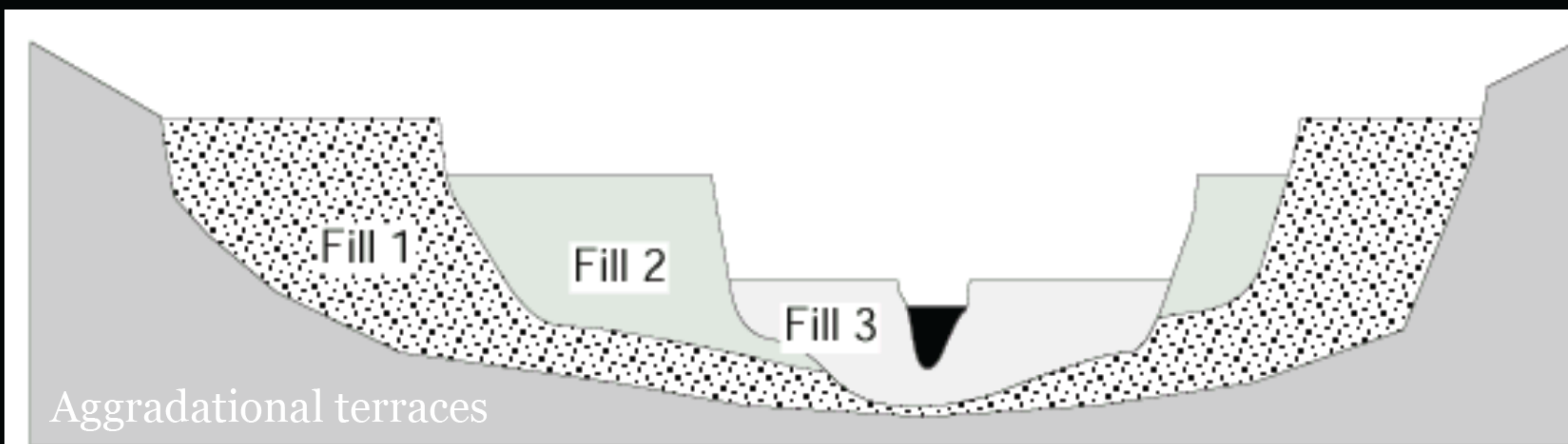
How to measure the erosion rate?

Mountain erosion rates have been estimated from river relief and precipitation, but in order to complete evaluation of the controls on erosion rates detailed, they use three kinds of measurements across different range of timescales.

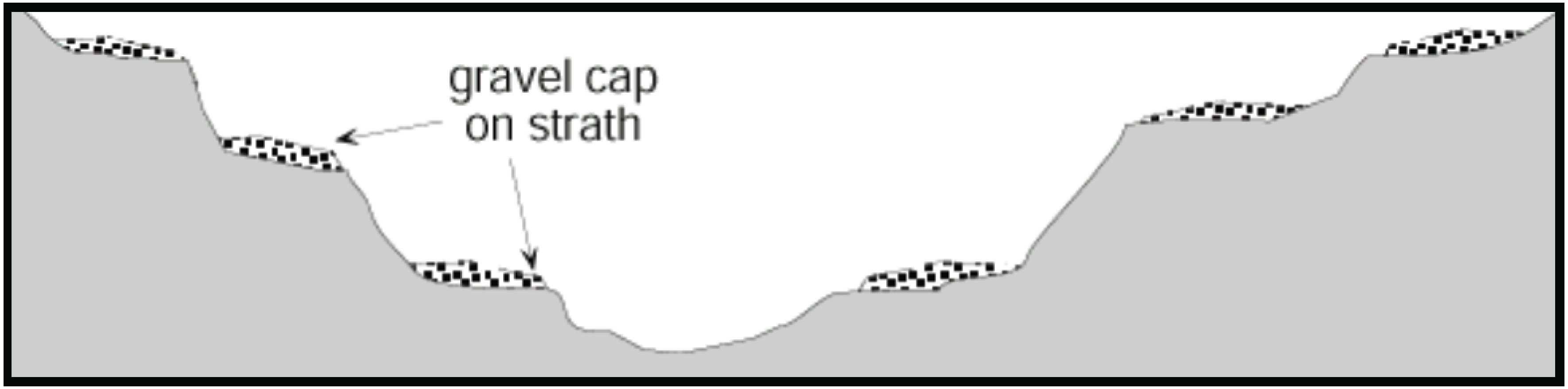
- Modern river sediment loads (Decadal-scale)
- Channel incision rate (Holocene)
- Thermo-chronometry: Fission track (million-year scale)

River terraces

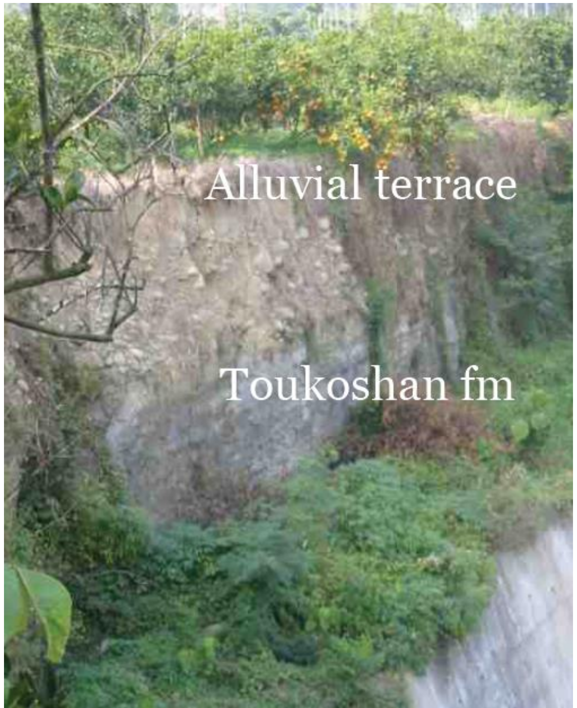
- River terraces are common examples of preserved sloping geomorphic features
  - Aggradational terraces (fill-terraces)
  - Degradational terraces (cut-, strath-terraces)



Strath terraces

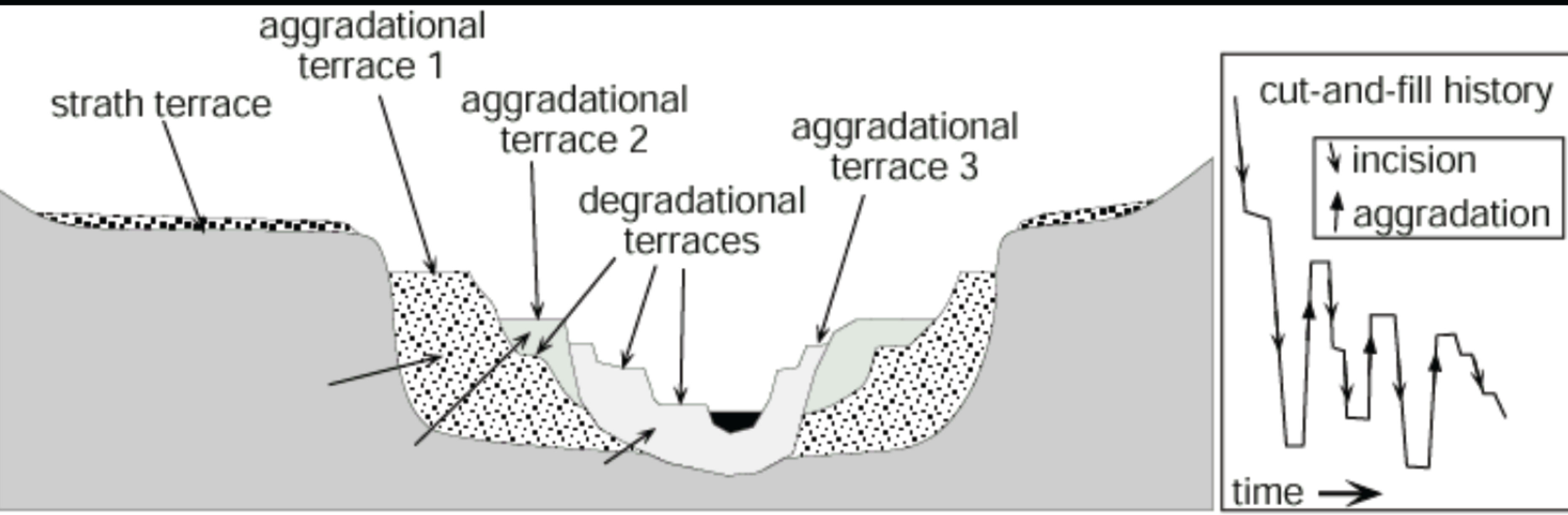


Alluvial terrace at Chiayi



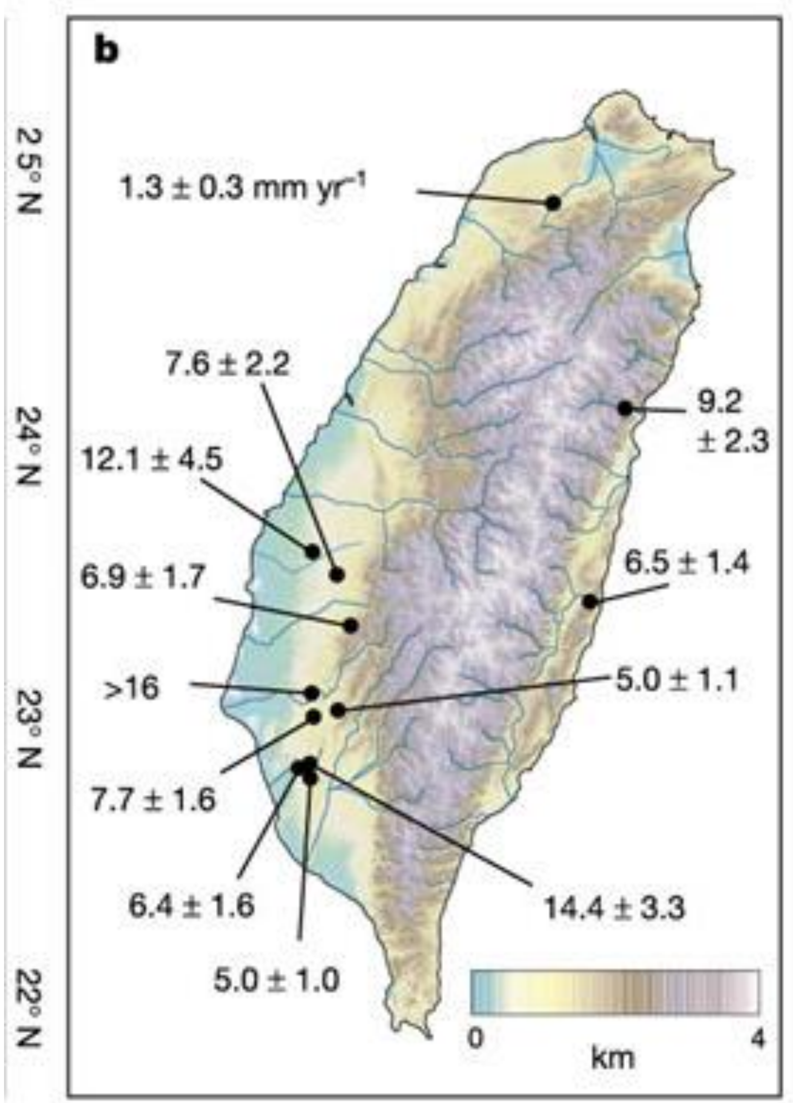
Litao, central range

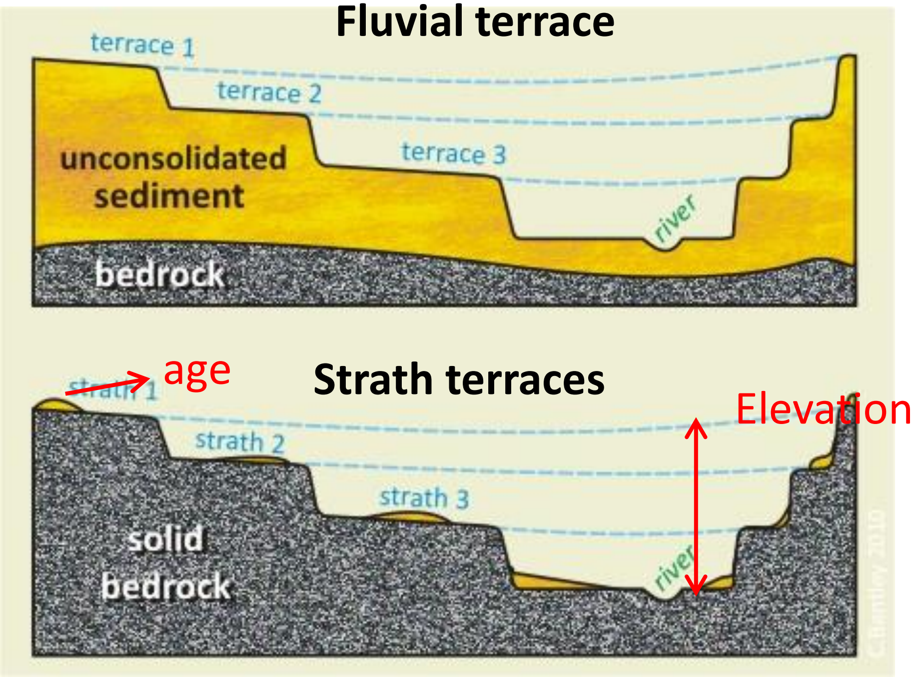
Summary about terraces



- Surface faulting
- Terrace warping
- Tilting of terraces

Channel incision rate (Holocene)





- Bedrock incision rates were obtained by dating organic material deposited on strath terraces formed as rivers incised through their bedrock substrate.
- Measurements are from bedrock terraces overlain by less than 5 m of channel deposit.
- Radiometric ages were calculated from **^{14}C** in wood or plant fragments in the alluvial layer.

由放射性定年計算長期侵蝕速率

地殼岩石冷卻因素：
1. 岩漿、熱液或變質事件
2. 構造運動或侵蝕作用

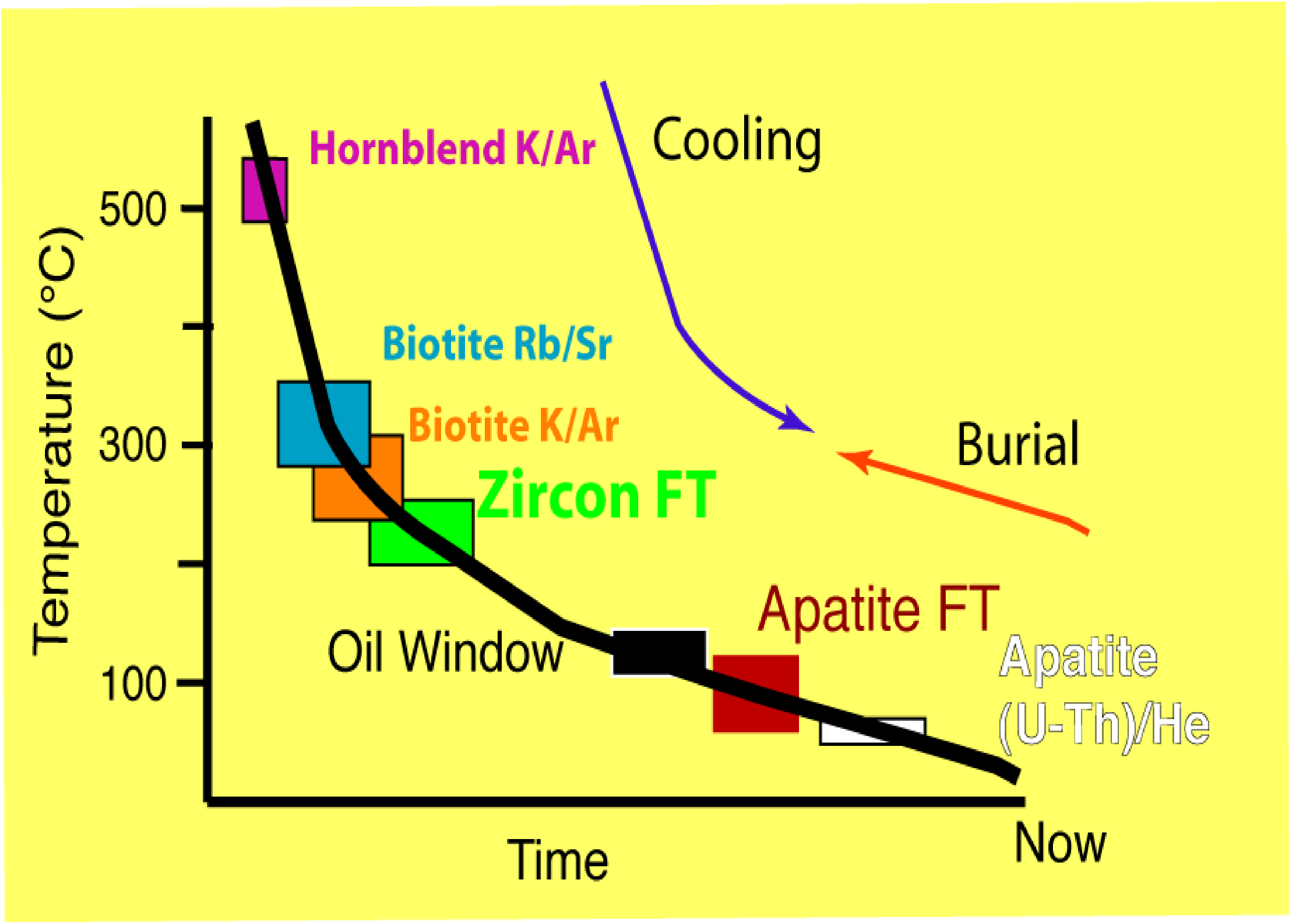
在岩石冷卻的過程中，對不同放射性定年系統的特定礦物必定會歷經其封存溫度

Apatite Fission Track

Zircon Fission Track

http://www.geotrack.com.au/gallery.htm

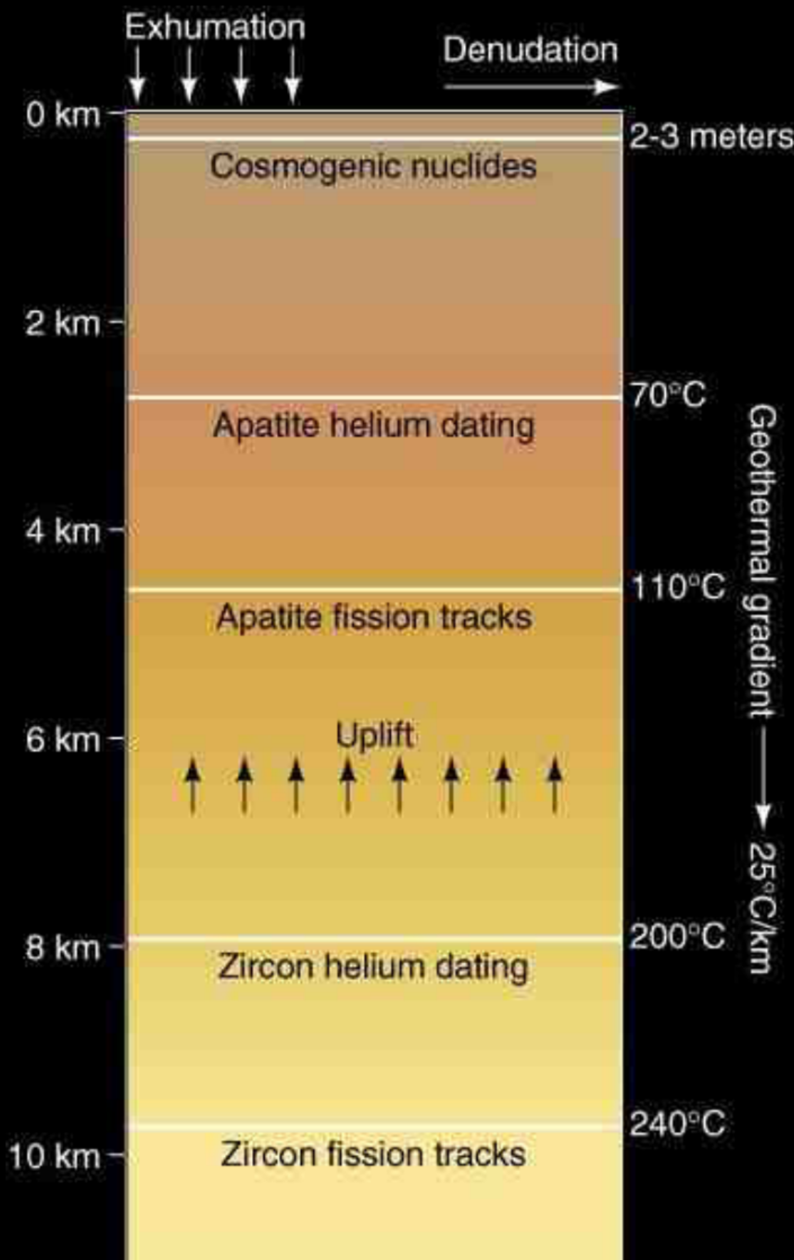
Radiometric dating systems and closure temperature for some minerals and associated paths



Radiometric dating systems and closure temperature for some minerals

Mineral and sating system	Closure temperature
Hornblende (K-Ar)	525±25°C
Muscovite (K-Ar)	325±25°C
Biotite (K-Ar)	300±25°C
K-feldspar (K-Ar)	200±25°C
Muscovite (Rb-Sr)	500±25°C
Biotite (Rb-Sr)	275±25°C
Monazite (U-Pb)	525±25°C
Sphene (fission track)	275±25°C
Zircon (fission track)	**225±15°C**
Apatite (fission track)	**120 ±20°C**

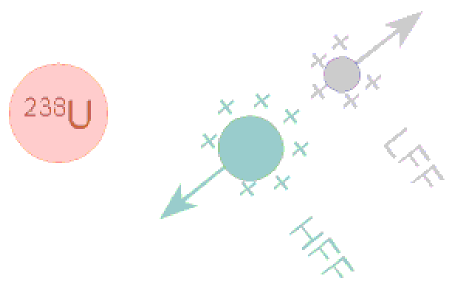
Radiogenic Methods



- Fission tracks damage the crystalline structure of minerals, but this damage will repair itself by annealing if the temperature is sufficiently high.
- Fission tracks and radiogenic helium do not give reliable ages for the original formation of surface rocks, but rather tells us how many years the rocks have been at or below their closure temperatures.

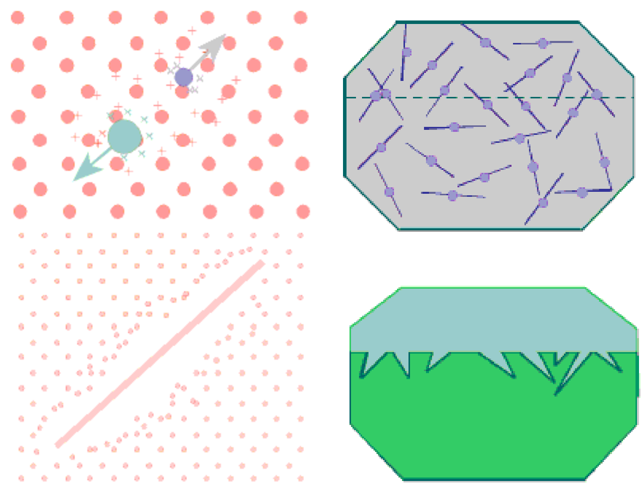
Thermo-chronometry: Fission track (million-year scale)

radioactive element releases energy

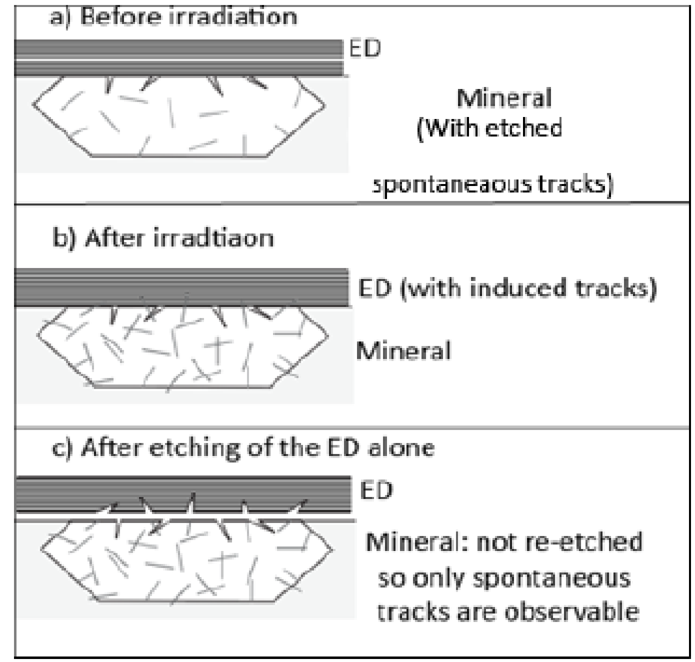


Unclear fission

produces highly-charged fission track



dating procedures and techniques



Fission track age

The **number** of tracks in an apatite grain depends on:

1. uranium content
2. Time (age)

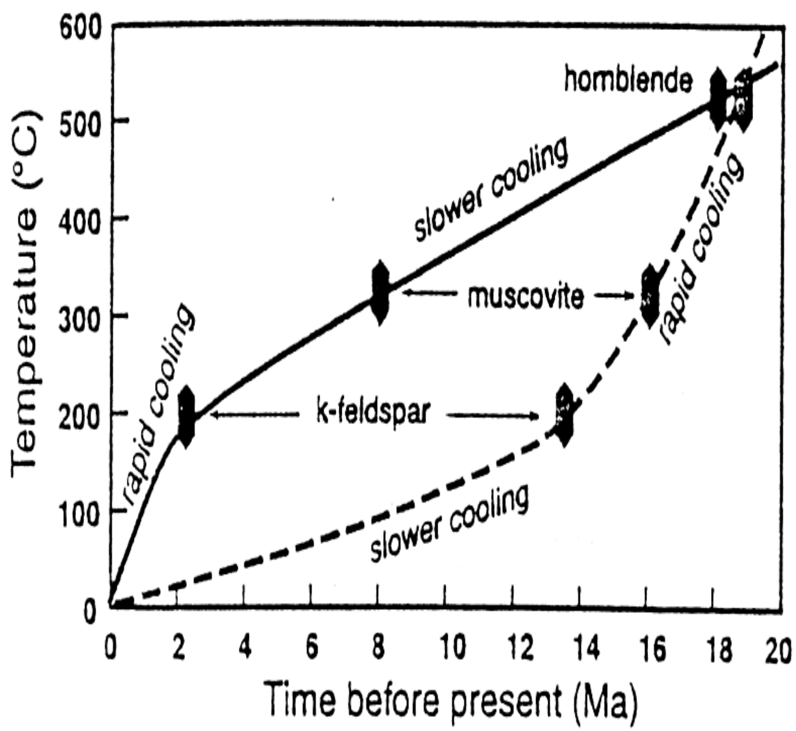
$$t = \frac{1}{\lambda_d} \ln \left[1 + \frac{\lambda_d \phi \sigma I \rho_s}{\lambda_f \rho_i}\right]$$

basic age equation

$\lambda_d = 1.551 \times 10^{-4}\ Ma^{-1}$; total decay constant of uranium (^{238}U)
$\lambda_f = 6.9 \sim 8.4 \times 10^{-17}\ Ma^{-1}$; fission decay constant (^{238}U)
Φ = the thermal neutron fluence
$\sigma = 580 \times 10^{-24}\ cm^2$; the thermal neutron cross section
$I = 7.2527 \times 10^{-3}$; $^{235}U/^{238}U$ isotopic abundance ratio
ρ_i , induced track density .
ρ_s , spontaneous track density.

(Fleischer et al. 1965)

FIGURE 7.14. Cartoon of contrasting cooling histories derived from ^{39}Ar-^{40}Ar dates on hornblende, muscovite, and potassium feldspar on two different rock samples



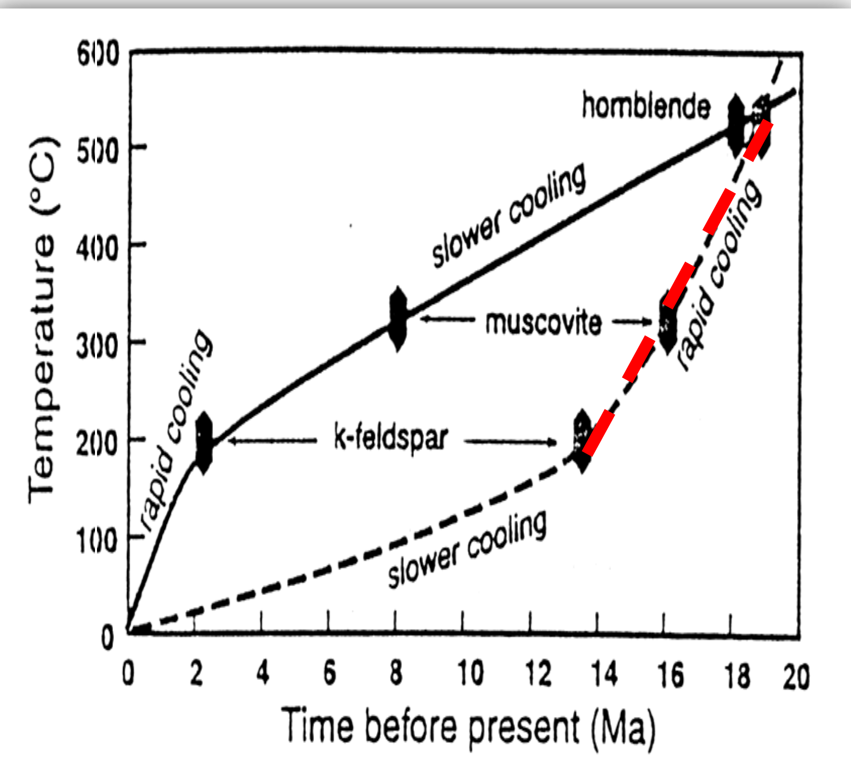
Cooling rate

Rapid cooling $100^{o}C$ / My

Slower cooling $1\text{-}20^{o}C$ / My

由於冷卻作用會持續到現今，所以常用來推論剝蝕速率的增快，例如：對現今的正斷層而言，表面侵蝕增快造成冷卻速率變快。綜合侵蝕和冷卻速率時，必須考慮地溫梯度，一般以$20\text{-}30^{o}C/Km$為地殼的地溫梯度。

結合侵蝕速率和冷卻速率



z = c/(dT/dz)　　z：深度

c：封存溫度

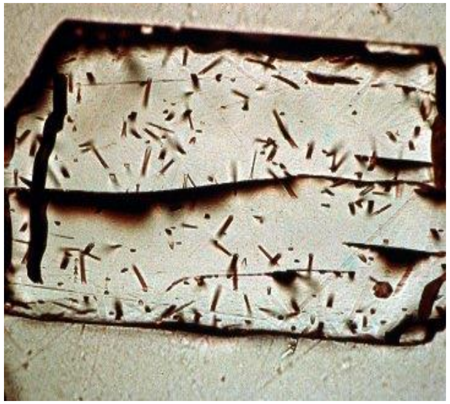
dT/dz：地溫梯度

E = z /a　　E：侵蝕速率

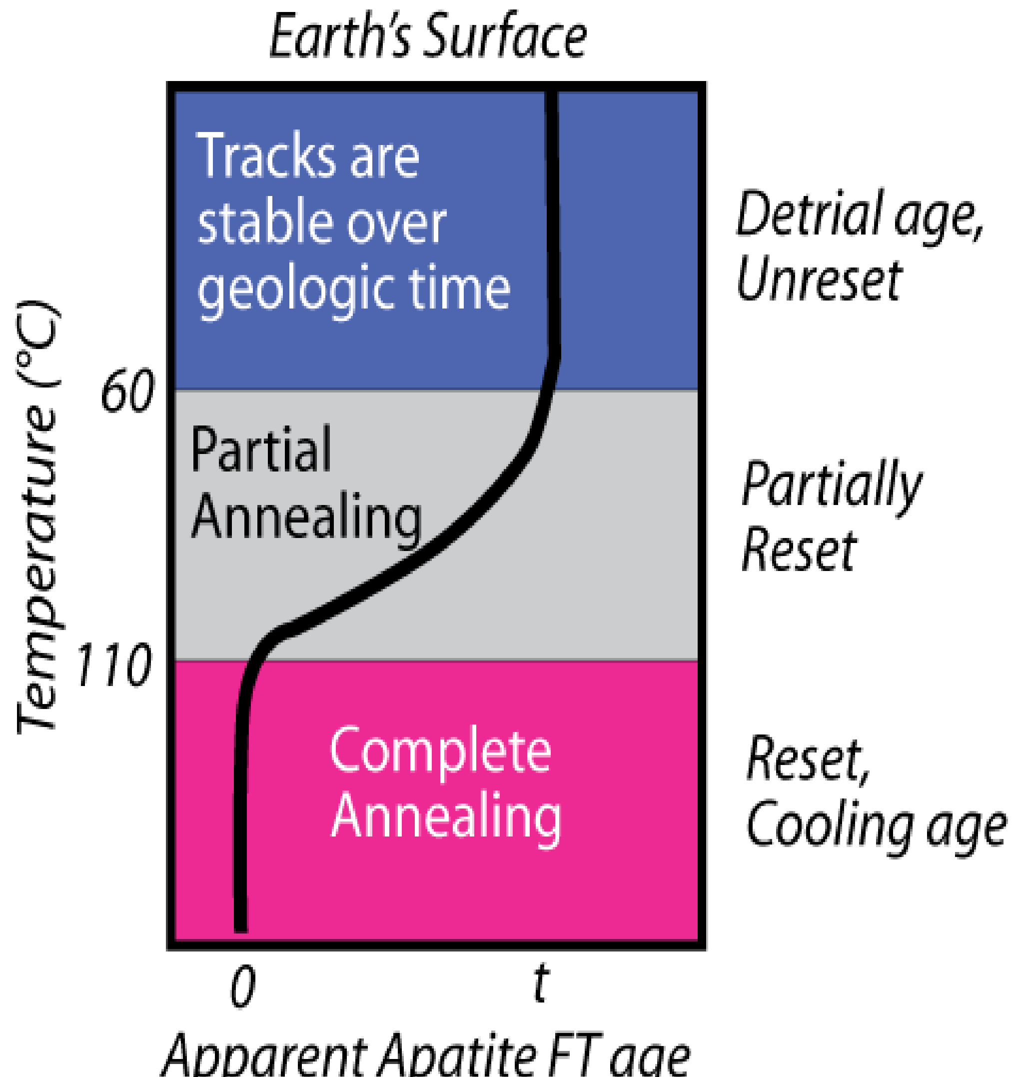
a：封存溫度的間隔時間

以上圖rapid cooling為例：當岩石溫度降到200ºC以下，約花了4Ma，以20-30ºC/Km為地殼的地溫梯度換算，得到3～5Km/My (3-5 mm/yr) 的剝蝕速率。

（Uncertainty: 古地溫梯度）

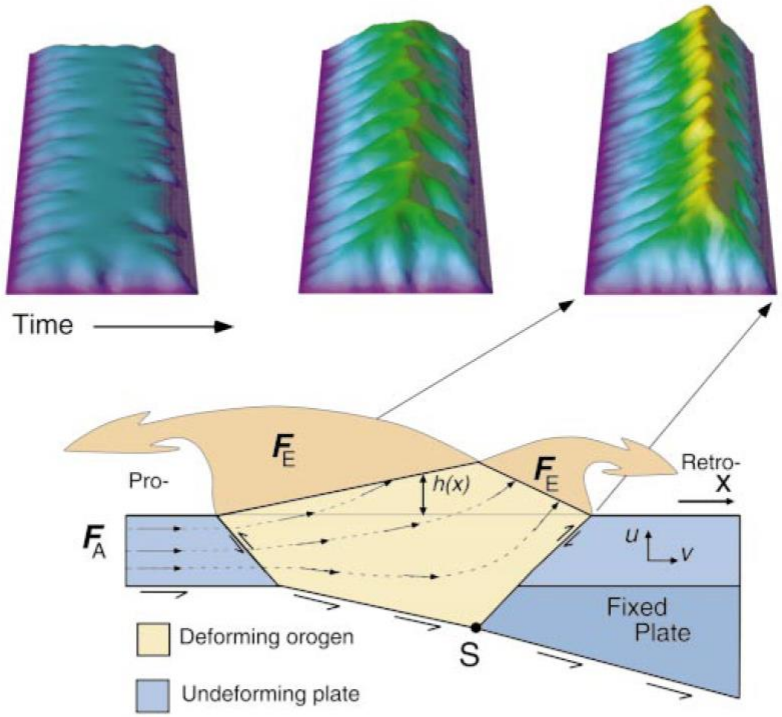


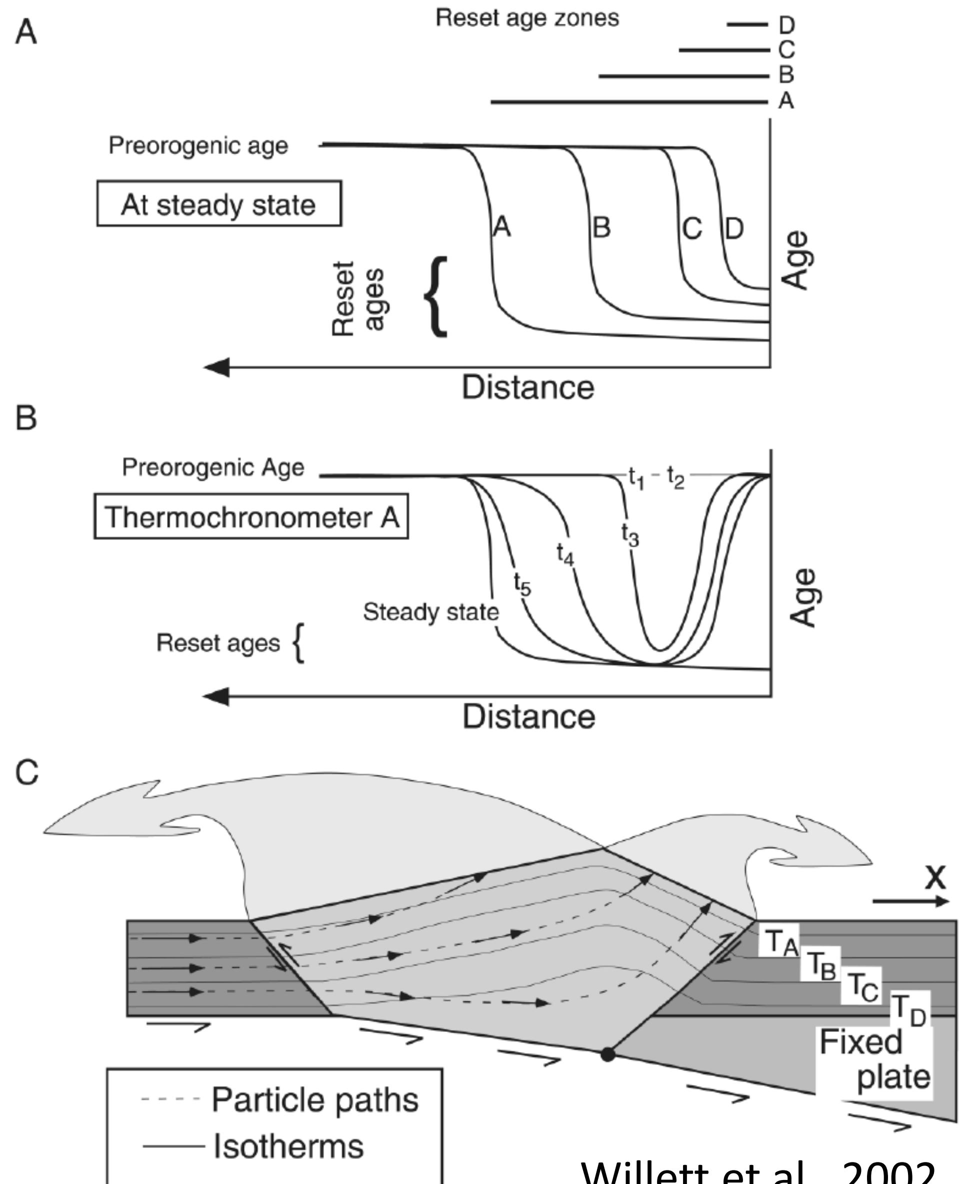
Apatite Fission Tracks



- Above 60°C, tracks accumulate over geologic time
- Between 110 and 60°C, not all tracks are annealed
- Below 110°, fission tracks are annealed (healed up and removed) quickly

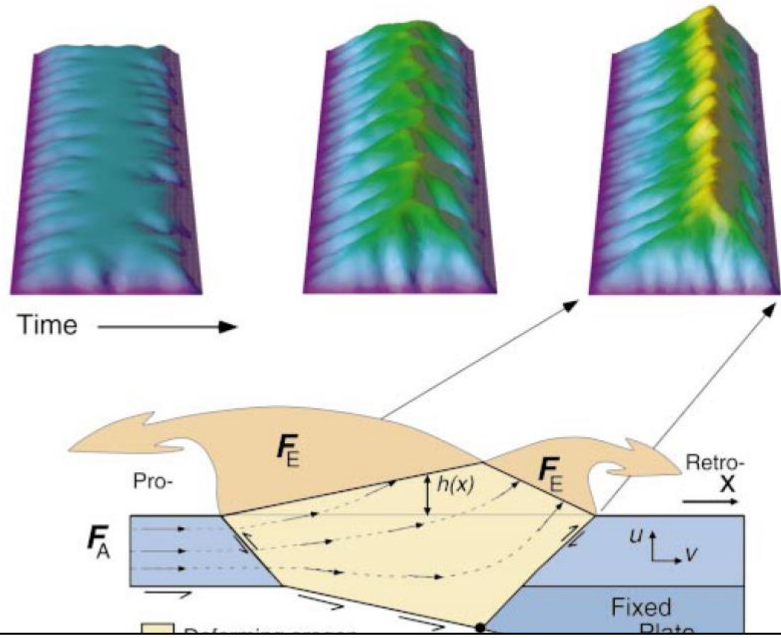
Thermo-kinematic evolution in a mountain belt



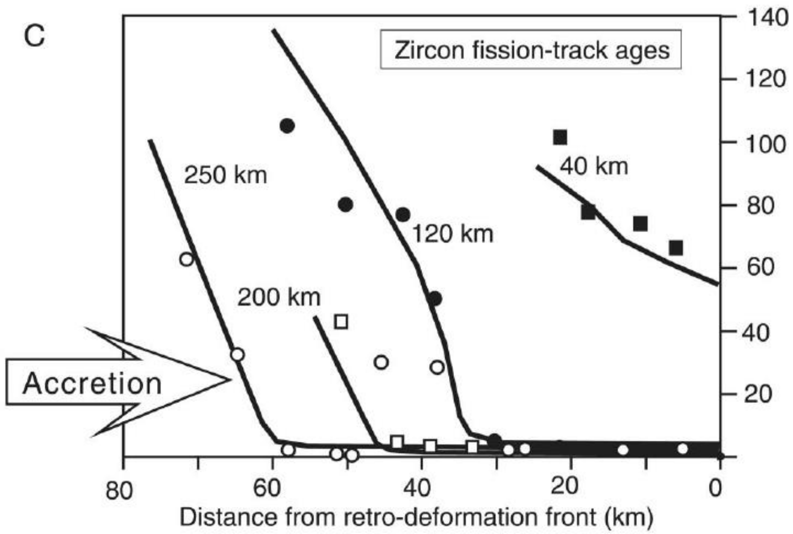


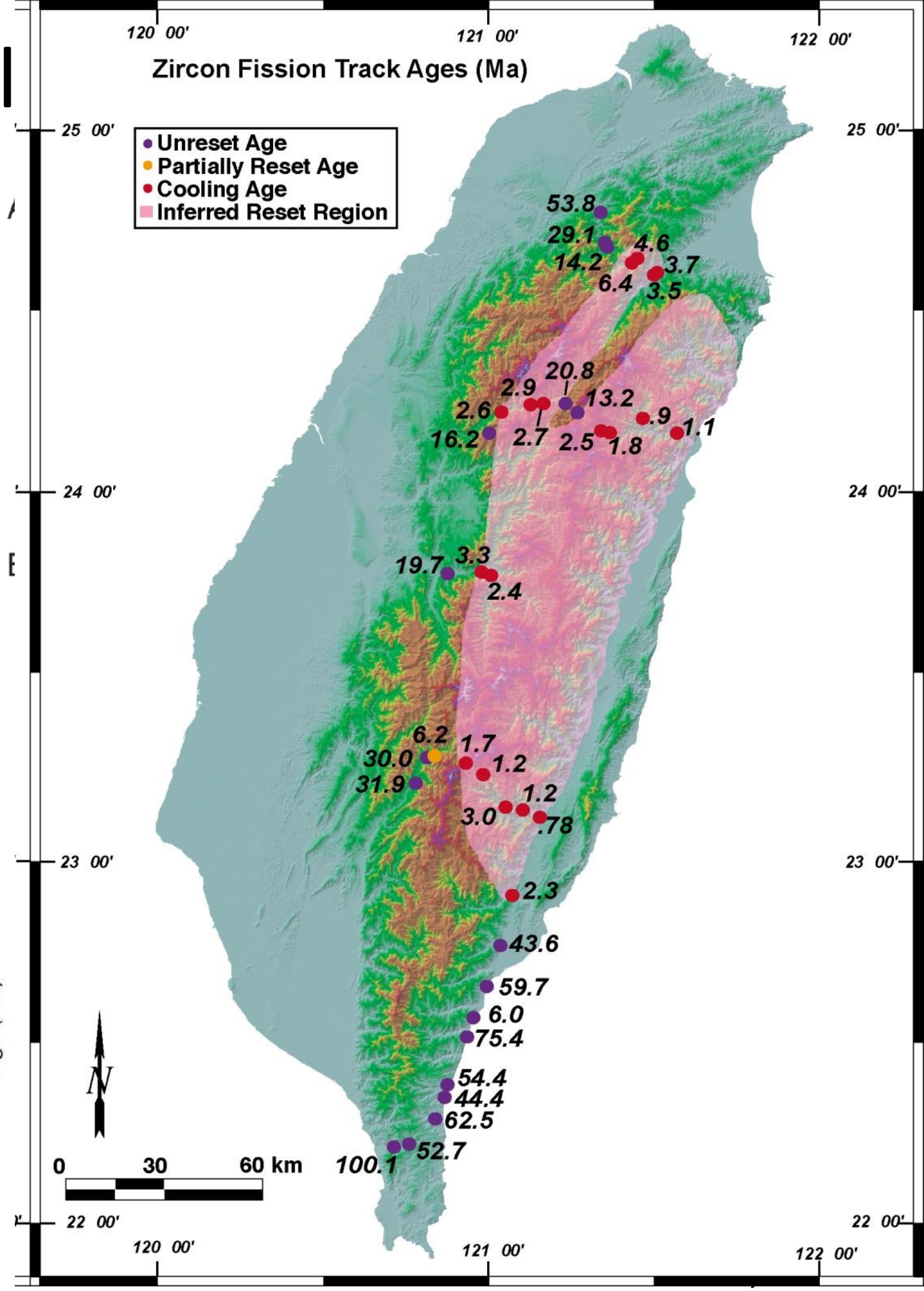
Willett et al., 2002

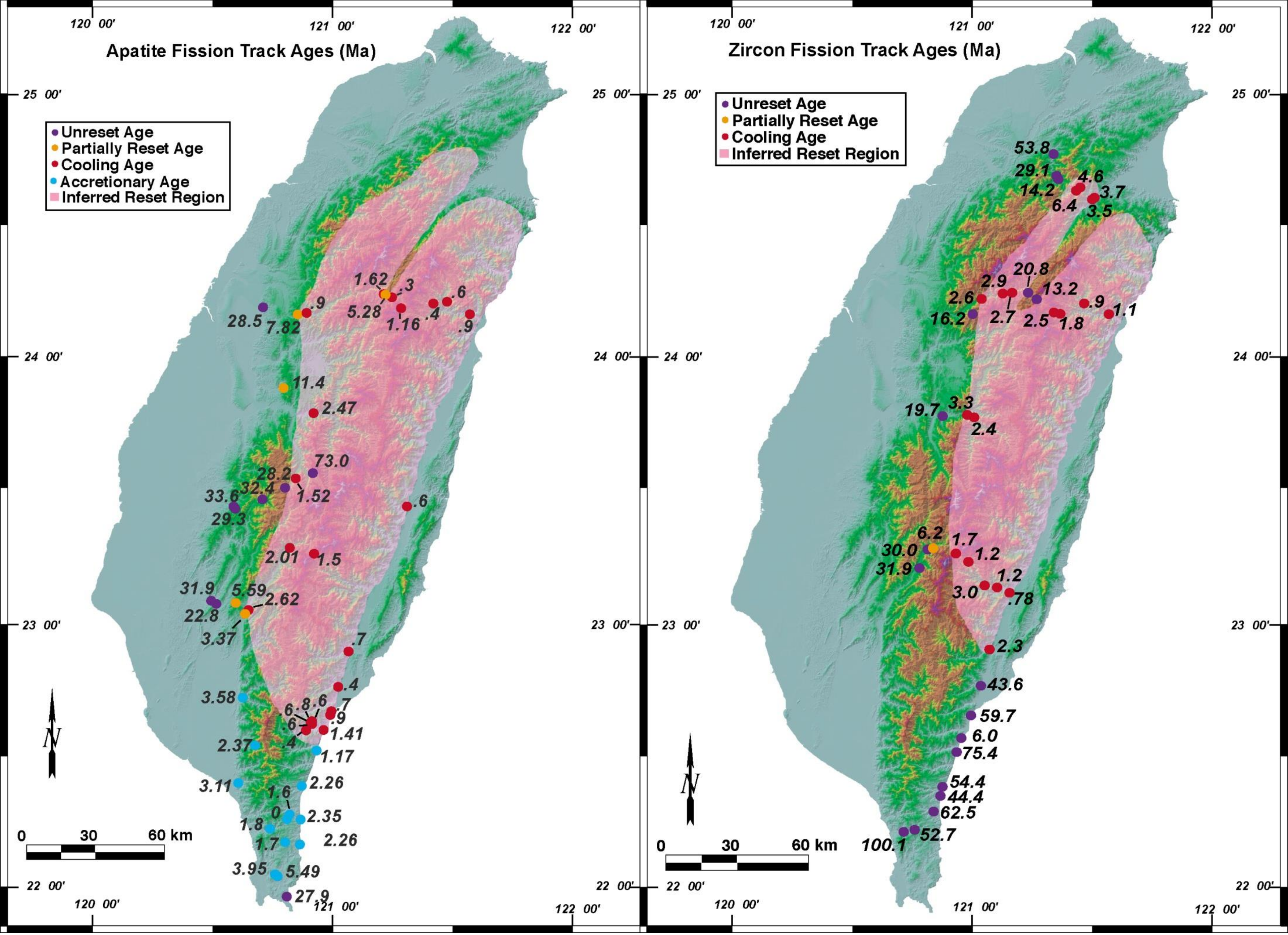
Thermo-kinematic evol



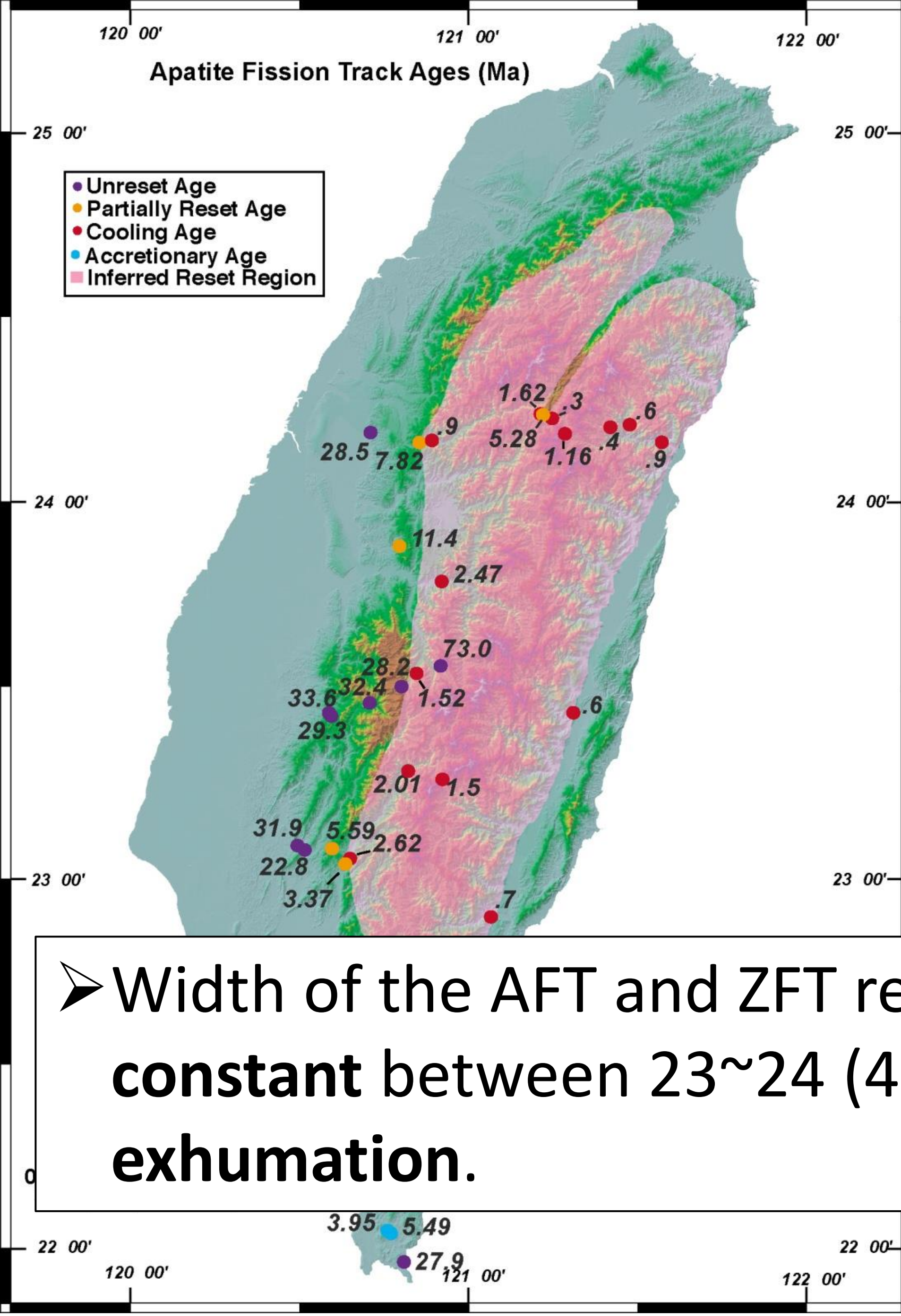
Steady state exhumation!!

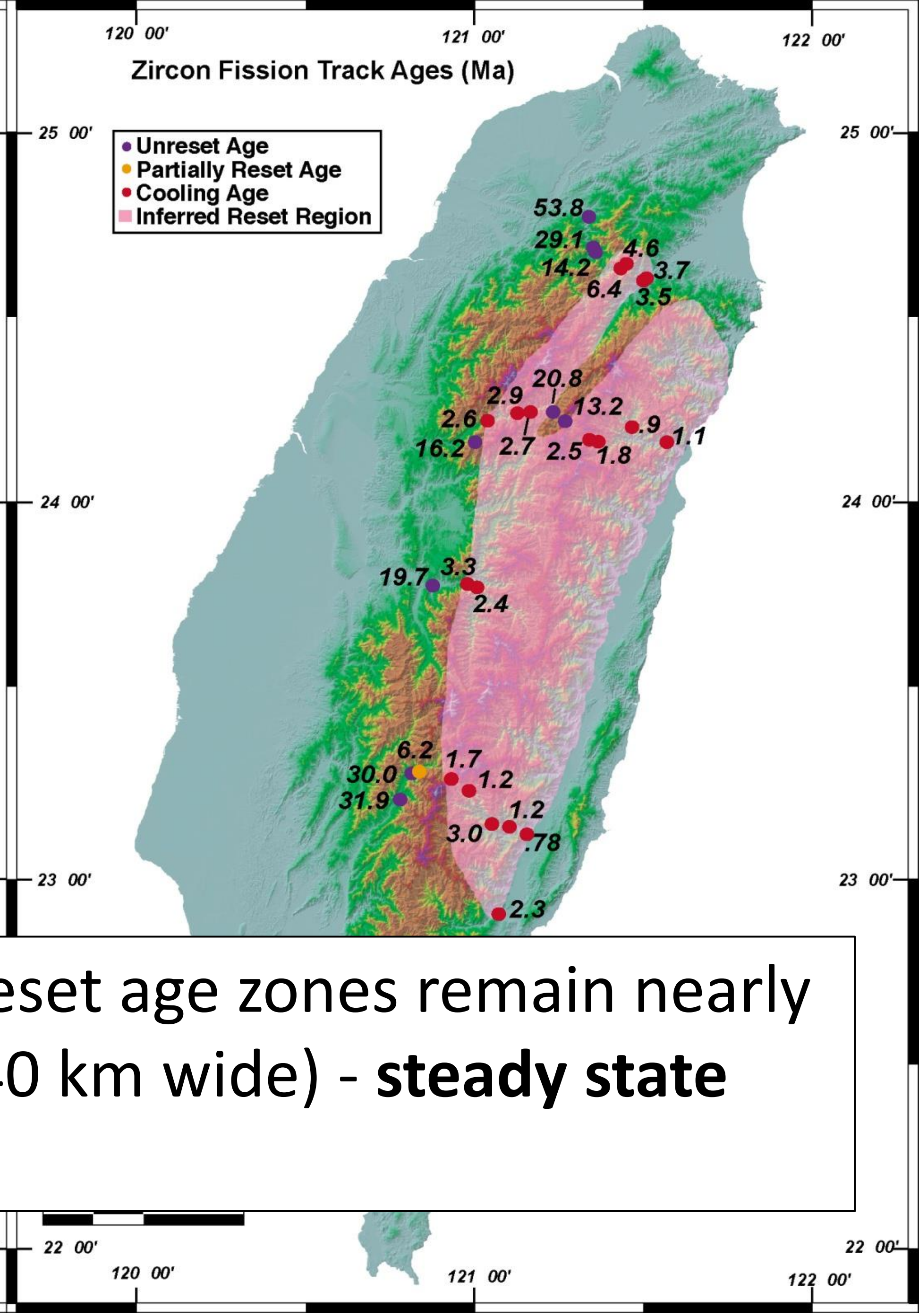




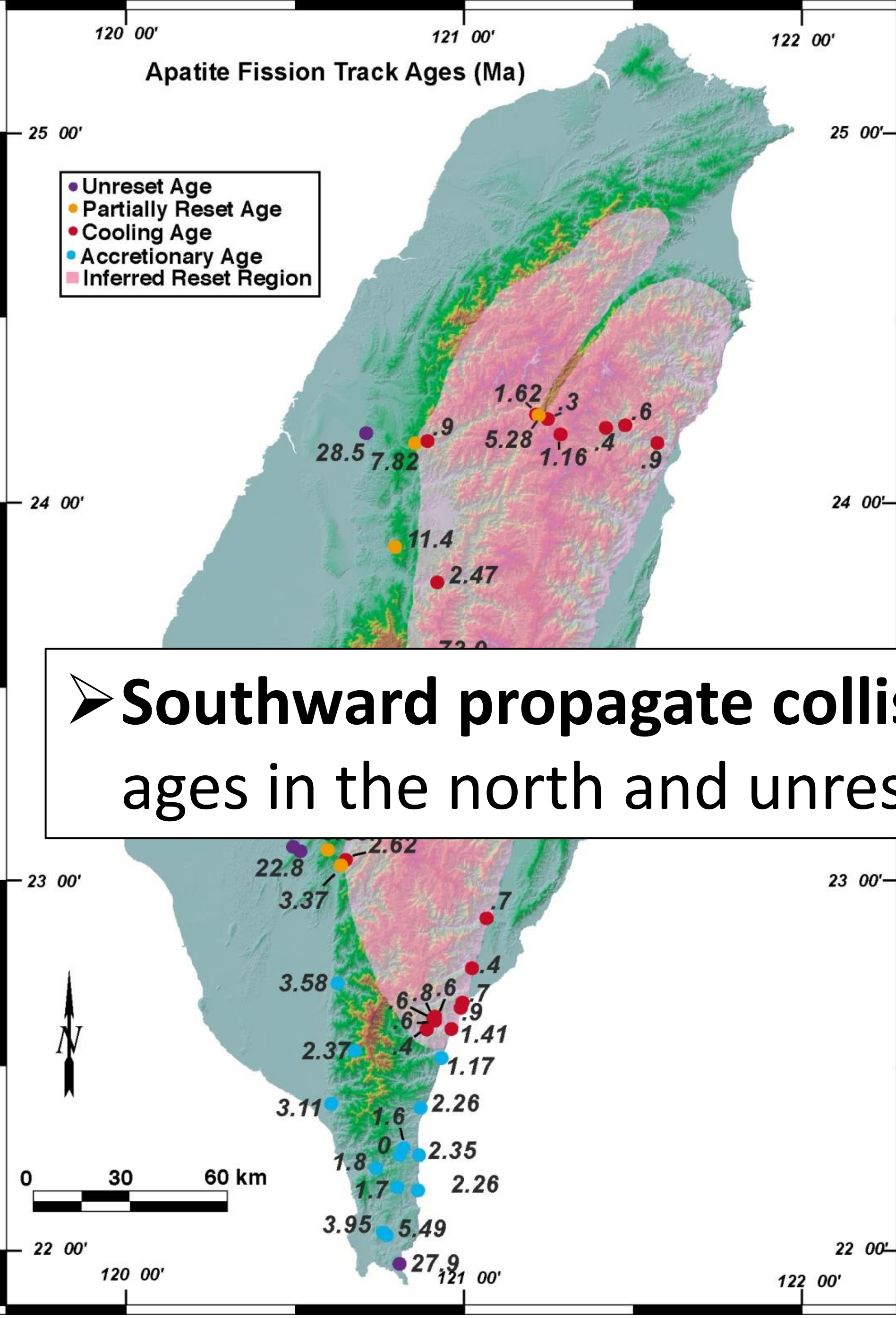


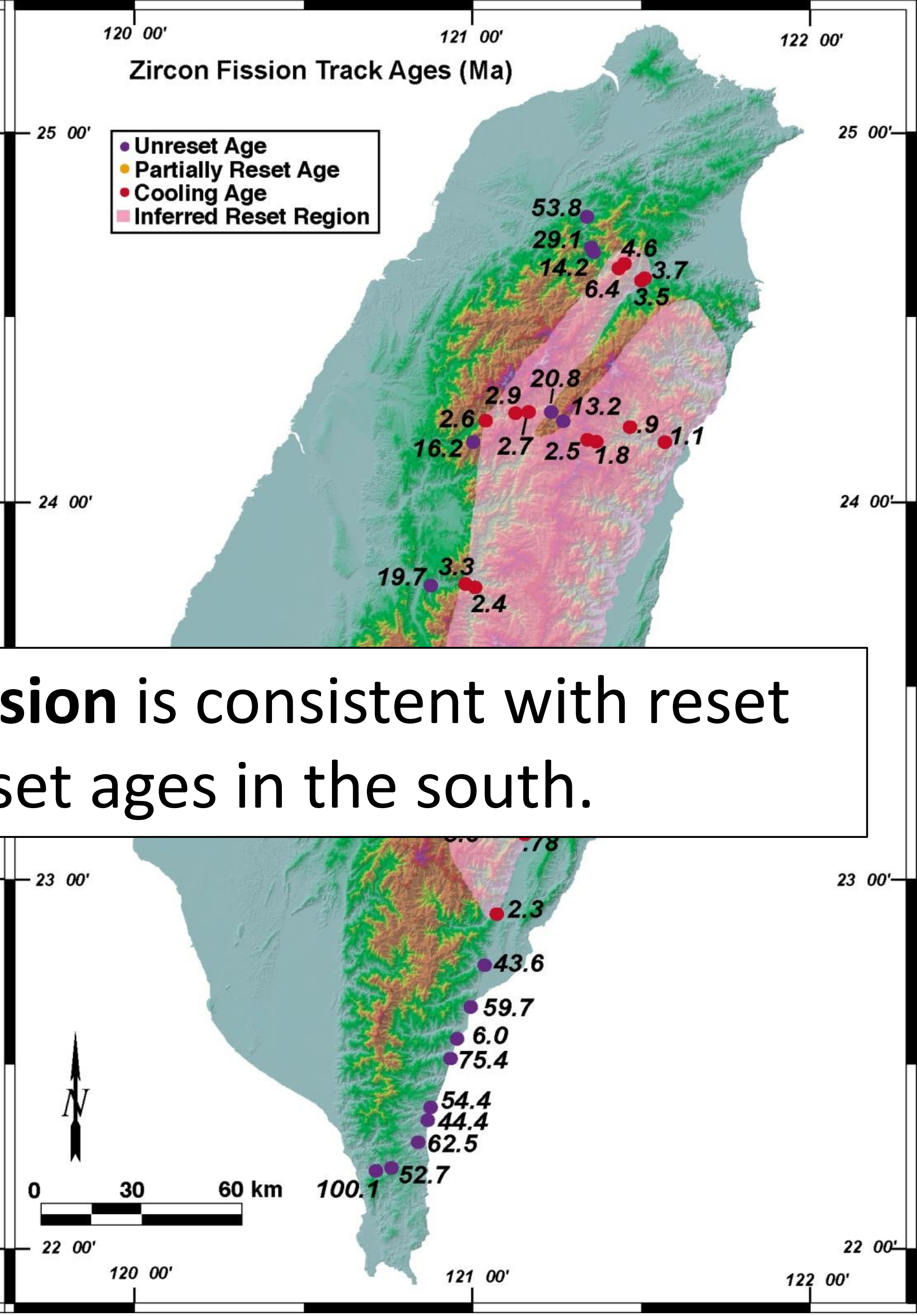
Apatite Fission Track Ages (Ma)
Unreset Age
Partially Reset Age
Cooling Age
Accretionary Age
Inferred Reset Region
120 00'
121 00'
122 00'
25 00'
24 00'
23 00'
22 00'
28.5
7.82
.9
1.62
.3
5.28
1.16
.4
.6
.9
11.4
2.47
73.0
28.2
1.52
33.6
32.4
29.3
.6
2.01
1.5
31.9
5.59
2.62
22.8
3.37
.7
.4
3.58
.6
.8
.6
.7
.9
.6
1.41
.4
2.37
1.17
3.11
2.26
1.6
0
2.35
1.8
1.7
2.26
3.95
5.49
27.9
0 30 60 km
N
Zircon Fission Track Ages (Ma)
Unreset Age
Partially Reset Age
Cooling Age
Inferred Reset Region
53.8
29.1
4.6
14.2
3.7
6.4
3.5
20.8
2.9
13.2
2.6
.9
1.1
16.2
2.7
2.5
1.8
19.7
3.3
2.4
6.2
1.7
30.0
1.2
31.9
1.2
3.0
.78
2.3
43.6
59.7
6.0
75.4
54.4
44.4
62.5
52.7
100.1
0 30 60 km
N



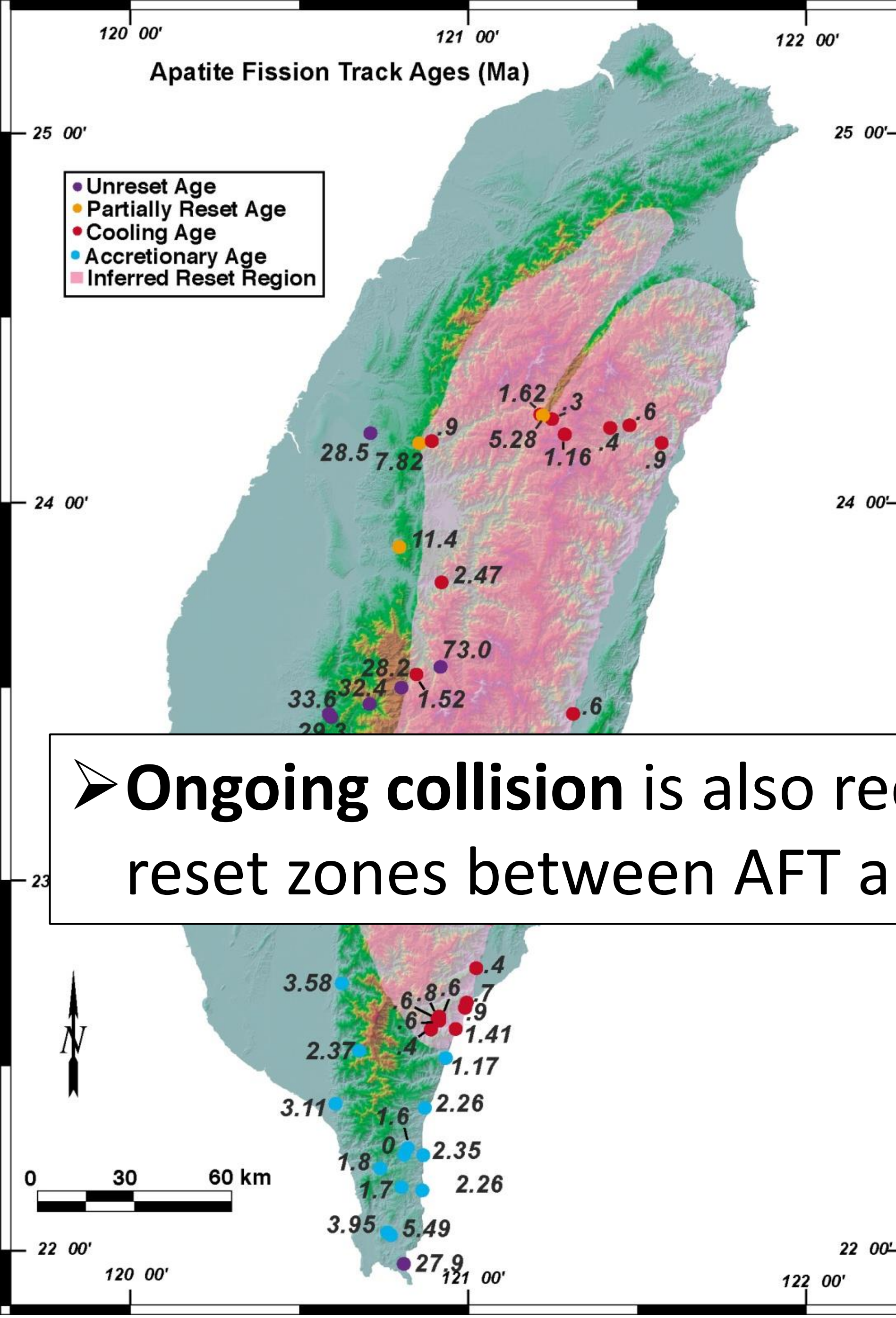


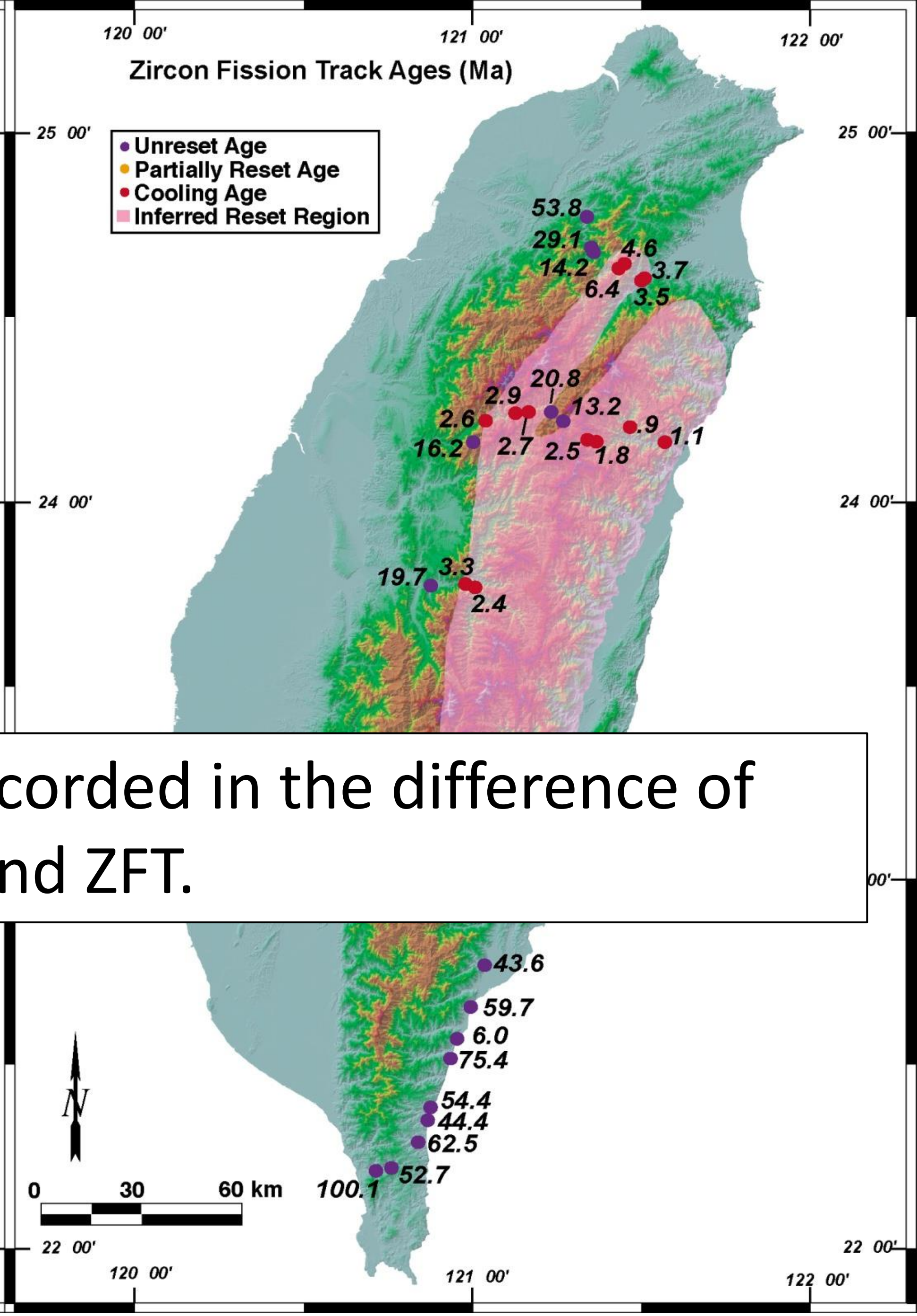
- Width of the AFT and ZFT reset age zones remain nearly **constant** between 23~24 (40 km wide) - **steady state exhumation**.



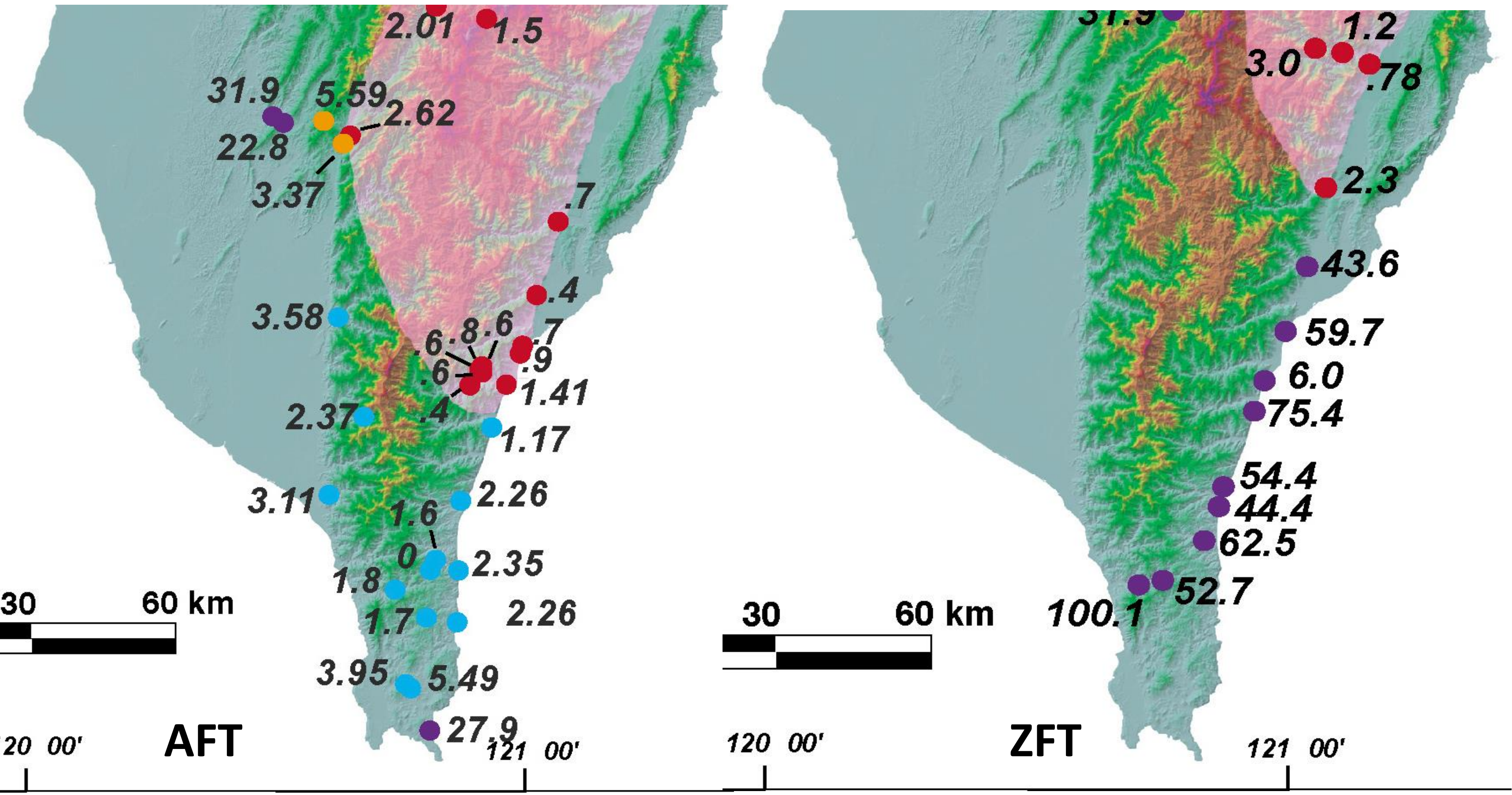


➢ **Southward propagate collision** is consistent with reset ages in the north and unreset ages in the south.





- **Ongoing collision** is also recorded in the difference of reset zones between AFT and ZFT.

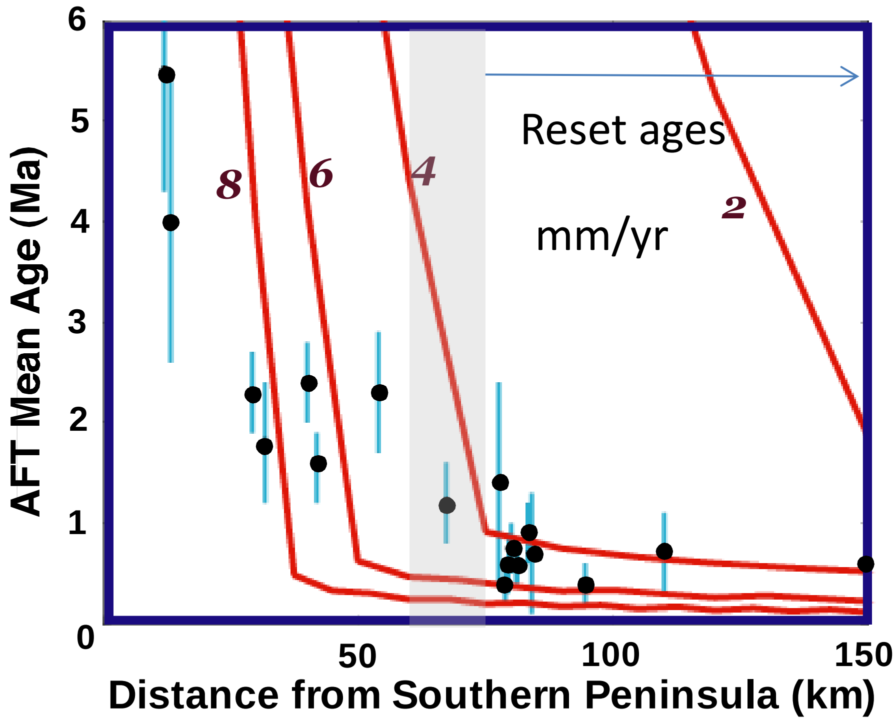


Southern Taiwan Ages: sediments reset by hot (high geothermal gradient) oceanic crust during burial

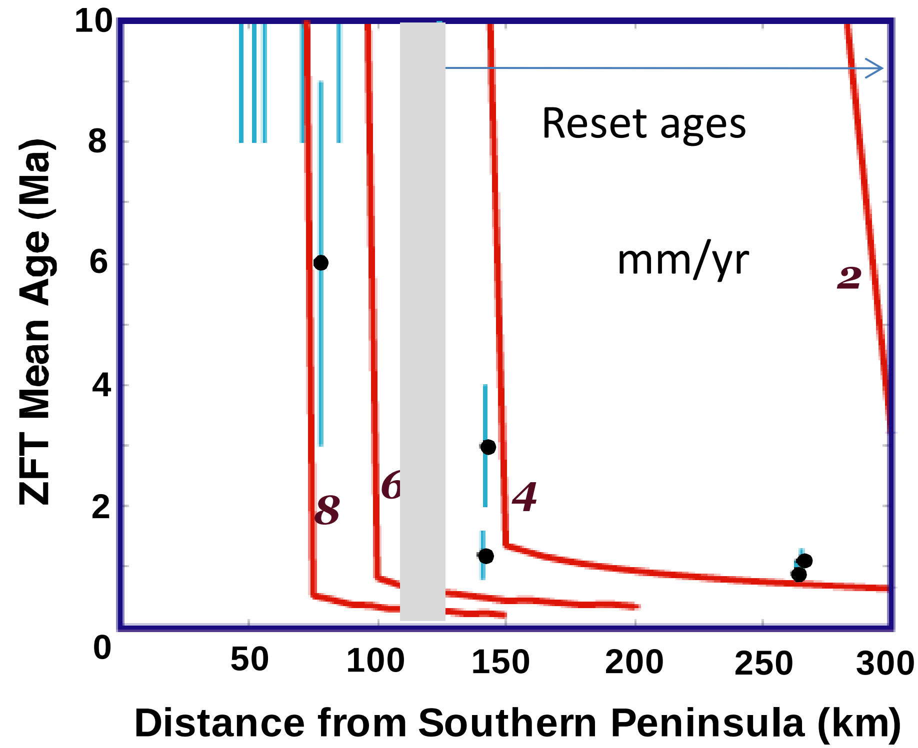
- Cooling by conduction with cold underthrust slab in accretionary wedge?
- Submarine erosion?
- Subaerial erosion starting at 2Ma?

Apatite and Zircon fission track ages as a function of distance from southern end of Taiwan

Best fit of erosion rate ~4-5 mm/yr



Best fit of erosion rate ~5-6 mm/yr

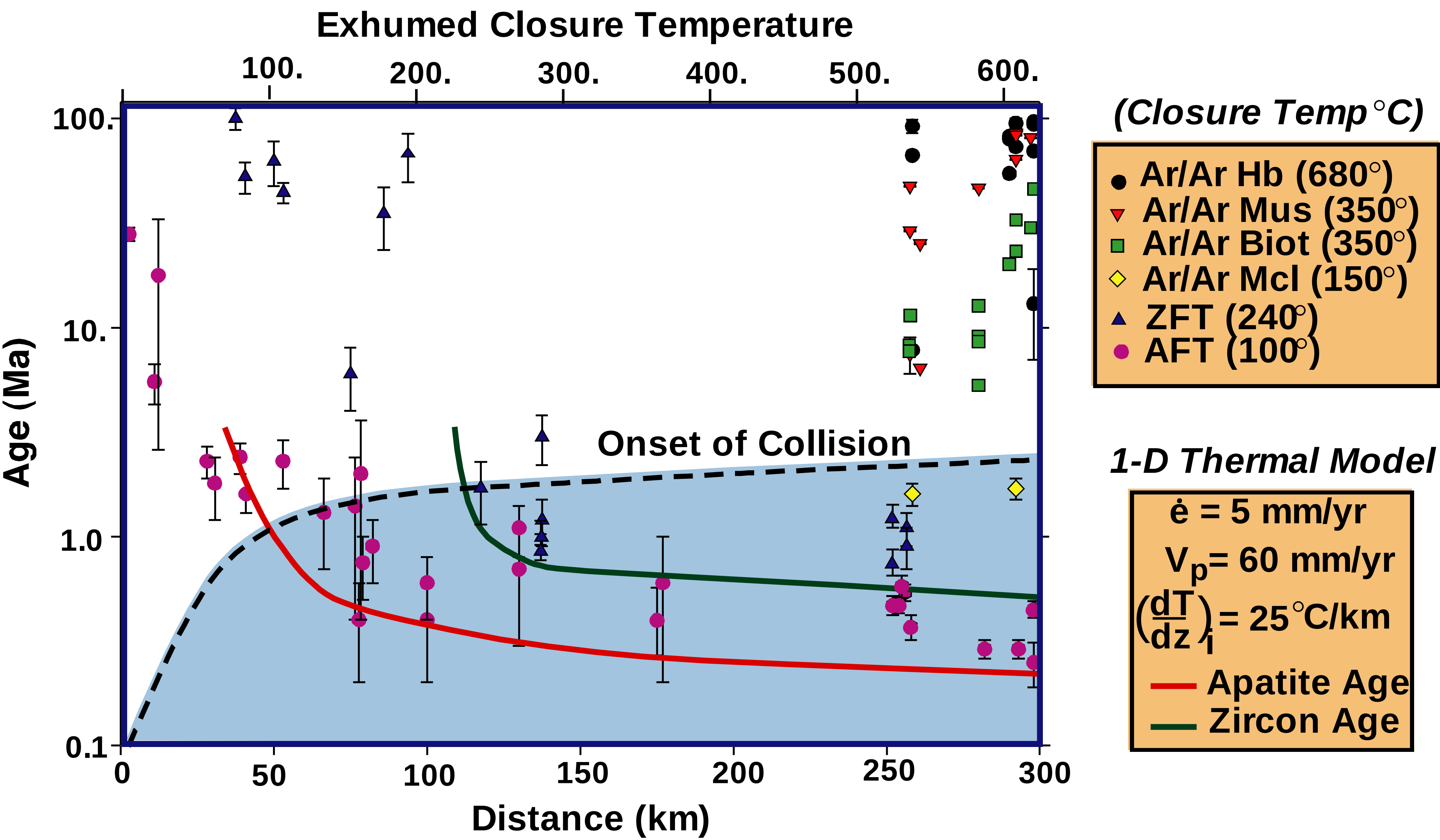


Parameters of 1-D thermal model see previous slide except various erosion rate

Note: Predicted reset ages become progressively younger with time or distance to the north

Transition from unrest to reset ages is very sensitive to the erosion rate

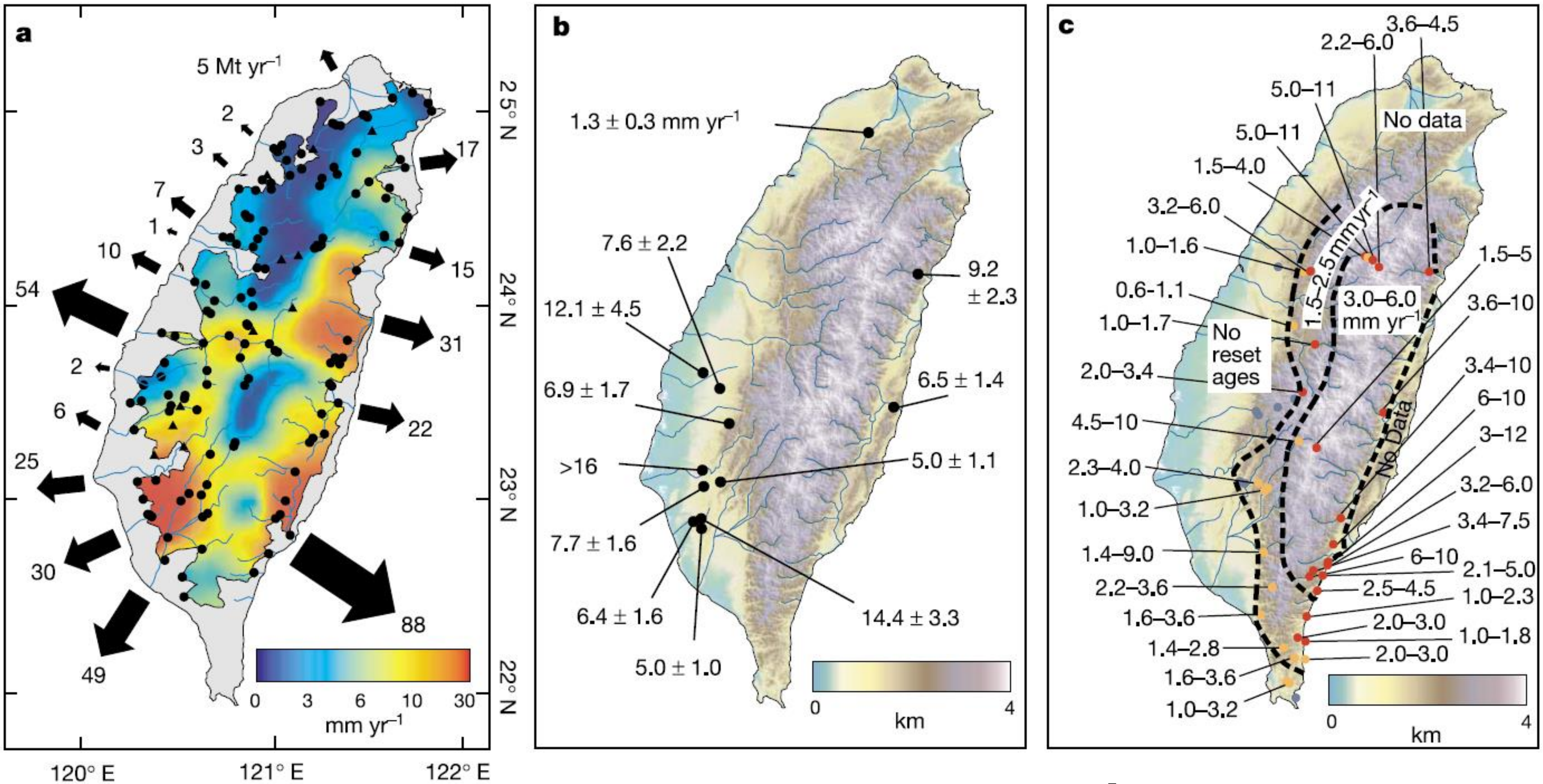
Willett et al., 2003



Willett et al., 2003

Erosion rates in Taiwan across multiple time scales

河流懸浮輸砂量 (~10yrs) 河床岩盤下切速率 (~10 kyrs) 裸露速率 (~Myrs)



Fluvial suspended sediment (~ 15 mm/y)

Bedrock strath incision rate (5-10 mm/y)

Exhumation rate, AFT (120°C) (3-6 mm/y)

Dadson et al. (2003)

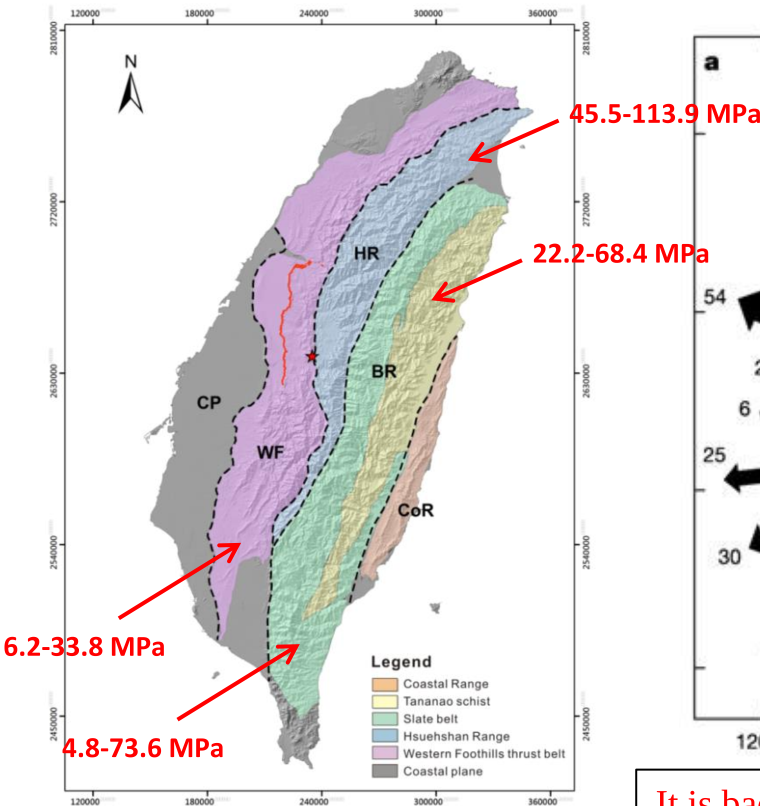
What controls the erosion rate?

After the measured erosion rates, we want to know what controls the patterns of erosion rate in decadal scale. Here, we have evaluated controls on erosion rates in Taiwan using…

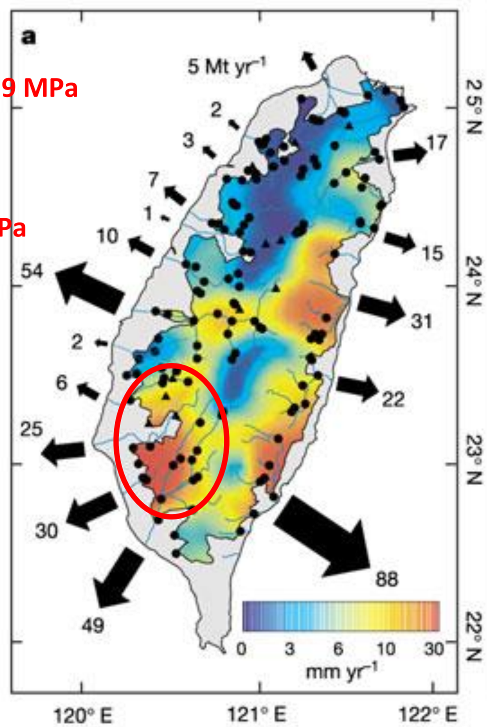
- Precipitation
- runoff
- Slope
- Substrate strength
- Stream power
- Seismic
- Storm

Substrate strength-controlled

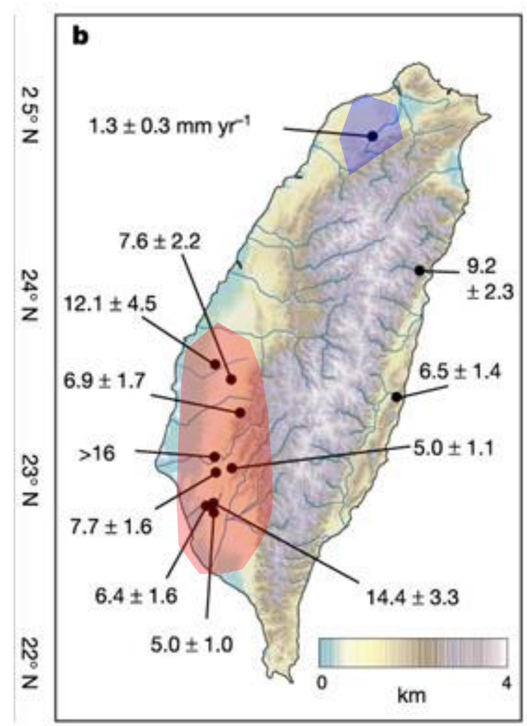
Tectonic units



Decadal-scale



Holocene

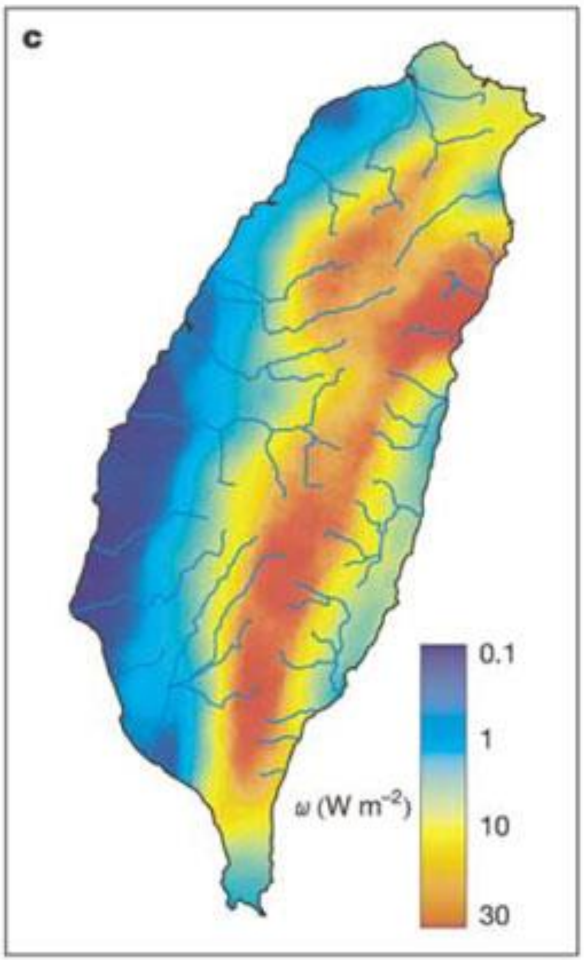


It is bad correlation between substrate strength and decadal scale erosion rate.

Region	Number of Samples	Uniaxial compressive strength (MPa) Min	Max	Mean	Standard Deviation	1σ range
Western Foothills	682	0.1	109.2	20.0	13.8	6.2 – 33.8
Hsueshan Range	88	5.1	219.9	79.7	34.2	45.5 – 113.9
Slate Belt	57	1.5	253.4	39.2	34.4	4.8 – 73.6
Tananao Schist	287	1.2	189.9	45.3	23.1	22.2 – 68.4

The effect of substrate strength was assessed using 1,114 measurements of uniaxial compressive strength at 23 sites across Taiwan.

Stream power-controlled



Unit stream power, ω

presented at 1-km grid resolution with 30-km circular moving mean applied.

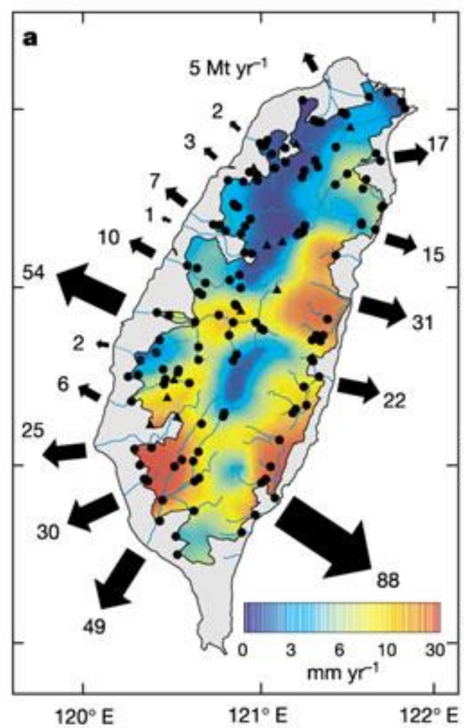
$$\omega = \rho g Q S / w, \ (W/m^2)$$

$$\downarrow \ w \fallingdotseq Q^{0.5}$$

$$\omega = \rho g Q^{0.5} S, \ (W/m^2)$$

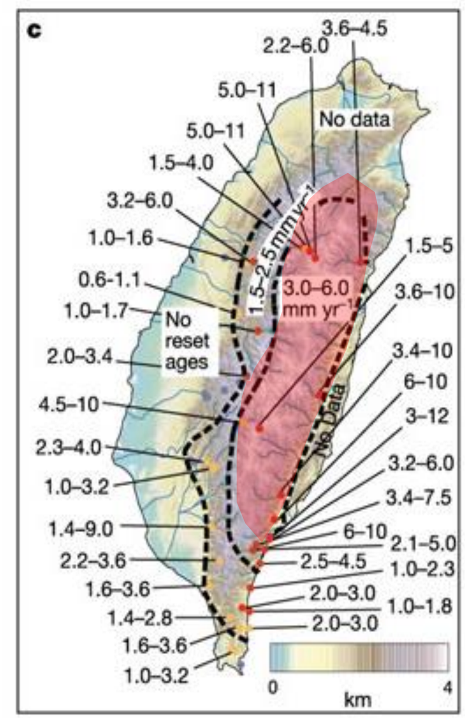
ρ, water density (1,000 kg/m^3)
g, gravity (9.8 m/s)
Q, water discharge (m^3/s)
S, channel slope (m/m)
w, channel width (m)

Decadal-scale

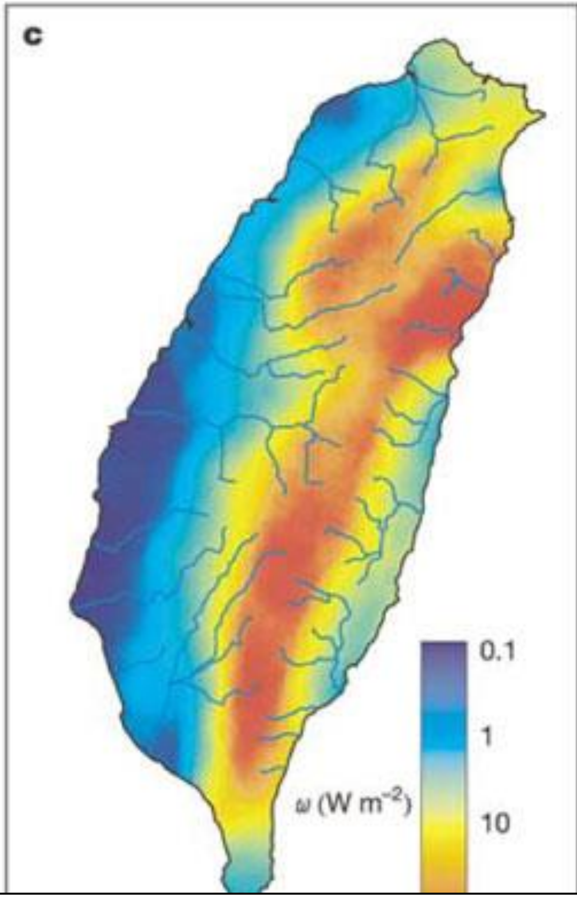


r^2=0.01

Million-year scale



Stream power-controlled



The stream power pattern emphasizes areas along the Central Range, it reflected by the exhumation rate. However, it does not match of the decadal erosion pattern.

circular moving mean applied.

$$\omega = \rho g Q S / w, \ (W/m^2)$$

$$\downarrow \ w \fallingdotseq Q^{0.5}$$

$$\omega = \rho g Q^{0.5} S, \ (W/m^2)$$

ρ, water density (1,000 kg/m³)
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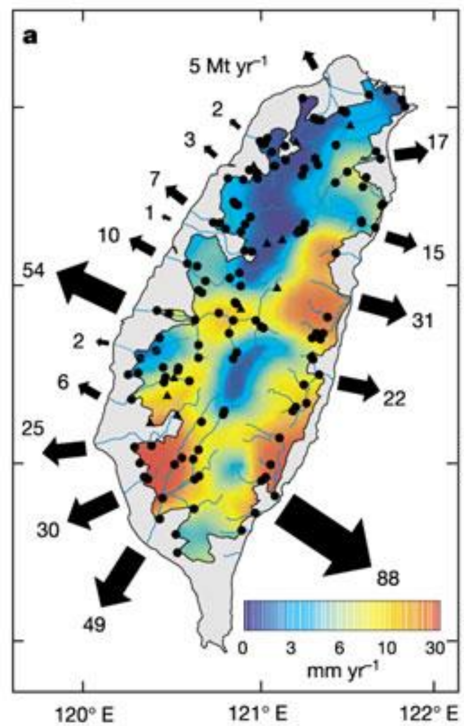
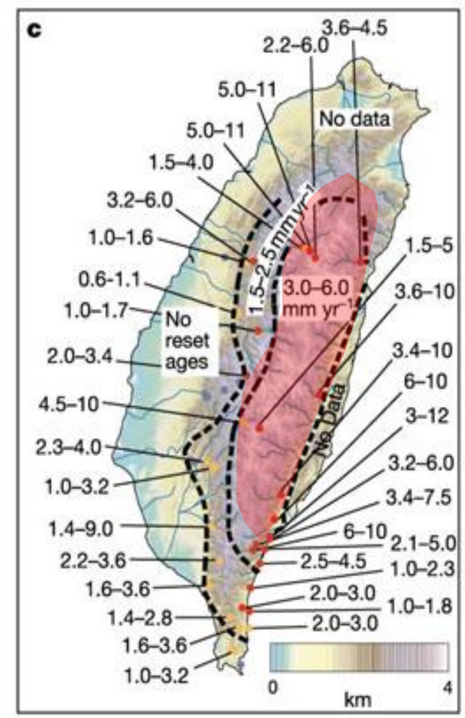
Decadal-scale



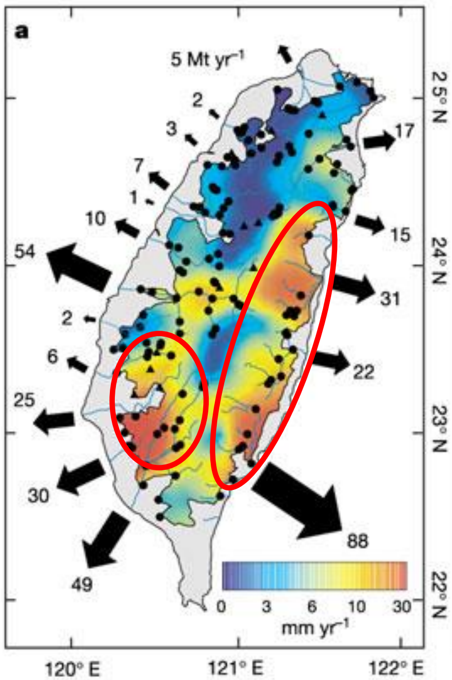
r^2=0.01

Million-year scale

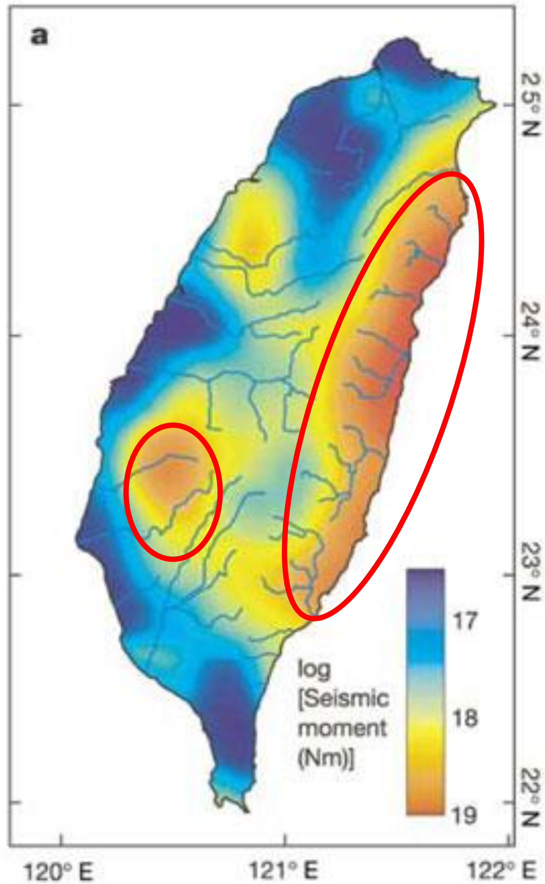


Seismic-controlled

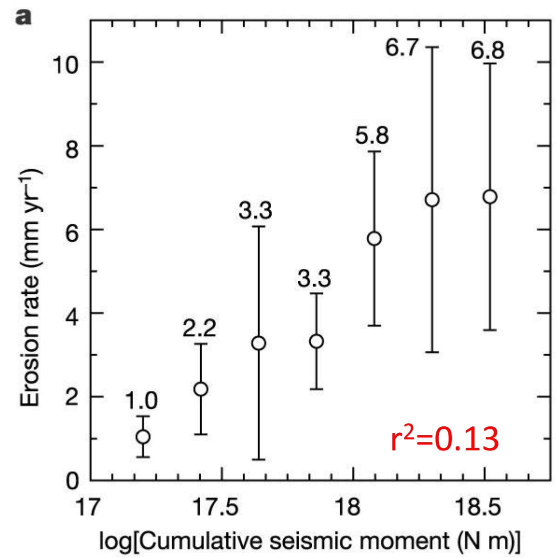
Decadal-scale



Cumulative seismic moment, M_0



M_0 = rigidity x fault area x fault slip



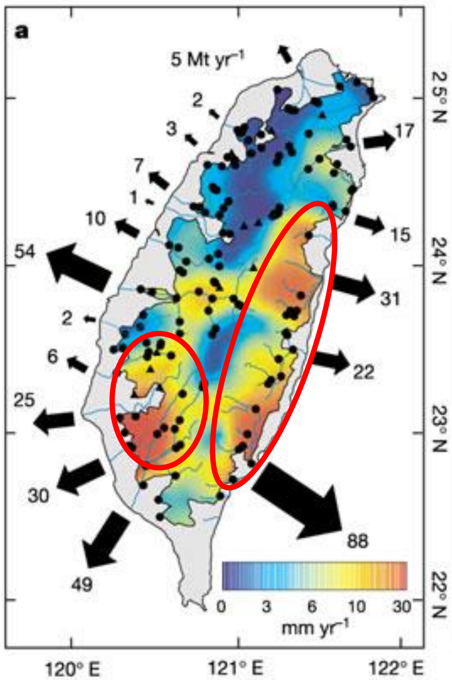
In total 128 drainage basins are shown, binned by mean cumulative seismic moment release within their boundaries.

In Taiwan there is a clear link between erosion and historical cumulative seismic moment release between 1900 and 1998, the results indicate that modern erosion rates are strongly influenced by large earthquakes.

Cumulative seismic moment computed from historical record of earthquakes greater than M_w = 5.0, between 1900 and 1998. Where seismic moment is not reported directly, we have estimated it from the listed magnitude using a global relation.

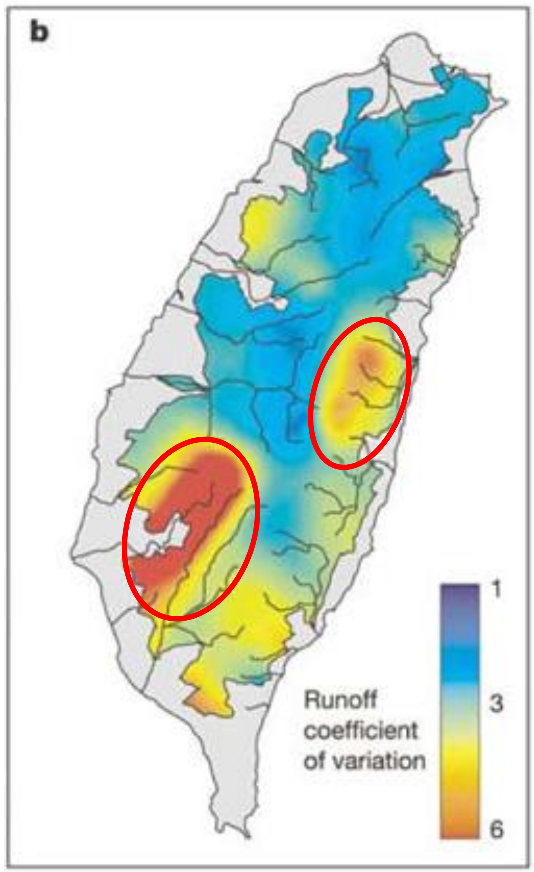
Storm-controlled

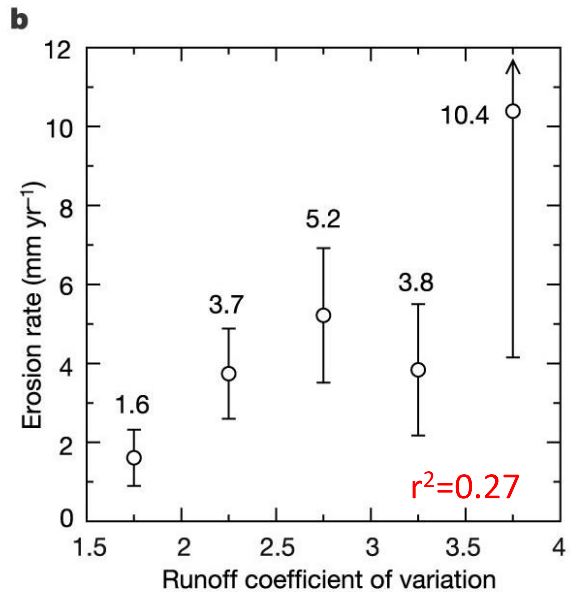
Decadal-scale



$$\frac{\text{standard deviation of runoff}}{\text{mean runoff}}$$

Runoff coefficient of variation





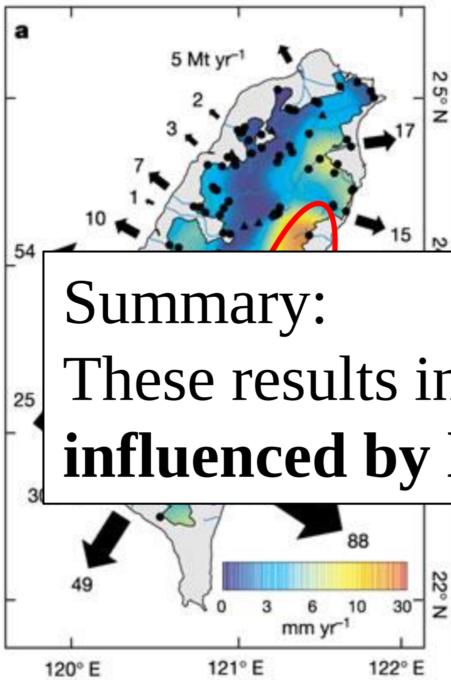
In total 128 drainage basins are shown, binned by coefficient of runoff variation defined by their water discharge record.

Runoff coefficient of variation, defined as standard deviation of runoff divided by mean runoff. Runoff (myr^{-1}) was measured as average annual river discharge divided by drainage area. Runoff coefficient of variation represents unusual runoff, in this case is **storm event**.

This is clear from the significant correlation between erosion rates and the coefficient of runoff variation, which represents storm incidence. We conclude that storm runoff is a first-order control on erosion rates in Taiwan.

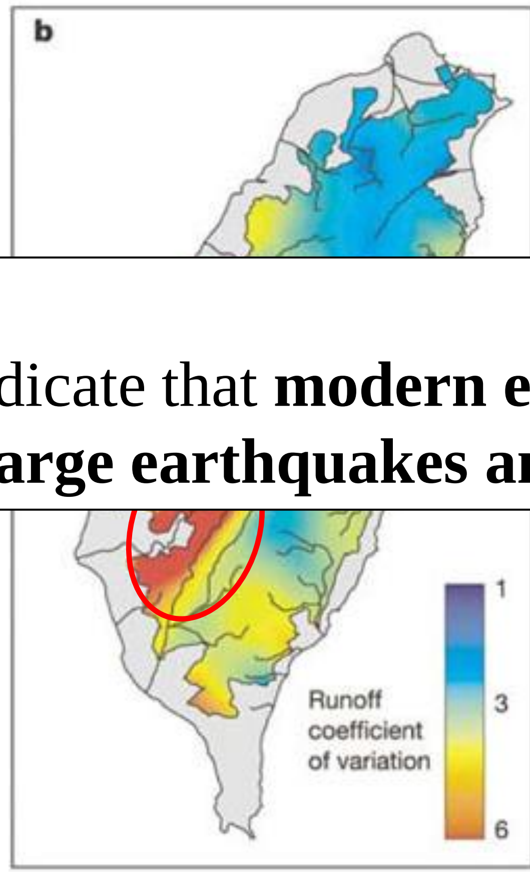
Storm-controlled

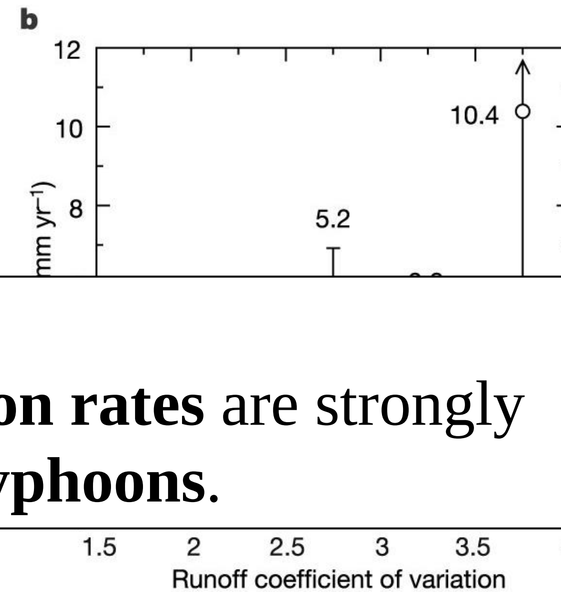
Decadal-scale



$$\frac{\text{standard deviation of runoff}}{\text{mean runoff}}$$

Runoff coefficient of variation





Summary:
These results indicate that **modern erosion rates** are strongly **influenced by large earthquakes and typhoons**.

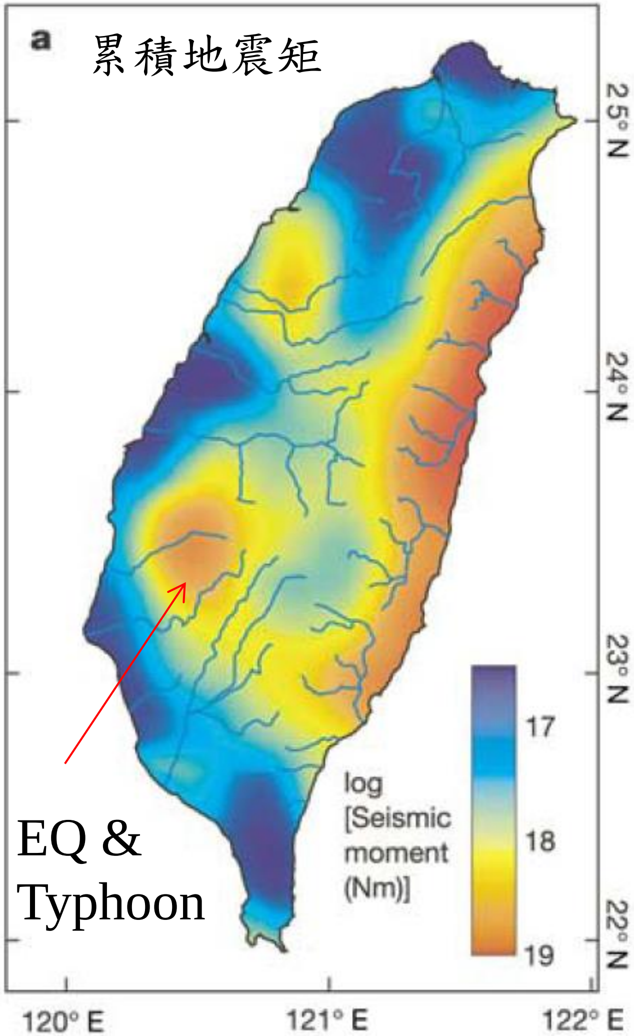
In total 128 drainage basins are shown, binned by coefficient of runoff variation defined by their water discharge record.

Runoff coefficient of variation, defined as standard deviation of runoff divided by mean runoff. Runoff (myr^{-1}) was measured as average annual river discharge divided by drainage area. Runoff coefficient of variation represents unusual runoff, in this case is **storm event**.

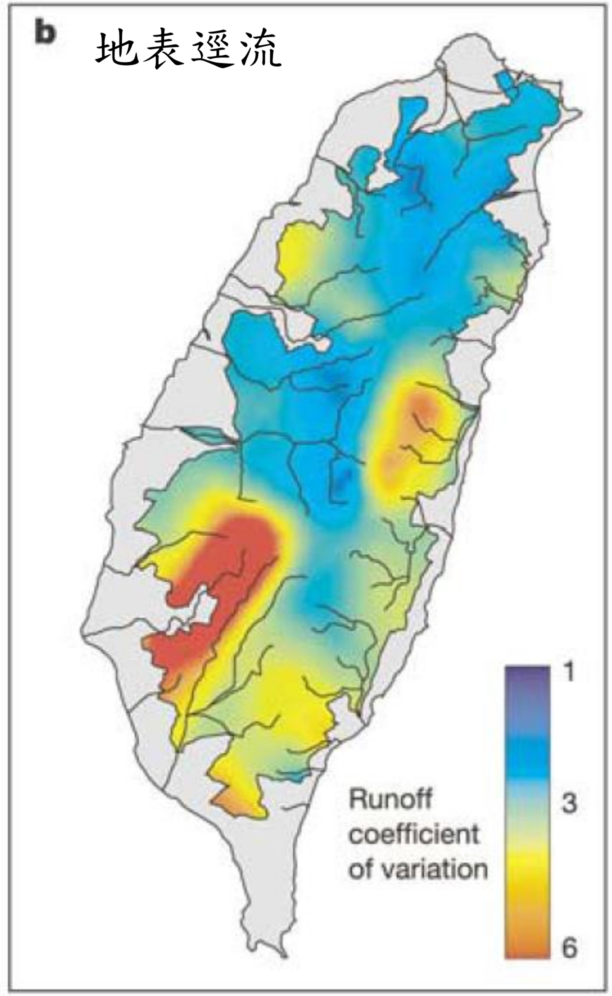
This is clear from the significant correlation between erosion rates and the coefficient of runoff variation, which represents storm incidence. We conclude that storm runoff is a first-order control on erosion rates in Taiwan.

Seismic, hydrological and topographic controls on denudation pattern

Dadson et al. (2003)

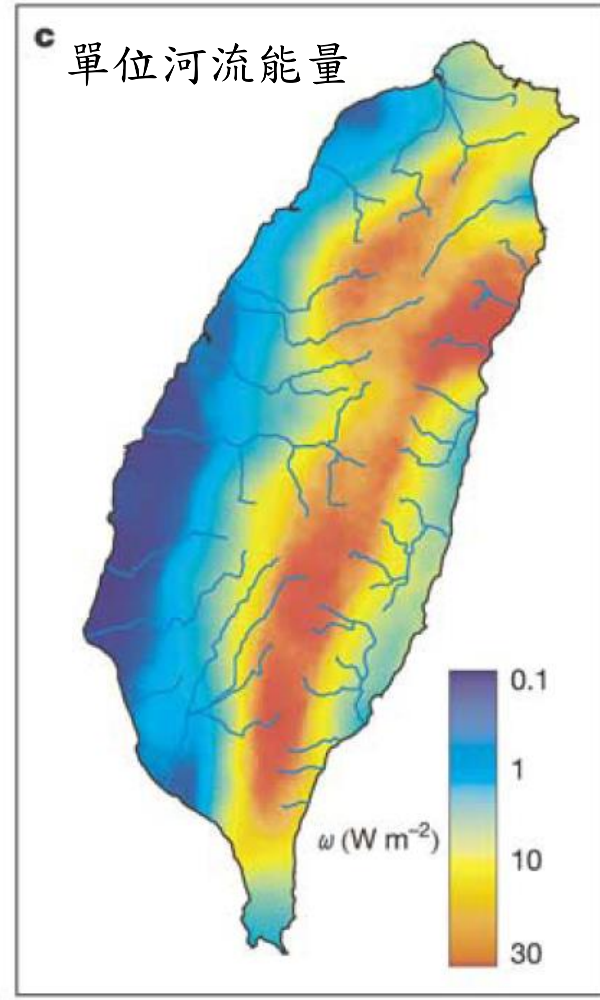


Cumulative seismic moment from historic earthquakes Mw> 5.0, 1900-1998



Average annual river discharge /drainage area

- storm-triggered landslide



Unit stream-power

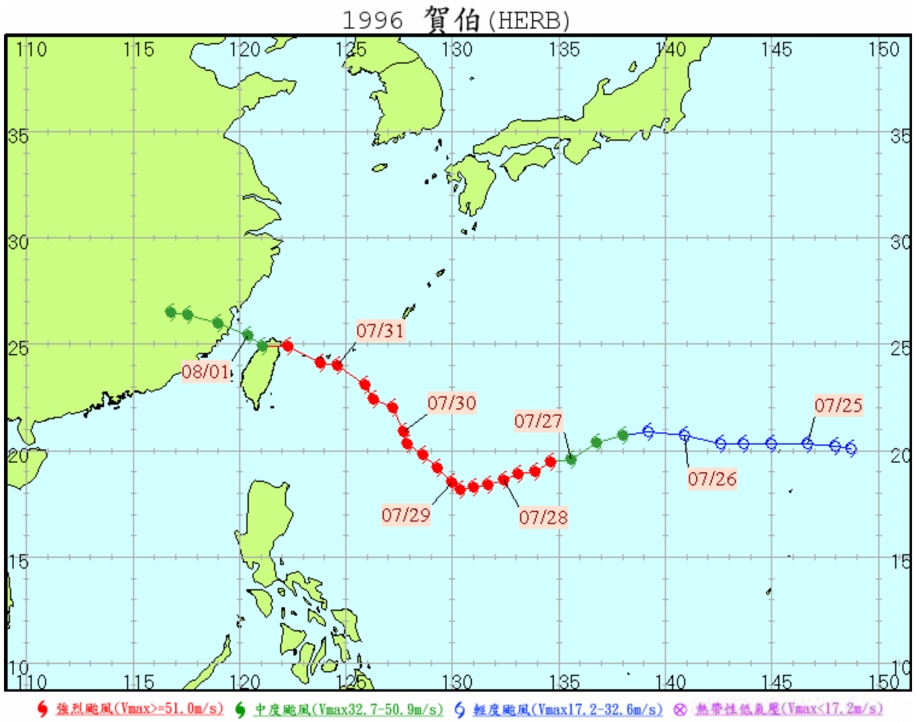
-Topography

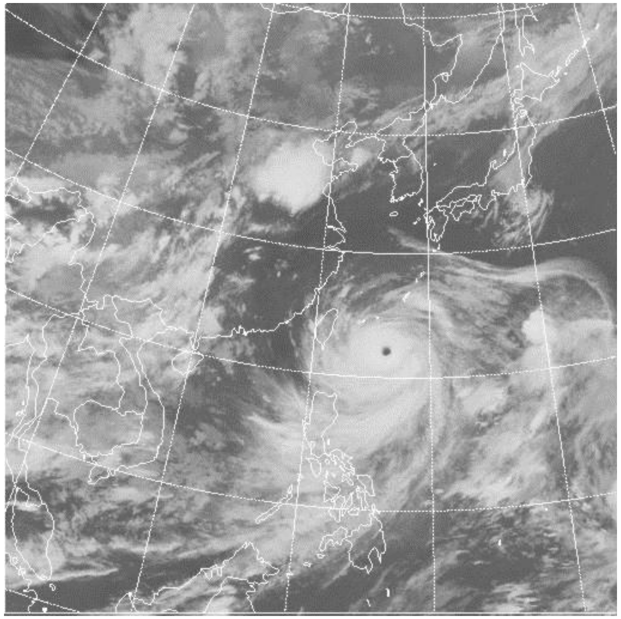
-Substrate strength

Example：Earthquake- and Storm-triggered landslides

1996/7/31~1996/8/2 Typhoon Herb

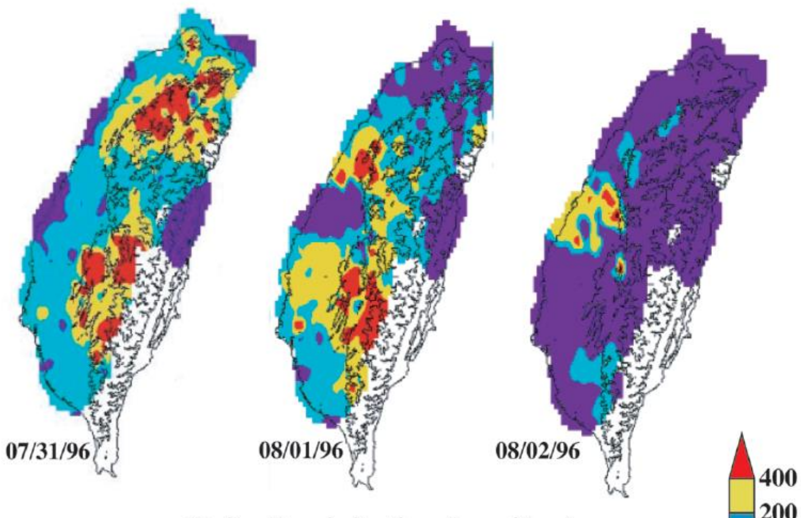
Typhoon Herb





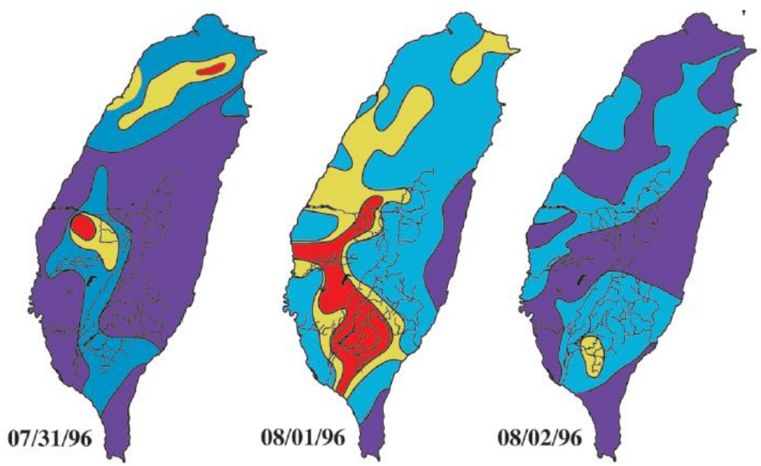
Typhoon Herb swept across Taiwan on July 31–August 2, 1996, it brought strong wind and heavy rain, triggered floods and landslides throughout the southern part of the island.

Example：Earthquake- and Storm-triggered landslides



Daily Precipitation (mm/day)

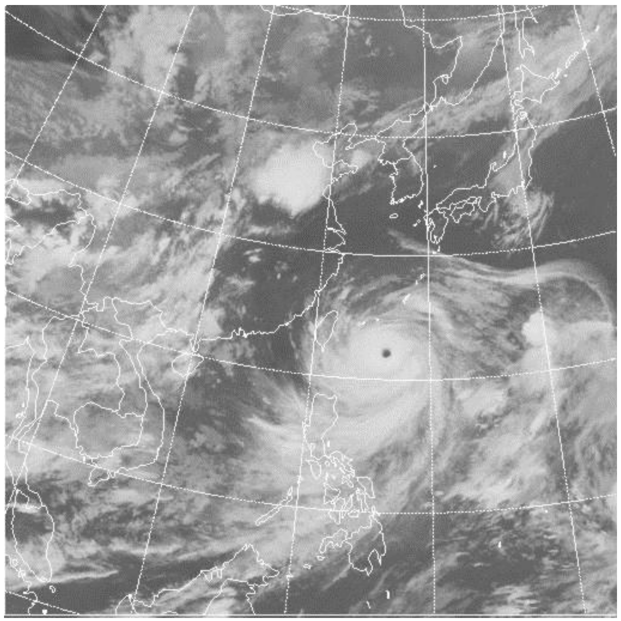
(based on rain gauge measurements made at 226 meteorological stations , data from CWB)



Daily Runoff (mm/day)

(based on data from 133 hydrologic stations , data from WRA 1997)

Typhoon Herb



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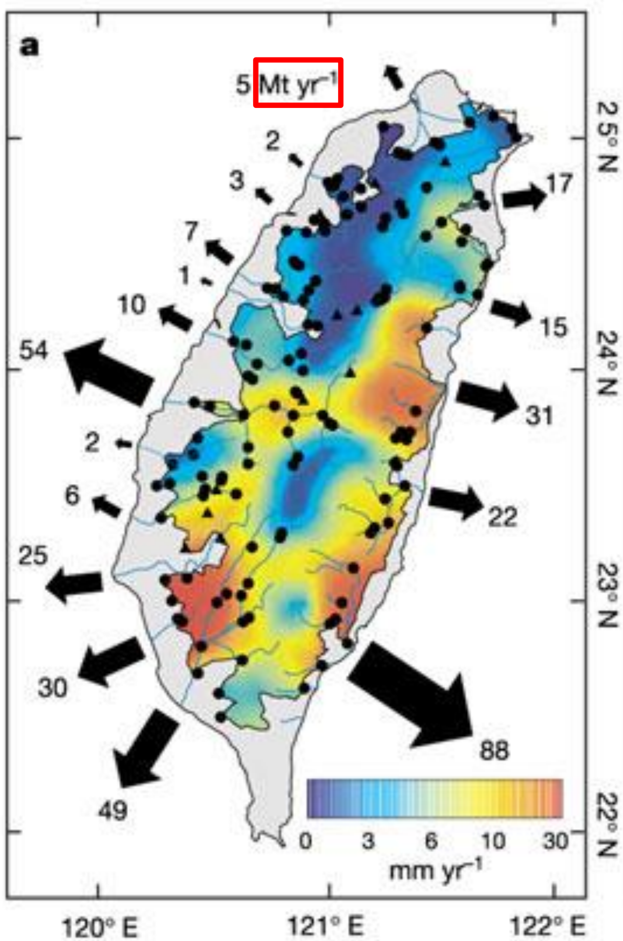
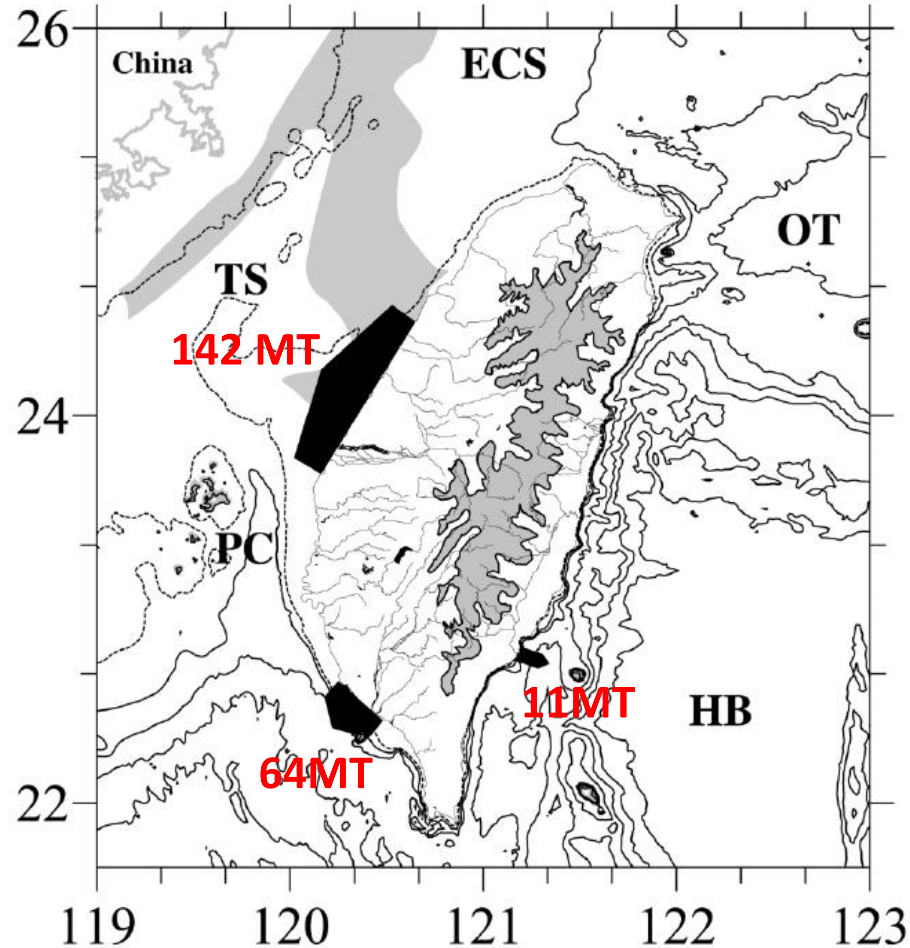
Example：Earthquake- and Storm-triggered landslides

Typhoon Herb



1970–1999,
average annual sediment.



Sediment discharge to the coastal ocean from nine Taiwan rivers following Typhoon Herb, during July 31–August 1, 1996.

Conclusions

- Oblique collision in Taiwan provides opportunity to measure rates of uplift and erosion.
- Exhumational SS reached for Apatite, but not Zircon.
- Fission track studies indicate erosion rates of 4 to 6 mm/yr.
- Onset of collision (mountain building) is ~5 Ma.
- Modern erosion rates are strongly influenced by large earthquakes and typhoons.