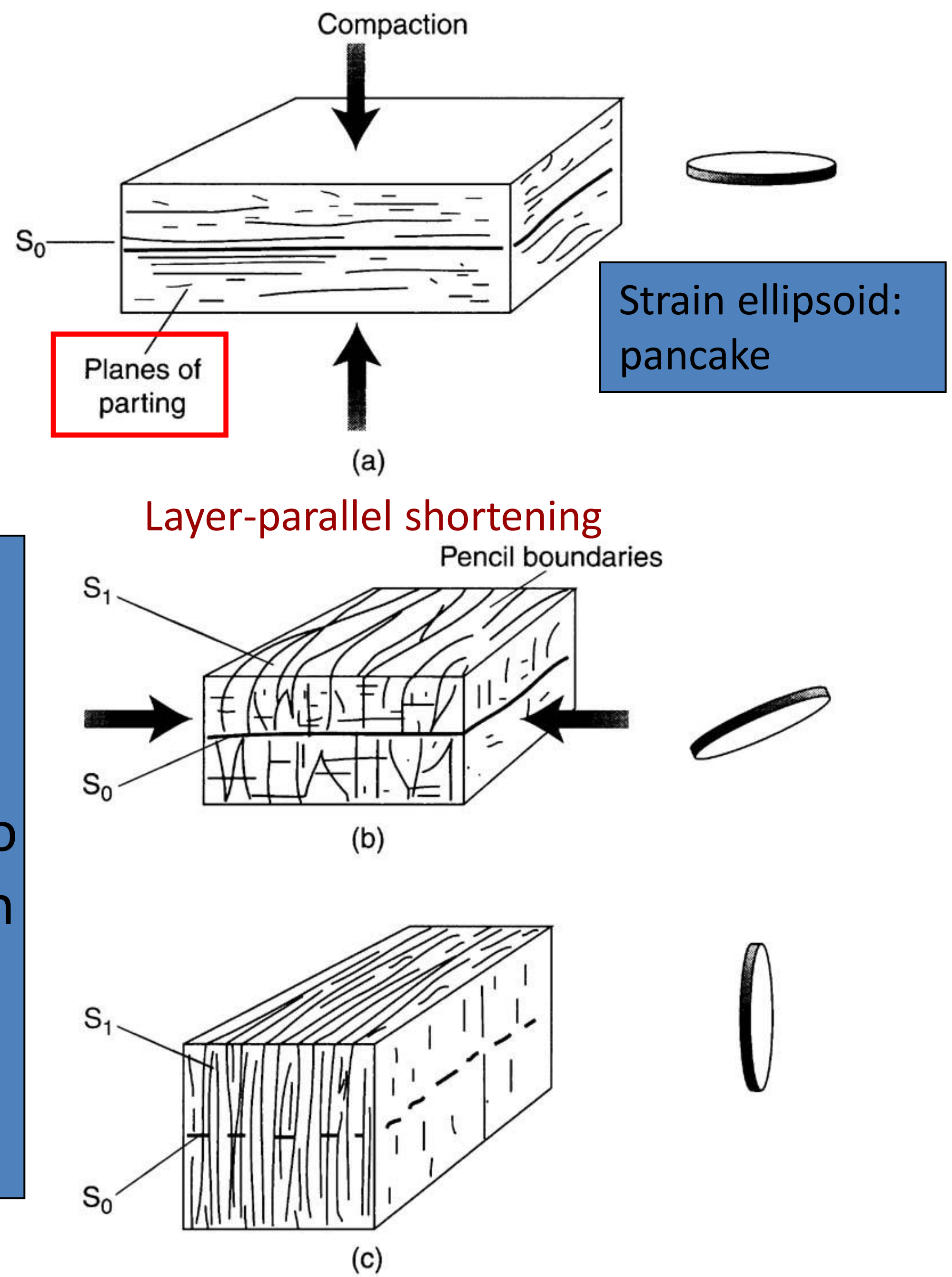
Metamorphic texture

- Prograde metamorphism: P-T increase
- Retrograde: P-T decrease
- Metamorphic (or P-T) paths can be found by analyzing metamorphic texture and mineral assemblages.
- Prograde metamorphic mineral parageneses are commonly overprinted by retrograde deformation structures and assemblages formed during exhumation

Progressive development of slaty cleavage via the formation of pencil structure

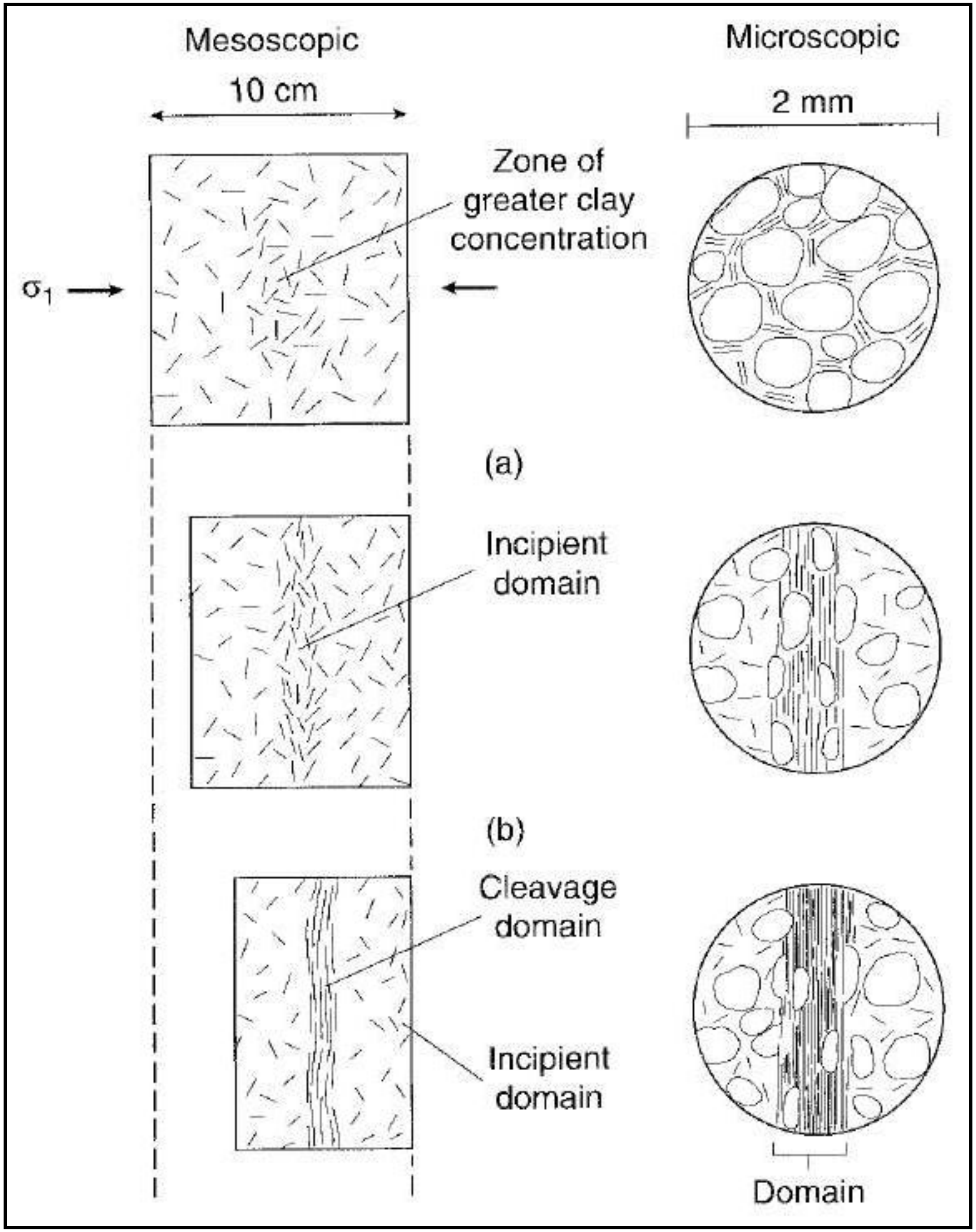


Cleavage formation process begin to take place: Large detrital phyllosilicates fold and rotate, while fine grain undergo pressure solution along domain perpendicular to the shortening direction, and new clay crystallizes.

Slaty cleavage（板劈理）

- Slaty cleavage is defined by strong dimensionally preferred orientation of phyllosilicates（頁矽酸鹽礦物）in a very clay-rich rock.

- Slaty cleavage forms under temperature condition that mark the onset of metamorphism (250ºC-350ºC), there is a notable decreasing in the amount of interlayered water in clays; that is, smectite (膨潤石 ,water-bearing clay) transforms to illite (伊利石).



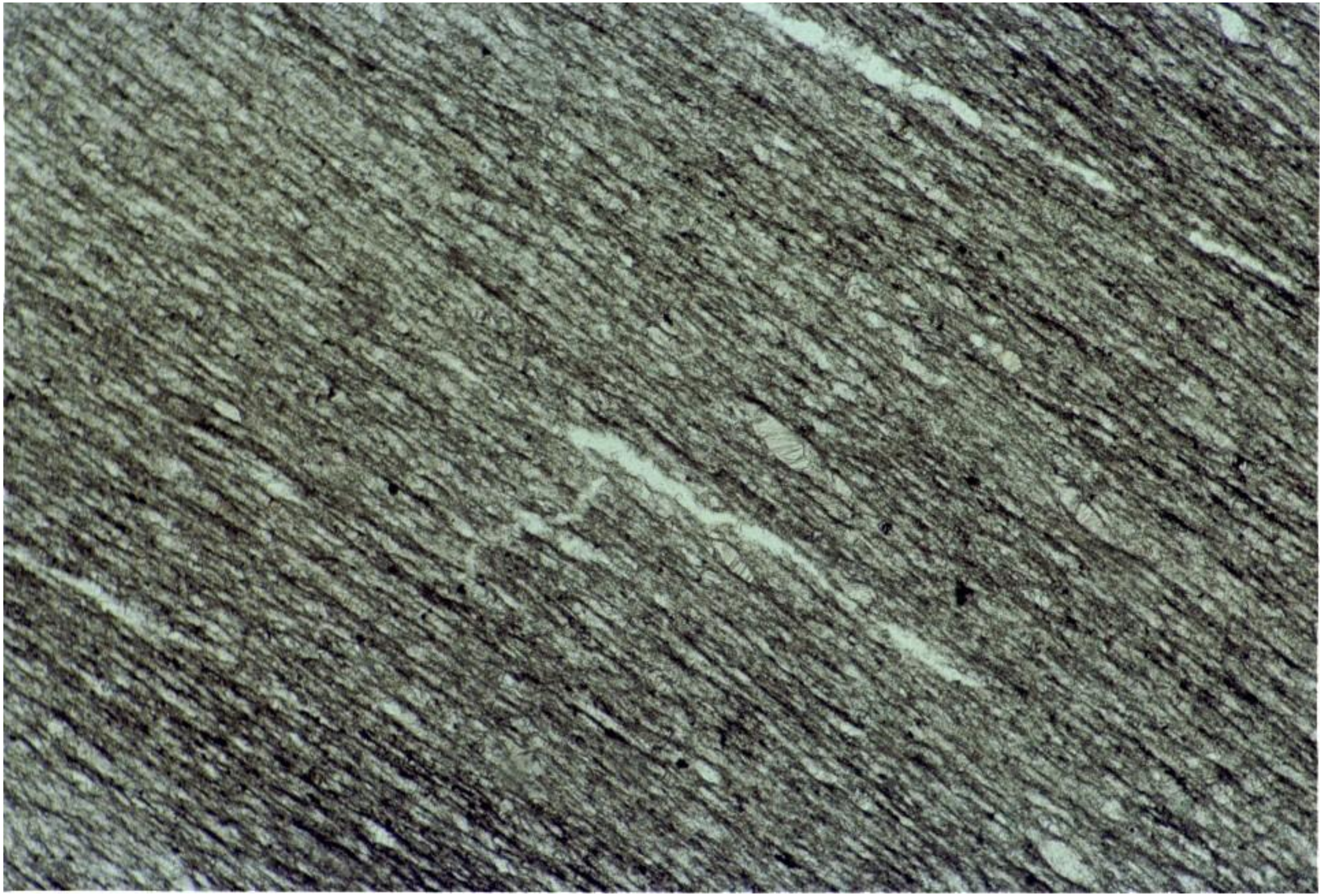
Pressure solution vs. rotation

- M-domains
- Q-F-domains

Can have volume loss > 50%

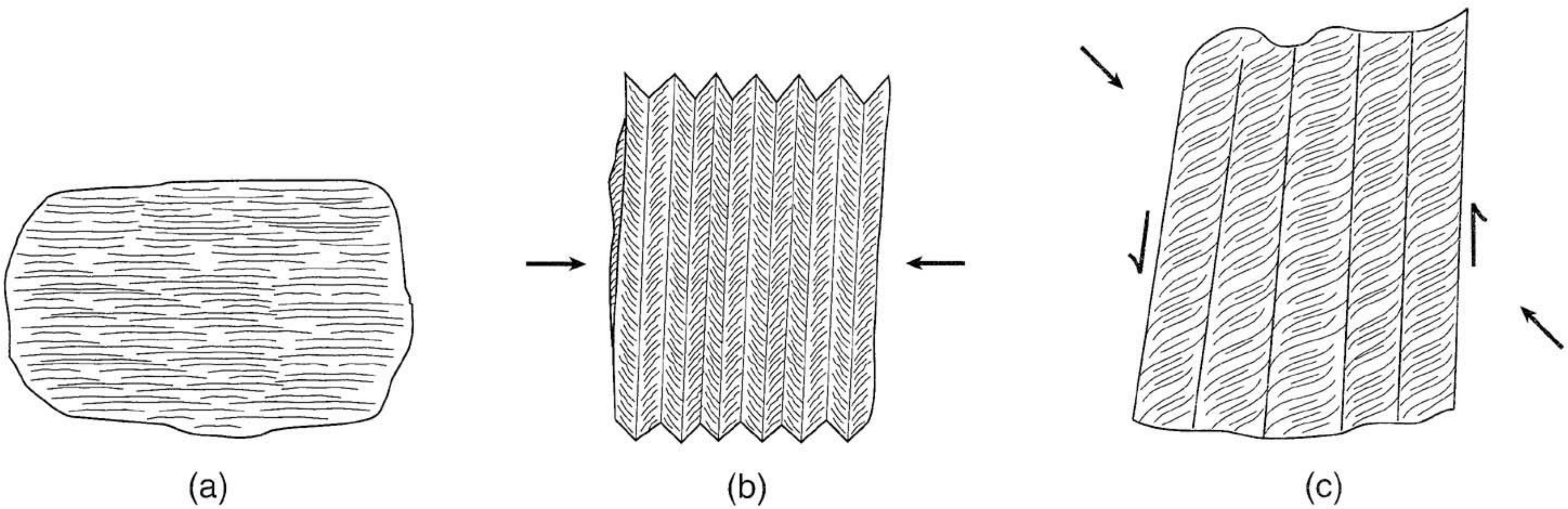
Slaty cleavage

台灣板岩地質區的板劈理



Crenulation Cleavage (夾皺劈理)

A lithology containing a closely and evenly spaced foliation that is shortened in a direction at a low angle of this foliation.



Symmetric crenulation cleavage

asymmetric (sigmoidal) crenulation cleavage

Crenulation cleavage (夾皺劈理)-secondary tectonic cleavage

- mm- to cm-scale folding of a pre-existing foliation
- Marks a second phase of deformation（褶皺夾質域）

Discrete crenulation cleavage – Distincet QF- and M-domains

Crenulation cleavage

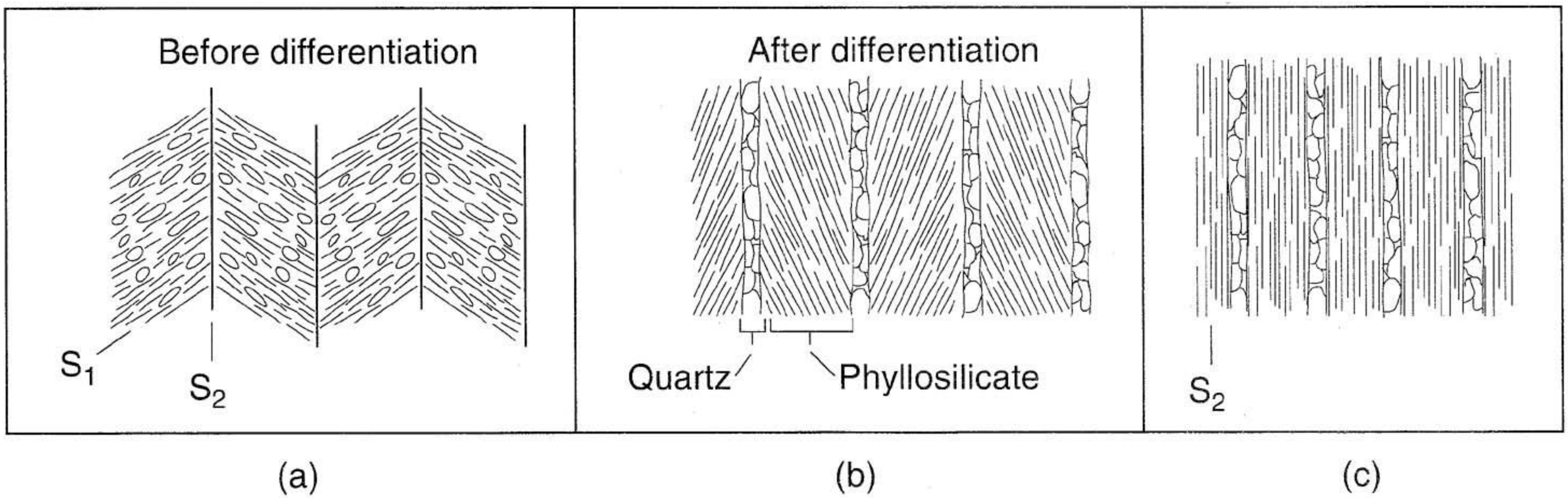
Crenulation cleavage in Gneiss
中橫白沙橋：溪畔片麻岩

zonal crenulation cleavage

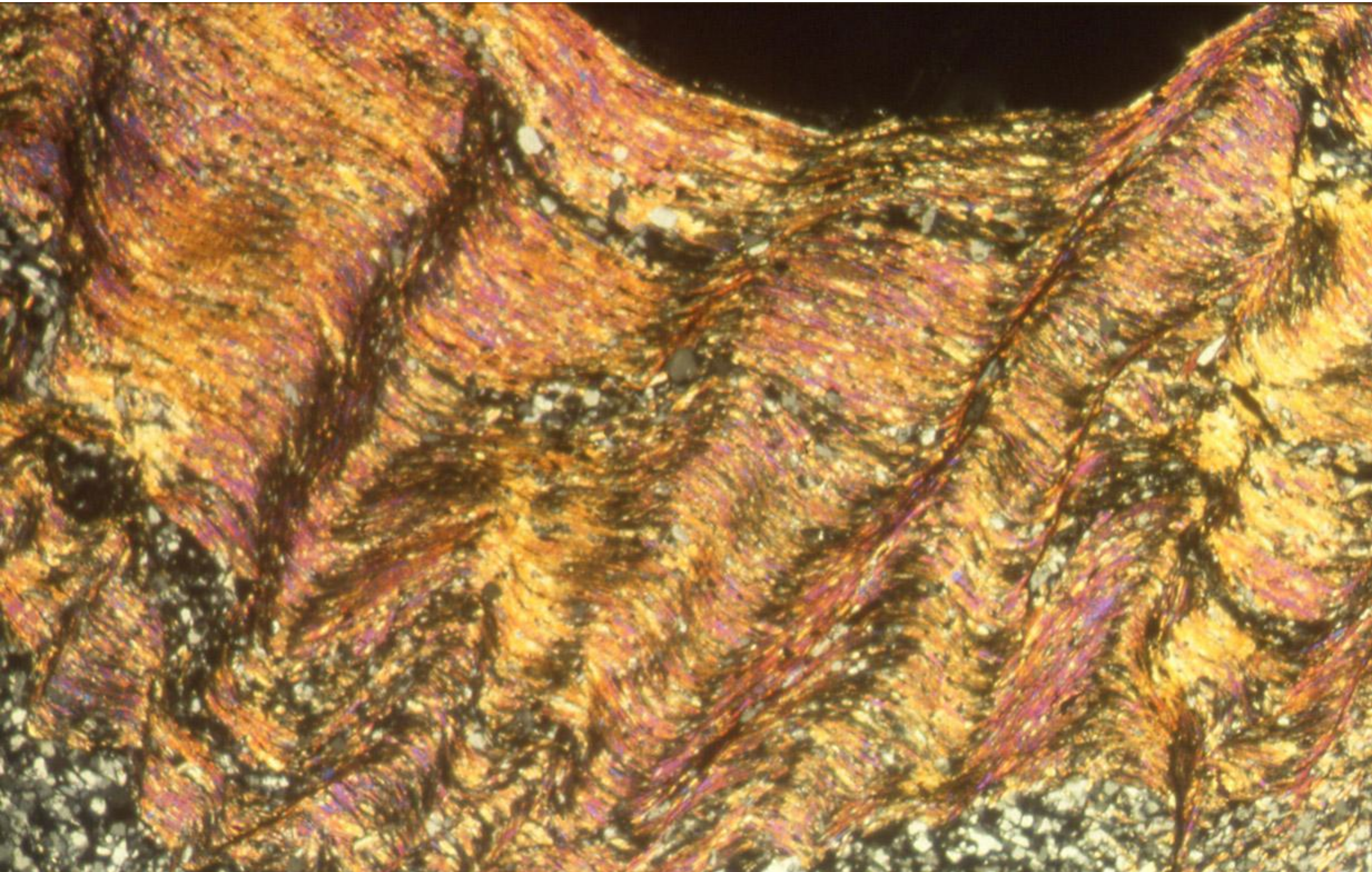
Crenulation cleavage of Mica schist（太魯閣天祥）

Mineral differentiation (礦物分異作用)during the formation of crenulation cleavage (夾皺劈理)

Crenulation cleavage forms under conditions that are also amenable to the occurrence of pressure solution (壓溶作用).



Qtz: Removed from limbs of the microfold and precipitates in the hinges as the crenulation cleavage forms.



Porphyroblasts (metamorphic crystals) – an indicator of earlier foliation

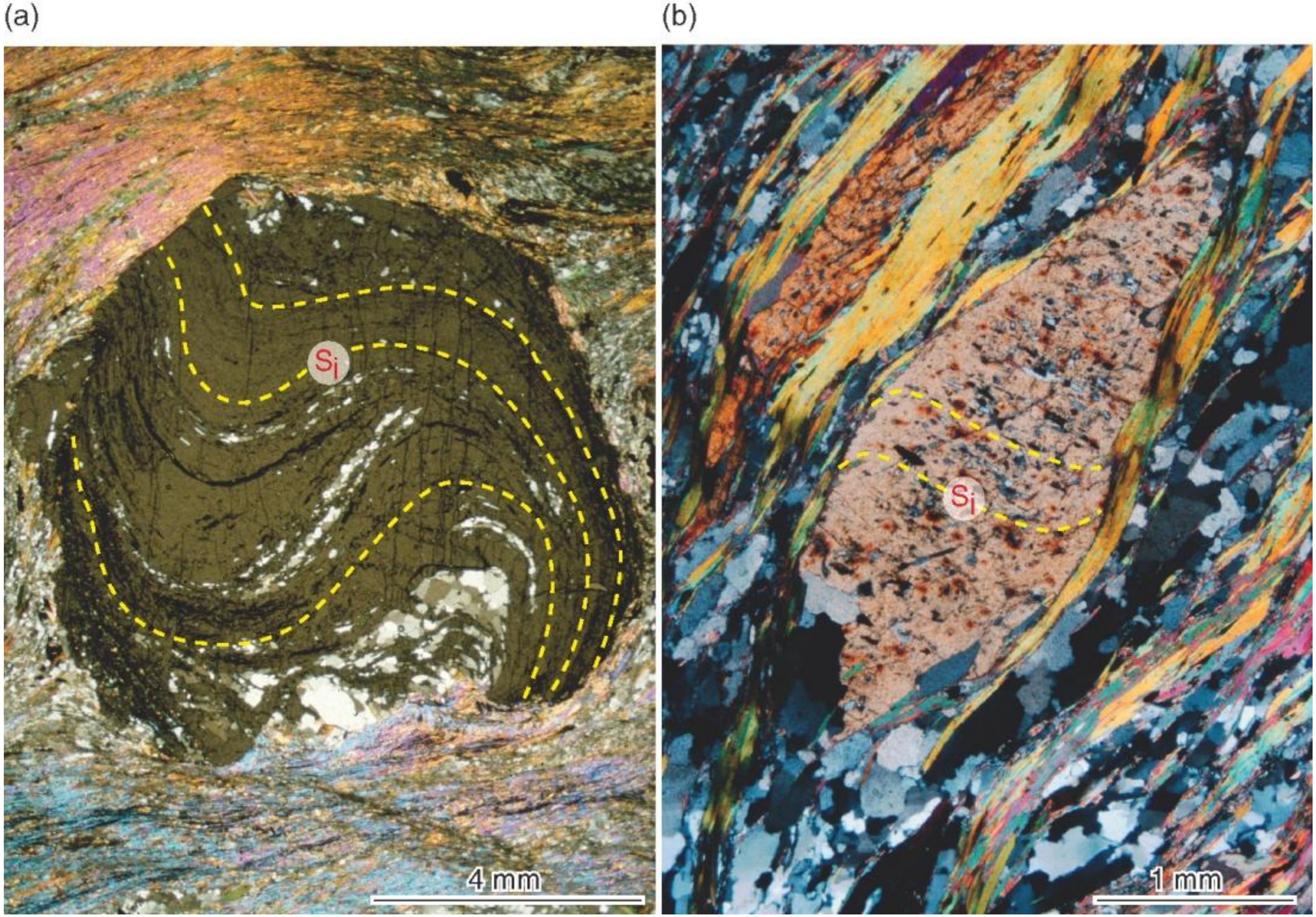


Figure 21.2 (a) Garnet porphyroblast in micaschist, showing sigmoidal pattern. The inclusion pattern is an earlier foliation now disconnected and at high angle to the external foliation. (b) Amphibole porphyroclast with (mostly) straight inclusion trails. Straight trails may indicate pre- or intertectonic growth, but the curvature close to the boundary may indicate that deformation initiated during the last part of the growth history.

Development of porphyroblasts

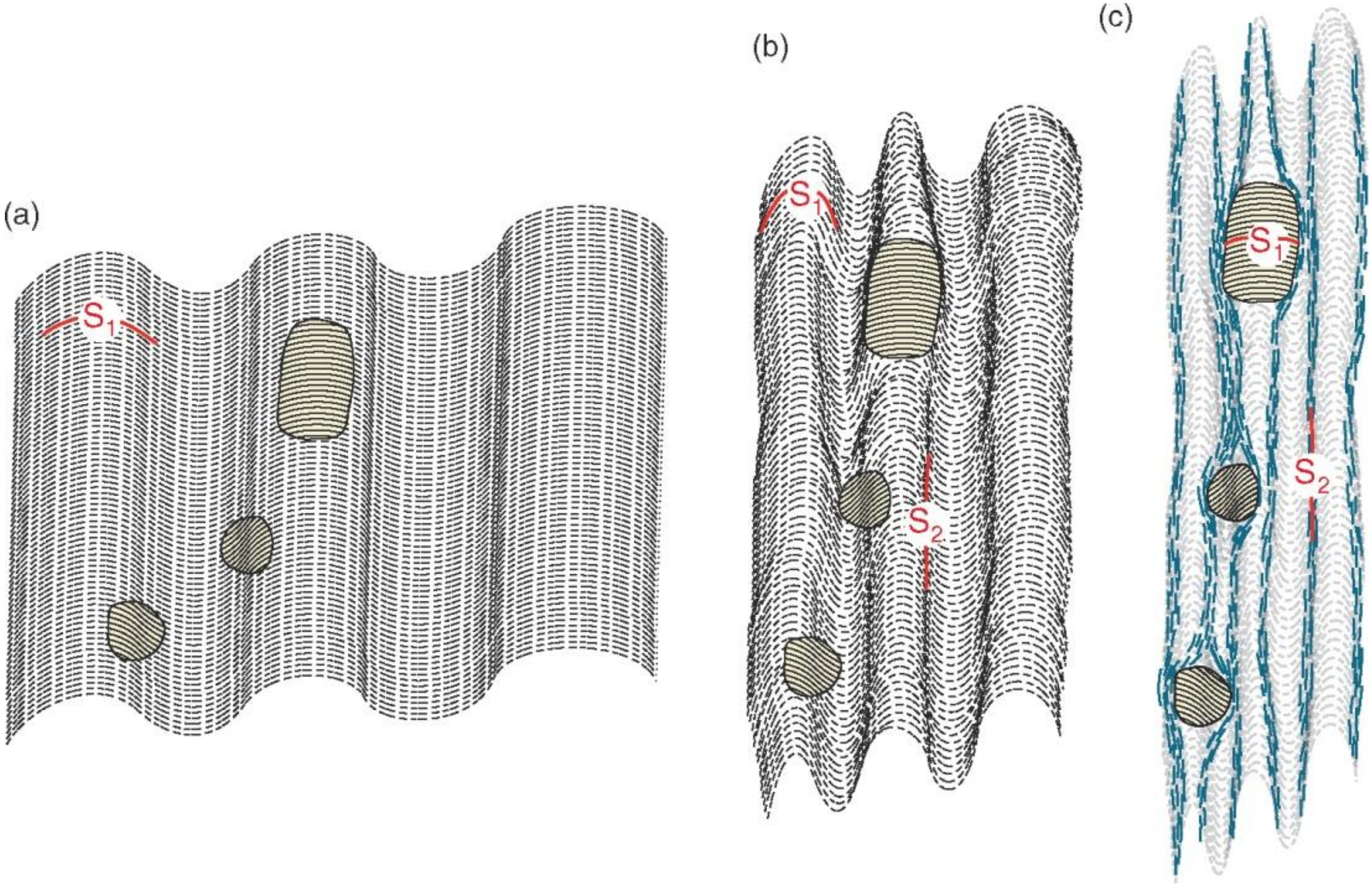


Figure 21.3 Development of prophyroblasts with an oblique internal foliation (S1) that was inherited from the rock fabric at the time of growth (a).

Deformation phase and Porphyroblasts

- Porphyroblasts can grow
  prior to
  during a given deformation phase
  after

  Pre- (inter)
  Syn- Tectonic
  Post-(inter)

- Syn-tectonic inclusion trails tend to be curved – rotated during further growth

- Pre-tectonic inclusion patterns tend to be straight – unless crenulated in the earlier deformation phase

- Post-tectonic porphyroblasts – the fabrics can be traced continuously through the porphyroblasts.

Gneissic layering and Migmatization (片麻岩層理與混合作用)

- Foliated gneiss (gneissosity): metamorphic rock in which the foliation is defined by compositional banding(成分條帶).
- Light-colored layers: feldspar and Qtz
- Dark-colored layers: amphibole (角閃石) / pyroxene (輝石) and/or biotite
- Gneiss formation (amphibolite to granulite facies, 角閃岩相到粒變岩相): muscovite reacts to form feldspar, so the rocks contains no schistosity.

片麻岩構造(gneissic structure)

沈積岩或火成岩在中、高度變質作用時，經過再結晶作用所發展出來的一種條帶形葉理。這種變質岩主要是由中粒到粗粒的礦物所組成。成份或顆粒大小不同的礦物常常分別聚集在一起而呈現成分不同的條帶構造(compositional banding)，而片狀的、板狀的或長條狀的礦物則排成平面構造且呈現方向性的排列，透鏡形與顆粒形的礦物則大致呈平行的排列。

Gneissic foliation (片麻岩片理)–變質分異礦物呈帶狀分佈

Figure 12.21 Gneissic banding, formed during shearing of a heterogeneous intrusive complex. High strains are required to reach this stage of transposition.

Gneissic layering and Migmatization (片麻岩層理與混合作用)

- Paragneiss (副片麻岩): Sedimentary protolith (由沈積岩變質而成的片麻岩).
- Orthogneiss (正片麻岩): Igneous protolith (由火成岩變質而成的片麻岩).
- Augen gneiss (魚眼狀片麻岩): Contains relatively large feldspar clasts floating in a fine-grained matrix.

Augen Gneiss (魚眼狀片麻岩)

http://www.psibertrip.com/geology/metamorphic.asp

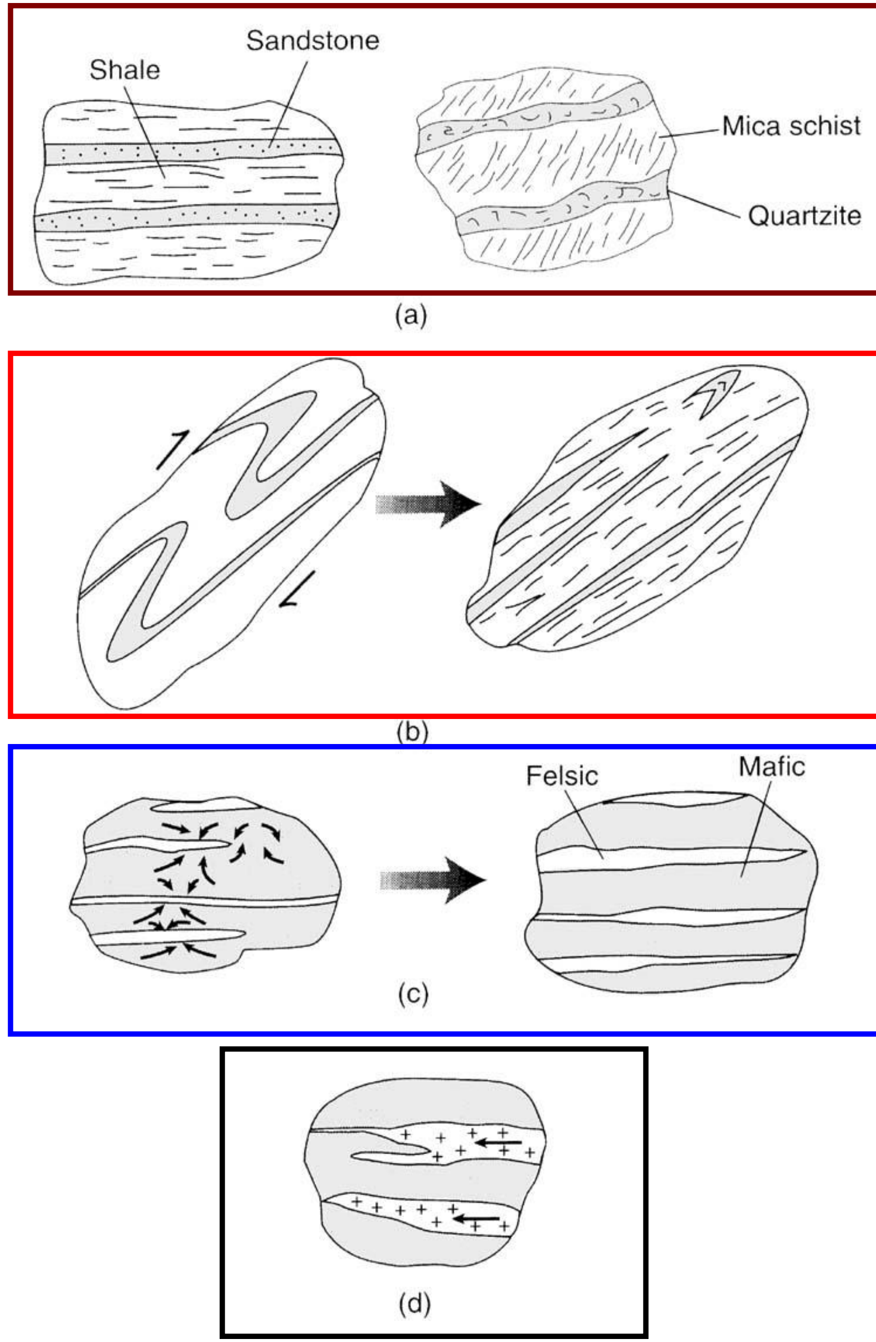
Mechanism of gneiss formation - requires compositional segregation

(a) Inheritance from an original lithology

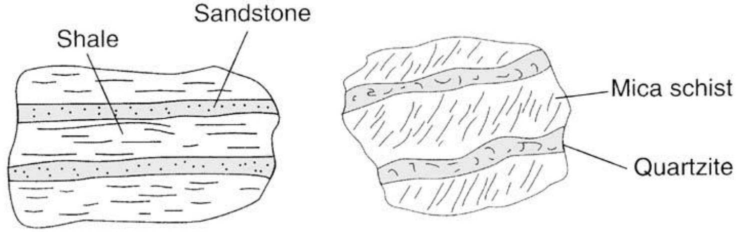
(b) Creation of new composition banding via transposition: Hinge of fold detached

(c) Metamorphic differentiation: Diffusion, ions to be excluded

(d) Igneous segregation: *Lit-par-lit* intrusion

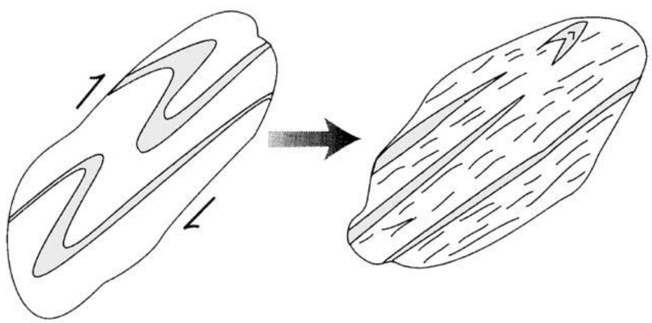


片麻岩成分條帶(compositional layering)的形成機制

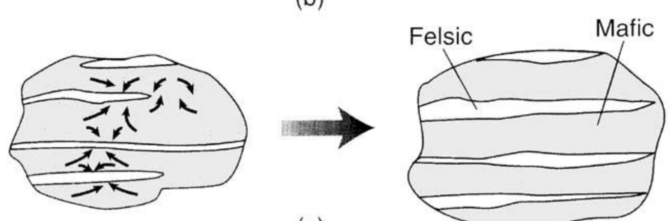


(a)

(a) 原岩為砂岩與泥岩，砂岩變質成為石英岩，泥岩變質為雲母片岩。

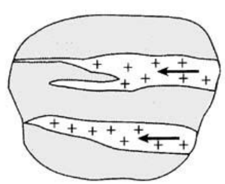

(b)

(b) 原岩的層狀構造經由岩層移置作用(transposition)形成成分不同的條帶構造。



(c)

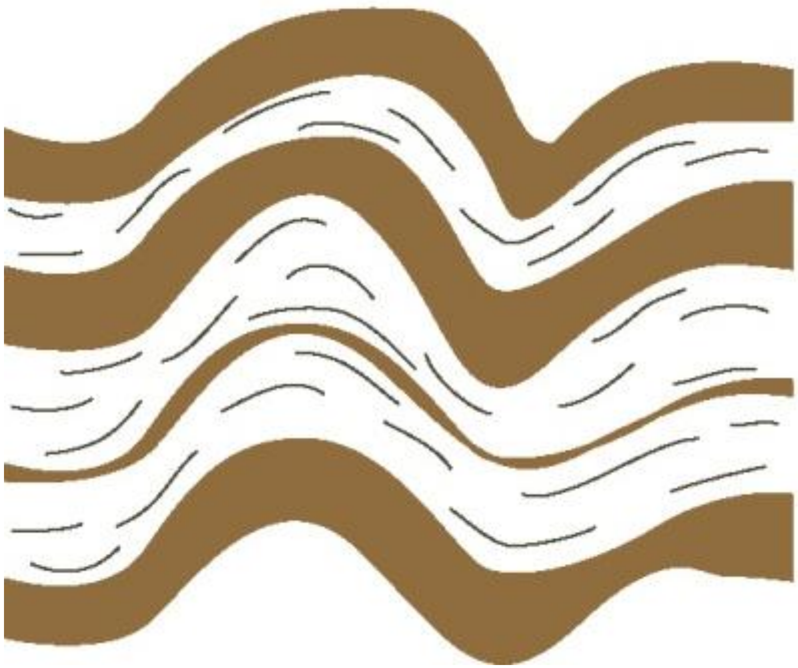
(c) 變質分異作用(metamorphic differentiation)造成白色的長石石英富集帶與黑色的鐵鎂礦物富集帶。


(d)

(d) 部分熔化作用產生的岩漿沿著弱面侵入變質岩，形成一層層的侵入岩構造(lit-par-lit intrusion)。

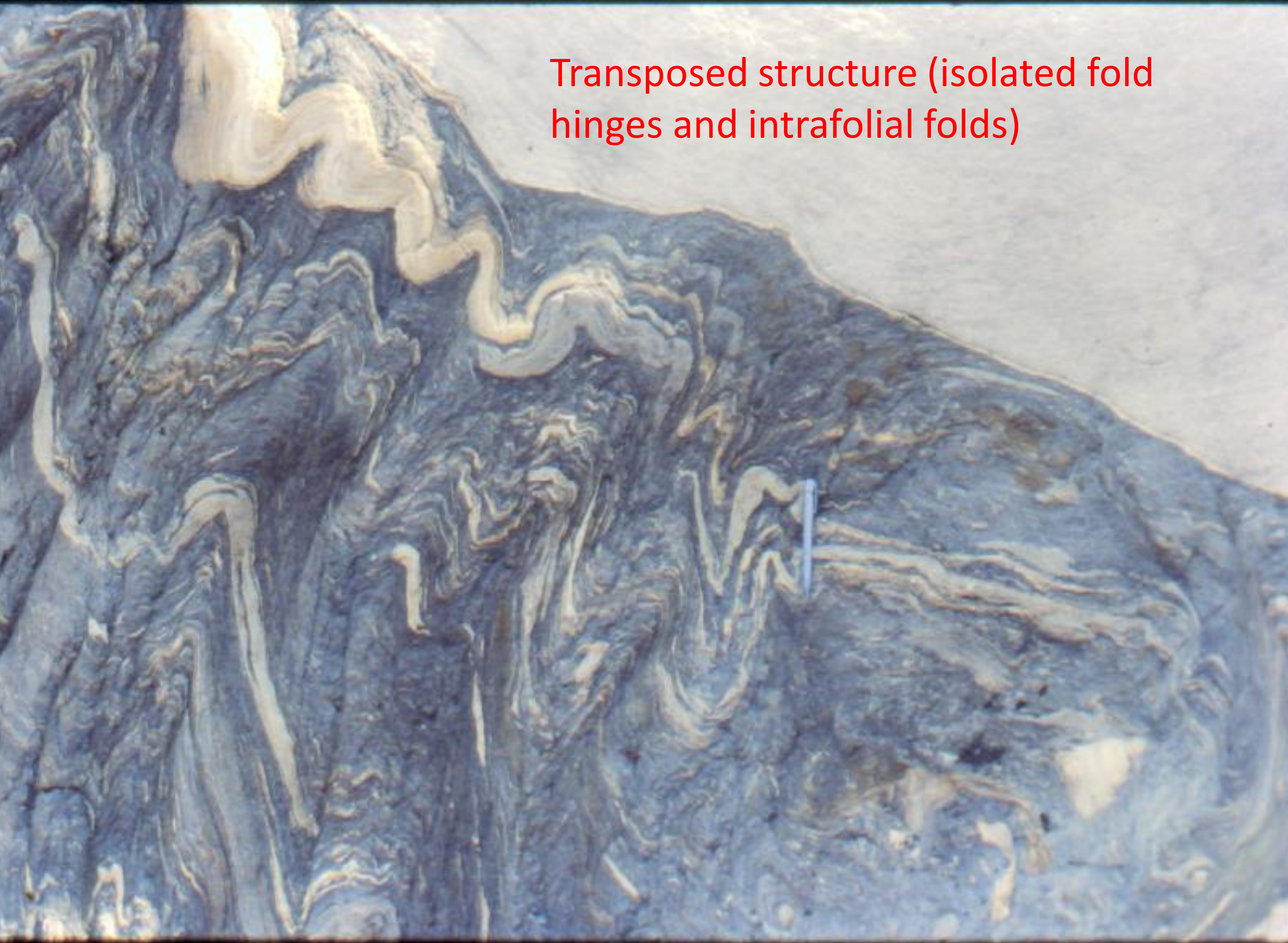
Both strain (co-axial and non-coaxial) and slip

(a)

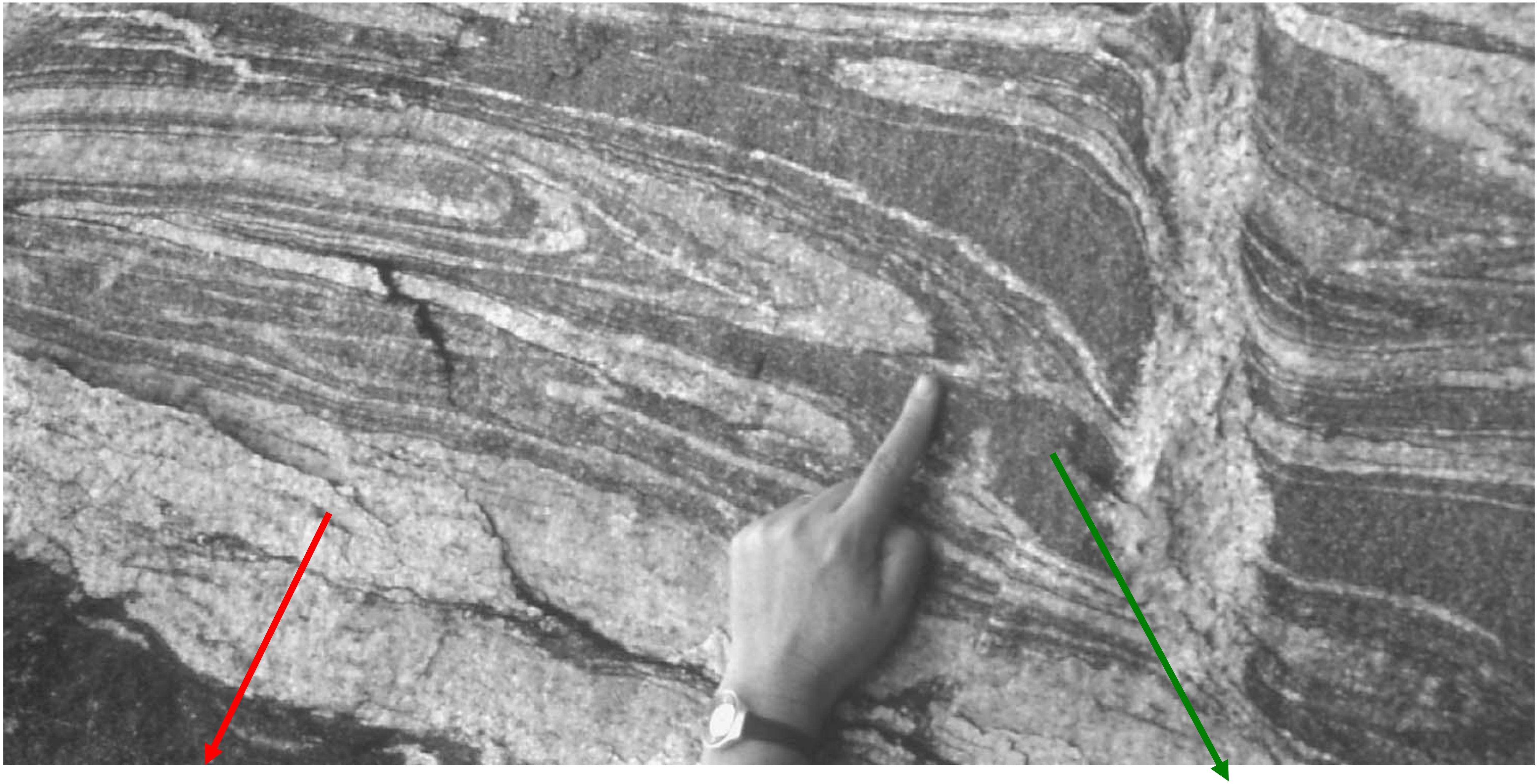


(b)

Figure 12.22 Schematic illustration of transposition by horizontal shortening and vertical extension. Both coaxial and non-coaxial strain can produce this result. The result (b) is a banded rock with intrafolial folds and isolated fold hinges. Note how the dominant foliation changes (transposes) from horizontal (a) to vertical (b).


Transposed structure (isolated fold
hinges and intrafolial folds)

Fold hinges in transposed (移置作用) gneiss:層理被葉理所移置的片麻岩中偶可觀察到殘留下來的褶皺軸部。



Felsic mineral (石英質): feldspar, Qtz

Mafic mineral (基質, 含鐵鎂的）: amphibole/pyroxene, biotite

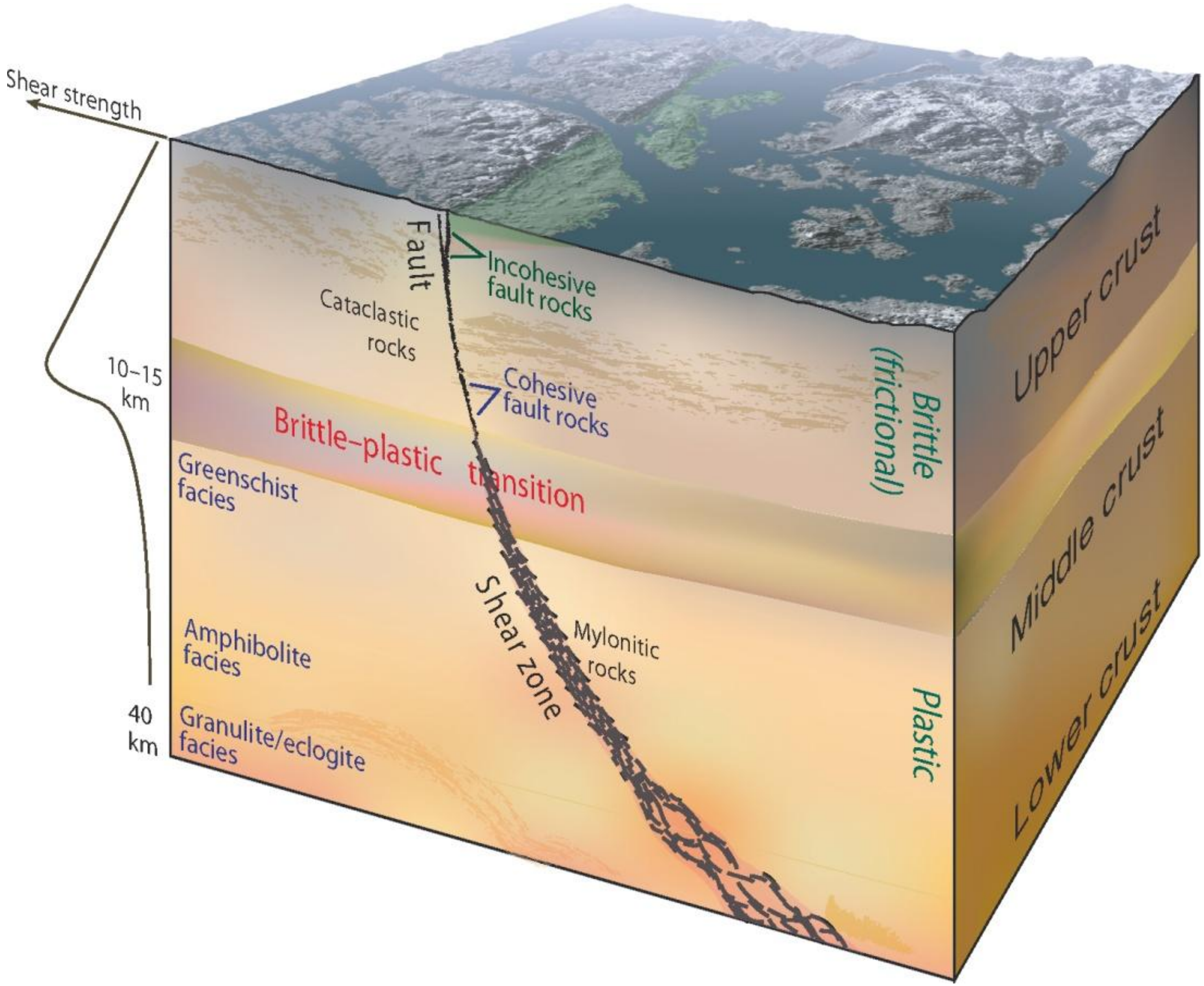
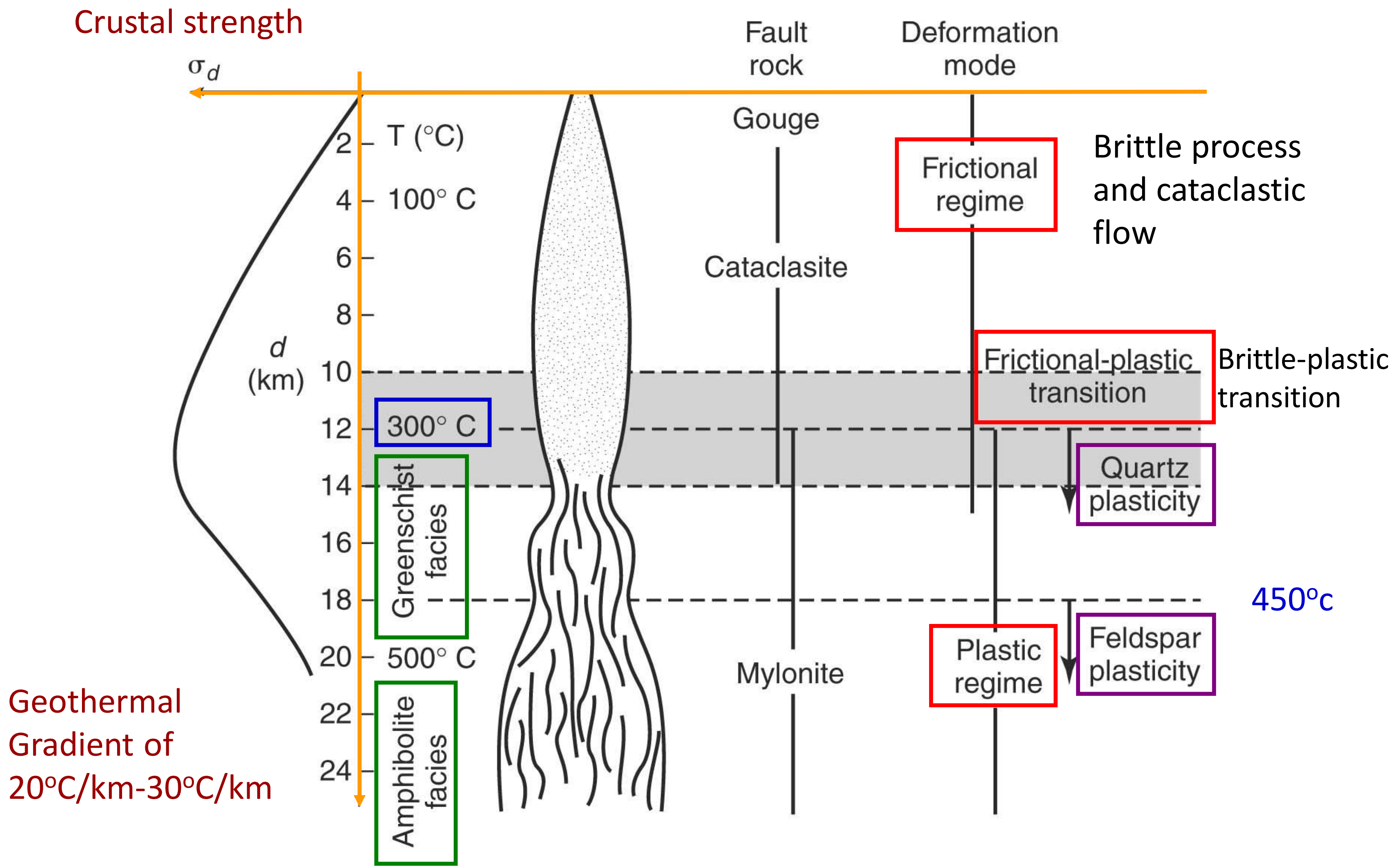
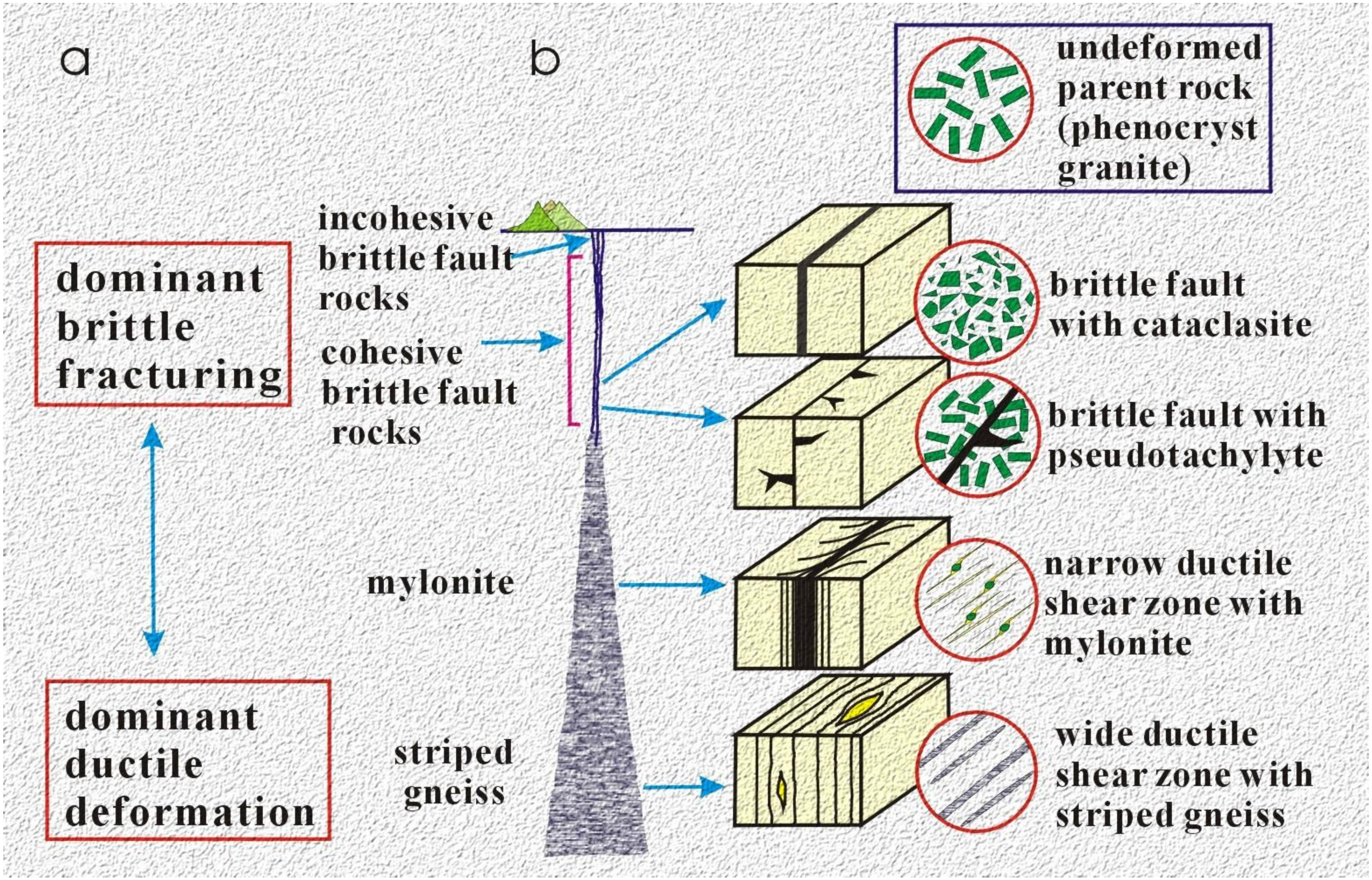


Figure 15.1 Simplified model of the connection between faults, which normally form in the upper crust, and classic ductile shear zones. The transition is gradual and known as the brittle-plastic transition. The depth depends on the temperature gradient and the mineralogy of the crust. For granitic rocks it normally occurs in the range of 10-15 km.

Sibson-Scholz fault model



Distribution of the main types of fault rocks with the depth in the crust



Mylonites (糜稜岩)

- A fault rock type with a relatively fine grain size as compared to the host rock and resulting from crystal-plastic processes.
- Dynamic recrystallization occurs at different temperatures

  Calcite ≥ 250°C

  Quartz ≥ 300°C

  Feldspar ≥ 450°C

動態再結晶作用(dynamic recrystallization)與靜態再結晶作用(static recrystallization)

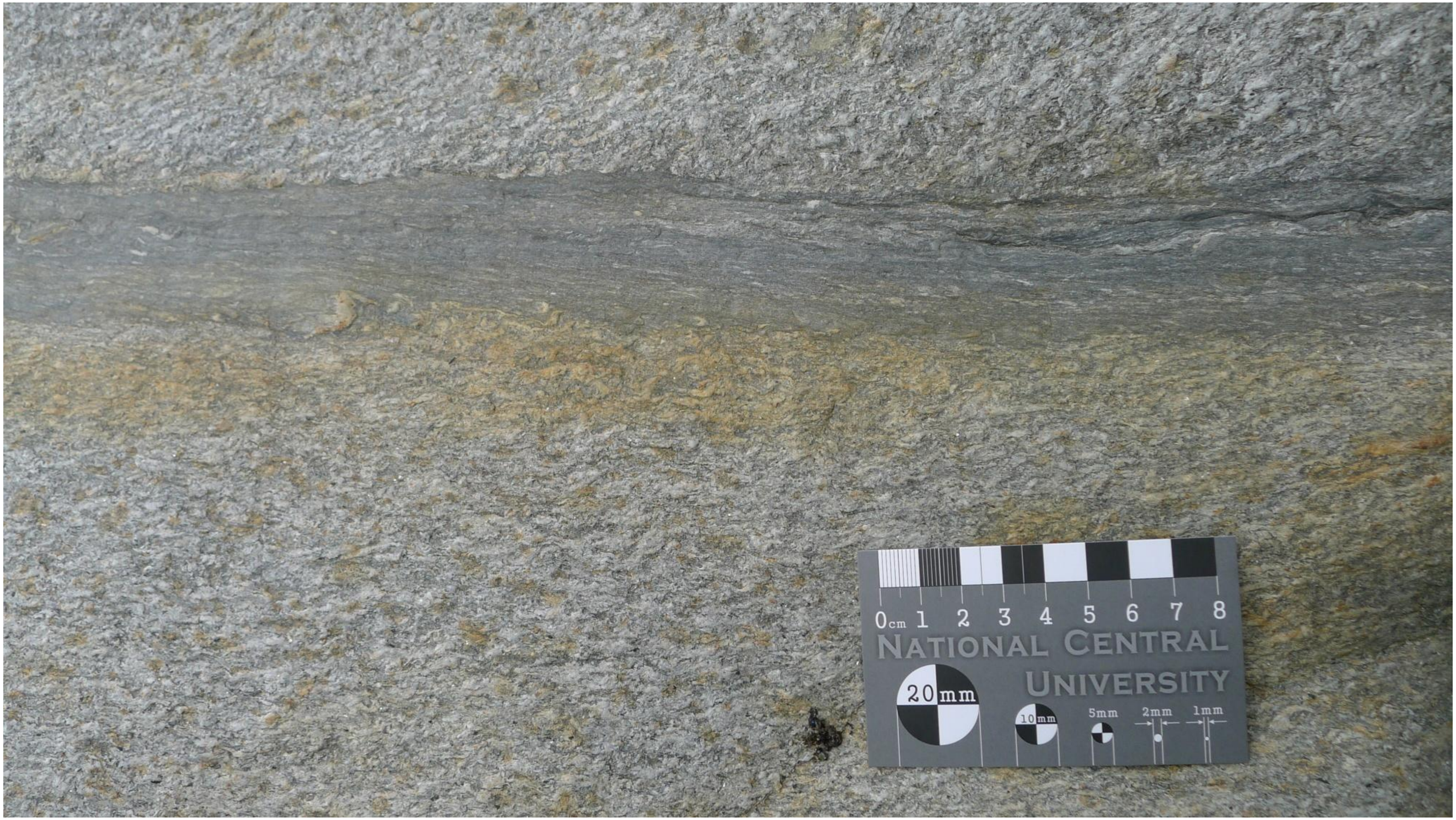
- 在均勻的應力場(isotropic stress)，或者軸差應力去除之後的應力場中的再結晶作用，稱為靜態再結晶作用，或者另稱為退火(Annealing)。

- 靜態再結晶作用與動態再結晶作用的差別在於經過靜態再結晶作用的顆粒會相當地大，而且很少有應變能留存。

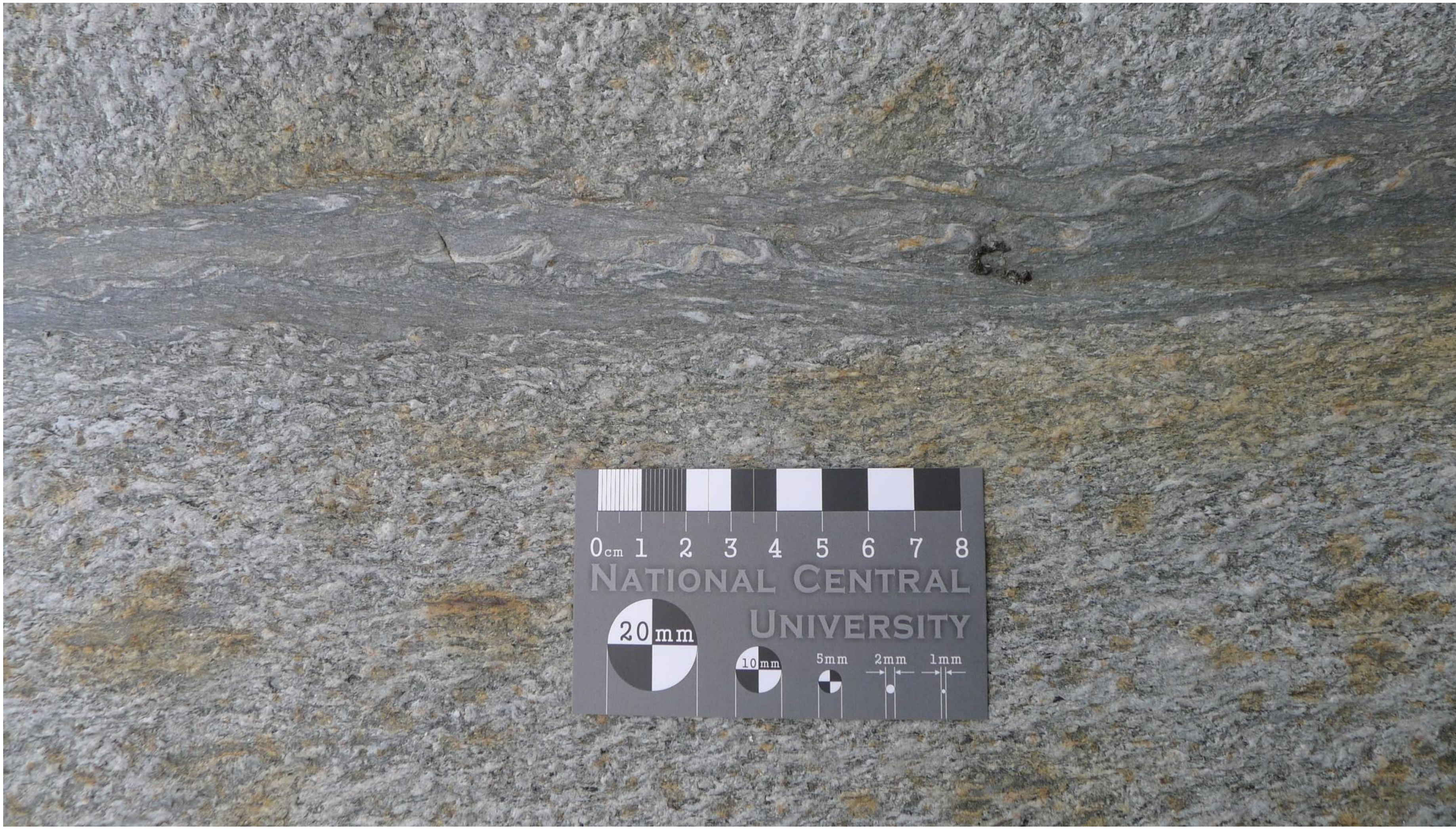
Figure 12.23 Mylonitic foliation formed by shear-related plastic grain size reduction of a coarse-grained granitic rock.

Mylonites in Gneiss-

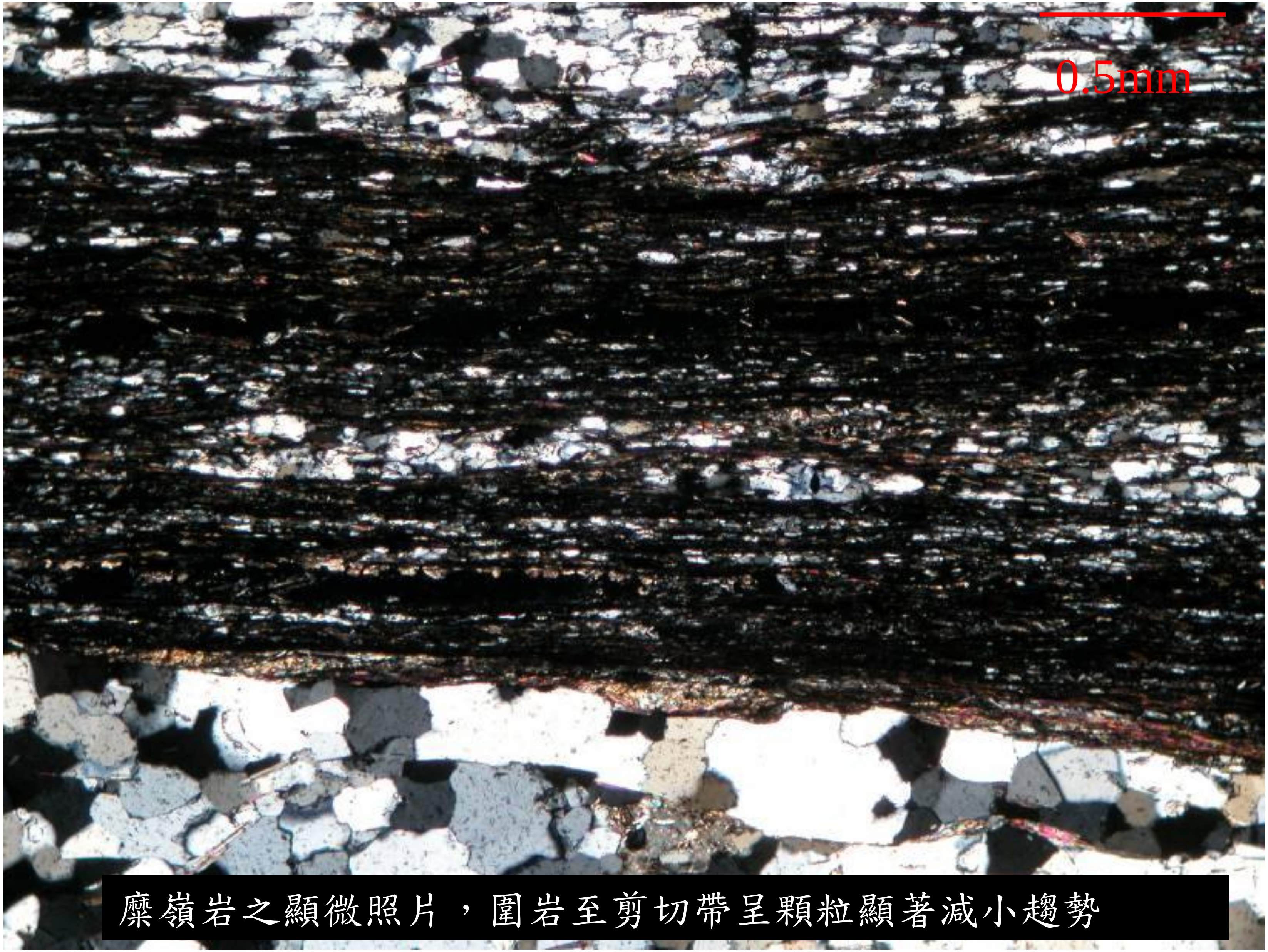
中橫白沙橋溪畔片麻岩與大理岩接觸帶



Mylonite foliation is parallel to the crenulation celavage


0cm 1 2 3 4 5 6 7 8
NATIONAL CENTRAL
UNIVERSITY
20mm
10mm
5mm
2mm
1mm


萬里溪出露之糜嶺岩帶



糜嶺岩之顯微照片，圍岩至剪切帶呈顆粒顯著減小趨勢

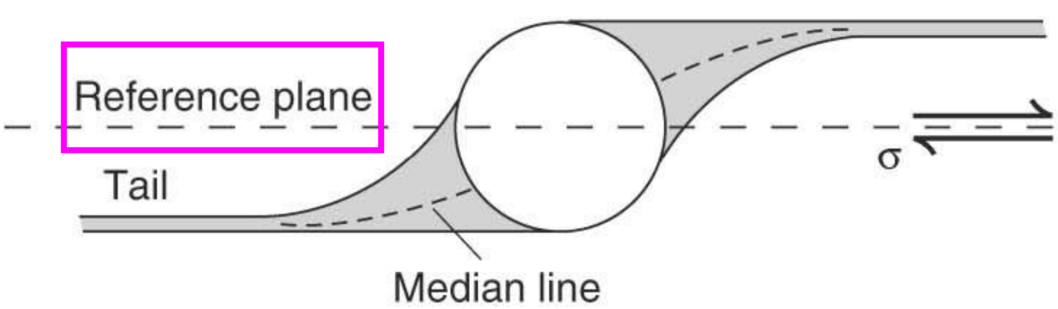
Shear-sense indicators

- Ductile shear zones concentrate displacement at deeper levels in the crust, where recognized markers that determine offset are often absent.
- Sense of displacement: describes the relative motion of opposite sides of the zone (left-lateral or right-lateral).
- Magnitude of displacement: distance over which one side moves relative to the other.

Types of Shear-sense indicators

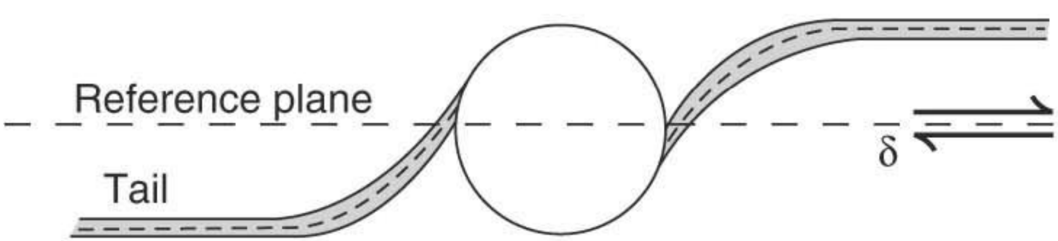
(1) Grain-tail complexes
(2) Disrupted grains
(3) Foliations
(4) Textures (or crystallographic fabrics)
(5) Folds

Grain-Tail Complexes: Rotated porphyroblasts (旋轉斑晶系)



(a)

σ-type: characterized by wedge-shaped tails that do not cross the reference plane when tracing the tail away from the grain



(b)

δ-type: the tail wraps around the grain such that if cross cuts reference plane when tracing the tail away from the grain

Rotate the Greek letter δ over 90°

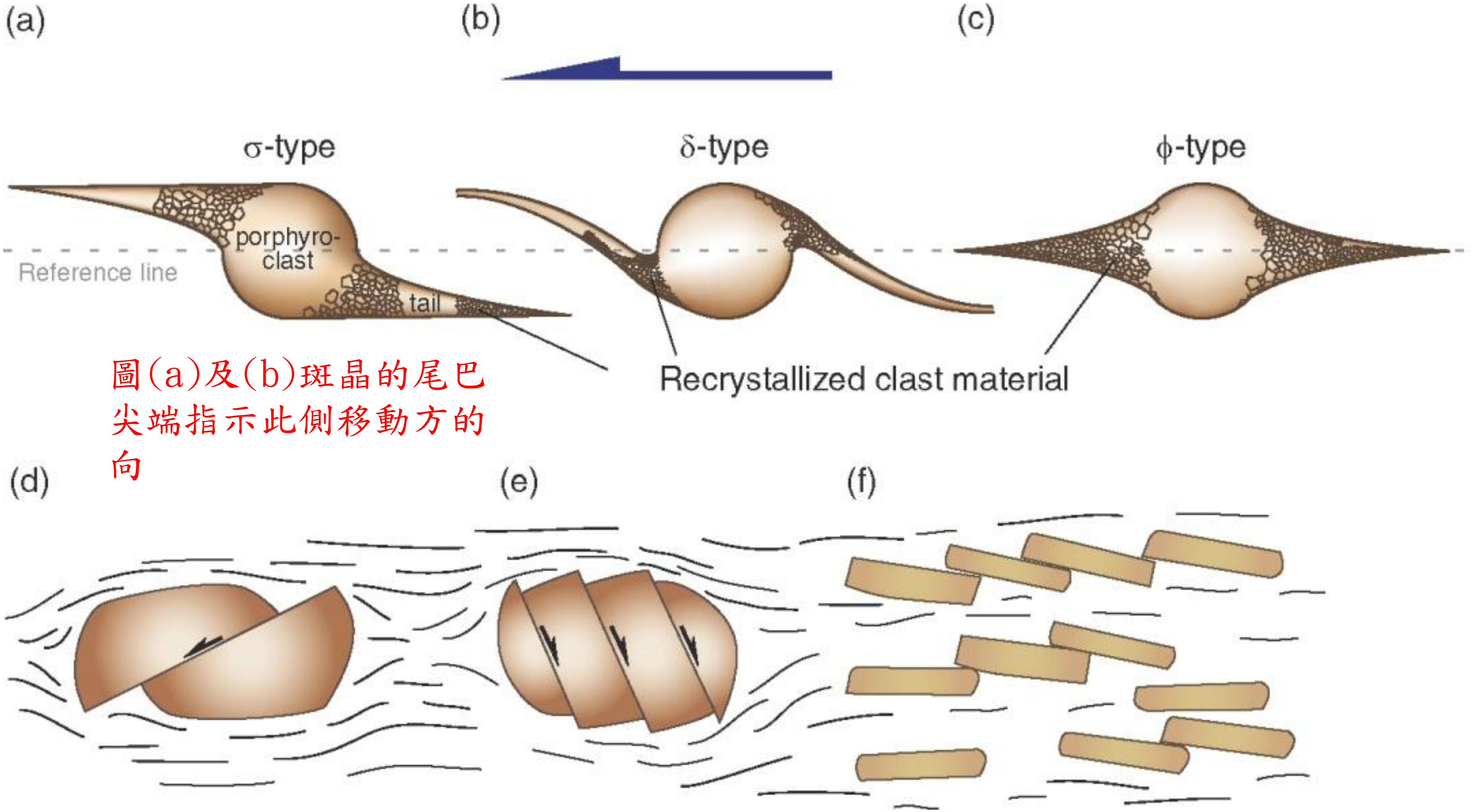
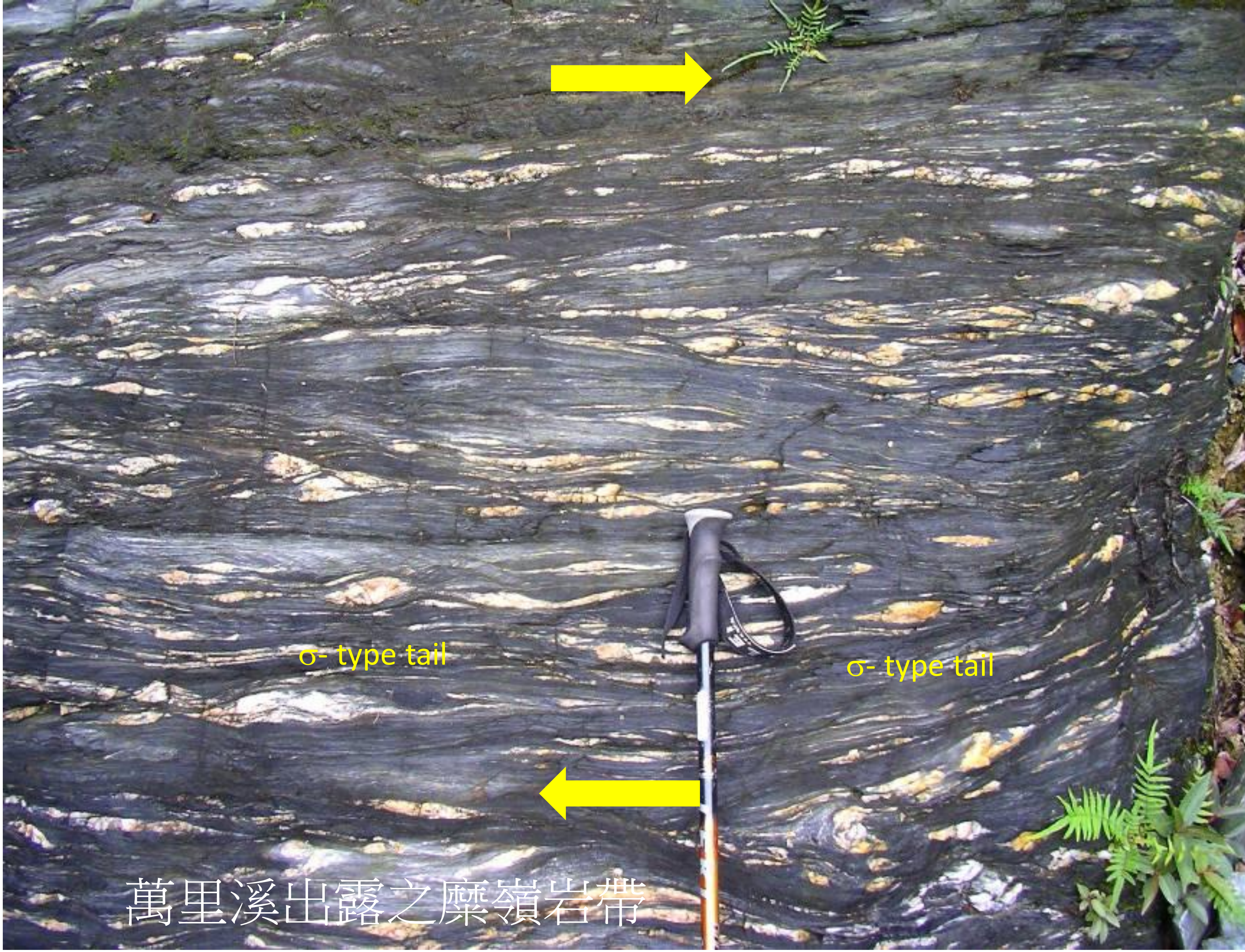


Figure 15.28 Porphyroclast systems. (a-c) Porphyroclasts with recrystallized tails. σ-type porphyroclasts have tails that do not cross the reference line, while the δ-type have tails that do. (a) and (b) show monoclinic symmetry (with the rotation axis being perpendicular to the page). The Φ-type is symmetric about the reference line. (d) Fractured porphyroclast with synthetic fracture. (e) Antithetic shear fractures. (f) Tiling (imbrication) of prophyroclasts. All structures (expect (c)) consistent with sinistral shear.


σ- type tail
σ- type tail
萬里溪出露之糜嶺岩帶

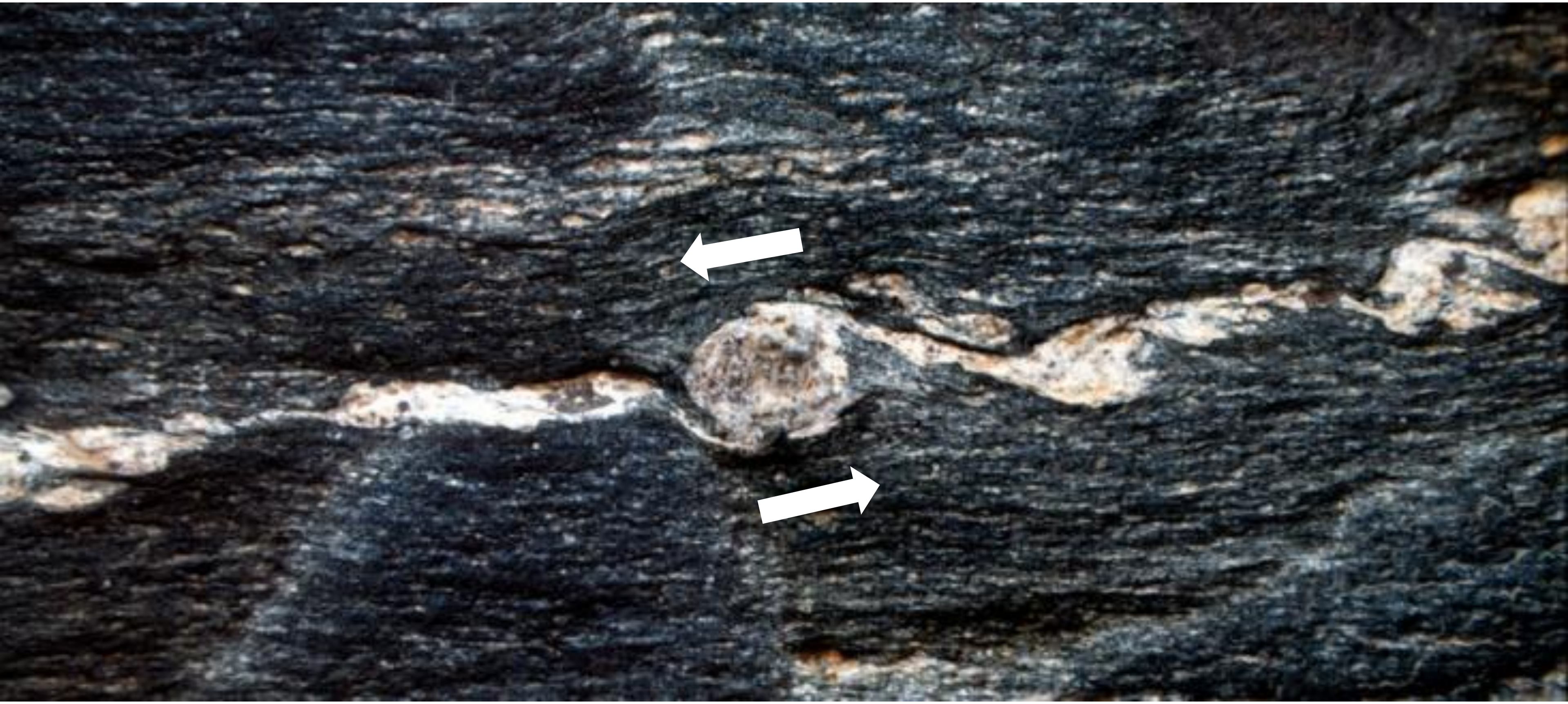
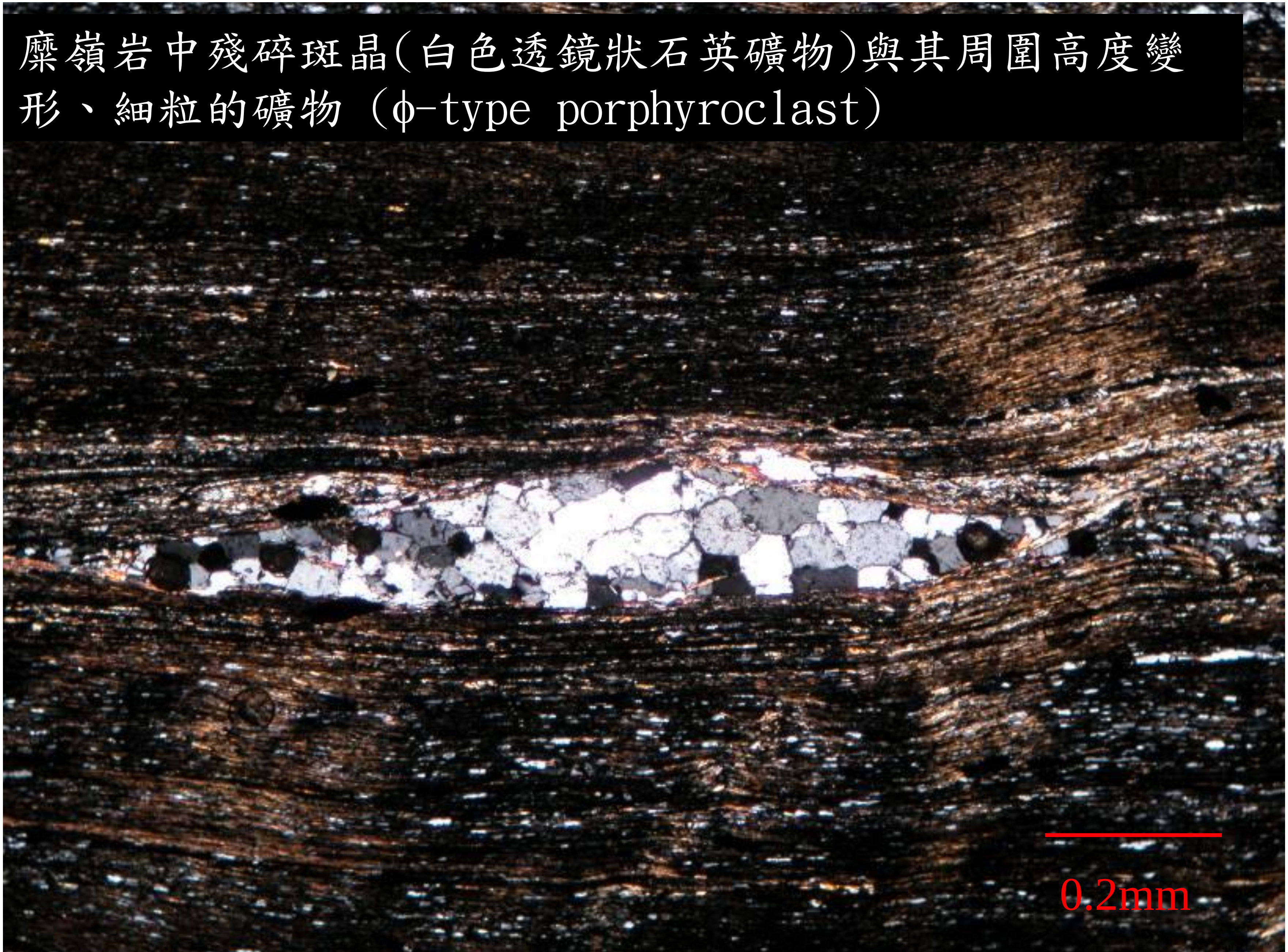


Figure 15.29 δ-porphyroclast indicating rotation during top-to-the-left shearing, consistent with the asymmetry of small-scale folds (right).

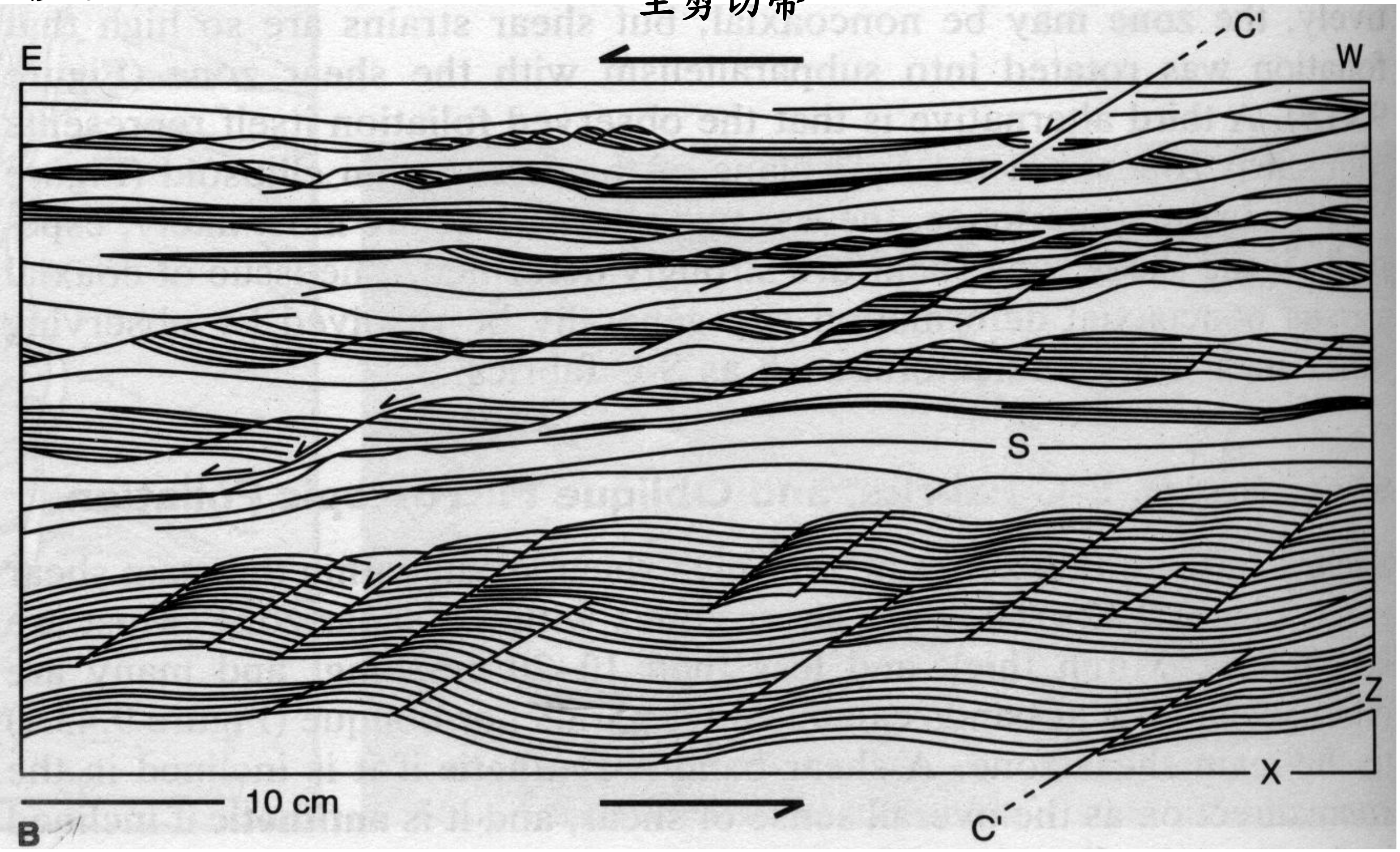

糜嶺岩中殘碎斑晶(白色透鏡狀石英礦物)與其周圍高度變形、細粒的礦物（ϕ-type porphyroclast）
0.2mm

剪切薄帶 (shear band)

- 塑性或韌性剪切（斷層)帶
- 高度剪切應變，剪切帶中之剪切帶
- 與葉理伴生並斜切葉理
- 位移量很小

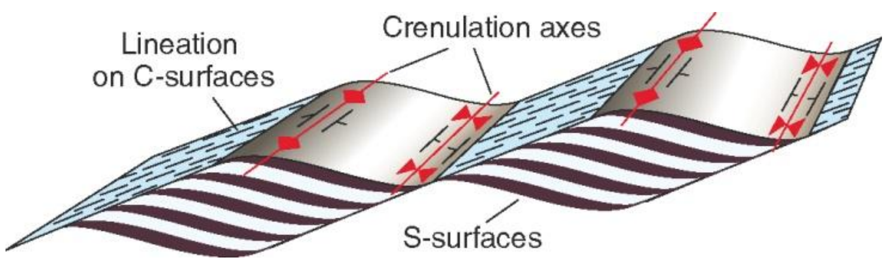
兩種組構型態:
S-C’ or S-C fabric
S (schistosity,片理)
C’ (Riedel shear azimuth)

主剪切帶



早期發育的片理組構-剪切應變小

S-C' Fabric



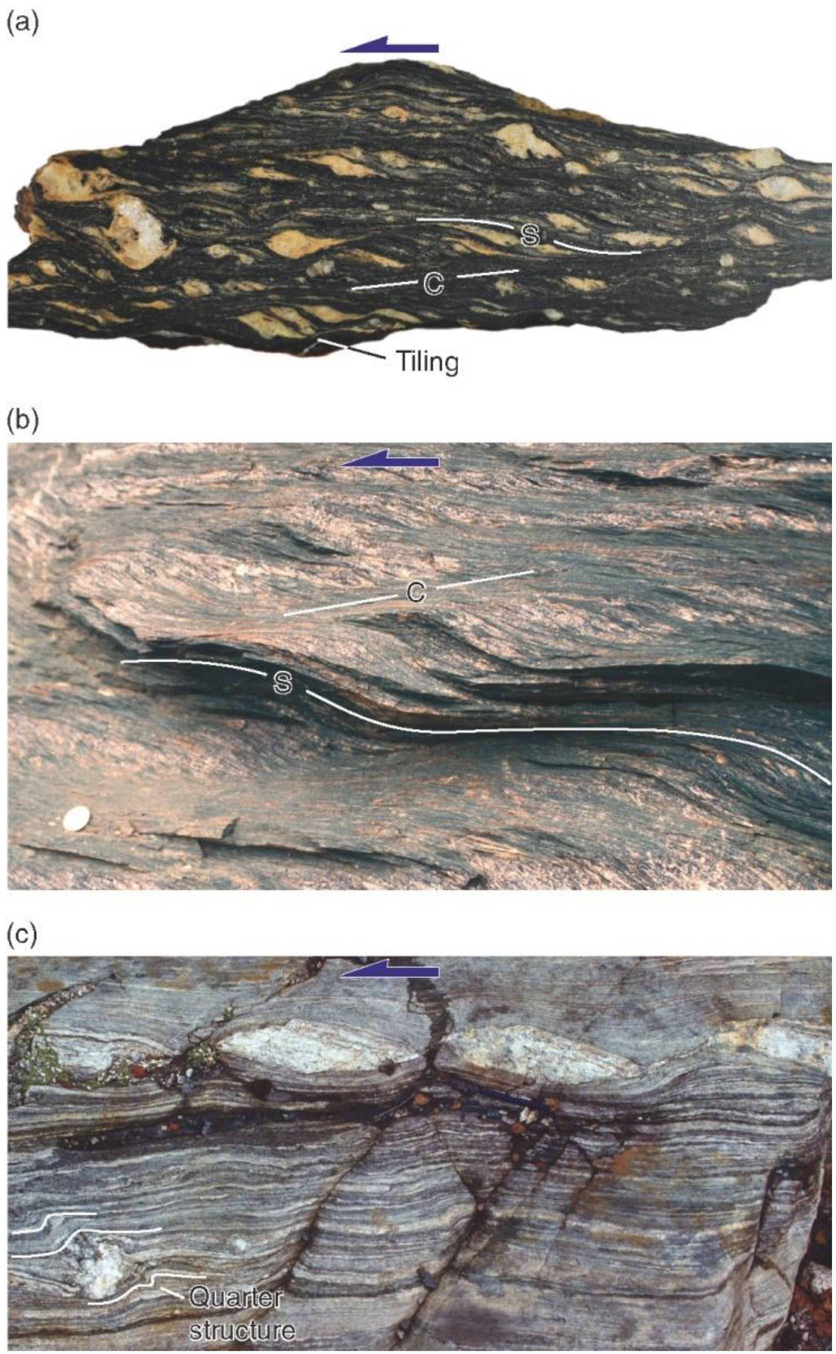


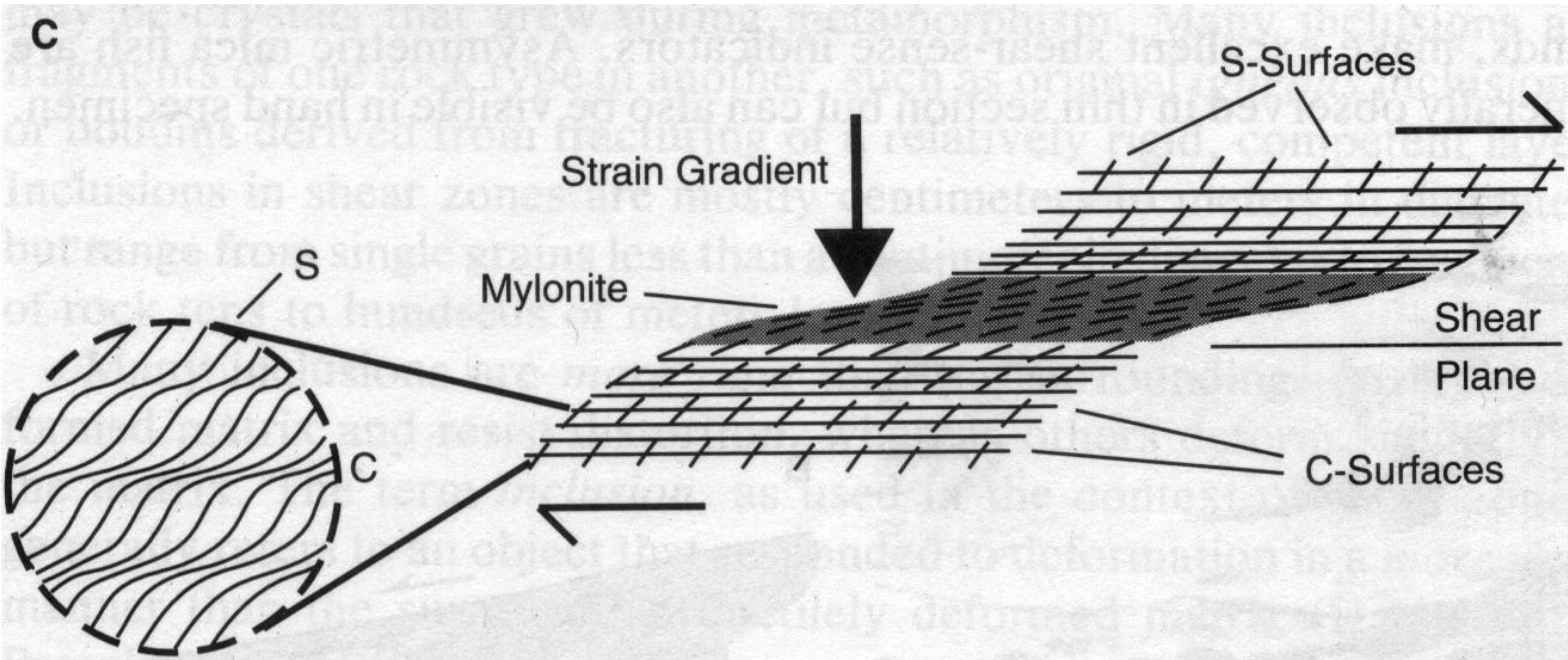
Figure 15.24 (a) S-C' structure in protomylonitic granite, Antarctica. Note tiling of feldspar porphyroclasts. (b) Shear bands in phyllite, together with asymmetric folds. Caledonian basal decollement. (c) Asymmetric boudins in granitic gneiss. Asymmetric folds around inclusion represent quarter structure. Caledonides east of Bergen.

剪切薄帶 (shear band) – 續

S-C fabric 晚期發育變質度及剪切應變大的葉理組構

S (schistosity) - 平行剪切帶內總額應變橢球體之XY面的面理(S)，在剪切帶內呈S形分布，隨持續應變旋轉逐漸平行C面理

C (cisaillement or shear band) - 糜稜岩面理(C)，是一系列平行主剪切帶，間隔排列的小型高度剪切應變帶



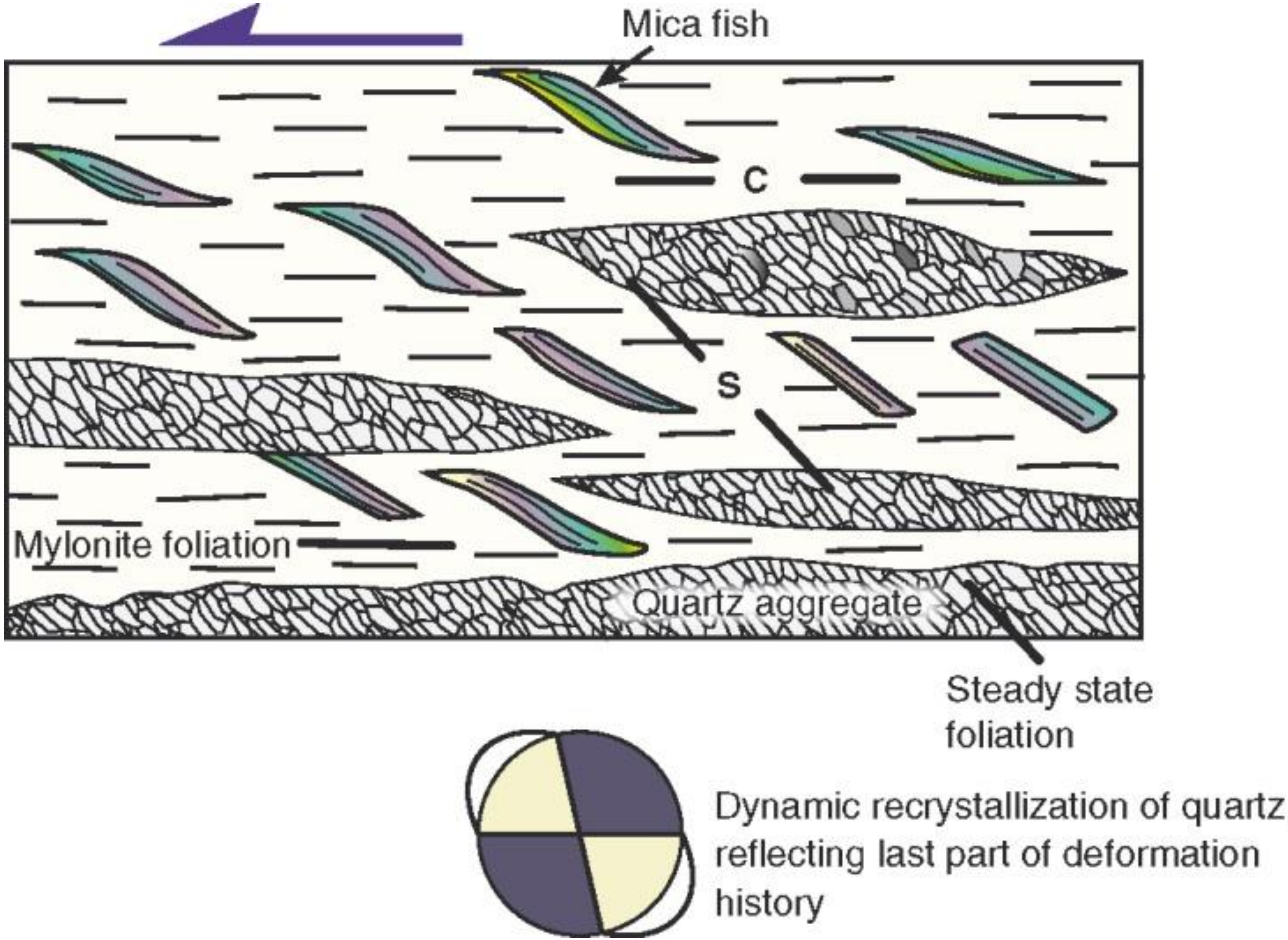


Figure 15.26 Typical S-C structures in quartz-mica-dominated mylonites.

S-C fabric

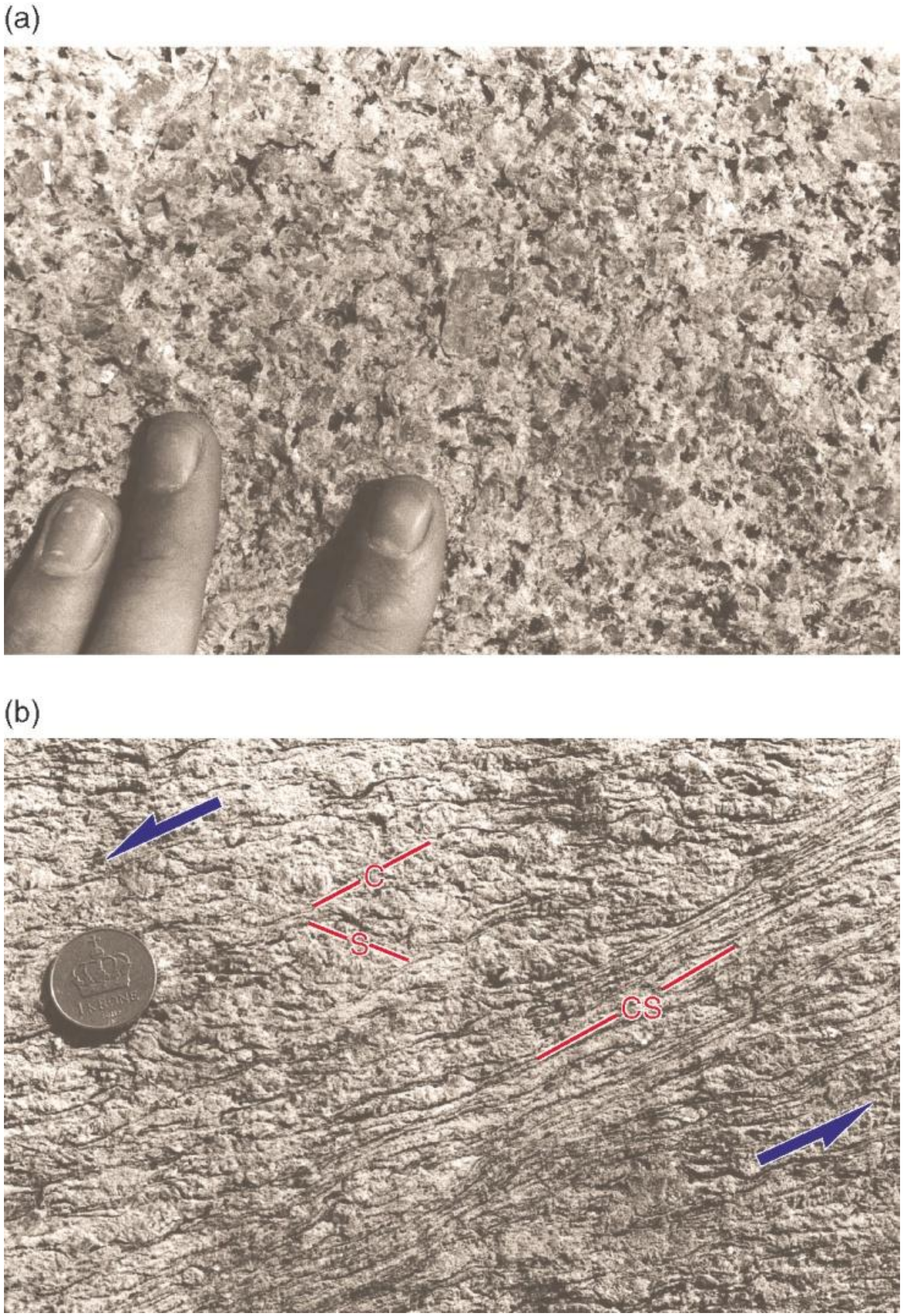


Figure 15.23 (a) Undeformed granite. (b) Sheared version of the same rock. Two sets of planar surfaces (S and C) are developed. S rotates to become subparallel with C in the zone of high strain. The combined foliation is named CS.

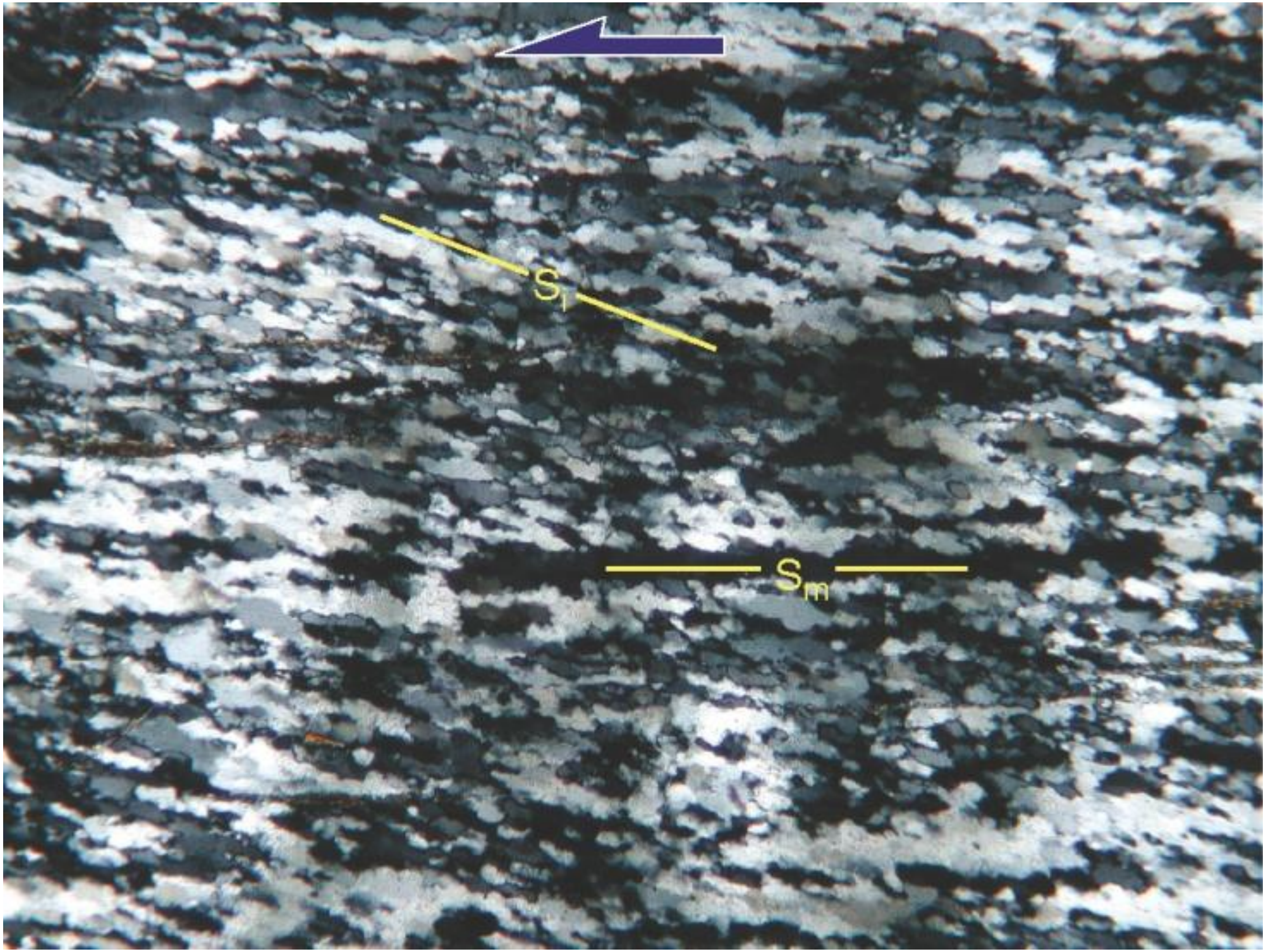
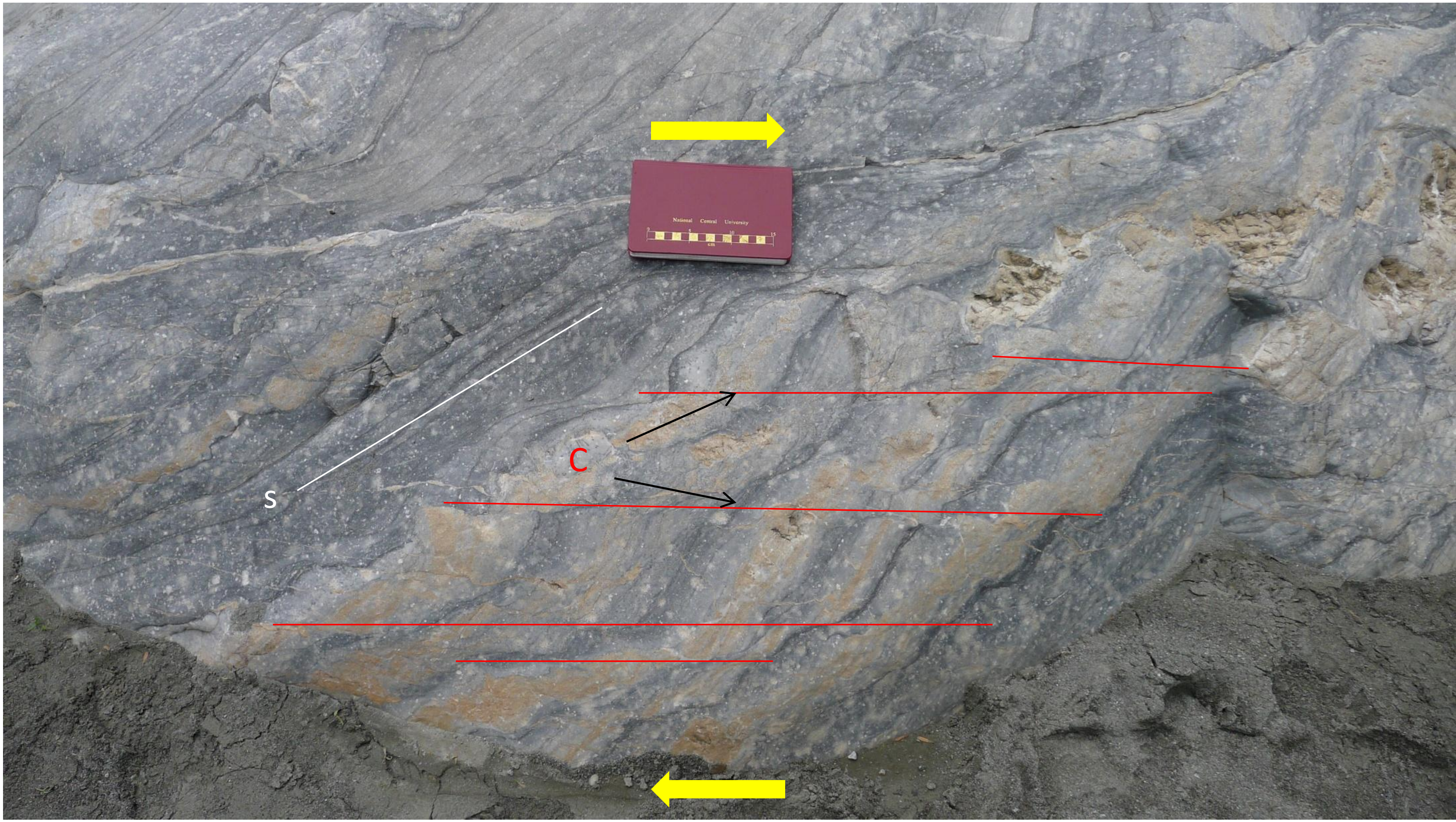
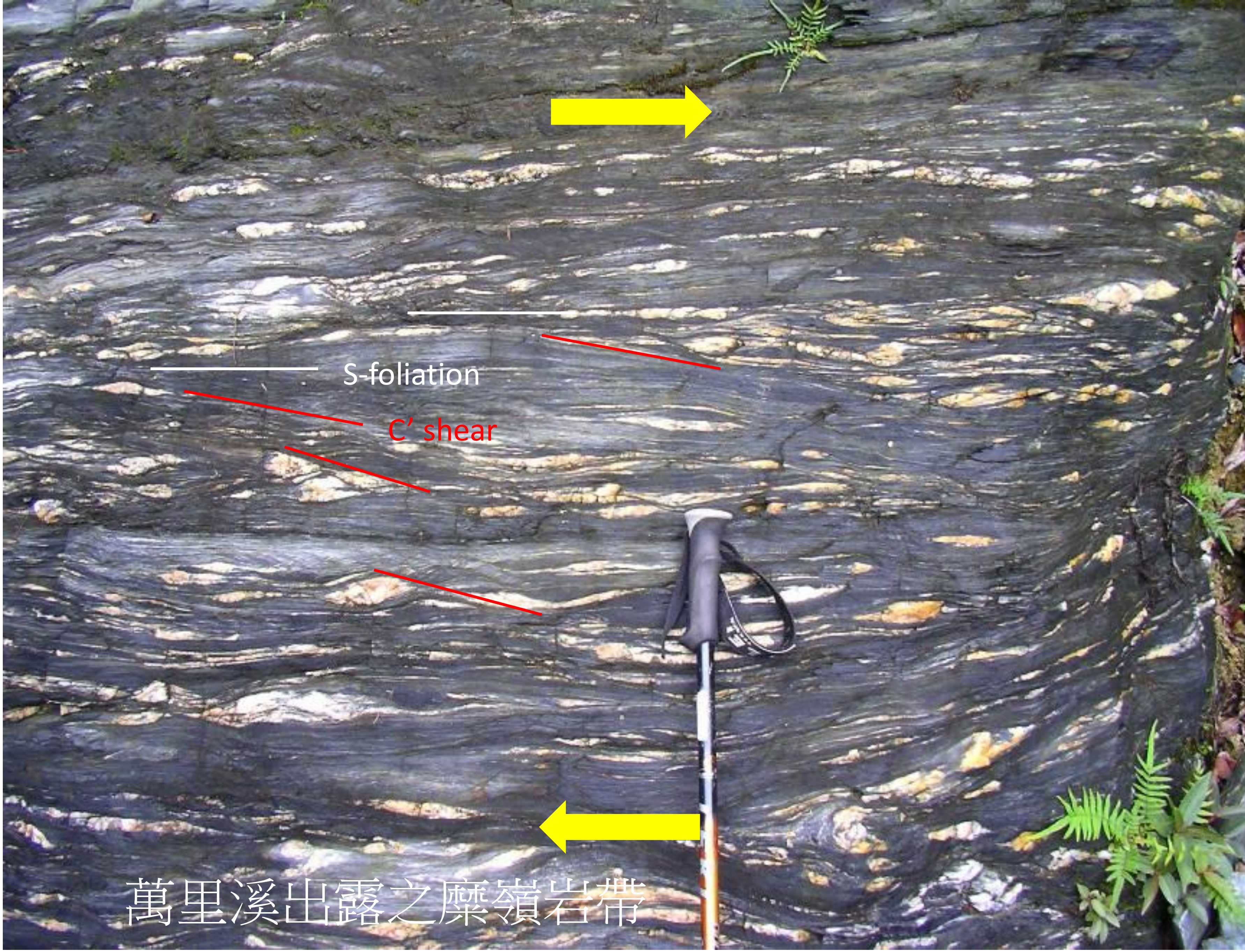


Figure 15.27 Thin section of a mylonite with a horizontal mylonitic foliation (S_m). The quartz grains are stretched in a direction Si oblique to S_m, and the angular relations are consistent with top-to-the left sense of shear. We could also use S-C terminology, where S_m represents C and S_i corresponds to S.

S-C fabric in marble-
中橫白沙橋溪畔片麻岩與大理岩接觸帶




S-foliation
C’ shear
萬里溪出露之糜嶺岩帶

Rotation of S-C fabric

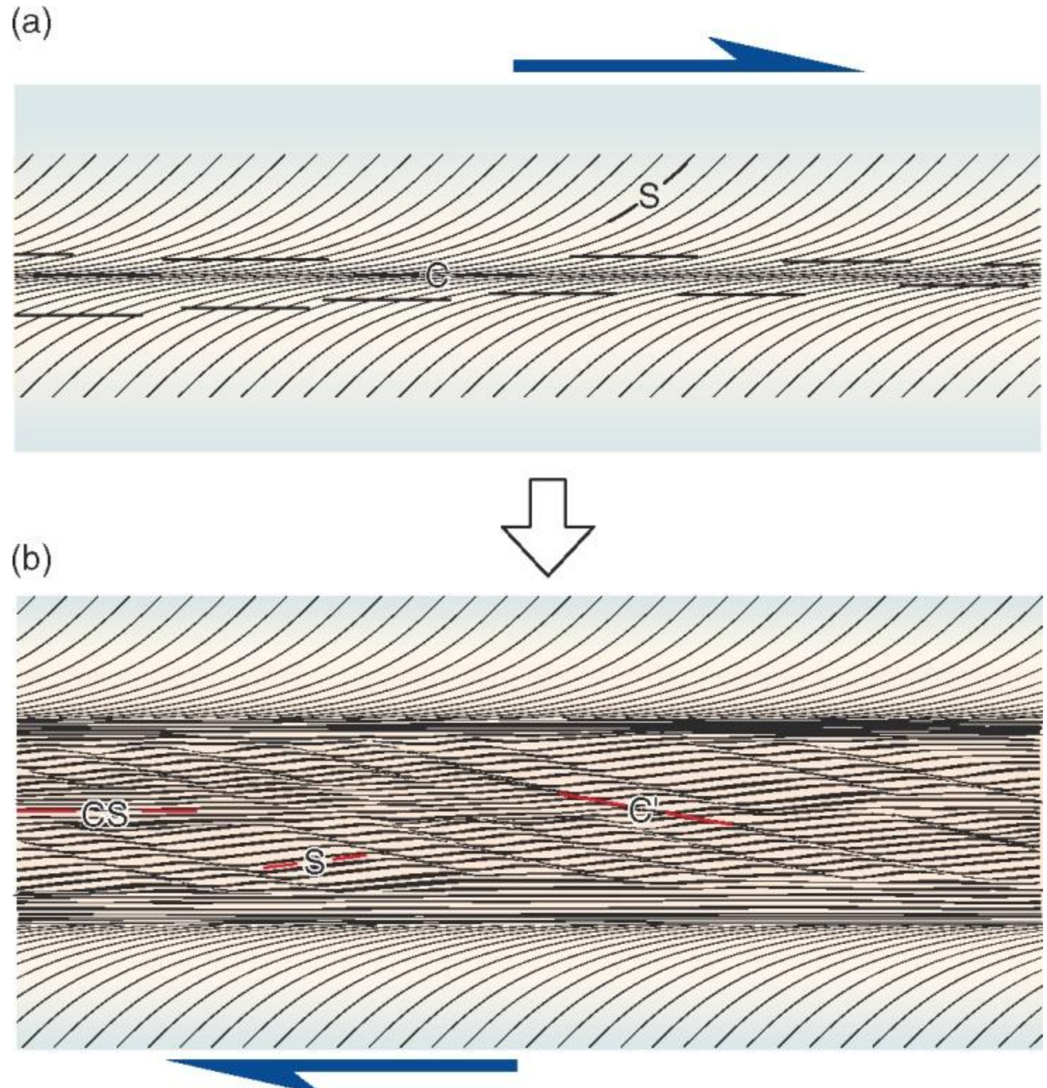
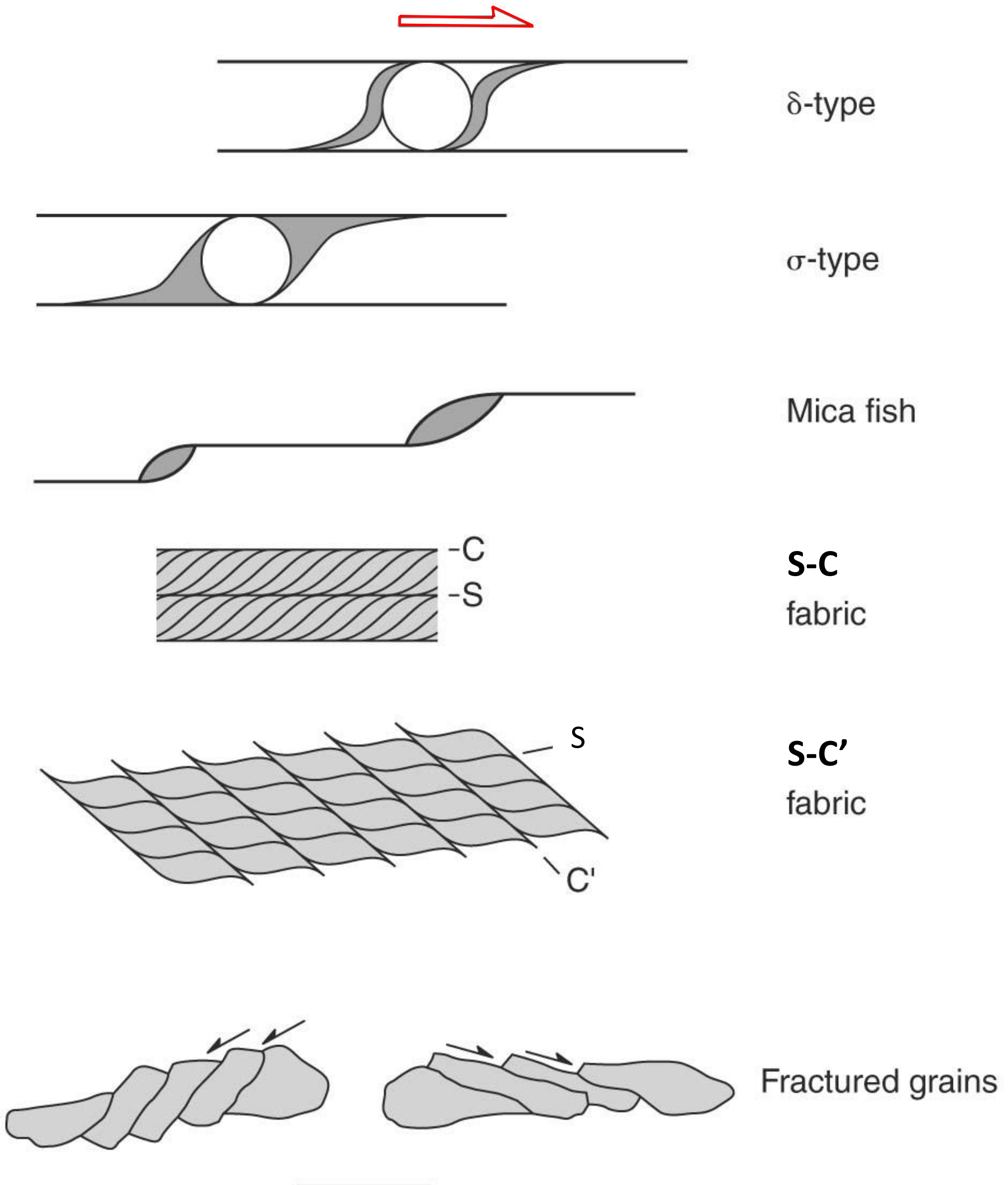
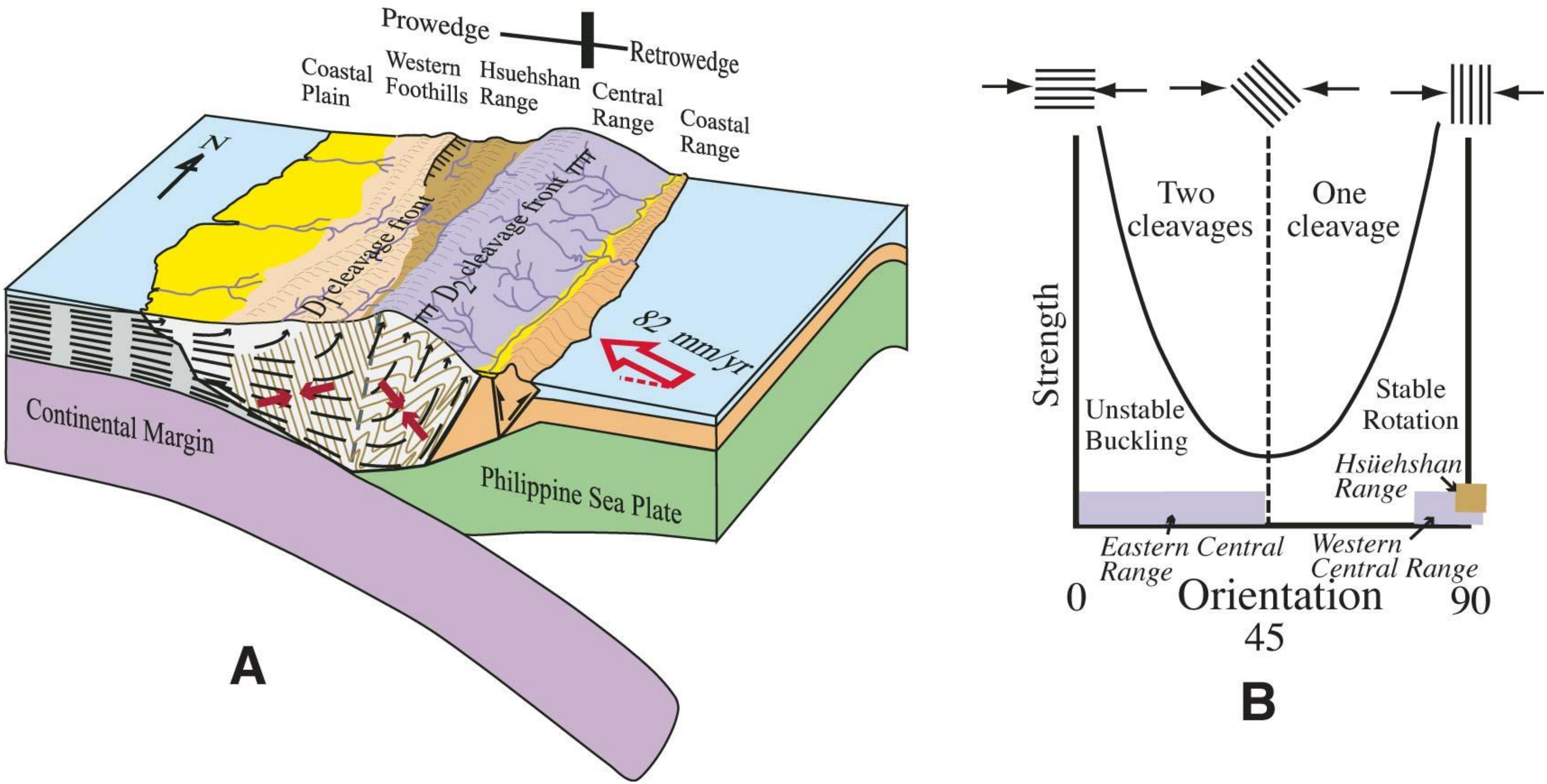


Figure 15.22 Schematic illustration of the development of S-C structures in a shear zone in a magmatic rock. (a) The new-formed foliation (S) is cut by shear surfaces (C) that parallel the shear zone margins. (b) Continued deformation rotates S into close parallelism with C, together referred to as a CS-foliation. New and oblique shear bands (C') form and back-rotate the CS-foliation, which then is called S.

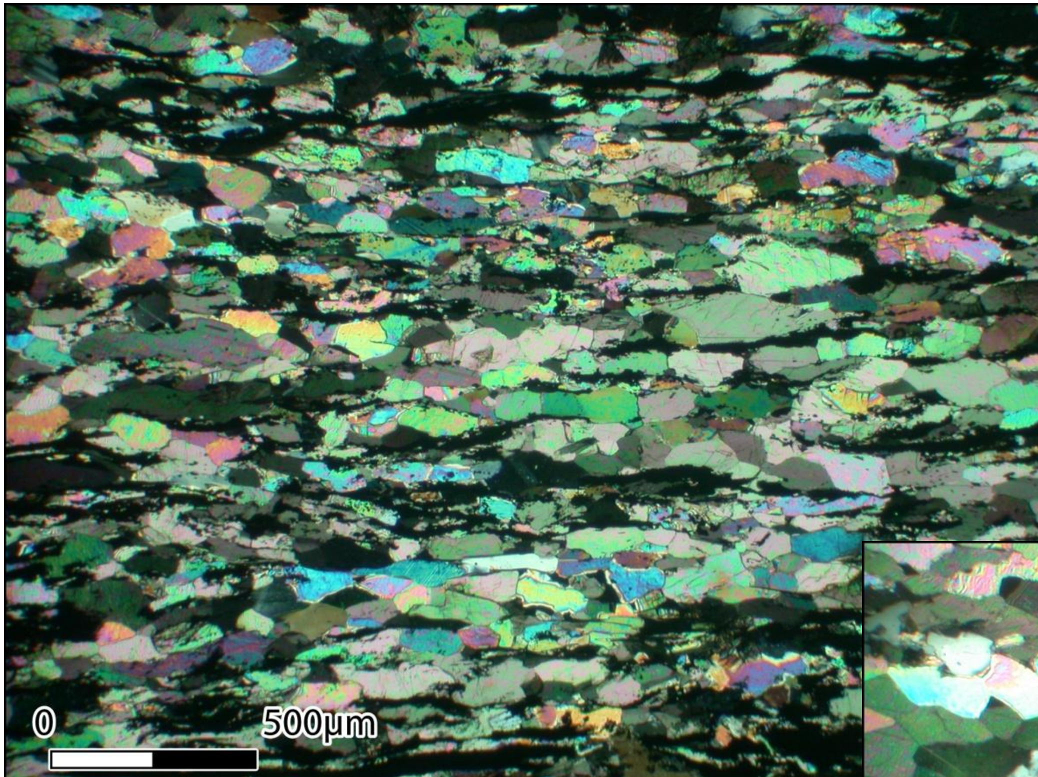
Summary diagram of shear-sense indicators

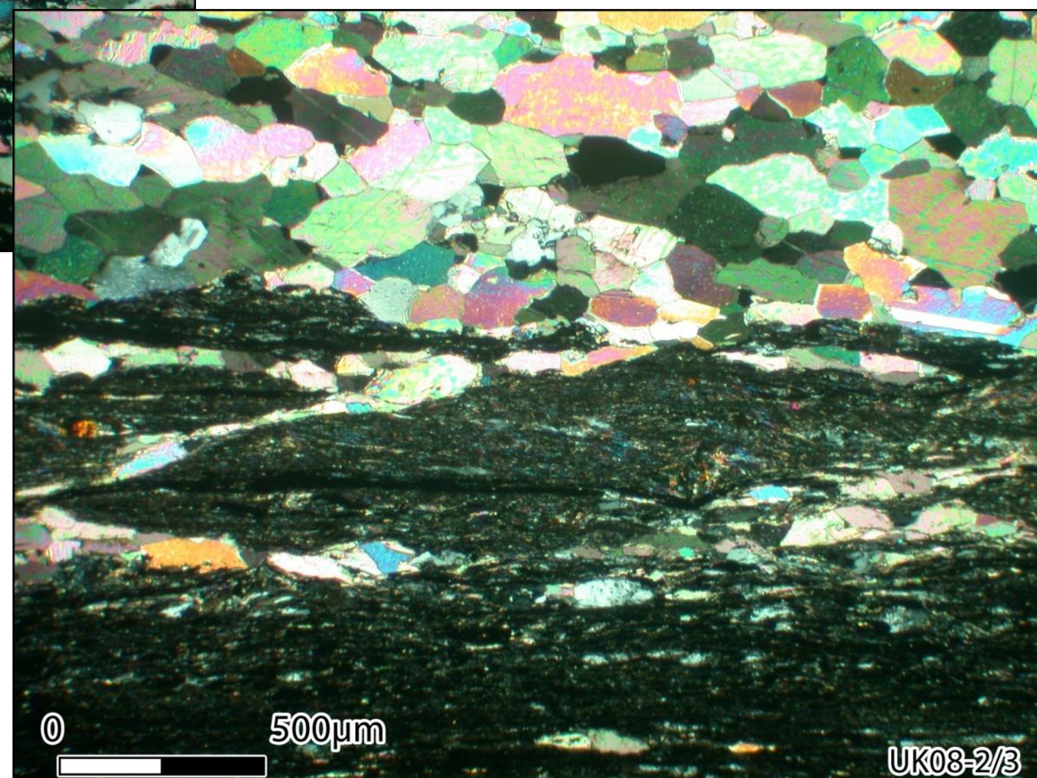


Speculations about the mechanical cause for backfolding



Fisher et al. 2007

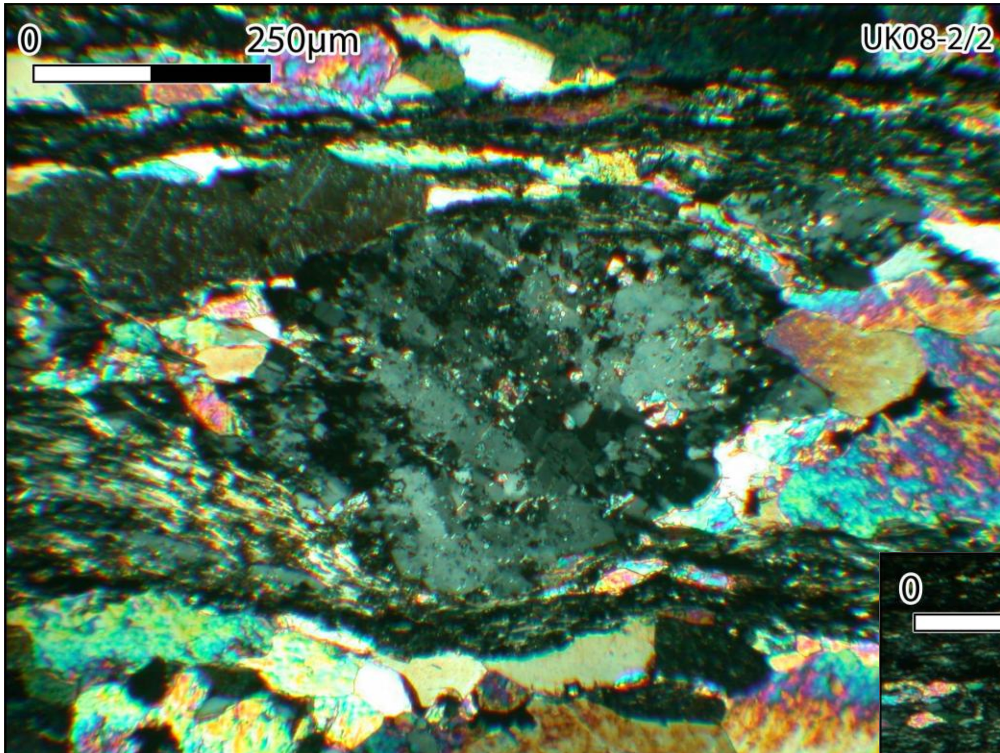


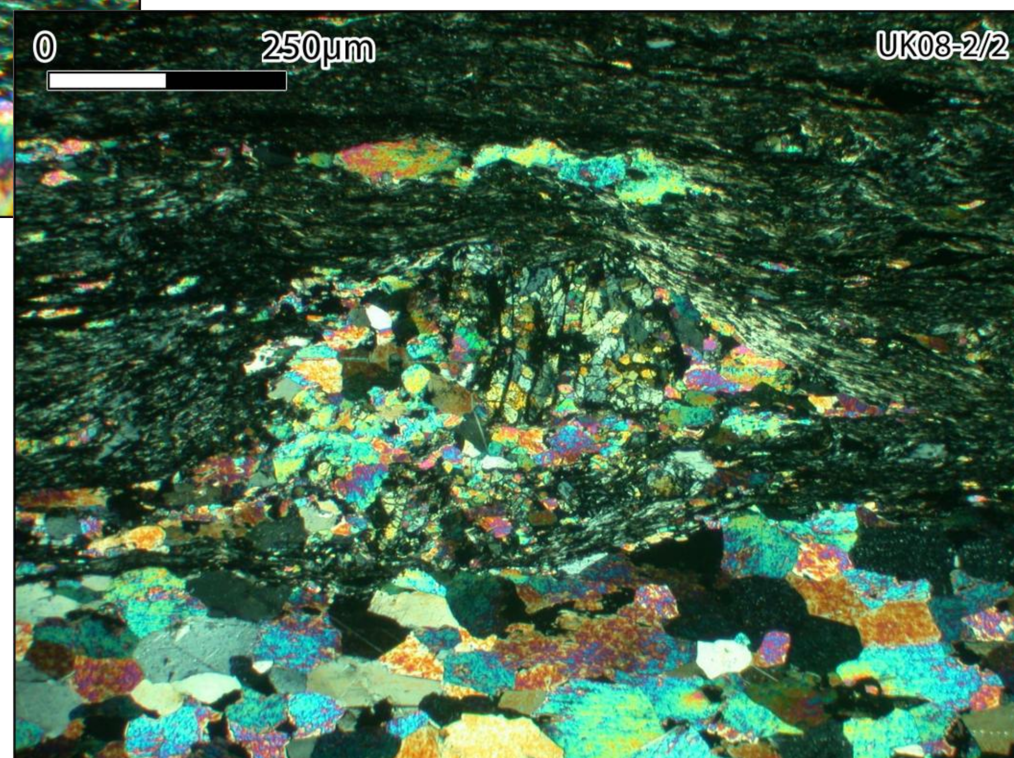


Calcimylonites

- well-defined metam. foliation
- Cc: SPO, high aspect ratios
  -> intraXX plasticity
- WM and Chl defining foliation
- s-c' shear bands -> mica fish

phyllites





- breakdown of Plag
- prograde growth of Epi/Zois

The base of the Cenozoic Slates succession of the Central Range has seen:

- dynamic recrystallisation
- T ≥ 250 - 300 °C

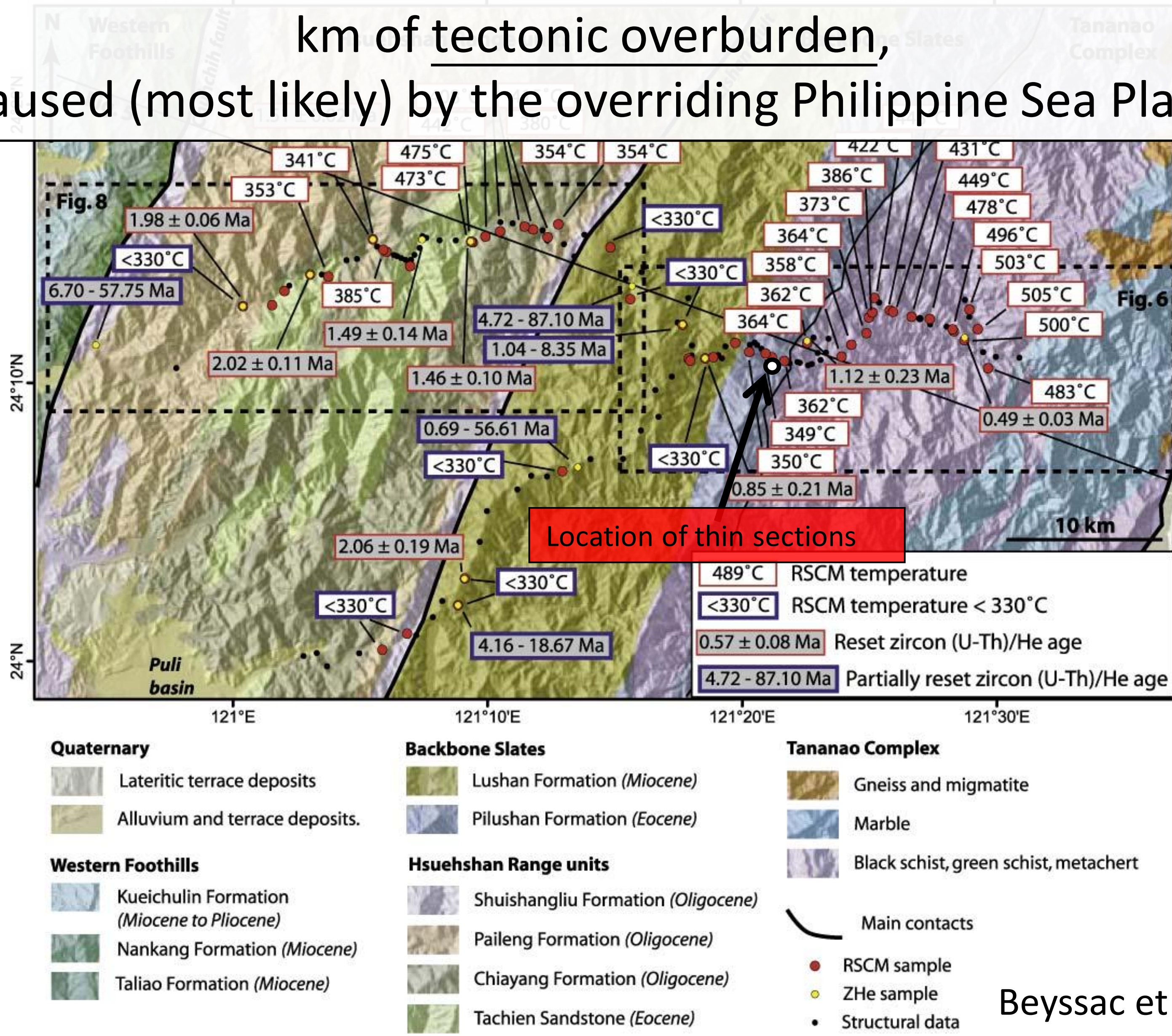
-> This ± agrees with T≈350°C by RSCM (Beyssac et al. 2007)

The base of the Cenozoic Slates succession of the Central Range has seen:

- dynamic recrystalization
- $T \geq 250 - 300\ ^{\circ}C$

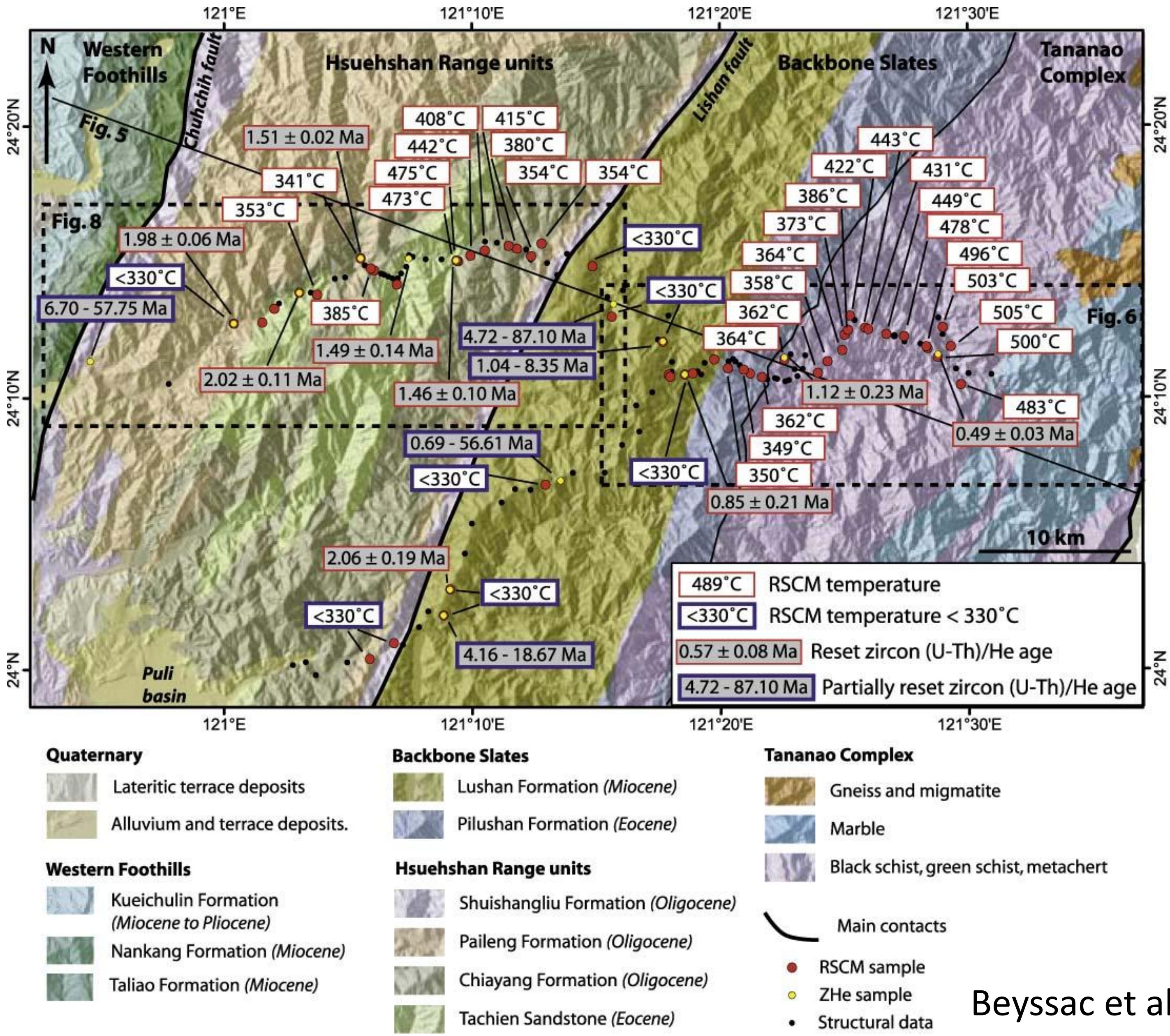
-> This $\pm$ agrees with $T \approx 350^{\circ}C$ by RSCM
(Beyssac et al. 2007)

The internal Cenozoic Slate Belt has seen up to or more than 10 km of tectonic overburden, caused (most likely) by the overriding Philippine Sea Plate.



Beyssac et al. 2007

The internal Cenozoic Slate Belt has seen up to or more than 10 km of tectonic overburden, caused (most likely) by the overriding PSP



Beyssac et al. 2007

Migmatite (混合岩)

當變質溫度很高時，岩石會開始熔化，但由於岩石是由不同的的礦物組成而成的，不同的礦物具有不同的熔點，因此熔點較低的礦物(例如石英、雲母與鈉質斜長石)會先熔解而成為液體(岩漿)，而熔點較高的礦物(例如橄欖石、輝石、角閃石與鈣質斜長石)仍然維持固體的狀態(refractory minerals)。這種只有部分的岩石熔化的作用稱為部分熔化作用(partial melting or anatexis)。進行部分熔化作用的岩石就像土石流一樣，未熔化的礦物或岩體會懸浮在黏稠的岩漿當中。當這些混雜在一起的固體與液體受到擠壓時，就會像土石流一樣地流動、變形，形成褶皺與再褶皺的構造。當溫度下降後，這種混合著酸性岩漿與基性岩塊的混合物就固化成為所謂的混合岩。

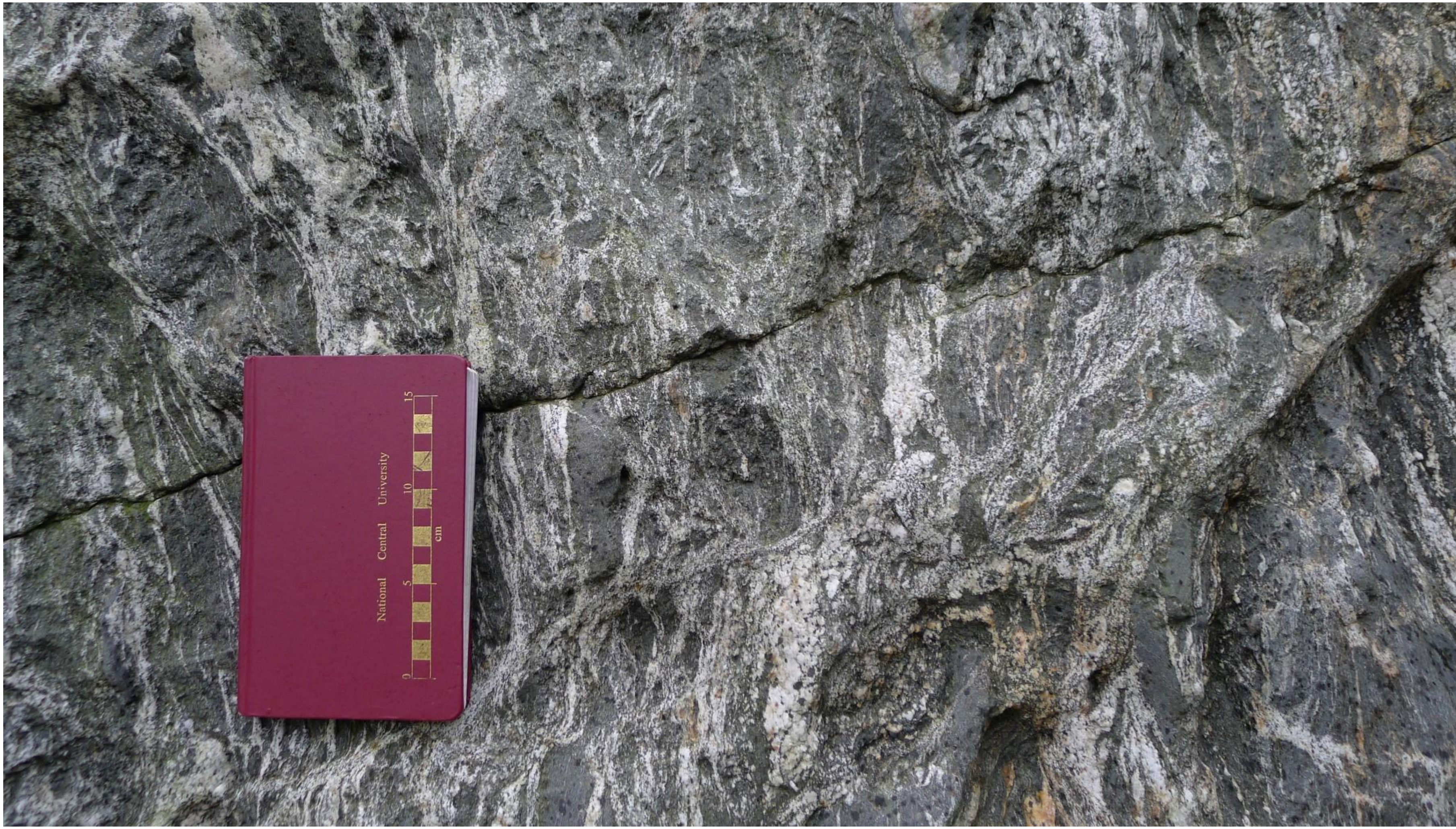
Migmatite（混合岩）

The metamorphic rocks exposed in this outcrop near Michigamme, Michigan are over 3 billion years old.

http://epod.usra.edu/archive/epodviewer.php3?oid=204160

Eric Cohen, Westhampton Beach High School

Migmatite in碧侯野溪溫泉

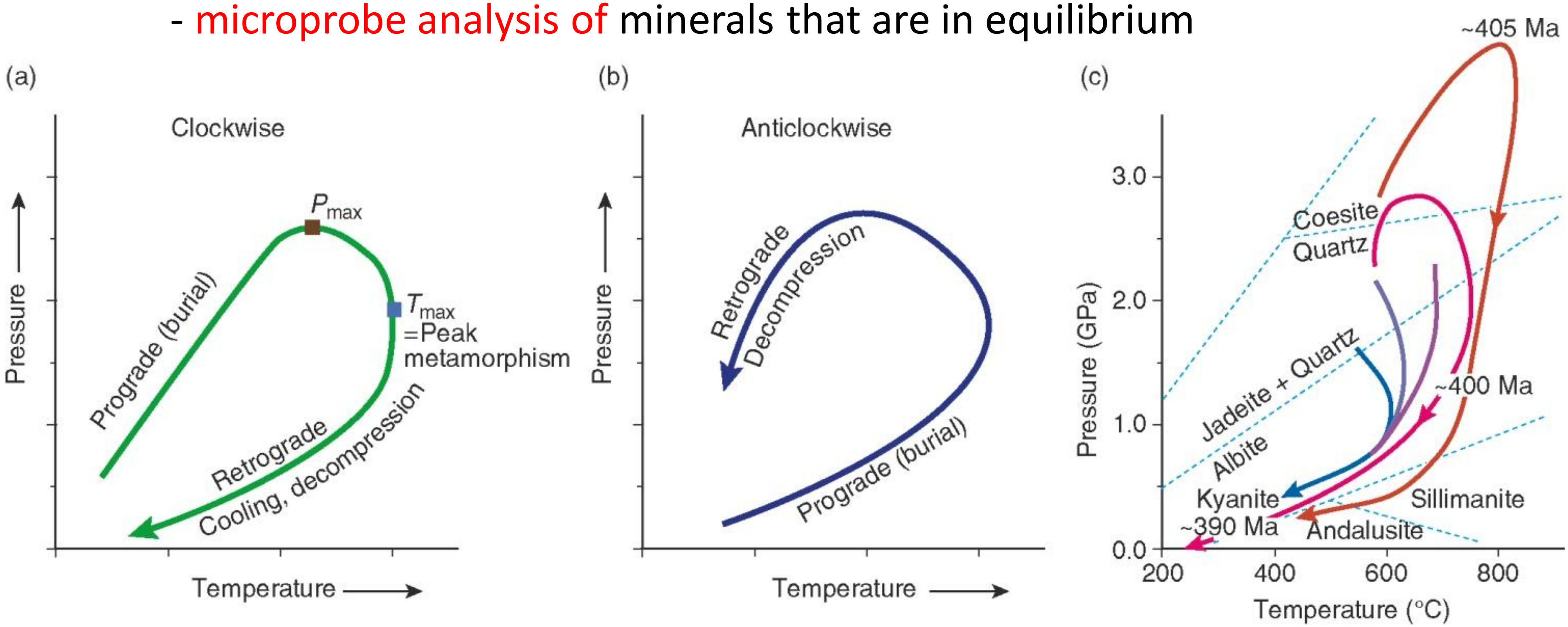

National Central University
0
5
10
15
cm

P-T Paths (Thermobarometry):

metamorphic conditions in pressure and temperature space

- mineral inclusions (different from matrix mineralogy) grow within porphyroblasts during deformation stages
- microprobe analysis of minerals that are in equilibrium

P-T-t paths

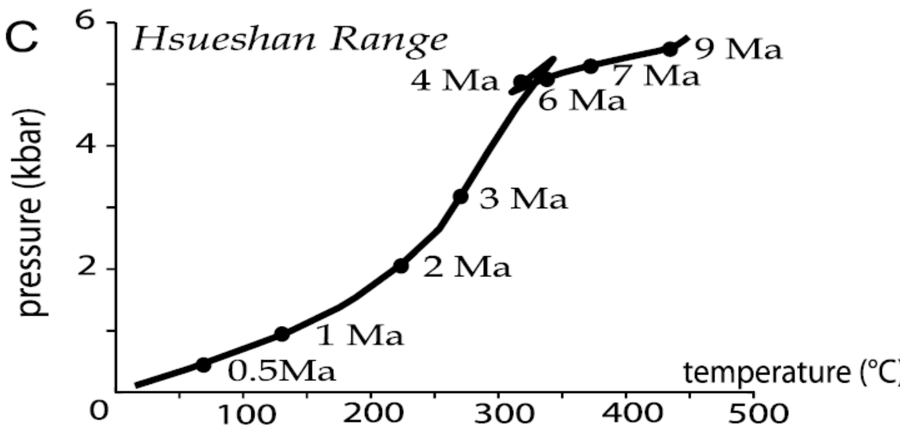


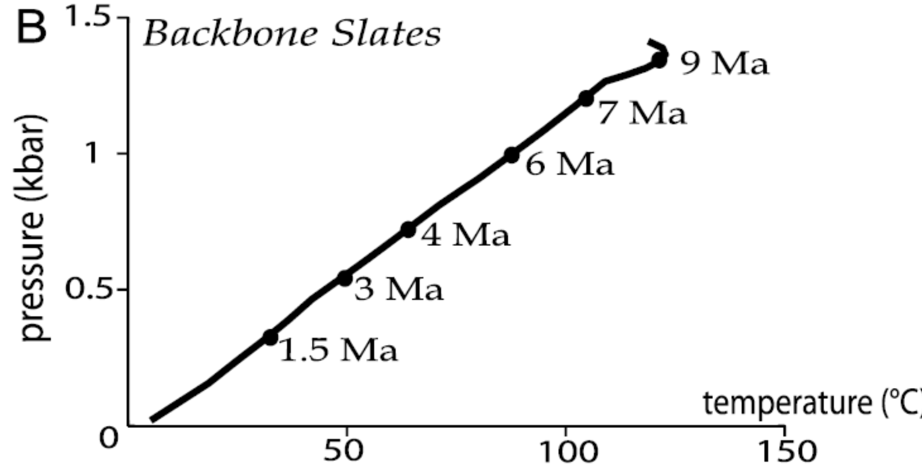
Rapid subduction

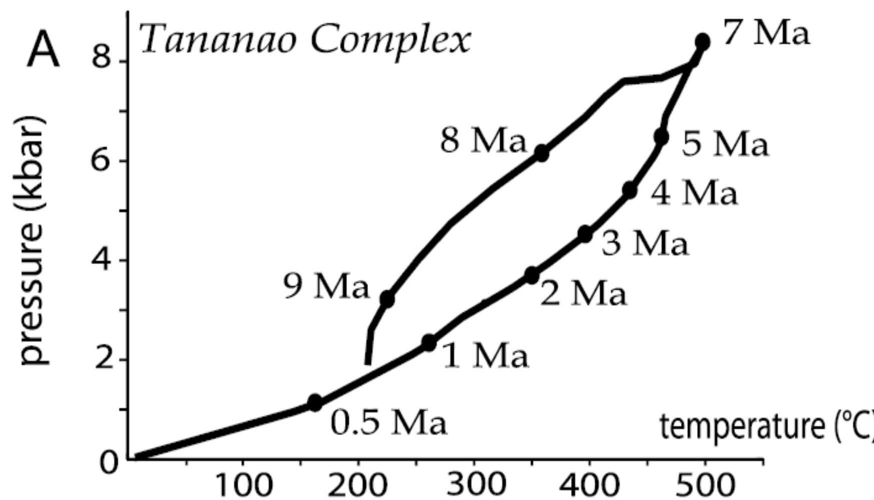
Rifting precedes orogeny

Figure 21.4 Clockwise (a) and anticlockwise (b) P-T paths for different locations in subducted Caledonian continental crust in southwest Norway, relevant to Figures 16.26 and 17.22. Based on compilation by Labrousse et al. (2004). Ages relate to the two deepest paths. Well-known phase transitions are shown for reference.

P-T-t paths predicted along the northern transect, and (a) the Chipan Gneiss within the TC (b) the BS, and(c) the core of the HR units. (Simoes et al., 2007)



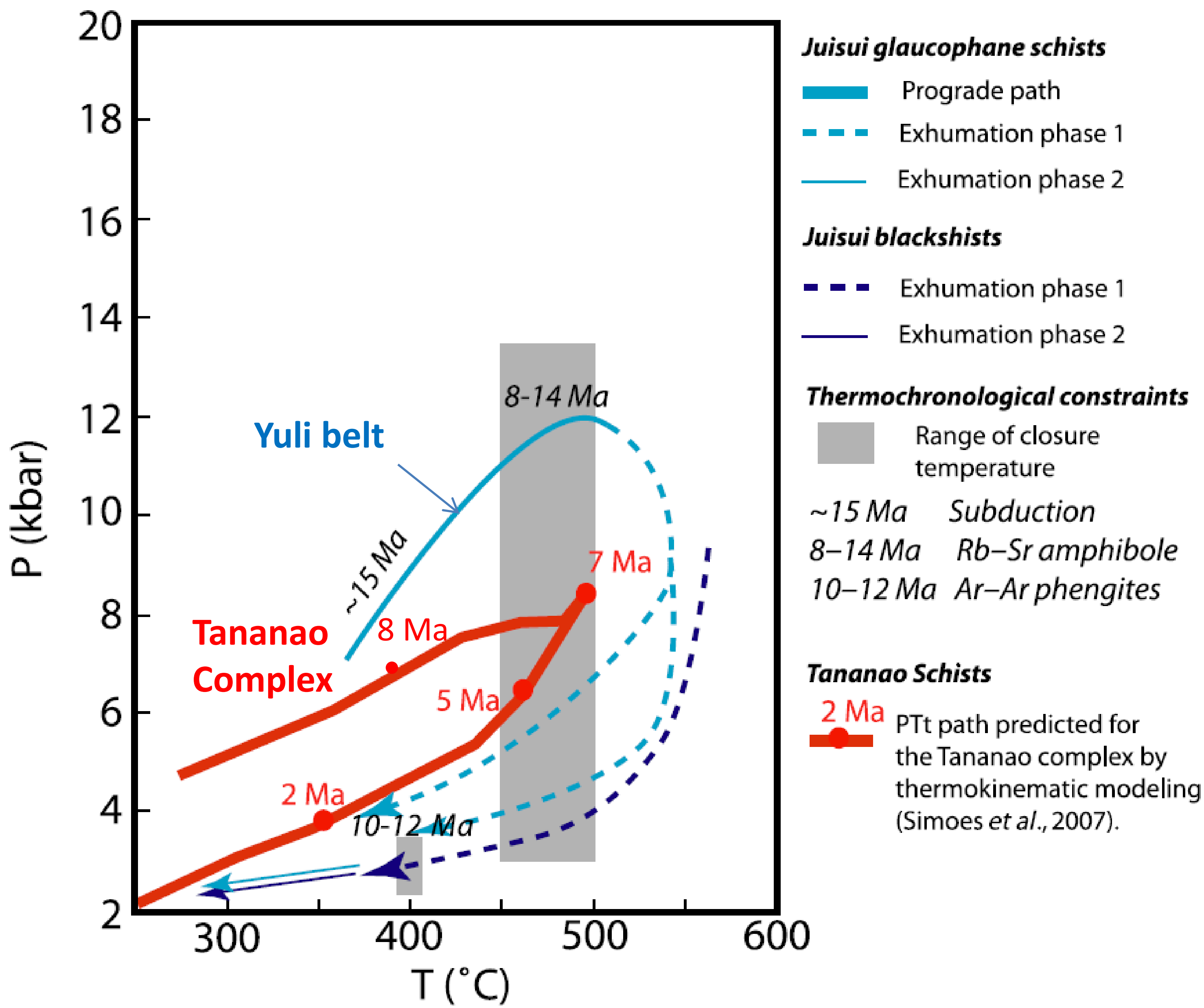




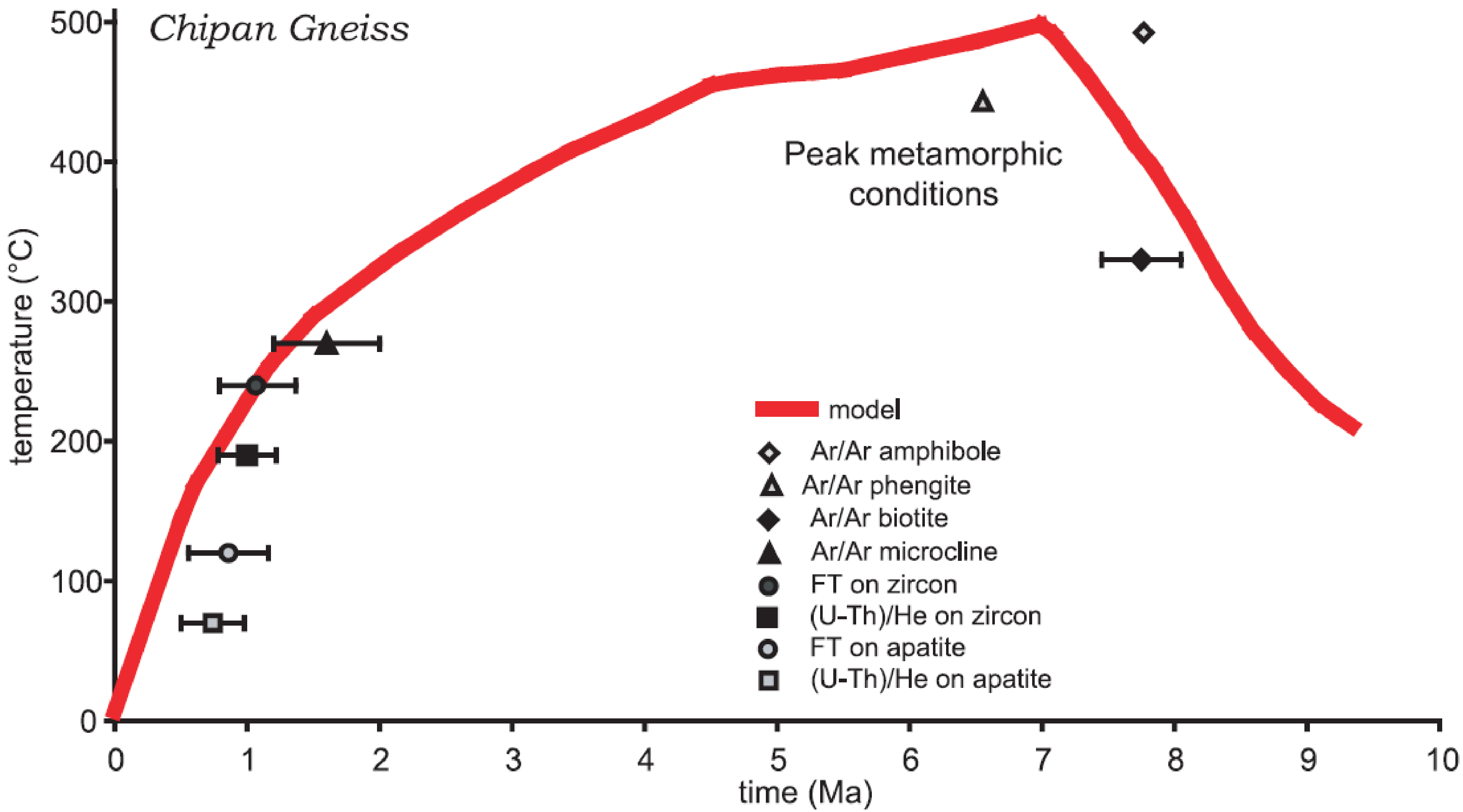
The BS and HR have simply cooled down from their temperatures within the initial passive margin.

TC underplated and now exhumed

Tentative P–T–t history for the HP metamorphic rocks from Juisui (瑞穗) and Wanjung



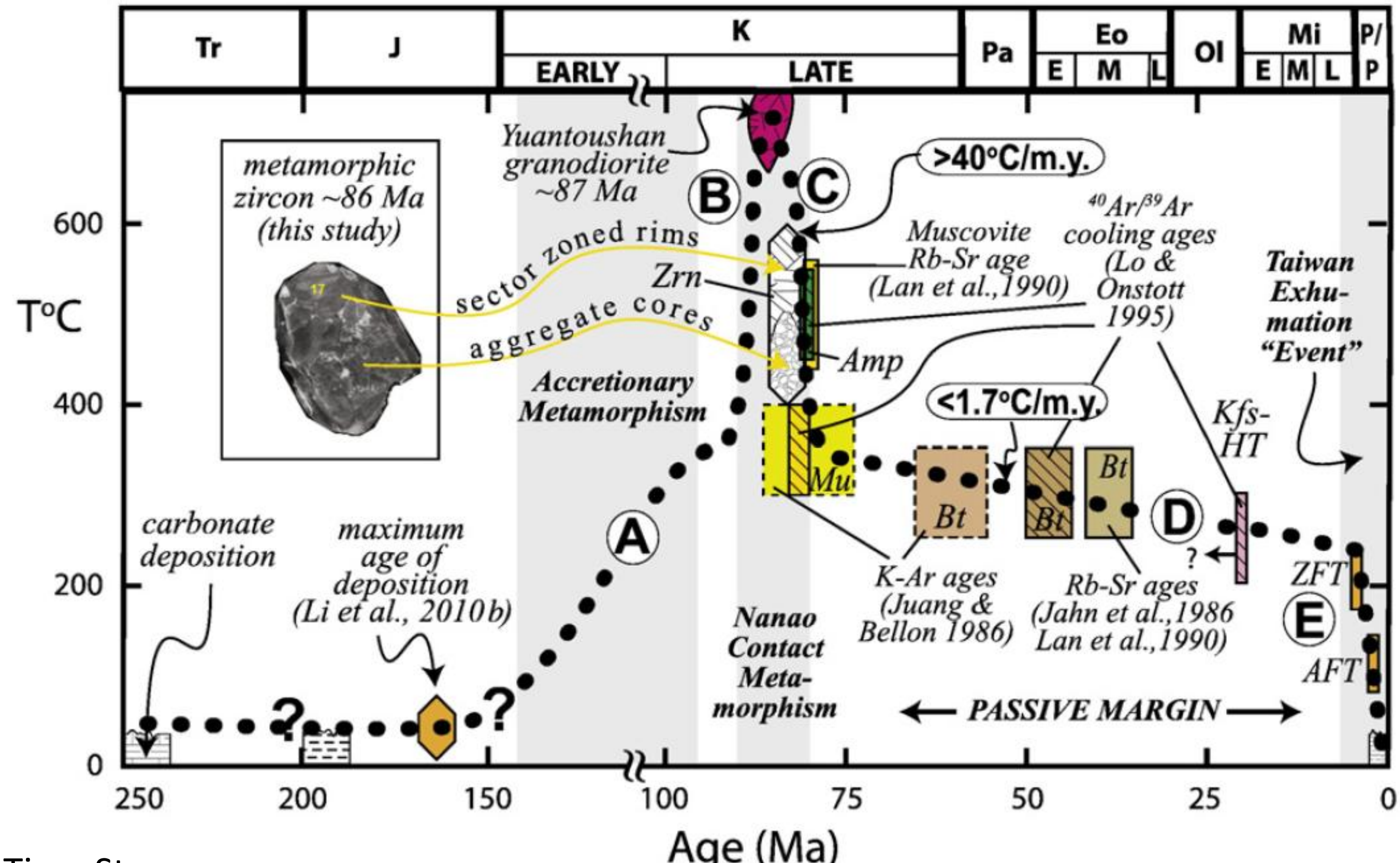
Time-temperature(T-t) path derived for the Chipan gneiss



$^{40}Ar/^{39}Ar$: biotite, microcline and reaction rims of amphiboles

Simoes et al., 2007

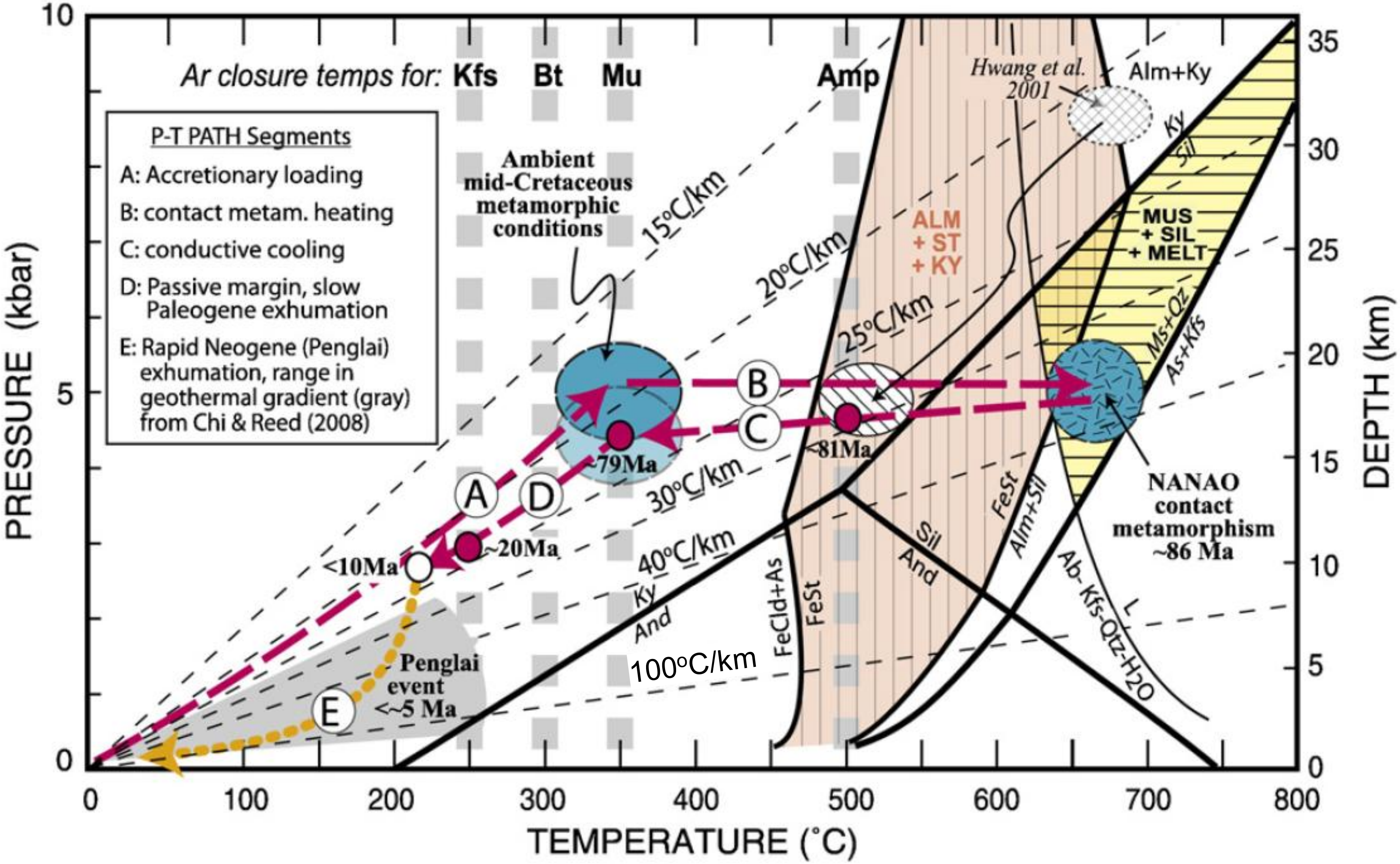
T-t history of Tananao complex in the Nanao region



Wintsch et al. 2011, Lithos

Time Stages
A: diagenesis
B: Contact Metamorphisms
C: Cooling
D: mid-continent residence
E: rapid cooling (Penglai orogeny)

P-T path of the rocks of the Tananao complex in the Nanao region



Wintsch et al. 2011