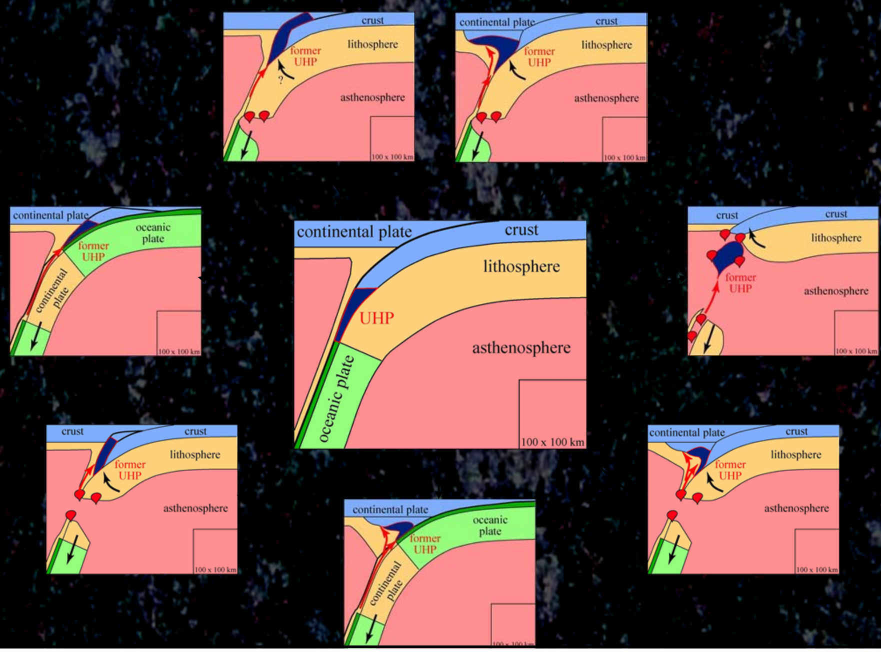
Exhumation of UHP Terranes

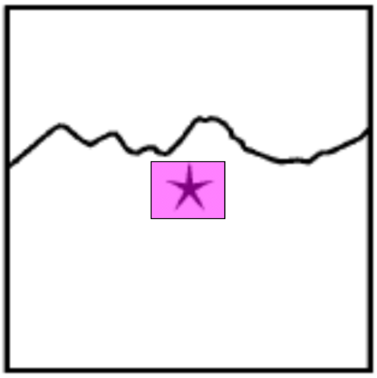
structural geology and geodynamic models

- overview of mechanisms
- Dabie–Sulu
- Norway
- New Guinea

UHP Exhumation Mechanisms



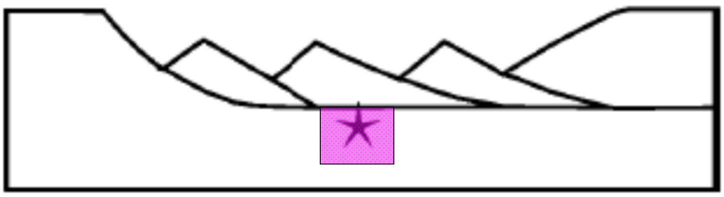
Fundamental Process: Erosion



demonstrably not fast enough

Froitzheim et al. (2003)

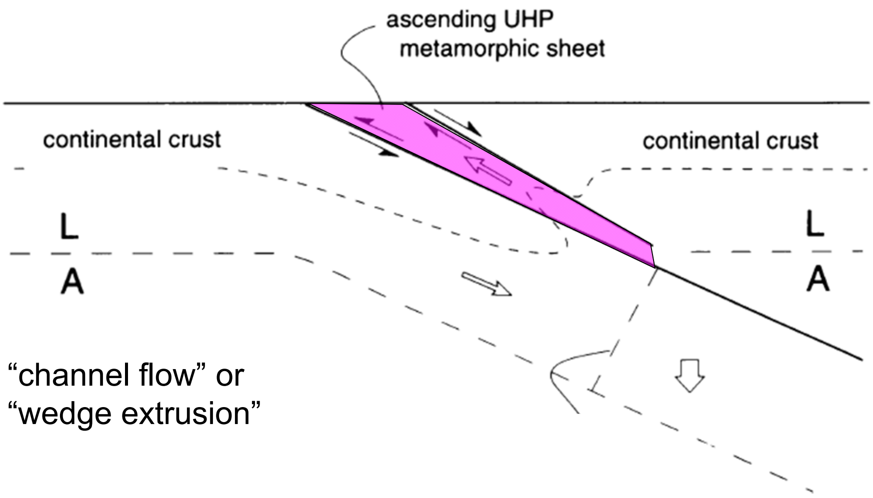
Fundamental Process: Extension



requires extraction of upper or lower plate

Froitzheim et al. (2003)

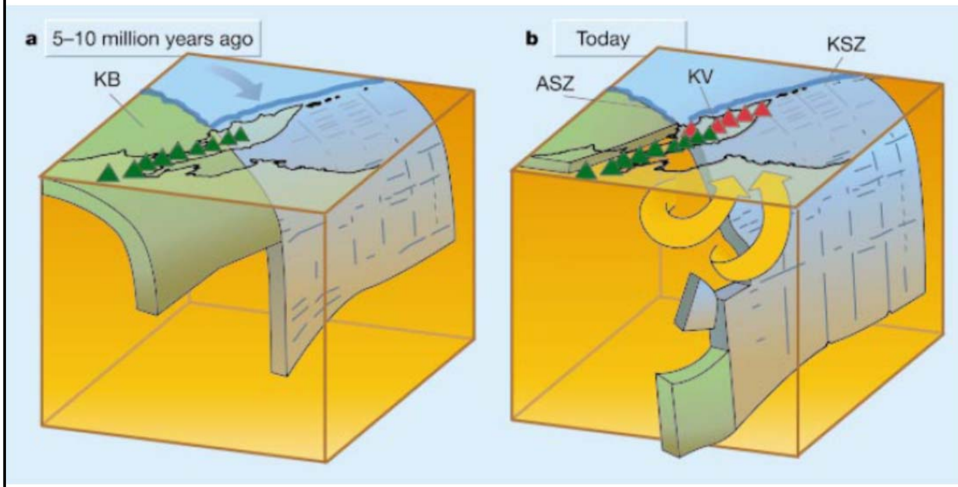
Fundamental Process: Extrusion



"channel flow" or
"wedge extrusion"

Ernst & Peacock (1996)

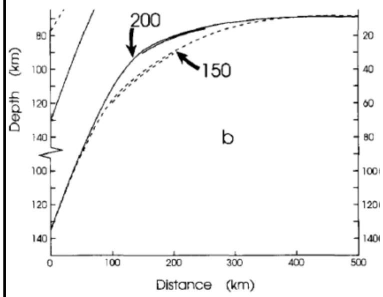
Plate-Scale Force: Slab Breakoff

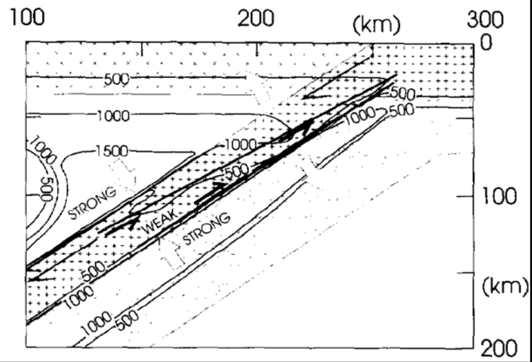


Kamchatka (Levin et al., 2002)

Plate-Scale Force: Slab Flexure

subduction of continent margin accompanied by increase in plate flexural strength; puts upward pressure on overriding plate.
Weak subducting crust between subducting mantle lithosphere & mantle of overriding plate may extrude.



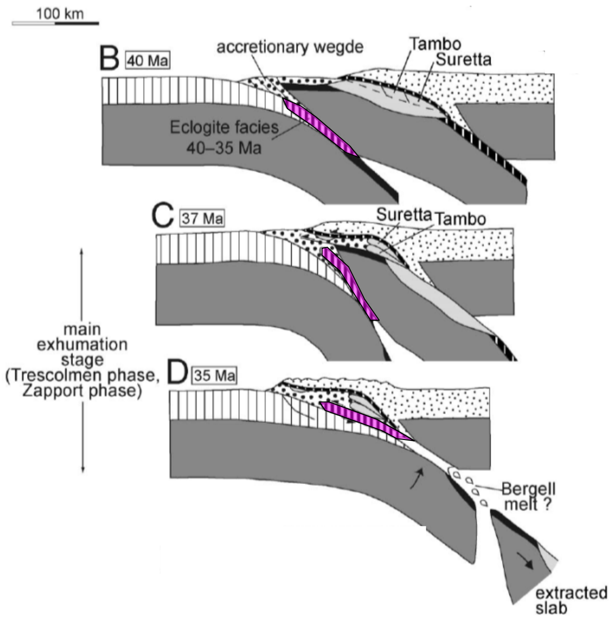


Hynes et al. (1996)

Plate-Scale Force: Slab Withdrawal

withdrawal of intervening mafic lithosphere;

this could work for nearly anywhere…would it leave any trace?



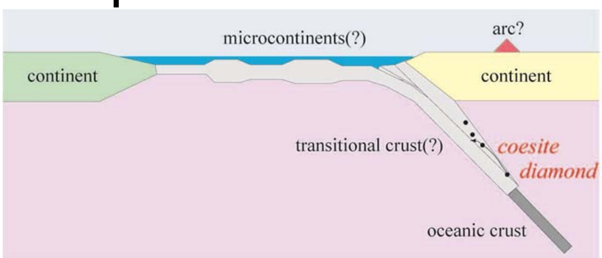
Froitzheim et al. (2003)

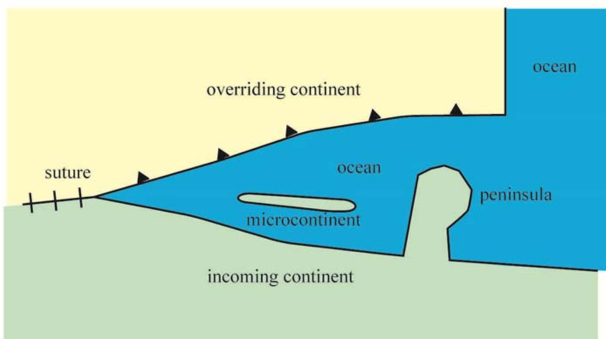
Plate-Scale Force: Slab Rotation

no good picture yet

Froitzheim et al. (2003)

Importance of 3D

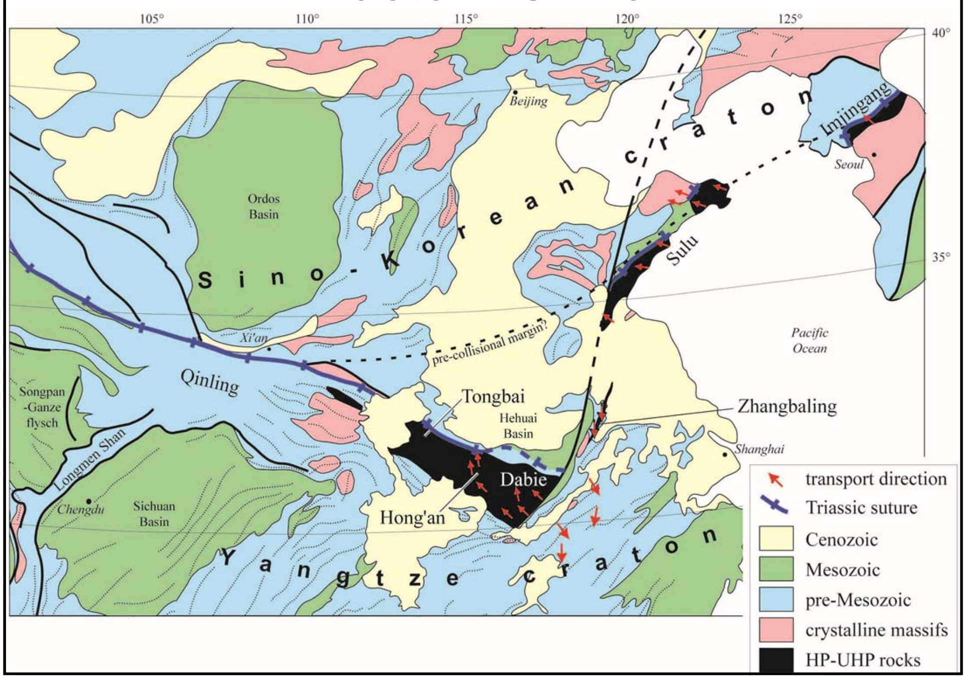


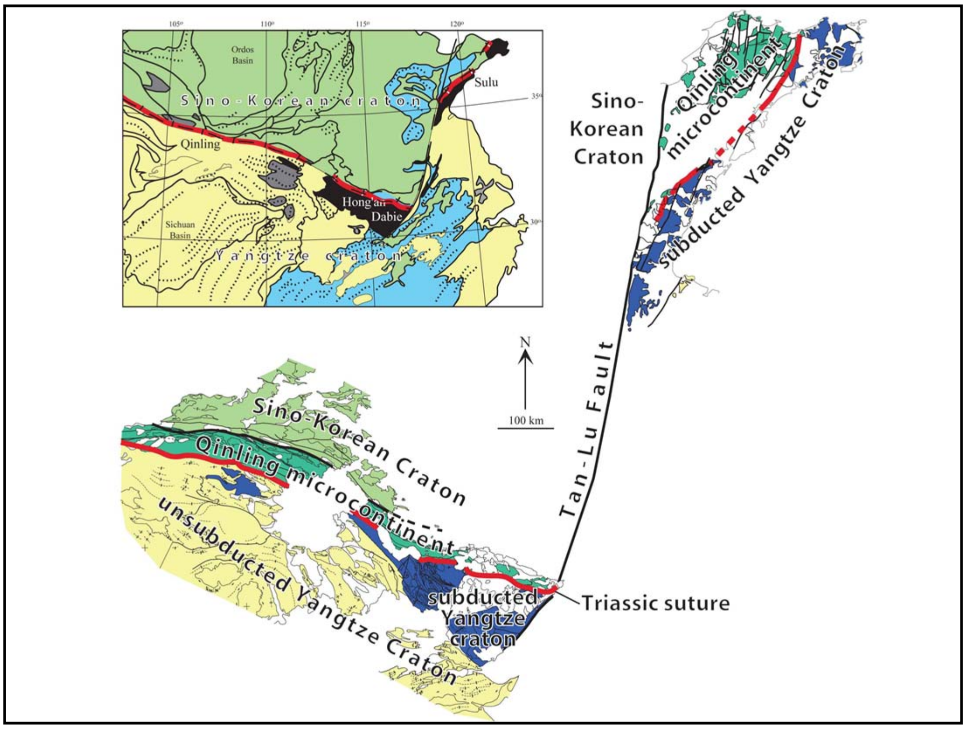


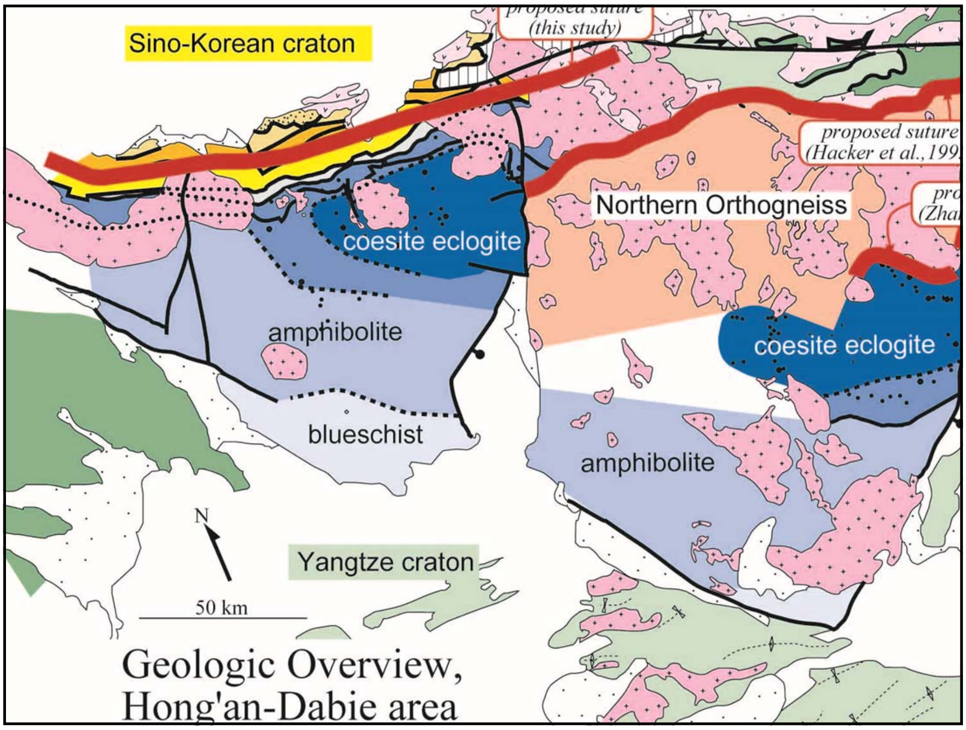
What Do We Need to Know to Determine How UHP Rocks Exhumed?

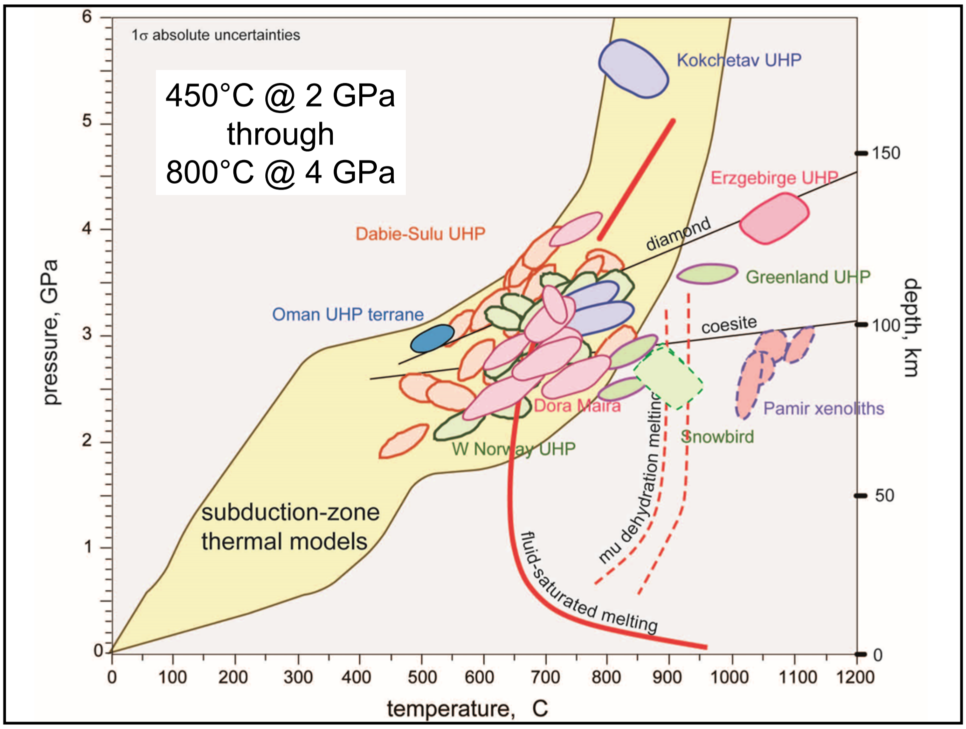
- scale of UHP terrane
  - large or small?
- deformation of terrane & boundaries
  - rigid or diapiric or ?
- rate of exhumation
  - including temporal & spatial variation
- P-T-d history
  - e.g., did slab pond at Moho?

Eastern China

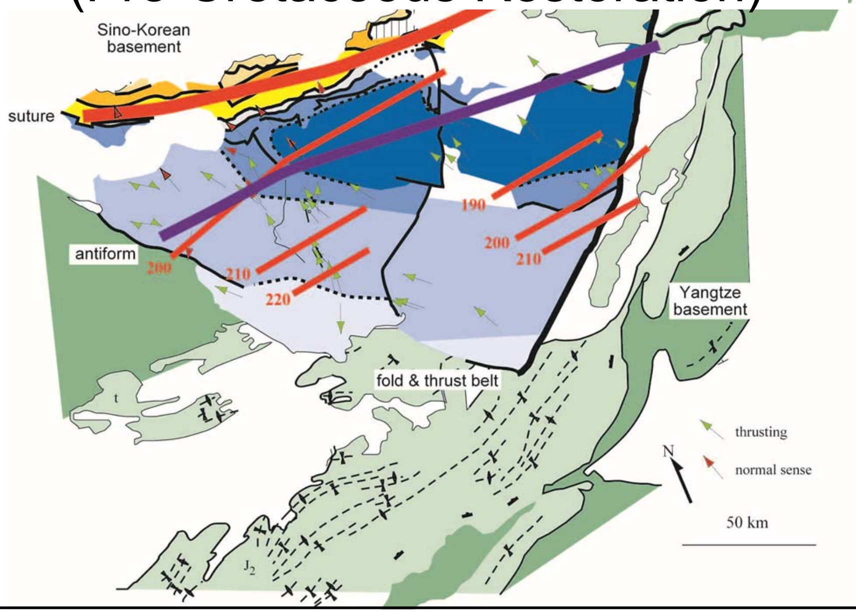



Ordos Basin
Sino-Korean craton
Sulu
Qinling
Hong'an
Dabie
Sichuan Basin
Yangtze craton
Sino-Korean Craton
Qinling microcontinent
subducted Yangtze Craton
Tan-Lu Fault
N
100 km
Sino-Korean Craton
Qinling microcontinent
unsubducted Yangtze Craton
subducted Yangtze craton
Triassic suture

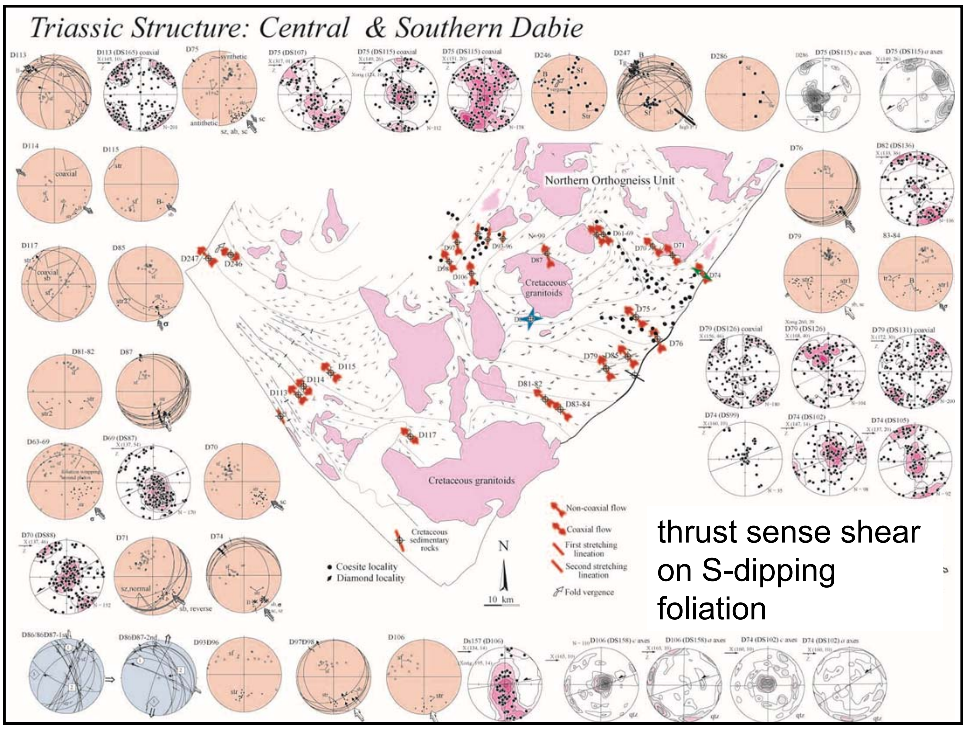

Sino-Korean craton
proposed suture (this study)
proposed suture (Hacker et al.,199
Northern Orthogneiss
coesite eclogite
amphibolite
blueschist
coesite eclogite
amphibolite
N
Yangtze craton
50 km
Geologic Overview, Hong'an-Dabie area

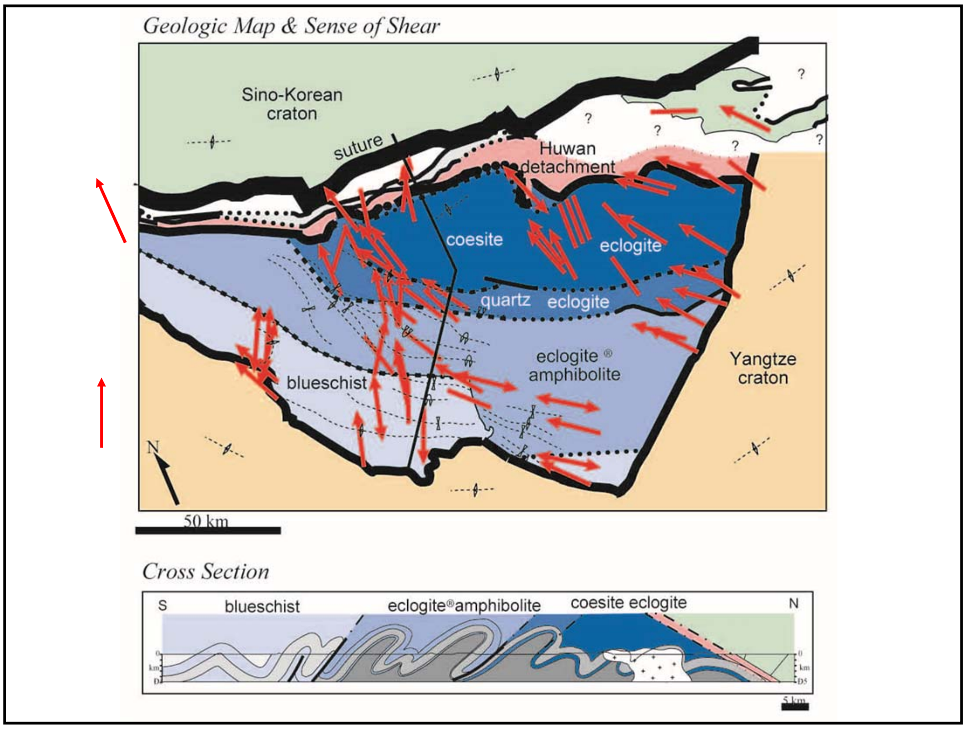


White Mica Age Gradient (Pre-Cretaceous Restoration)

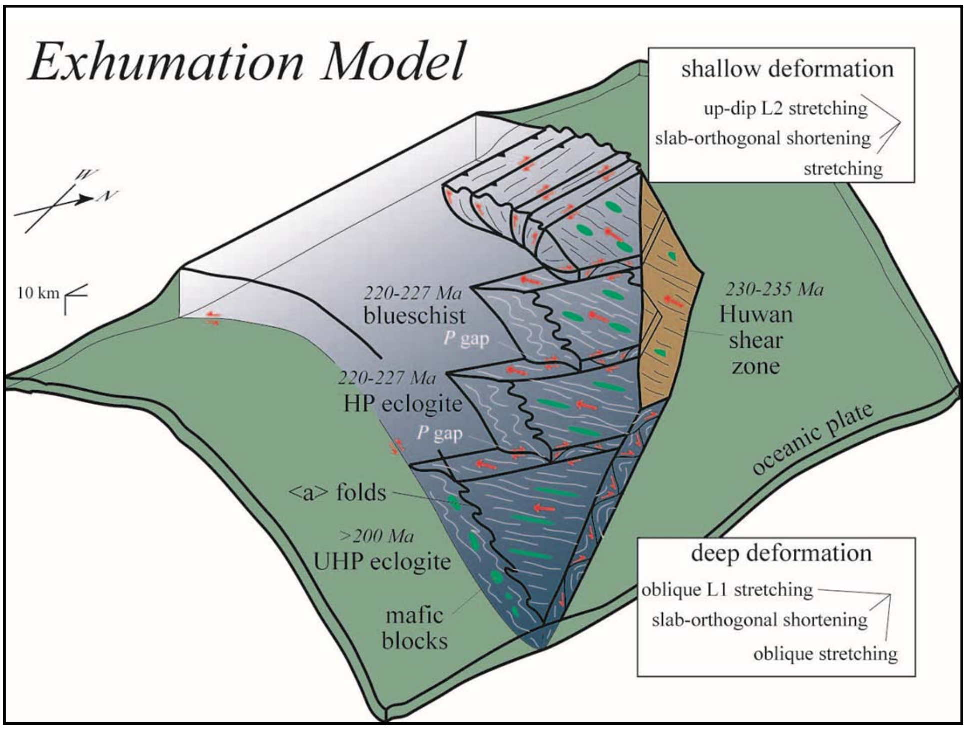



NW

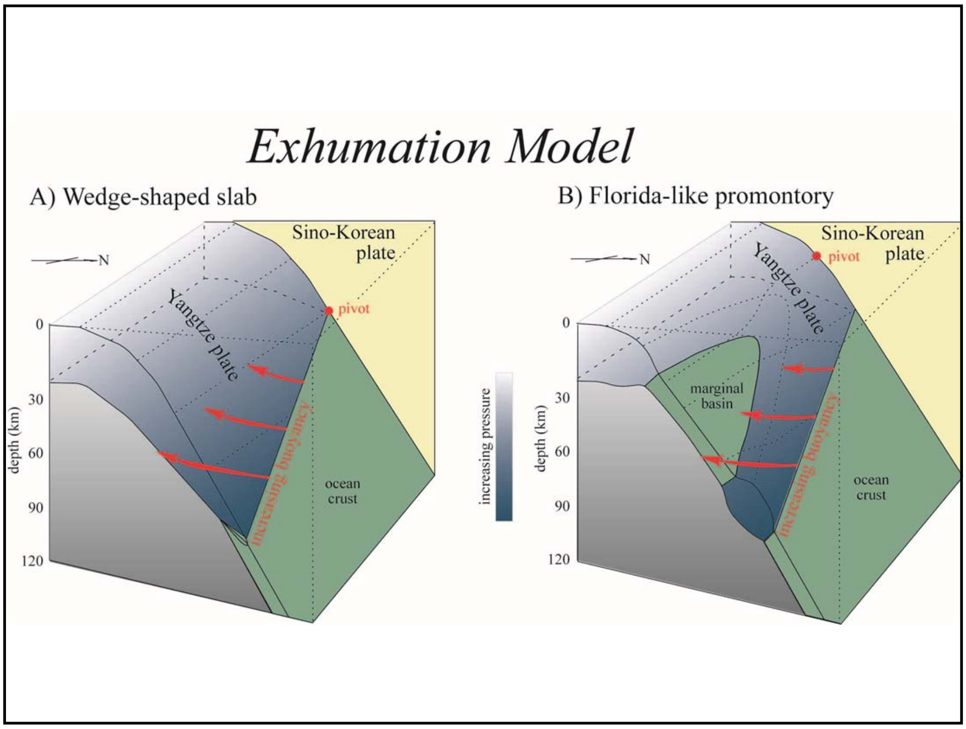

Triassic Structure: Central & Southern Dabie
Northern Orthogneiss Unit
Cretaceous granitoids
Cretaceous granitoids
Cretaceous sedimentary rocks
Non-coaxial flow
Coaxial flow
First stretching lineation
Second stretching lineation
Fold vergence
Coesite locality
Diamond locality
N
10 km
thrust sense shear on S-dipping foliation

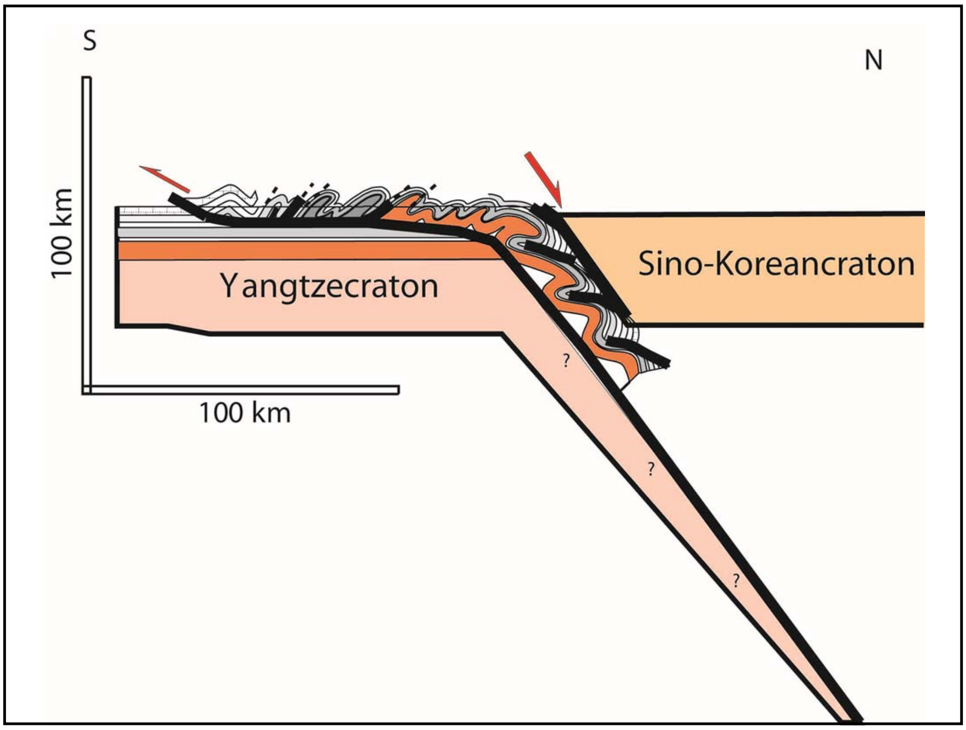


Geologic Map & Sense of Shear
Sino-Korean craton
suture
Huwan detachment
coesite
eclogite
quartz eclogite
eclogite ® amphibolite
blueschist
Yangtze craton
N
50 km
Cross Section
S
blueschist
eclogite®amphibolite
coesite eclogite
N

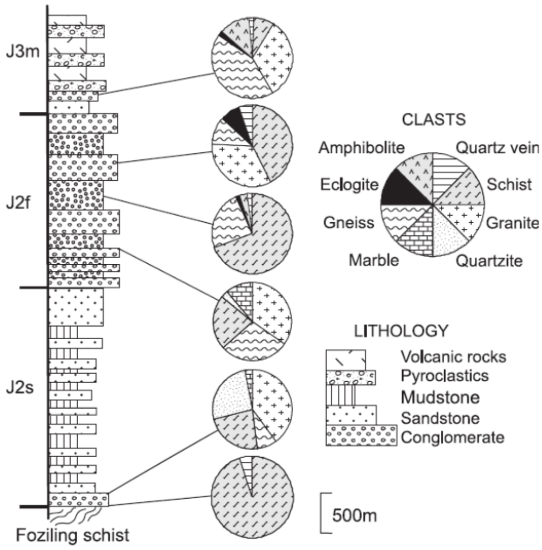


Exhumation Model
shallow deformation
up-dip L2 stretching
slab-orthogonal shortening
stretching
W
N
10 km
220-227 Ma
blueschist
P gap
220-227 Ma
HP eclogite
P gap
<a> folds
>200 Ma
UHP eclogite
mafic blocks
230-235 Ma
Huwan shear zone
oceanic plate
deep deformation
oblique L1 stretching
slab-orthogonal shortening
oblique stretching


Exhumation Model
A) Wedge-shaped slab
B) Florida-like promontory
N
Sino-Korean plate
pivot
Yangtze plate
increasing buoyancy
ocean crust
depth (km)
0
30
60
90
120
increasing pressure
marginal basin

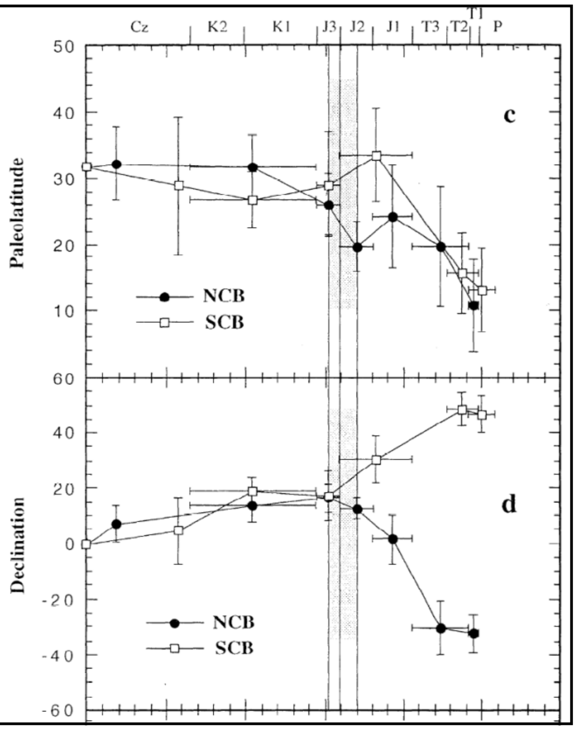

S
N
100 km
100 km
Yangtzecraton
Sino-Koreancraton
?
?
?

UHP Detritus in J2 Basins



Q. Wang et al. (2003)

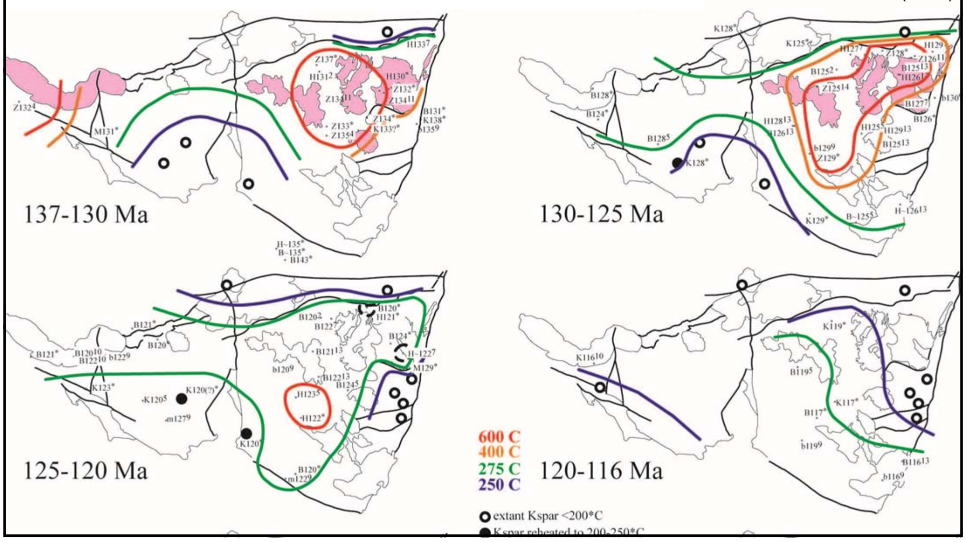
Paleomag Shows Shortening Until Late Jurassic



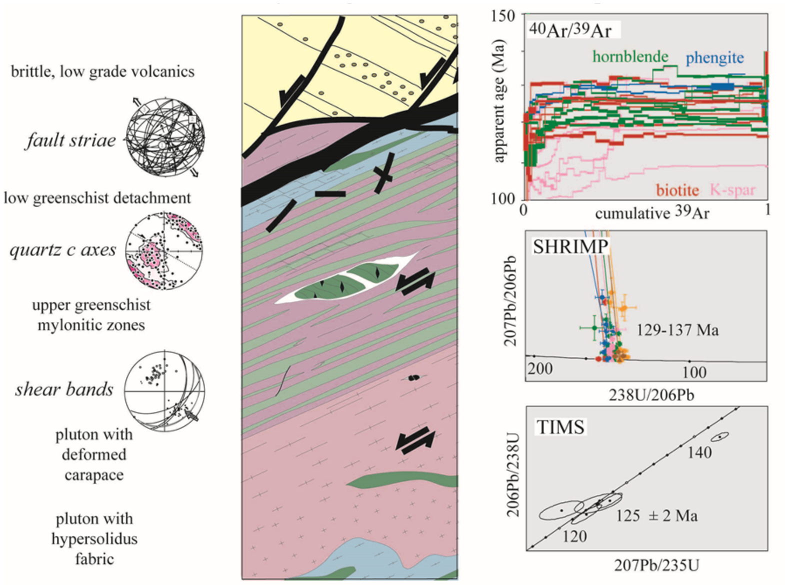
Gilder et al. (1997)

N Dabie Cretaceous Magmatism

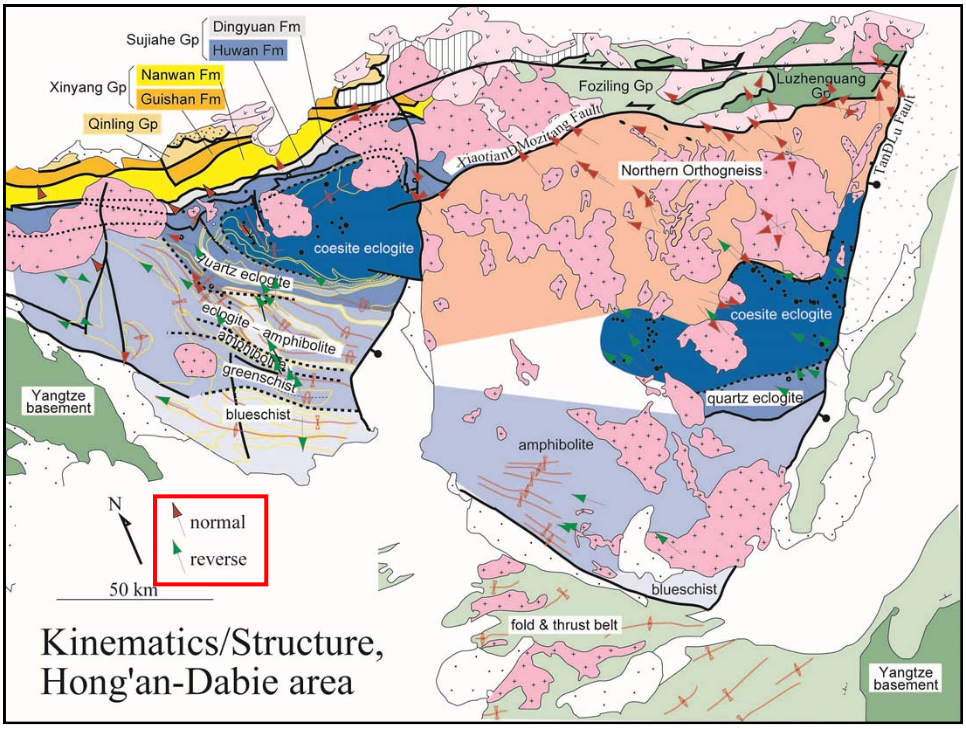
Ratschbacher et al. (2000)

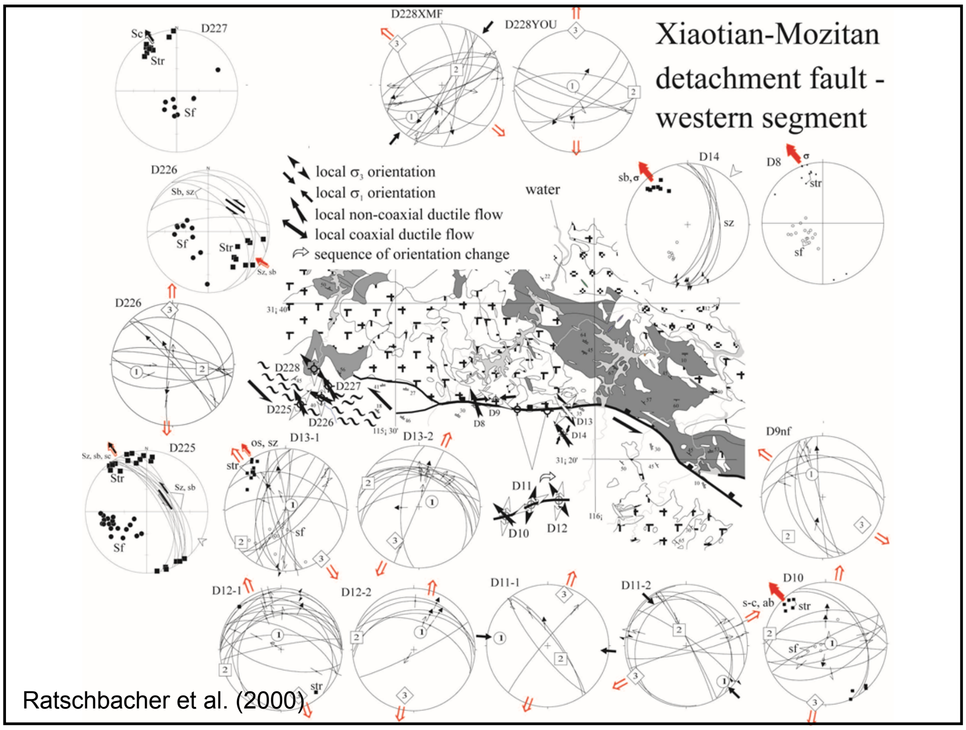


N Dabie Core Complex

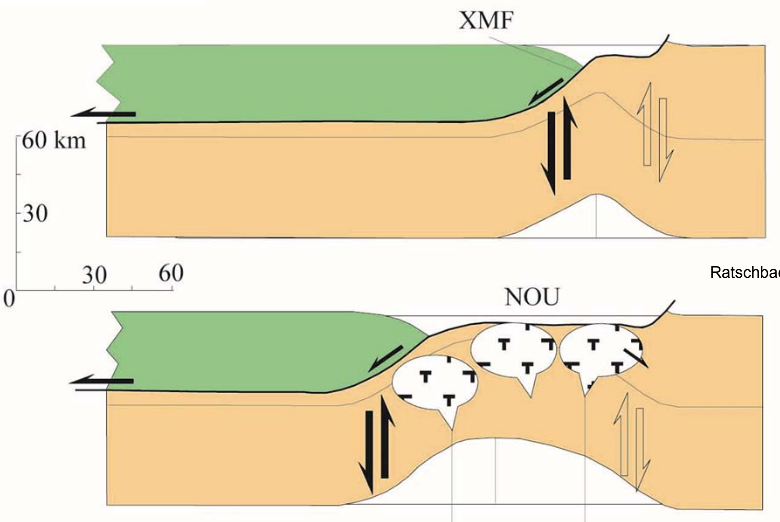


Ratschbacher et al. (2000)


Sujiahe Gp
Dingyuan Fm
Huwan Fm
Xinyang Gp
Nanwan Fm
Guishan Fm
Qinling Gp
Foziling Gp
Luzhenguang Gp
Xiaotian-Mozitang Fault
TanLu Fault
Northern Orthogneiss
coesite eclogite
quartz eclogite
eclogite
amphibolite
greenschist
blueschist
Yangtze basement
normal
reverse
N
50 km
fold & thrust belt
Kinematics/Structure,
Hong'an-Dabie area

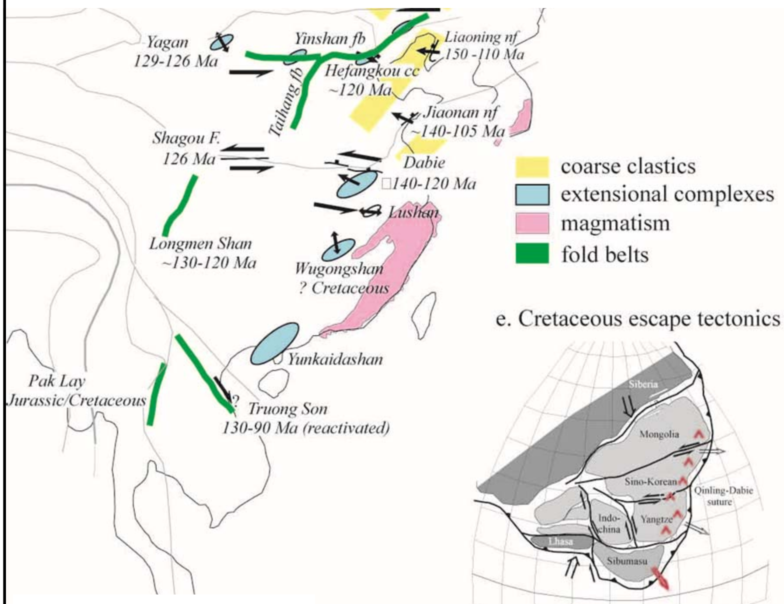

Xiaotian-Mozitan
detachment fault -
western segment
local σ3 orientation
local σ1 orientation
local non-coaxial ductile flow
local coaxial ductile flow
sequence of orientation change
water
Ratschbacher et al. (2000)

N Dabie Core Complex



Ratschbacher et al. (2000)

Cretaceous Overview



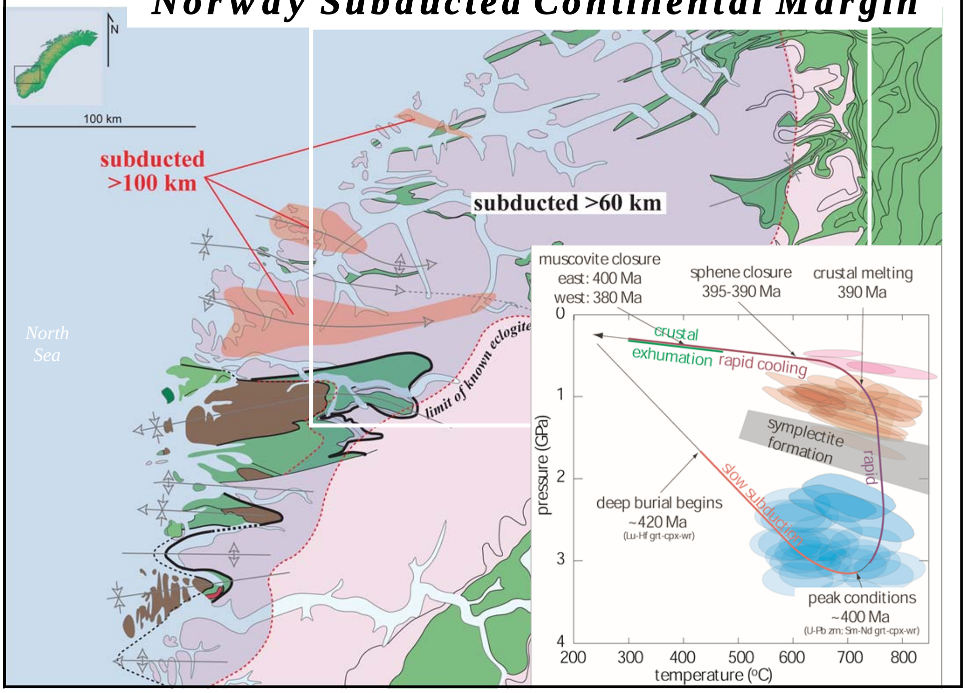
Ratschbacher et al. (2000)

Dabie–Sulu Summary

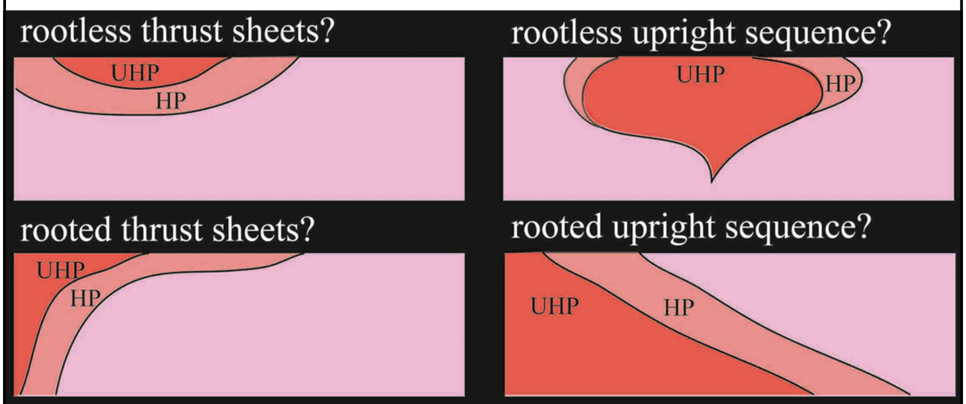
- triangular UHP–HP slab
- >150 km along strike
- >150 km subducted depth
- >10 km thick
- 750 Ma passive margin
- no coeval magmatism
- 825–850°C, 3.3–4.0 GPa
- exhumed in <30 m.y.
  by normal-sense shear
  & subhorizontal extrusion

exhumation by
- buoyancy (up dip+pivot)
- local slab pull (pivot)
- weak lateral boundary (horizontal extrusion)

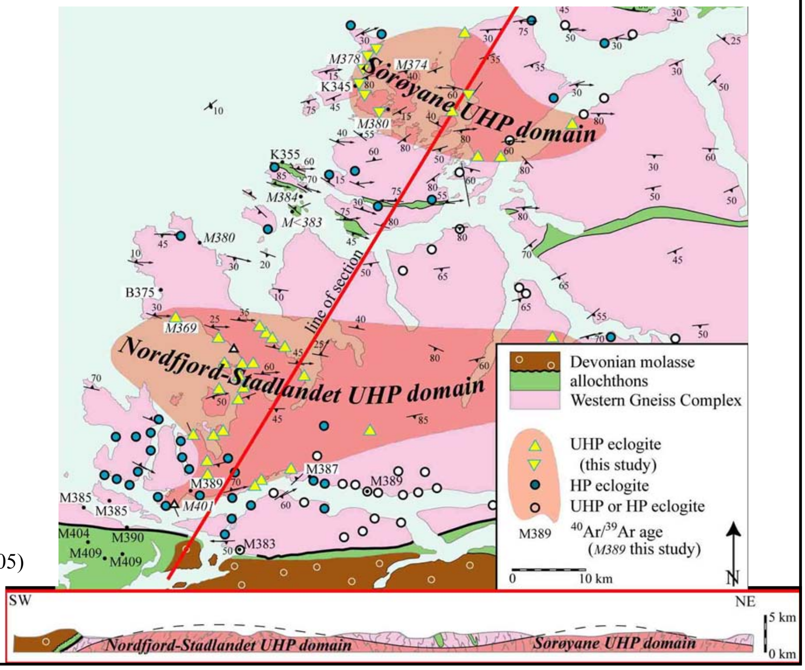
Norway Subducted Continental Margin



Structure & Scale of UHP Terrane

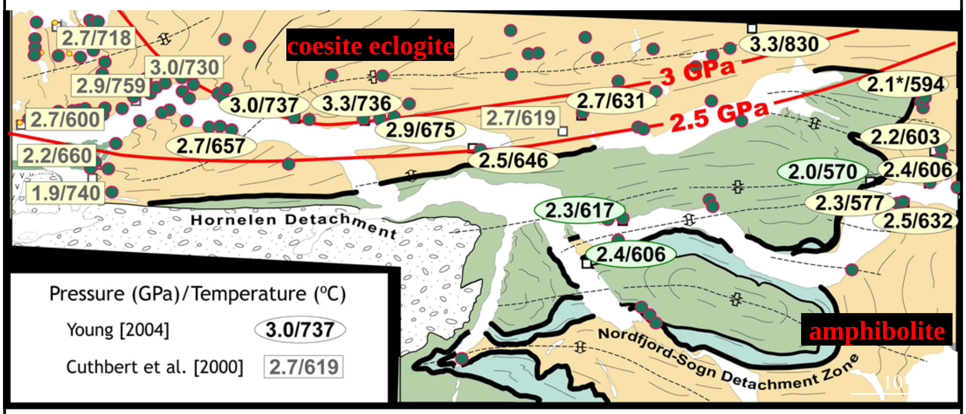


UHP Domains are Distinct



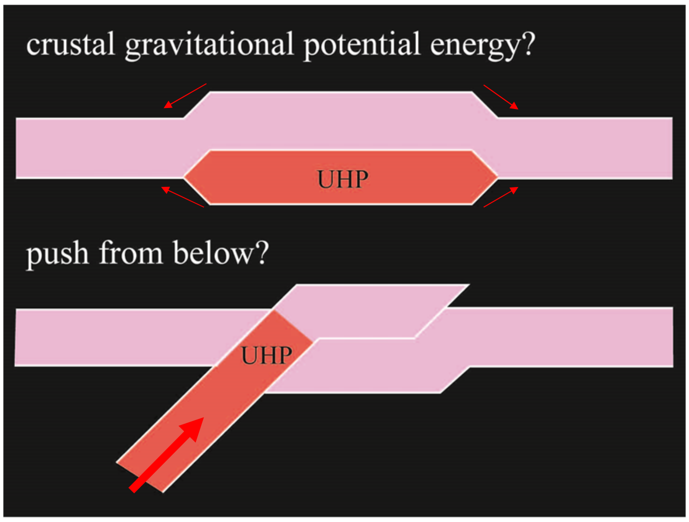
Root et al. (2005)

Continuous, Thinned UHP → HP Gradient

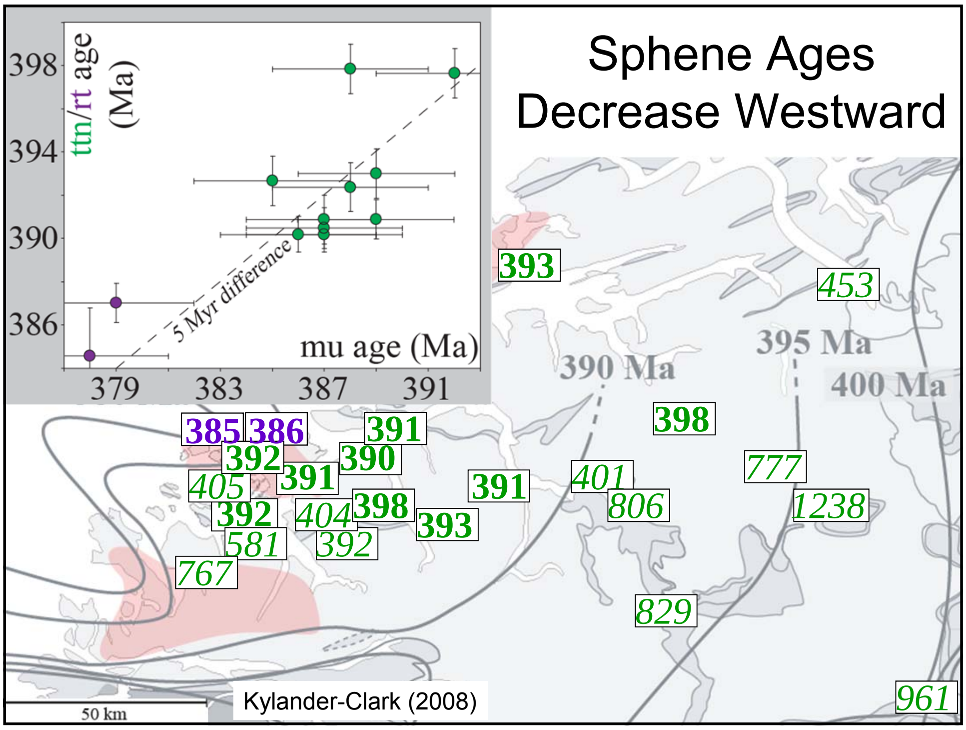


Young et al. (2006)

What Drove Crustal Exhumation?

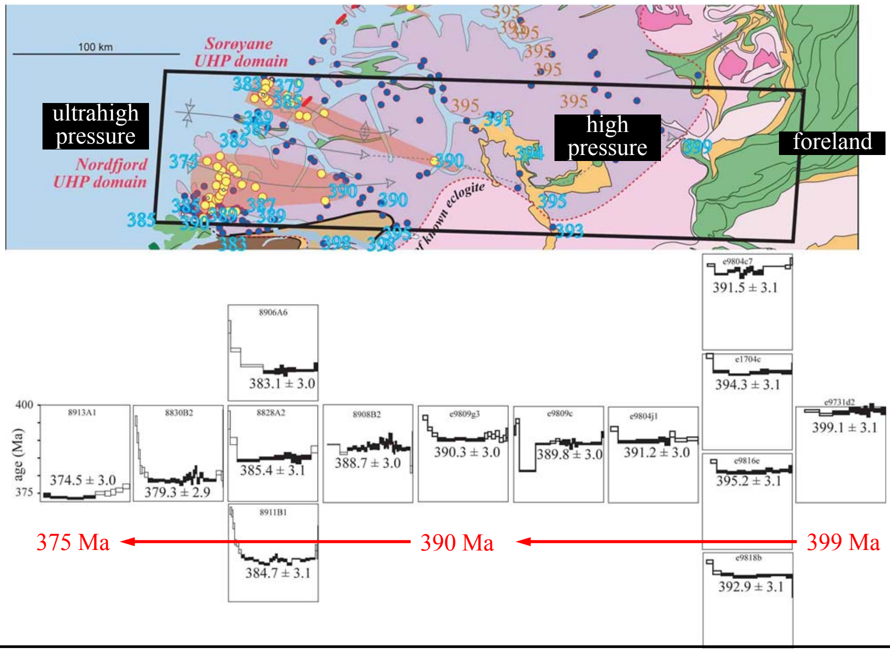


Sphene Ages Decrease Westward



Kylander-Clark (2008)

White-Mica Ages Decrease Westward

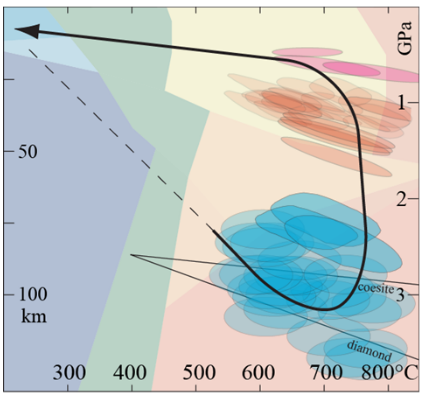


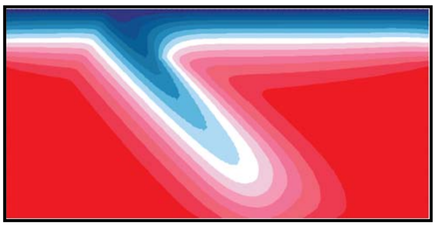
Subduction In Core, Exhumation in Foreland

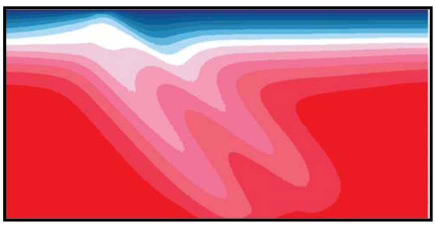
Nic EBSD pic

Thermal model: Thick or thin?

peak: ~750ºC
exhumation: ~750ºC

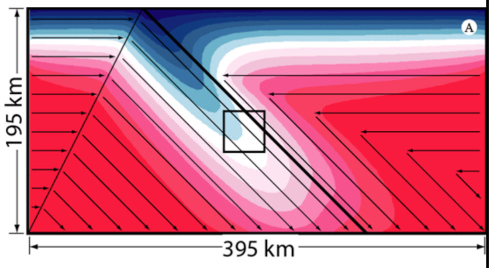


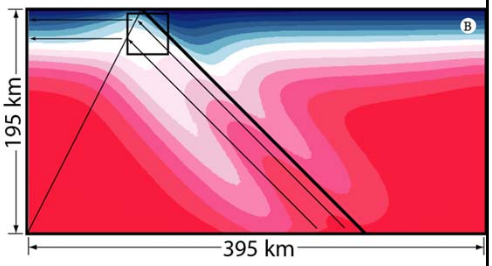




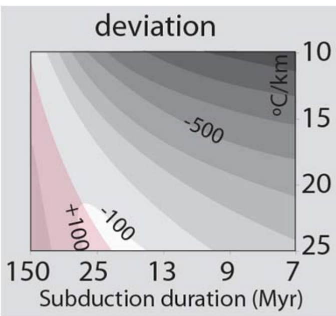
Thermal Model Parameters

- fixed parameters
  - subduction at 45º
  - exhum.: 5 mm/yr (10 Myr)
  - 40 km thick crust
- variables
  - subduction style
    - pre-existing
    - incipient
  - thermal profile
    - 10–25ºC/km
  - subduction rate
    - 1–21 mm/yr plate velocity
    - 0.7–15 mm/yr vertical rate





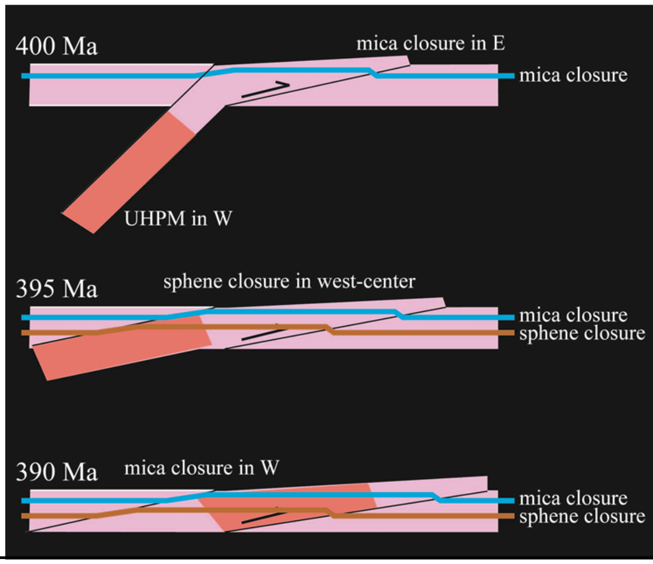
Best fit model



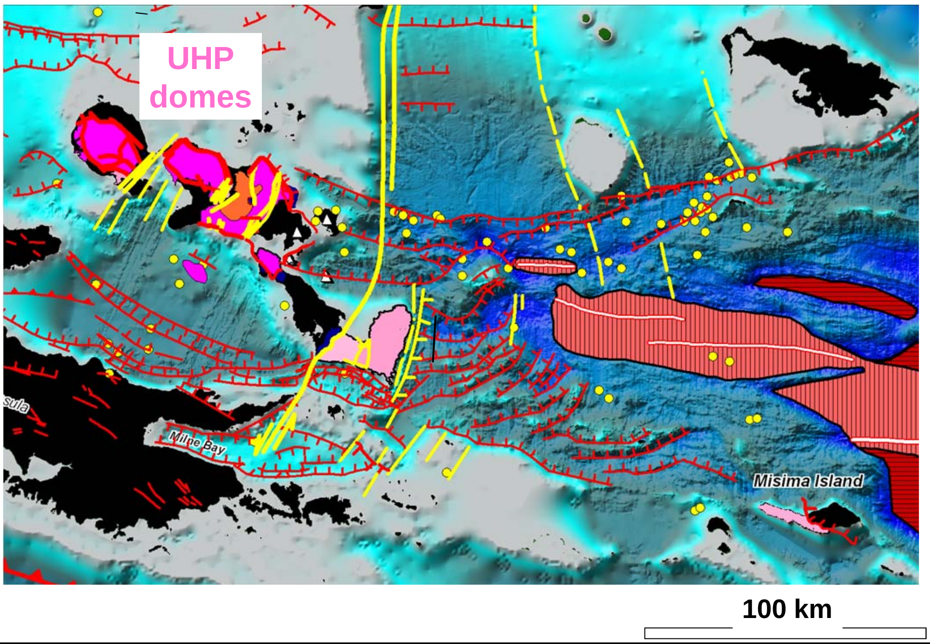
- thick slab (>20 km)
- intracontinental subduction
- hot initial geotherm
- slow subduction rate

Tectonic Model

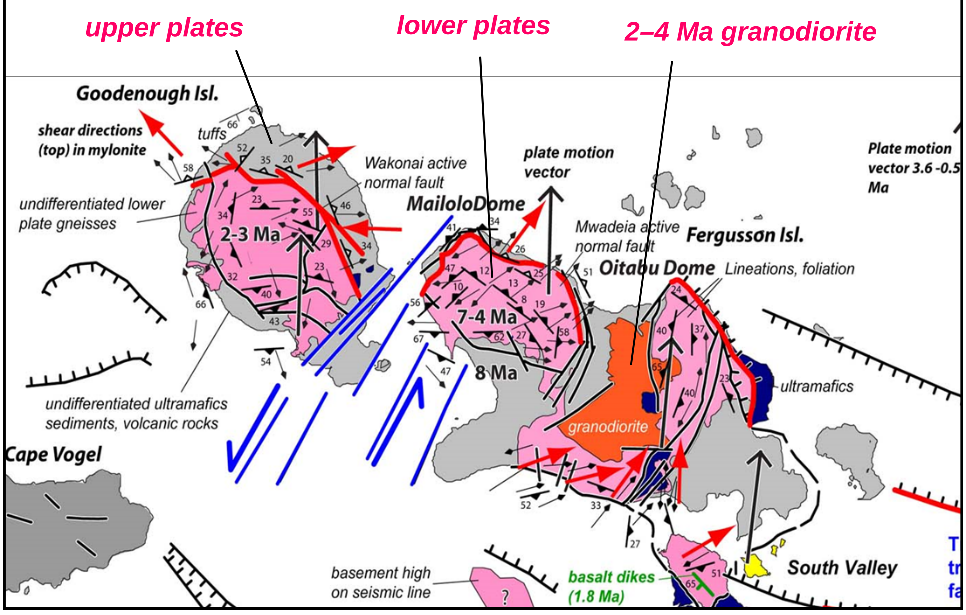
coherent, 40-km thick UHP ‘porpoise’



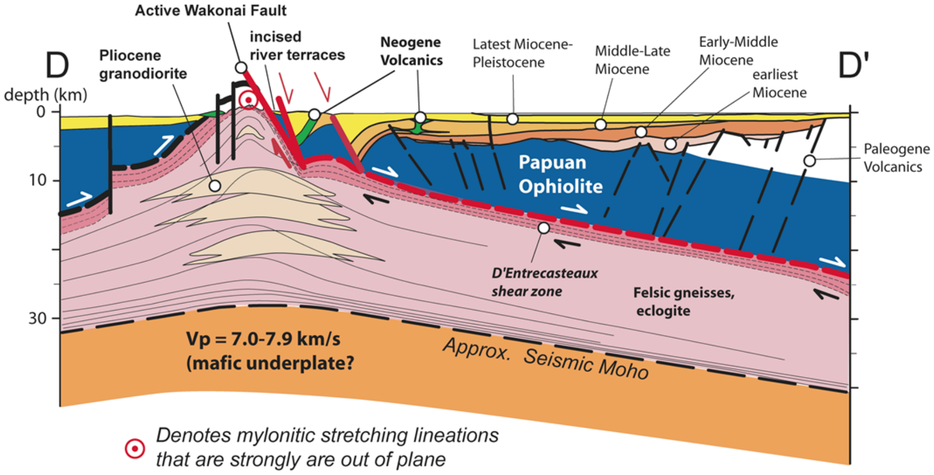
New Guinea: the Youngest UHP Domain



Structural Overview



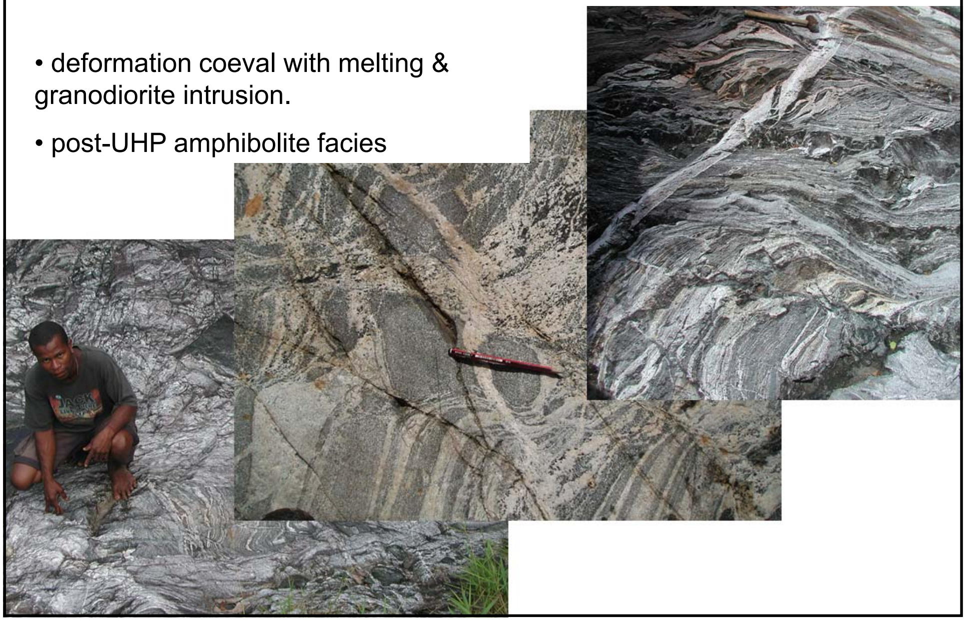
Larger-Scale Structural Setting



Francis et al. (1987); Taylor and Huchon (2002)

Core Zone Gneiss

- deformation coeval with melting & granodiorite intrusion.
- post-UHP amphibolite facies



Rapid, Isothermal Exhumation

eclogites as young as 2 Ma

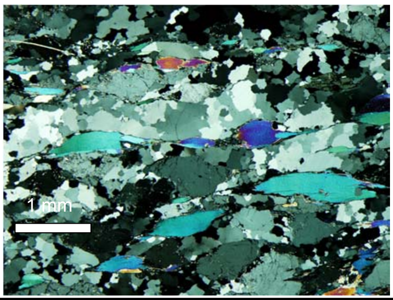
hornblende ~2.4–2.7 Ma

mica 1.4–1.9 Ma

apatite FT: 0.4–0.9 Ma

(Baldwin et al.; Hill & Baldwin, 1993;Monteleone et al., 2007)

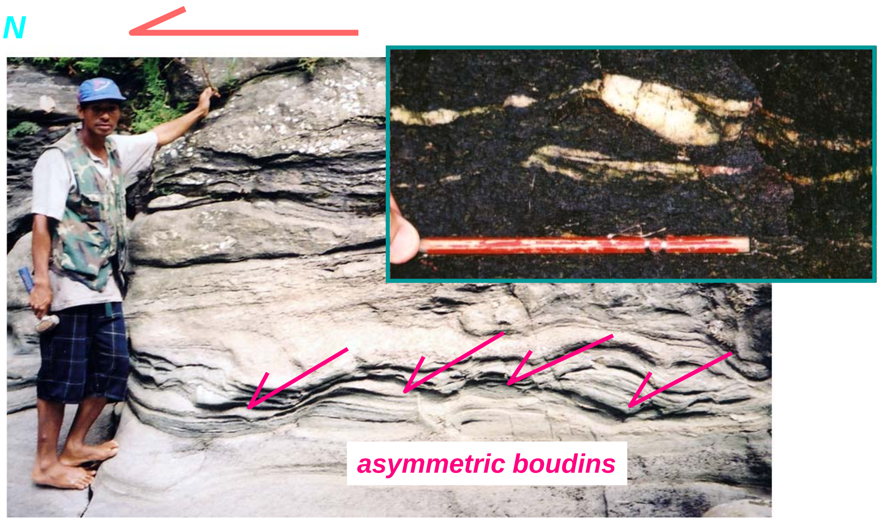
1 km Mylonitic Carapace Above Core

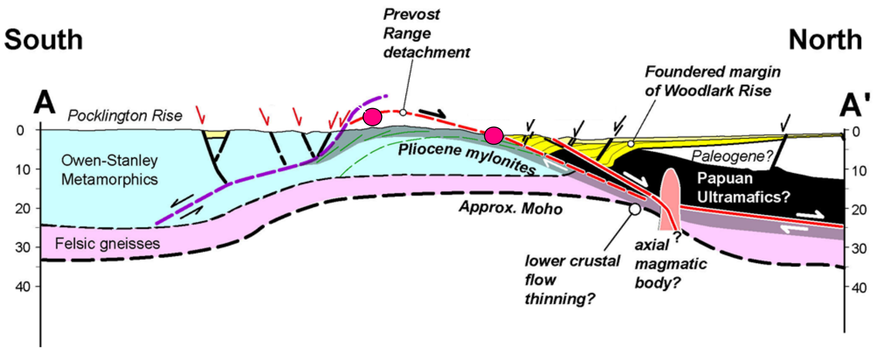


mylonitization during melting & amphibolite facies

concordant with core fabrics, but higher strain

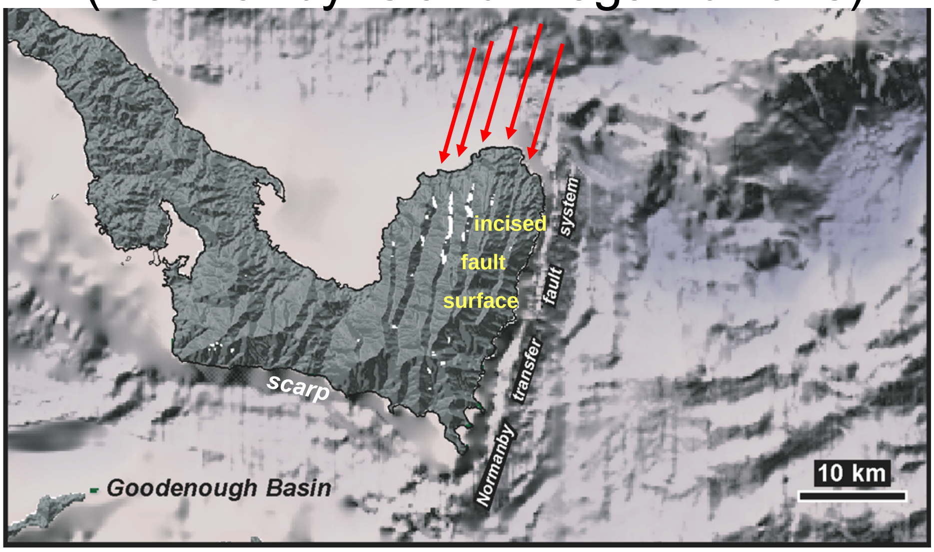
Ductile Extension





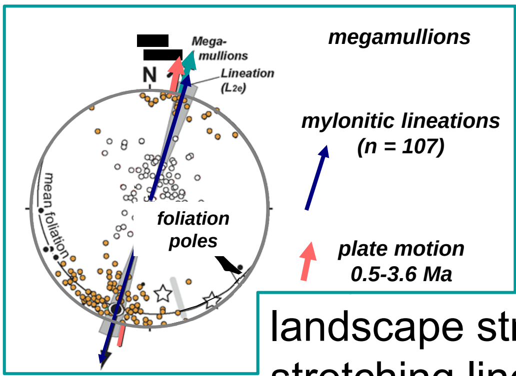
- mylonite muscovite closure ages imply W propagation of extension @ ~50 km/Ma)
- >50 km of dip slip in <5 Myr = >10 mm/yr. Ar age gradient parallel to dip implies slip rate of >24 ±5 mm/yr (near plate-tectonic rate)

Brittle–Ductile Detachments (Normanby Island megamullions)



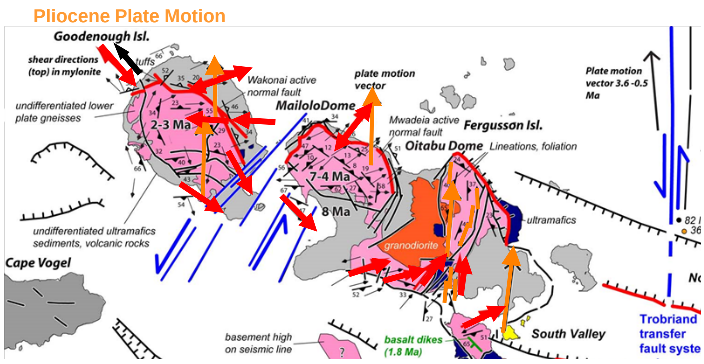
Little et al., 2006

Brittle–Ductile Faults Dominate Plate Tectonic “budget”



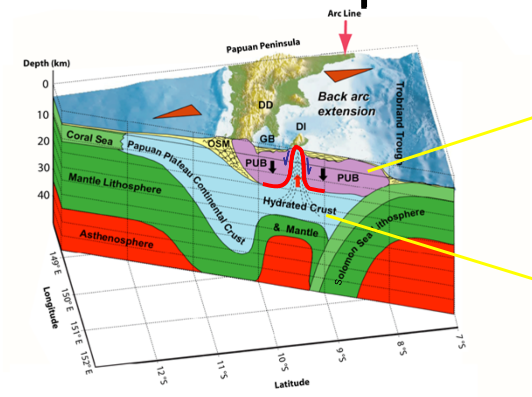
landscape striae & stretching lineations parallel to plate motion

Ductile Lineations not Radial & not Parallel to Plate Motion



- *eclogites may young westward*
- *shear sense top-E on S sides of domes & top-W on N sides*

Crustal Diapir Model



dense ophiolite

weak, hot, lower-density felsic crust

Does not explain

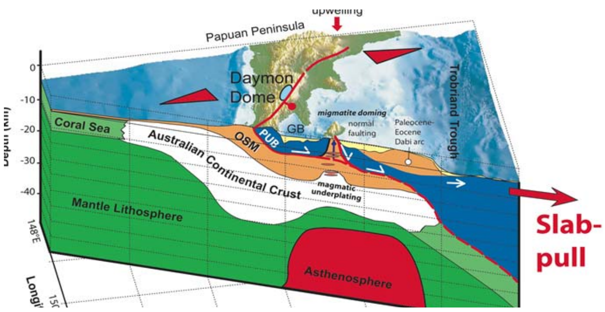
1. young UHP metamorphism

2. non-radial lineation pattern

3. dominance of top-NE shear on domes

4. active normal faults

Microplate Rotation–Slab-Reversal Model

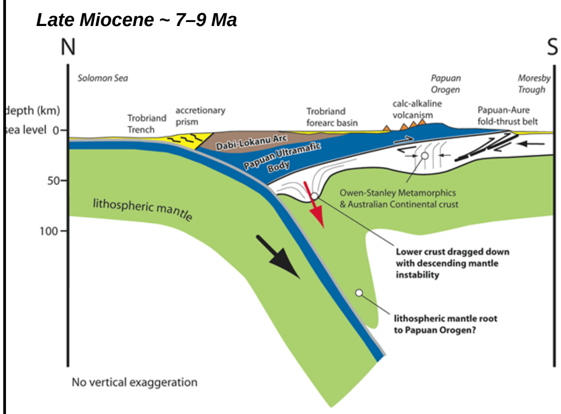


Minuses:
Plate motion since 7 Ma insufficient to carry HP rocks from 100 km at 2–3 cm/yr (PUB is gently dipping).

Does not explain
- why HP metamorphism is so young
- NE-trending lineation pattern oblique to plate motion
- uplift of domes or their foliation pattern

(e.g., Webb et al., in prep.)

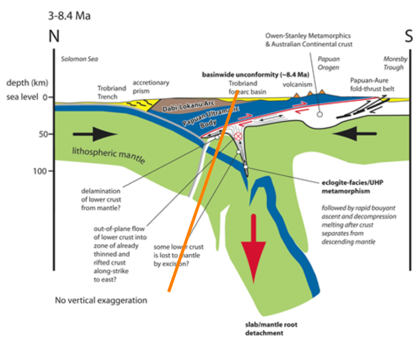
Two-stage, Mantle Delamination–Crustal Slingshot Model

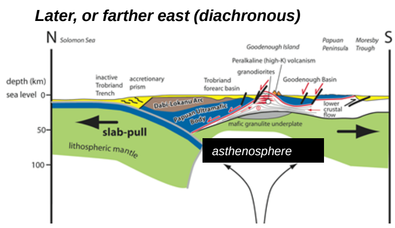


Trobriand subduction waning

Papuan–Peninsular Orogen reactivated. 20–30 km further shortening causes unstable mantle “drip” that pulls lower crust down

Mantle Delamination Propagates Westward





Woodlark Rift begins: asthenospheric upwelling, rift volcanism

lower crustal blob folded into mantle & enjoys UHPM. After delamination from mantle it rebounds (“sling-shot”); widespread melting during ascent.

buoyant return flow of “bolus” is up-dip along the PUB “lid” *and* rift-parallel

extensional necking of “lid” allows low-density “bolus” to breach as gneiss domes

Advantages of Mantle Delamination–Slingshot Model

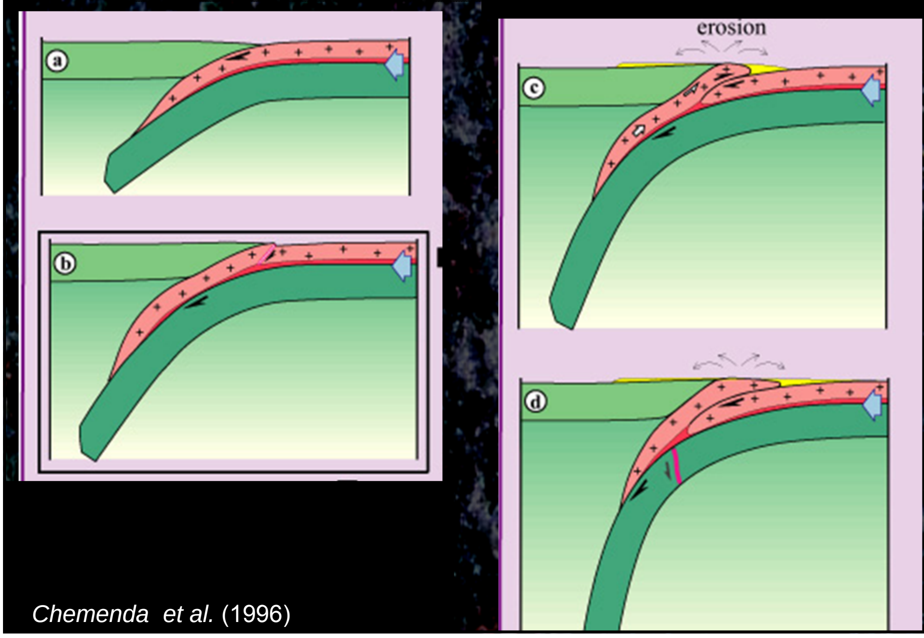
1. Links UHPM & continental rifting
2. Explains young UHP metamorphism
3. Explains rapid ascent (2–3 cm/yr) of UHP rocks & near-isothermal decompression
4. Explains D'Entrecasteaux gneiss domes & pattern of stretching lineations & shear sense
5. Explains death of Trobriand subduction system, sudden(?) appearance of mantle-derived (incl. adakitic) volcanic rocks, & onset of rapid Woodlark extension (slab-pull imbalance)

Conclusions for New Guinea

- "Classical" MCC's in eastern Woodlark Rift (Misima, Normanby Islands) predate lithospheric breakup by 3–7 m.y.
- Prolonged, rapid slip occurs on single normal faults, rotating them to low dips. These accommodate 10's km of slip at 1–2 cm/yr in the plate-motion direction, and are a chief element of the rift strain budget.
- Lower crust of the Woodlark rift is weak and flowed laterally for 10's km to remove crustal thickness gradients in <5 Myr.
- Young UHP rocks in a rift setting & their return to the surface at 2–3 cm/yr, volcanism & sudden onset of extension can be explained by a "slingshot" model that combines crustal diapirism/extensional flow with translation of an ophiolitic lid to unroof the rocks. Rifting & UHPM are linked by a mantle delamination process that evolved westward.

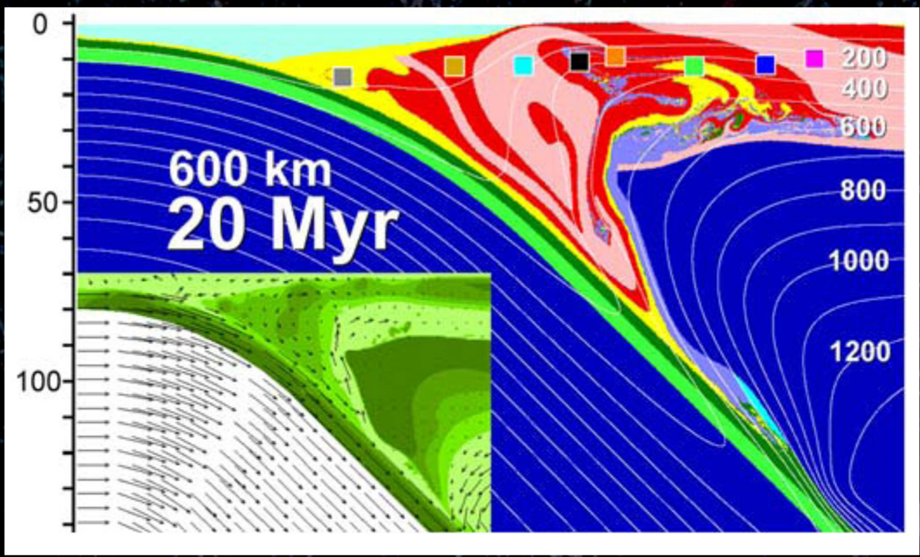
Models

'Chemenda' Models



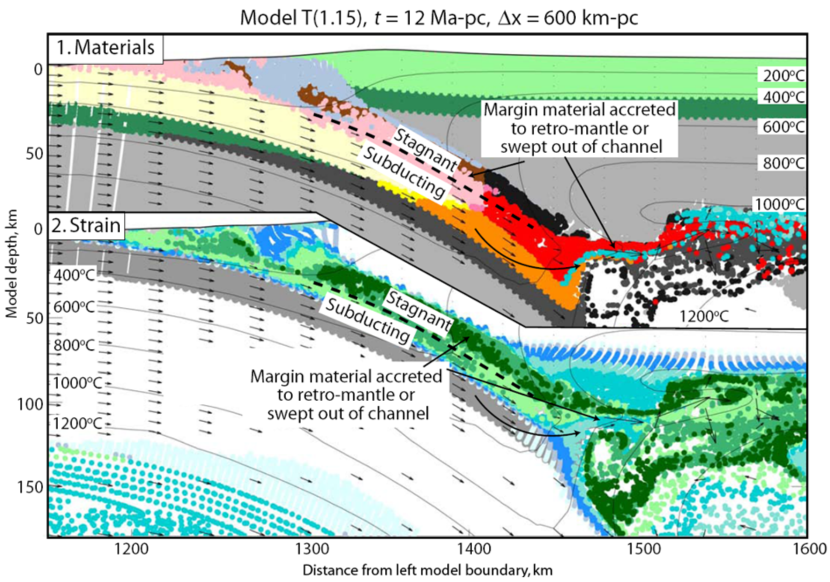
Chemenda et al. (1996)

Gooey Geodynamic Models



Gerya & Stöckhert [2006]

Reasonable Model



Warren et al. (2008)