# Rheology at Ultrahigh Pressure

- principal questions
- relevance of rheology
- model rheologies
- field observations that constrain rheology

## Principal Questions

- Deformation Partitioning

  subducted & exhumed as coherent & intact sheet

  or strongly deformed?
- Size of UHP body

  km or hundreds of km?
- Transformation volume

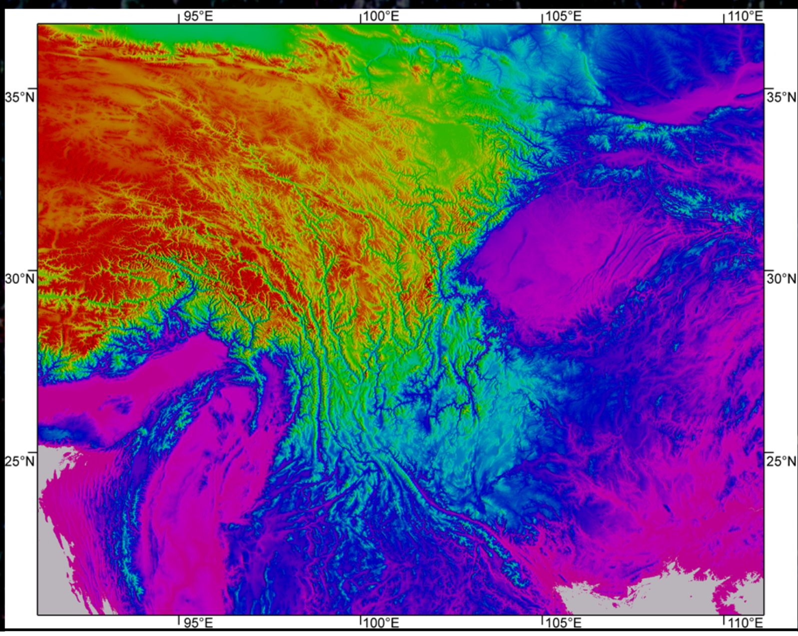
  local or wholesale?

# Relevance of this Inquiry

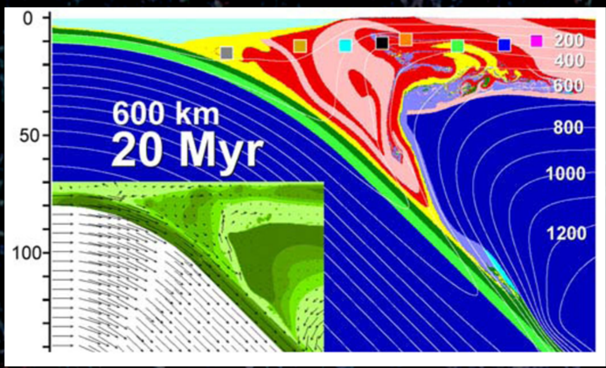
Answers to these questions bear on

- rheology of quartzofeldspathic (lower) crust
- magnitude of stress
- body forces available to effect subduction or exhumation
- applicability of geodynamic models

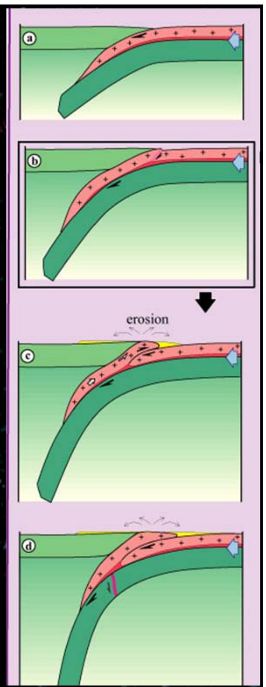
# Expectations of Lower Crustal Flow



# Gooey Geodynamic Models



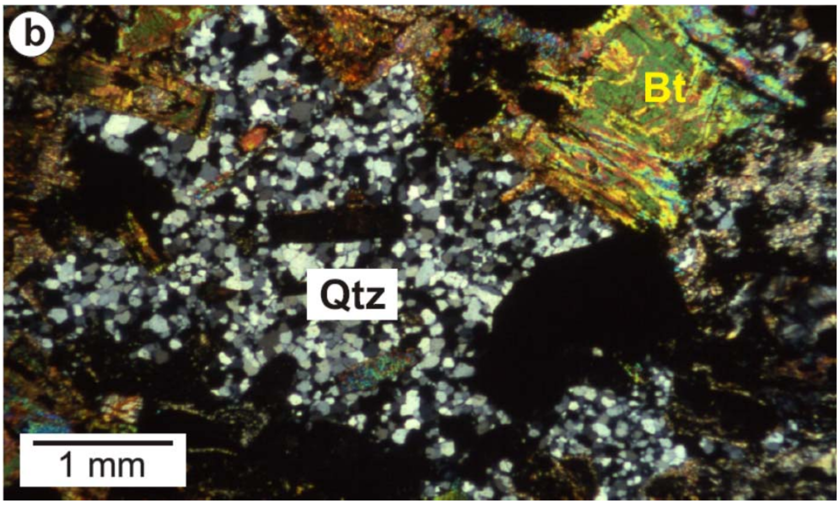

*Gerya & Stöckhert* [2006]




*Chemenda et al.* (1996)

# Example of High Strength at High P&T

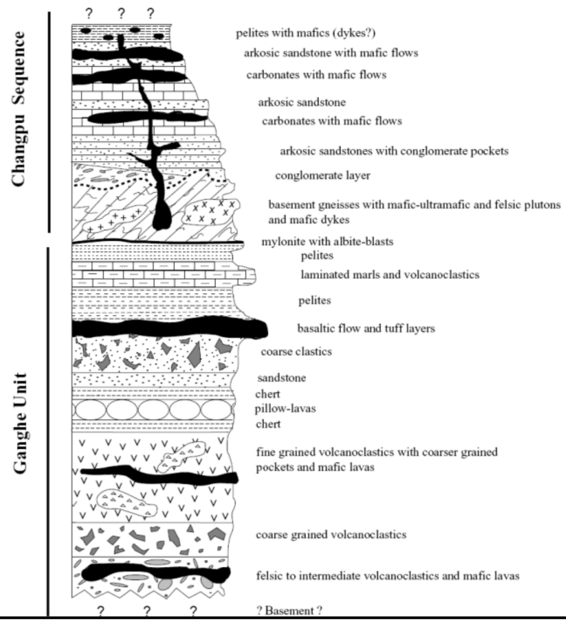
# Undeformed coesite pseudomorphs




Dora Maira

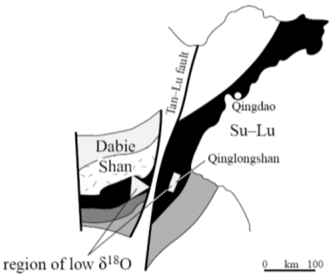
Compagnoni & Rolfo (2003)

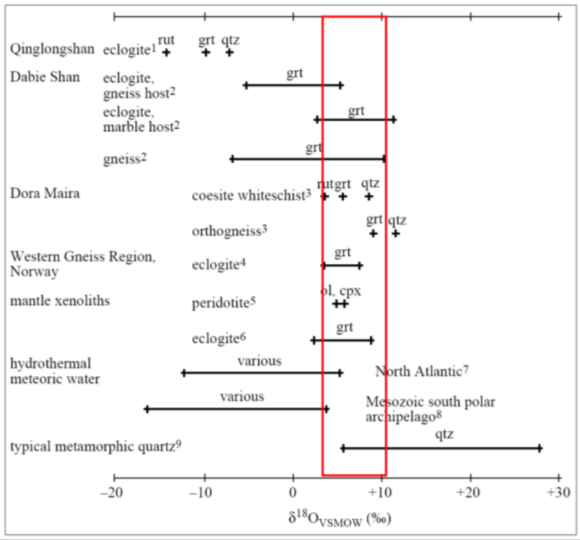
# Preserved Supracrustal Sequence




Schmid (2000)

# Preserved Hydrothermal Alteration

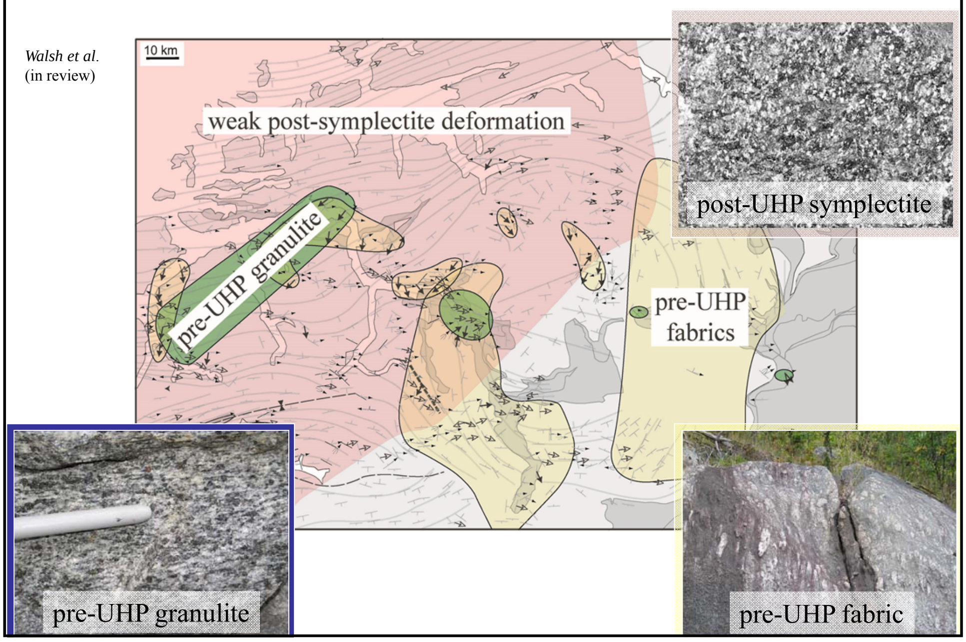


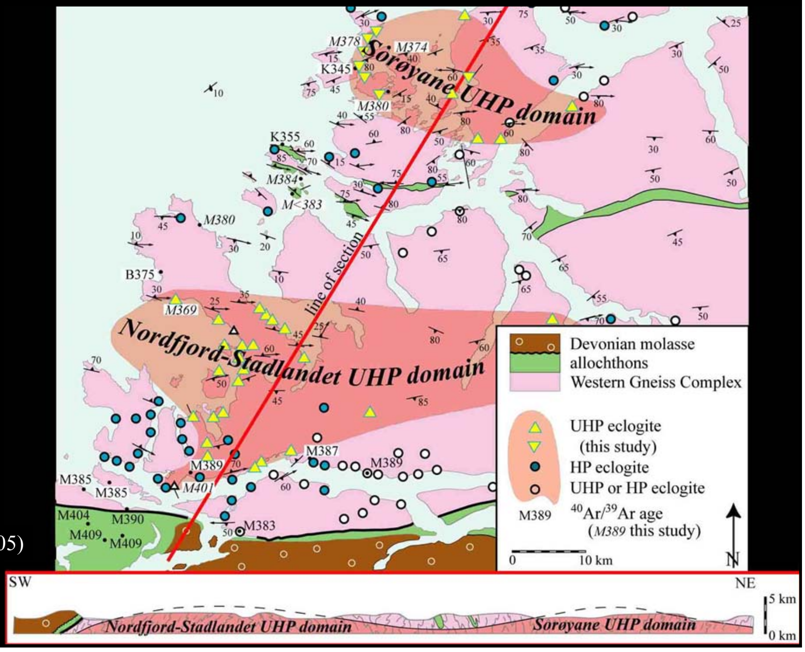

Rumble et al. (1998)

# Preserved pre-UHP Features on Regional Scale

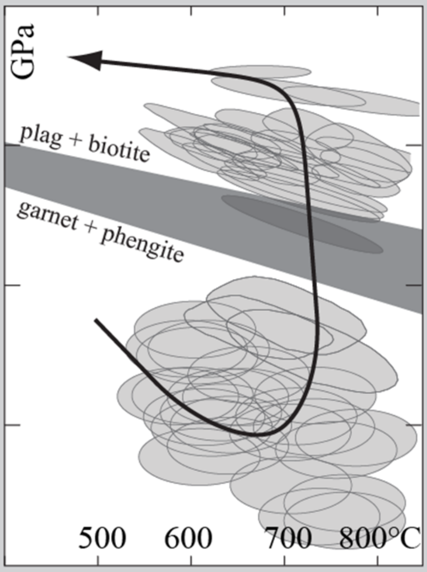
*Walsh et al.*
(in review)



# Discrete UHP Domain Boundaries




*Root et al.* (2005)

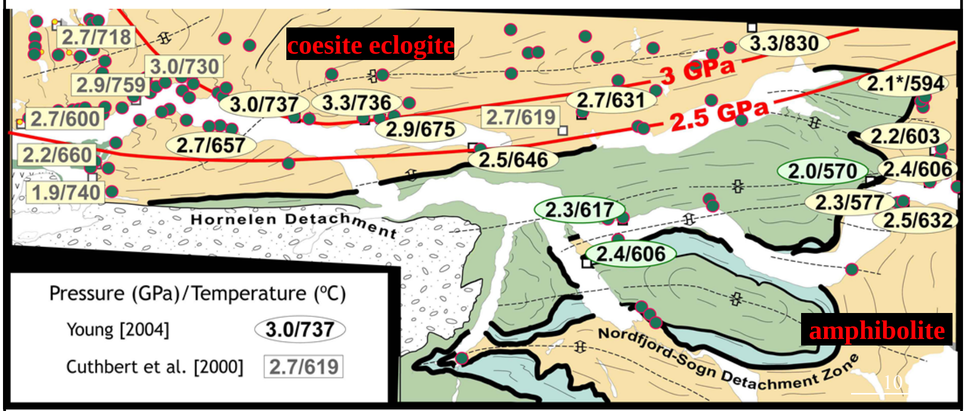



static overprint

no deformation
<1.5 GPa

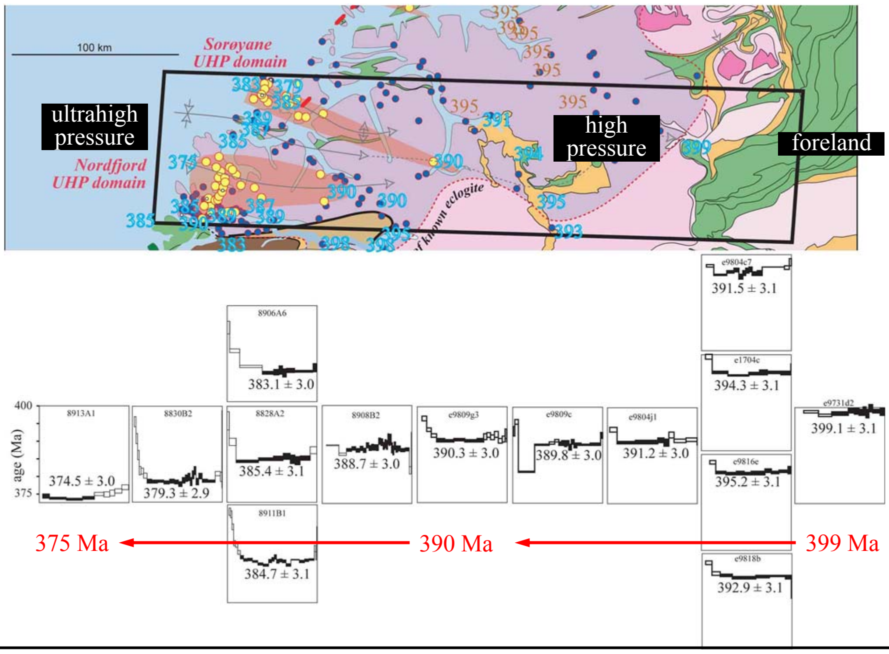
# Continuous UHP → HP Gradient, Norway

~2X vertical thinning

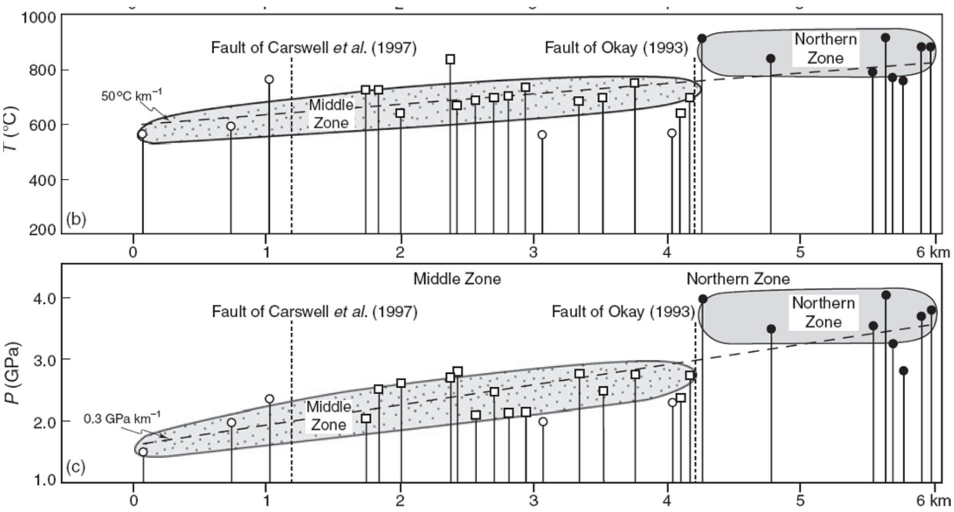



*Young et al.* (2007)

# Smooth White Mica Age Gradient



## Continuous UHP → HP Gradient, Dabie



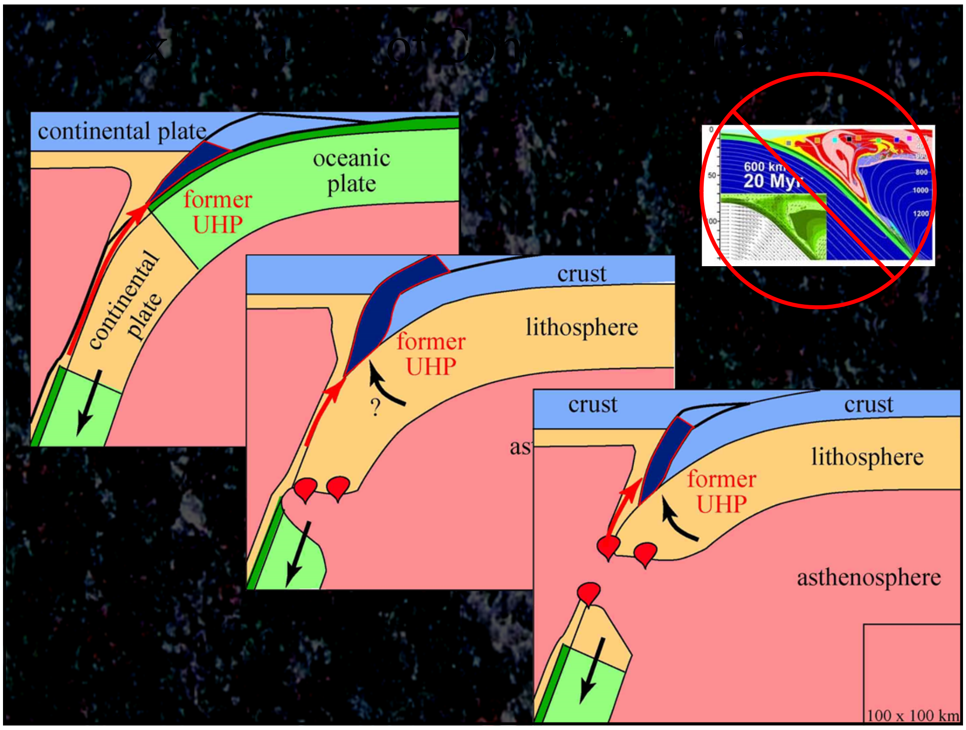

Dabie Shan

Shi & Wang (2006)

## Relatively Coherent Slab

- smooth eclogite *P*–*T* gradient
- smooth muscovite age gradient
- allochthons extend across orogen
- E-ward diminishing deformation
- wholesale transformation to hi *P* & low *P*

60,000 $km^2$ x 20 km ≈ $10^6$ $km^3$




# Greater Significance

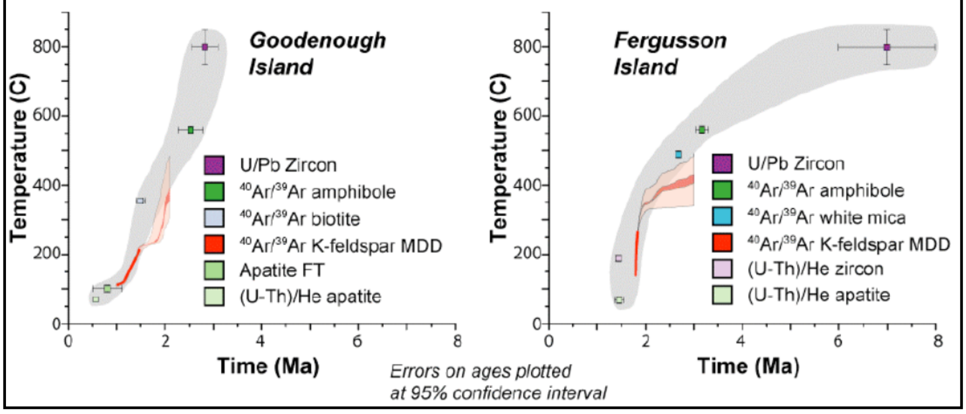
rheology observations indicate

- stresses are low or quartzofeldspathic crust is strong
- new geodynamic models are needed

# Rates of UHP Tectonic Processes

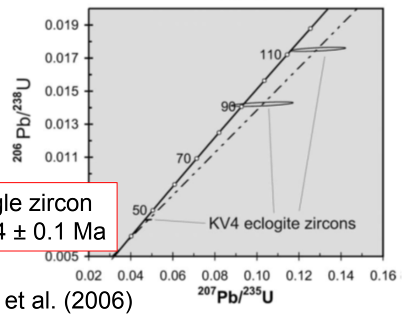
- rate/duration of continental subduction?
- rate/duration of exhumation?

# New Guinea 3–7 Myr

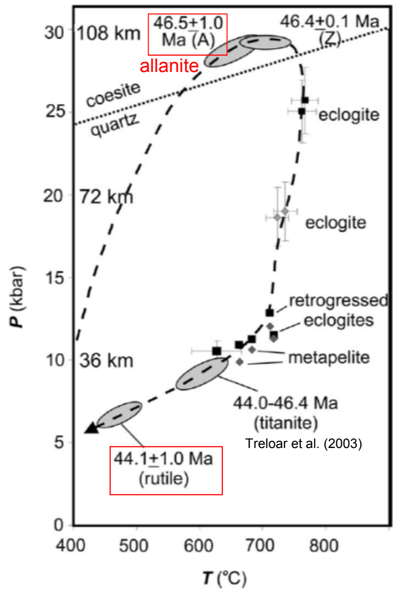


# Kaghan Valley, Pakistan

zircon/allanite – rutile
46.4 ± 0.1 – 44.1 ± 1.0 Ma
= 2.2 Myr for ~75 km

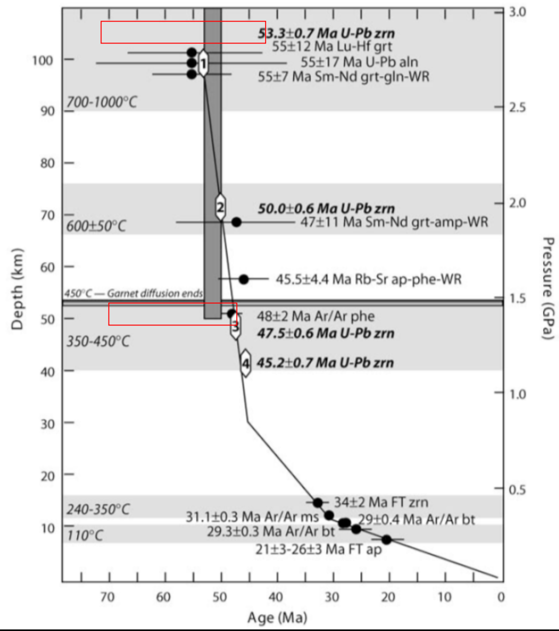



Parrish et al. (2006)



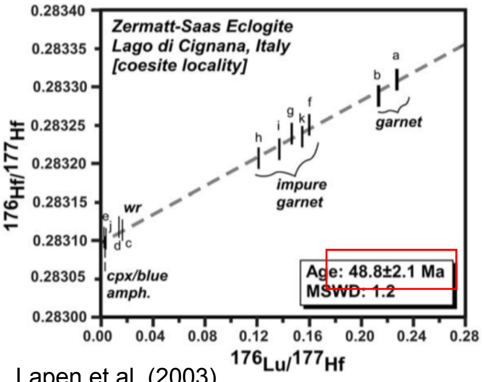

# Tso Morari, India

zircon – phengite
53.3 ± 0.7 – 48 ± 2 Ma
= 5 Myr for ~50 km



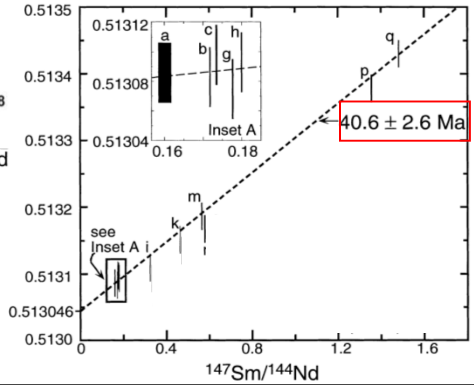

Leech et al. (2007)

# Lago Cignana



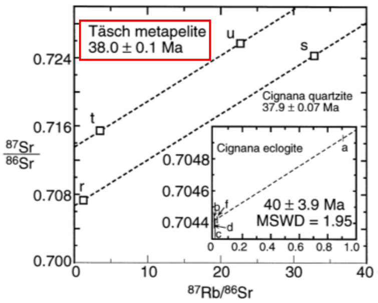

Lapen et al. (2003)

Amato et al. (1999)



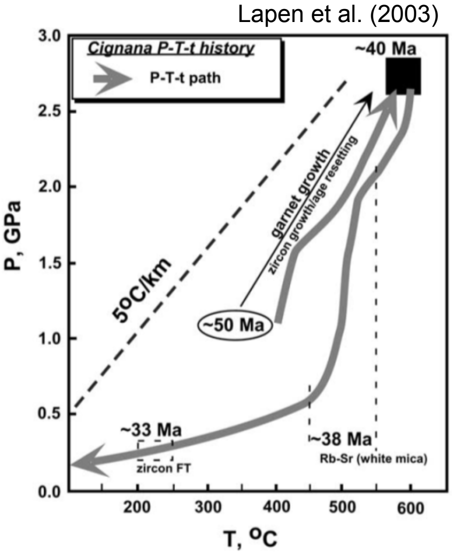

Lu/Hf – Sm/Nd
48.8 ± 2.1 – 40.6 ± 2.6
= 8.2 ± 3.3 Myr for burial

# Lago Cignana



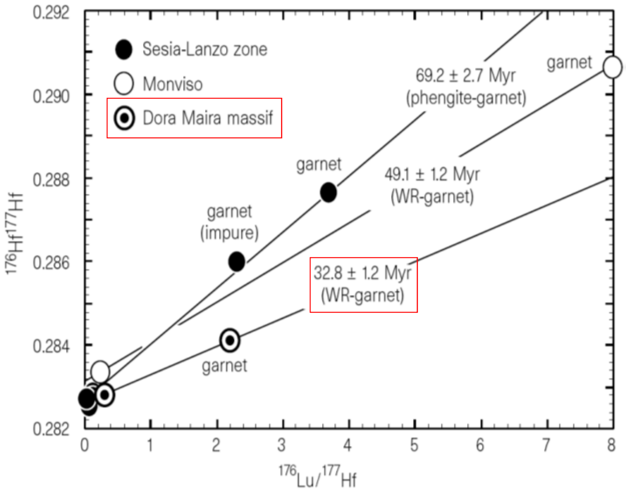

Amato et al. (1999)

Lapen et al. (2003)

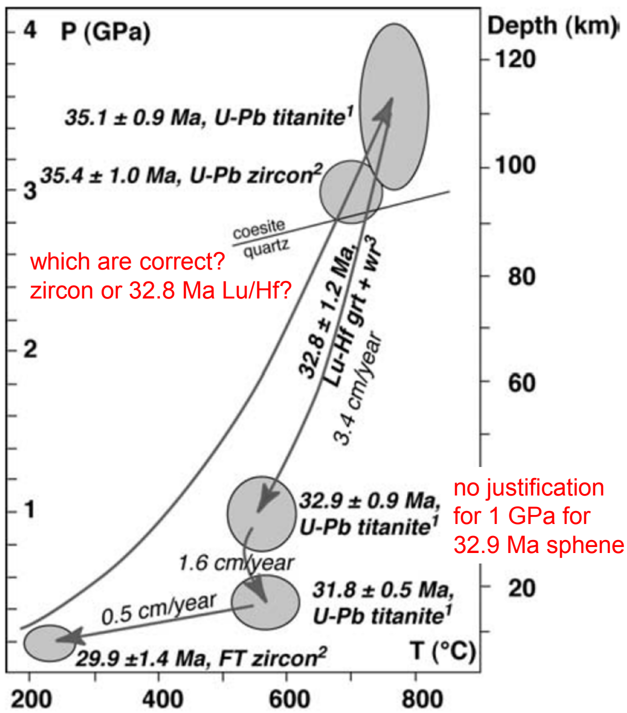



Sm/Nd – Rb/Sr
40.6 ± 2.6 – 38.0 ± 0.1 Ma
= 2.6 ± 2.6 Myr for ~50 km

# Dora Maira




Duchene et al. (1997)

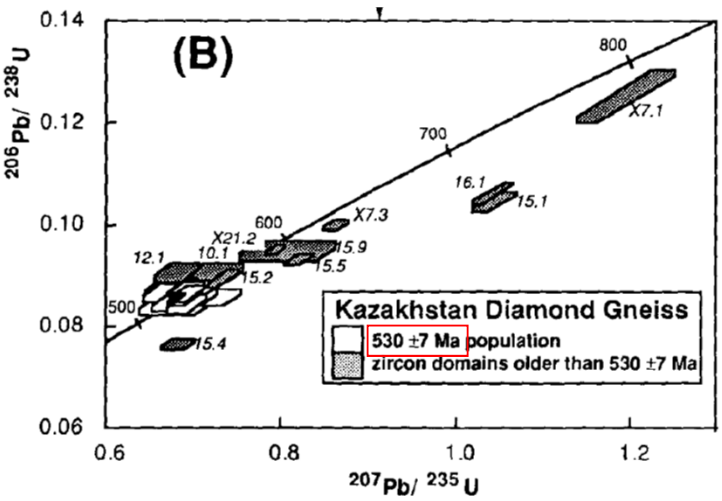



Dora Maira
Rubatto et al. (2003)

# Dora Maira

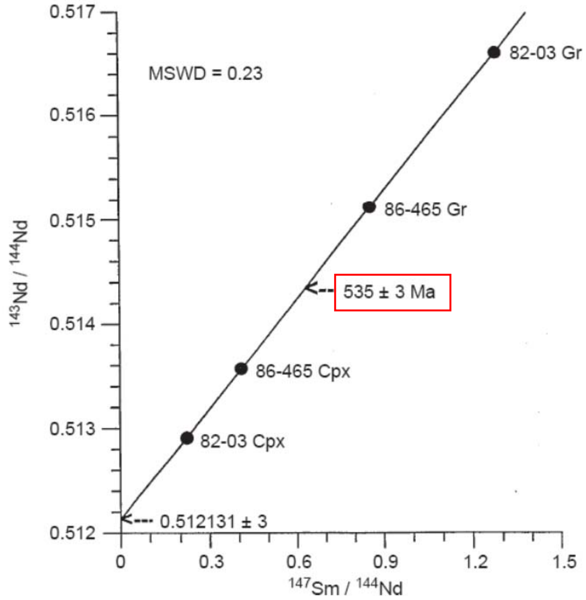
Lu/Hf – zircon fission track
32.8 ± 1.2 – 29.9 ± 1.4 Ma
= 2.9 ± 1.8 Myr for ~70 km

# Kokchetav



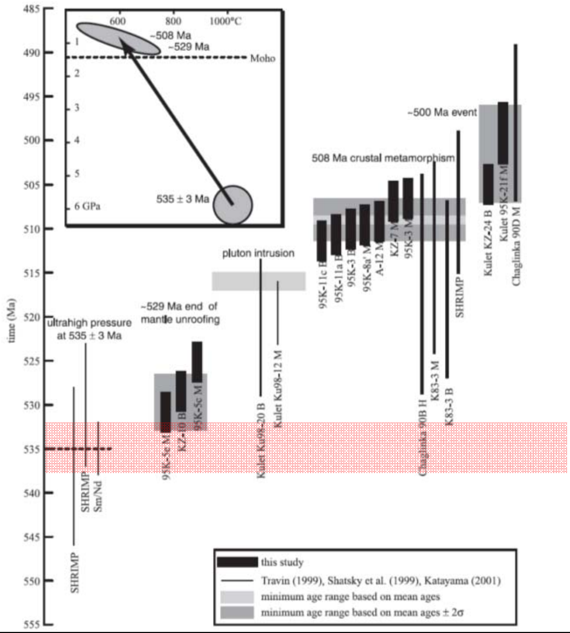

Claoué-Long et al. (1991)

# Kokchetav Massif



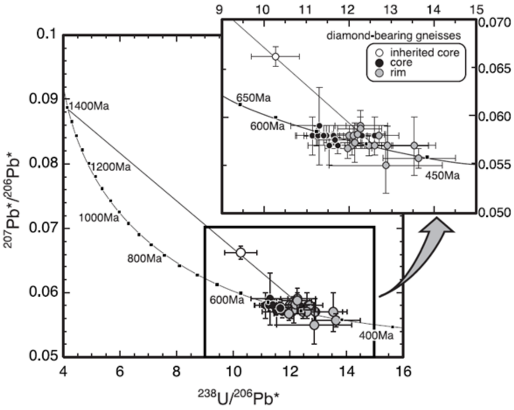

Shatsky et al. (1999)

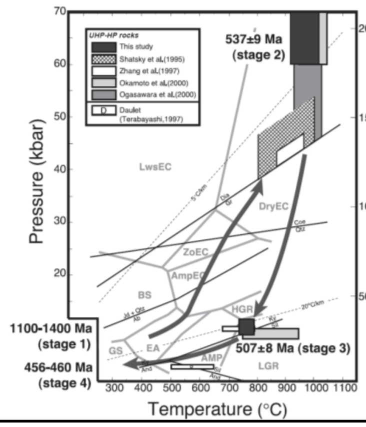
# Kokchetav Massif




Hacker et al. (2003)

# Kokchetav Massif




Katayama et al. (2001)

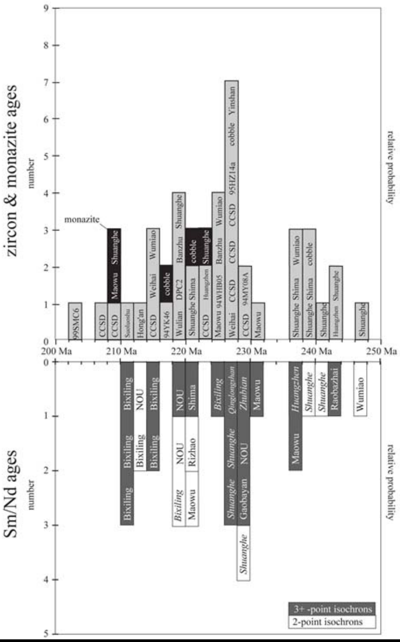
# Kokchetav Massif

535 ± 3 – 529 Ma

~ 4 Myr for ~100 km

Hacker et al. (2003)

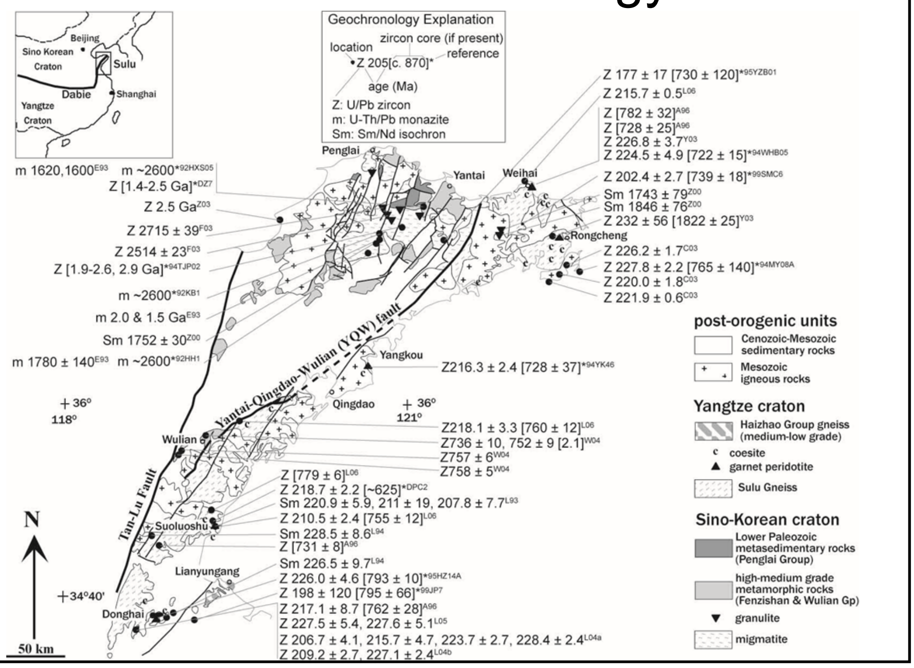
## Dabie–Sulu Significant High-T Chronologic Database




- zircon (only concordia ages)
- Sm/Nd (many low-MSWD ≥ 3-point)

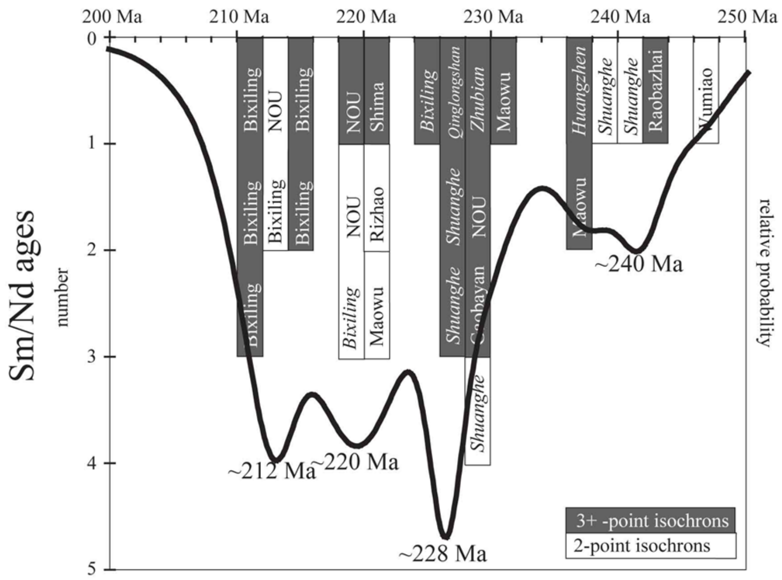
*Ames et al*. [1996]; *Ayers et al*. [2002]; *Chavagnac & Jahn* [1996]; *Chavagnac et al*. [2001]; *Chen et al*. [2003]; *Hacker et al*. [1998, 2000, 2006]; *Jahn et al*. [2003]; *Leech et al*. [in press]; *Li et al*. [1993, 1994, 2000, 2004]; *Li* [1996]; *Liu et al*. [2001, 2004a, 2004b, 2004c, 2005]; *Maruyama et al*. [1998]; *Okay et al*. [1993]; *Rowley et al*. [1997]; *Wan et al*. [2005]; *Xie et al*. [2004]; *Yang et al*. [2003]; *Zheng et al*. [2005]

## Sulu Geochronology



# Suggestion of 4 Sm/Nd Populations

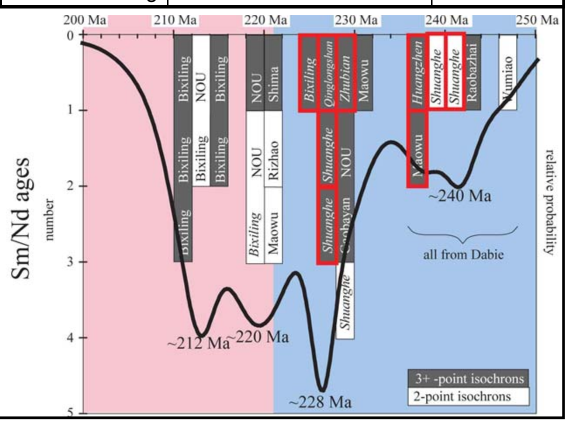
- 240, 228, 220, 212(?) Ma from either 2-pt or 3-pt isochrons




# Credibility Aided by Rb/Sr Mica

| place | Sm/Nd (Ma) | Rb/Sr (Ma) |
|---|---|---|
| Zhubian | 229 | 224 |
| Qinglongshan | 227 | 220 |
| Shuanghe | 242, 238, 229, 226, 226 | 219 |
| Huangzhen | 236 | 230 |
| Bixiling | 225 | 214 |

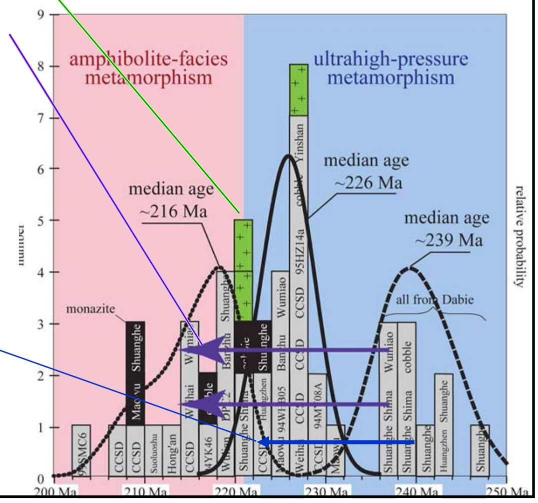
- [*Chavagnac and Jahn*, 1996; *Chavagnac et al.*, 2001; *Li et al.*, 1994, 2000, 2004]




➢best Sm/Nd UHP age(s)
≥ 225 Ma

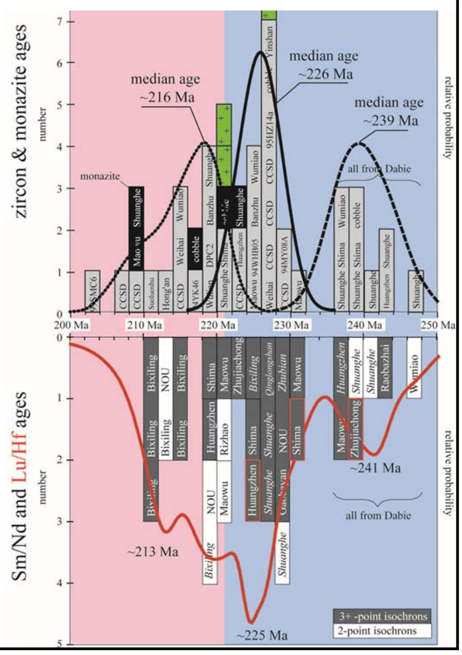
## Concordant Zircon Ages

- post-UHP shoshonitic plutons
- UHP mantles/amphibolite ri
  - Wumiao 238–220 / 220–214 Ma
    [*Maruyama et al.*, 1998]
  - Donghai 242–220 / 219–205 Ma
    [*Liu et al.*, 2004a, 2004b, 2005]
- decreasing Lu/Hf ratio
  [*Wu et al.*, 2006]

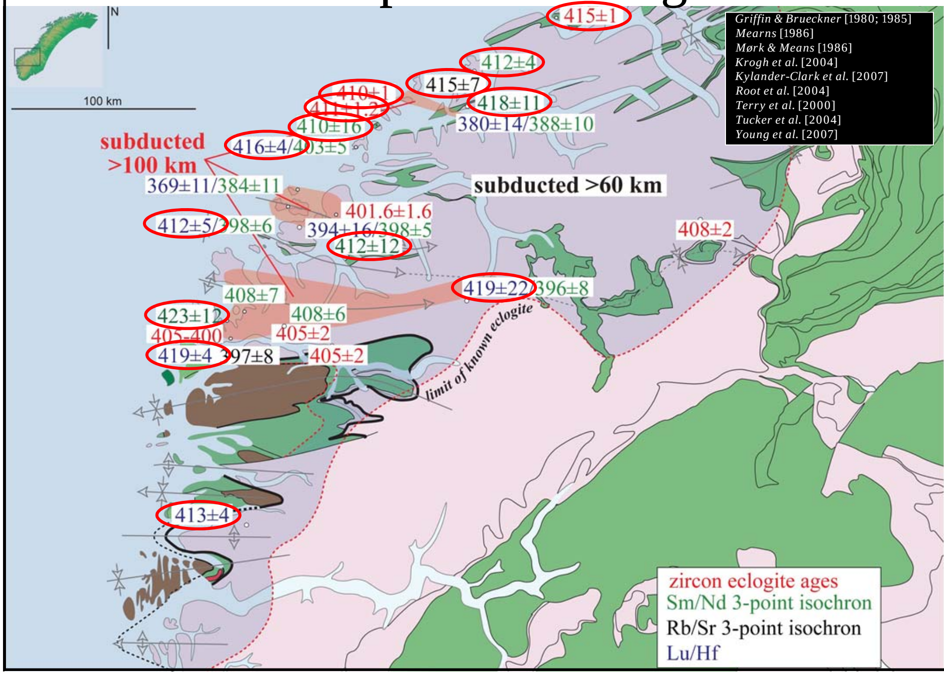



## 13–20 Myr UHP interval

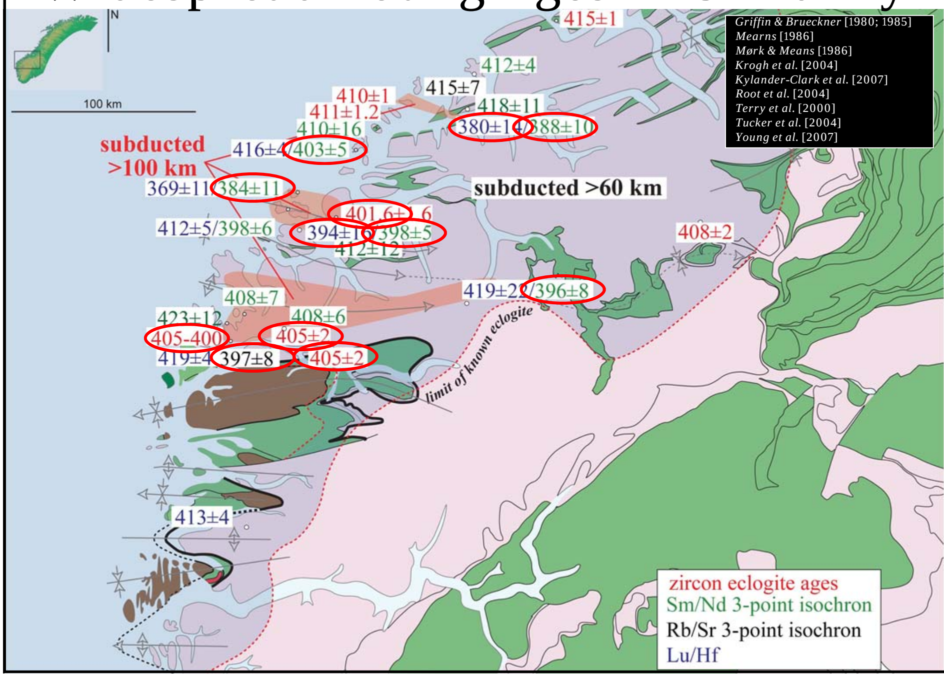
- 240 Ma or 227 Ma ‘events’ result of partial resetting?
  - no, U/Pb = Sm/Nd & 3 Myr interregnum in both
- two separate units?
  - no, Shuanghe–Shima area has both ‘events’



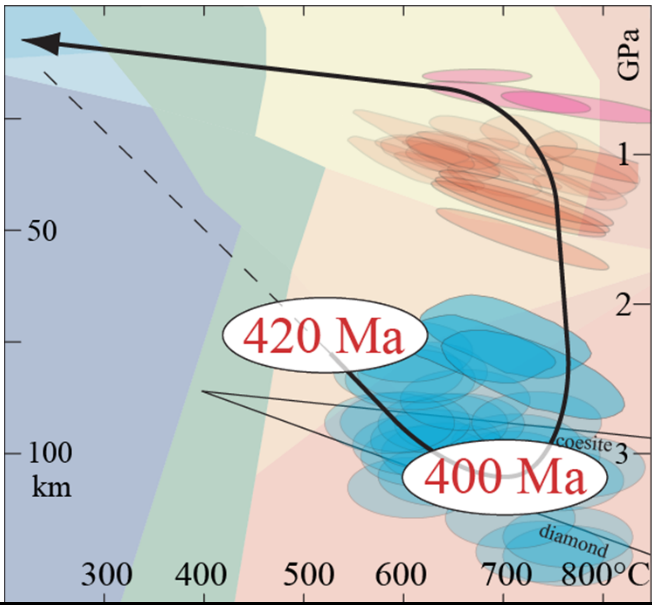
# Widespread Old Ages



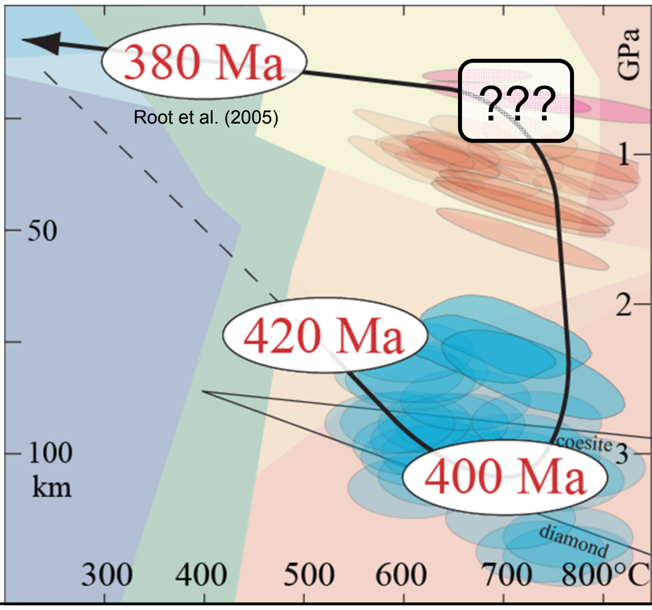

# Widespread Young Ages = 15–20 Myr



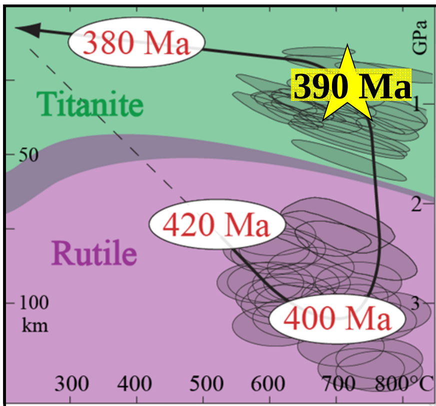
## 20+ Myr of Subduction: <4 mm/yr

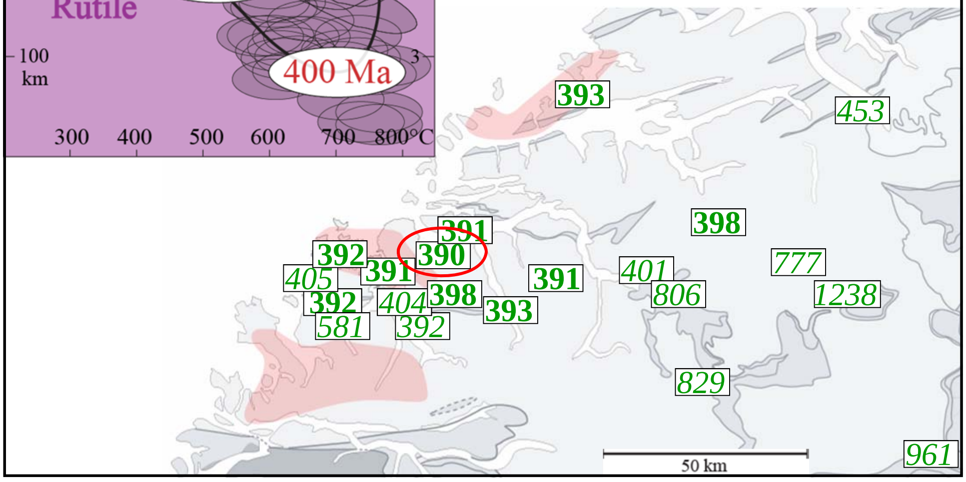



## Exhumation rates?



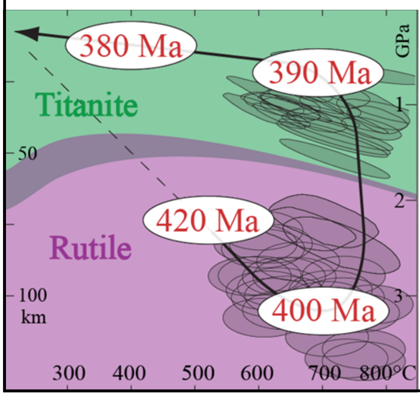
# Exhumation in <10 Myr

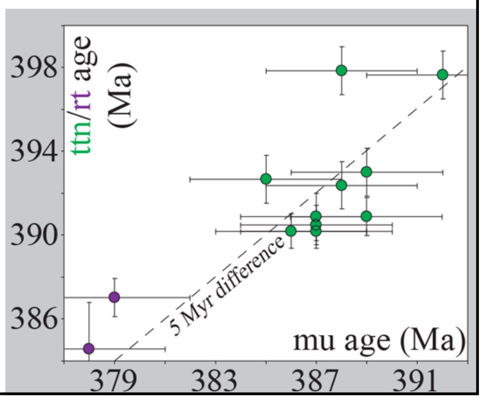


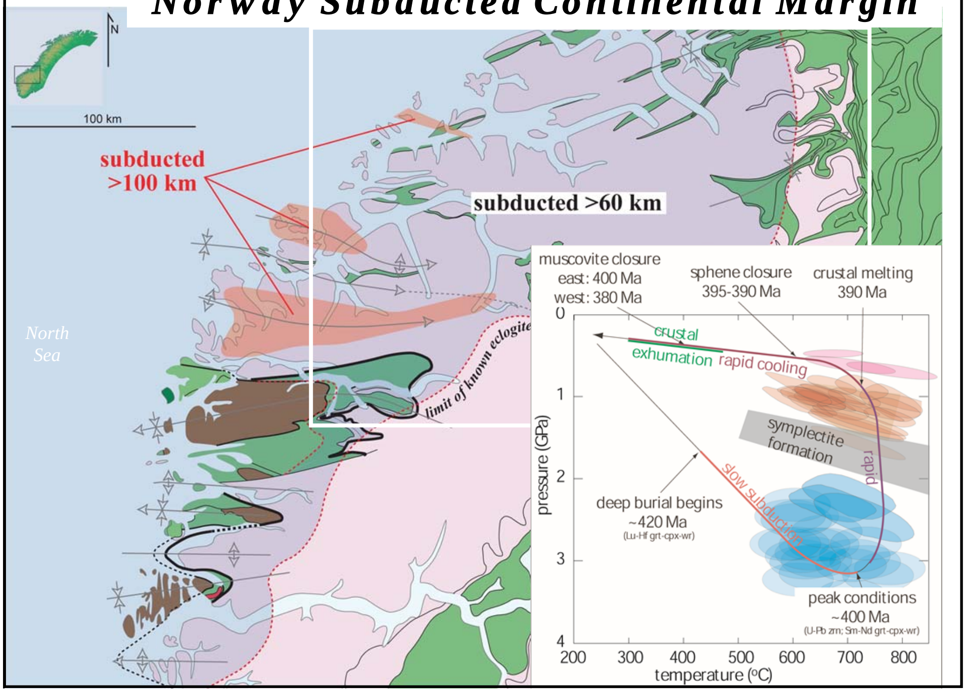

## Norway Exhumation Rate Summary

- exhumation rate
  - ~10 Myr after UHP: ~5–6 mm/yr
- cooling *after* exhumation ~70°C/Myr



# Norway Subducted Continental Margin




# Erosion Rates

TABLE 2. Erosion rates by surface processes.

Burbank (2002)

| Erosion process | Location | Measured | Rate of | Reference |
|---|---|---|---|---|
| Bare bedrock weathering | Wind River Range, Wyo. | Cosmogenic isotope abundance | 5–20 m/m.y. | Small *et al.* (1997) Bierman (1994) |
| Rock-to-regolith conversion | San Gabriel Mtns, Calif. | Cosmogenic isotope abundance | ≈350 m/m.y. | Heimsath (1999) |
| River incision | Indus River, Pakistan | Cosmogenic isotope abundance | 5–10 km/m.y. | Burbank *et al.* (1996) |
| River incision | Himalayan Foreland | Deformed, dated terraces | 10 mm/y | Lavé and Avouac (2000) |
| Bedrock landsliding | Southern Alps, New Zealand | Frequency magnitude data | 5–15 km/m.y. | Hovius *et al.* (1997) |
| Glacial erosion | Alaska, New Zealand, Asia | Sediment volumes, reported rates | 1–30 km/m.y. | Hallet *et al.* (1996) |
| Glacial erosion | Nanga Parbat | Glacial sediment load | 5–7 mm/y | Gardner and Jones (1993) |

# Erosion Rates

Blythe (1998)