Continental subduction and (ultra)high-pressure rock exhumation: contrasting numerical models based on the Alps and Caledonides

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Overview

Question: how are **ultrahigh-pressure rocks** formed and exhumed?

Test hypotheses using numerical geodynamic models

Focus on **integrating model results and observations**

Outline

1. Overview and key questions

2. Modeling approach

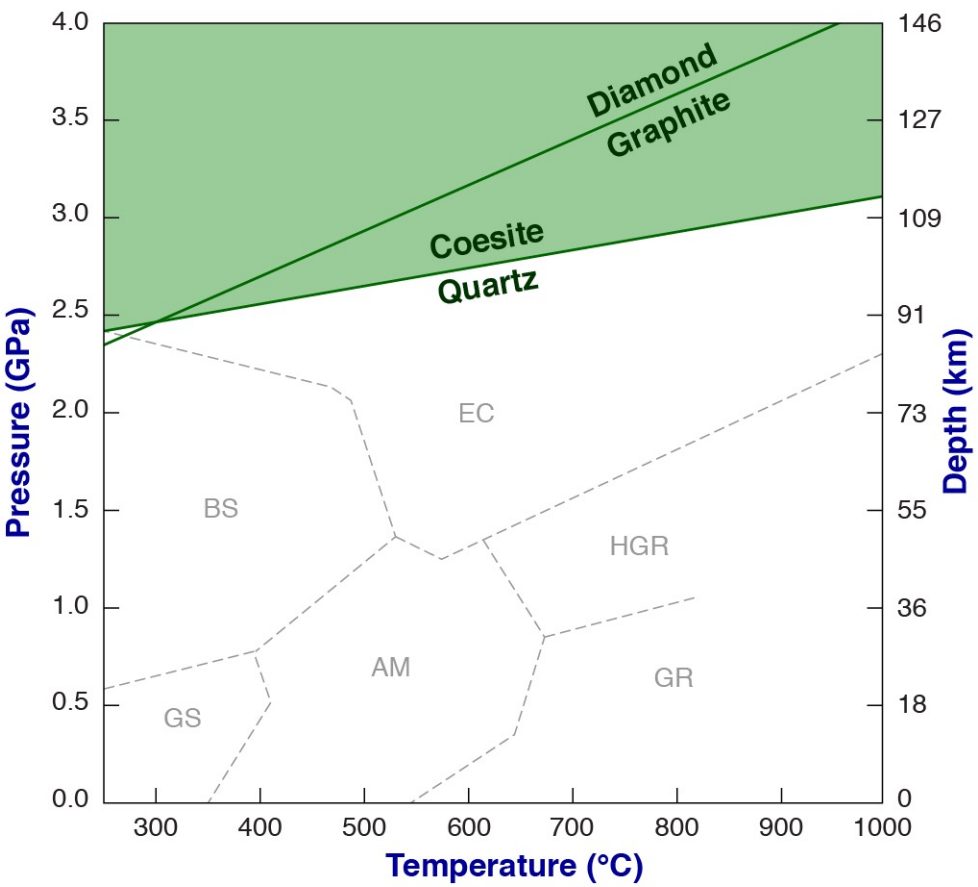
3. Integrating models and observations: *the Alps and Caledonides*

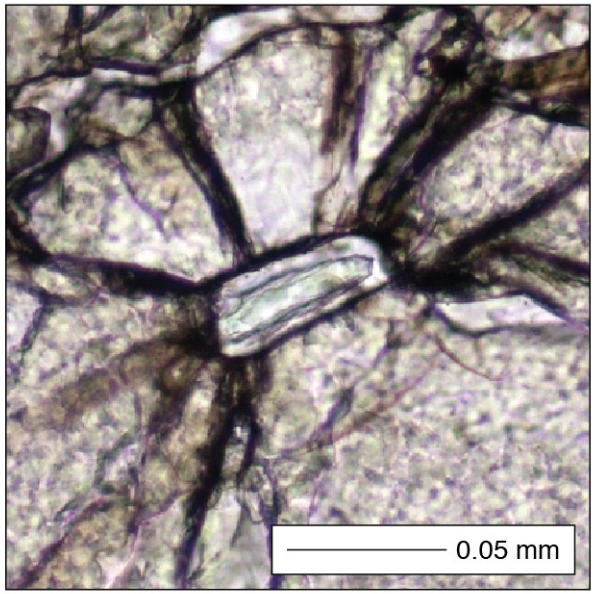
4. Conclusions

Examples of UHP rocks from the Alps (top; Oxford Atlas of Metamorphic Rocks) and Western Norway.

1. Formation and exhumation of UHP rocks: overview and key questions

Ultra-high-pressure metamorphism





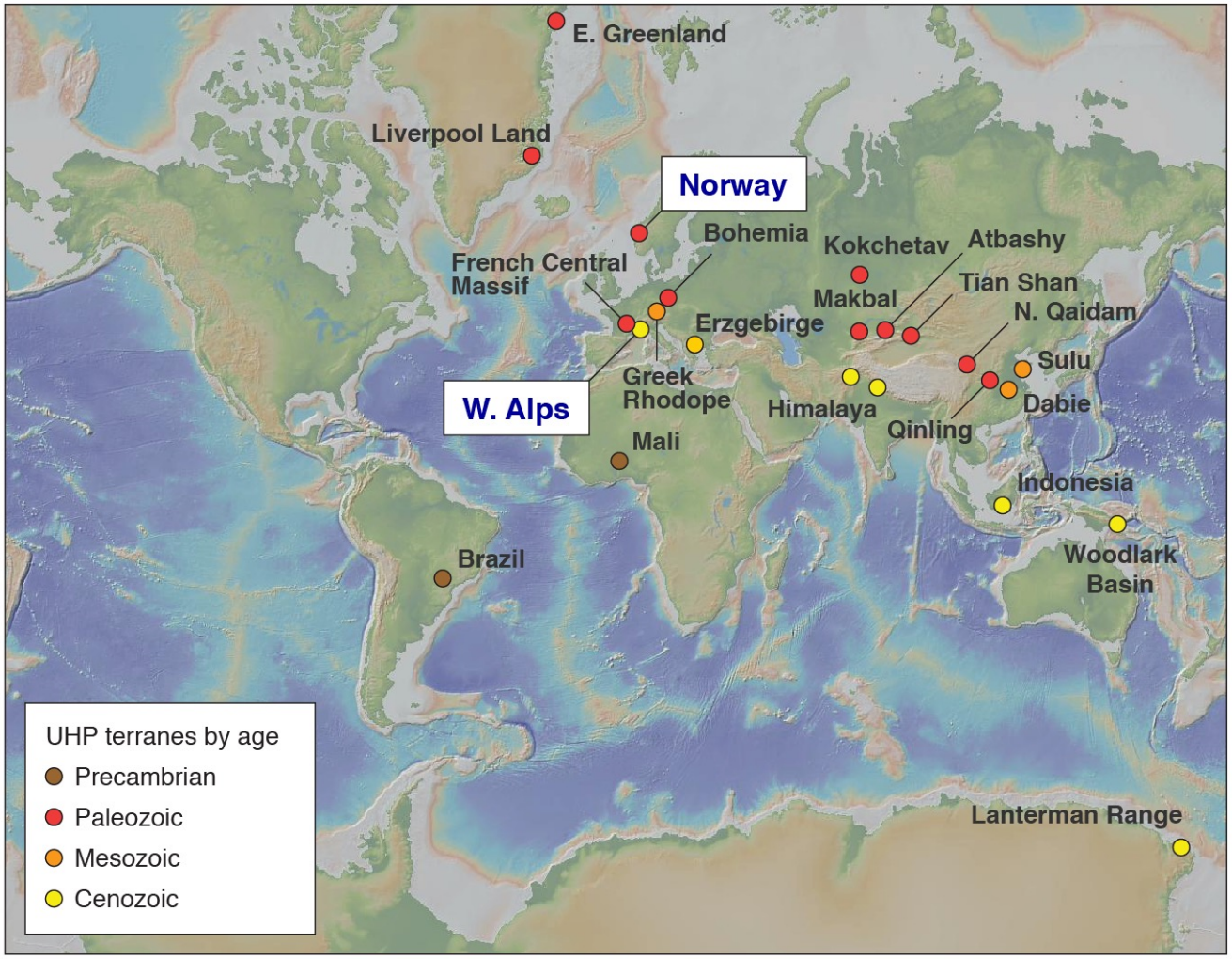
Defined as metamorphism within stability field of coesite

Implies subduction of crustal rocks to depths >90 km

Or alternatively tectonic overpressure…

Metamorphic facies from Liou et al. (2004). Coesite from Butler et al. (2013).

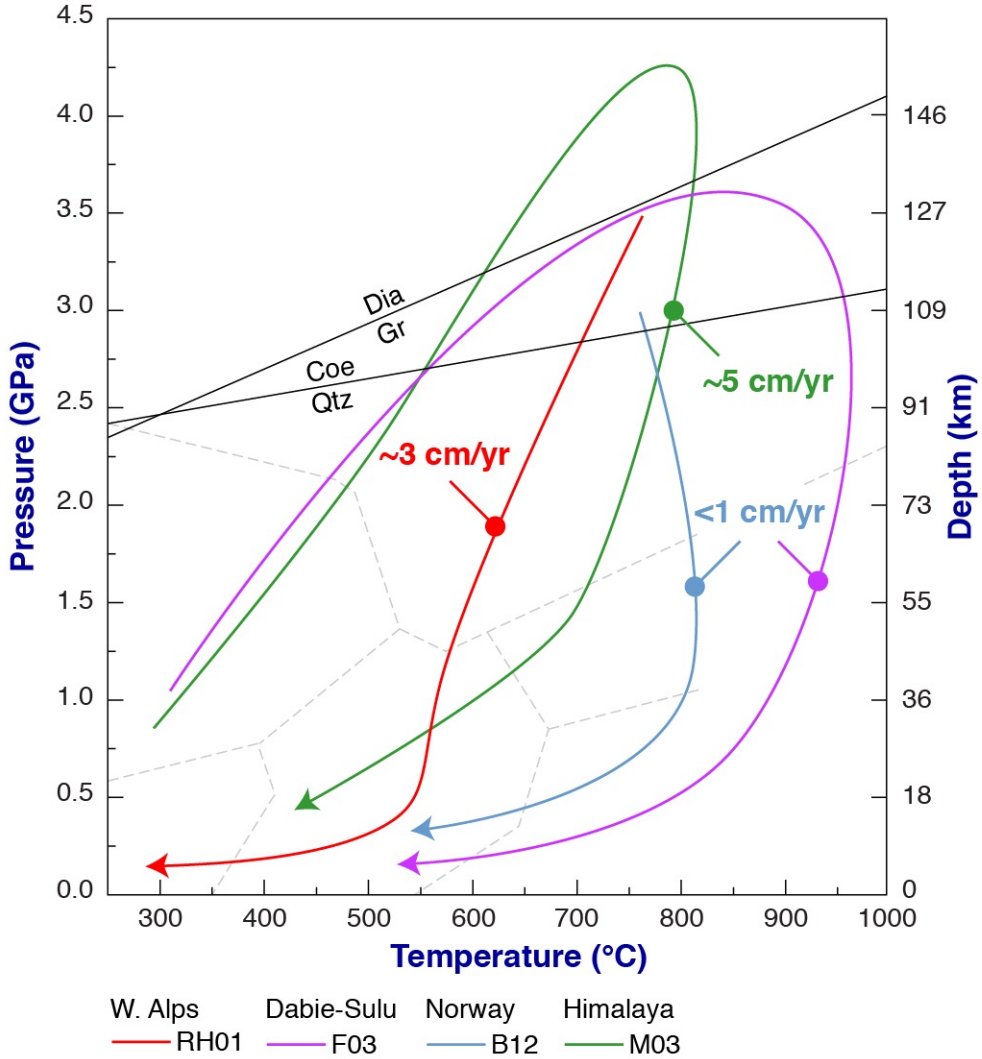
Global distribution of UHP terranes



Found in many Phanerozoic collision zones (mostly Eurasian)

Locations from Liou et al. (2004); DEM from Ryan et al. (2009)

P-T-t paths from UHP terranes



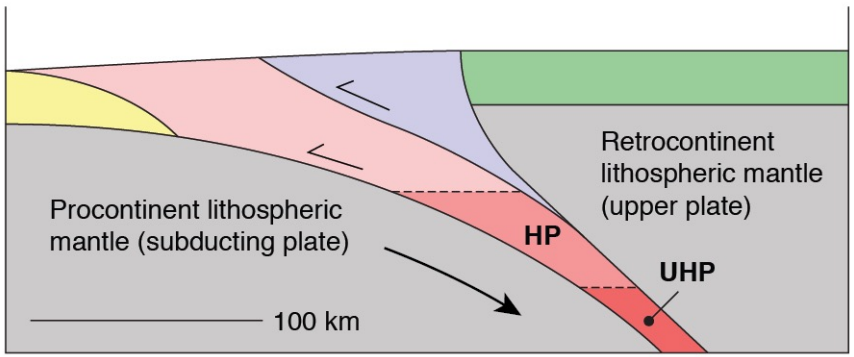
P–T conditions
~2.5–4 GPa/600–900°C

Initial exhumation rates <1–5 cm/yr

What causes UHP metamorphism and rapid decompression?

Refs. in Kylander-Clark et al. (2012).

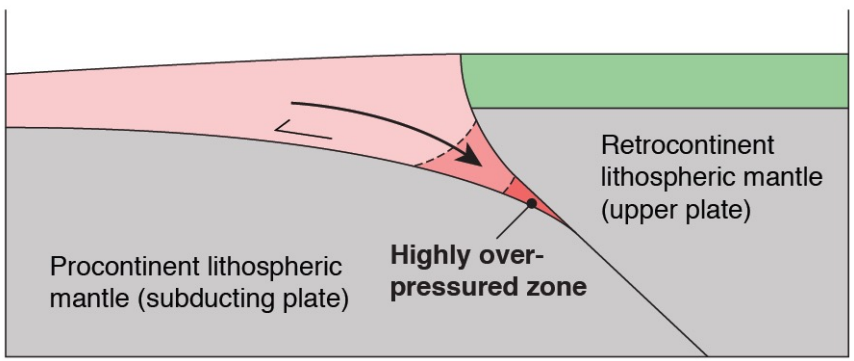
How are UHP rocks formed?



Crustal subduction?

crust coupled to slab and subducted to >90 km (= strong crust?)

(England & Holland, 1979; Ernst et al., 1997; Ernst & Liou, 1999; many others)



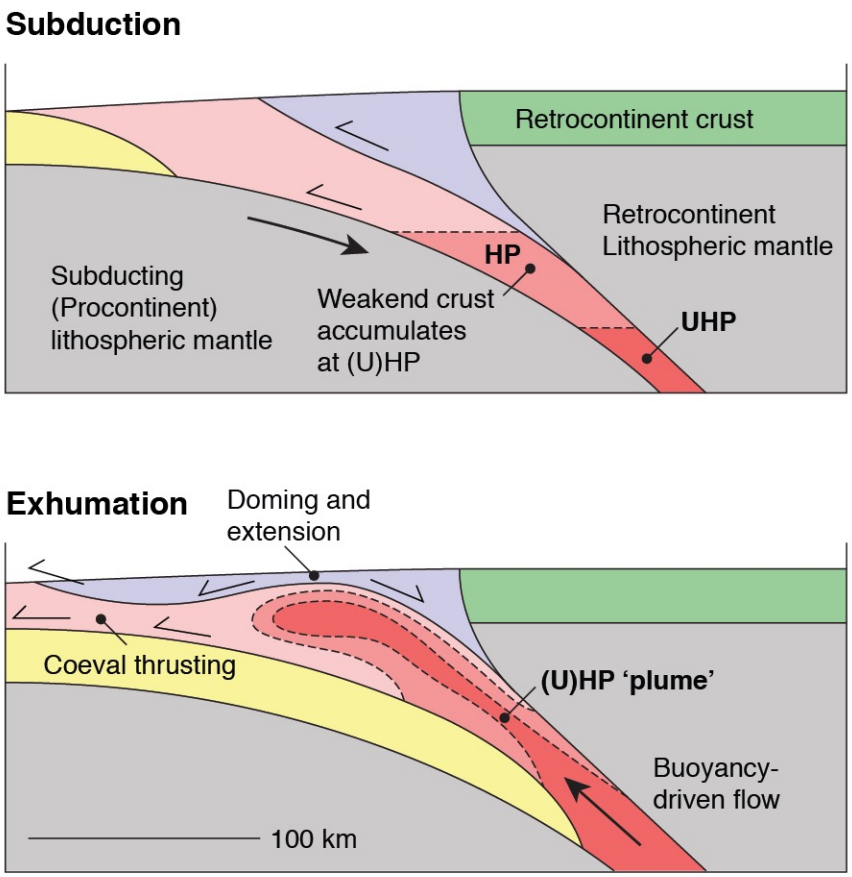
Tectonic overpressure?

mean stress >> P_{litho}

Flow constrictions, rheology, other mechanisms

(Mancktelow, 1995; 2008; Vrijmoed et al., 2009; Li et al., 2010; Schmalholtz & Podladchikov, 2013)

How are UHP rocks exhumed?



Buoyancy-driven channel flow?

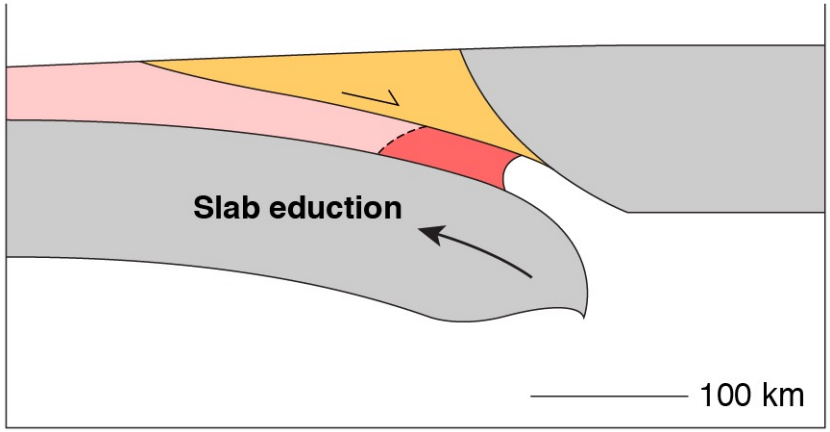
crust coupled to slab and subducted to >100 km

(England & Holland, 1979; Ernst et al., 1997; Ernst & Liou, 1999; many others)

Many numerical models

Burov et al. (2001), Gerya et al. (2008), Yamato et al. (2008), Warren et al. (2008), Sizova et al. (2012)

Additional exhumation mechanisms



Slab 'eduction'?

'reverse subduction' following slab break-off

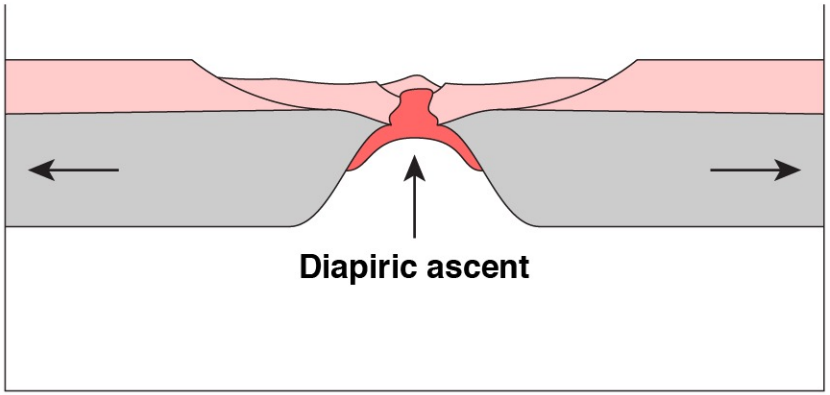
(Norwegian Caledonides; Andersen et al., 1991; Duretz et al., 2012)

Diapiric ascent?

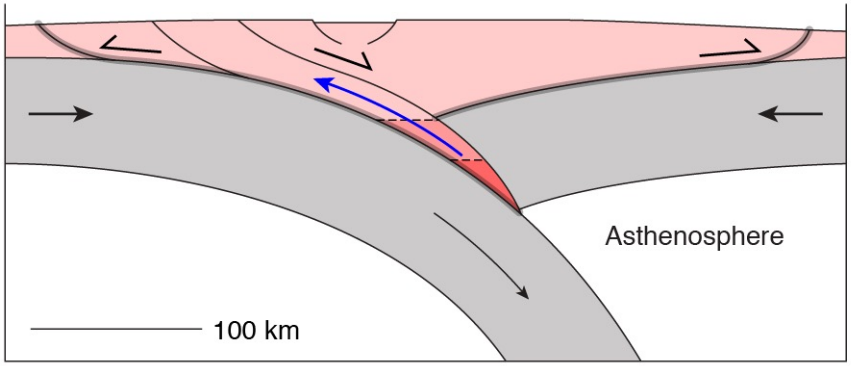
UHP crust underplated during earlier subduction

Exhumation initiated by rifting

(Woodlark Basin; Ellis et al., 2011)



Extension, but at what scale?

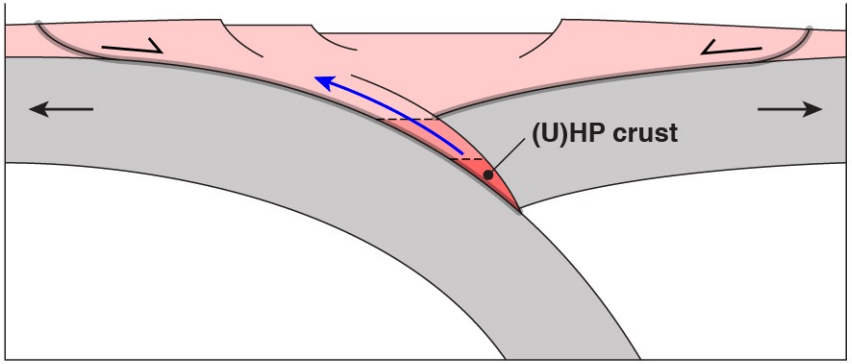


'Within-orogen' extension
during plate convergence

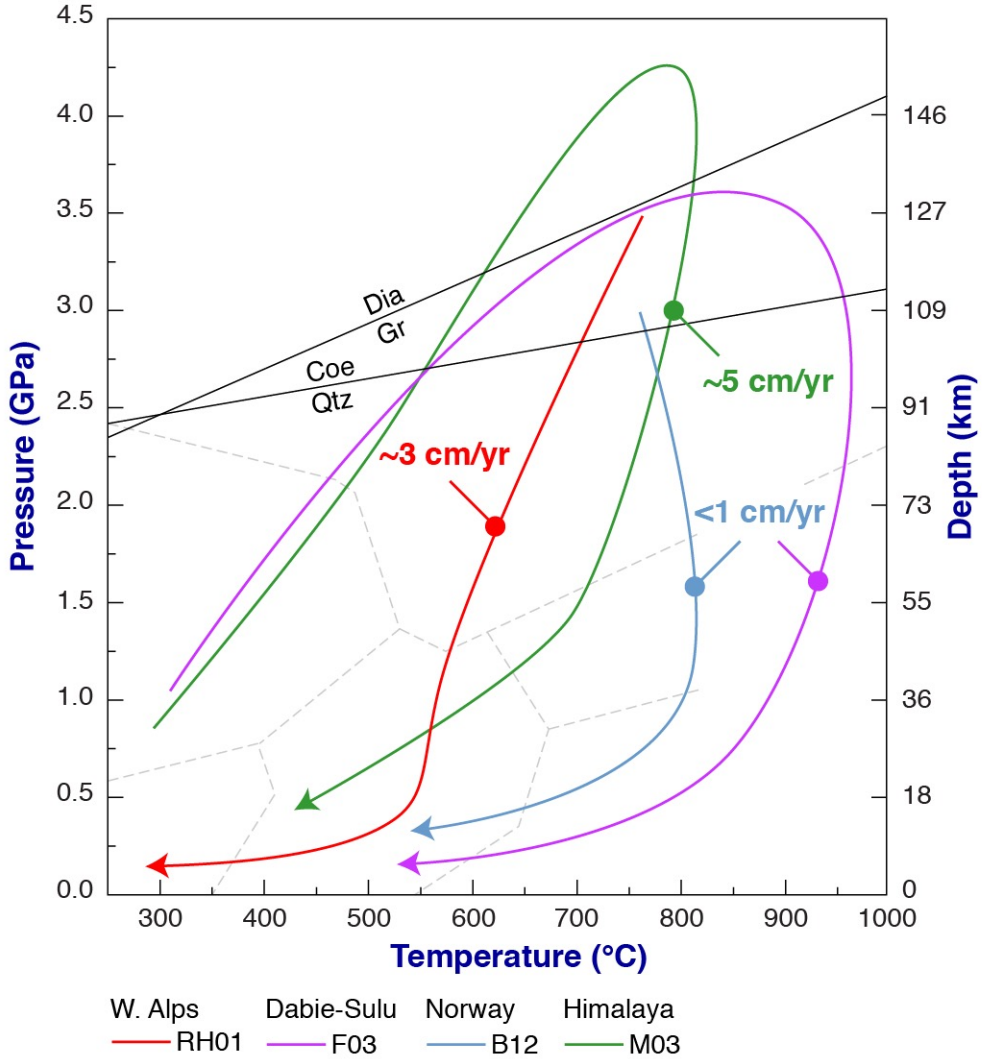
(Platt, 1993; Warren et al., 2008; Beaumont et al., 2009)

Lithosphere-scale extension
during plate-divergence

(Platt, 1993; Andersen, 1998; Fossen, 2010; Little et al., 2011)



No 'one size fits all' model



Sizes of UHP terranes
~500–30,000 km^2

Larger terranes take longer
(burial through exhumation)

Many larger terranes hotter
related to size of orogen?

Contrasts linked to orogenic 'stage'?

(Kylander-Clark et al., 2012)

Refs. in Kylander-Clark et al. (2012).

Fundamental questions

How are UHP rocks formed?

- *burial or overpressure?*

How are UHP rocks exhumed?

- *what are the processes and controls?*
- *different mechanisms for different orogens?*

What about the variety among UHP terranes?

- *what explains differences in orogenic stage, P-T, size, exhumation rates?*

2. Modeling approach

SOPALE code

Incompressible Stokes flow

$$\frac{\partial \sigma_{ij}}{\partial x_i} - \frac{\partial P}{\partial x_j} + \rho g_i = 0 \quad i, j = 1, 2$$

$$\frac{\partial v_i}{\partial x_i} = 0 \quad i = 1, 2$$

Energy balance

$$\rho c_p \left(\frac{\partial T}{\partial t} + v_i \frac{\partial T}{\partial x_i} \right) =$$

$$K \frac{\partial}{\partial x_i} \frac{\partial T}{\partial x_i} + A_R + A_{SH} + v_2 \alpha g T \rho \quad i = 1, 2$$

2D thermal-mechanical FEM computation of visco-plastic creeping flows
(Fullsack, 1995)

'nested' high-res mesh, simple form of domain decomposition

Algorithms for modeling…

- *slope-dependent erosion*
- *metamorphic phase changes/volume change*
- *strain-weakening*

Constitutive equations

Drucker-Prager yield stress

$$(J_2')^{1/2} = P\sin\phi_{\text{eff}} + C\cos\phi_{\text{eff}}$$

J'_2 = second invariant of deviatoric stress, P = pressure, ϕ = effective angle of internal friction

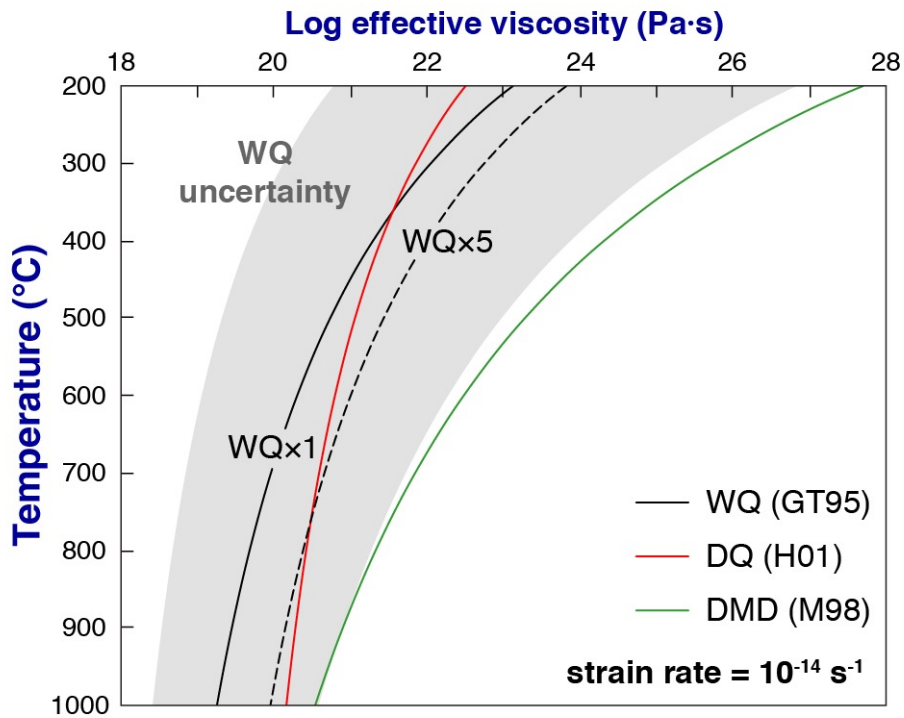
Power-law flow

$$\eta^v_{\text{eff}} = \frac{f}{W_s} A^{-1/n} \dot{I}_2'^{(1-n)/2n} exp\left(\frac{Q + PV^*}{nRT_K}\right)$$

I'_2 = second invariant of deviatoric strain rate, A = pre-exponential factor, n = stress exponent, Q = activation energy, V^* = activation volume

f = scaling factor, W_s = strain-weakening factor

Viscous flow laws and scaling



Experimentally-determined flow-laws

- *measurement uncertainty in parameters (A, Q, n, V*)*
- *extrapolation to geological conditions*
- *simple 'f-scaling' in our models*

$$\eta_{\text{eff}}^{v} = \frac{f}{W_s} A^{-1/n} \dot{I}_2'^{(1-n)/2n} exp\left(\frac{Q + PV^*}{nRT_K}\right)$$

WQ=wet quartzite (Gleason and Tullis, 1995), DQ=dry quartzite (Hirth et al., 2001), DMD=dry Maryland diabase (Mackwell et al., 1998), WOL=wet olivine, DOL=dry olivine (Karato and Wu, 1998)

Model results and application

A **working model of collisional orogenesis** should explain…

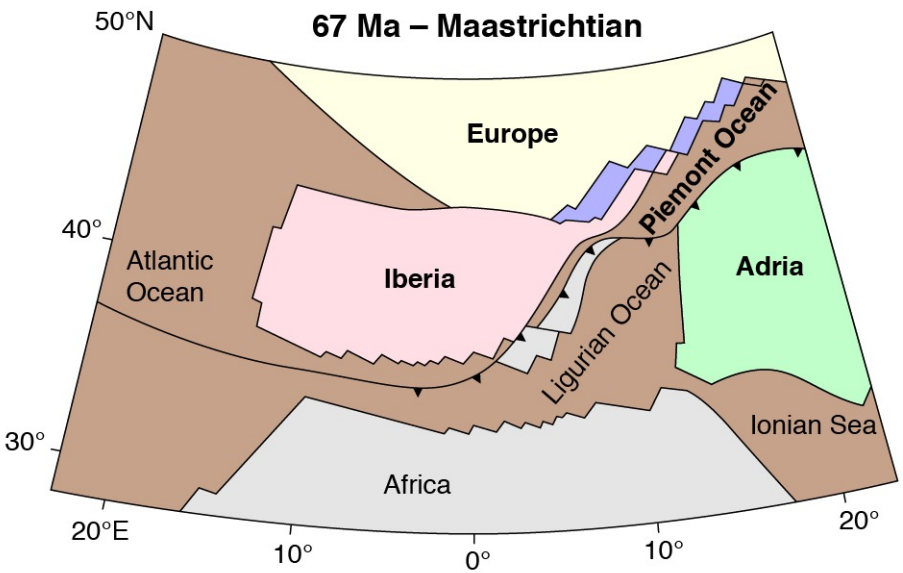
- *crustal structure*
- *deformation*
- *kinematics*
- *metamorphism (P-T paths)*
- *timing*

Requires an integrated approach… no single constraint is enough (e.g., *P-T* data not diagnostic)

Impossible (?) to quantify uncertainty for some things (e.g., interpretations of structures)

4. Examples: the Alps and Caledonides

The Western Alps



Alpine orogeny

Late Cretaceous to Cenozoic ocean closure and Adria-Europe collision

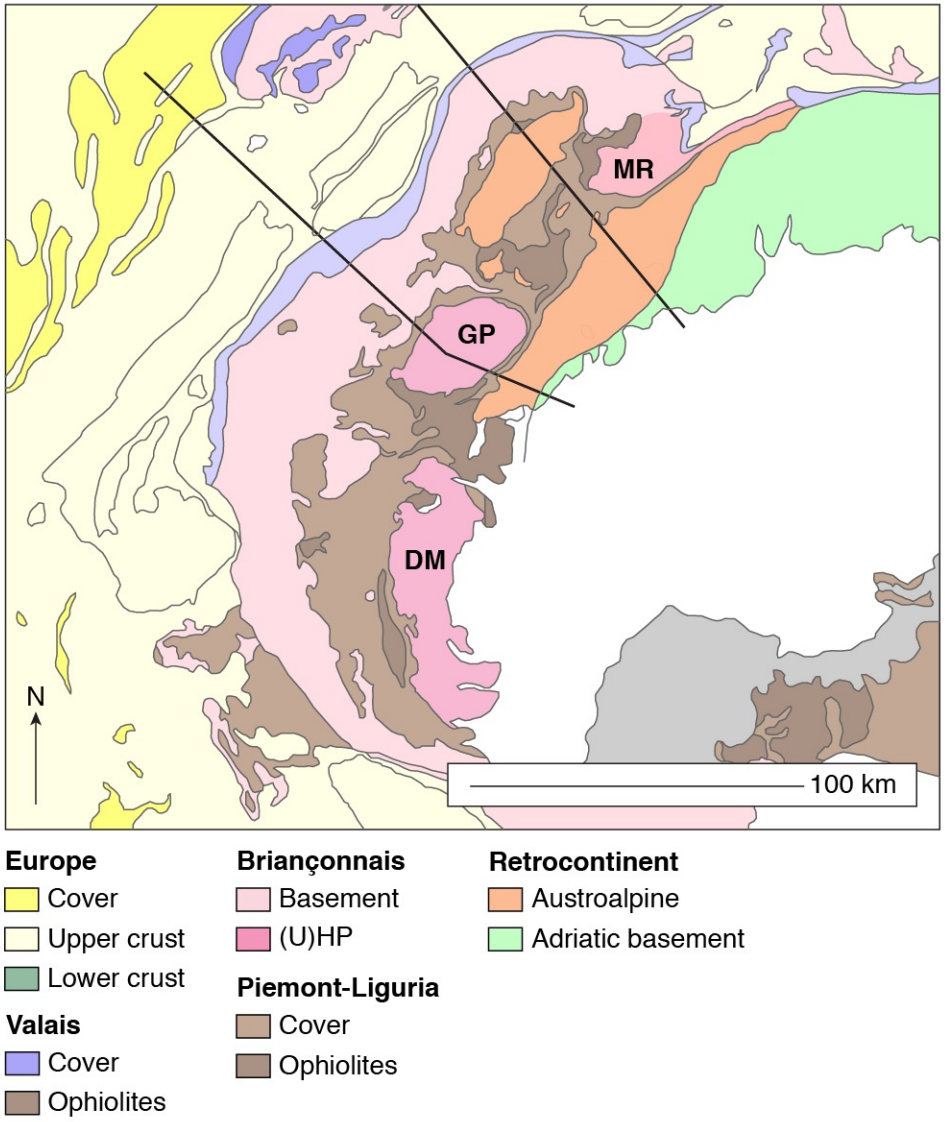
(North)west vergent thrusting/nappe folding,

(U)HP rocks in multiple paleogeographic domains

Highest-P in Internal Crystalline Massifs and associated oceanic crust

Modified from Handy et al. (2010).

The Western Alps



Modified from Schmid et al. (2004).

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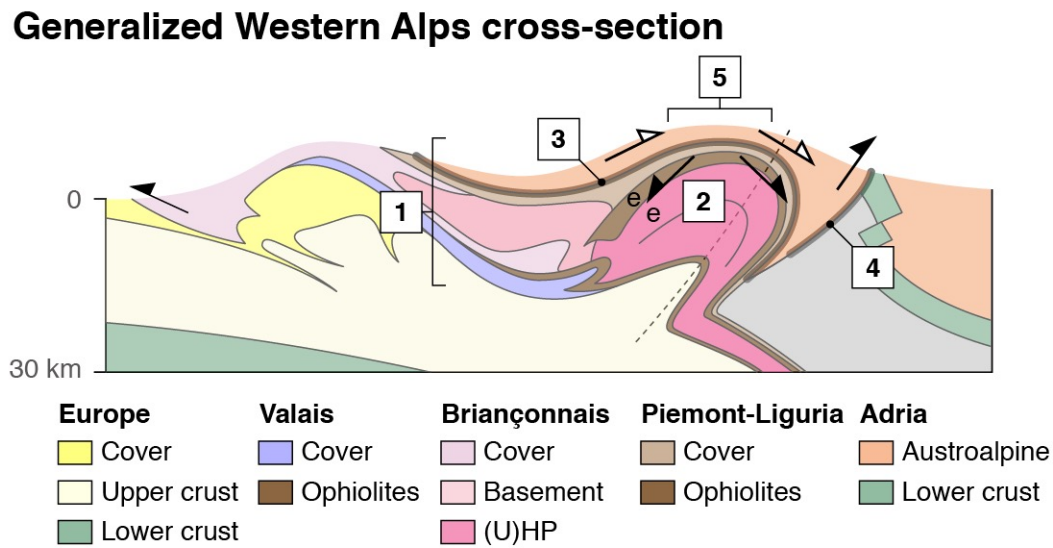
Key tectonics features/processes



Key features

1. Northwest-vergent nappe stacking

2. (U)HP metamorphism ~3.5 GPa/760°C*, ~49-35 Ma (earliest stages of collision)

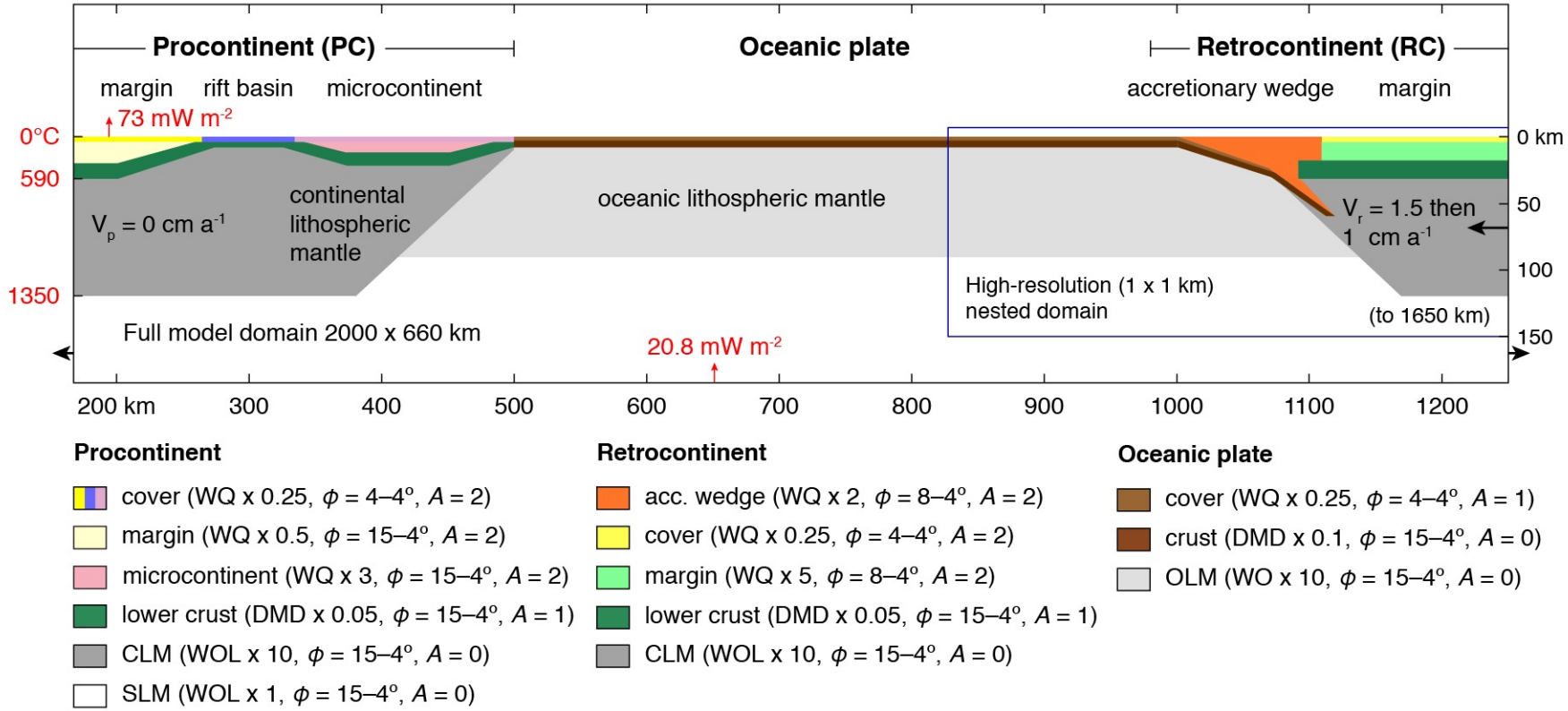
3. Rapid exhumation (1–3 cm/yr) by crustal-scale normal faulting while foreland thrusting continued

4. Bivergent thrusting/backfolding

5. Late local extension/doming during ongoing convergence

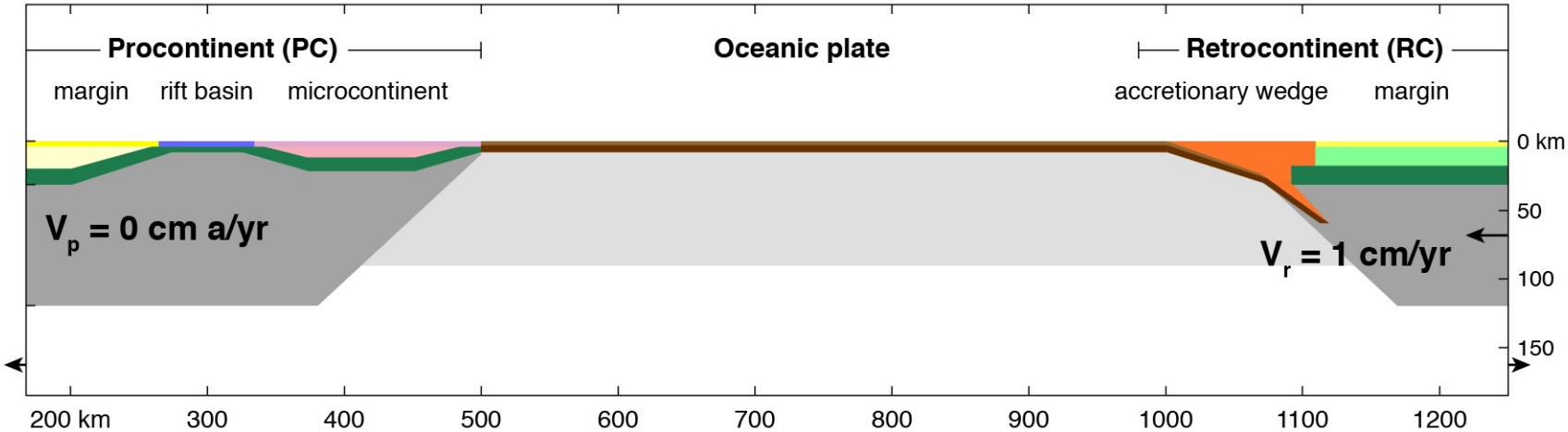
Section generalized from Schmid et al. (2004). See refs. in Butler et al. (2013).

Alpine-type model design



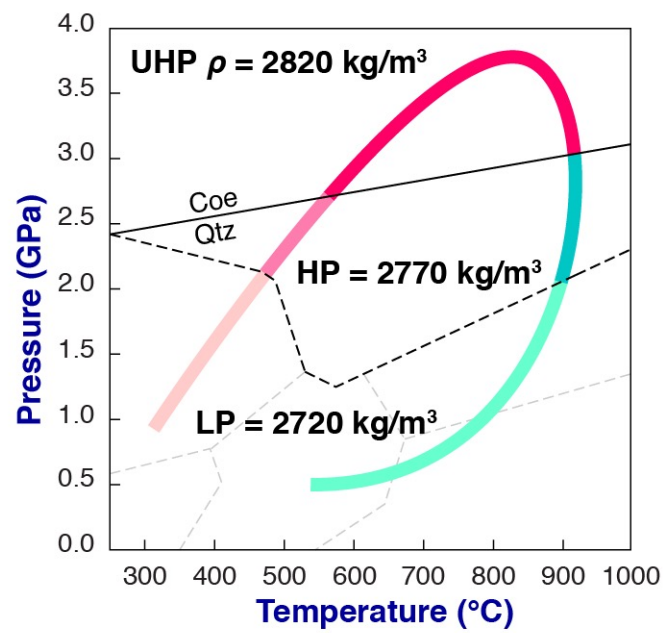
Based on Alpine paleogeography…
microcontinent = Briançonnais, rift basin = Valais, and margin = Europe

Alpine-type model design



Procontinent

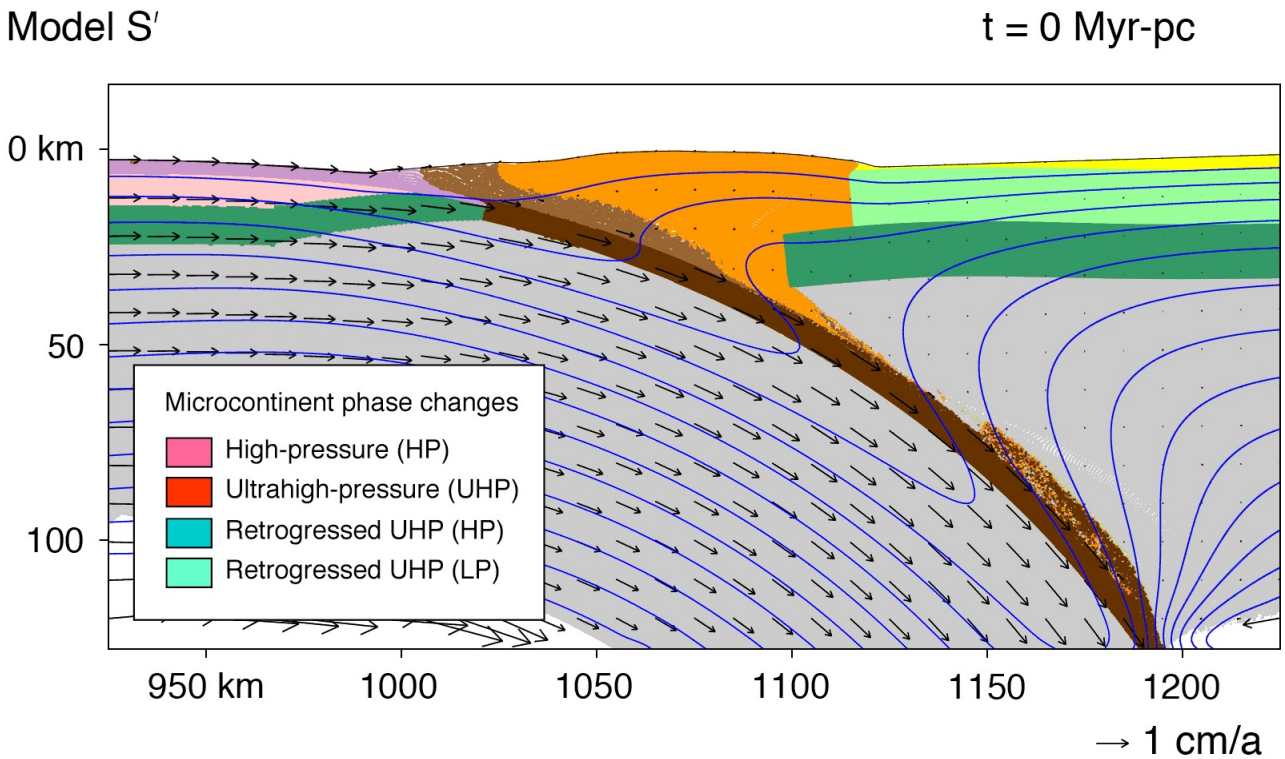
- cover (WQ x 0.25, ϕ = 4–4°)
- **margin (WQ x 0.5, ϕ = 15–4°)**
- **microcontinent (WQ x 3, ϕ = 15–4°)**
- lower crust (DMD x 0.05, ϕ = 15–4°)



Microcontinent changes density with *P–T* during subduction and exhumation

Phase 1: microcontinent subduction

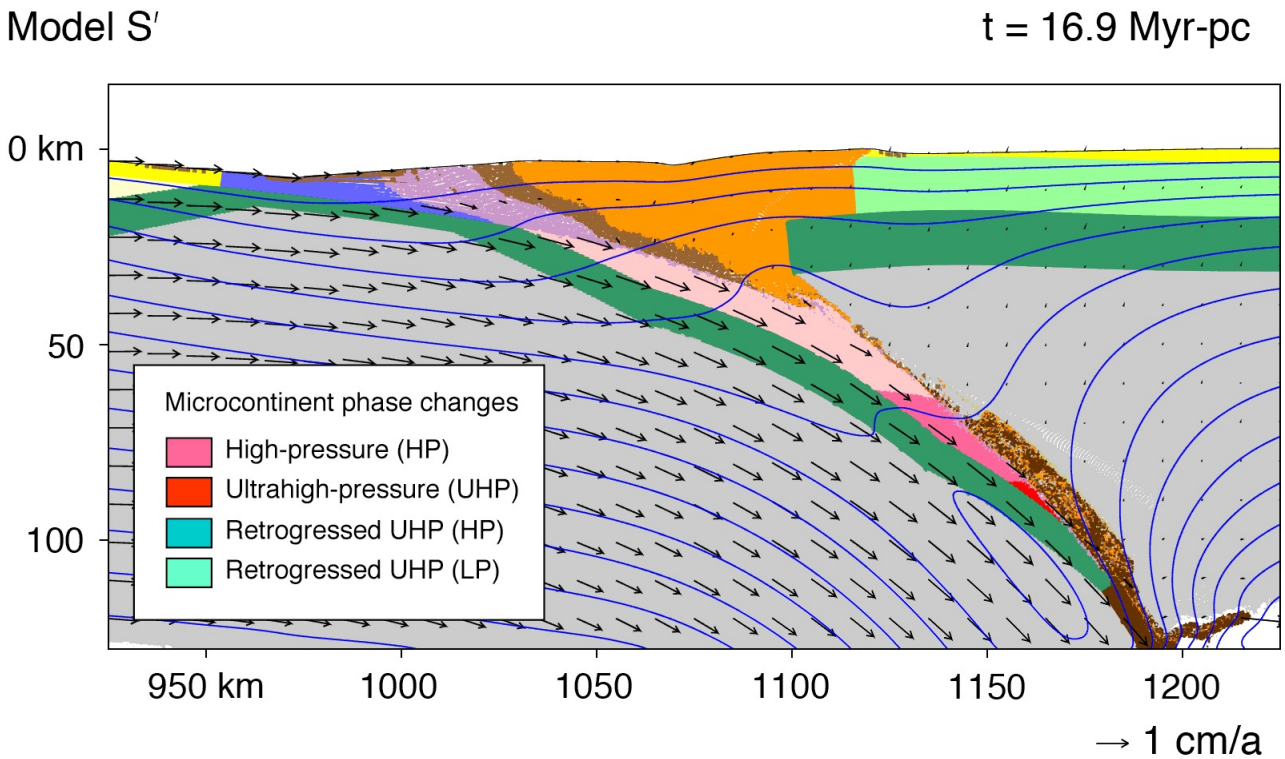
Model time in ‘Myr post-collision’



Phase 1:

- microcontinent upper crust buried to UHP conditions
- accretion of weak ‘cover’

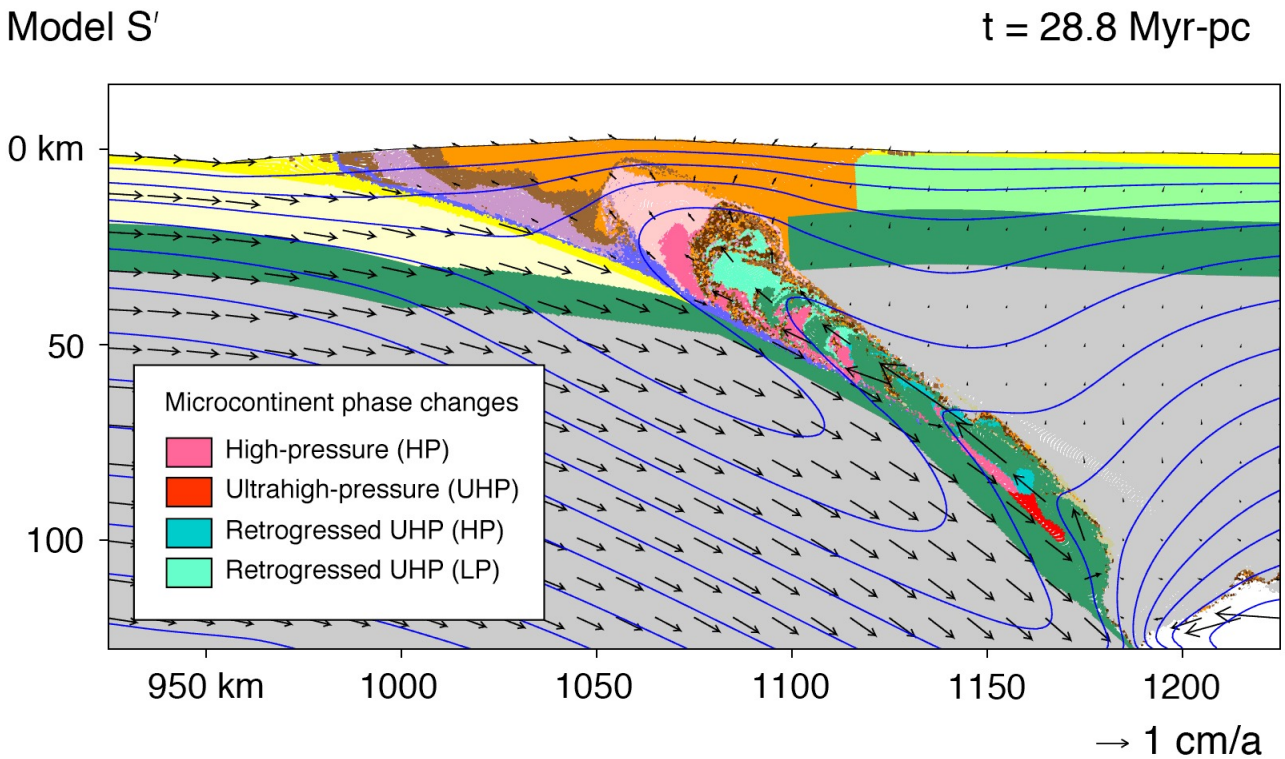
Phase 2: exhumation



Phase 2:

- buoyancy drives flow of ‘plume’ up subduction channel
- coeval normal faulting and shortening during intrusion

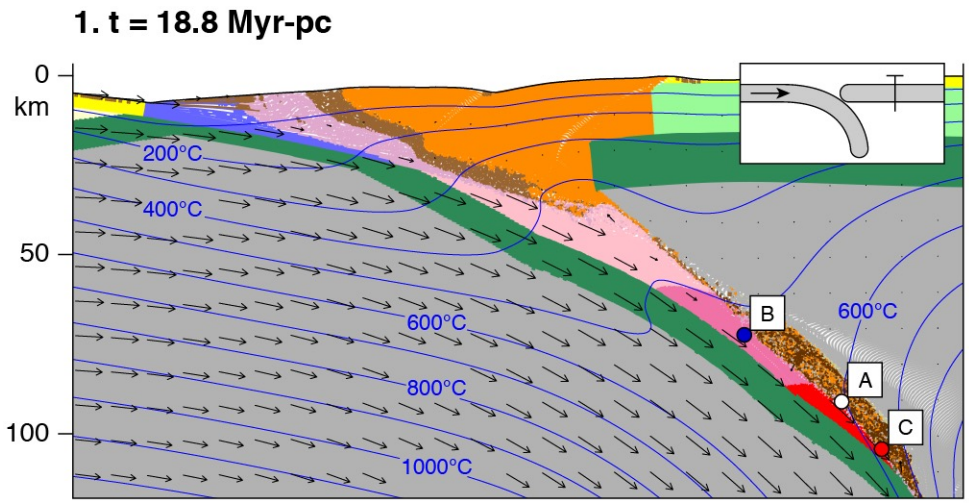
Phase 3: bivergent deformation

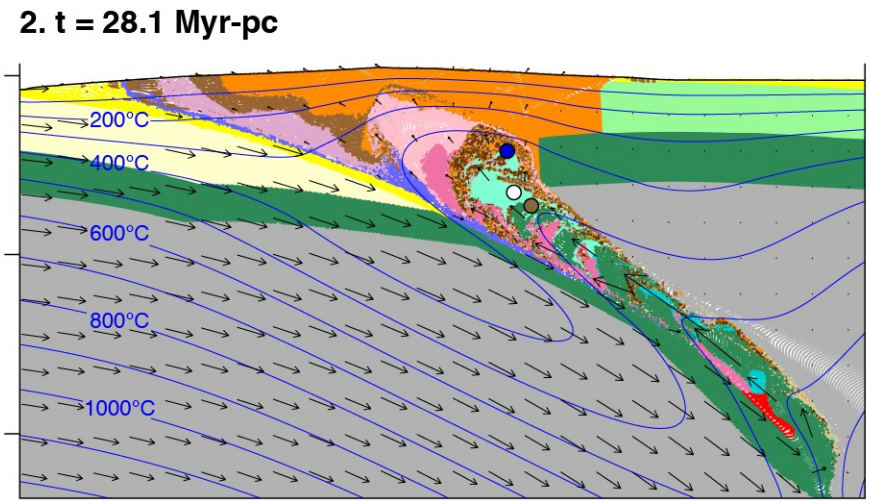


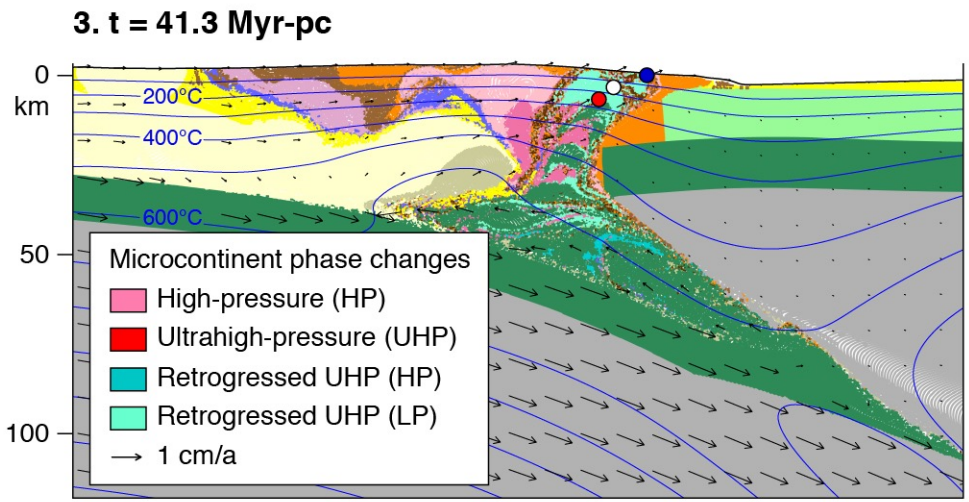
Phase 3:

- doming and extension above plume
- subduction channel clogged
- backfolding of plume

Alpine-type model results





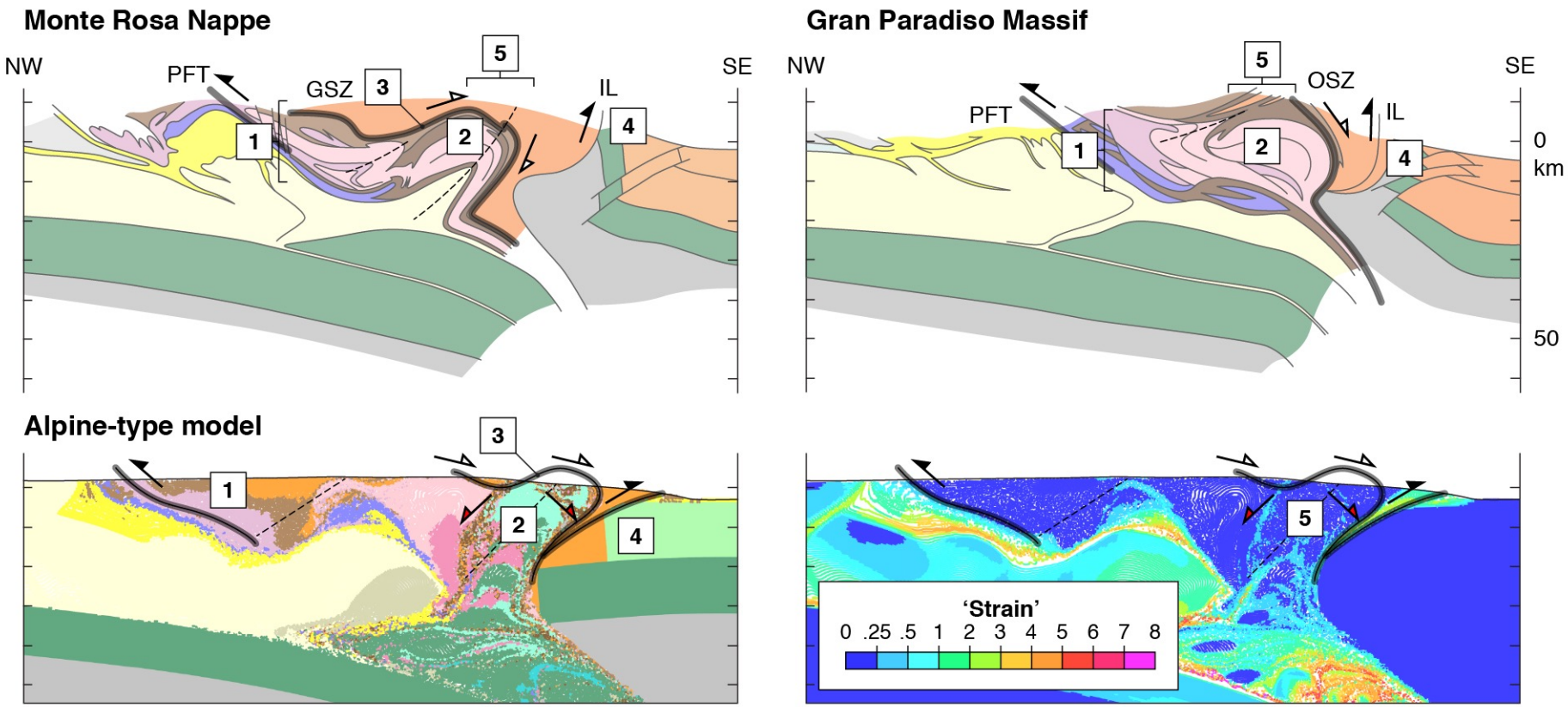


1. Subduction and UHP metamorphism

2. UHP exhumation

3. Bivergent thrusting and doming

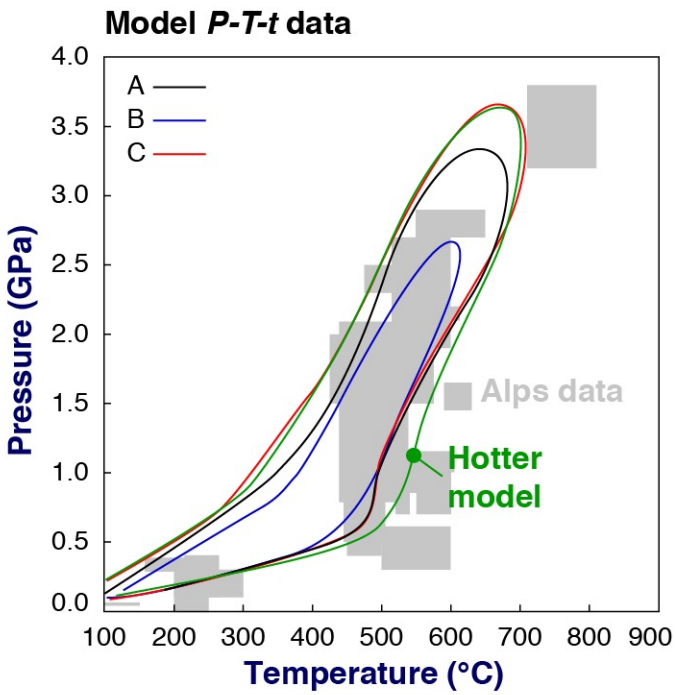
Comparison with crustal structure

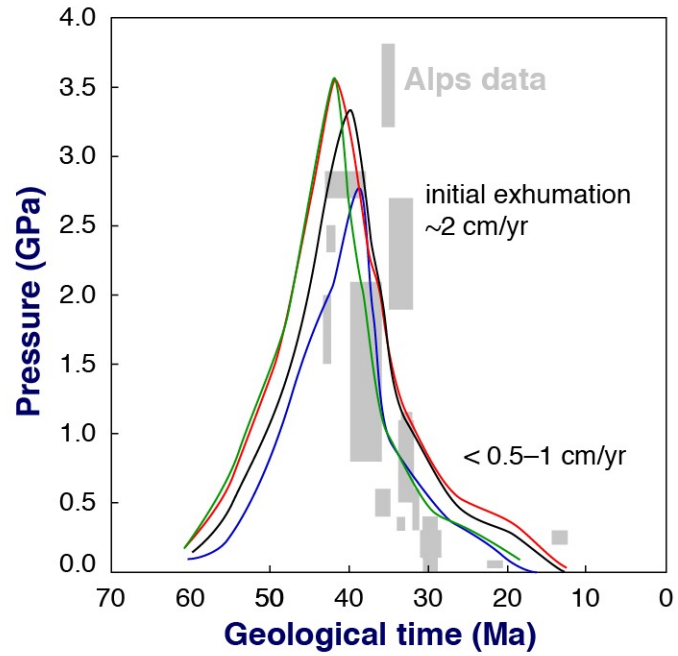


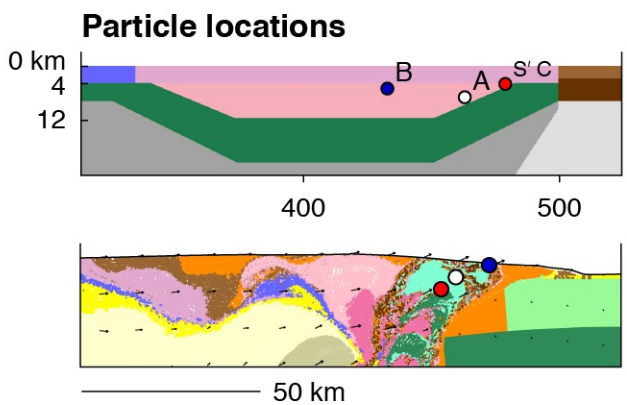
(1) nappe accretion, (2) (U)HP metamorphism (age/P-T decreasing down section), (3) rapid exhumation by crustal-scale normal faulting, (4) bivergent thrusting, (5) late extension and doming

Cross sections from Schmid et al. (2004).

Comparison with *P-T-t* data





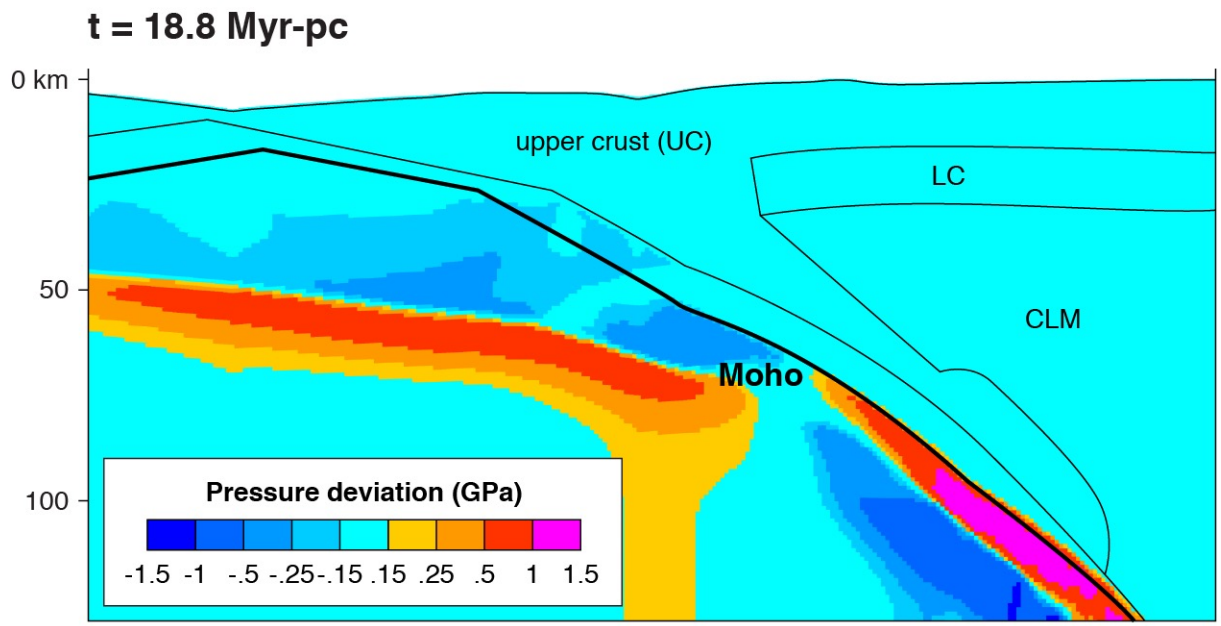


Reproduces range of *P-T* data
but somewhat cool

Two-stage exhumation, rates
within range of data

See Butler et al. (2013) for sources.

Role of tectonic overpressure?



Pressure 'deviation' = mean stress – P_{litho}

Crust and subduction channel ±0.15 GPa

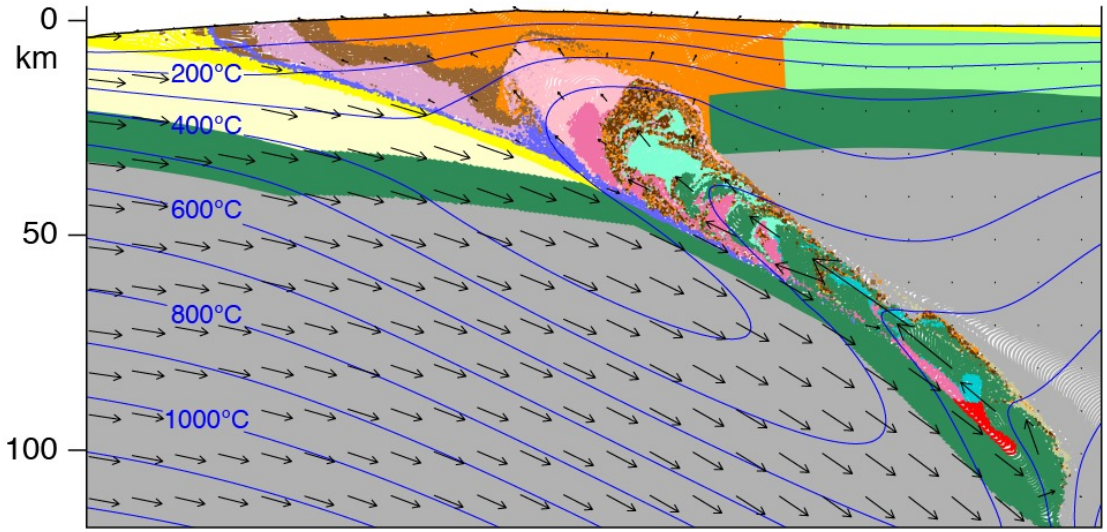
Large overpressures only in strong lithospheric mantle where deformation is plastic… limited to ~0.35 × P_{litho}

Burial, not overpressure main cause of UHP metamorphism in these models

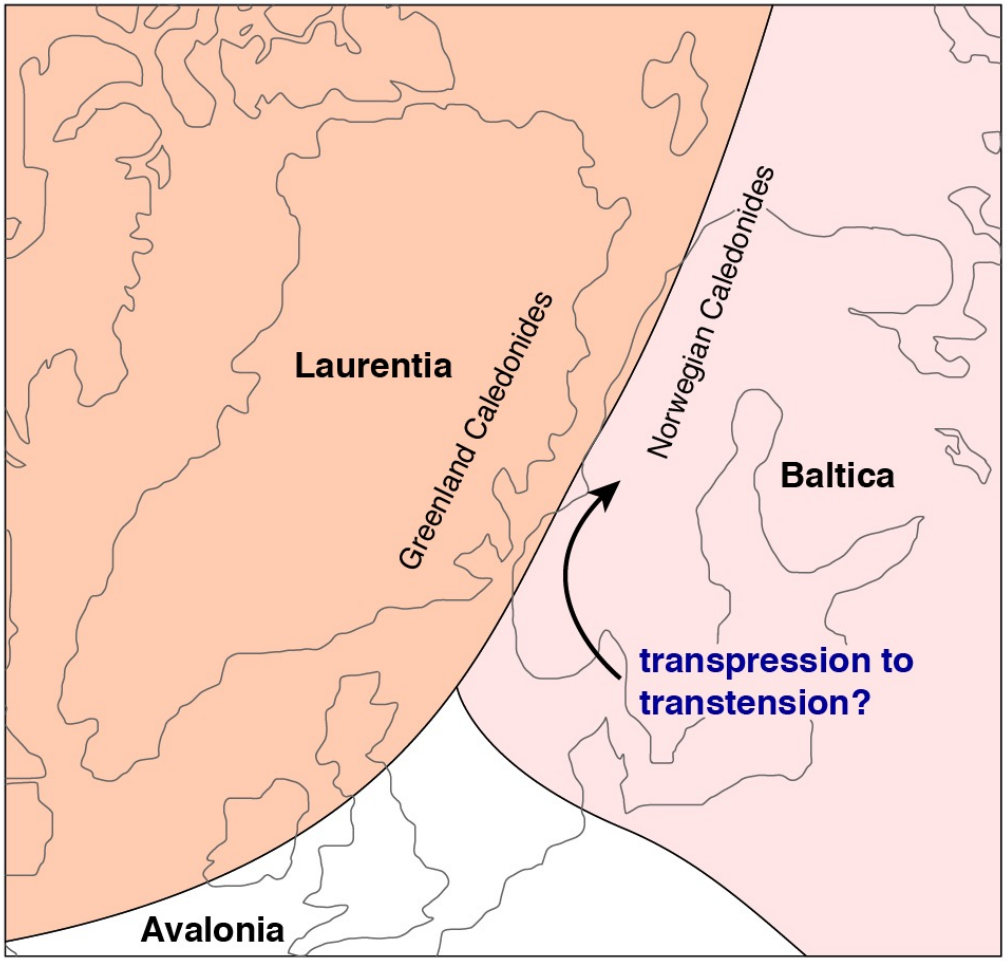
Alpine-type model summary

Western Alps UHP exhumation explained by buoyancy-driven channel flow

- *self-consistent model… Alpine-like processes are emergent features*
- *buoyancy drives 'within-orogen' extension, not plate divergence, rollback, etc.*



The Norwegian Caledonides



Caledonian orogeny

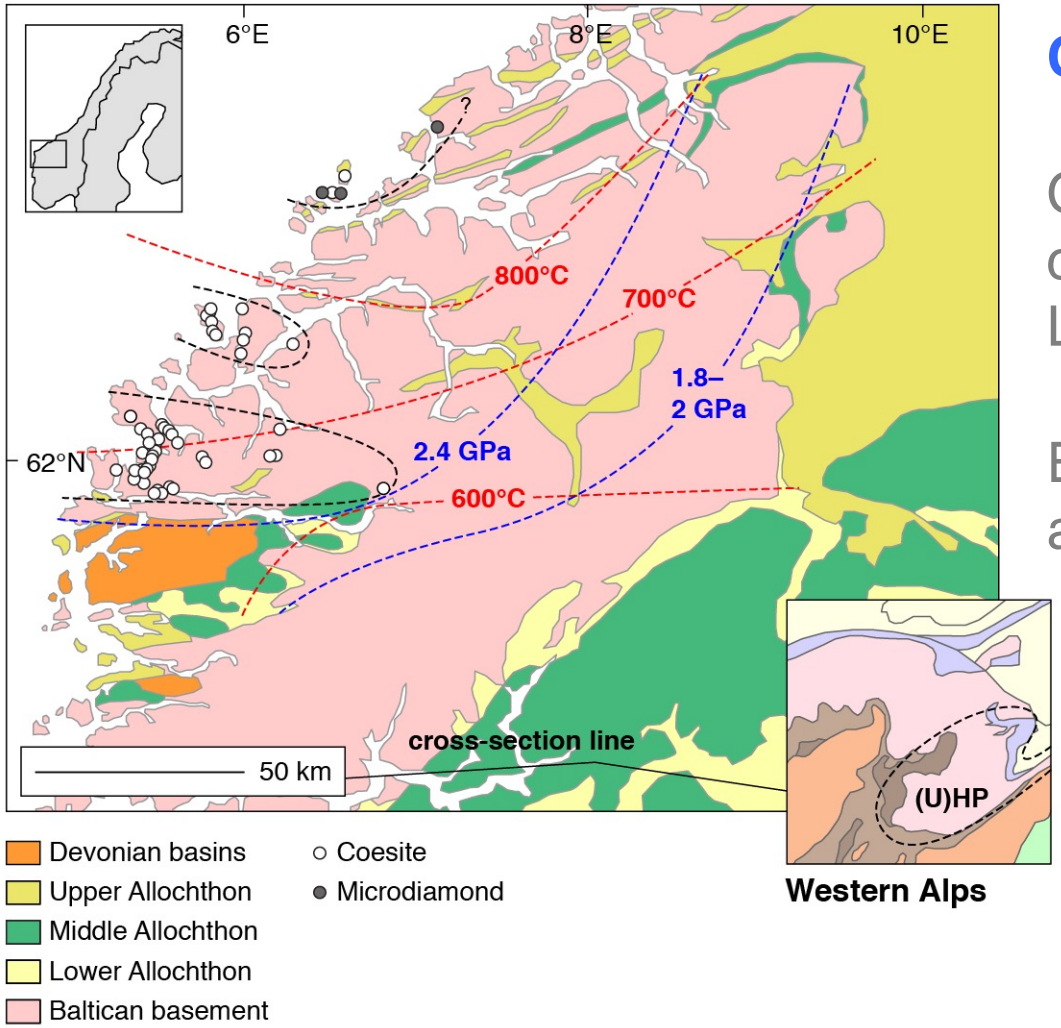
Ordovician-Silurian ocean closure and Baltica-Laurentia collision

Devonian transpression changes to transtension

Late to post-orogenic UHP exhumation

Modified from Wikipedia (!).

The Norwegian Caledonides



Caledonian orogeny

Ordovician-Silurian ocean closure and Baltica-Laurentia collision

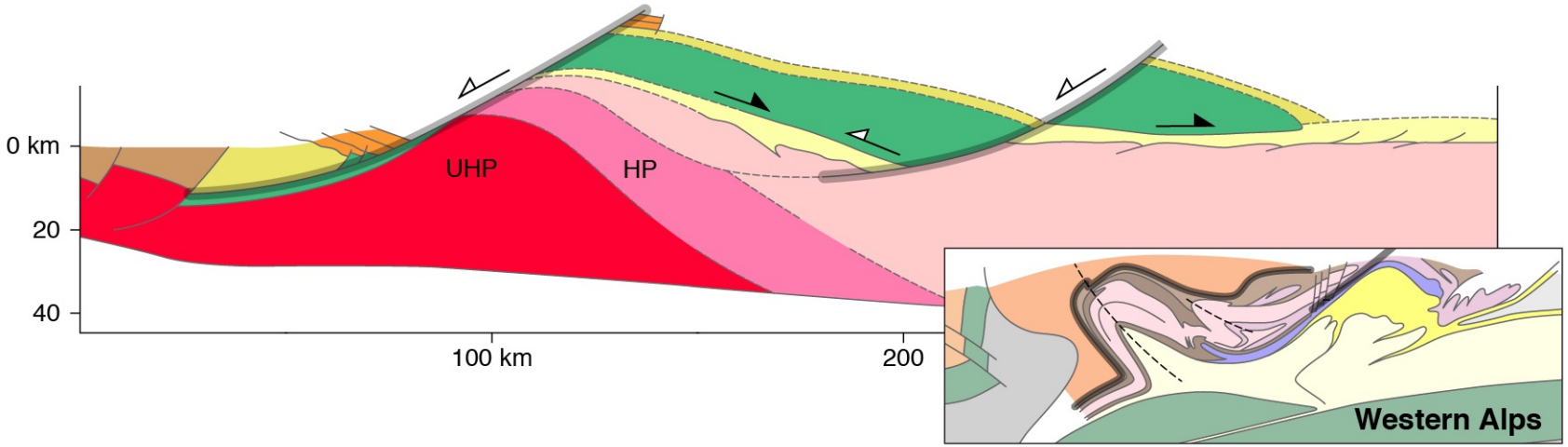
East-vergent thrusting of allochthons over Baltica

UHP metamorphism in allochthons (early) and basement (late)

Focus on Devonian late-orogenic UHP metamorphism and exhumation of Western Gneiss Region (WGR)

Data from Hacker et al. (2010).

Key tectonics features/processes



1. W–E thrusting and nappe accretion (allochthons)

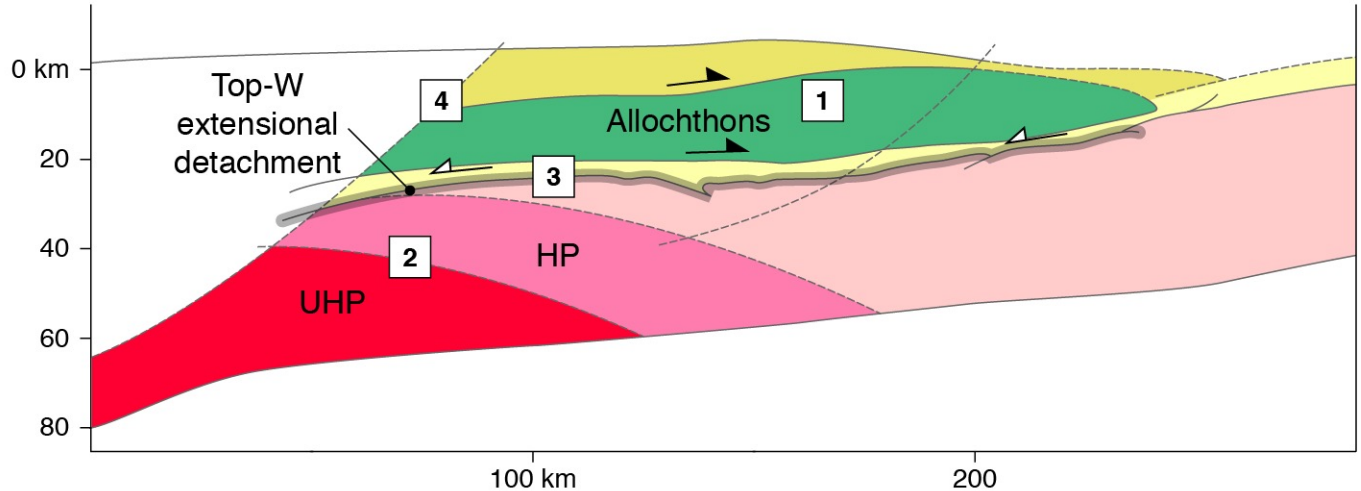
2. UHP metamorphism ~3.5 GPa/800°C (increasing toward W), ~415–400 Ma

3. Slow exhumation (<1 cm/yr), by top-W shearing… no thrusting? Related isothermal decompression

4. Late shallow crustal-extension

Cross section modified from Milnes et al. (1997).

Key tectonics features/processes



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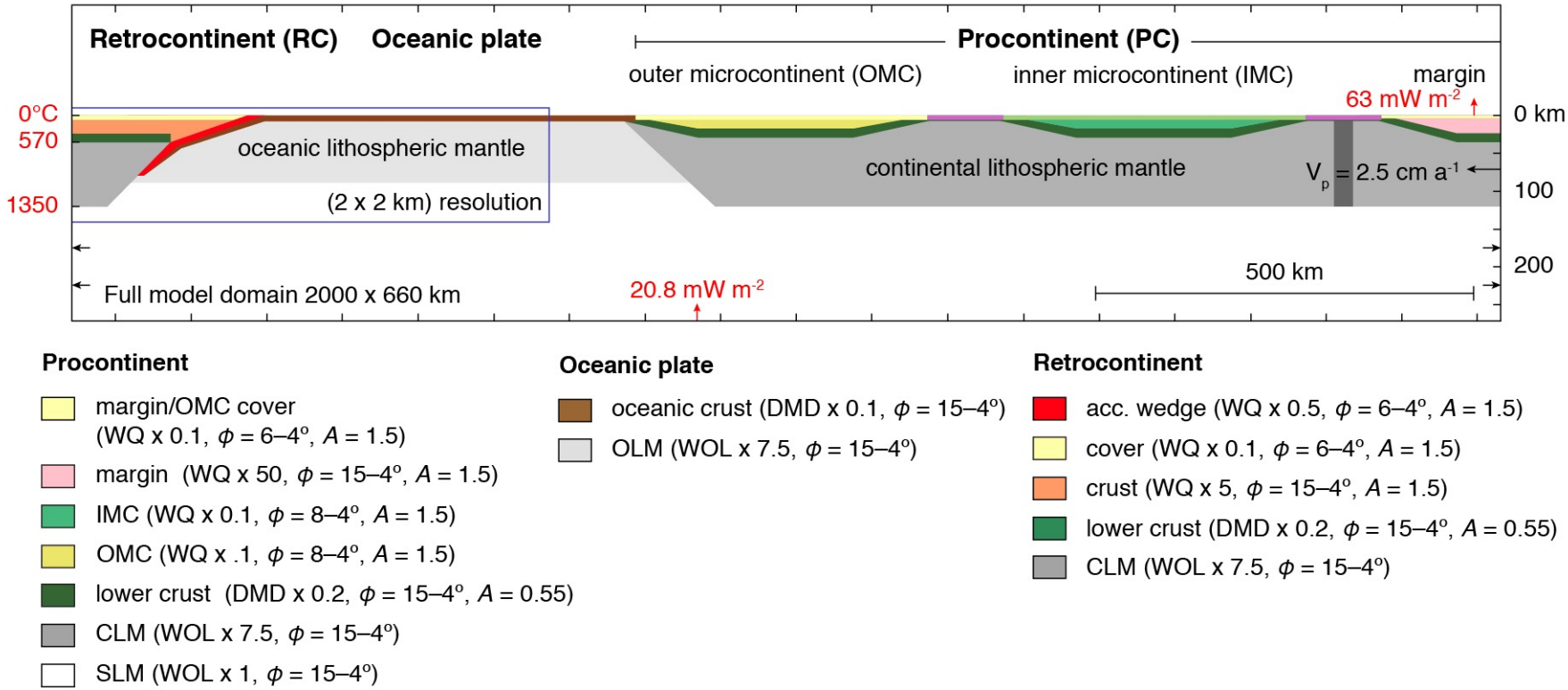
Cross section modified from Milnes et al. (1997).

Caledonides vs. Western Alps

In contrast with the Western Alps…

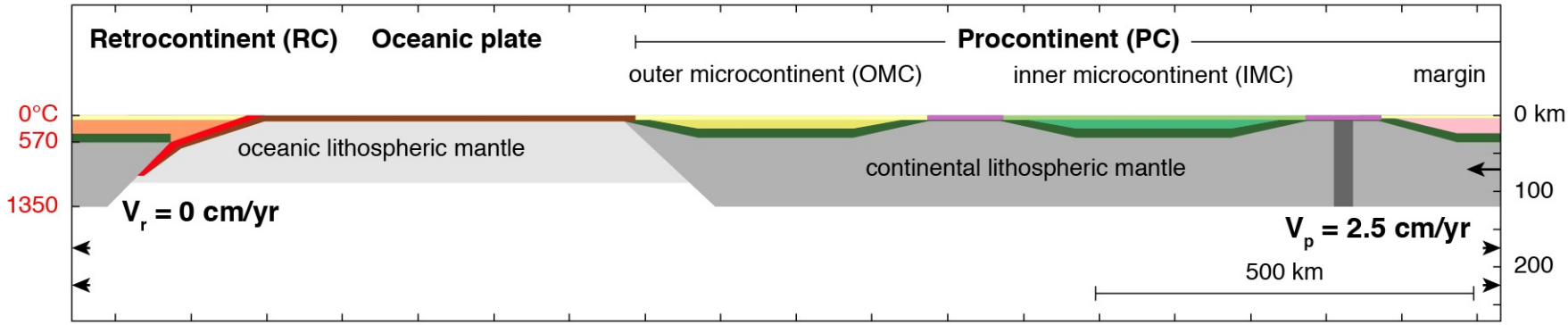
- *larger orogen and UHP terrane*
- *UHP metamorphism and exhumation at higher T*
- *'longer' metamorphism, slower exhumation (<1 vs. 3 cm/yr)*
- *no thrusting during exhumation*
- *exhumation at end of convergence and divergence*

Caledonide-type model design



Based on simplified view of Caledonian paleogeography…
microcontinents = allochthons, margin = Baltica basement

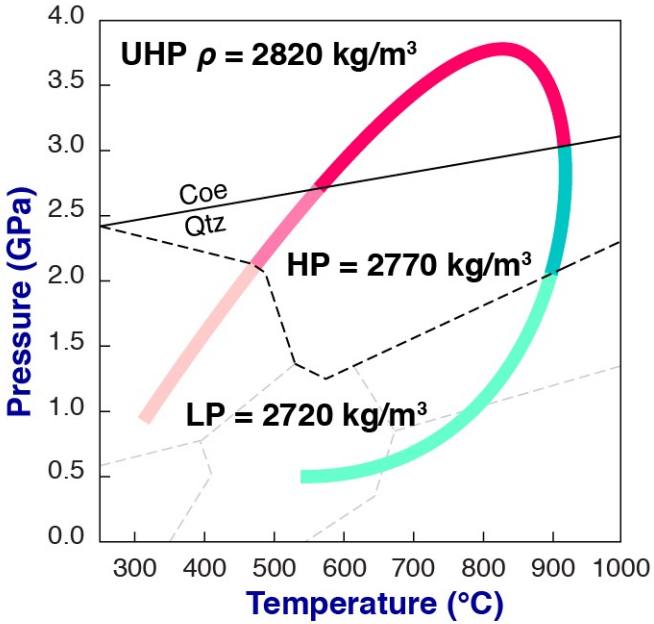
Caledonide-type model design



Procontinent

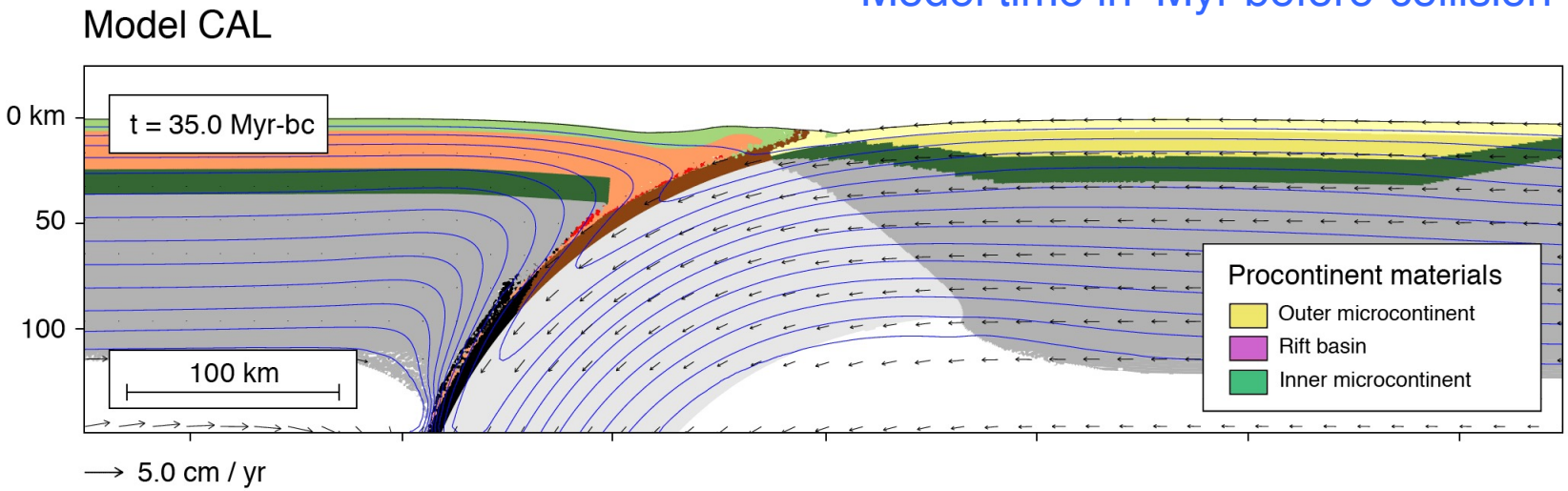
- cover (WQ x 0.1, ϕ = 4–4°)
- **margin (WQ x 50, ϕ = 15–4°)**
- lower crust (DMD x 0.1, ϕ = 15–4°)

Strong crust required to **keep margin coupled to slab**



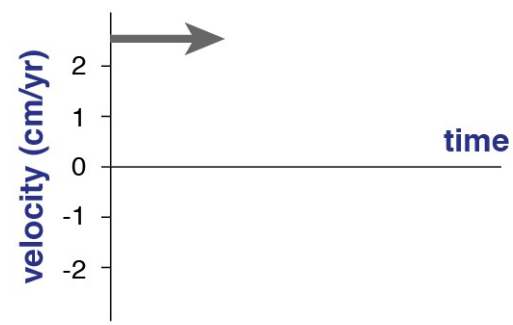
Phase 1: terrane accretion

Model time in ‘Myr before-collision’



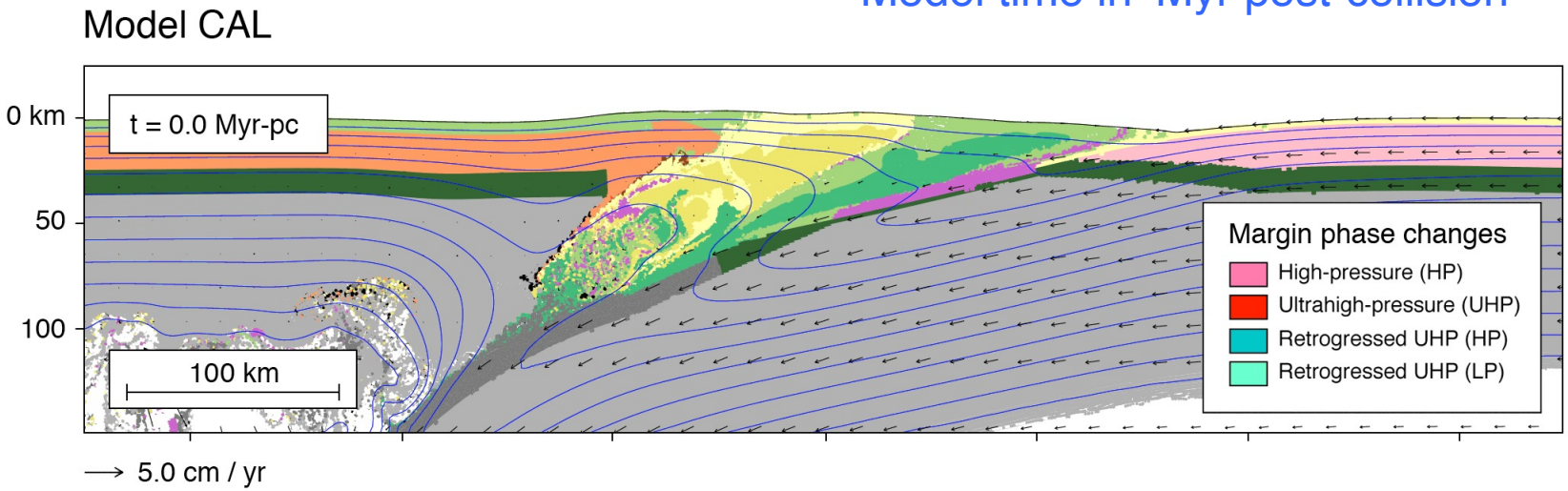
Phase 1:

- accretion of allochthons
- early UHP metamorphism in allochthons
- construction of large orogenic wedge



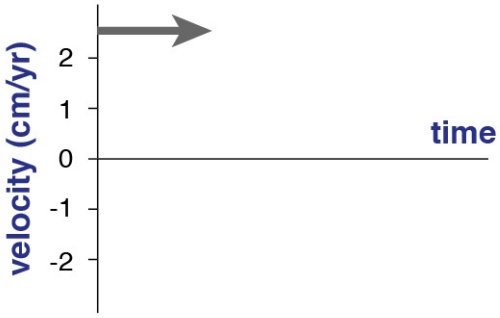
Phase 2: margin underthrusting

Model time in ‘Myr post-collision’

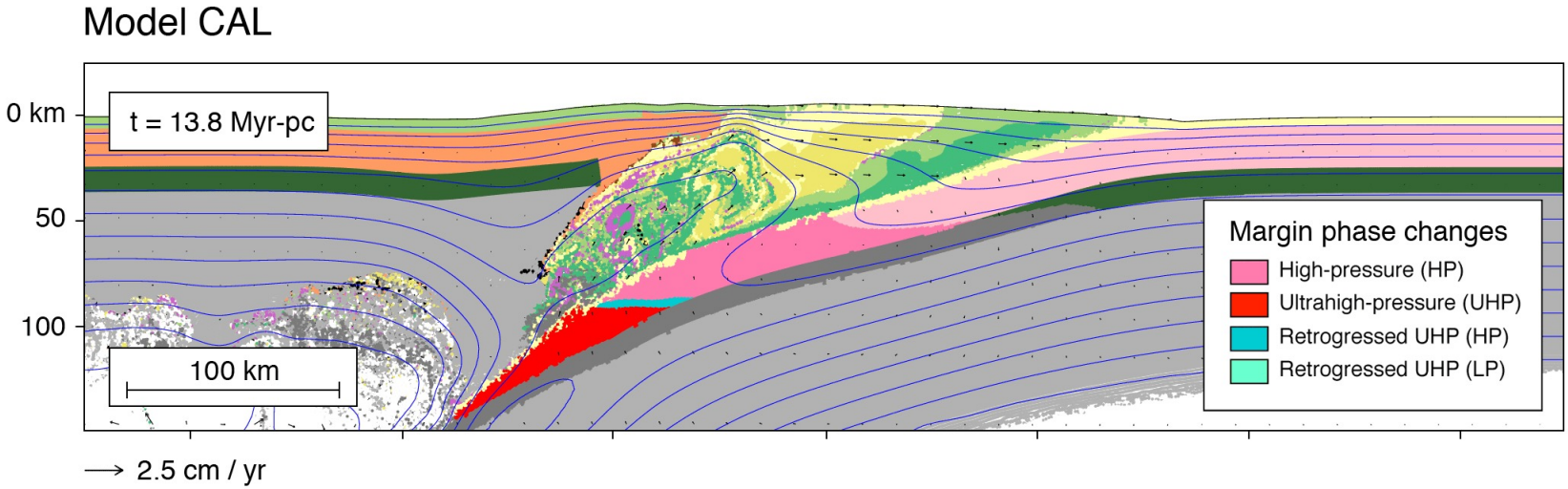


Phase 2:

- collision of margin with accreted terranes
- strong margin subducted beneath orogenic wedge
- UHP metamorphism

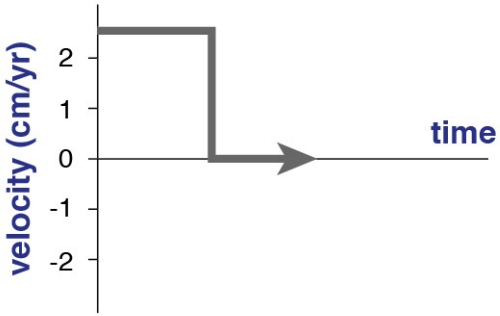


Phase 3: quiescence

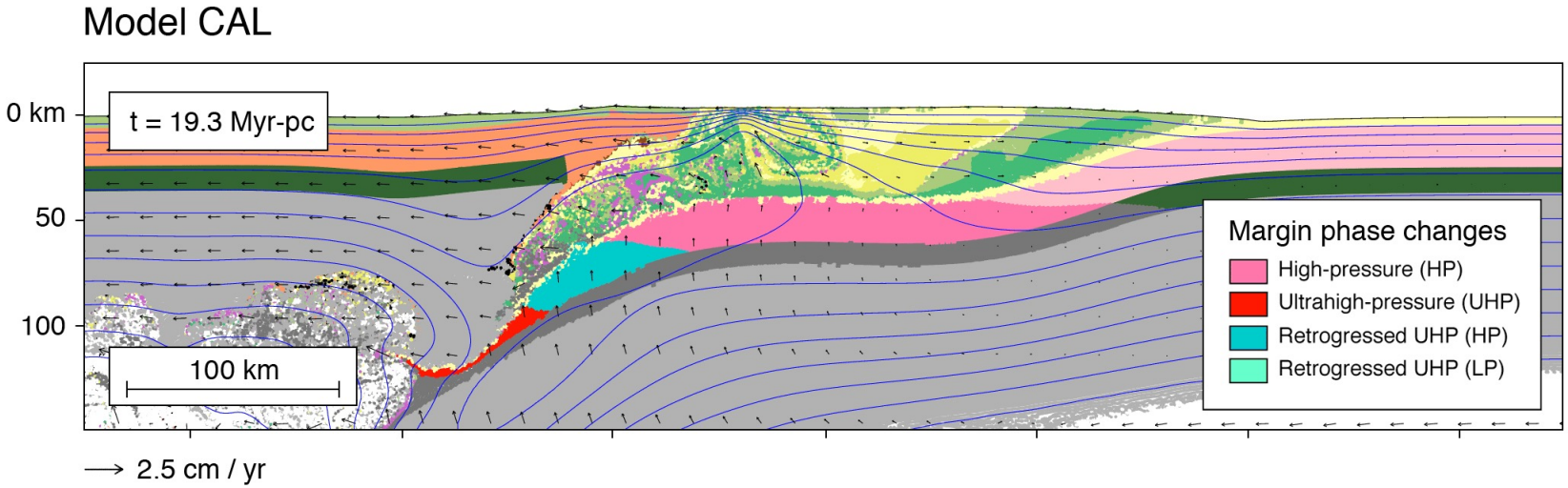


Phase 3:

- 0 cm/yr representing transition to transtension
- thermal relaxation of orogen
- gravitational spreading of wedge
- minor exhumation of UHP margin

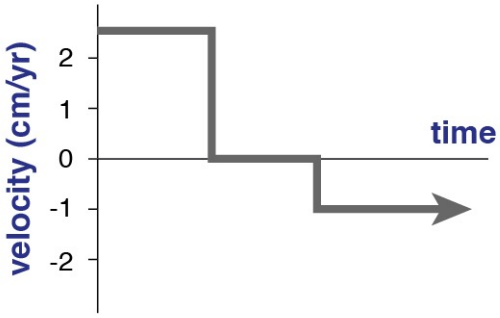


Phase 4: extension

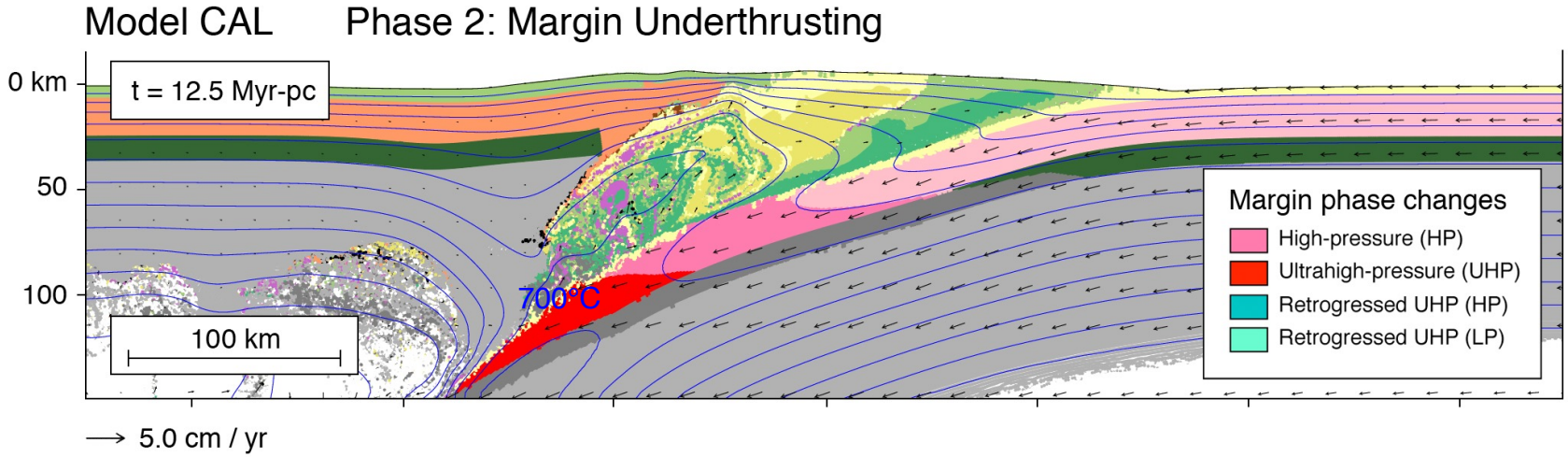


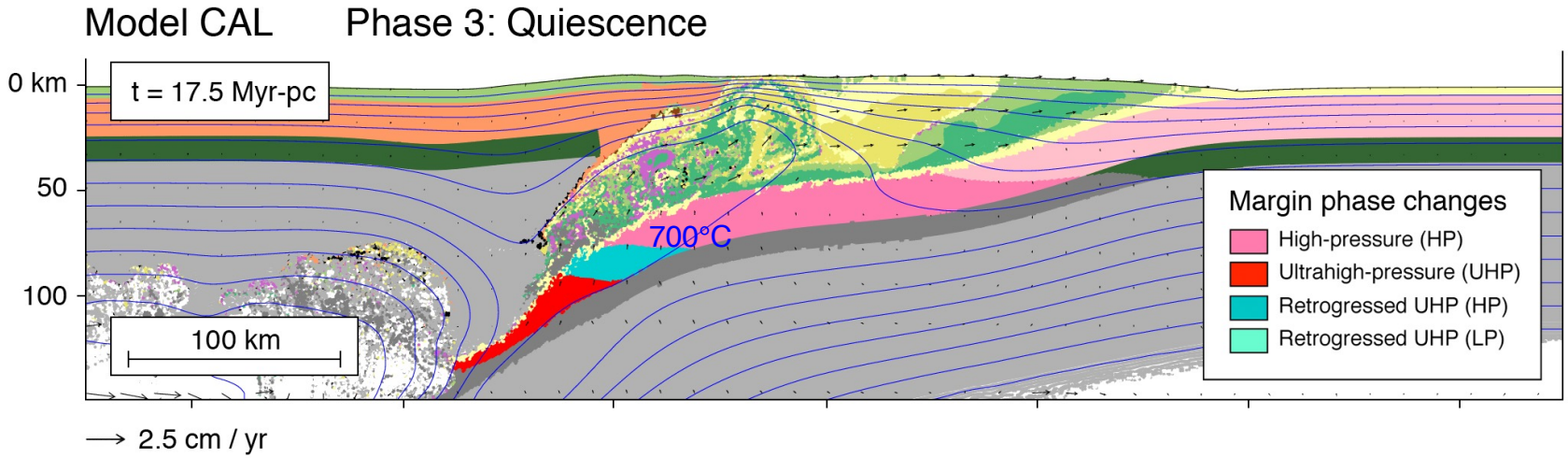
Phase 4:

- 1 cm/yr plate divergence representing transtension
- normal-sense shear above exhuming UHP margin
- minimal internal deformation
- high-T amphibolite facies overprint

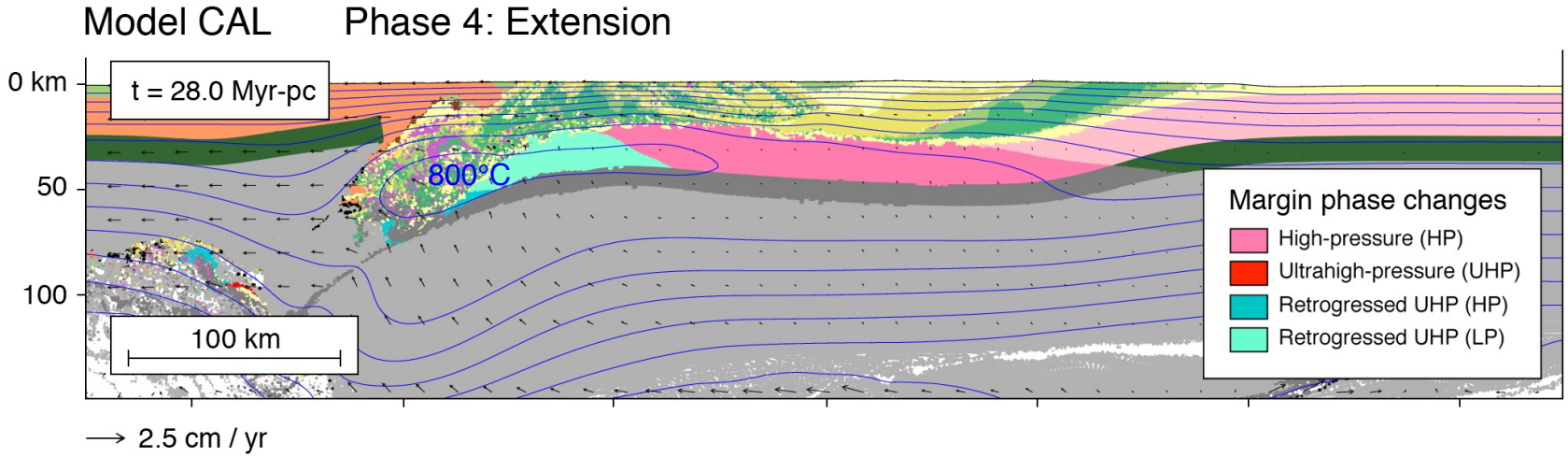


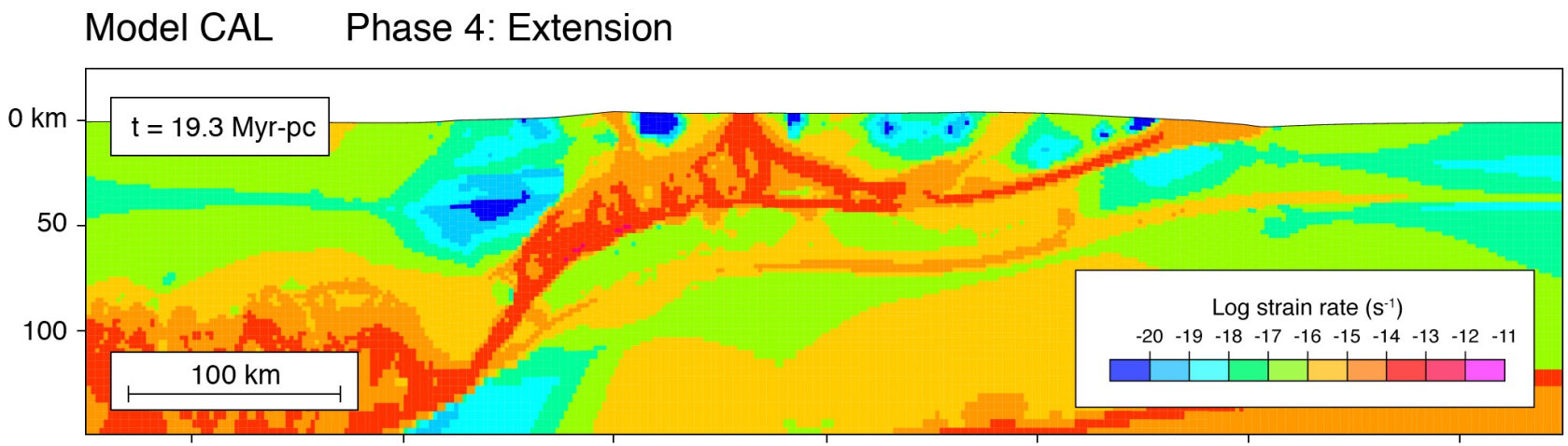
Caledonian-type model results



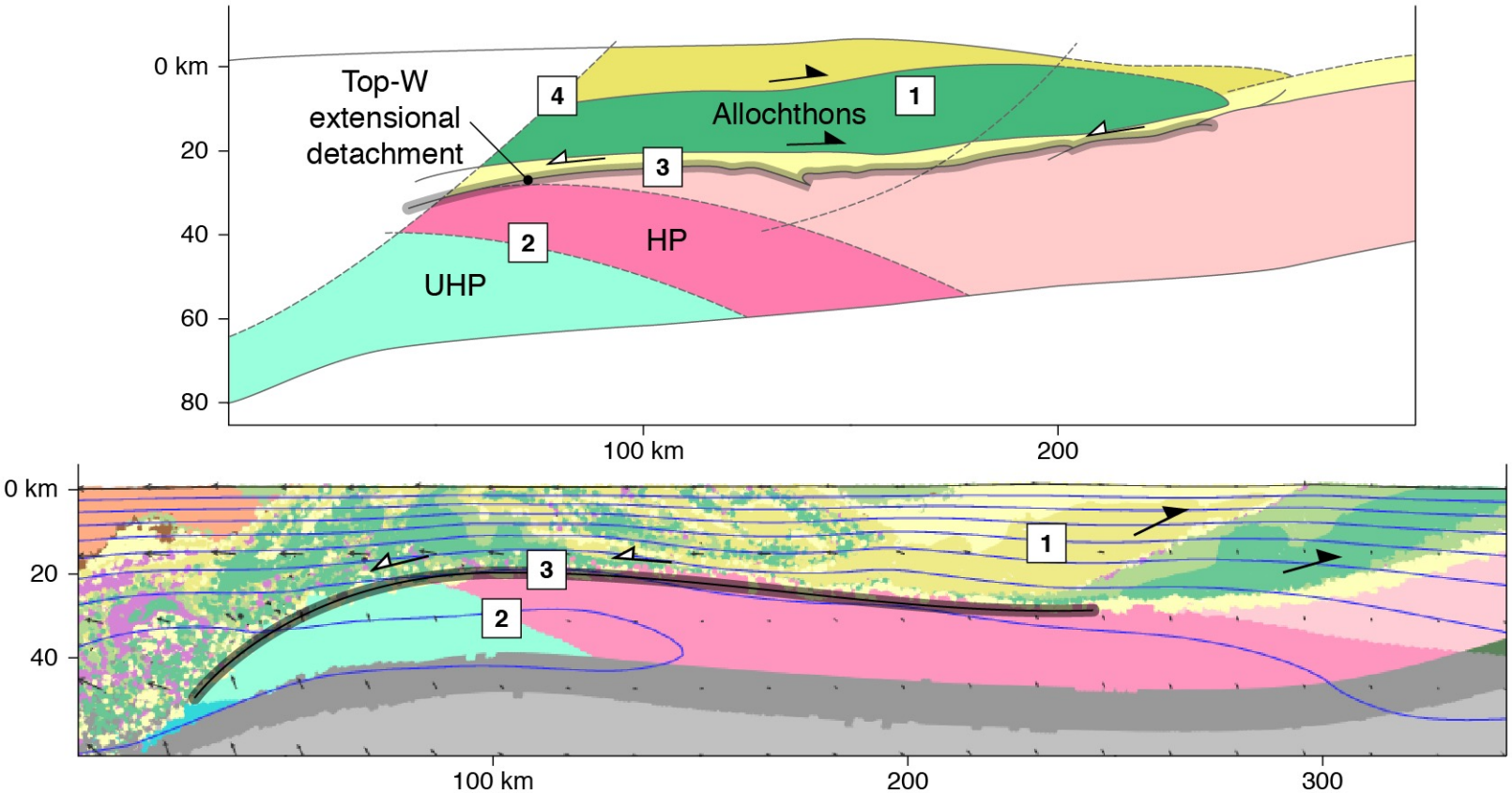


Caledonian-type model results



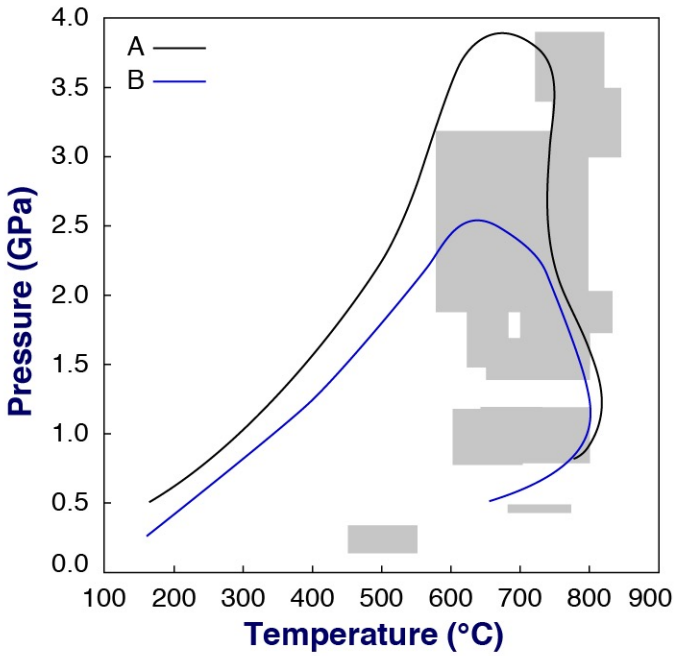


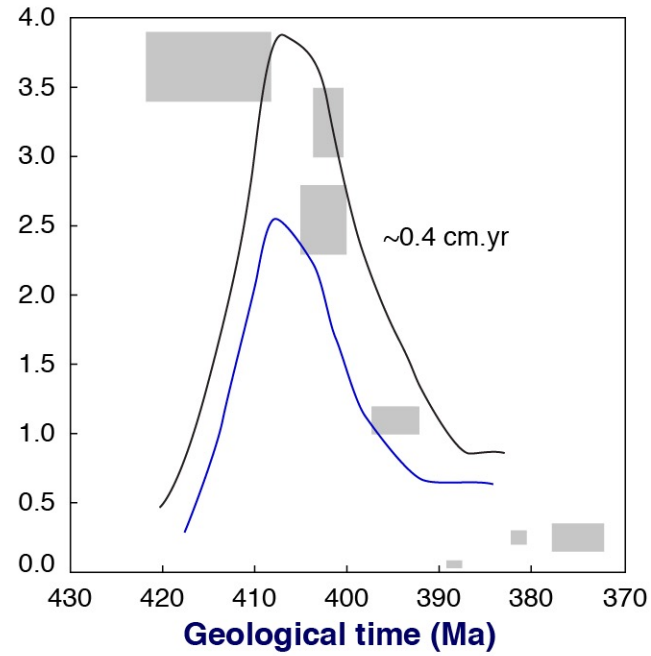
Comparison with crustal structure

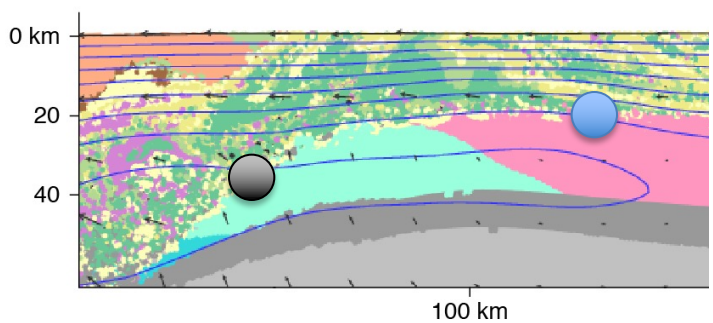


(1) allochthon accretion, (2) UHP rocks (higher-P grading to lower-P), (3) ductile normal-sense shear zone

Comparison with P-T data







T at UHP achieved after quiescent period

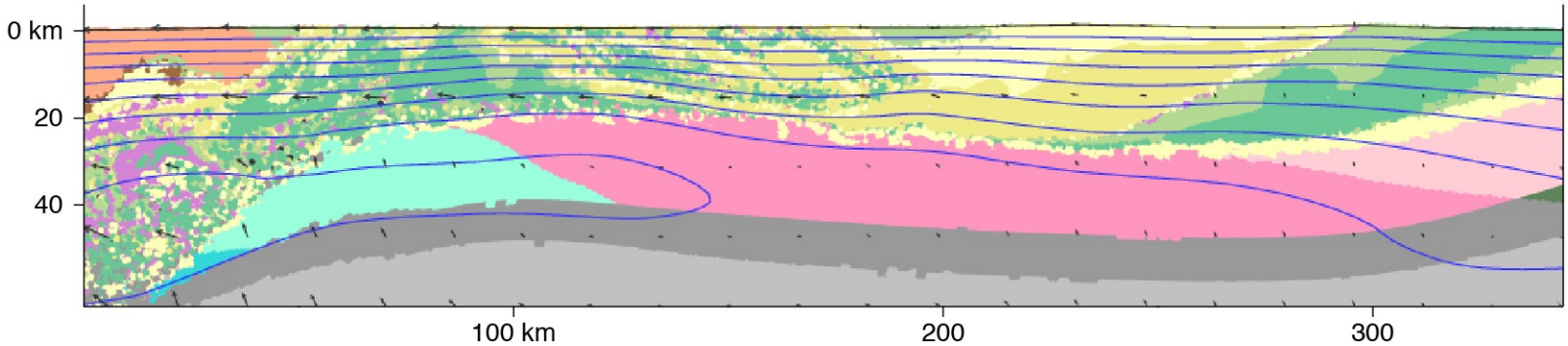
High-T overprint at crustal depths

Slow exhumation

Caledonide-type model summary

Western Gneiss Region UHP exhumation explained by plate-divergence and buoyant rebound

- *accounts for apparent lack of shortening during exhumation*
- *high-T requires slow burial or quiescent phase*
- *Resistance to detachment/channel flow implies very strong crust (=granulite protolith)*



Summary

Western Alps

Buoyancy driven channel flow explains…

- rapid exhumation
- syn-orogenic extension
- stacking of small UHP and lower-P units

Norwegian Caledonides

Plate divergence explains…

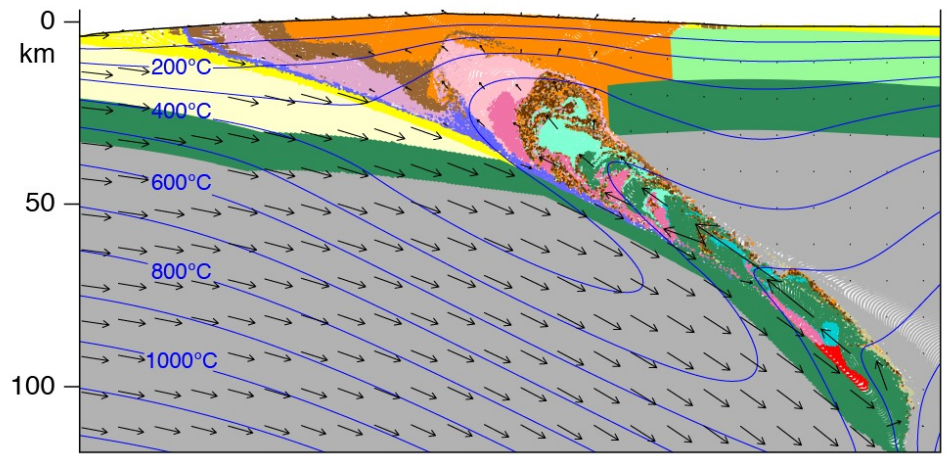
- slow exhumation
- absence of shortening during exhumation
- relatively minor internal deformation

Temperature histories reflect differences size and duration of orogeny/UHP metamorphism, and exhumation mechanism

Summary

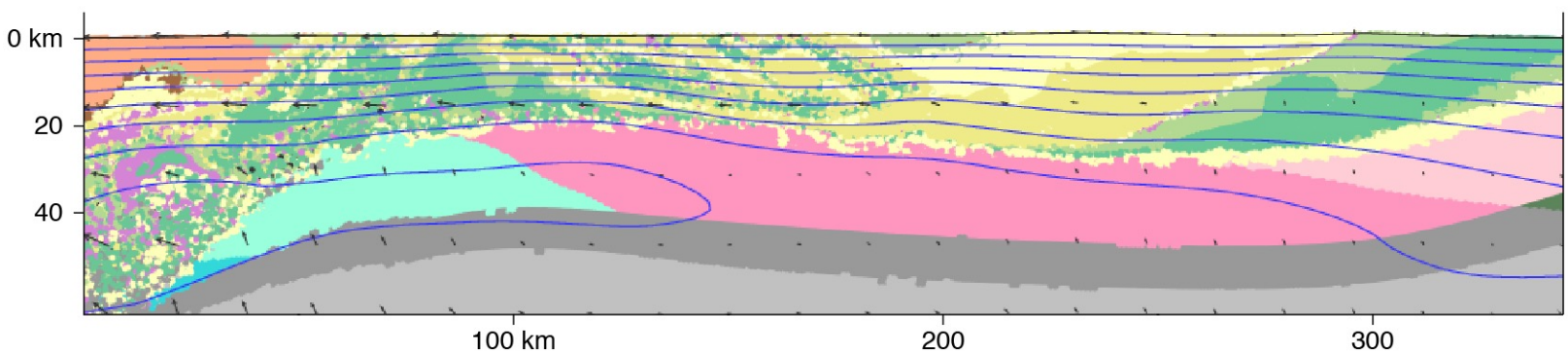
Western Alps

UHP Exhumation by buoyancy driven channel flow



Norwegian Caledonides

UHP exhumation by plate divergence



Conclusions

1. UHP terranes explained by **continental subduction, overpressure not necessary**

2. Exhumation accomplished by mechanisms including **buoyancy-driven channel flow** and **plate-divergence**

3. Models ‘work’ because they reproduce **a broad range of tectonic constraints from the Alps and Caledonides**

Can we use these models to understand other orogens/UHP terranes?

Acknowledgements

CIG meeting organizing committee

Douglas Guptill (code development)

NSERC

Model limitations…

What do we need to better understand these processes?

Rheology

- *effects of pressure/fluids on crustal rocks*
- *flow-laws for crustal compositions*
- *effects of metamorphic reactions (weakening?)*

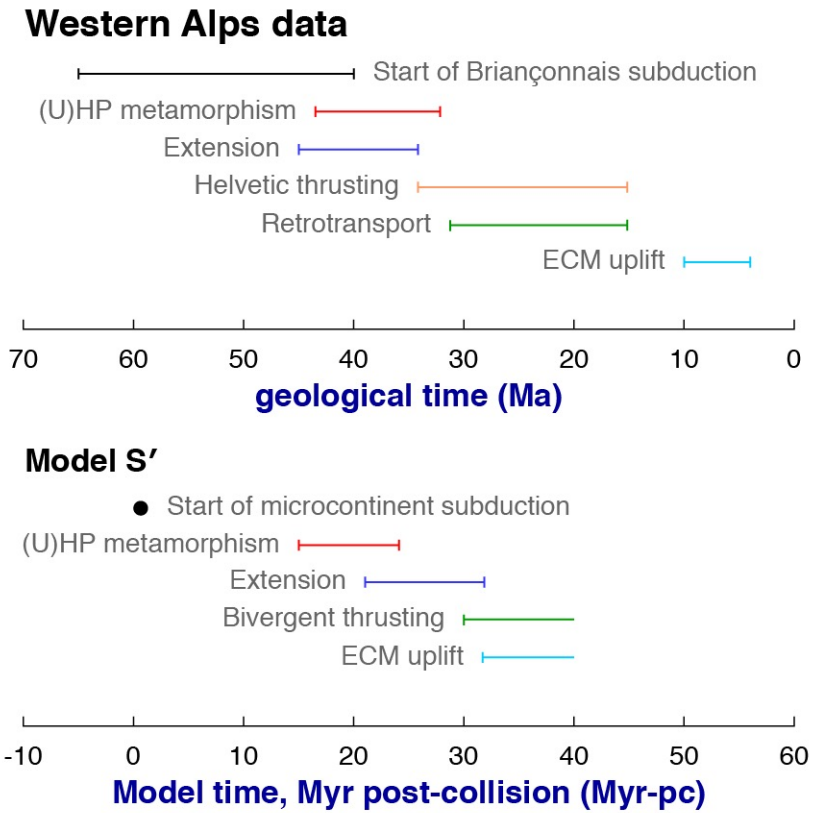
Higher-resolution models

- *necessary to address structural complexity*
- *more realistic strain-localization*

3D models

- *particularly for transpressional/tensional settings*

Alps timeline comparison



Model time aligned with geological time **assuming 'collision' 60 Ma**

Sequence of events and timing OK even with constant ~1 cm/yr convergence

See Butler et al. (2013) for sources.