Convergent margins processes
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four possible collision modes

- Instable pure or simple shear
- Pure shear
- Folding
- Stable subduction
important controlling parameters of subduction

- resistance of the upper and lower plate
- erosion/sedimentation rate
- convergence rate
- phase changes
- rheology
- thermo-rheological profile

Graphs showing:
- quartz and diabase resistance profiles at different stress levels (\(\sigma_1-\sigma_3\) en MPa)
- Cold and hot regions in the profile
SUBDUCTION NUMBER:

\[ S = \frac{\Delta x}{\ell_s} \]

(subduction length)

SUBDUCTION FEASIBILITY:

Peclet number \(\gg 1\)

\[ Pe = \frac{\text{advection rate}}{\text{diffusion rate}} \]
Newton's 2nd law of motion
\[ \rho g_i + \frac{\partial \sigma_{ij}}{\partial x_j} = \rho \frac{\partial V_i}{\partial t} \]

Heat Diffusion, Production, Advection
\[ \frac{D T}{D t} = \frac{\partial}{\partial x_i} \left( \chi \frac{\partial T}{\partial x_i} \right) + \frac{H_r}{\rho C_p} - V_i \frac{\partial T}{\partial x_i} \]

Constitutive laws
\[ \frac{D \sigma}{D t} = F(\sigma, u, V, \nabla V, \ldots, T, \ldots) \]

Additional laws
\[ \rho = f(P, T) \quad \nabla h_s \frac{\partial t}{\partial t} - \nabla(k_e \nabla h)^m \nabla h_s = 0 \]

Viscous
\[ \dot{\varepsilon} = A \exp \left( -\frac{E}{RT} \right) \sigma^n \]

Elastic
\[ \sigma_{ij} = \lambda \delta_{ij} \sum_k \varepsilon_{kk} + 2\mu \varepsilon_{ij} \]

Plastic
\[ \tau = (\tan \varphi) \sigma_n + C_0 \]
Gaussian difference equations for polygonal elements (Malvern, 1969)

\[ \int_s n_i f \, ds = \int_A \frac{\partial f}{\partial x_i} \, dA \]

where \( \int_s \) is the integral around the boundary of a closed surface;
\( n_i \) is the unit normal to the surface, \( s \);
\( f \) is a scalar, vector or tensor;
\( x_i \) are position vectors;
\( ds \) is an incremental arc length; and
\( \int_A \) is the integral over the surface area,

\[ \langle \frac{\partial f}{\partial x_i} \rangle = \frac{1}{A} \int_A \frac{\partial f}{\partial x_i} \, dA \]

\[ \langle \frac{\partial f}{\partial x_i} \rangle = \frac{1}{A} \int_s n_i f \, ds \]
Strain – stress – force – velocity increments

\[ \Delta \varepsilon_{ij}^{(e)} = \frac{1}{2} \left( \frac{\partial v_i^{(e)}}{\partial x_j} + \frac{\partial v_j^{(e)}}{\partial x_i} \right) \Delta t \]

\[ \frac{\partial v_i^{(e)}}{\partial x_1} = \sum_{k=1}^{3} v_i^{(k)} \cdot \beta_k, \quad \frac{\partial v_i^{(e)}}{\partial x_2} = \sum_{k=1}^{3} v_i^{(k)} \cdot \gamma_k. \]

\[ \sigma_{ij}^{(e)} = M(\sigma_{ij}^{(e)}, \Delta \varepsilon_{ij}^{(e)}, S_i) \]

\[ F_i^{(n)} = -\sum \frac{1}{2} \sigma_{ij}^{(e)}(n_j^{(1)} \Delta l^{(1)} + n_j^{(2)} \Delta l^{(2)}) \]

\[ v_i^{(n)}(t + \Delta t) = v_i^{(n)}(t) + \left[ F_i^{(n)} - \alpha |F_i^{(n)}| \text{sign}(v_i) \right] \frac{\Delta t}{m_{\text{inert}}} \]

The damping term

Large strain formulation (Jaumann's correction)

\[ dt_{\text{crit}} = \min \left( \frac{\Delta x}{\sqrt{K / \rho_{\text{inert}} / G}}, \eta \right) \]

\[ Re = \frac{\rho_{\text{inert}} VL}{\eta} \]

\[ \sigma_{ij} := \sigma_{ij} + (\omega_{ik} \sigma_{kj} - \sigma_{ik} \omega_{kj}) \Delta t \]

where

\[ \omega_{ij} = \frac{1}{2} \left\{ \frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i} \right\} \]
\[
\begin{align*}
\bar{\varepsilon} &= \dot{\varepsilon}_{ii}/3 \\
e_{ij} &= \dot{\varepsilon}_{ij} - \delta_{ij} \bar{\varepsilon} \\
\bar{\sigma} &= \sigma_{ii}/3 \\
\tau_{ij} &= \sigma_{ij} - \delta_{ij} \bar{\sigma} \\
\end{align*}
\]

\[
\left\{\begin{array}{l}
\varepsilon^{\text{elas}} + \varepsilon^{\text{vis}} + \varepsilon^{\text{plast}} - \varepsilon = 0 \\
e^{\text{elas}} = \dot{\tau}/2G \quad \text{elastic part} \\
e^{\text{vis}} = \tau/2\eta \quad \text{viscous part} \\
F = \tau^* + \sin \phi \sigma^* - \cos \phi C_0 \\
\tau^* = \sqrt{(\tau_{11} - \tau_{22})^2/4 + \tau_{12}^2} \\
\sigma^* = (\sigma_{11} + \sigma_{22})/2 = (\tau_{11} + \tau_{22})/2 + \bar{\sigma} \\
F(\lambda) - F^{\text{old}} = 0 \\
\frac{dt}{dt} = 0 \\
Q = \tau^* + \sin \psi \sigma^* \\
\dot{\sigma} = 3K(\bar{\varepsilon} - \lambda \sin \psi / 3) \\
\dot{\varepsilon}_{ij}^{\text{plas}} = \lambda \frac{\partial Q}{\partial \sigma_{ij}}
\end{array}\right.
\]

Extended Maxwell solid  
Kelvin solid  
Burgers’ solid
Continental Lithosphere: THICK MULTI-LAYER with EVP rheology
Erosion - sedimentation

Progressive phase changes

Thermodynamic processes

(THERIAK ; PERPLEX)

\[ \rho = f(P,T) \]

\[ G = \sum_{i=1}^{n} \mu_i N_i \]

\[ \frac{\partial h_s}{\partial t} - \nabla (k_e (\nabla h)^m \nabla h_s) = 0 \]
Predicted seismic velocities (m/s)

$V_p$

$V_s$
Summary of the numerical method

**Large strain/transformations**

**viscous-elastic-plastic rheology:**
- Non-associated Mohr-Coulomb law
- Softening-hardening
- Non-linear ductile creep

**Thermo-mechanical coupling**
- Latent heat sources
- Radiogenic sources
- Frictional dissipation

**Thermodynamic coupling**

**Coupling with surface processes**

**Free surface as upper boundary condition**

**Dynamic particle-in-cell remeshing**

**Inertial mode is possible**
Typical initial setup

Reference experiment
Collision/Subduction experiments:
1. Influence of the convergence rate
Dependence on shortening rate. Snapshot at $\Delta x = 180$ km

$Pe \approx 5$
$S = 0.2$

$Pe \approx 10$
$S = 0.9$

$Pe \approx 20$
$S = 1$

1.5 cm/y
12 Myr

3 Myr
2. Influence of thermo-rheological profile
Thermal age of 25 Ma $T_m = 850^\circ$C, $dx = 330$ km, $t = 5.5$ Ma, 2x3 cm/yr

Influence of thermo-rheological age - A1: CREME - BRULEE RHEOLOGY (SOFT)

$S < 0.1$

 Thermal age of 25 Ma $T_m = 850^\circ$C, $dx = 330$ km, $t = 5.5$ Ma, 2x3 cm/yr
Example: Pannonian Basin / Carpathians

Burov et al, 2007

Figure: Spakman
Thermal age of 90 MA, $T_m = 600°C$, $d x = 330$ km, $t = 5.5$ Ma, 2x3 cm/yr

Influence of thermo-rheological age – A2 JELLY SANDWICH (MIDIUMLM)

$S < 0.3$

Marker

Time = 1.8e+14

Depth (km)
Thermal age of 200MA, $T_m = 500^\circ C$, $dx = 330$ km, $t = 5.5$ Ma, $2 \times 3$ cm/yr

$S \sim 0.7$

Influence of thermo-rheological age - B1 JELLY SANDWICH RHEOLOGY

Marker
Thermal age of 300MA, \( T_m = 450°C \), \( d_x = 330 \text{ km} \), \( t = 5.5 \text{ Ma} \), \( 2 \times 3 \text{ cm/yr} \)

\[ S \sim 1. \]

Influence of thermo-rheological age – C1 JELLY – SANDWICH RHEOLOGY

Temperature (°C)

Time = \( 1.7 \times 10^{14} \)

Time = \( 1.1 \times 10^{7} \)

Marker

thermal age of 300MA, \( T_m = 450°C \), \( d_x = 330 \text{ km} \), \( t = 5.5 \text{ Ma} \), \( 2 \times 3 \text{ cm/yr} \)
STRONG (Te > 60 km) lithosphere, FAST collision (India-Asia > 5 cm/y)
Very fast (6 cm/y) 
Q - D1

Time = 5.3 Myr
Fast (3 cm/y)

Q-D1

Time = 5.8 Myr

Time = 7.63 Myr
Fast (6 cm/y)
Q-D2
Dependence on rheology: summary

- $S = 1$
  - $T_e > 40$ km
  - $T_m < 450^\circ$C

- $S = 0.7$
  - $T_e = 20$ km
  - $S = 0.7$

- $S = 0.5$
  - $T_e = 20$ km
  - $T_m < 650^\circ$C

- $S = 0.1$
  - $T_e = 20$ km

- $S = 0$
  - $T_e = 20$ km
  - $T_m = 600^\circ$C

5 Myr
Moho temperature = Thermotectonic Age = thermo-rheological profile
Strong (diabase) lower crust promotes folding.
3. Influence of coupling with surface processes
Final stages of subduction-collision, as function of convergence and erosion rate

<table>
<thead>
<tr>
<th>Time (Myr)</th>
<th>Convergence Rate</th>
<th>Erosion Rate</th>
<th>Diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 - 1.5</td>
<td>no subduction</td>
<td>S=0.1</td>
<td></td>
</tr>
<tr>
<td>1.75 - 1.75</td>
<td>no subduction</td>
<td>S=0.21</td>
<td></td>
</tr>
<tr>
<td>2.02 - 2.02</td>
<td>no subduction</td>
<td>S=0.42</td>
<td></td>
</tr>
<tr>
<td>3.1 - 3.1</td>
<td>S=0.6</td>
<td>S=0.8</td>
<td></td>
</tr>
</tbody>
</table>

Time = 6.5 Myr
Dependence on efficiency of surface erosion rate ($k$)

$\frac{dh}{dt}=0$ mm/yr ($k=0$)

$\frac{dh}{dt}=6$ mm/yr ($k=500$)

$\frac{dh}{dt}=12$ mm/yr ($k=3000$)

$\frac{dh}{dt}=20$ mm/yr ($k=6000$)

Maximal erosion rate and subduction length as function of $k$, convergence rate 60 mm/yr
1. First 0 to 5 Myr: similar initial development

- Continental subduction and formation of a small accretion prism mainly of lower crustal material
  - k = 50
  - k = 500
  - k = 3000
  - k = 6000

3. After 8 Myr, subduction scenarios become different

- Sediment ends up before, as whole-scale folding with excessively unrealistic topography becomes impossible due to buckling and cannot be compensated by extension

4. Subduction still goes on

- 500 km of subduction, coupling occurs and stem enters into pure collision mode with topography
A simulation compatible with Indian-Asian collision

- **Geotherm 450 Ma**
  \( T_{Moho} = 400^\circ C \)

- **High initial convergence rate**
  \( 6cm/y \)

- **About 700km of subduction**

\[ \Delta x = 660km \]
Phase 1 ($dx=0-220\text{km}$): deformation at suture

- **Erosion:** $1\text{cm/annum}$
- **Vertical velocity:** $1\text{cm/annum}$

**Lower crustal prism**

- $\Delta x=200\text{km}$

**Transitory regime...**

- $\Delta x=170\text{km}$
- $\Delta x=220\text{km}$
Phase 2: Major thrust fault activity

All deformation is concentrated on a single thrust during 250 km of shortening.

Δx = 260 km
Δx = 320 km
Δx = 450 km

- Erosion: 2 cm/annum
- Vertical velocity: 2.5 cm/annum
- Horizontal velocity: +3 cm/annum, -3 cm/annum
- Topography: 12 km

It controls all surface deformation.
Phase 3: accretion of a large crustal prism

Δx = 520km
Δx = 600km
Δx = 660km

Successions of frontal thrusts towards South

→ Formation of an asymmetric chain above the prism

erosion

vertical vel.
1 cm/an

horizontal velocity
+3cm/y

topography
8 km

Δx = 660km

-3cm/y
1 cm/an
Topography evolution

Phase 1

Phase 2

Phase 3

Position of the suture zone
\( \Delta x = 660 \text{km} = \text{Actual Himalaya?} \)

**From** \( \Delta x = 0 \text{ to } 220 \text{km} = \text{Himalaya between 50 and 30 Ma?} \)

- Deformation (backthrusting at suture)

\( \Delta x \text{ from 220 to 460 km} = \text{Himalaya between 20 and 15 Ma?} \)

**Major Thrust = MCT?**

- Lower crustal exhumation

**Extension to the North of the thrust = the Southern Tibetan Detachment (STD)?**

**\( \Delta x \) from 0 to 220 km = Himalaya between 50 and 30 Ma?**

- Lower crustal exhumation

**STD**

- Large prism developed at South of suture
- Comparable size of the crustal prism
- Deformation localized along the Frontal Thrust
End-member case:
Low Pecklet number (i.e. slow)
Convergence
Slow Alpine Collision I: Oceanic phase

PhD thesis of Ph. Yamato;
Yamato et al., 2007
Oceanic subduction

1. Oceanic wedge seems to stay steady during 15-20 My
2. Continental subduction
3. Internal crystalline massif exhumation

(a) Upper Cretaceous (~70-60 My)
- Obduction (Chenallet)
- Sl. calcarious schists
- 2: Overthrust of flysch
- 1: Helminthoids flysch

(b) Eocene (~55-45 My)
- Dauphinois flysch (40-35 My)
- Black flysch Briantonnais (45-40 My)
- Vise and a part of Sul-L. Molès ases

(c) Oligo-Miocene (~25 My)
- Molès ases
- Molès ases
- Pre-D2
- P(kbar)
- Depth (km)

15 to 1.2 mm.an⁻¹
4.5 to 1.125 mm.an⁻¹
Stable case

- Strong continental crust

Instable case

- Weak continental crust

Initial geometry

Accretion prism stability

- Initial geometry

- Strong continental crust

- Weak continental crust

- Old upper plate

- Low sediment viscosity

- Schistes go down

- Pelite less rich in Al

- \( V = 1.5 \text{ cm.an}^{-1}; \ V = 6 \text{ cm.an}^{-1} \)
PhD thesis of Ph. Yamato; Yamato et al., 2007
Burov and Yamato, 2007

wait ...
Time = 12.0221 Ma
The Results: Evolution of an accretion prism

T(°C)

~ 1 Ma
~ 5 Ma
~ 10 Ma

T(°C) 0 700 1380
The Results

**Observed versus predicted P-T-t paths**

Exhumation rates of sediments in the accretion prism
Serpentinite layer (light, weak) below the oceanic crust: important condition for oceanic subduction.
Slow Alpine Collision II: continental phase

PhD thesis of Ph. Yamato; Yamato et al., 2007
Alpine lithosphere-asthenosphere system

(Courtesy of E. Kissling)

138-165 km depth range

‘Adriatic slab’

‘European slab’

detached part

Lippitsch et al. 2003, JGR

Schmid et al. 2004

( Courtesy of E. Kissling)
SLOW collision, WEAK (Te<30 km) lithosphere
Influence of the crustal rheology

Croûte QD = Quartz - Diabase  Croûte QQ = Quartz - Quartz  Croûte DD = Diabase - Diabase

PhD Thesis
Yamato, 2007
Influence of convergence rate

at $\Delta x = 5\%$ at $t = 20$ Myr

$\Delta x = 5\%$

$t = 20$ Ma

$25$ Ma

$100$ km

$03$ mm.an$^{-1}$

$12.5$ Ma

$100$ km

$06$ mm.an$^{-1}$

$8.33$ Ma

$100$ km

$09$ mm.an$^{-1}$

$6.25$ Ma

$100$ km

$12$ mm.an$^{-1}$

$2.5$ Ma

$100$ km

$30$ mm.an$^{-1}$

$\Delta x = 8\%$

$\Delta x = 12\%$

$\Delta x = 16\%$

$\Delta x = 40\%$
Influence of erosion ($k$) on collision mode

$t = 20 \text{ Ma}, \Delta x = 8\%, V_{\text{tot}} = 6 \text{ mm.an}^{-1}$

$k = 3000 \text{ m}^2\text{y}^{-1}$

$k = 1500 \text{ m}^2\text{y}^{-1}$

$k = 500 \text{ m}^2\text{y}^{-1}$
Reference case: evolution details

~0 Ma

~5 Ma

~10 Ma

~20 Ma
Reference case: predicted P-T-t paths

P-T-t Path
altitudes (km)

3000 m².an⁻¹
1500 m².an⁻¹
500 m².an⁻¹

Distance par rapport au bord gauche de la boîte (km)
Exhumation rates as function of the erosion rate (first 20 Myr)

Top: markers that have achieved 20-40 kbar and 300-700°C

Bottom: markers that have achieved 10 kbar.
Summary of the parametric study of slow continental convergence

3 major parameters

Convergence rate
Erosion
Rheology of the continental crust

Effect of the convergence rate

Effect of erosion

Yamato, 2007
Burov and Yamato, 2007
Oceanic versus continental subduction

**SUBDUCTION OCEANIQUE**
- érosion (ring & Brandon, 1994, 1998) + tectonique de surface
  - < 2 mm.an⁻¹
  - 2 à 5 mm.an⁻¹
- underthrusting + underplating (Platt, 1986)
- analogue à la circulation en coin (Cloos, 1982, 1985)

**Matériel exhumé:** Sédiments

**SUBDUCTION CONTINENTALE**
- 0.5 à 5 mm.an⁻¹
- point F < 2 mm.an⁻¹
- érosion + tectonique de surface
- Forces de volumes
- ~ 10 mm.an⁻¹
- Zones de découplage

**Matériel exhumé:** Croûte continentale + Sédiments (analogue à Jolivet et al., 2003)

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**Matériel exhumé:** Sédiments + Croûte océanique

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**Matériel exhumé:** Croûte continentale + Sédiments + Croûte océanique
Some Perspectives

- Detailed study of impact of fluid circulation + P-T impact on rheology + melting + latent heat production.
- Parametrization of shear heating. Rheology of aggregates

- Some new problems: obduction

... and 'exhumation'!
SUMMARY

- Viscous-elastic-plastic rheology and rheological structure (not simply integrated strength) of both convergent plates is of crucial importance. Some commonly inferred (from rock mechanics) rheological profiles are mechanically prohibited (e.g., CB): possibility to constrain rheology from models!

- Models need to reproduce in sufficient detail a wealth of the observed features such as accretion prism and topography evolution, fault distribution, sedimentary mass balance, P-T-t paths for the exhumed rock, surface heat flow, present day seismic velocity structures etc. Structural and P-T-t data become VERY important constraints on the models.

- Convergence rates < 1-2 cm/y or > 10 cm/y are incompatible with subduction mechanisms. Continental subduction is a short-lived stage (1-5 My for the Alpes, 15 My for India) of continental convergence. For oceanic subduction, fluids (serpentinization) condition stable asymmetric subduction.

- Topography, but also DEEP subsurface evolution strongly depend on dynamic interplays between subsurface and surface processes

- Need to account for deep mantle dynamic (and phase transitions) at list down to the depth of 650 km

- Phase transitions and evolution of the mechanical properties of rocks as function of P-T and fluid content need to be taken into account (next challenge !)
SUMMARY

- In difference from oceanic subduction, continental subduction requires far-field forcing and is strongly conditioned by rheological structure of the lithosphere. Strong mantle lithosphere and high initial convergence rate (> 2x1.5 cm/y) are the primary conditions for continental subduction.

- Evolution of collision zones depends on the rheology and crustal thickness of both, the upper and the lower plate. Crust-mantle decoupling in the subducting plate may drive crustal thickening in the upper plate.

- Crustal material may be drawn to 100-150 km depths - the HP-UHP exhumation mechanisms are different for different convergence styles and rates - Structural and P-T-t data become important constraints on the models.

- Fast convergence rates (e.g., 5 cm/y, Himalaya) favour polyphase evolution with several episodes of crustal prism evolution and exhumation.

- In real world, slow-down of the convergence rate during collision should play a primary role for exhumation and further evolution of collision.

- Topography, but also DEEP subsurface evolution strongly depend on dynamic interplays between subsurface and surface processes.