Propagation of tectonic waves

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1) Crust stability *vs* lithosphere instability

Crustal deformation results from the disequilibrium between boundary stresses and buoyancy stresses arising from lateral density variations within the lithosphere. The positive buoyancy of the light crust with respect to the underlying mantle induces a tendency to collapse (a_c). The cool and dense thermal boundary layer forming the lithospheric mantle has a negative buoyancy which tends to generate Rayleigh-Taylor instabilities in the lithosphere (a_θ).
Here we show that an alternative domain in which deformation is propagated laterally dominates in continents.

Stress balance : $4L_0\frac{\partial}{\partial x}\eta\frac{\partial u}{\partial x}=\frac{\partial M}{\partial x}$, M is the moment of the lithospheric mass anomalies $M=\int_0^{+\infty}\delta\rho g z\,dz$

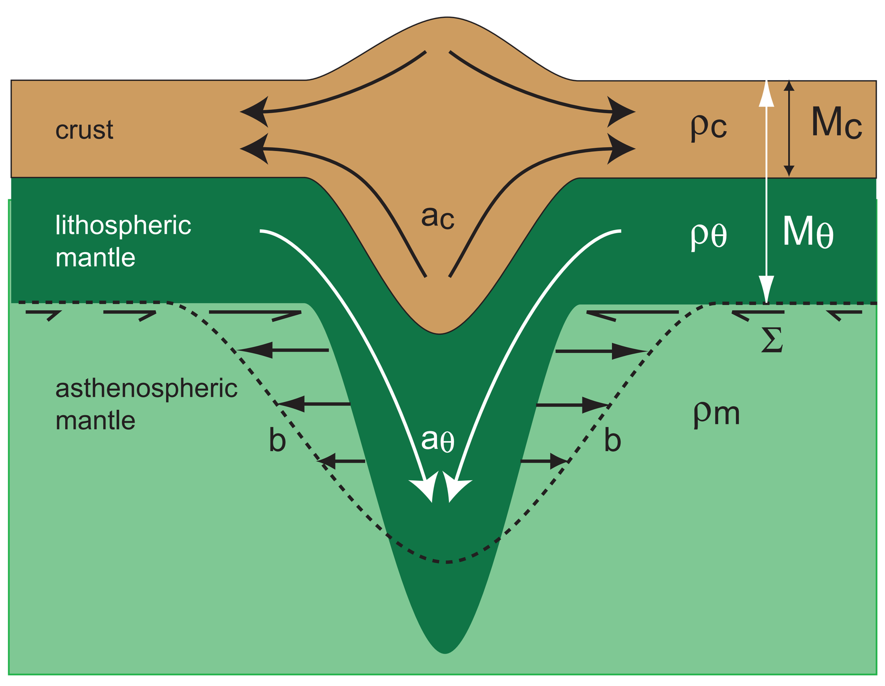
Moments
- Crustal : $M_c=\frac{1}{2}\rho_c g(1-\frac{\rho_c}{\rho_m})S^2$
- Thermal : $M_\theta=-\frac{1}{3}\rho_m\alpha\Delta\theta g L^2$

Elevation : $h=\frac{\rho_m-\rho_c}{\rho_m}S-\frac{1}{2}\alpha\Delta\theta L$

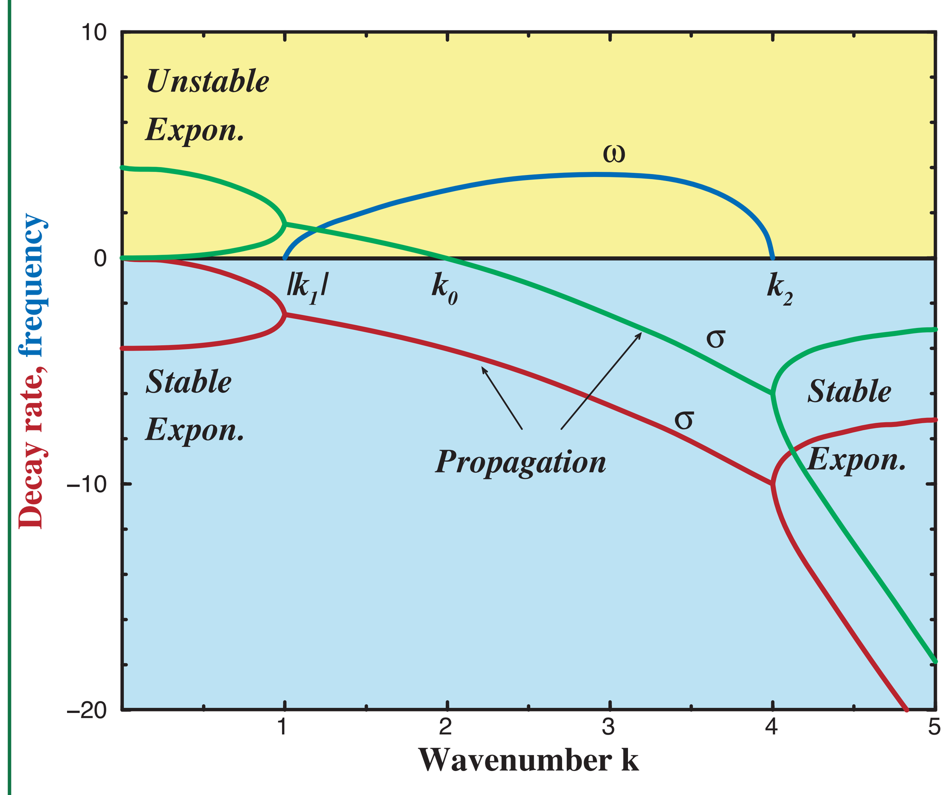
Transport
- mass conservation : $\frac{\partial M_c}{\partial t}+u\frac{\partial M_c}{\partial x}+2M_c\frac{\partial u}{\partial x}=0$
- heat conservation : $\frac{\partial M_\theta}{\partial t}+u\frac{\partial M_\theta}{\partial x}+2M_\theta\frac{\partial u}{\partial x}=\kappa\frac{\partial^2 M_\theta}{\partial x^2}$

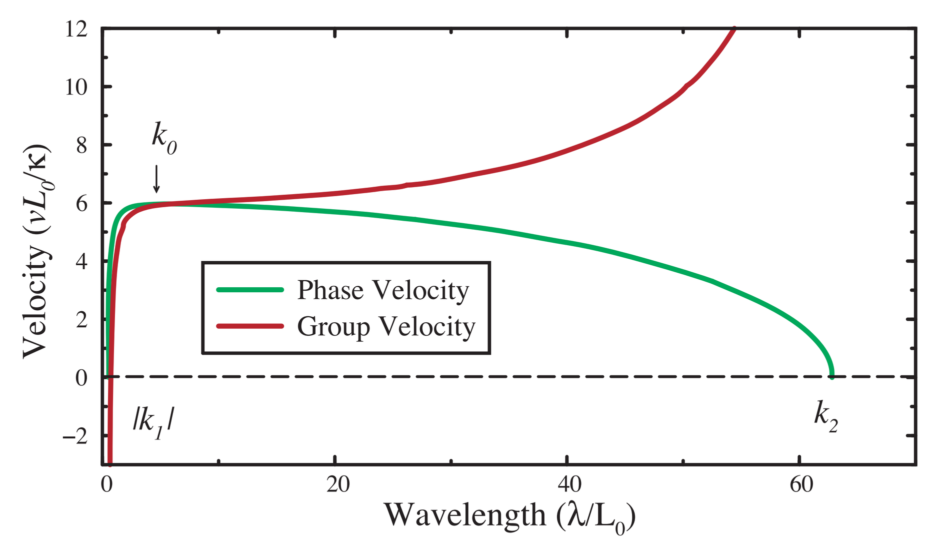
a_c : transport of the crustal moment
a_θ : transport of the mineralogical mantle moment
b : lateral diffusion of the thermal moment

g: gravitational acceleration
S: crustal thickness
h: elevation
ρ_c: crustal density
ρ_m: asthenospheric mantle density
ρ_θ: lithospheric mantle density
$\Delta\theta$: temperature increase across the lithosphere



2) Stability analysis





Let's assume that the solution is a uniform state + infinitesimal perturbations. In dimensionless form :

$$\tilde{M}_c = M_c^0+\epsilon m_c(x,t)$$
$$\tilde{M}_\theta = M_\theta^0+\epsilon m_\theta(x,t)$$
$$\tilde{u} = \epsilon u(x,t)$$

Assuming that all terms of order ε go as *exp(ikx + σt)*, we show from the above equations that :

$$2\sigma^2+\sigma(M_\theta^0+M_c^0+2k^2)+k^2M_c^0=0$$

$$k_1=\frac{(\sqrt{|M_\theta^0|}-\sqrt{M_c^0})}{\sqrt{2}}\qquad k_2=\frac{(\sqrt{|M_\theta^0|}+\sqrt{M_c^0})}{\sqrt{2}}$$

* If *0 < k < |k1|* or *k > k2*, the roots are real :

$$\sigma=\frac{1}{2}(k_1k_2-k^2)\pm\frac{1}{2}\sqrt{(k_1^2-k^2)(k_2^2-k^2)}$$

* If *|k1| < k < k2*, the roots are imaginary (σ = *Real*(σ) + *i*ω) :

$$Real(\sigma)=\frac{1}{2}(k_1k_2-k^2)\qquad \omega=\frac{1}{2}\sqrt{(k^2-k_1^2)(k_2^2-k^2)}$$

A propagating mode develops with phase velocity ω/k and group velocity *dω/dk*.

And if Real(σ) = 0, the system undergoes a pure propagating mode, with *:*

$$k_0=\sqrt{k_1k_2},\ \text{and}\ \omega=\frac{1}{2}k_0(k_2-k_1)$$

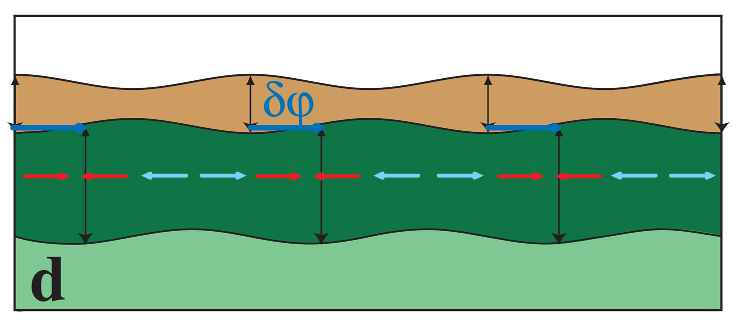
and propagates with a group velocity (= wave velocity) :

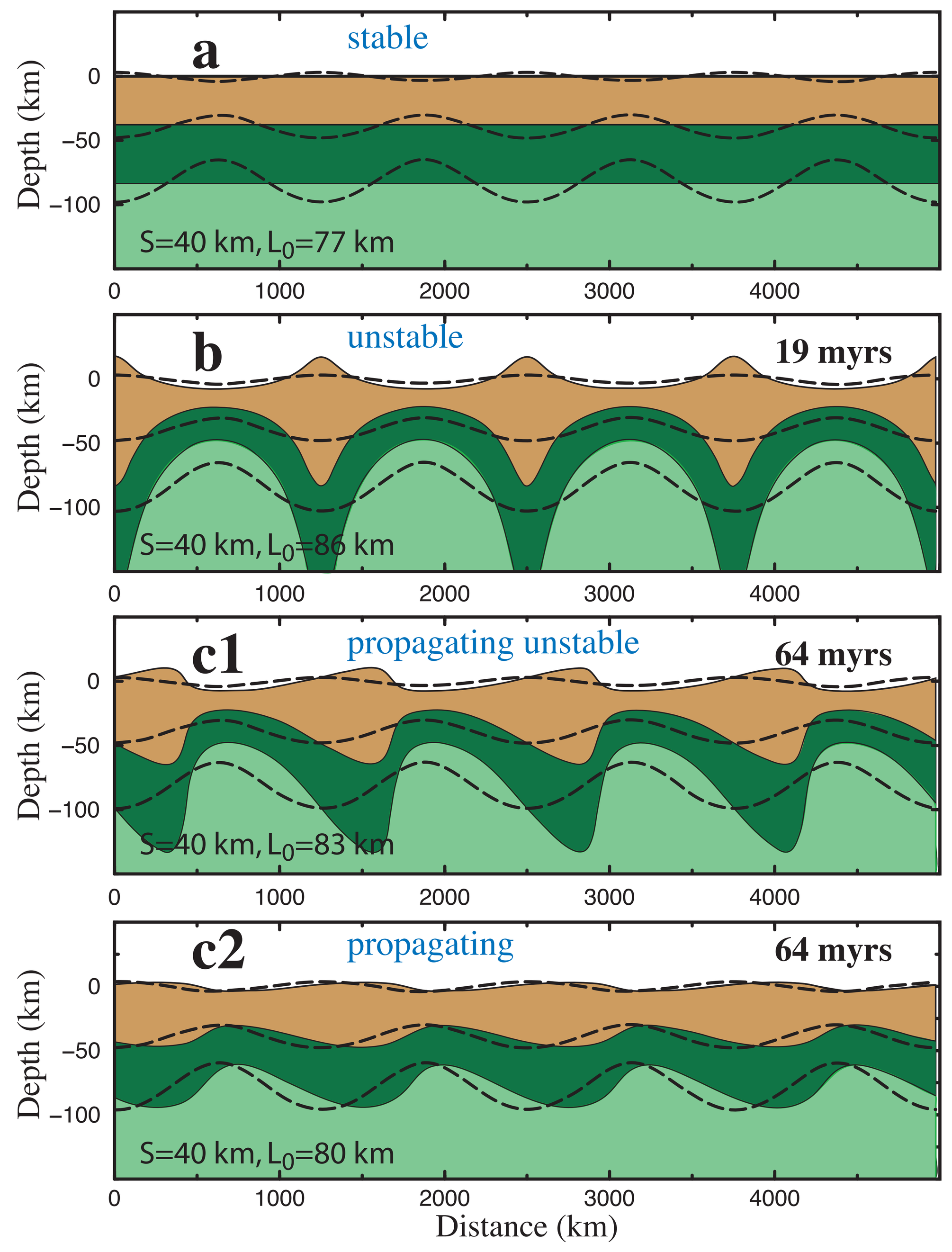
$$\boxed{v_p=\frac{1}{2}\sqrt{\frac{\kappa\rho_c(\rho_m-\rho_c)g}{L_0\eta\rho_m}}S}$$ *(real units)*

With S=40 km, L=83 km, η=2 10^{21} Pa s, L0=50 km, propagation occurs for wavelengths between 26 km and 3140 km, i.e. most of continental tectonics are in the propagating mode. Typical values for velocity are 3.2 to 6.4 mm yr^{-1}. Constant amplitude propagation occurs for k0=287 km at v_p=3.7 mm yr^{-1}.

3) Non-linear solutions

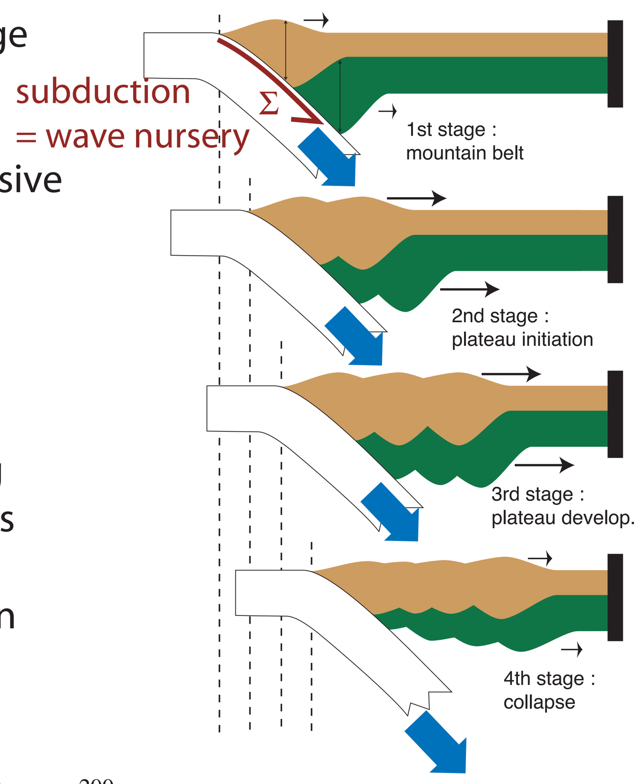
A full solution of our set of equations can be calculated to test the validity of the results of the stability analysis.
Three situations arise :
(a) The crust dominates the system which restores uniform thicknesses. Boring !
(b) The lithosphere dominates : the instability rapidly destabilizes the whole system and becomes a regular Rayleigh-Taylor instability.
(c) The system is in the propagating mode. In the unstable domain (c1), the asymetric development of the instabilities resembles a series of subductions. In the purely propagating case, the waves propagate indefinitely. In the propagating mode, the thickness variations are out of phase (d).





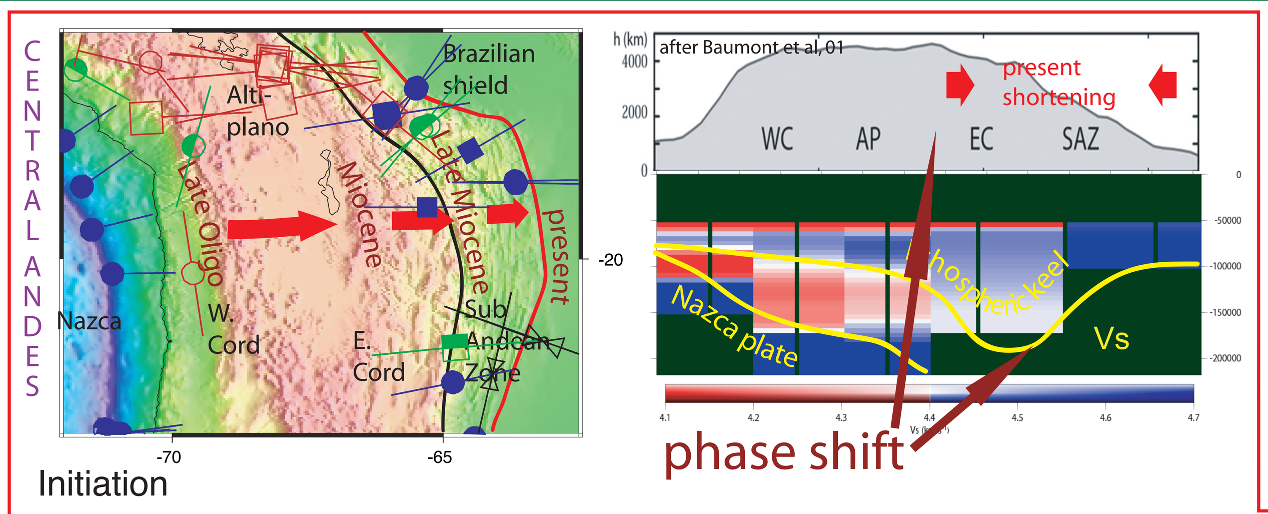
The thickness variations of the lithosphere are in advance to those of the crust, in the direction of propagation. They induce compression and thus thickening on the right hand side of the mountain range that collapses on the left hand side.

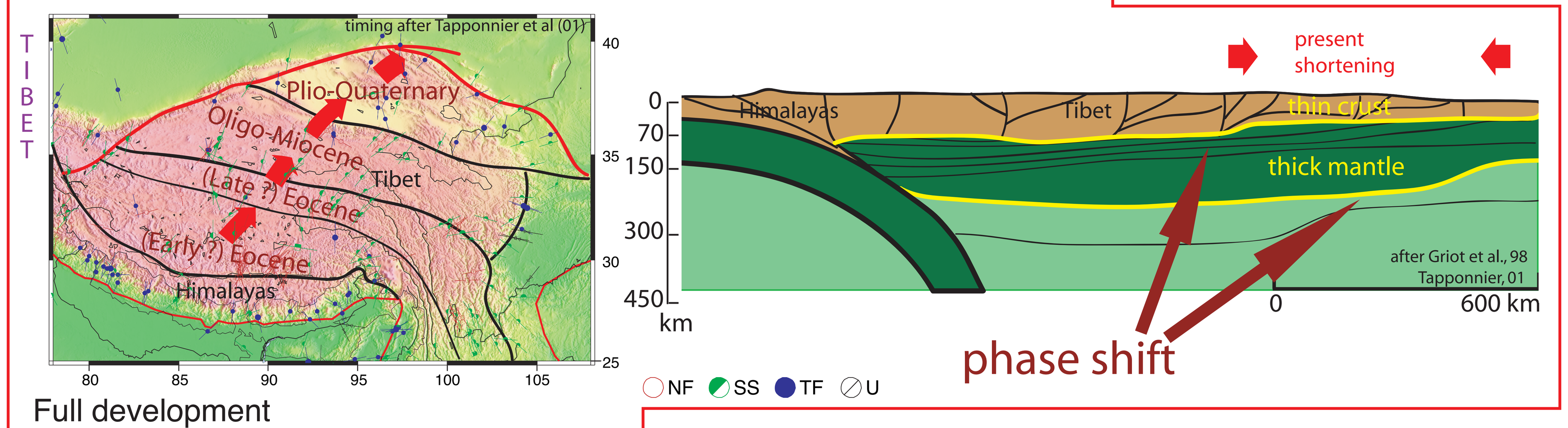
The tectonic evolution of high plateaus can be summarized in a 4 stage development sketch. Each stage currently exists on Earth :
i) gaussian mountain belt : compression (*e.g.* Southern Andes).
ii) short plateau : stresses are neutral next to the subduction, compressive hinterland (*e.g.* Central Andes).
iii) wider plateau : extension next to the the subduction, compression hinterland (*e.g.* Tibet).
iv) collapse : extension everywhere (*e.g.* W. Cordilleras).

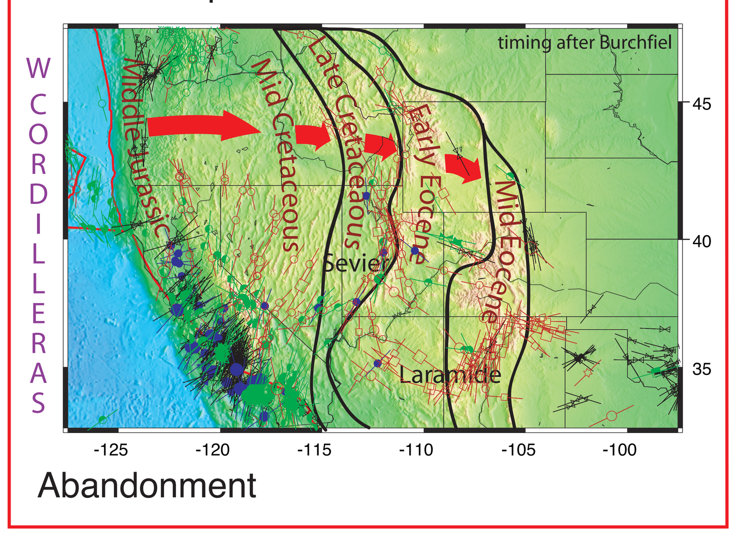


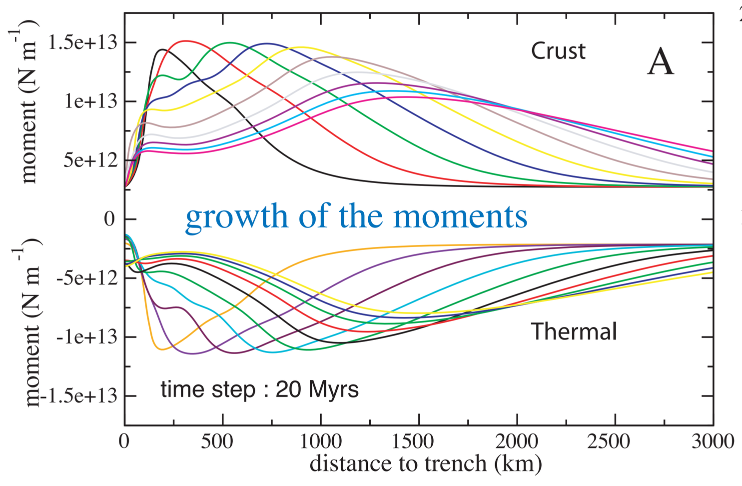
4) High plateaus

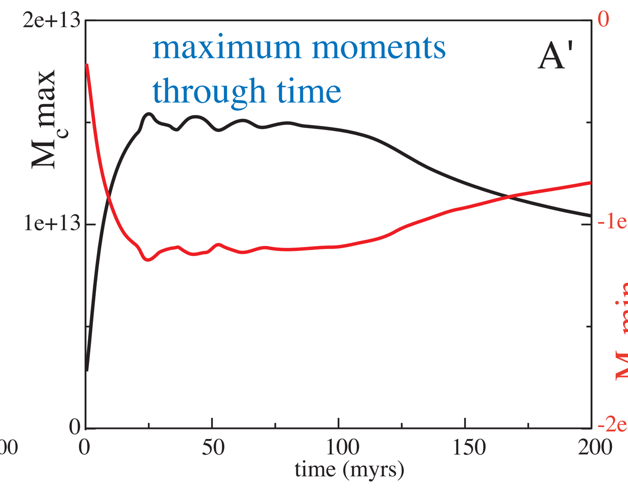
Tectonic waves transfer deformation away from subduction zones. Our model (A) shows the evolution of a lithosphere submitted to a interplate traction Σ (model recycled from Husson & Ricard, 2004 now including lithospheric instabilities). This model is compatible with tomographic observations (Andes, Tibet) and stress data.
Note that this model of high plateaus is in the stable propagating mode but the ratio of initial moments can also lead to destabilization hinterland or even pure steady state propagation .
Cosmetic improvements (B, viscosity increases hinterland) generate even better plateau shape.

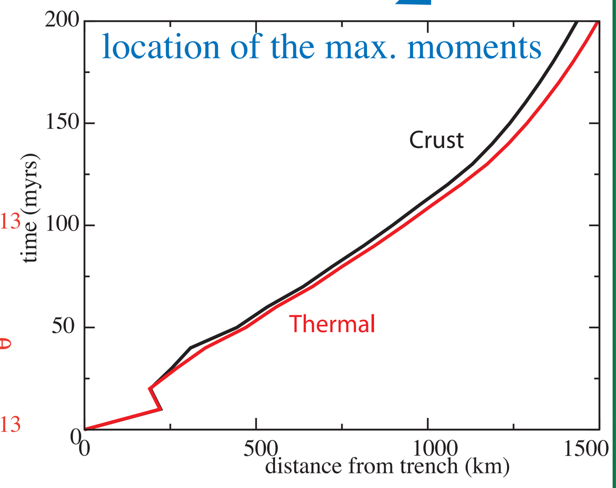






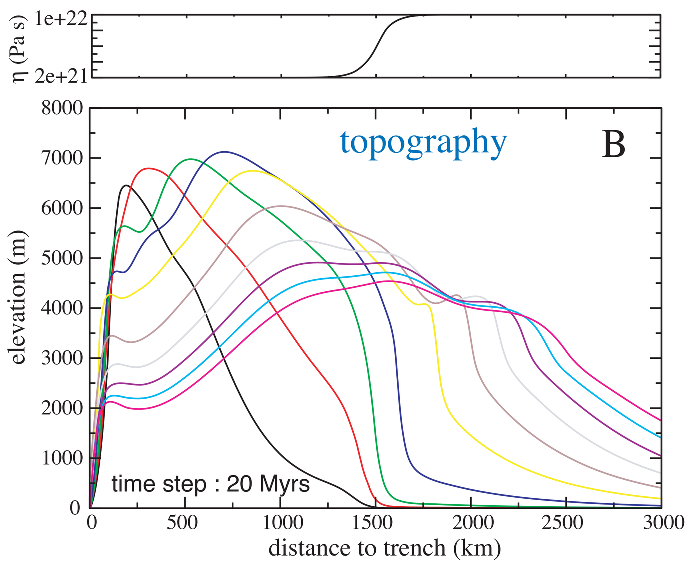






5) Conclusions

The concept of tectonic waves offers an alternative solution to the stability / instability of the crust / lithosphere sandwich. This third mode transfer deformation throughout the lithosphere at typical rates of 0.5 mm/yr to 10 mm/yr, depending on the wavelength of the orogen and on the ratio of the thermal and crustal moments. Most of the continental domain falls into this propagative mode.
This mechanism successfully explains the development of high plateaus : tectonic waves are triggered at subduction zones and then propagate. The timing of orogenesis in the Andes, Tibet, or American Cordilleras confirm that deformation propagates hinterland, and the structures of their crust and lithosphere in these mountain belts match the predictions of our models. These examples suggest that continental lithosphere is in the unstable propagating mode.
Another application of this propagative mode could be the self activation of rifts.



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