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BACKGROUND AND METHODS

Part I - Growth of orogenic wedges during continental subduction

General setting : Orogenic wedges develop in subduction settings due to plate convergence involving large shortening and deformation of the crust (Fig. A). This paper focus on orogens caused by subduction of a continental margin lower-plate under an oceanic or continental upper-plate following oceanic subduction. After closure of the oceanic domain, subduction of the lithospheric mantle induces deformation of the continental crust and controls the structural asymmetry of the mountain belt (Dewey and Bird, 1970; Mattauer, 1986 ; Malavieille & Chemenda, 1997 ; Beaumont et al., 2000; Avouac, 2003). Since the fundating works by Davis, Dahlen and Suppe in the Eighties (Davis et al., 1983; Dahlen et al., 1984), mountain belts have been often considered by geologists as crustal scale accretionary wedges (e.g., Malavieille, 1984; Platt, 1986) whose deformation mechanisms can be satisfactorily described by a Coulomb behavior. The theory gives a simple mechanical setting allowing to define different tectonic regimes depending on wedge stability : critical, undercritical, overcritical (Dahlen, 1984). Then, it has been shown that orogens commonly adopt a distinct geometry with a low-tapered pro-wedge facing the subducting plate, and a high-tapered retro-wedge on the internal side. This concept of doubly vergent accretionary wedge is widely explored since the nineties (Beaumont et al., 1992; Willett et al., 1993; Ellis and Beaumont, 1999; Pfiffner et al., 2000; Naylor et al., 2005; Selzer et al., 2008). Erosion has rapidly been added as a significant parameter (Dahlen & Suppe, 1988; Dahlen, 1988; Dahlen & Barr, 1989) because the impact of material transfer on the mechanics and structural evolution of sub-aerial wedges relative to submarine ones is major (Simpson, 2006). The topography of mountain belts depends of the behavior of continental rock units, itself depending on growth and evolution of faults. Models involving plastic (Chapple, 1978; Willett et al., 1993) or viscous behavior account well for displacements and produce velocity fields close to what is observed in mountain belts, but they do not generate clear displacement discontinuities as faults did. Thus, although the Coulomb wedge model gives a rigorous mechanical frame to study the dynamics of orogenic wedges, it presents some limits as it does not account for deformation processes at the scale of individual tectonic instabilities (Naylor et al., 2005). Analysis is more complex when introducing surface processes whose interactions with tectonics change the mechanical state of the wedge at different time and length scales. The removal of material from the surface, involves a continuous deformation changing the way in which the critical state is maintained. If the tectonic (shortening) and climatic conditions (erosional potential) remain stable, the wedge reaches a dynamic steady state (Jamieson and Beaumont, 1989; Willett, 1999; Willett and Brandon, 2002; Hilley and Strecker, 2004) in which the incoming fluxes (accreted material) are compensated by the outgoing fluxes (material removed by erosion). According to these models, the velocity field of the crust and, hence, the exhumation paths of rock particles, depend on erosion at the surface (e.g., Horton, 1999; Persson & Sokoutis, 2002). Consequently, any changes in erosion rates potentially result in a modification of the strain pattern and thus in the evolution of the wedge.

Décollements : Various processes of crustal decoupling exist during continental subduction, at great depth, or in the orogenic wedge due either to fluid overpressure (Cobbold et al., 2001) inducing weak crustal zones of strain concentration along brittle or plastic shear zones or weak décollement layers in the sedimentary cover (Banks and Warburton, 1991). During continental subduction, the whole or only part of the incoming rock sequences is accreted to the wedge depending on the location of the décollements that allow material to be detached from the subducting plate. The part which is not involved in wedge growth is dragged deeper into the mantle. At lithospheric scale, oceanic and continental subduction have been described by a simple setting (e.g., Malavieille, 1984) that is used as a first order kinematic boundary condition for many modeling approaches (Fig. A). The location of velocity discontinuities (the "S points" in numerical models, e.g., Beaumont et al., 1994) determines the amount of accreted versus subducted material and controls which part of the continental crust is subducted with the mantle (the whole crust or part of upper-crust). In orogenic wedges, several kinematic singularities can exist mainly due to the mechanical layering of the continental crust, they can be activated (simultaneously or not) during the tectonic evolution. Such a crustal layering can be lithologic (e.g. basement cover interface, or weak layers in a sedimentary sequence), rheologic (e.g., thermo-mechanical changes during subduction or fluids pressure changes) or inherited from a former tectonic history (e.g., the structural heritage of an extended margin prior to continental subduction). During mountain building, these weak zones have a major impact on the mechanical behavior (Brun, 2002) as they constitute potential décollement zones. How and where these décollements develop and how they influence the mechanics and structural evolution of the orogenic wedge are major questions (see Stockmal et al., 2007).

Exhumation : Exhumation of metamorphic rocks in mountain belts is a debated problem and many papers have been published to date, some focusing on early exhumation of very high-pressure rocks in subduction channel settings, others on exhumation processes in the frame of the orogenic wedge itself. We focus here on exhumation in wedges submitted to erosion-sedimentation. To analyze the kinematics of material transfer, particle paths have been studied in numerical (e.g., Dahlen & Suppe, 1988) or experimental wedges (e.g., Konstantinovskaia & Malavieille, 2005). They define an accretionary flux directed from bottom to top in the wedge body explaining the vertical advection of material at the origin of thickening and relief development. Without erosion, these paths do not represent exhumation paths, they only reflect uplift of material or uplift of topography (England & Molnar, 1990). Because exhumation in orogenic wedges requires erosion (or at least normal faulting), the way of exhumation depends on the internal dynamics and conversely, on how this dynamics is modified by erosion (Horton, 1999 ; Burbank, 2002). Models show that local uplift induced by basal accretion can generate localized high angle slopes. Applied to nature, such deformation mechanisms occurring at depth in wedges would favor strong erosion and high denudation rates above domains of underplating. Thus, due to internal strain partitioning, denudation rates will vary along a mountain belt transect because erosion controlled exhumation is very sensitive to the vertical component of displacement. In the same manner, the part of the wedge located above the main décollement behave passively and is generally poorly deformed during accretion. As the portion located between the underplating zone and the domain of active frontal accretion does not undergo strong deformation, its angle of slope remains low, suffering only minor erosion and consequently few exhumation. Due to uplift and erosion, it is affected by wide amplitude folding of its basal contact, resulting in characteristic large scale synformal structures (which remnants often outcrop as klippen of exotic materials resting on top of the orogenic wedge), separated by antiformal culminations of basement rocks ("metamorphic complexes").

Décollement induced deformation partitioning largely controls particle trajectories and strain patterns. One way to investigate orogen dynamics is to look at the ages recorded by different thermochronometers across it (Kühni & Pfiffner, 2001; Willett & Brandon, 2002). Exhumation of rocks means the approaching of a rock particle to the Earth's surface, which is, e.g. recorded by cooling rates calculated from thermochronologic data, whereas uplift of rocks means the displacement of rocks with respect to the geoid England & Molnar (1990). The study of material paths (trajectories) in mountain belts provides useful insights on their kinematic evolution. Surface processes strongly influence the timing, localization and amplitude of rock displacements in the varying members of an orogenic wedge. The comparison of their trajectories in experiments performed with and without erosion/sedimentation underscores this influence on material transfer (e.g., Cruz et al., 2008). The variations in rates of erosion and sedimentation modify the extent, the morphology, the structures, the timing of development and the material paths in the different models. Particles located in the converging lower-plate or in the upper-units above the main décollements show complex uplift paths related to deformation partitioning and various tectonic stages. At the scale of a mountain belt each tectonic unit records an individual specific exhumation path. Thus, exhumation rates calculated on the basis of simulated thermochronometry without knowledge of the particles trajectories and internal structure may result in erroneous estimations.

Normal faults : Coulomb wedge theory supports the idea that when the mechanical state changes from critical to overcritical, gravitational forces may cause local extension and subsequent normal faulting (Dahlen et al., 1984). Indeed, if there is no (or only minor) erosion (for example in submarine prisms), normal faults are required in the wedge body for exhumation to occur. Such models have been applied to mountain belts (e.g., Platt, 1986). If we check the effect of erosion and piemont sedimentation on wedge dynamics in a stability field diagram (Dahlen, 1984), it decreases the slope angle and as a consequence displaces the stability field, favoring an evolution from overcritical to stable or from stable to undercritical state (Leturmy et al., 2000). This trend does not favor extension. Thus, although extension is commonly invoked to explain exhumation of metamorphic rocks and synchronous enigmatic zones of normal shearing observed in most mountain belts, in many cases, this cannot be the dominant mechanism. Since many years, uplift induced normal sense shear zones and concommitant brittle normal faults (developed at lower depth) are described in both ancient (e.g. the Variscan belt, Pérez-Estaùn et al., 1991) or active mountain belts (e.g. the Taiwan belt, Crespi et al., 1996). Interpretation of such deformation features in the frame of mountain building is still controversial today and proposed models range between end-members involving compressional (convergent) or extensional (divergent) settings. Experiments with décollements and erosion suggest an alternative way to develop crustal scale normal sense shear zones during continental subduction. Such structures can be the result of the vertical shear induced by strain partitioning within the orogenic wedge (Fig. B). Continuous uplift of underplated crustal units relative to comparatively stable surrounding rocks favors vertical shear and as a consequence a strong stretching and thinning of the formerly stacked tectonic units. At depth these domains are characterized by the development of foliation zones of combined pure and simple shear deformation with a normal sense shearing component. They evolve to brittle normal faults superimposed on former ductile foliation when reaching upper-crustal domains during synconvergence erosion assisted uplift.

Backthrusting : Depending on the behavior of the backstop upper-plate, specific models suggest that underplating induced deformation at the back part of the wedge evolves through continuous shortening. When the upper-plate becomes thinner due to combined effect of uplift and surface erosion, large scale backthrusting may develop in the hinterland, changing material transfer paths in the orogen (Fig. C).

Part II - Modeling principles, techniques and limits

The sandbox devices (Fig. A) are generally composed of a basal plate bounded by two lateral glass walls. A motor pulls a plastic sheet with a surface on which basal friction can be specified. The analogue granular materials deposited on the plastic sheet have frictional properties satisfying the Coulomb theory and they correctly mimic a non-linear deformation behavior of upper-crustal rocks (Lohrman et al., 2003). They are generally accreted against a backstop (that simulates the undeformed part of the upper-plate lithosphere) developing a thrust wedge during convergence. Upper-plate backstop can be rigid or deformable depending on the material used. In some experiments, we have used materials with a cohesion higher than pure sand. A synthesis on scaling of models, and characterization of analogue materials is given in Graveleau (2008). A maximum convergence of 2.5 m allows large shortening deformation of the models. Influence of erosion, sedimentation and structural heritage on model wedges is studied using an empiric approach (see for example in; Bonnet et al., 2007; 2008). Generally, after the development of a proto thrust wedge (equivalent to the early accretionary wedge developed in submarine conditions), erosion of the model is performed by hand with a thin metal plate (the sand in excess being removed using a vacuum cleaner) to keep the slope at a constant angle. In some cases, a proto sand-wedge is built to allow rapidly a self location of the velocity discontinuity in the model. Erosion of the units is applied independently of their compositional nature, as a function of surface deformation. To obtain a condition of flux and topographic steady-state (e.g., Willett and Brandon, 2002), the domains of high surface slope which develops locally due to internal deformation of the wedge were first eroded each 2cm of model shortening. Then all the material in excess relative to the mean steady state profile is removed. This simple approach could be compared to an erosion affecting more the domains of high surface deformation and subsequent uplift than the areas where surface is less deformed. Such conditions are close to what is expected in wedges submitted to high erosion rates such as Taiwan or New Zealand.

When sedimentation is integrated, it is performed by sprinkling sand. Different situations have been tested with variable amounts of the material eroded from the growing wedge deposited in front of the wedge at the place where the slope breaks and thrusts propagate (this was the case for the experiments devoted to the Alps, where past deformation and erosion rates have been lower than in Taiwan).

Introduction of weak layers of glass beads in the incoming sequence of material allows to simulate décollements and also to take into account the structural heritage of a subducting margin (former normal faults in basement). The internal glass bead layer serves only as a décollement if its internal strength is lower than the strength along the basal detachment interface (Kukovski et al., 2002).

Obviously, our simple 2D approach presents several approximations due to the limits imposed by the experimental procedure. It does not take into account the isostatic response of the lower plate, but as we study the growth of wedges close to a steady state, we assume that these effects do not affect drastically our first order results. The chosen way to perform erosion and sedimentation is also very important in the experiments as it will influence the location and evolution of deformation in the wedge. At the moment, there is no experimental work which perfectly accounts for the complex natural erosion processes. Some 2D numerical modeling better approach what is suspected to be natural erosion laws, but they also fail somewhere as erosion in mountain belts remains a 3D problem. Thus, although today, analogue models are not properly scaled to analyze quantitatively the interactions between tectonics and surface processes, this approach allows to outline several first order behavior of thrust wedges suffering erosion and foreland sedimentation. Plastic deformation at depth plays a major role in the geometry and kinematic evolution of orogenic wedges. Thus, another experimental limit concerns the progressive transition from brittle to plastic behavior that is not properly described by sand. Nevertheless, as the size of our model sand wedges is big, the important diffuse deformation suffered by the granular materials at depth tends to mimic macroscopically a plastic behavior, developing structures which geometry and evolution are close to what is observed in mountain belts. Thus, although the mechanics of our materials is far from well understood, our empirical approach may be able to give significant insights on the growth of accretionary belts.

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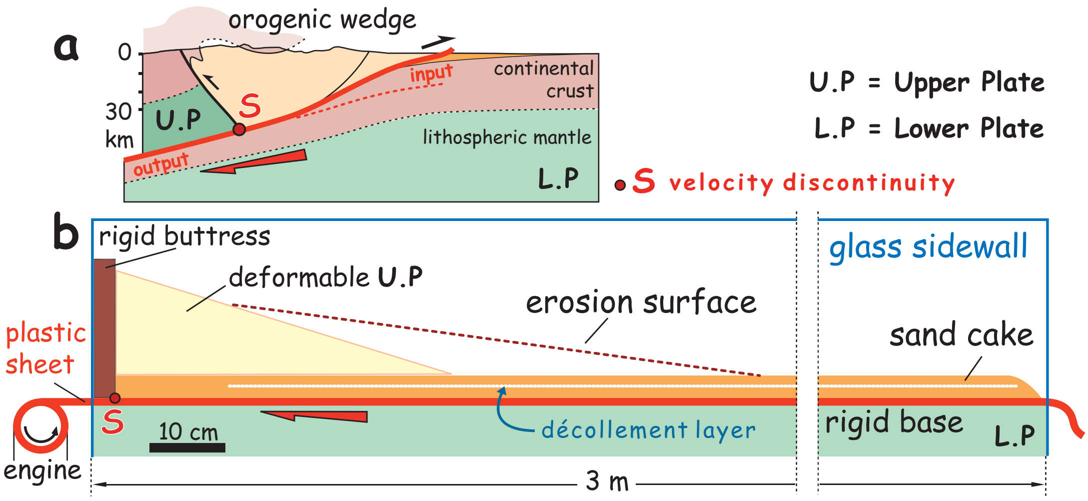
Figure captions

Figure A : a) Kinematic setting of continental subduction. b) Schematic setting used for analogue modeling of thrust wedges. Backstop geometries and rheologies can be modified. Dotted line represents the chosen erosion surface.

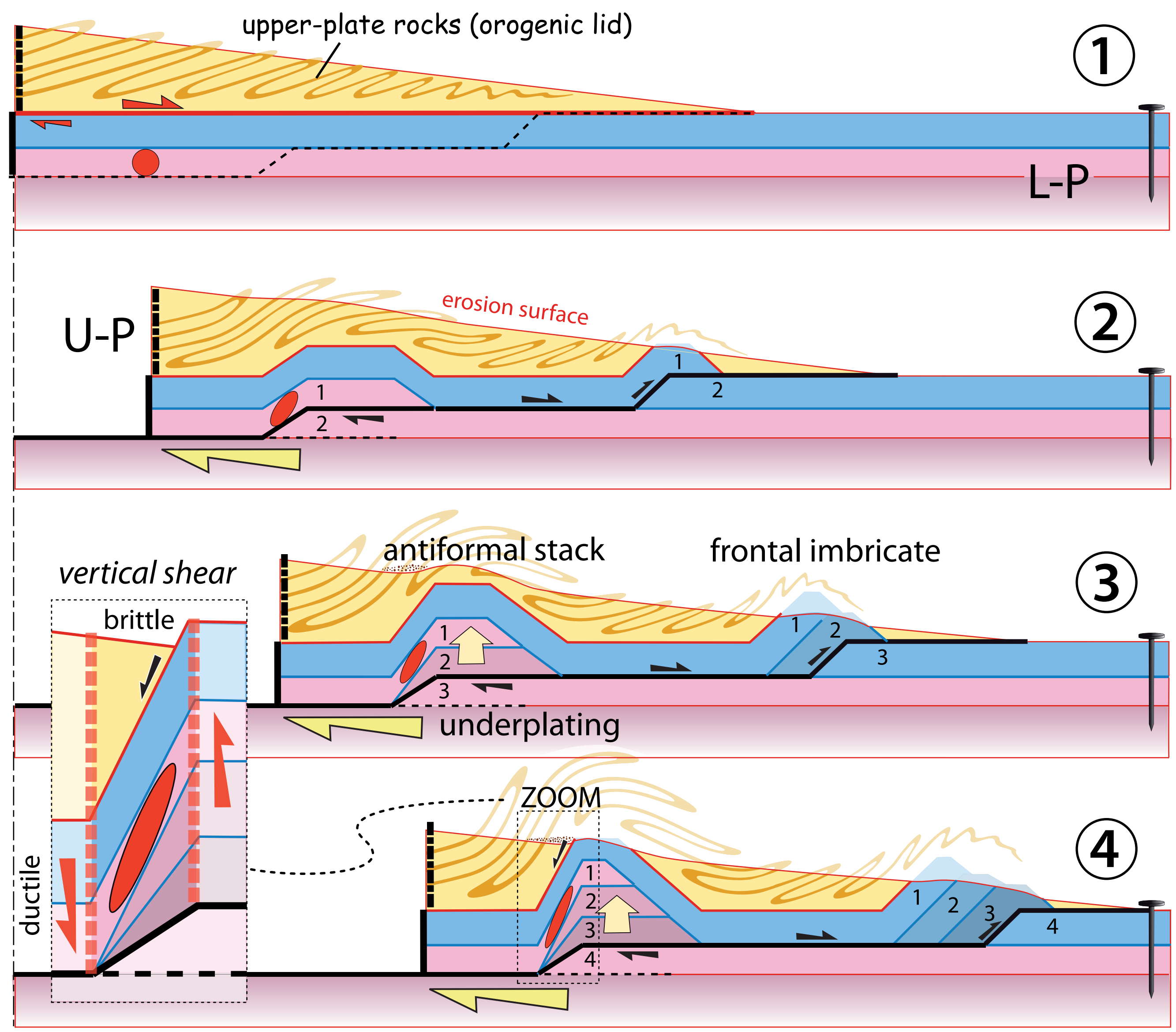
Figure B : Cartoon showing deformation partitioning and kinematics of thrust units in a décollement type wedge. Notice the deformation of upper plate (orogenic lid) resting on top of the former refolded décollement. Early folds are suggested to show evolution of U-P geometry. A possible deformation mechanism responsible for vertical shear inducing stretching and thinning of the underplated units is schematized. Red ellipsoids show resulting strain. U-P = pre-structured upper-plate, L-P = basement lower-plate.

Figure C : Conceptual model of orogenic wedge growth showing the impact of surface processes; a) end of oceanic subduction stage (early exhumation of high pressure rocks in the subduction channel), b) subduction of the continental margin, stacking of underplated crust units and uplift favored erosion of the upper plate, c) a new stage of basal accretion develops in the foreland inverting inherited features of the margin, d) during the late stages, major backthrusting develops at the back of the wedge due to strong thinning of the upper plate lid by erosion. Synformal U.P. klippen are preserved between domains of underplating.



a
orogenic wedge
0
30
km
U.P
S
input
continental
crust
lithospheric mantle
output
L.P
U.P = Upper Plate
L.P = Lower Plate
S velocity discontinuity
b
rigid buttress
deformable U.P
erosion surface
glass sidewall
sand cake
plastic
sheet
S
10 cm
décollement layer
rigid base
L.P
engine
3 m

Figure A



upper-plate rocks (orogenic lid)
1
L-P
U-P
erosion surface
2
1
2
1
2
antiformal stack
frontal imbricate
vertical shear
brittle
3
1
2
3
1
2
3
underplating
ductile
ZOOM
4
1
2
3
4
1
2
3
4

Figure B

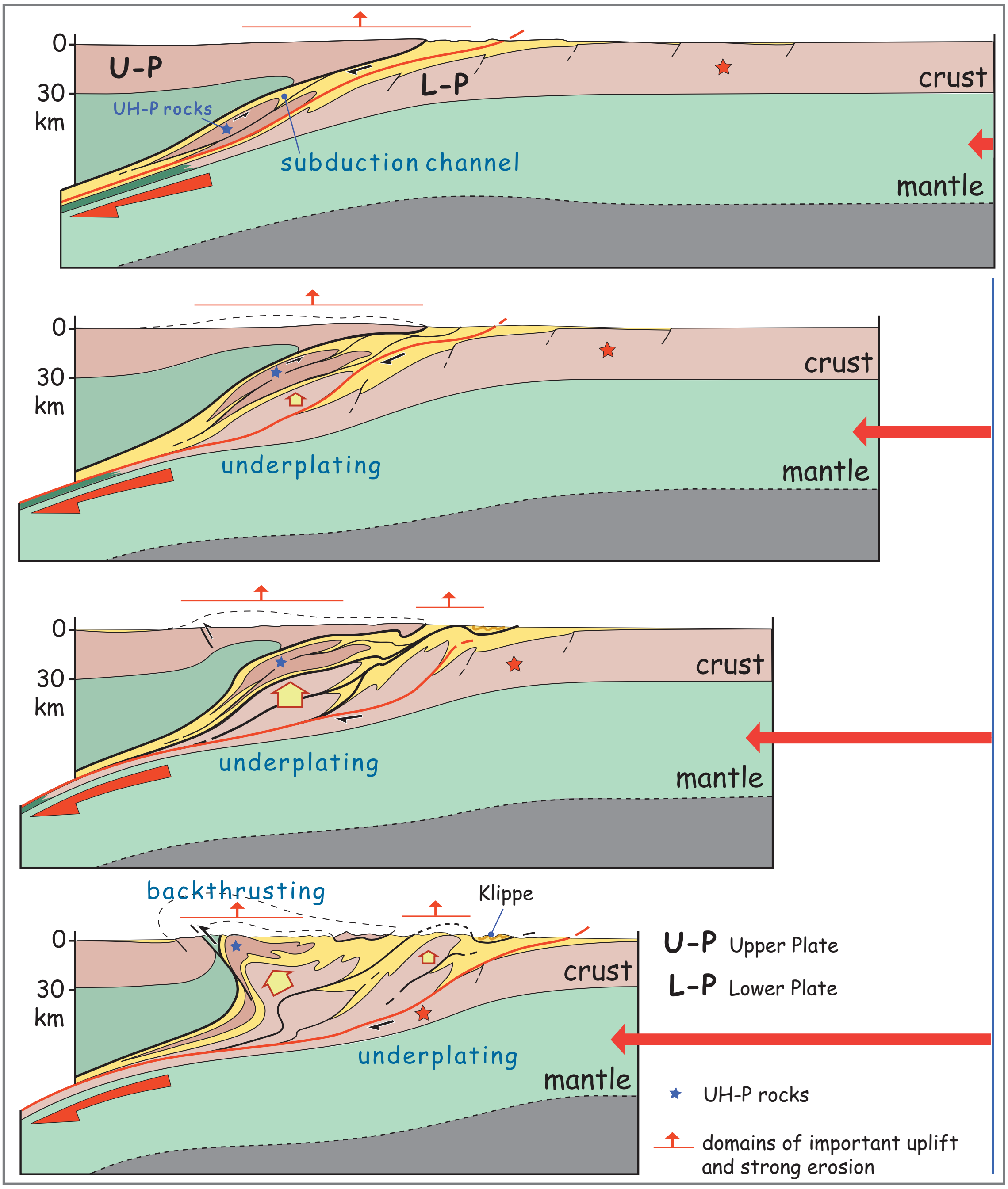

0
30
km
U-P
L-P
UH-P rocks
subduction channel
crust
mantle
underplating
backthrusting
Klippe
U-P Upper Plate
L-P Lower Plate
UH-P rocks
domains of important uplift and strong erosion

Figure C