Trabajos de Geología, Universidad de Oviedo, 29 : 23-28 (2009)

Oviedo (Spain) 1-3 July 2008 International Meeting of Young Researchers in Structural Geology and Tectonics
YORSGET

Impact of surface processes on the dynamics of orogenic wedges: analogue models and case studies

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Abstract: In recent years attention has been paid to the major role of surface processes on the evolution of mountain belts on different time scales. In this study, sandbox experiments are used to better characterize the complex interactions between surface processes and tectonics. Models results are then applied to better analyze deformation and kinematics of recent active or ancient orogens (case studies are chosen in the Taiwan belt, the Alps and the Hercynian belt).

Keywords: orogenic wedges, tectonics, surface processes, erosion, sedimentation, analogue modelling.

The geological history of orogenic wedges records both the main phases of tectonic evolution and the coupled influence of deep geological processes (plate rheology and kinematics, metamorphism, magmatism) and surface processes (erosion, sedimentation, climate). In recent years, the major role of surface processes has been highlighted in numerous studies dealing with the evolution of orogens on different time and space scales. For example, the impact of erosion and sedimentation on fault growth, exhumation processes and deformation history of accretionary orogens is widely studied through geological and experimental approaches. Several studies (e.g. Gutscher *et al.*, 1996; Naylor and Sinclair, 2007) show that the behavior of wedges (punctuated activity of localized thrusts, cyclical behaviour of wedge growth events, simultaneous combination of different deformation mechanisms) is more complex than described by the Coulomb wedge theory (e.g. Dahlen *et al.*, 1984), which assumes homogeneous deformation on the long-term, depending on friction, basal dip angle and surface slope. Other recent modeling works confirm this observation (e.g. Bonnet *et al.*, 2007; Simoès *et al.*, 2007), showing that erosion and sedimentation play a major role in controlling deformation, fault activation and cyclicity of processes. Using analogue modelling, we aim to better characterize the interactions between the tectonic processes responsible for mountain building and climate dependant surface processes. The results of the models are then applied to case studies chosen in several domains of the Taiwan belt, the Alps and the Hercynian belt, to better analyze structure, deformation, fault kinematics, exhumation and evolution of recent active or fossil mountain belts.

Modelling the impact of surface processes in orogenic wedges

Coulomb-sand-wedges are submitted to large shortening, erosion and sedimentation, under topography and flux steady-state conditions. A constant surface slope is maintained during shortening, allowing a dynamic study of deformation structures and material transfer in the wedge. Different boundary conditions and parameters are tested (basal friction, rate of erosion and sedimentation, presence of décollements, structural heritage, material input vs. output). We analyze the exhumation patterns, the mode of fault propagation and displacement patterns by strain partitioning of vertical vs. horizontal displacement (e.g. Konstantinovskaia and Malavieille, 2005). Models show that thrust wedges do not behave as homogeneous Coulomb wedges, but present domains of localized deformations evolving in space through time. Thus, aerial wedges grow as a result of different mechanisms acting simultaneously during shortening: 1) frontal accretion of imbricated thrust units leading to the development of the foreland, 2) backthrusting allowing the growth of a doubly vergent wedge, and 3) underplating leading to the formation of antiformal stacks of duplex units in internal zones. Enhanced by erosion, such mechanisms are responsible for a specific geometry and kinematics of deformation during accretionary processes. Experiments with simple laws of erosion and sedimentation show that denudation in the internal part of the wedge is controlled by active erosion and underplating. Models involving décollement layers present surprising fault kinematics and growth processes. Kinematic analysis shows a punctuated signal of thrust activity and a cyclical behavior of deformation mechanisms acting in erosional thrust wedges. Consequently, the rates of surface uplift, frontal accretion, underplating and subsequent exhumation are controlled by complex interactions between erosion, sedimentation and wedge mechanics. In addition, such feed-back mechanisms exert a strong control on the development of foreland basins.

Case studies

Taiwan

In the active Taiwan orogen, the variability of the tectonic signal is revealed through middle-term rates of thrust accretion, surface uplift and exhumation, which are estimated from field analysis of deformed geomorphic markers and thermochronological studies (e.g. Beyssac *et al.*, 2007; Simoès *et al.*, 2007). This kinematics of deformation has been analyzed by analog models involving erosion, in which décollement layers induce underplating at depth, thus sustaining the growth of the wedge (Malavieille *et al.*, 2007). During shortening of the models, most of the horizontal displacement on faults is accounted for by few very active thrusts located at the wedge front, whereas inside its inner part, former faults are relatively inactive and passively uplifted. The major part of deformation in the wedge body is associated with

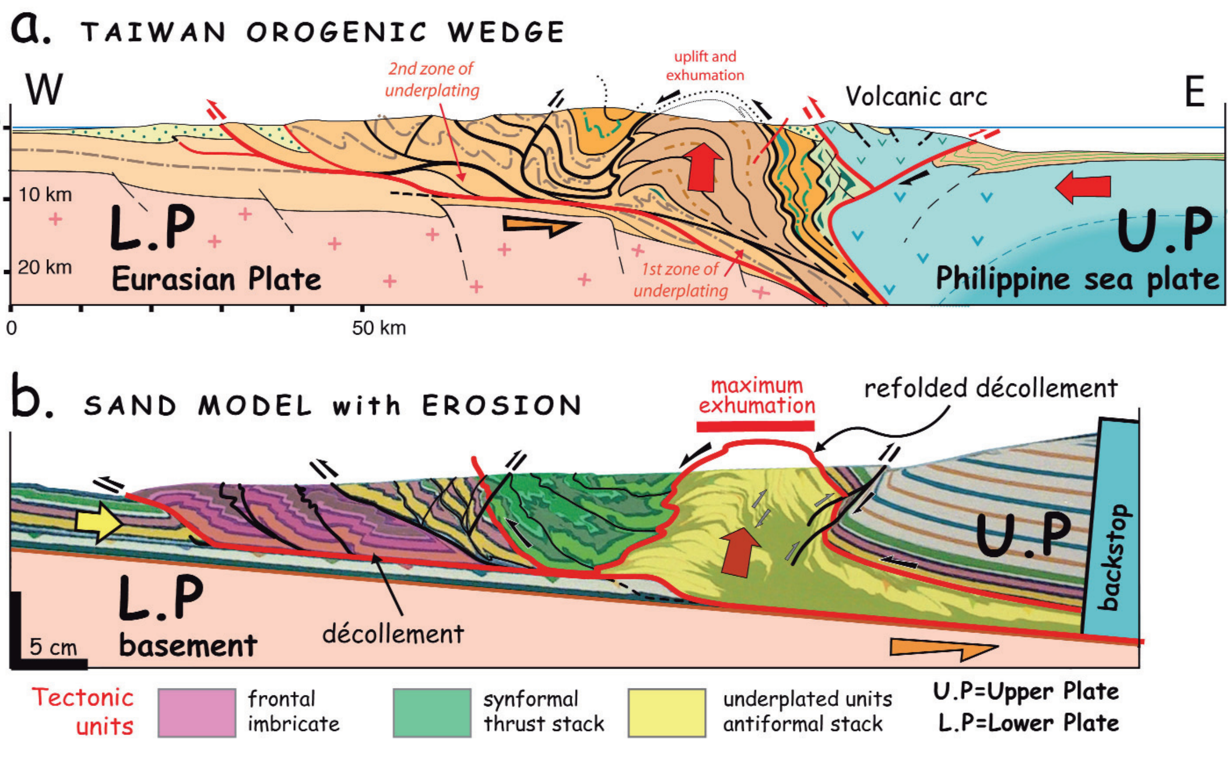

Figure 1. Interpretive geological section of Taiwan inspired by an analog model of thrust wedge involving a décollement layer. Combined erosion and underplating favor development of an exhumation window.

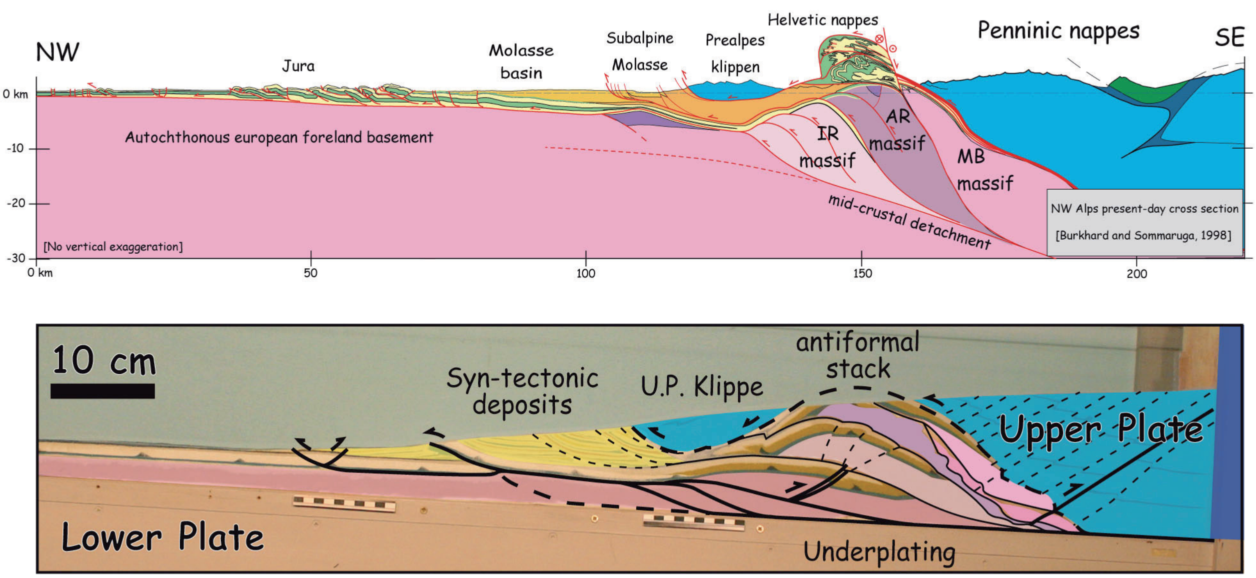

Figure 2. Sandbox experiment showing the impact of erosion, sedimentation and of the structural heritage characterizing a thinned continental margin on the structure of a mountain belt. Final stage of experiment is compared to a section of the NW Alps foreland (Burkhard and Sommaruga, 1998).

underplating, inducing vertical displacement paths for the deformed materials. Such surprising partitioning between horizontal displacements in the external domains and vertical movements in the inner parts of the wedge is a direct consequence of simultaneous frontal accretion and underplating controlled by décollement layers and erosion. Thus, the main mechanisms of Taiwan wedge growth can be described as accretion in the frontal part of the thrust wedge and underplating of tectonic units under the Central Range, involving strong uplift and thickening of the internal domain and rapid exhumation of deep metamorphic rocks against the Philippine Sea upper-plate (Fig. 1). These results have significant implications for geologists who study kinematics of active faults in active mountain belts as they raise questions on the traditional view of wedge growth by continuous forward in-sequence imbricate thrusting.

Alps

We have modelled the impact of erosion, sedimentation and structural heritage on deformation mechanisms acting in the Alpine thrust wedge when it becomes exposed (Fig. 2). Scaled models are designed to fit the major discontinuities (décollement layers, inherited normal faults and subsequent basins) present in the European continental margin involved in subduction (Bonnet *et al.*, 2007). Models show that combined effects of structural heritage and erosion-sedimentation control the geometry and kinematics of structures. Variations in erosion and sedimentation rates induce different wedge geometries that are compared with different sections of the Alpine chain (Bonnet *et al.*, 2008). Experiments emphasize the relatively passive role of the formerly-structured Penninic upper-plate. The emplacement of penninic klippen and the relationships between the Alpine foreland and the molasse basin are better characterized.

Montagne Noire

The Hercynian Montagne Noire (part of the French Massif Central) is classically described as a kind of metamorphic core complex cropping out as a window through an upper-plate nappe edifice composed of less metamorphic but severely folded Paleozoic sedimentary rocks. Interpretation of the area is controversial and many models mainly based on strain analysis in the gneissic core have been proposed to explain geological structure, deformation kinematics and core rocks exhumation. Some invoke emplacement of the gneissic dome by buoyancy forces in an extensional setting involving flow in the lower-crust (e.g. Van den Driessche and Brun, 1992), others a diapiric uplift of basement rocks during compressional tectonics (e.g. Faure and Cottereau, 1988), but none of them really take into account the role of erosion. In the light of our experiments we propose an alternative view that better accounts for the general structure, observed deformation and Hercynian tectonic setting (Fig. 3). It shows that in past fossil orogens, surface processes also played a major role in mountain building. These

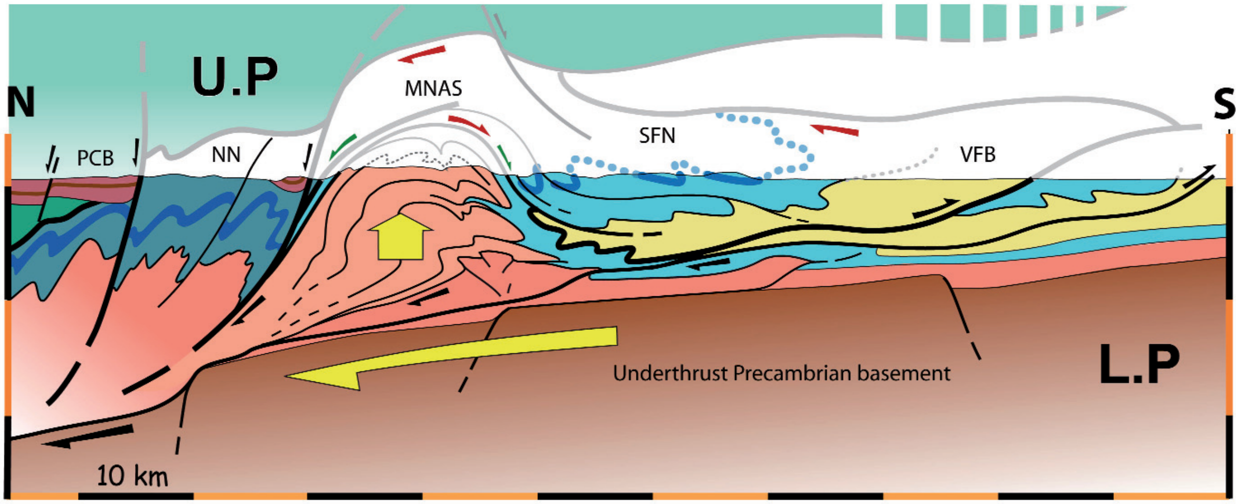

Figure 3. Interpretive section of the Montagne Noire involving underplating of gneissic nappes under the Paleozoic cover nappes of the upper-plate (U.P). Localized underplating is maintained and amplified by erosion and foreland sedimentation. PCB: Permo-Carboniferous Basins; NN: Northern Nappes; MNAS: Montagne Noire Antiformal Stack; SFN: Southern Fold Nappes; VFB: Visean Foreland Basin.

evolutionary processes may account for the structural evolution of other segments of the Variscan belt, for example in northwest Spain (e.g. Pérez-Estaún *et al.*, 1991).

Discussion

Models show that surface processes play a major role in controlling relief morphology, fault evolution, uplift inside the orogen and localization of exhumation. They interact with tectonic processes on different time scales to maintain the dynamic equilibrium (balance) of orogenic wedges. The variations in rates of erosion and sedimentation significantly modify the tectonic structure, morphology, timing of fault activation, material transfer and the exhumation of deep rocks.

Role and behavior of the subducting lower-plate

The role of structural heritage and particularly the occurrence of décollement levels in the subducting sequence of the lower-plate is fundamental and determines partitioning of heterogeneous deformation. During continental subduction, crustal discontinuities (previous structural heritage, changes in the paleogeography of sedimentary basins or contrasted mechanical boundaries in the crust) induce localized domains of underplating that themselves induce zones of localized strong uplift and subsequent topographic relief anomalies in the upper-plate. Such a growing mechanism is enhanced by erosion that maintains stable an area of localized exhumation through long periods of time. It allows a critical taper to be maintained, although the wedge does not grow through classical imbricate thrusting. These combined processes are responsible for the development of most dome-shaped antiformal stacks of metamorphic units that commonly characterize the internal domains of mountain belts resulting from continental subduction. As potential décollements generally exist in a subducting continental margin (brittle-ductile transition, basement cover interface, weak layers in the sedimentary sequence), deformation mechanisms are complex and evolve through time. Décollements are refolded and become successively inactive when being incorporated in the upper nappes edifice. Thus, changes in the depth of the décollements will characterize structural evolution of a growing orogenic wedge.

Role and behavior of the upper-plate (orogenic lid)

In mountain belts, the nature of the upper-plate is determined by the pre-continental subduction history. It may consist of: 1) continental rocks of a previously rifted and thinned continental margin (e.g. Austro-Alpine nappes), 2) oceanic rocks of the former intra-oceanic subduction zone upper-plate involving remnants of a volcanic arc (Philippine sea Plate and Luzon arc in Taiwan), and 3) deformed sedimentary rocks and ophiolites of a former accretionary wedge (also Taiwan or the Alps). During the early stages of orogenic wedge growth, the upper-plate behaves passively and is generally poorly deformed. Then, due to underplating and erosion, it is continuously thinned and affected by wide-scale refolding of its basal contact. This evolution results in typical large scale synformal structures (remnants of which often outcrop as klippen of exotic materials resting on top of the orogenic wedge), separated by antiformal culminations ("metamorphic complexes" of mountain belt lower-plates). A direct consequence of such behavior is the impact of erosion and underplating on exhumation of metamorphic rocks. Zones of rapid uplift induce steep topographies subjected to strong erosion, both inducing high denudation rates and normal faulting. For many years, these uplift-induced normal sense shear zones and concommitant brittle normal faults have been described within most of both ancient (e.g. the Variscan belt, Pérez-Estaún *et al.*, 1991) or active mountain belts (e.g. the Taiwan belt, Crespi *et al.*, 1996). Interpretation of such deformation features is still controversial today and proposed models range between end-members involving compressional (convergent) or extensional (divergent) settings. Our observations and wedge modelling give an alternative hypothesis for this paradoxical coexistence. The development of zones of normal faulting in the vicinity of the main antiforms is a direct consequence of underplating and erosion. As deformation remains localized in restricted areas inducing strong uplift, the lateral boundaries of the uplifted cores are subjected to strong differential motions involving zones of concentrated vertical shear. Such deformation kinematics is responsible for the development of zones of ductile normal shear at depth and localized normal faults in the upper parts of the brittle crust. Both ductile and brittle progressive deformations are coeval and appear juxtaposed at the end of wedge growth (due to exhumation sustained by erosion). Thus, such zones of normal faulting do not reflect orogen scale extensional tectonics but only a local accommodation of vertical movements during convergence.

The foreland basins

In most orogens, filling of foreland basins depends on: 1) geometry, structure and behavior of the flexured lower-plate, 2) tectonics of the foreland, and 3) drainage efficiency that controls the longitudinal transport of sediments far from the mountain relief. Experimental results suggest that the amount of sediment stored in the foreland basins has a direct influence on the structural style and kinematics of the orogenic wedge. It may be responsible for important structural changes observed along strike in the orogens. Thus, mechanical forcing seems at least as significant as climatic changes that are often invoked to explain variability in the morphostructural evolution of mountain belts. In the experiments, as important volume of analogue materials is eroded from the geological record, the combined effect of punctuated frontal thrusts, internal thickening and syndeformational erosion-sedimentation leading to a cyclic vanishing of tectonic units. Thus, some of the tectonic structures accommodating the convergence are definitively removed by erosion and no trace remains. In addition, units of the foreland basin involved in the accretionary process are continuously recycled by erosion-sedimentation processes, making it difficult to analyze the sedimentary record. This confirms that shortening estimates from restored cross sections in mountain belts are most likely underestimated.

To summarize, analog models enable us to: 1) characterize the tectonic processes responsible for wedge growth, 2) better analyze, measure and model the kinematics and strain partitioning (i.e. amount of horizontal shortening vs. vertical movement on different time scales), and 3) study the impact of climate controlled surface processes on long-term deformation (steady-state growth or not, cyclicity of deformation processes) and determine the role of non-stationary processes in mountain building. Different evolutionary stages characterize the orogenic wedges from the submarine deformation events that follow oceanic subduction and accretionary wedge formation, to the mountain building stage involving steep aerial reliefs subjected to surface processes that completely change the tectonic behavior of the growing wedge.

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