Impact of erosion, sedimentation, and structural heritage on the structure and kinematics of orogenic wedges: Analog models and case studies

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ABSTRACT

Interaction between surface and tectonic processes plays a key role in the structural evolution, kinematics, and exhumation of rocks in orogenic wedges. The deformation patterns observed in analog models show that strain partitioning has a strong impact on the vertical component of displacement of tectonic units, which in return favors erosion in domains of important uplift. Partitioning is controlled by tectonic processes and by climate-dependent surface processes, including erosion and sedimentation. The effects of partitioning include localization of deformed domains, exhumation above areas of deep underplating, and steady-state maintenance of wedges for long time periods. Simple models illustrate well how the morphostructural evolution of mountain belts is determined by these complex interactions.

INTRODUCTION

Orogenic wedges record the tectonic evolution and the coupled deep geological (rheology and kinematics, metamorphism, magmatism) and surface (climate-dependent erosion and sedimentation) processes active along convergent margins. Their role is highlighted in studies dealing with the evolution of orogens at different time and space scales (see part I of supplemental information, GSA data repository[1]). The role of erosion and sedimentation on fault growth, exhumation, and deformation in accretionary orogens is widely studied through geological, experimental, and numerical approaches (e.g., Bonnet et al., 2007; Stockmal et al., 2007). Here, insights from simple sandbox models are used to show how interactions between surface processes and the mechanical behavior of the orogenic wedge influence its structures, deformation kinematics, exhumation mechanisms, and evolution. Case studies (Taiwan, the Alps, and the Variscan belt) characterizing several first-order tectonic processes are discussed in light of the experiments.

ANALOG MODELS

Analog experiments dealing with the growth of thrust wedges have been performed over many years at the Geosciences Montpellier Laboratory, providing insights for the ideas discussed here. Analog experiments present significant advantages. They help account for tectonic instabilities and provide complementary information on accretion processes and deformation at the scale of discrete tectonic structures. Large-scale convergence can be tested, which is a necessary step when studying the role of subduction in the growth of mountain belts. Experiments can integrate erosion and sedimentation, allowing us to characterize the impact of surface processes on the structure and evolution of accretionary wedges (see part II of supplemental information, GSA data repository [see footnote 1]).

Modes of Accretion

Experiments without erosion (Fig. 1) show the geometry, structure, and kinematics of end-member thrust wedges formed by accretion only. They illustrate two main modes of accretion, depending on boundary conditions and rheology of incoming layers. (1) Frontal accretion: Wedges with a high basal friction are characterized by a high taper angle and by growth through imbrication of long tectonic units bounded by low-angle thrusts. Backthrusts are minor and develop within the body of the wedge. Wedges with a low basal friction are characterized by a low taper angle and by growth through frontal accretion of new tectonic units involving forward propagation of a basal décollement (Lallemand et al., 1994). Because the stress field in the wedge is symmetric (sigma one is close to horizontal; Stockmal, 1983), deformation involves conjugate thrust faults forming pop-up structures. As new thrusts propagate the deformation forward, former thrusts or newly formed thrusts can be activated out of sequence inside the wedge to allow the wedge to maintain an ideal "accretionary" (critical) taper (e.g., Dahlen et al., 1984). (2) Basal accretion (or underplating): Wedges with multiple décollements are complex (Fig. 1C). Two main growth mechanisms act simultaneously in different parts of the wedge: (i) frontal accretion above the upper décollement located within the incoming material, and (ii) deep underplating of thrust slices (basal accretion) at the rear due to duplex formation above a basal lower detachment (Gutscher et al., 1998). The resulting low-angle slope of the frontal part of the wedge reflects the low-friction upper décollement, whereas higher slope angles are a consequence of the higher basal friction that controls domains of underplating.

Experiments with Simulated Erosion and Sedimentation

Erosion and sedimentation involve material transfer, which modifies wedge dynamics (supplemental information, part II [see footnote 1]). Two models, based on accretion of a homogeneous material sequence, illustrate the direct effect of erosion

[1]GSA supplemental data item 2010039, additional information on geological background and modeling method, is available at www.geosociety.org/pubs/ft2010.htm; copies can also be obtained by e-mail to GSAToday@geosociety.org.

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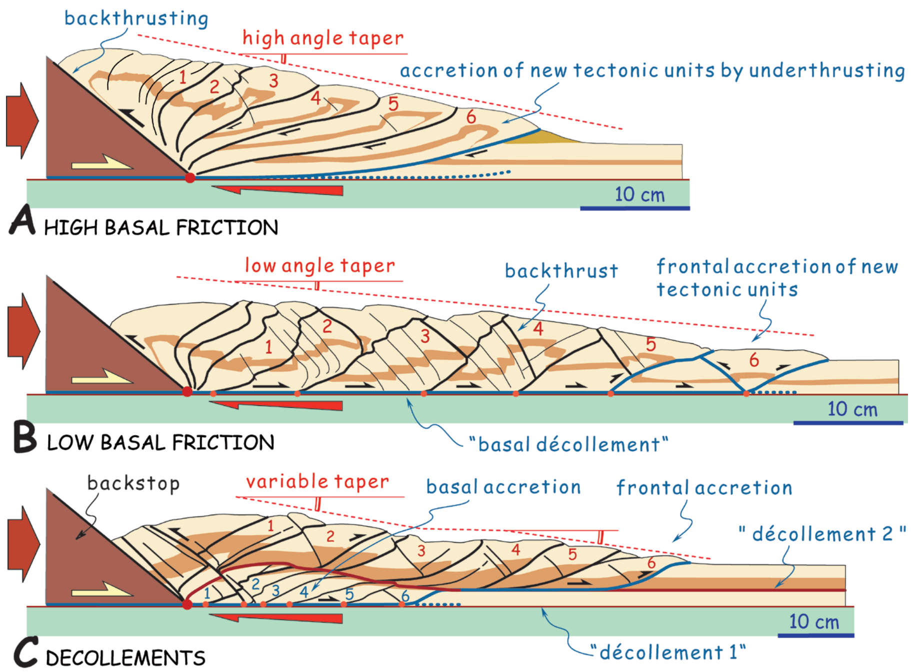

Figure 1. Models without erosion showing the main mechanisms of wedge growth and corresponding critical taper. (A) High basal friction model. (B) Low friction. (C) Multiple décollements.

on structure and material transfer (Figs. 2A and 2B); these can then be compared to similar experiments without erosion. The diversity of exhumation patterns is controlled by the mode of fault propagation, which is influenced by basal friction (high or low). For an equivalent amount of shortening, the vertical component of exhumation is higher for wedges with high basal friction. Uplift of material occurs along subvertical thrusts in the middle of low-friction wedges, versus on inclined (20–50°) thrusts in the rear of high-friction wedges. The vertical exhumation rate increases with time, and the material accreted later is rapidly transferred to the main exhumation zone, compared to the material accreted earlier.

"Décollement"-type models are designed with a low-friction layer of glass microbeads within the incoming sand layer and a high-friction basal detachment (Konstantinovskaia and Malavieille, 2005). The material below the weak layer is underplated under the rear part of the wedge, while above the décollement, the wedge front deforms by frontal accretion. From the frontal part of the wedge to the backstop, respectively, we have (Fig. 2C) (1) a frontal imbricate of thrust sheets; (2) a synformal stack of thrust units (resting above the décollement) previously accreted to the front and progressively deformed; and (3) an antiformal stack of underplated thrust units that refold the upper décollement surface. During continuous shortening, the kinematics of deformation reflects the interaction between wedge mechanics and erosion. Basal accretion and erosion favor the growth of an antiformal stack in the rear of the wedge. Uplift and subsequent exhumation of the underplated units occur along low-angle thrusts that progressively steepen due to subvertical shearing at the back of the wedge. An upper thrust wedge develops above the décollement, leading to progressive frontal imbrication of thrust sheets. When incorporated into the wedge, the thrust units are steepened to near vertical due to continued shortening and surface erosion. The former thrust units of the upper wedge are preserved, between the rear antiformal stack and the frontal imbricate, within a synformal "klippe." Frontal and basal accretion are interdependent. During the final stages of shortening, high-angle backthrusts can develop at the rear of the wedge, favoring the upward transfer and exhumation of accreted basal units.

CASE STUDIES

Here we focus on three mountain belts, each chosen to highlight specific processes revealed by analog models. The Taiwan case shows well the strong partitioning of active deformation that develops during rapid convergence. The Western Alps illustrate the impact of Mesozoic extensional structural heritage and the role of sedimentation in the foreland. The Variscan Montagne Noire shows how normal and thrust faults can be linked kinematically.

Taiwan

Taiwan is a good place to study mountain building during the transition from oceanic to continental subduction. The obliquity of plate convergence involves the progressive subduction of the continental margin of China, inducing the fast growth of the mountains (Suppe, 1981). Due to the high convergence rate (~8 cm/yr) of the Eurasian and Philippine Sea plates, deformation and erosion rates are extreme (horizontal shortening >2 cm/yr on seismogenic faults, with vertical motions up to 3 cm/yr). Catastrophic erosion involving landslides induced by typhoons and earthquakes have sculpted in a few million years the sharp relief of the island. Today, most of the shortening is accounted for by a few major faults on the western foreland side of the wedge and along its backside hinterland against the Philippine Sea upper-plate (Fig. 3). Middle-term shortening estimates show that ~4 cm/yr is absorbed across the frontal faults (Simoès and Avouac, 2006), whereas, on the backside, ~3 cm/yr of shortening occurs on the Longitudinal Valley faults (Angelier et al., 2000; Shyu, et al., 2006) and ~2 cm/yr offshore within the Philippine Sea plate (Malavieille et al., 2002). Little horizontal shortening occurs within the hinterland, and there is a strong partitioning of deformation. Such a

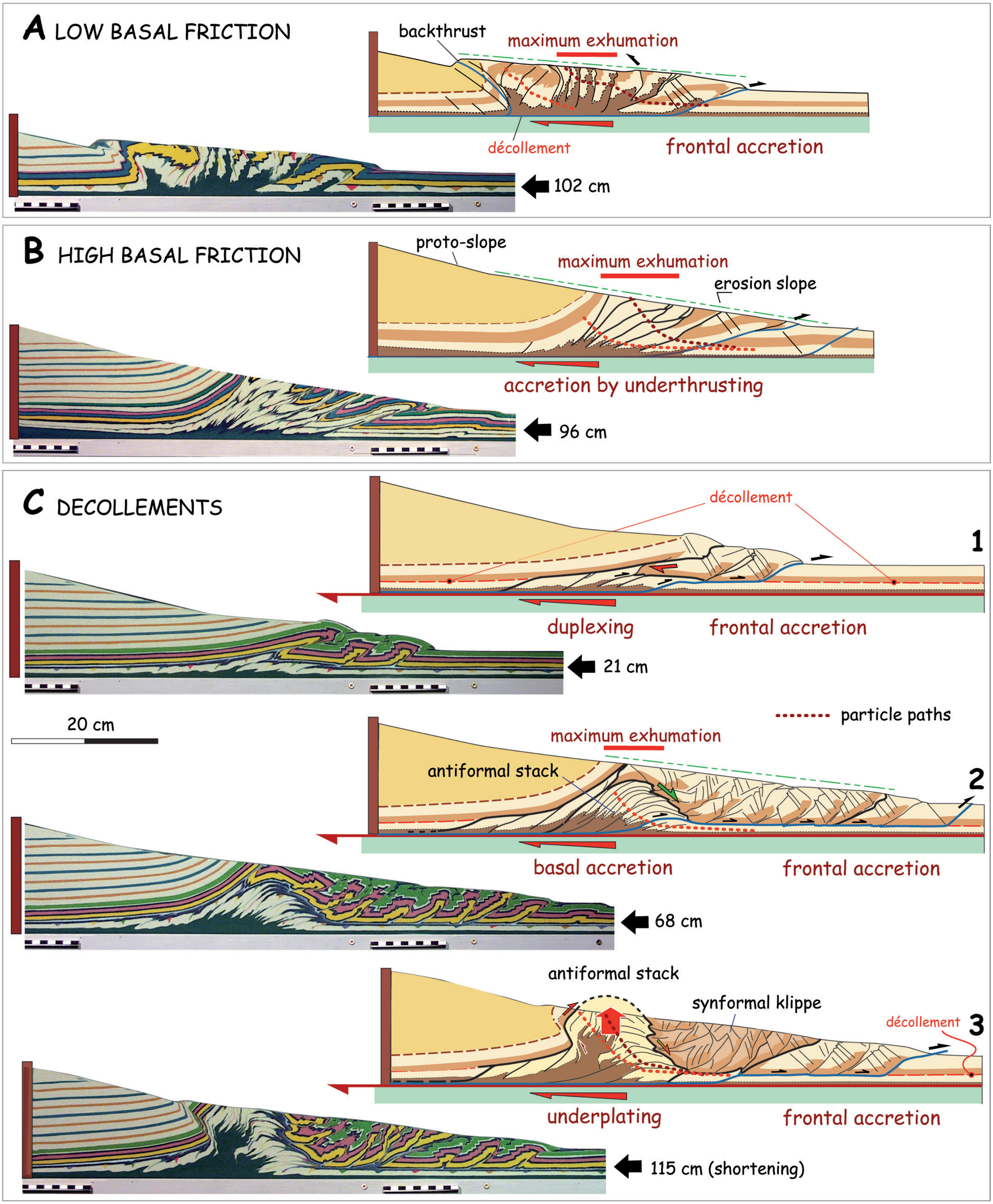

Figure 2. Models with erosion (flux steady state) showing particle paths (dotted lines) and domains of maximum exhumation. (A) Low basal friction model. (B) High friction. (C) Impact of décollements: 1—frontal accretion and basal duplex formation, 2—basal accretion (underplating), and 3—growth of an antiformal stack, wide amplitude folding of former imbricate thrusts (synformal klippe), and backthrusting.

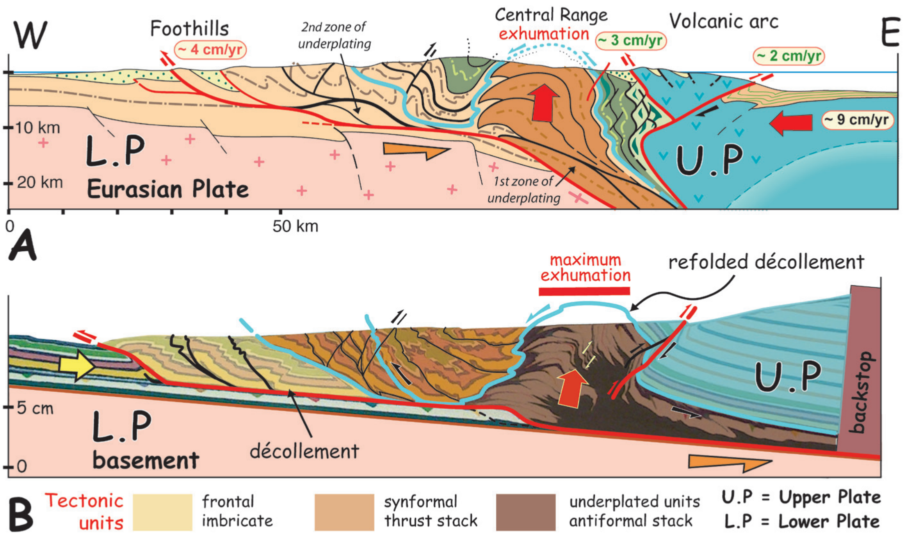

Figure 3. (A) Interpretive geological section of Taiwan orogenic wedge inspired by (B) experiment with décollement and erosion. Medium-term shortening rates on main active faults are indicated.

kinematic pattern closely matches the behavior of experimental erosional wedges with décollements (Fig. 3B). This suggests that the main mechanisms of growth can be described by frontal accretion in the foreland foothills and underplating of tectonic units at depth under the hinterland, involving strong uplift and exhumation. Intracrustal décollements localized within the subducting continental margin of Eurasia favor this style of deformation partitioning and wedge growth. Together with new constraints on the thermal evolution and exhumation of the Central Range (Beyssac et al., 2007), analog models and thermokinematic numerical models (Simoès et al., 2007) involving erosion, in which underplating at depth sustains the growth of the orogenic wedge, account well for the growth of the Taiwan orogenic wedge.

The Alps

Geologic sections across the Swiss Alps (e.g., Escher et al., 1997) reveal the significance of the Mesozoic extensional structural heritage and underscore the importance of surface processes in the structural evolution of a mountain belt. To characterize deformation mechanisms involving a prestructured continental margin, a series of experimental models were designed (Bonnet et al., 2007) using data from a restored section across the western Alps proposed by Burkhard and Sommaruga (1998). The aim was to (1) better understand the impact of erosion and sedimentation on the tectonic structure and evolution of the Alpine wedge, and (2) analyze the role played by structural heritage. The first model is run without erosion (Fig. 4A) and the second with erosion and sedimentation (Fig. 4B). Without erosion, a high-friction wedge develops. In response to shortening, basement imbricates overthrust each other using inherited weaknesses. The unstructured part of the basement is then accreted. With simulated erosion and sedimentation, frontal accretion occurs in the foreland, and basal accretion and subsequent underplating occur in the hinterland. The combined effect of tectonics, erosion, and sedimentation focuses exhumation in the domain of underplating. Subsequent uplift isolates a synformal klippen nappe composed of

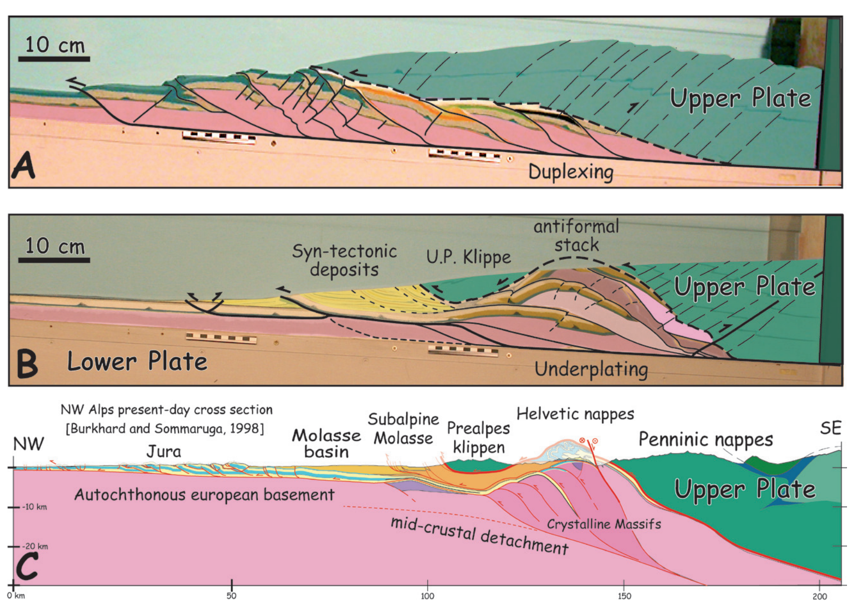

Figure 4. (A) Model simulating impact of structural heritage of a continental margin without erosion to be compared to (B), the same model with erosion and syntectonic sedimentation applied to the Alps (Bonnet et al., 2007), and (C), geologic section across the Swiss Alps (after Burkhard and Sommaruga, 1998).

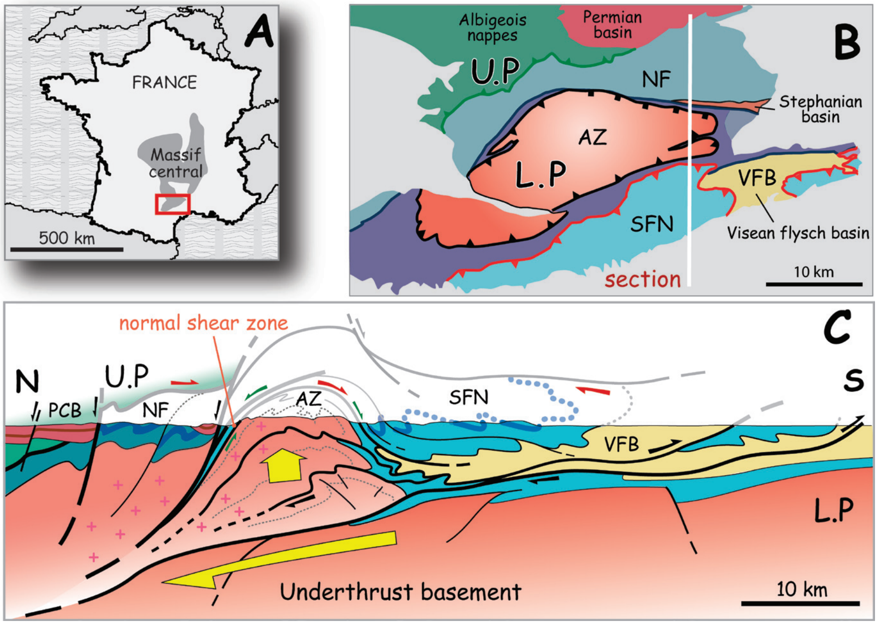

Figure 5. (A) Location of the Montagne Noire. (B) Structural map. (C) Interpretive cross section showing an alternative hypothesis for dome formation and enigmatic normal shear zones and faults observed on its northern flank (NF). The southern recumbent fold nappes (SFN) emplaced on the foreland basin are passively deformed during development of the Axial Zone (AZ) antiformal stack. PCB—Permian and Upper-Carboniferous basins; VFB—Visean Foreland Basin; L.P—lower plate; U.P—upper plate.

imbricated thrust units. Frontal accretion therefore leads to cyclic syndeformational removal of a substantial volume of foreland sediments. At the end of shortening, the different units have been largely eroded. The foreland basin and the orogenic lid, including its frontal klippe, come to rest upon syntectonic deposits. Underplated duplexes formed an antiformal stack that localized rapid synconvergence exhumation and that ultimately reached the surface, appearing as a tectonic window.

Models suggest that for natural orogenic wedges, when convergence can no longer be mechanically accommodated by subduction of lower-plate basement units at depth, deformation is taken up by underplating. This mechanism allows the tectonic units detached from the subducting lower plate to be accreted to the upper plate, contributing to wedge growth. It requires intracrustal décollement zones, the location of which are controlled by the kinematics of subduction, the thermomechanical conditions in the wedge, the structural heritage, and by erosion. In the experiments, the structural heritage of the lower plate (weak levels of glass beads) defines the size of thrust units and favors the initiation of underplating. The process continues spontaneously in the homogeneous part of the basement due to burial and increasing stress with depth. Thus, underplating develops through different structural levels in a thrust wedge and can simultaneously or successively affect different parts of the subducted crust.

Models that combine erosion and sedimentation show that if the erosion/sedimentation budget is not balanced, in the sense that more material is removed from the system than is deposited in the foreland basin (i.e., output is greater than input), an important record of the tectonic history of the orogenic wedge will be missing. This is the case in the Alpine foreland basin, where more than half of the sediments have been carried out of the system by large rivers into neighboring sinks (Kuhlemann et al., 2002). In addition, as parts of the foreland basin are incorporated into the orogenic prism, and then cannibalized by erosion, section balancing may lead to a significant underestimation of global shortening.

Variscan Montagne Noire

The Variscan orogen developed during the Gondwana-Laurasia collision, with progressive migration of crustal thickening to external parts of the belt from Devonian to middle Carboniferous times accompanied by Barrovian-type metamorphism and progressive southward thrusting (Matte, 2007). The Montagne Noire forms the southernmost part of the Variscan French Massif Central (Figs. 5A and 5B). The area is divisible into three tectonostratigraphic units from the internal hinterland domains to the foreland, respectively: (1) the Northern Flank upper-plate with a southward tectonic vergence, consisting of low-grade lower Paleozoic folded and faulted metasedimentary units; (2) the Axial Zone lower-plate, which is a high-grade metamorphic antiform of gneiss, migmatite, and micaschist of Proterozoic to Ordovician age; and (3) the kilometer-scale recumbent fold nappes of the Southern Slope (upper-plate) composed of low-grade Paleozoic sequences. Foreland basin Visean flysch sediments include synorogenic olistolites and are deformed, forming south-verging nappes. The upper-plate nappes are separated from high-grade lower-plate basement units by major fault zones that record a complex pattern of deformation (Aerden and Malavieille, 1999). The steep north-dipping fault zone bounding the Axial Zone–Northern Flank tectonic units is characterized by polyphase deformation, including late normal-sense shearing. Upper Carboniferous molasse-type sediments are exposed in a narrow strip north of this boundary. Two end-member models have been proposed to explain these relationships. The first is that the development of normal shear zones and intermontane basins was caused by late-orogenic extension (Echtler and Malavieille, 1990) involving the growth of a metamorphic core complex (Van den Driessche and Brun, 1992), the Axial Zone. The second postulate is that all large-scale structures were acquired in a compressional setting (e.g., Matte, 2007). However, neither of these end-member models takes into account the fundamental role of erosion. Experiments that involve erosion point to an alternative model (Fig. 5C) that combines simultaneous uplift (induced by local underplating of basement units) and erosion during convergence. This synconvergence mechanism accounts well for the geometry of tectonic units, fault kinematics (development of normal sense shear zones), and metamorphic relationships between the high-grade core zone and the surrounding low-grade fold nappes. Other mountain belts, such as the Alps (Mosar, 1999), the Himalaya (Bollinger et al., 2004), the Variscan belt of NW Spain (Pérez-Estaùn et al., 1991), Oman (Michard et al., 1994), New Caledonia (Lagabrielle and Chauvet, 2008), and Alpine Corsica (Molli et al., 2006), where exhumed antiformal metamorphic domes bound by normal sense fault zones are exposed and where underplating is suspected, need to be revisited in light of the general mechanisms outlined here (see supplemental data Fig. B [see footnote 1]).

CONCLUSIONS

Our experiments show that thrust wedges behave in a complex manner, even for simple settings and model materials. Internal deformation mechanisms and faulting control the shape, topography, taper variability, and structural evolution of the wedge. Models show that two main modes of accretion characterize wedge growth: frontal accretion and basal accretion (underplating). Erosion and sedimentation control material transfer from the surface and directly influence the internal dynamics of wedges. Surface erosion allows long-term localization of domains of basal accretion, promoting the development of large basement nappes, favoring rapid exhumation of deep rocks, and, when combined with sedimentation in the foreland, can contribute to maintain a wedge in a steady-state for long periods of time.

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