Impact of erosion and décollements on large-scale faulting and folding in orogenic wedges: analogue models and case studies

Clement Perrin, Luca Clemenzi, Jacques Malavieille, Giancarlo Molli, Alfredo Taboada, Stéphane Dominguez

To cite this version:

HAL Id: hal-03519254
https://hal.science/hal-03519254
Submitted on 10 Jan 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
Impact of erosion and décollements on large scale faulting and folding in orogenic wedges: analogue models and case studies

Clément Perrin a, d,*, Luca Clemenzi a, b, c, Jacques Malavieille a, Giancarlo Molli b, Alfredo Taboada a and Stéphane Dominguez a.

a Géosciences Montpellier, Université Montpellier 2, Place E. Bataillon, 34095 Montpellier cedex 5, France
b Dipartimento di Scienze della Terra, Università di Pisa, Via S.Maria, 53, 56126 Pisa, Italy
c Dipartimento di Fisica e Scienze della Terra, Università degli Studi di Parma, Parco Area delle Scienze, 157/A 43100 Parma, Italy
d Géoazur, Université de Nice-Sophia Antipolis, Centre National de la Recherche Scientifique (UMR 7329), Observatoire de la Côte d'Azur, 250 av Albert Einstein, 06560 Valbonne, France

* Corresponding author. Present address: Géoazur. Université de Nice-Sophia Antipolis, Bât 4, 250 av Albert Einstein, Les Lucioles 1, Sophia-Antipolis 06560 Valbonne, France. Tel.: +33 (0)4 83 61 86 82 / Fax: +33 (0)4 92 94 26 10.
E-mail address: clement.perrin@geoazur.unice.fr (C. Perrin)

5876 words (without references and captions); 114 references; 1 table; 10 figures; 2 figures in supplementary material

Running title: Modeling erosional fold and thrust belts
Abstract: Deformation mechanisms, long-term kinematics and evolution of fold and thrust belts submitted to erosion are studied through 2D analog experiments involving large convergence. First order parameters tested include: i) décollements and/or plastic layers interbedded at different location within analog materials; ii) synconvergence surface erosion.

Weak layers, depending on their location in the model, favor deformation partitioning characterized by the simultaneous development of: i) underplating domains in the inner part of the wedge (basal accretion); ii) frontal accretion where the wedge grows forward. Interaction between tectonics and surface processes influence this behavior. Development of antiformal thrust stacks controlled by underplating show small- and large-scale cyclicity.

Thin plastic layers induce folding processes, which are studied at wedge scale. Recumbent and overturned folds, with large inverted limbs, develop in shear induced asymmetric deformation regime via progressive unrolling of synclinal hinges. Surface erosion and underplating at depth induce further rotation (passive tilting) and horizontalization of fold limbs.

Models results give insights to discuss the mechanisms responsible for the large-scale structures (i.e., antiformal nappe stacks, klippen and kilometer scale recumbent fold-nappes) encountered in several mountain belts such as the Montagne Noire (French Massif Central), the Galicia Variscan belt (Spain) or the Northern Apennines (Italy).
Orogenic wedges are characterized by complex geological structures growing and evolving over long time periods (e.g. Fossen 2010). Their building is mainly controlled by the general mechanics of subduction and by the interactions between tectonics and surface processes that modify wedge dynamics through material transfer (e.g. Malavieille 2010). Because subduction orogens suffer large convergence, the long-term deformation is intense and generates specific structures which mechanisms of genesis are still not completely understood. Among them, the way large-scale recumbent fold-nappes observed in several mountain belt forelands grow and evolve remains enigmatic (Fig. 1). The most beautiful examples in Europe are situated in the Montagne Noire (Southern French Massif Central), Galicia Mountain Belt, (Spain) or the Northern Appennines (Italy). For example, during the Variscan Orogen, large-scale fold-nappes with huge inverted limbs (sometime of more than ten kilometers of amplitude) have been created without (or with very low) metamorphism (e.g. Matte 1968; Arthaud 1970). Other large scale structures are common in mountain belts, such as antiformal stacks of thrust units and subsequent frontal klippen which can be sometimes related to deformation partitioning and subsequent basal accretion of duplex structures (e.g. Elliott & Johnson 1980; Price 1981; Platt et al. 1985; Hatcher 1989; Gutscher et al. 1996; Burkhard & Sommaruga 1998; Mosar 1999; Kukowski et al. 2002; Avouac 2003; Malavieille 2010; Konstantinovskaia & Malavieille 2011; Long et al. 2011; Webb et al. 2011). Basal accretion activity is generally not constant during the long-term convergent history of orogenic wedges, alternating underthrusting of new tectonic slices with the internal deformation of the already accreted ones, or even with the migration of the underplating locus to a new place. Such a cyclical underplating behavior could promote, at a whole wedge scale, an alternate change from supercritical to subcritical taper condition, in turn favoring
alternations between horizontal and vertical shortening observed in many orogens 
(e.g. Bell & Johnson, 1989; Bell & Sapkota 2012; Aerden et al. 2013). What 
mechanisms control large scale folding, basal accretion and its cyclicity remain an 
open question.

Analog modeling is an efficient tool to unravel the main mechanisms controlling the 
dynamics of orogenic wedges. Various experimental studies have investigated the 
influence of geometrical, kinematical and rheological parameters on the evolution of 
thrust wedges (see a review in Graveleau et al. 2012). One of the most important 
parameter highlighted is the layering of the accreting crustal materials that induces 
mechanical heterogeneity and deformation partitioning. Such a heterogeneous 
rheology of accreted rock sequences is the result of various factors: stratigraphy of the 
incoming crustal layer (e.g. Davis & Engelder 1985; Mulugeta 1988; Liu & Dixon 
Costa & Vendeville 2002; Koyi & Vendeville 2003; Konstantinovskaia & Malavieille 
2005; Stockmal et al. 2007; Malavieille 2010; Smit et al. 2010), décollements in a 
sedimentary sequence or basement-cover interface (e.g. Konstantinovskaia & 
Malavieille 2011), rheological evolution of the crust due to P-T changes through time 
(Carry et al. 2009; Gueydan et al. 2009), or structures and fabrics inherited from an 
earlier tectonic history (Sutton & Watson 1986; Holdsworth et al. 1997; Butler et al. 
2006, 2008; Bonnet et al. 2007, 2008). Among the large number of previous 
experimental studies of thrust wedges involving multiple décollements, only a few 
have suggested that faults development and evolution of structures could be cyclical 
under specific deformation conditions (e.g. Mulugeta & Koyi 1992; Gutscher et al. 
1998a; Malavieille 2010).
Analog models allow to investigate the importance of surface processes (i.e. erosion and sedimentation) and their influence on the dynamics of accretionary wedges (e.g. Baby et al. 1995; Larroque et al. 1995; Storti & McClay 1995; Mugnier et al. 1997; McClay et al. 1999; Persson & Sokoutis 2002; McClay et al. 2004; McClay & Whitehouse 2004; Konstantinovskaia & Malavieille 2005, 2011; Graveleau & Dominguez 2008; Cruz et al. 2008, 2010; Malavieille 2010; Smit et al. 2010). Folding represents another aspect of deformation processes investigated using analog experiments but, although studied at different scales through different experimental setups (e.g. Abbassi & Mancktelow 1990; Grujic & Mancktelow 1995; Tikof & Peterson 1998; Bazalgette & Petit 2007; Noble & Dixon 2011), fold development have rarely been investigated at the scale of a whole accretionary wedge.

This study address five major questions: 1) how do décollements influence deformation partitioning within thrust wedges, and their long term evolution, 2) which mechanisms govern the development of large scale overturned folds commonly preserved in mountain belt forelands as synformal fold-nappes klippen, 3) what controls the growth of large scale antiformal structures that develop concomitantly in the hinterland, 4) what are the interactions between relatively strong plastic layers versus weak décollements, and 5) what is the impact of surface processes on all these mechanisms? We present results of an analog modeling approach that takes into account large amounts of shortening of mechanically heterogeneous, multilayered materials and simultaneous surface erosion. Our first goal is to analyze the role of strain partitioning in relation with material transfer by erosion. Then, we study the impact of thin plastic layers interlayered in the incoming material on folding mechanisms and on its evolution at the scale of a fold and thrust wedge. The main
experimental results are discussed and compared to large-scale tectonic structures from several mountain belts to better interpret their geometry and kinematic evolution.

Experimental set up and procedure

The experimental set-up simulates the basic geometry and the main mechanisms of a subduction zone where lower plate crustal materials sink beneath an upper plate. This domain of the upper-plate located above the subduction interface corresponds in the experiments to a deformable proto-forewedge equivalent to the units of the orogen already accreted, deformed and structured following subduction. All experiments are performed under normal gravity field in a classical sandbox (see Malavieille 1984 and Konstantinovskaia & Malavieille 2005, 2011), adapted to allow large shortening (over 200 cm) and presenting a flexure of the basal plate taking into account the curvature of a subducting plate.

The sandbox (Fig. 2) is 10 cm wide and 300 cm long, with a vertical rigid buttress. At the base a thin plastic strip (dacron cloth) exits from the device through a thin slot located at the base of the buttress. It is pulled by a computer controlled step by step electric motor. Analog materials materializing the upper crust rocks of the lower plate are deposited onto the plastic strip and are dragged toward the backstop. As they cannot exit from the device, they are accreted against the upper-plate backstop. A thin layer of sand is glued on the upper surface of the plastic strip, leading to a very rough surface. It creates a high basal friction ($\mu_b \approx 0.5$) between the basal strip and the analogue material of the models. According to the critical wedge theory (Davis et al. 1983; Dahlen et al. 1984; Dahlen 1984), the strength of the basal décollement
influences the dipping of the main thrusts and backthrusts and the surface slope angle of a wedge that satisfies the yield conditions.

Three different materials are used in the models. 1) Aeolian sand, with a density of 1690 kg/m³, well rounded grains, less than 300µm in size, coefficient of internal friction (\(\mu_0\)) is 0.57 and the cohesion (C) is 100-150 Pa. It composes the upper plate protowedge and a large part of lower plate layers. 2) Glass microbeads poured in the sandcake are used to model weak layers (décollements). Diameter is 100/200 µm, and the perfect roundness of the grains leads a smaller coefficient of internal friction (\(\mu_0 = 0.44\)) and a negligible cohesion. 3) Plasticine is used to simulate folding because it presents a plastic behavior. It is composed by mineral oils, waxes and a solid filler made of fine powder (15µm). It does not contain water, does not dry, and can be reused. The Plasticine is melted in an oven (softening point between 39 and 42°C) and poured in a 200 x 9.8 cm mold. After cooling, 1 mm thin layers are sliced and then included in the multilayered model. To observe the final deformation of the plastic layer at the end of experiment, we have carefully cleaned the sand around the fold limbs. Practically, in the experimental procedure, when a plasticine layer is emplaced in the sand cake, the width of the thin plasticine sheet is slightly lower than the space between the two glass sidewalls to avoid parasitic effects of lateral friction along the glass. So, less than 1 mm of sand separates the plastic layer from the sidewall. As a consequence, what we can observe directly through the glass sidewall is not the plasticine layer itself, but the thin coloured sand marker which outlines its deformation.
Aeolian sand and glass microbeads are commonly used in physical modeling studies as analogue of upper crustal rocks with a brittle behavior. The scaling factor between their mechanical properties and those of the natural prototype is $10^5$ (Krantz 1991; Schellart 2000; Lohrman et al. 2003). The same $10^5$ scaling factor is therefore used for model dimensions (1 cm = 1 km), in order to satisfy the fundamental scaling theory for analogue modelling (Hubbert 1937, 1951; Horsfield 1977; Ramberg 1981; Davy & Cobbold 1991; Graveleau et al. 2011). Plasticine is a non-Newtonian fluid characterized by strain rate-dependant plastic yielding and strain hardening. At constant temperature, the constitutive flow law for plasticine is given by $\dot{E} = C\sigma^n$, where $\dot{E}$ is the strain rate, $C$ is a material constant, $n$ is a stress exponent, and $\sigma$ is the differential stress (McClay 1976; Ranalli 1995). The apparent dynamic viscosity ($\eta$) of plasticine is given by one half the ratio between the differential stress and the strain rate: $\eta = \sigma/(2\dot{E})$.

Considering that experiments were carried at constant room temperature ($T \sim 22-25°C$) and that the strain rate of the plasticine layer during deformation is constant and very low ($\dot{E} = 1 \times 10^{-3} \text{ s}^{-1}$) then $\eta = 4 \times 10^7 \text{ Pa s}$. This value of viscosity was determined by mechanical experiments on plasticines (Schöpfer & Zulauf 2002; Zulauf & Zulauf 2004) whose composition is similar to the plasticine used in our analogue models.

The yield strength of a plasticine layer with millimetric thickness is roughly equivalent to the compressional strength of a sand layer with centimetric thickness. Thus, the strength contrast between plasticine layers and granular layers (sand or glass microbeads) in our models is roughly equivalent to the strength contrast between ductile yet strong rock layers (such as limestone) and weak rock layers (such as
siltstones or shale). This strength contrast is typical of sedimentary sequences observed in foreland and intra-mountainous basins in orogenic wedges.

Thirteen experiments have been run (Table 1). Among them, seven are chosen as representative to describe the main results of our study. Erosion has been applied to most of them, following the procedure described here below. First, an initial shortening without erosion is applied to the models, allowing the development of a wedge shaped topographic relief. This first step of wedge growth could be considered as the analogue of wedge development in a poorly erosional submarine setting. Then, erosion is applied step by step, each 2 cm of convergence (see digital screen in experiment pictures for shortening values), simulating a climate-dependent erosion in a subaerial wedge setting and keeping a constant evolution of the wedge topography. It is performed by scraping off all the material rising above an imposed erosion surface and then removing it with a vacuum cleaner. The slope of this erosion surface can be variable or fixed and predetermined. In the former case the slope of the erosion surface is adjusted step by step, in order to follow the “instantaneous” average slope of the wedge, just smoothing in this way the small scale irregularities of the topographic profile without altering its average slope. In the latter case an average tilted erosion profile dipping from 3 to 10° toward the foreland is maintained (Konstantinovskaia & Malavieille 2005, 2011; Bonnet et al. 2007, 2008). This slope corresponds to the critical taper slope of a dry sand wedge (Davis et al. 1983). In this case, local erosion rates are directly controlled by the activity of thrusts. Even if the role of sedimentation has not specifically been taken into account in this study, small piggy back basins that develop during wedge growth have been filled while performing erosion to avoid unrealistic foreland topographies.
Experimental results

Our new set of experiments complements previous modeling works on orogenic processes carried out at the Geosciences Laboratory in Montpellier, which outline the impact of coupling between surface and tectonic processes and the important role of décollement levels during deformation (see, Malavieille et al. 1993; Larroque et al. 1995; Konstantinovskaia & Malavieille 2005, 2011; Bonnet et al. 2007, 2008; Malavieille 2010). Décollement layers favor the mechanical decoupling of stratified material of the subducting plate and consequently, induce deformation partitioning. While upper units are accreted at the toe of the wedge during propagation of the deformation front (frontal accretion), lower units are underthrusted below the main décollement fault and accreted at the base of the wedge by duplexing and underplating (i.e. basal accretion). This partition between vertical and horizontal accretion has a major impact on the organization of tectonic structures, deformation and exhumation of deep units (e.g. Gutscher et al. 1998; Bonini 2001, 2003; Adam et al. 2002; Kukowski et al. 2002; Konstantinovskaia & Malavieille 2005, 2011; Bonnet et al. 2007, 2008; Hoth et al. 2006, 2007, 2008; Malavieille 2010).

Influence of weak layers

A microbeads layer deposited on the top surface of the lower plate (experiment 1, Fig. 3a) favors underthrusting of the tectonic units below the protowedge in the first steps of experiments. During shortening, the wedge grows mostly in sequence by frontal accretion and shows the typical structure of a simple sand wedge with no décollement in the incoming sequence. We recognize typical structures of high basal friction wedges built up by underthrusting of long tectonic units (e.g. Malavieille et al. 1992;
Lallemand et al. 1994; Gutscher et al. 1998a, 1998b; Nieuwland et al. 2000; Agarwal & Agrawal 2002; Kukowski et al. 2002; Konstantinovskaia & Malavieille 2005; Graveleau et al. 2012). In some cases, when the deformation front advances toward the foreland through the nucleation of a new thrust, the previous frontal thrust remains active until the end of the experiment. Internal deformation of individual forward vergent thrust units is accommodated by small backthrusts and only few large backthrusts propagate through the whole wedge.

A microbeads layer positioned at ~1/3 of the total lower plate thickness favors remarkable strain partitioning (experiment 4, Fig. 3b). Materials of the upper portion of the subducting plate are deformed by frontal accretion, leading to the development of a typical low basal friction thrust wedge. Given the reduced thickness of the materials deformed by frontal accretion and the reduced basal friction, both the wedge taper angle (Fig. 3b) and the spacing between new thrust faults, are smaller than in experiment 1. Materials of the lower portion of the subducting plate are deformed by underplating and basal accretion (Fig. 3b). As already described in previous papers (e.g. Mulugeta & Koyi 1992; Gutscher 1996, 1998a), underplating is not a steady-state process. More in detail, it can be noted that the evolution of the duplex structure is characterized by the activity of: i) large-offset faults (continuous lines in Fig. 3b and 3c) allowing the accretion of a new unit at the base of the wedge; ii) small-offset faults (dotted lines in Fig. 3b and 3c), allowing the accommodation of the internal deformation of individual underplated units (Adam et al. 2002; Kukovski et al. 2002; Hoth et al. 2008). The large shortening (of the experiments presented in this paper) also allowed a second type of cyclicity to be observed at the whole-wedge scale. When the first antiformal stack of underplated units reaches a critical size, it becomes
inactive and the locus of underplating shifts to a more external position (e.g. toward the foreland) where a second antiformal stack starts developing. The first underplating domain is thus passively accreted and becomes part of the wedge upper-plate. Such a mechanism of accretion repeats itself cyclically during the long-term evolution of a wedge.

Growth of the antiformal stacks leads to some localized uplift of the overlying portion of the wedge as manifested by the shape of the topographic profile, which shows two evident bumps corresponding with the deep duplexes. By contrast the topographic profile is quite regular in wedges lacking strain partitioning (Fig. 3a and 3b).

A microbeads layer located at shallow depth in the sandcake has a slight influence on active deformation, without leading to efficient strain partitioning (experiment 6, Fig. 3d). Only second order small thrust units develop along the weak layer, involving the upper portion of the subducting plate. Such small thrusts are regularly alternated with major thrusts involving the whole subducting plate, and can therefore be considered local splays of the main thrusts. The overall architecture of the wedge is that of a classical high basal friction wedge, similar to the one obtained without microbeads layer (Fig. 3d).

**Influence of a plastic layer on folding**

In experiment 10 (Fig. 4a) the introduction of a plastic layer in the subducting plate drastically changes the tectonic style and kinematic evolution of the wedge, and leads to folding processes at the scale of a whole accretionary wedge. The main mechanisms of folds development in the experiment with no erosion are described Fig. 5. Development of folds begins by buckling of the plastic layer, which is
accommodated by a pop up structure in the overlying “brittle” sand layer. The wavelength of buckling and the folding mechanism are controlled by the strength contrast between the relatively strong yet ductile plasticine layer and weaker sand layers (see previous section). Soon afterwards, the folding amplitude increases, folds become asymmetric and overturned, controlled by progressive shearing deformation induced by the growth of the prism. Shearing is partly responsible for the development of the long inverted limbs, but the plastic layer is never disrupted or stretched enough to be cut, thus allowing unrolling of the synclinal hinge. Fold growth proceeds by continuous unrolling of the synclinal hinge which causes existing nearby thrusts to become inactive, while new ones form. Then, the inactive faults are passively transported along the inverted fold limb, although some can be reactivated by out-of-sequence thrusting.

Impact of surface erosion
The effect of surface erosion is tested on wedges characterized by different tectonic styles. In experiment 6, a simple high friction thrust wedge showing no strain partitioning or folding is submitted to erosion. It is comparable to experiment 1, except the latter did not include erosion. Figure 3d outlines the similar tectonic styles of both models, and similar taper angle of their pro-wedges.

Experiment 5 (Fig. 3c) shows the effects of erosion on a wedge characterized by strong strain partitioning, to be compared with experiment 4, which has the same initial setup but no erosion. In both models permanent underplating leads to the development of a large antiformal stack formed by basal accretion of duplex units. It induces uprising of internal domain and subsequent localized surface uplift. In model
5, however, surface uplift enhances localized surface erosion, which in return favors further uplift and localization of underplating. As shown in figure 3c the final product of this process is the exhumation of underplated units in localized areas.

In experiment 11 (Fig. 4b) a model involving a plastic layer is submitted to erosion in order to investigate the impact of surface processes on the dynamics of folding. Compared to experiment 10, which has the same initial setup, experiment 11 shows several differences in the general tectonic style. Despite erosion of anticlinal fold hinges, shear deformation increases the length of the inverted sequence, which is associated with the unrolling, and migration of the synclinal fold hinge. Frontal accretion spreads but the amount of shortening accommodated through each folded tectonic unit is higher. The material removed by erosion delays the growth of the wedge and thus its ability to propagate the deformation forward through new tectonic units. Although the anticline hinge is being removed by erosion, unrolling of the syncline hinge continues suggesting that the inverted limb is not submitted to traction. The diffuse shear deformation involved in the core of folds due to asymmetric shortening could be responsible for the forward migration (relative to the undeformed foreland) of the synclinal hinge.

To summarize the main differences, we note that each unit is more intensely deformed and that the length of fold limbs is greater in the experiment with erosion. In addition, for an equivalent amount of shortening, less tectonic units were formed.

Brittle/ductile multilayer and underplating

In experiments 10 and 11, large-scale isoclinals folds developed with an average final overturning of the limbs ranging between 30° and 50°. These modeling results cannot
explain what is commonly observed in many natural mountain forelands where large
scale inverted fold limbs rest close to horizontal over kilometers. Thus, important
questions remain: what mechanism is responsible for the huge overturning observed?
And, does this mechanism occur during folds development or by rigid rotation due to
late tilting? In order to answer these questions, we have taken into account the
insights from the experiments involving basal accretion. As previously shown,
décollement layers play a key role during deformation and interactions with surface
processes, that seems major too for the development of folding during the growth of
fold and thrust belts.

In experiment 13 (Fig. 4c) we tested the impact of heterogeneous layering involving
décollements, brittle and plastic behaviors (very common in foreland belts). The
model combines strain partitioning, folding and surface erosion. A 5 mm thick layer
of sand is placed between a 1 mm thick plasticine sheet and the 3 mm thick weak
layer of glass microbeads. The complete evolution of the experiment is described in
the figure 6. Erosion begins after 15 cm of shortening and the wedge slope is
sustained at about 3° during shortening (60% at the end of the experiment). During
convergence, fold hinges are rapidly eroded, while active thrusting occurs in the core
of folds. Six folded tectonic units were obtained and a large domain of deeply
accreted units is exhumed behind the prism. Note that we also observed the cyclical
behavior of underplating as described previously.

The structures located above the décollement layer are passively deformed and
uplifted due to basal accretion, tilting the back part of folded tectonic units. These
depth accretionary processes are responsible for the important overturning and rotation
of the flanks of folded structures. During continuous shortening, the kinematics of
deformation reflects the complex interaction between wedge mechanics and erosion.
At the final stage most of the folded units from the backpart of the wedge have been removed by erosion. Finally, three different tectonic domains characterized by specific deformation features are juxtaposed. From the frontal part of the wedge to the backstop respectively, we have (Fig. 6): a frontal imbricate of thrust and fold sheets; a synformal klippe of folded units previously accreted to the front and progressively deformed; and, an antiformal stack of underplated thrust units refolding the upper décollement layer.

Discussion and case studies

Results of this series of experiments give some insights for the interpretation of several debated features of the forewedge domain of mountain belts formed in continental subduction settings. Chosen case studies are discussed in the light of our experimental results. The last model, which contains the main features described in previous sections, is used to illustrate the general mechanisms explaining the relationships between the main tectonic units of natural orogenic wedges (Fig. 7).

Examples from the Variscan Belt

The Variscan orogen developed during the Gondwana-Laurasia collision from Devonian to middle Carboniferous times (e.g. Matte 2007). The Montagne Noire in southern French Massif Central and the Galicia Mountains in northwest Spain represent segments of this orogen characterized by a foreland fold and thrust belt domain associated with a syntectonic foreland basin (e.g. Arthaud 1970; Matte 1968; Pérez-Estáun et al. 1991; Simancas et al. in press). Low-grade tectonic units mainly composed by sedimentary rocks of the Paleozoic cover (schists, limestones and quartzites of Cambrian to Carboniferous ages) are intensely folded and juxtaposed
with antiformal stacks of Proterozoic to Cambrian metamorphic basement rock units largely exhumed in the hinterland. The Montagne Noire which forms the southernmost part of the Variscan French Massif Central (Fig. 8) is generally subdivided into three tectonostratigraphic units (e.g. Gèze 1949; Arthaud 1970). (1) A Northern Flank upper-plate unit with a southward tectonic vergence, consists of folded and faulted low-grade lower Paleozoic metasedimentary rocks. (2) An Axial Zone lower-plate unit, is formed by an antiformal structure of crystalline rocks (gneiss, migmatite, and micaschist) of Proterozoic to Ordovician age. This metamorphic domain composed by high grade rocks has been variously interpreted in terms of: diapirism (e.g. Gèze 1949; Beaud 1985; Charles et al. 2009), contractional tectonics (Arthaud et al. 1966; Mattauer et al. 1996; Aerden & Malavieille, 1999; Soula et al. 2001; Matte, 2007; Malavieille 2010), emplacement in a crustal scale strike-slip setting (e.g. Nicolas et al. 1977; Franke et al. 2011), or as extensional metamorphic core complex (e.g. Echtler & Malavieille, 1990; Van den Driessche & Brun 1992). In fact, most authors agree on the geological evidences for a contractional history followed (or assisted) by gravity induced extensional processes favoring exhumation, detachment formation and diapirism in the evolutionary stages of the orogen. (3) A Southern Flank, well known in the literature for the kilometer-scale recumbent fold nappes, is composed by very low-grade Paleozoic sedimentary sequences. The south verging nappes stack is intimately associated with syntectonic Visean flysch sediments deposited in a foreland basin setting, in a shallow marine environment. The upper-plate nappes are separated from high-grade lower-plate basement units by major fault zones that record a complex pattern of deformation (e.g. Echtler & Malavieille 1990; Aerden & Malavieille 1999). Figure 8 shows an interpreted cross section of The Montagne Noire (Malavieille 2010).
Similar key structures of the Galicia Mountain Belt are outlined on the cross-section of figure 9, modified from Pérez-Estàun et al. (1991). Proterozoic metamorphic units outcrop in the internal domain while a domain of large scale recumbent folds made of Cambrian quartzite/limestone characterizes external foreland units. These kilometric scale folds present horizontal or overtilted limbs (Matte 1968; Pérez-Estàun et al. 1991). Note that in this segment of the Variscan belt, a cyclical basal accretion may have occurred at large scale, as two antiformal stack structures formed during wedge growth.

Comparing wedges architecture and analog models, we can outline geometrical and kinematic similarities. As observed in models involving décollements and brittle/plastic behavior, there is a good analogy between the geometric configuration of the folded superficial domain and the underlying deeper structures. Where underplating develops, the folded units located above the décollement layer are strongly tilted by subsequent uplift in the antiformal stack domain. This can be compared to the fold-nappes structures of the Galicia belt or Montagne Noire. In the parts of the orogenic wedge located far from the locus of basal accretion, large scale folds are simply overturned. During the growth of the Montagne Noire, syntectonic flysches (Visean) are deposited at the toe of the wedge due to erosion of developing fold nappes (Southern flank). At the same time, basal accretion is active during the growth of the prism involving underthrusting of sliced Proterozoic basement and subsequent uplift at the back of the overturned fold domain. Already deformed Upper Paleozoic units are overtilted by progressive uplift. The décollement layer allowing strain partitioning between shallow and deep parts of the wedge is located along the
main inherited discontinuity, between the crystalline basement and the Paleozoic cover.

Figure 6 highlights the major effect of erosion on deformation processes. During wedge growth, due to combined basal accretion, surface uplift and erosion, continuous folding affects tectonic units of the upper-plate that remain at the same structural level in the upper crust whereas large domains of deep metamorphic units of the lower-plate are exhumed. Thus, the deformation mechanisms highlighted in our study may explain how the large scale recumbent fold-nappes with inverted limbs of 10 km develop, and why they suffered only slight or no metamorphism.

Northern Apennines

The Apennines are a fold and thrust mountain chain constituting the backbone of the Italian peninsula. Figure 10a outlines some aspects of the northernmost portion of this chain (e.g. Molli 2008). The internal zone is characterized by a metamorphic core where two main exhumed tectonostratigraphic units outcrop. The lowermost is the Apuane unit, a low grade metamorphic unit showing greenschist assemblages (deepest estimated burial: ~ 20 km). On the western side of the core, the Apuane unit is overlaid by the Massa unit, an HP greenschist facies metamorphic unit with higher grade P/T peak conditions (estimated deepest burial: ~ 25/30 km). The whole metamorphic core is overlaid by the Tuscan Nappe, an anchimetamorphic unit with a deepest estimated burial of ~ 7 km, which in turn is overlaid by Subligurian and Ligurian non-metamorphic units and by the Epiligurian basin (e.g. Fellin et al. 2007 and references therein). In a central portion, east of the Alpi Apuane, the chain is characterized by a recumbent fold domain (Fig. 10b) where the Tuscan Nappe is folded in a kilometric-scale recumbent structure (the Val di Lima fold), with an
outcropping kilometers long inverted limb. This recumbent fold shows minor
structures related with superimposed deformations (Baldacci et al. 1992; Fazzuoli et
al. 1998) with development of the long inverted limb by progressive hinge migration
(Botti et al. 2010).

The overall geometrical configuration of the analyzed segment of the Apennines (Fig.
10) can be interpreted in the light of our models. The combined action of basal
accretion and underplating of tectonic units produced the growth of a syn-
metamorphic antiformal stack (Molli & Vaselli 2006) responsible of strong uplift and
exhumation by submarine (in the early stages) and later surface erosion (Molli et al.
2002; Fellin et al. 2007). Erosion-processes were associated with tectonic thinning by
normal-slip reactivation of the basal thrust of the unmetamorphic units at the hanging
wall and the metamorphic core at the footwall (Carmignani & Kligfield 1990; Molli et
al. 2002; Fellin et al. 2007; Molli 2008). Moreover, the growth of the antiformal stack
may have induced progressive tilting of the basal detachment and the formation of
recumbent geometry of the folded Tuscan unit in the Lima Valley (Fig.10a,b).

Indeed, the locus of basal accretion and the folded domain are close enough to
presume the influence of the underlying deep structures on the passive rotation of the
fold limbs. Model results can give some more hints on the processes that may have
influenced the geological evolution of the metamorphic core, suggesting that two
successive episodes of underplating, could have been responsible for the syn-
contractional juxtaposition of the Massa unit above the Apuan unit.

Open questions in other mountain belts

Mechanisms responsible for deformation structures and exhumation processes
developed in the Himalayas are presently widely discussed through two main kind of
models (ductile channel flow, e.g. Nelson et al. 1996; Beaumont et al. 2001; Jamieson et al. 2004; and wedge extrusion in a thrust system, e.g. Burchfiel & Royden 1985; England & Molnar 1993; Guillot & Allemand 2002, Webb et al. 2007, Kali et al. 2010). Our study outline simple mechanisms that seem to be consistent with the observed large-scale geological structures (antiformal stacks, synformal klippen of fold and thrust units), in agreement with the second orogenic wedge model.

Conclusions

Interaction between climate controlled surface processes including erosion, sedimentation and deformation processes plays a key role in the structural evolution, kinematics and exhumation of rocks in orogenic wedges. During continental subduction, the role of the rheologic layering of the crust can be major as it determines the partitioning of deformation in a growing orogenic wedge into domains undergoing horizontal and vertical accretion. Partitioning is first controlled by tectonic processes, but material transfer induced by surface processes exerts a strong feed-back on wedge dynamics. Insights from analog models applied to natural cases allow us to emphasize several first order interaction mechanisms that result from this coupling. Experiments show that strain partitioning is not systematic but depends on the position of weak layers in the layered incoming sequence. They show a cyclical behavior of basal accretion, leading to episodic underplating of tectonic units, which has a strong impact on the vertical component of displacement of rock material. In turn, it changes surface slopes favoring erosion in domains of strong surface uplift. In addition, our experiments offer an explanation for the enigmatic domains of non-metamorphic large scale fold nappes units observed in the foreland of many orogenic wedges. To a first order, the dynamics of folding involves rolling of a synclinal hinge
and develop exclusively overturned fold types. This mechanism was observed, in particular, for multilayered models constituted of both strong yet ductile layers and comparatively weaker granular layers.

The influence of the deep wedge dynamics, such as the growth of basal duplexes, causes further rotation of fold structures, leading to the horizontalization of fold limbs, while erosion processes keep the folded units in a superficial low-grade metamorphic domain. Natural wedges (e.g. Galicia, Montagne Noire and Northern Apennines) present close similarities to the experiments described herein, both in terms of architecture and orogenic dynamics. Other orogenic wedges exposing similar structures such as exhumed antiformal metamorphic domes juxtaposed with domains of largely folded upper-crustal rock sequences need to be revisited in the light of the general mechanisms here outlined.

Future work should concentrate on multilayered models with different rheological contrasts (e.g. weak ductile layers and strong brittle layers) to determine other possible large-scale folding mechanisms in the shallow domains of orogenic wedges.

Acknowledgements

Our modeling work has benefitted from the technical assistance of C. Romano. Many thanks to Nina Kukowski who helped us improving an early version of the manuscript. This study has been partly funded in the frame of the ACTS ANR project. The contribution by Clemenzi has benefitted from an Erasmus Placement exchange and funding between Pisa and Montpellier Universities. This paper benefitted from constructive review by D.G.A.M. Aerden and an anonymous reviewer.
References


ARTHAUD, F. 1970. Etude tectonique et microtectonique comparée de deux domaines Hercyniens : les nappes de la Montage Noire (France) et l'anticlinorum de l'Iglesiente (Sardaigne). Publications de l'université des Sciences et Techniques du Languedoc,
Montpellier. Série Géologie Structurale, 1.


LALLEMAND, S., SCHNURLE, P. & MALAVIEILLE, J. 1994. Coulomb theory applied to accretionary and non-accretionary wedges - Possible causes for tectonic erosion


Matte, P. 1968. La structure de la virgation hercynienne de Galice (Espagne). *Géologie Alpine, 44.*


Molli, G., Giorgetti, G. & Meccheri, M. 2002. Tectono-metamorphic evolution of
the Alpi Apuane Metamorphic Complex: new data and constraints for geodynamic models. *Bollettino della Società Geologica Italiana*, volume speciale n.1, 789-800.


RAMBERG, H. 1981. Gravity, deformation and the earth's crust, 2nd edition,


SHELLART, W. P. 2000. Shear test results for cohesion and friction coefficients for different granular materials: scaling implications for their usage in analogue modelling. Tectonophysics, 324, 1-16


WEBB, A. A. G., SCHMITT A. K., HE, D. & WEIGAND E.L. 2011. Structural and
geochronological evidence for the leading edge of the Greater Himalayan Crystalline

ZULAUF, J. & ZULAUF, G. 2004. Rheology of plasticine used as rock analogue: the
### Table 1. Parameters used for the thirteen experiments. (Models described in the text are in bold)

<table>
<thead>
<tr>
<th>Experiment name</th>
<th>Total shortening (cm)</th>
<th>Protowedge Length (cm)</th>
<th>Protowedge Slope (°)</th>
<th>Lower plate Length (cm)</th>
<th>Total thickness (cm)</th>
<th>Termination Position* (cm)</th>
<th>Plastiline Present</th>
<th>Plastiline Thickness (cm)</th>
<th>Plastiline Position* (cm)</th>
<th>Erosion Start† (cm)</th>
<th>Erosion Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp 1</td>
<td>150</td>
<td>61</td>
<td>7</td>
<td>3.1</td>
<td>Straight</td>
<td>Top lower plate</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Exp 2</td>
<td>150</td>
<td>66</td>
<td>4</td>
<td>3.1</td>
<td>Straight</td>
<td>Top lower plate</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Exp 3</td>
<td>160</td>
<td>80</td>
<td>2</td>
<td>3.1</td>
<td>Gradual</td>
<td>Top lower plate</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Exp 4</td>
<td>180</td>
<td>74</td>
<td>0</td>
<td>3.1</td>
<td>Straight</td>
<td>Top lower plate</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Exp 5</td>
<td>201</td>
<td>74</td>
<td>0</td>
<td>3.1</td>
<td>Straight</td>
<td>Top lower plate</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>30</td>
<td>Variable</td>
</tr>
<tr>
<td>Exp 6</td>
<td>198</td>
<td>66</td>
<td>4</td>
<td>3.1</td>
<td>Straight</td>
<td>Top lower plate</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>30</td>
<td>Variable</td>
</tr>
<tr>
<td>Exp 7</td>
<td>220</td>
<td>66</td>
<td>4</td>
<td>3.1</td>
<td>Straight</td>
<td>Top lower plate</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>20</td>
<td>Fixed (5°)</td>
</tr>
<tr>
<td>Exp 8</td>
<td>160</td>
<td>80</td>
<td>2</td>
<td>3.3</td>
<td>Gradual</td>
<td>Top lower plate</td>
<td>Yes</td>
<td>0.3</td>
<td>1.7</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Exp 9</td>
<td>167</td>
<td>90</td>
<td>0</td>
<td>3.3</td>
<td>Gradual (-15cm)‡</td>
<td>Top lower plate</td>
<td>Yes</td>
<td>0.2</td>
<td>1</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Exp 10</td>
<td>163</td>
<td>90</td>
<td>0</td>
<td>3.3</td>
<td>Gradual (-15cm)‡</td>
<td>Top lower plate</td>
<td>Yes</td>
<td>0.1</td>
<td>1</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Exp 11</td>
<td>193</td>
<td>90</td>
<td>0</td>
<td>3.3</td>
<td>Gradual (-15cm)‡</td>
<td>Top lower plate</td>
<td>Yes</td>
<td>0.1</td>
<td>1</td>
<td>Yes</td>
<td>25</td>
</tr>
<tr>
<td>Exp 12</td>
<td>175</td>
<td>80</td>
<td>2</td>
<td>3.3</td>
<td>Gradual</td>
<td>Top lower plate</td>
<td>Yes</td>
<td>0.2</td>
<td>1.5</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Exp 13</td>
<td>200</td>
<td>90</td>
<td>0</td>
<td>3.5</td>
<td>Gradual (-15cm)‡</td>
<td>Top lower plate</td>
<td>Yes</td>
<td>0.1</td>
<td>1.7</td>
<td>Yes</td>
<td>15</td>
</tr>
</tbody>
</table>

Notes:
* Height from base plate
† Amount of initial shortening without erosion
‡ Lower plate ends before the backstop
Fig. 1. Cartoon showing two folding mechanisms to generate large-scale overturned folds in fold and thrust belts. The first mechanism involve an important burial whereas the second one allows the development of large folds with slight burial. (a) Buckling and folding during compressional shortening followed by shearing and tilting of fold limbs; (b) Fold amplification by thrusting and subsequent shearing, unrolling and migration of the synclinal hinge in the frame of a fold and thrust wedge; (c) Simplified kinematic sketch of the same process. Coloured circles are passive markers regularly spaced in the folded layer.

Fig. 2. Experimental set-up. The width of the device is 10 cm.
Fig. 3. Initial configuration and final result of models involving a microbeads layer located at different heights (“d” on sketch). (a) Classical high friction thrust wedge. The thrust front propagates in a piggy-back style, but some faults remain active after the nucleation of new faults at the front. (b) Strain partitioning: duplexing at the base of the wedge and frontal accretion at the toe. Note the cyclical behavior of underplating. (c) Impact of surface erosion on the wedge dynamics, location of
underplating and exhumation of underplated units. (d) Underplating is inhibited when décollement is too shallow. Shortening in cm on digital screen.

**Fig. 4.** Initial setting and final stage of model involving a thin layer of plasticine (Hp: Height of the plasticine layer on sketch). (a) Case no erosion. Folds are overturned with an angle between 30° and 50°; (b) Same experiment with erosion; (c) Brittle/plastic model with décollement layer and erosion. Shortening in cm on digital screen.
Fig. 5. Kinematic model of folding. The thick line with circles represents the plasticine with displacement indicators.
Fig. 6. Evolution of complex model involving brittle/plastic multilayer, erosion and décollement layer. Upper units situated above décollement layer are composed of sand and plasticine; deep units below décollement layer are composed of sand. At the final stage (e), three domains are juxtaposed: (1) exhumation of deep rocks, (2) the domain of recumbent folds and (3) the overturned folds.
Fig. 7. Relationships between cyclical duplexing and kinematics of folding in a brittle/plastic model with erosion and décollement level.

**Fig. 9.** Cross-section of Variscan Belt in Galicia, Spain (modified from Pérez-Estàun et al. 1991). U.P.: Upper Plate; L.P.: Lower Plate.

**Fig. 10.** (a) Cross section of the Northern Apennines, Italy (modified from Molli 2008). (b) Cross-section of the Val di Lima fold structure (modified from Baldacci et al. 1992). T: Tertiary; J-K: Jurassic-Cretaceous; Tr: Triassic.