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Interaction of Surface Erosion and Sequential Thrust Progression: Implications on Exhumation Processes

SANTANU BOSE[a] and NIBIR MANDAL[b]
[a]Experimental Tectonics Laboratory, Department of Geology, University of Calcutta,
35 Ballygunge Circular Road, Kolkata – 700 019
[b]Indian Institute of Science Education and Research, HC 7, Salt Lake City, Kolkata – 700 106
Email: bose.santanu@gmail.com

Abstract: This paper investigates the evolution of thrust wedges with concomitant surface erosion, and its bearing on the exhumation processes in orogenic belts. We performed sandbox experiments, simulating syn-orogenic erosion on forelandward sloping surfaces (~4°). Experiments show that the erosion process has a significant control on the progression of frontal thrusts. In case of no-erosion condition, wedges with high basal friction develop frontal thrusts with strongly increasing spacing. In contrast, for the same basal friction the thrusts show uniform spacing as the wedge development involves concomitant surface erosion. On the other hand, the erosion promotes reactivation of hinterland thrusts in wedges with low basal friction. We show that erosion-assisted thrust reactivation is the principal mechanism for exhumation of deeper level materials in orogens. Efficiency of this mechanism is largely controlled by basal friction. The exhumation of deeper level materials is limited, and occurs within a narrow, sub-vertical zone in the extreme hinterland when the basal friction is high ($\mu_b = 0.46$). In contrast, the process is quite effective in wedges with low basal friction ($\mu_b = 0.36$), resulting in exhumation along gently dipping foreland-vergent thrusts as well as along thrusts, subsequently rotated into steep attitude. The zone of exhumation also shifts in the foreland direction in the course of horizontal movement. Consequently, deeper level materials cover a large area of the elevated part of the wedge.

Keywords: Orogenic wedge, Thrusting, Sandbox experiments, Basal friction, Reactivation.

INTRODUCTION

In collisional tectonics the lithosphere deforms at a large scale by sequential thrusting, and attains wedge shaped geometry, called *orogenic wedge*. Several studies show that the growth of orogenic wedges and the progression of sequential thrusts mutually control each other (Persson and Sokoutis, 2002; Konstantinovskaia and Malavieille, 2005). The Coulomb Wedge Theory has been proposed to enumerate the dynamic stability of orogenic wedges, considering a frictional base. According to this theory, a wedge does not slide on the frictional base, but deforms internally until it achieves a critical taper (Chappel, 1978; Davis et al. 1983; Dahlen, 1984). The wedge at its critical taper would tend to slide on its base, leading the system on the verge of failure. The critical taper of a wedge, defined by the surface (a) and the basal (b) slopes, is a function of the coefficient of friction at the wedge base and the angle of internal friction of the wedge material (Fig.1a; Dahlen, 1990).

Surface processes, namely erosion, control the surface slope and thereby the stability of wedges. Several workers have dealt with lithospheric deformations in most orogenic belts under the influence of erosion processes (Beaumont et al. 2001; Harrison et al. 1992, 1998; Royden et al. 1997; Yin and Harrison, 2000). The uprise of orogens re-sets the atmospheric circulation, promoting erosional activities in the hinterland. Surface denudation resulting from erosion in turn affects the stability of the orogen (Persson and Sokoutis, 2002; Konstantinovskaia and Malavieille, 2005; Willet, 1999). However, syn-orogenic erosion is generally coupled with deposition of the eroded material in the foreland (Royden, 1996), which again influences lateral propagation of the orogen. The equilibrium of a growing mountain is thus sensitive to the erosion versus deposition rates.

A direction of tectonic studies inspects the exhumation mechanisms of deep crustal rocks to the earth surface. Several tectonic models, such as channel flow models, have been proposed to explain rock uplift in orogens. Recent studies suggest that surface erosion plays an important

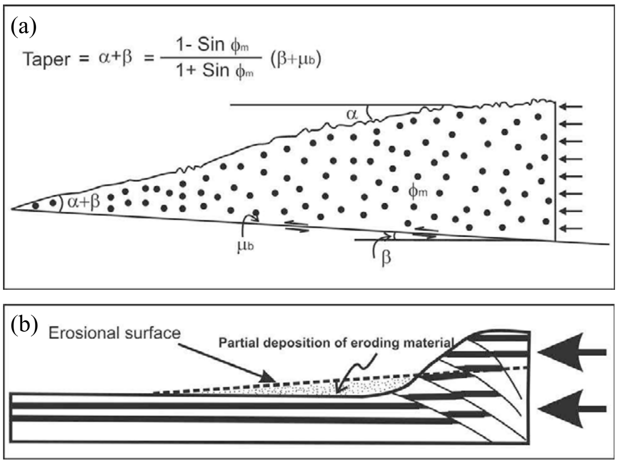

Fig.1. **(a)** Diagram of critical taper of a Coulomb wedge (*after* Dahlen, 1990) as a function of the co-efficient of basal friction (μ_b) and the angle of internal friction (ϕ_m). α and β are the surface and basal slopes respectively. **(b)** Schematic sketch illustrating the mode of erosion used in sandbox experiments.

role in controlling the course of uplift and final exhumation to the surface (Beaumont et al. 1996; Dahlen 1984; Konstantinovskaia and Malavieille, 2005; Willet, 1999). Based on field observations, a good correlation between the zones of maximum erosion and exhumed high-grade metamorphic rocks has been established (Beaumont et al. 1992; Koons, 1990; Thompson et al. 1997). This has also been demonstrated in analogue model experiments (Konstantinovskaia and Malavieille, 2005). The erosion processes also control the progression of frontal thrusts. In case of non-erosional conditions, successive thrusts develop with a systematic spatial arrangement, which is a function of several factors, such as bed thickness, basal friction, basal slope, surface slope and topographic variation (Bombolakis, 1986; Panian and Pilant, 1990; Mandal et al. 1997; Schott and Koyi, 2001; Mulugeta and Koyi, 1987; Bose et al. 2009). Recent experimental studies show that the erosion processes perturb such sequential frontal thrust progression, and greatly modify the final thrust architecture (Konstantinovskaia and Malavieille, 2005). However, it is still to be investigated how syn-orogenic erosion can influence thrust progression under different mechanical conditions at the base, which is an important issue for understanding the process of exhumation. In this study we address this issue, and show varying exhumation patterns in orogenic wedges with contrasting basal friction.

Earlier experiments showed that the spatial distribution of imbricate thrusts varies with basal friction (Bose et al. 2009). Higher basal friction promotes continuous increase in spacing between the consecutive thrusts with wedge growth. In the case of low basal friction, thrust spacing attains a constant spacing between consecutive thrusts when the deformation is large. However, these studies do not take into account the role of syn-orogenic erosion. In this study we investigate the effect of erosion on the pattern of thrust progression in sandbox experiments. The experiments allow us to decipher the exhumation patterns of deeper level materials in thrust wedges growing with concomitant surface erosion. In this paper we present results obtained from sets of sandbox experiments conducted with low ($\mu_b = 0.36$) and high ($\mu_b = 0.46$) basal friction.

EXPERIMENTAL METHODS

We adopted the conventional method of sandbox experiments (Mulugeta, 1988; Mulugeta and Koyi, 1987, 1992; Huiqi et al. 1992; Marshak and Wilkerson, 1992; Mandal et al. 1997; Bose et al. 2009). Dry non-cohesive natural sand (Coulomb material) with an average grain size of less than 500 mm, bulk density $r = 1.6$ gm/cm^3 and internal co-efficient of friction, $\mu = 0.57$ (Hubbert, 1951; Davis et al. 1983) was used as an experimental material. Loose sand materials provide a better approximation for scaled model experiments for large-scale brittle deformations in the uppermost crust (Davis et al. 1983; Mulugeta, 1988; Liu et al. 1992; Mandal et al. 1997). Models were prepared by sieving alternate layers of sand of contrasting colours as used by the earlier workers (Davis et al. 1983; Mulugeta, 1988; Liu et al. 1992; Mandal et al. 1997; Marques and Cobbold, 2002; Lujan et al. 2003; Koyi, 1995; Yamada et al. 2006; Bose et al. 2009). Sand masses were sieved on a horizontal rigid base to form a layered sand bed. The sand bed had basal friction (μ_b) with a rigid base, which was varied in the experiments.

Sand models were deformed in pure shear by moving a vertical rigid wall (cf. planar backstop used elsewhere, e.g. Davis et al. 1983; Mulugeta, 1988; Liu et al. 1992; Mandal et al. 1997; Lujan et al. 2003; Koyi, 1995; Yamada et al. 2006) from one side at a constant velocity of 0.3 mm/s. With progressive horizontal shortening a wedge developed against the backstop. We introduced surface erosion to the wedge at a regular interval. Different workers have modeled such erosion in different ways (Konstantinovskaia and Malavieille, 2005; Persson and Sokoutis, 2002). We simulated the erosion process in the following manner. Using a vacuum cleaner the sand materials were removed from the surface of wedge along an inclined plane (Fig.1b, cf. Konstantinovskaia and Malavieille, 2005). The inclination was held constant (~ 4°) during an experimental run. The erosion event occurred following attainment of a desired level of hinterland elevation by the wedge. We continuously observed the process of wedge development, using a camera kept at a fixed distance from the model. We conducted experiments with low and high basal friction (μ_b). To obtain low basal friction (μ_b= 0.36), boric powder was sprinkled over the basal surface. For high-basal friction (μ_b= 0.46), we ran the experiments on a coarse (30 mesh) sandpaper base. The four side glasses of the sandbox were cleaned and dried carefully by heating, the purpose of which was to remove surface moisture and to avoid sticking of sand to side glasses during the experimental run.

EXPERIMENTAL FINDINGS

Our sandbox experiments show that syn-orogenic erosion significantly modifies the spatial arrangement of successive frontal thrusts in a prograding wedge. In case of no erosion, thrust spacing is mostly controlled by the basal friction. Successive thrusts increase their spacing monotonically when the basal friction is high, and individual thrusts show large displacements (Fig.2a, Bose et al. 2009). The thrust spacing pattern is quite different in the syn-orogenic erosion condition. It is characterized by a more or less uniform spacing (Fig.2b). On the other hand, the frontal thrust progression in presence of surface erosion is unsteady when the basal friction is low (Fig.3). Thrust spacing is somewhat irregular. Furthermore, the wedge formation involves out-of-sequence thrusting in the hinterland.

We studied the exhumation process of deeper level materials under the influence of syn-orogenic erosion in experimental thrust wedges. Experiments show that the exhumation occurs in specific locations of the growing wedge. Reactivation of early thrusts in the hinterland plays a major role in channeling of basal level materials to the surface undergoing denudation by erosion (cf. Beaumont et al. 2001). However, the mode of exhumation varies significantly with basal friction, and the spatial extent of exhumation zones is inversely proportional to basal friction. In case of low basal friction, deeper materials get exhumed along foreland-vergent, gently dipping thrusts as well as vertical thrusts in the hinterland. This gives rise to V-shaped channel for exhumation from the base to the surface of wedges (Fig.4). The location of exhumation shifts forelandward, and becomes active along relatively newer thrusts. This is how exhumed materials are distributed in several locations, encompassing almost the entire elevated part of the wedge. The process of exhumation is quite limited in wedges with high basal friction. It occurs only along a narrow zone that forms by reactivation of rotated earlier

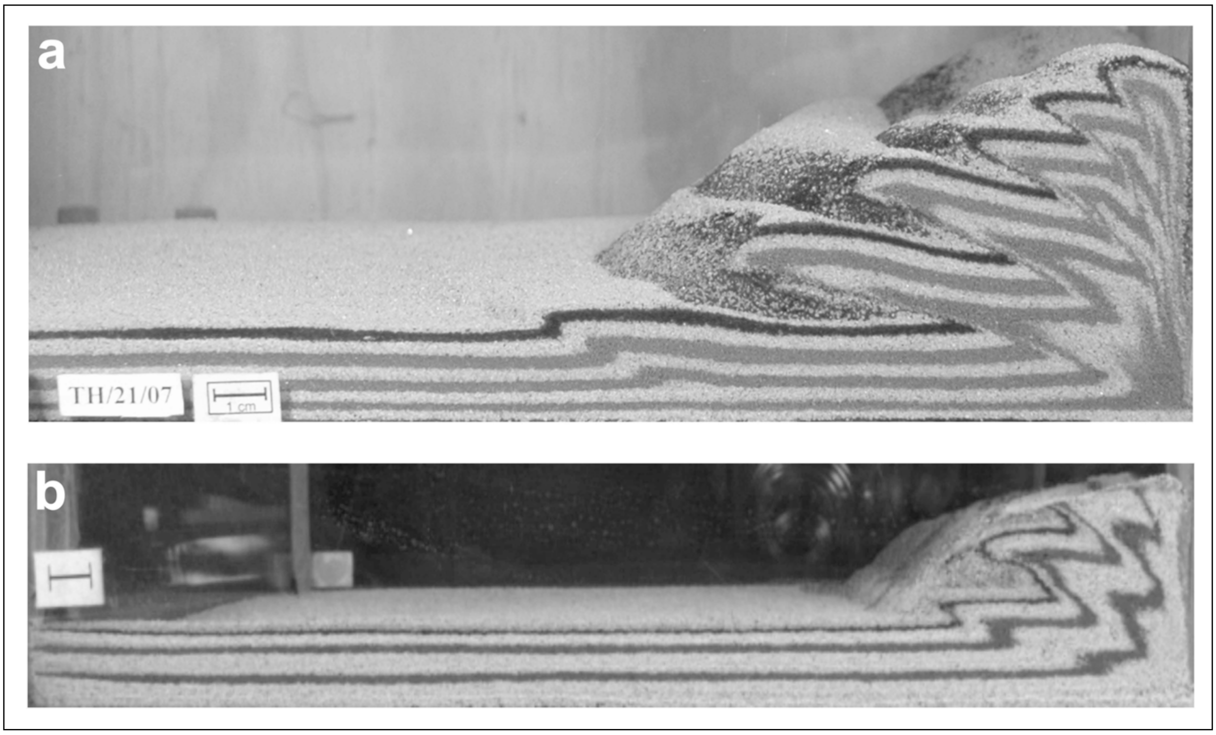

Fig.2. Thrust sequences in sand models with high basal friction (μ_b = 0.46). **(a)** Model with no erosion. **(b)** Model with syn-thrusting erosion. Note that frontal thrusts in (a) show a strong variation in their spacing, whereas the spacing remains more or less uniform in (b). Models were deformed by horizontal contraction (right to left). Scale bar: 1 cm.

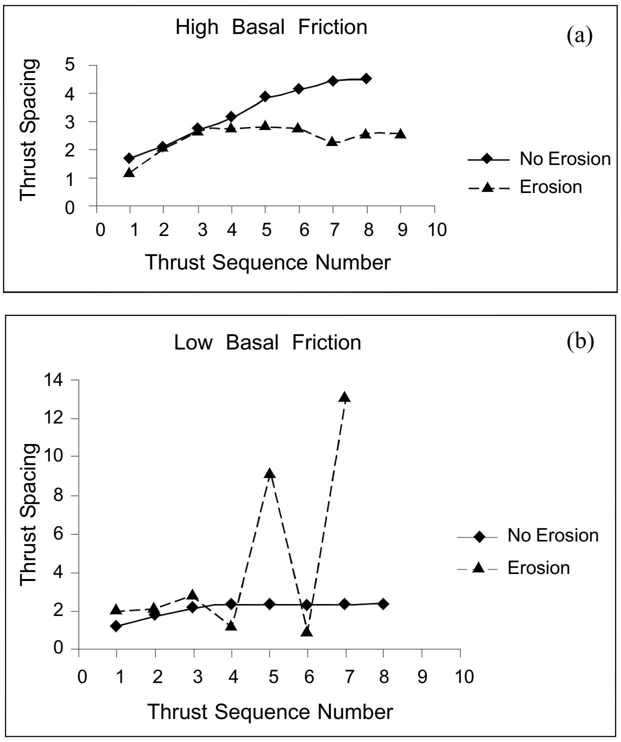

Fig.3. Variations of thrust spacing (in mm) in successive steps of frontal thrust progression. **(a)** high basal friction. **(b)** Low basal friction. Note the variation in their spacing with "erosion" or with "no erosion".

thrust at the extreme hinterland (i.e. wedge interface with the backstop in experiments). This zone remained active throughout the deformation, and no new exhumation zone formed during forelandward propagation of the wedge. Consequently, wedges with high basal friction are characterized by a narrow exhumation zone compared to wedges with low basal friction described above (Fig.4).

This difference in exhumation behavior can be attributed to contrasting wedge growth with basal friction. Wedges with high basal friction grow dominantly in the vertical direction due to stacking of successive thrust sheets. Thus, the wedge elevation increases at higher rates compared to wedges with low basal friction (Bose et al. 2009). Deeper materials cannot be exhumed to the wedge surface unless their rates of uplift exceed the net rate of elevation change of the wedge surface (determined by the difference in the rates of denudation and surface uplift). Thus, in experiments with high basal friction, the net rate of elevation increase is very high, allowing little exhumation of deeper level materials to the surface.

DISCUSSION

Most of the mountain belts undergo surface erosion during their uplift. Recent studies show that such syn-orogenic erosion can control the kinematics of wedge growth and uplift of deep-crustal materials (e.g. Beaumont et al. 2001; Konstantinovskaia and Malavieille, 2005). Intuitively, erosion processes lower the overburden load and thereby promote the rate of uplift of deeper level materials. However, our study indicates that erosion-driven exhumation processes can vary to a large extent depending upon contrasting basal friction. In general, wedges with high basal friction grow vertically rapidly, leaving a limited scope for exhumation of deeper level materials even if they underwent surface erosion. On the other hand, wedges with low basal friction grow dominantly in the frontal direction, and show intense reactivation of hinterland thrusts when surface erosion occurs. This process of reactivation promotes rapid exhumation of deeper level materials to the surface. Many orogenic belts show lateral variations of basal friction. Based on our experimental findings, we suggest that the abundance of deep-crustal rocks exposed in the elevated regions of mountain belts can be different in different transects. Regions containing deep-seated dècollement with low basal friction are likely to show extensive exhumed rocks in the hinterland, as observed in the eastern Himalaya (Avouac, 2007). It is possible to decipher such regions considering the overall orogenic slope that manifests the magnitude of basal friction. Areas of low basal friction would be characterized by relatively gentle orogenic slopes.

In this study we have kept the coefficient of internal friction of sand at a constant value. However, the physical parameter can vary in natural settings due to different geological factors, e.g., pore fluid pressure. According to the equation (Fig.1a), the critical taper is inversely proportional to internal friction. Thus, a stable thrust wedge is likely to have lower taper for higher values of internal friction. On the other hand, experimental results under high basal friction condition show that the rate of uplift becomes intense when the wedge develops with large taper angle. Intuitively, we thus propose that geological factors causing reduction in internal friction would increase the taper and thereby, the rate of uplift in the wedge.

The interaction of wedge growth and surface erosion is well reflected in the spatial arrangement of sequential frontal thrusts. Experiments show that wedges growing in absence of erosion form frontal thrusts with continuously increasing spacing when the basal friction is high, whereas those with low basal friction develop thrusts with a more or less constant spacing. The styles of thrust progression become different in wedges undergoing surface erosion. For high basal friction, successive thrusts formed

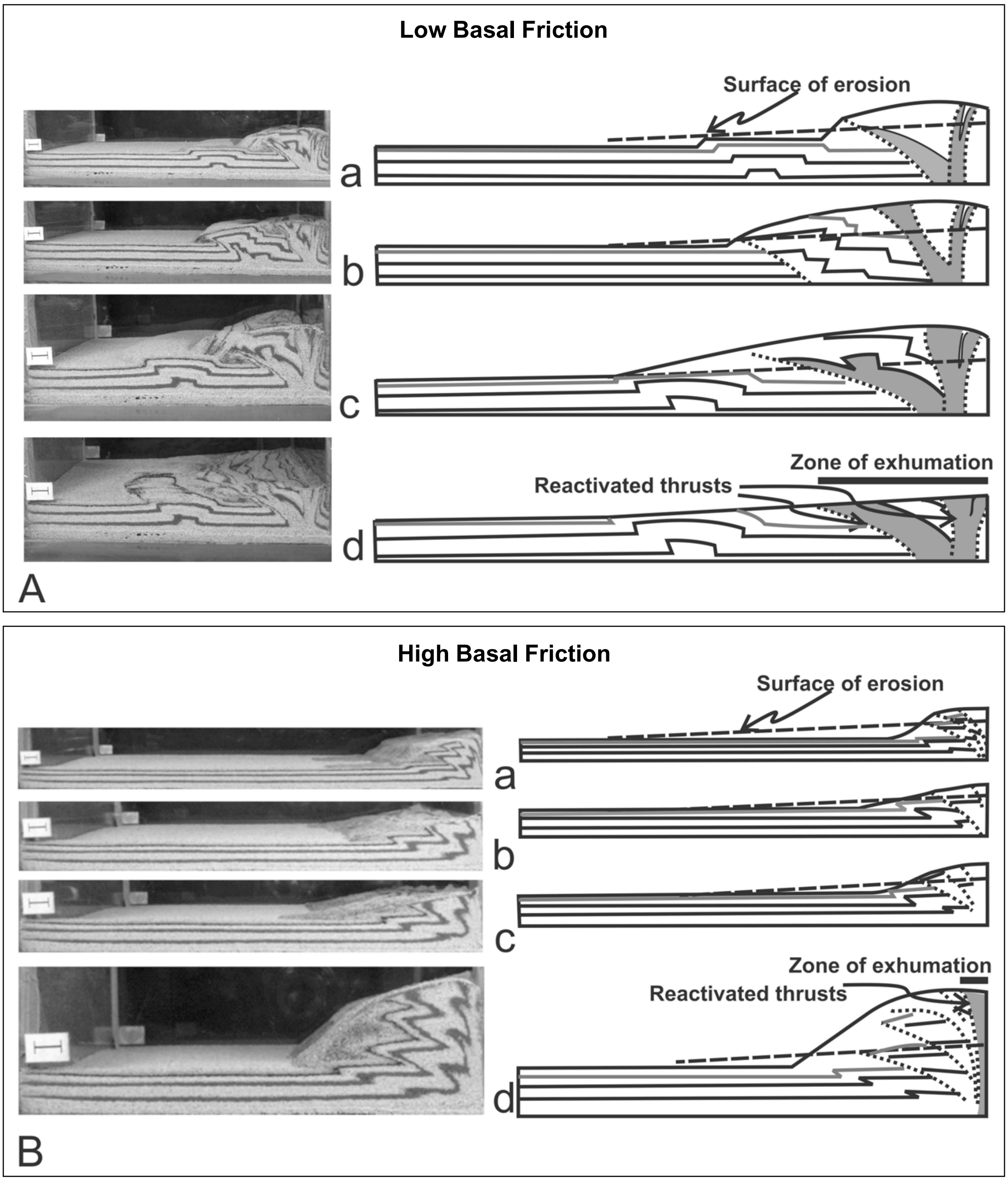

Fig.4. Patterns of exhumation of deeper level materials in thrust wedges with **(a)** low and **(b)** high basal friction, undergoing syn-thrusting erosion. Exhumation zones are shown in shaded areas.

maintaining a constant spacing. In case of low basal friction, the spacing was noted to be unsteady, which probably resulted from intermittent reactivation of earlier thrusts in the hinterland. These experimental results represent a specific condition for erosion events that were carried out by maintaining a constant elevation in the hinterland. However, the rate of erosion can vary in the course of mountain uplift, and the hinterland elevation may not remain at the same level. Depending upon the relative rates of erosion and surface uplift, the orogenic wedges can gain increasing or decreasing hinterland elevation during their forelandward propagation. Thus, the spatial distributions of thrusts in such settings are likely to be different from that inferred from our experiments with constant wedge elevations.

A number of models have been employed to explain the pattern of uplift paths for exhumation to the surface. For example, migmatitic rocks exposed on north of the MCT in the Himalayan Mountain belt are believed to have been exhumed as partially molten deep-crustal materials flowing along a south vergent inclined channel (Beaumont et al. 2001). The mechanism of uplift is mostly guided by buoyancy forces. In case of Coulomb wedges (which is relevant to the present study), the uplift patterns will be entirely guided by the thrust architecture prevailing in the hinterland of the wedge. Deeper-level materials in orogenic wedges with low basal friction are routed up along both sub-vertical and relatively gently dipping frontal thrusts in the hinterland, forming a 'V' pattern, with a slice of shallow level materials in the middle. The experiments also reveal that Coulomb wedges involve foreland migration of exhumation zones due to frontal progression of thrusts. This kind of changing location of exhumations cannot be explained by other mechanical models, such as channel flow models.

Earlier experimental studies (Konstantinovskaia and Malavieille 2005) demonstrate localization of exhumation zones essentially along steeply dipping thrusts in wedges with low basal friction. In contrast, our experiments show exhumation localization also along foreland-vergent inclined thrusts that form in the subsequent stages of wedge development. These thrusts rotate backward to steepen their inclinations during uplift of deeper level materials along them. This difference in the two experimental results might be due to a difference in model considerations. Konstanovskaia and Malavieille (2005) introduced a protowedge in the initial model. However, we did not consider such an initial geometrical constraint in an undeformed crustal section.

CONCLUSIONS

1. The magnitude of friction on the décollement determines how the erosion process can influence the development of a thrust wedge.
2. In case of no-erosion condition, successive thrusts form with strongly increasing lateral spacing on décollements with high friction, whereas they tend to form with a more or less constant spacing when the wedge growth accompanies surface erosion. Erosional conditions lead to unsteady thrust spacing for décollements with low friction.
3. Wedges growing on low-friction décollements show intense reactivation of thursts in the hinterland when they undergo surface erosion. Such reactivation promotes uplift of deeper level materials and thereby exhumation processes in the wedges.
4. Exhumation zones are of limited extent in wedges with high friction décollement.

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