Varying frontal thrust spacing in mono-vergent wedges: An insight from analogue models

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Sandbox experiments are used to study frontal thrust fault spacing, which is a function of physical properties within the thrust wedge. We consider three styles of thrust progression in mono-vergent wedges: Style I, II and III. In Style I, frontal thrusts progress forelandward, maintaining a constant spacing, whereas Style II and Style III progression show increasing and decreasing spacing, respectively. The three styles are shown as a function of the following factors: basal friction (μ_b), initial surface slope (α) and basal slopes (β), and surface erosion. For high μ_b ($\sim$0.46), thrust progression occurs in Style II when $\alpha < 2^\circ$ and $\beta < 0.5^\circ$, and in Style III when α and β are high ($\alpha > 2^\circ$ and $\beta > 0.5^\circ$). Style II transforms to Style I when the wedge undergoes syn-thrusting surface erosion. In contrast, low-basal friction ($\mu_b = 0.36$) gives rise to either Style I or III, depending on the magnitudes of α and β. Conditions with $\alpha = \beta = 0$ developed Style I, whereas Style III in conditions with any non-zero values of α and β. In this case, surface erosion caused the process of thrust progression unsteady, and prompted out-of-sequence thrusting in the wedge. This study finally presents an analysis of the three styles, taking into account the following two parameters: (1) instantaneous increase of hinterland thickness ($\Delta H_e/H_e$) and (2) forelandward gradient of wedge thickness ($\delta H/\delta x$). Experimental data suggest that thrust sequences develop in Style II for low $\delta H/\delta x$ and large $\delta H_e/H_e$ values and, in Style III as either $\delta H/\delta x$ increases or $\Delta H_e/H_e$ drops.

1. Introduction

Crustal lithosphere in the active convergent plate boundaries undergoes sequential thrusting, forming tectonic wedges in the mountain belts and subduction zones. A line of tectonic studies is concerned with the mechanical modelling of wedges, assuming that the upper crust deforms like a Coulomb material (Chapple 1978; Davis *et al.* 1983; Dahlen *et al.* 1984). These models explain the development of a Coulomb wedge as if a sheet of granular material piles up in front of a moving bulldozer, comparable to the overriding lithospheric plate in the convergent setting. The phenomenon has been theorized to explain the wedge dynamics as a function of geometrical and mechanical parameters. The theory postulates that the wedge material deforms internally until it attains a critical taper. A critically tapered wedge would tend to slide stably at its base without any further internal deformation. Furthermore, the wedge at its critical taper turns to be on the verge of failure, forming thrusts. A critically tapered wedge develops successively new frontal thrusts in the course of its forelandward progression (Mulugeta 1988; Liu *et al.* 1992; Mandal *et al.* 1997; Schott and Koyi 2001;

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Agarwal and Agarwal 2002; Bose *et al.* 2009). This study deals with varying thrust spacing observed in natural fold-thrust-belt, which involves primarily the upper brittle part of the lithosphere (Butler 1992; Jadoon *et al.* 1992; Goff *et al.* 1996; Panian and Wiltschko 2004).

Despite significant advancement in thrust tectonics, understanding of thrust locations and their spatio-temporal variations is still incomplete. Several earlier studies took into account the effects of inherent topographic, mechanical heterogeneities or frictional coefficient in basal detachment to demonstrate localization of a thrust ramp in convergent tectonic zones (Wiltschko and Eastman 1982; Davis and Engelder 1985; Knipe 1985; Bombalakis 1986; Platt 1986; Cello and Nurr 1988; Geiser 1988). In a recent study Panian and Wiltschko (2007) have, however, argued that ramp localization can occur without any such inherent imperfection in the system. Using finite element models they have shown that plastic shear bands preferentially localize frontalward in the form of thrust ramps, maintaining a definite distance from the earlier ramp. According to their models, ramp spacing in a tapered crustal section decreases forelandward, as can be enumerated from a linear relation between thrust spacing and bed thickness (Liu *et al.* 1992; Mandal *et al.* 1997). On the other hand, some sandbox experiments exhibit increasing ramp spacing in beds with a uniform initial thickness, which is attributed to increasing hinterland elevation of thrust wedges (Mulugeta and Koyi 1987; Bose *et al.* 2009). Frontal thrust progression can occur with a uniform spacing only when a stable elevation of the wedge is maintained (Bose *et al.* 2009). There are several factors, such as surface erosion, surface slope and basal slope, that control the growth of tectonic wedges, and in turn govern the process of frontal thrust progression. Recent field and experimental observations suggest that focused surface denudation can result in localization of thrusts (Avouac and Burov 1996; Konstantinovskaia and Malavieille 2005; Hoth 2006; Hoth *et al.* 2006).

All the studies discussed above dealt with thrust wedges developing on rigid bases with frictional contact. However, many fold-and-thrust belts show a ductile horizon at their base. Smit *et al.* (2003) have shown that the relative strength of brittle cover and ductile base (brittle–ductile coupling) controls the mode of frontal thrust progression. Weak brittle–ductile coupling, depending on basal slope (β) and shortening velocity (V), promotes backward thrusting sequences, which are replaced by frontward thrust sequences, as the brittle–ductile coupling becomes strong with lowering β and increasing V. The coupling strength also determines the spacing of frontal thrusts. In case of strong coupling, frontal thrusts form at closed spacing that remains uniform during frontward thrust progression. The spacing shows an inverse relation with the brittle–ductile coupling.

Several researchers have shown that the development of thrust sequences depends also on the geometry of the overriding plate and the nature of its mechanical contact with the accretionary wedge. For example, frontal and back thrusts can form spatially in close association, forming a complex architecture when the indenting plate pushes into the Coulomb crustal material (Malavieille 1984; Koons 1990; Storti *et al.* 2000; Persson and Sokoutis 2002). Other researchers have reported similar thrust architecture, taking into account the effect of a singularity of basal velocity (Willett 1999; Storti *et al.* 2000). The style of thrust sequences becomes more complex when the process occurs simultaneously with synorogenic surface erosion, as observed in sandbox experiments (Konstantinovskaia and Malavieille 2005; Bose and Mandal 2010).

It follows from the above discussions that the progression of frontal thrusts is a product of different interacting surface and tectonic processes. Many mountain belts, for example, the Himalayan front contain relatively simple thrust sequences characterized by systematically arranged foreland vergent thrusts (Srivastava and Mitra 1994; DeCelles *et al.* 1998; Avouac 2007). This type of thrust architecture has been widely investigated using both analogue and numerical models, considering *mono-vergent* Coulomb wedges formed against vertical buttresses (Mulugeta and Koyi 1987, 1992; Mulugeta 1988; Liu *et al.* 1992; Marshak and Wilkerson 1992; Mandal *et al.* 1997; Gutscher *et al.* 1998a, b; Panian and Wiltschko 2007; Bose *et al.* 2009). We performed sandbox experiments to study the progression behaviour of frontal thrusts in such mono-vergent wedges. Based on the *initial spacing* of successive frontal thrusts in sandbox experiments, we define three principal styles of thrust progression (figure 1).

- *Style I*: Frontal thrusts progress in the foreland direction, maintaining a constant spacing. This type of thrust sequence is observed in many fold-thrust-belts, e.g., Sulaiman FTBs (Jadoon *et al.* 1992).
- *Style II*: Progression of frontal thrusts occurs with continuously increasing lateral spacing, as observed in the Pyrenees (Goff *et al.* 1996; Panian and Wiltschko 2004).
- *Style III*: Thrust spacing continuously decreases during the progression.

These three types of thrust sequences were simulated in sandbox experiments, considering the

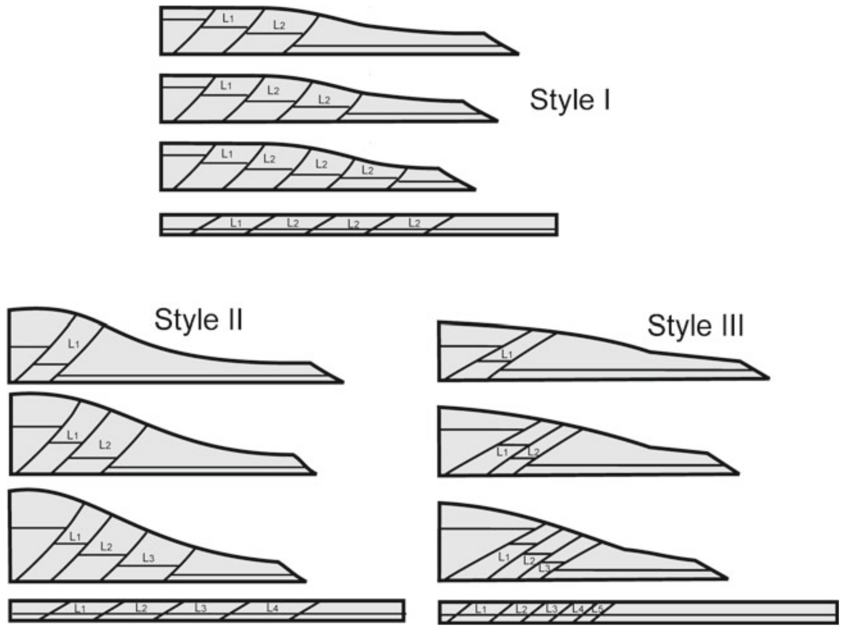

Figure 1. Three styles of frontal thrust progression (left to right): Style I – progression with constant spacing (L_2), Style II – progression with increasing spacing ($L_1 < L_2 < L_3 \ldots$) and Style III – progression with decreasing spacing ($L_1 > L_2 > L_3 \ldots$). Restored sections of the thrust sequences are shown at the bottom.

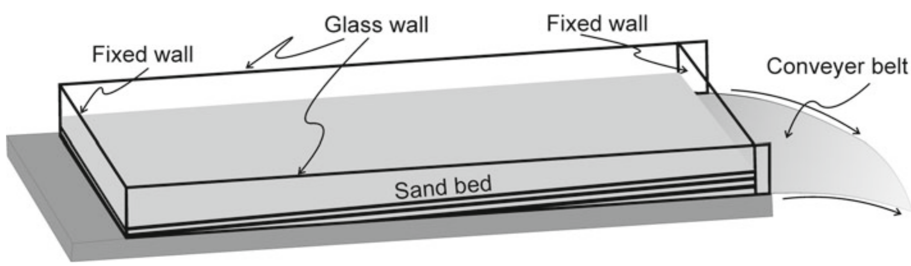

Figure 2. Schematic sketch of the laboratory set-up for sandbox experiments (not in scale).

following factors: basal friction (μ_b), surface slope (α) and basal slope (β) of the wedge. Based on the experimental findings, we present a detailed account of factors controlling these three styles of thrust progression, and suggest that they can be used as potential indicators of geological conditions.

2. Experimental method

Sandbox experiments were performed employing the conventional method for simulation of mono-vergent thrust wedges (Mulugeta and Koyi 1987, 1992; Mulugeta 1988; Liu *et al.* 1992; Marshak and Wilkerson 1992; Mandal *et al.* 1997; Agarwal and Agarwal 2002; Bose *et al.* 2009). Models were prepared with dry non-cohesive natural sand (mean grain size ∼500 μm). The model materials have frictional properties satisfying the Coulomb theory (Dahlen *et al.* 1984) and can be used as analogues of upper crustal rocks. The sandmass was chosen with a bulk density $\rho \sim 1.6$ gm/cm^3 and internal co-efficient of friction, μ, was measured and found to be 0.57 and the cohesion, $C_0 = 20$ Pa. Earlier experiments also suggest that 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). The method of model preparation was similar to that used in earlier studies (Davis *et al.* 1983; Mulugeta 1988; Liu *et al.* 1992; Koyi 1995; Mandal *et al.* 1997; Lujan *et al.* 2003; Yamada *et al.* 2006; Bose *et al.* 2009). The sandbox apparatus consisted of a 100 cm long and 25 cm wide glass-sided walls, resting upon a conveyor belt (figure 2). 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. To reduce the amount of friction, a lubrication of glass wall was done before sand deposition. Moreover, the effect of sidewall friction is negligible in our experiments as the ratio of the area of contact of sand cake along the sidewall and the mylar base remains close to 0.1 (Souloumiac *et al.* 2012). In the box dry sands of contrasting colours were sieved alternately to develop a layered bed.

Sand beds were deformed by horizontal contraction against a rigid planar buttress in a regionally plane strain condition. The rate of relative basal velocity was 0.3 mm/s. During an experimental run, we continuously recorded the process of sequential thrusting, keeping the camera at a fixed distance from the model. Thrust spacing measured from successive stages were photographed at the instant of initiation of new thrusts along the basal detachment. We conducted experiments with low and high basal friction (μ_b). To obtain low basal friction ($\mu_b = 0.36$), boric powder was sprinkled over the basal surface (mylar paper). For high-basal friction ($\mu_b = 0.46$), we ran the experiments on a coarse (30 mesh) sandpaper base.

The evolution of thrust belts is greatly controlled by synorogenic surface erosion processes (Molnar and England 1990; Willett *et al.* 1993; DeCelles and Mitra 1995; Willett 1999). In this experimental study, we thus considered the erosion process as another controlling factor. Different researchers have modelled synorogenic erosion in different ways (Persson and Sokoutis 2002; Konstantinovskaia and Malavieille 2005). We followed a simple method where the surface erosion was induced intermittently, maintaining a constant surface slope. The present surface topography of an active mountain belt with concomitant surface erosion, e.g., the Himalaya, shows an average slope of erosion-induced topography in the order of 4° (Avouac 2007). Considering this natural setting, we modelled erosion surfaces in sandbox experiments with a slope of around 3° and 4°. However, both sets of experiments yielded similar results. The erosion process was simulated by removing sand from the surface of the growing wedge along a plane with the desired slope (cf. Konstantinovskaia and Malavieille 2005). In this manner we eroded the wedge intermittently in the course of an experimental run, maintaining a constant hinterland elevation at the time of erosion event (figure 3). The hinterland thickness was kept at 3 cm, which scales to about 15–20 km thick crustal section, lying on the basal detachment, a setting similar to the Himalayan tectonic wedge resting on the Main Himalyan Thrust (MHT) (Avouac 2007). Natural orogenic wedges involve simultaneous tectonic uplift and surface erosion. However, we divided an experimental run into a large number of small steps, and introduced surface erosion, as described above, intermittently, which simulated more or less continuous events of tectonic and surface erosion processes in wedge development. It may be recalled that eroded materials from the elevated landmasses in mountain belts do not entirely run out from the system, but a fraction of eroded materials get deposited in front of the growing orogenic wedge,

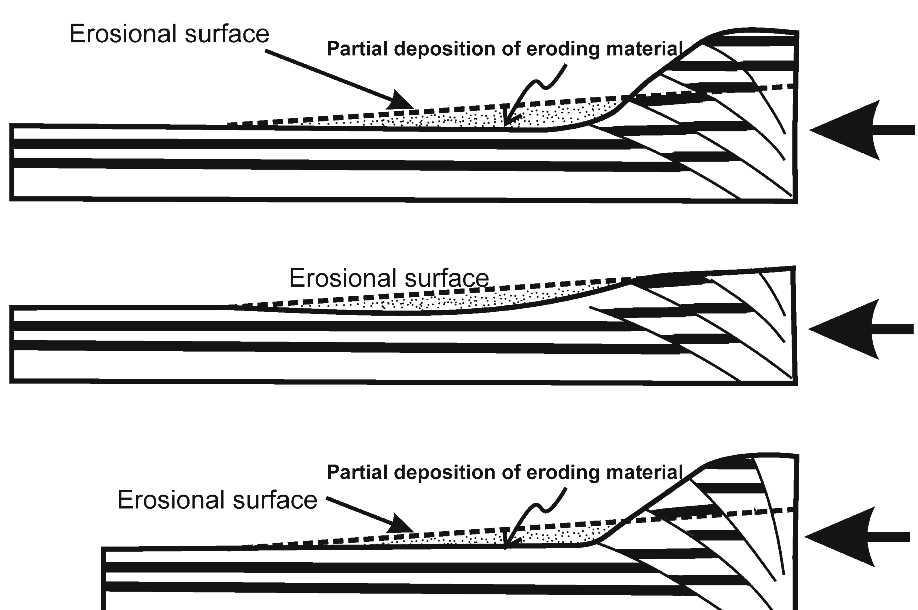

Figure 3. Modelling of surface erosion in sandbox experiments. Dash line indicates the surface following erosion of the wedge.

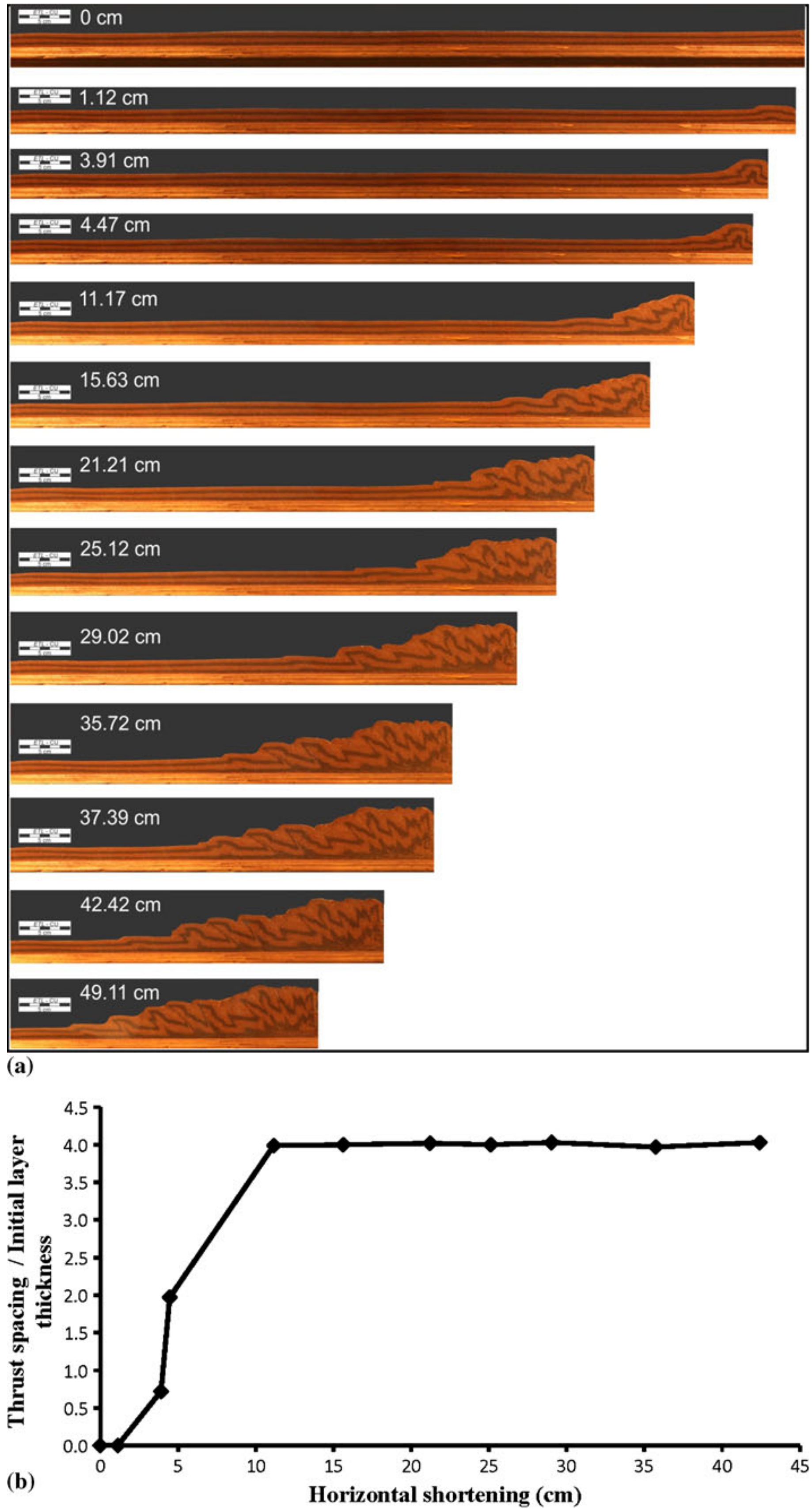

Figure 4. (**a**) Sandbox model showing Style I progression in wedge with low basal friction ($\mu_b = 0.36$). Surface slope, $\alpha = 0$ and basal slope, $\beta = 0$. (**b**) Plot of consecutive thrust spacing as a function of bulk shortening in the model.

as reflected from alluvial deposits of the Indo-Gangetic Plain in front of the Himalayan wedge (Avouac 2007). To simulate such natural system, some of the eroding materials was thus allowed to deposit on the wedge front to maintain a uniform surface slope of the wedge following the erosion (figure 3).

3. Model results

We investigated the styles of thrust progression in sandbox experiments, considering different combinations of basal slope (β), surface slope (α) and basal friction (μ_b). In a set of experiments, the sand bed had a uniform thickness ($\alpha = 0$ and $\beta = 0$) (Dahlen 1984; Mulugeta 1988; Mulugeta and Koyi 1987, 1992; Mandal *et al.* 1997; Bose *et al.* 2009). We also ran experiments on tapered sand beds with either an initial surface slope ($\alpha = 1$–$3°$) or a basal slope ($\beta = 1$–$2°$). The objective of these experiments was to find out geometrical and physical conditions that govern the style of frontal thrust progression. For convenience, we present below separately the experimental results describing the conditions necessary for styles I, II and III progression.

3.1 *Style I thrust progression*

A set of experiments was performed without any surface erosion in the sandbox models. Thrust progression took place in Style I when the basal and

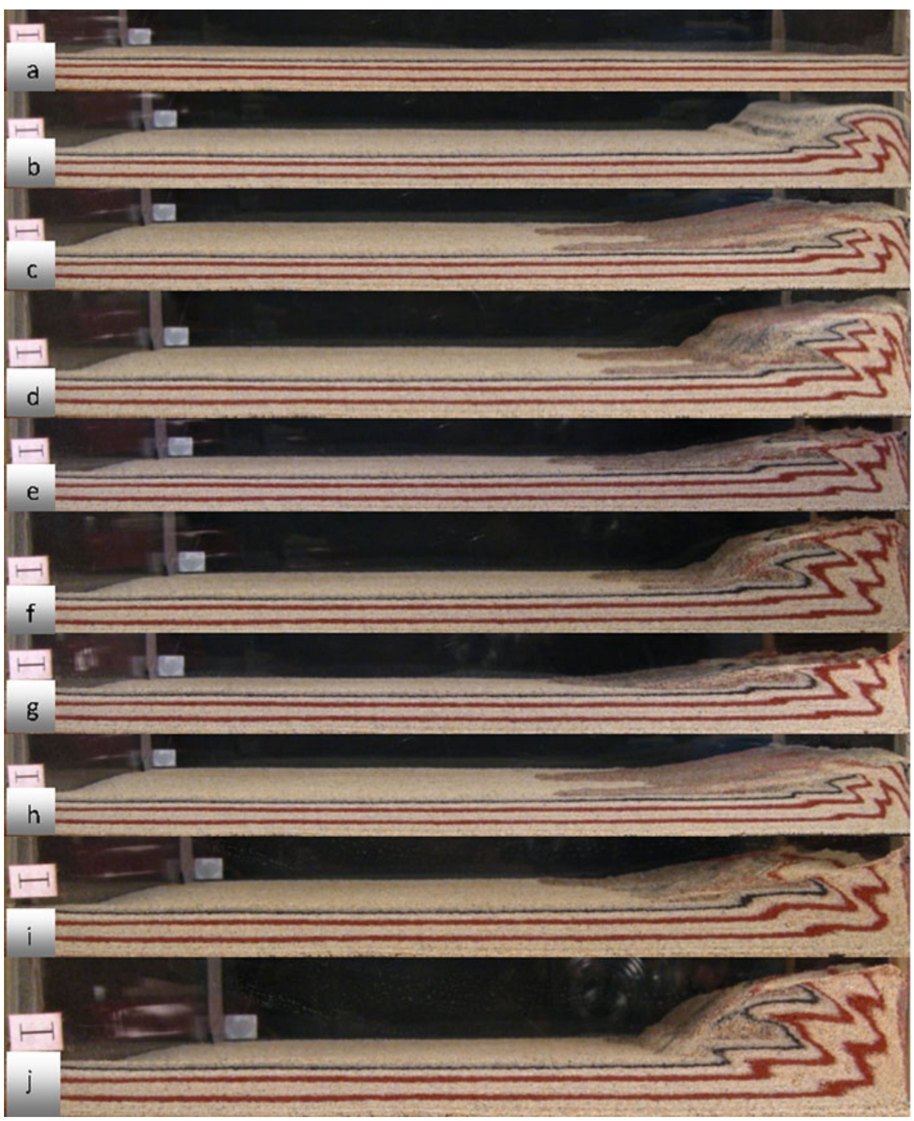

Figure 5. Style I thrust progression in models with high basal friction ($\mu_b = 0.46$), undergoing concomitant surface erosion. $\alpha = \beta = 0$. Scale bar: 1 cm.

surface slopes were simultaneously zero (i.e., $\alpha = 0$, $\beta = 0$) and the basal friction was low ($\mu_b \sim 0.36$). At the initial stage successive frontal thrusts formed at a narrow spacing. However, later thrusts increased their spacing, but immediately attained a stable spacing, forming a Style I sequence (figure 4a and b). For the same geometrical condition, the thrust style for high basal friction ($\mu_b \sim 0.46$) differed from that described above. Frontal thrust spacing in this case did not stabilize, but continued to increase during forelandward progression, as demonstrated from earlier experiments (Bose *et al.* 2009; figure 3c). However, it turned to show a constant spacing when the wedges underwent intermittent surface erosion, and gave rise to Style I sequence (figure 5).

Low basal friction, in contrast, showed thrust progression quite unsteady when the wedge involved surface erosion. Out-of-sequence thrusting was an active process, following intermittent erosion events (figure 6), as reported also from earlier studies (Konstantinovskaia and Malavieille 2005). Moreover, materials deposited in front of the wedge modified the location of new frontal thrusts, and thereby continuously changed thrust spacing in the sequence.

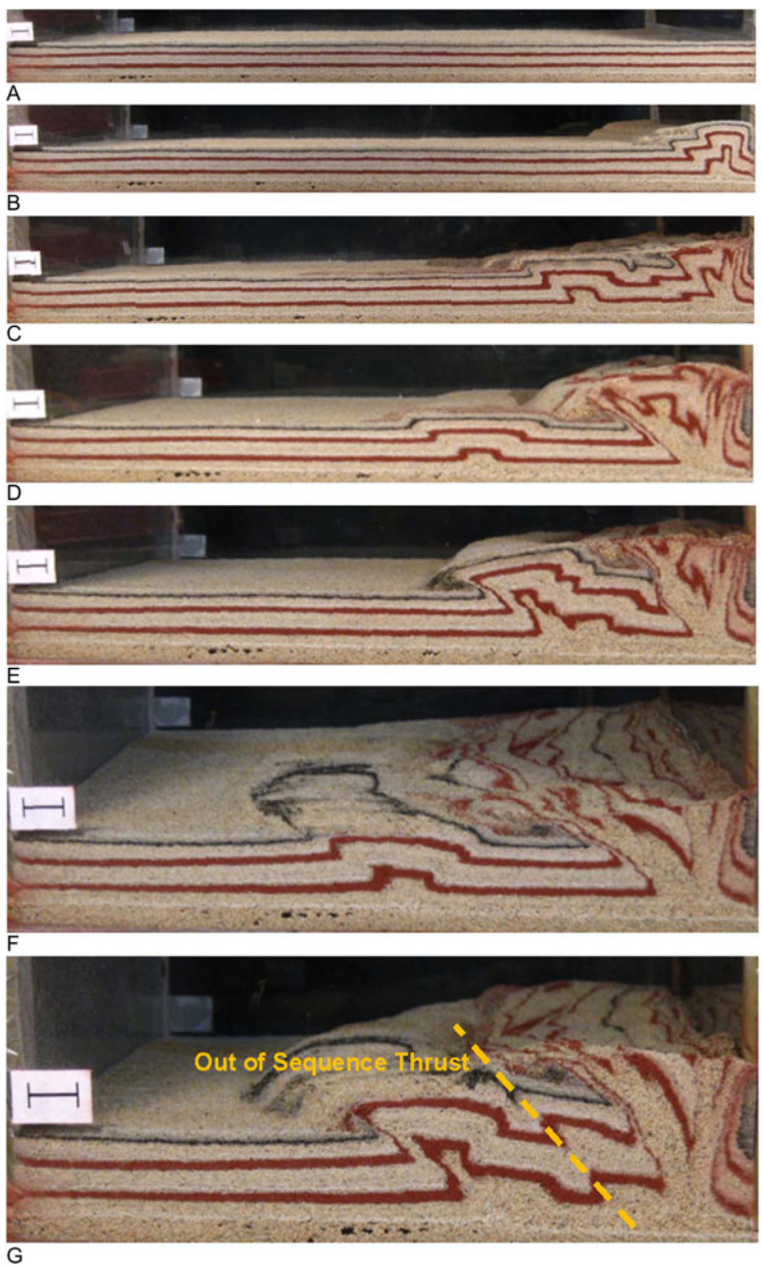

Figure 6. Development of thrusts in sandbox model with low basal friction ($\mu_b = 0.36$), accompanying syn-thrusting surface erosion. Dash line shows location of out-of-sequence thrust. $\alpha = \beta = 0$. Scale bar: 1 cm.

Different conditions of Style I thrust progression are summarized in table 1.

3.2 *Style II thrust progression*

Sandbox models produced successive frontal thrusts with increasing spacing (Style II) only in high-basal friction condition ($\mu_b \sim 0.46$). We first investigated the style of thrust progression for $\alpha = 0$ and $\beta = 0$. This condition gave rise to thrust progression at a close spacing at an early stage, which increased monotonically foreland-ward, showing no tendency of approaching a stable value, in contrast to that observed in low-basal friction condition (figure 7). We ran these experiments with models of different bed thicknesses, and obtained similar fashion of thrust progression. Increasing thrust spacing was noticed both in thin (10 mm) and thick (25 mm) beds. The experimental results indicate that horizontal beds produce wedges with thrust progression in Style II (figure 7a, b), irrespective of initial bed thickness, if the basal detachment has high friction.

High-basal friction conditions showed Style II thrust progression in other settings also. We performed experiments with an initial surface slope ($\alpha = 2°$), where the sand layers progressively thin out in the foreland direction. According to earlier theory and experiments (Mulugeta and Koyi 1987; Mandal *et al.* 1997; Panian and Wiltschko 2007), thrust spacing is directly proportional to bed

Table 1. *Conditions for three styles of thrust progression.*

	No erosion Surface slope (α)		No erosion Basal slope (β)		Erosion
	$\alpha = 0$	$\alpha > 0$	$\beta \sim 0$	$\beta > 0$	$\alpha = 0$ and $\beta = 0$
Low basal friction ($\mu_b = 0.36$)	Style I	Style III	Style I	Style III	Unsteady progression
High basal friction ($\mu_b = 0.46$)	Style II	Style II	Style II	Style III	Style I

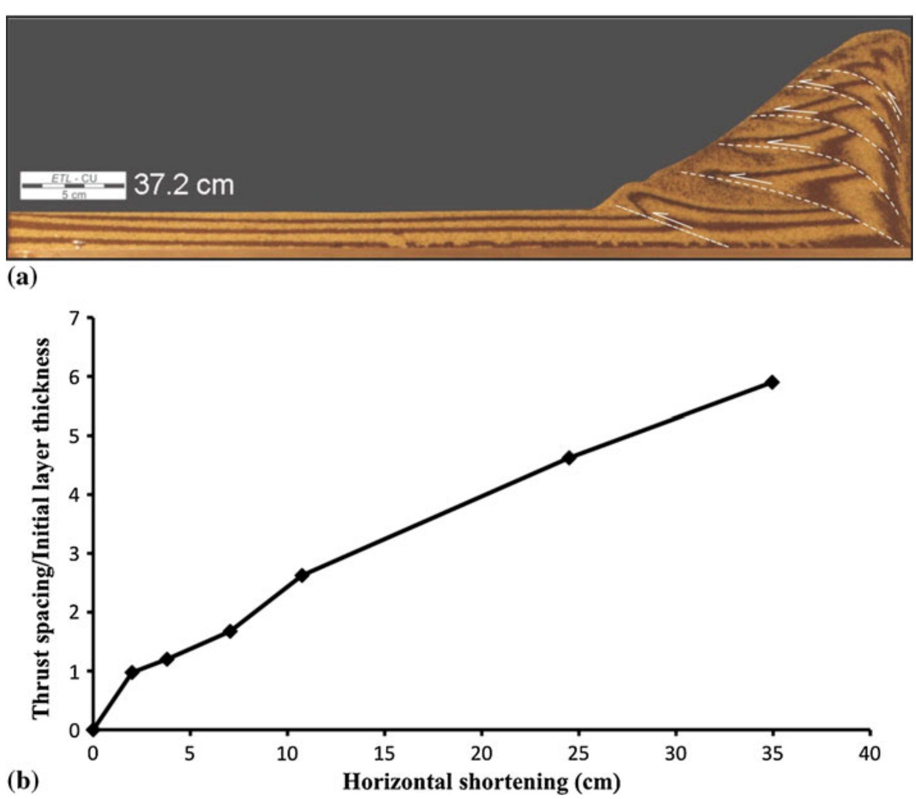

Figure 7. (**a**) Style II thrust progression in sand model with high basal friction. $\alpha = \beta = 0$. (**b**) Plot of experimental data of successive thrust spacing, indicating Style II thrust sequence.

thickness, implying decreasing frontal thrust spacing towards foreland. However, in the present experiments thrust spacing steadily increased even the bed thinned in the frontal direction (Style II progression; figure 8). Thrust architectures produced by Style II progression characteristically consist of low-angle thrusts that are stacked vertically up with increasing spacing.

Wedge models with concomitant surface erosion show that the process of frontal thrust progression takes place with a more or less constant spacing, as in Style I (figure 5). Frontal thrusts abruptly increased their spacing as soon as the erosion process ceased (figure 9). Experimental results suggest that high basal friction can give rise to Style II progression only when the synorogenic erosion process does not cause much denudation of the growing orogenic wedges. The conditions for Style II thrust progression are summarized in table 1.

3.3 *Style III thrust progression*

Experiments showed Style III progression when basal friction was low and α or $\beta > 0$ (table 1). For $\alpha = 0$, frontal thrusts progressed with a constant spacing (Style I) when $\beta = 0$. But, with a small increase in β ($\sim 1°$), the spacing decreased in the course of progression, forming a Style III sequence (figure 10a, b) (cf. Panian and Wiltschko 2007). Experiments with surface slope ($\alpha > 0$), also produced the same style (figure 11a, b). The models produced frontal and back thrusts simultaneously, as documented in many earlier experiments (Persson and Sokoutis 2002). They ramped up from the same location, forming anticlinal structures. They decrease in size in consistent with decreasing frontal thrust spacing.

Models with high basal friction produced this style of thrust sequence only when α or β had large values ($\alpha > 2°$ or $\beta > 0.5°$). However, the degree of variation in thrust spacing reduced in the foreland direction (figure 12).

3.4 *Kinematic analysis of thrust styles*

Experimental results presented in the preceding sections suggest that successive frontal thrusts can form at a uniform (Style I) or a varying horizontal spacing (Style II and Style III). In this section we analyze the three styles in the context of wedge growth. Using experimental data we recognize two

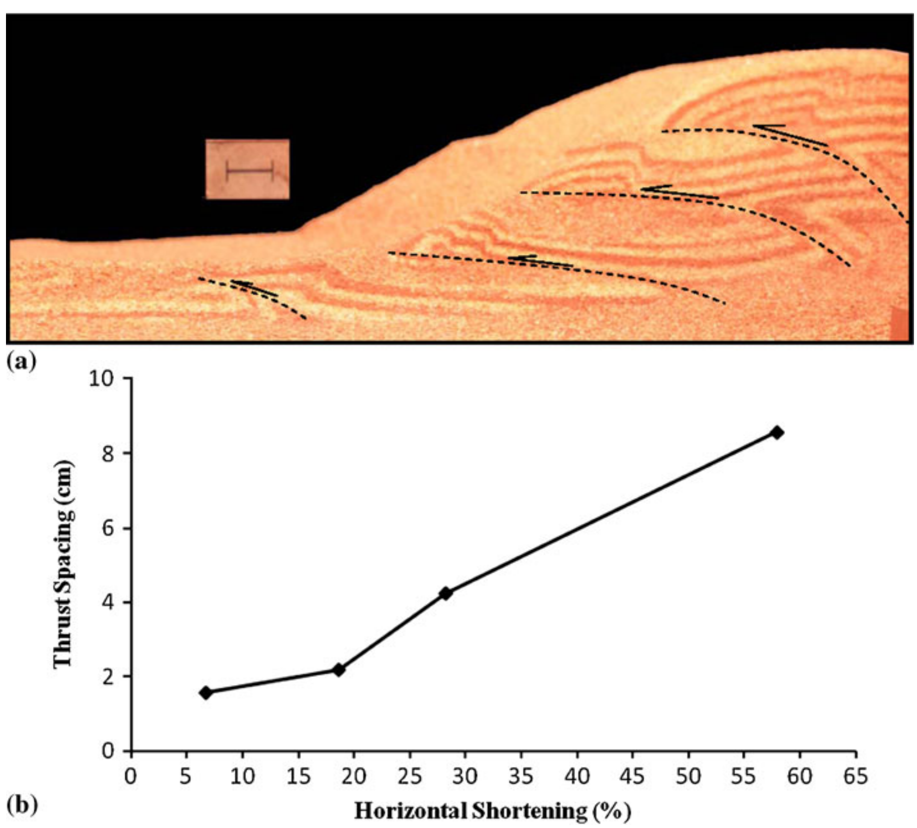

Figure 8. (**a**) Style II thrust progression in sandbox model with high basal friction. $\alpha = 2°$, $\beta = 0$. (**b**) Experimental data of successive thrust spacing, indicating Style II thrust sequence. Scale bar: 1 cm.

Figure 9(a). Abrupt increase in thrust spacing following cessation of surface erosion (see stage 'i' in the figure). Surface slope, $\alpha = 0$ and basal slope, $\beta = 0$.

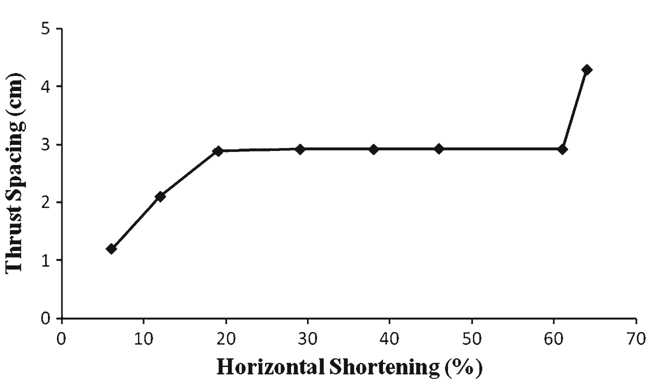

Figure 9(b). Plot of successive thrust spacing with bulk shortening. Note steep increase in spacing following thrust sequence number '9'. Scale bar: 1 cm.

independent parameters: (1) gradient in bed thickness ($\delta H/\delta x$) and (2) change in hinterland elevation ($\Delta H_e/H_e$) at an instant (figure 13). The first parameter is determined by the initial geometrical setting (α and β), whereas the latter parameter depends on several physical factors, such as basal friction, surface erosion. Earlier studies have shown a direct proportionality of thrust spacing with bed thickness (H) (Mulugeta and Koyi 1987; Liu *et al.* 1992; Mandal *et al.* 1997), implying decreasing thrust spacing with decreasing bed thickness in the foreland direction ($\delta H/\delta x > 0$). On the other hand, increasing hinterland elevation ($\Delta H_e/H_e > 0$) causes thrust spacing to increase (Bose and Mandal 2010). Instantaneous thrust

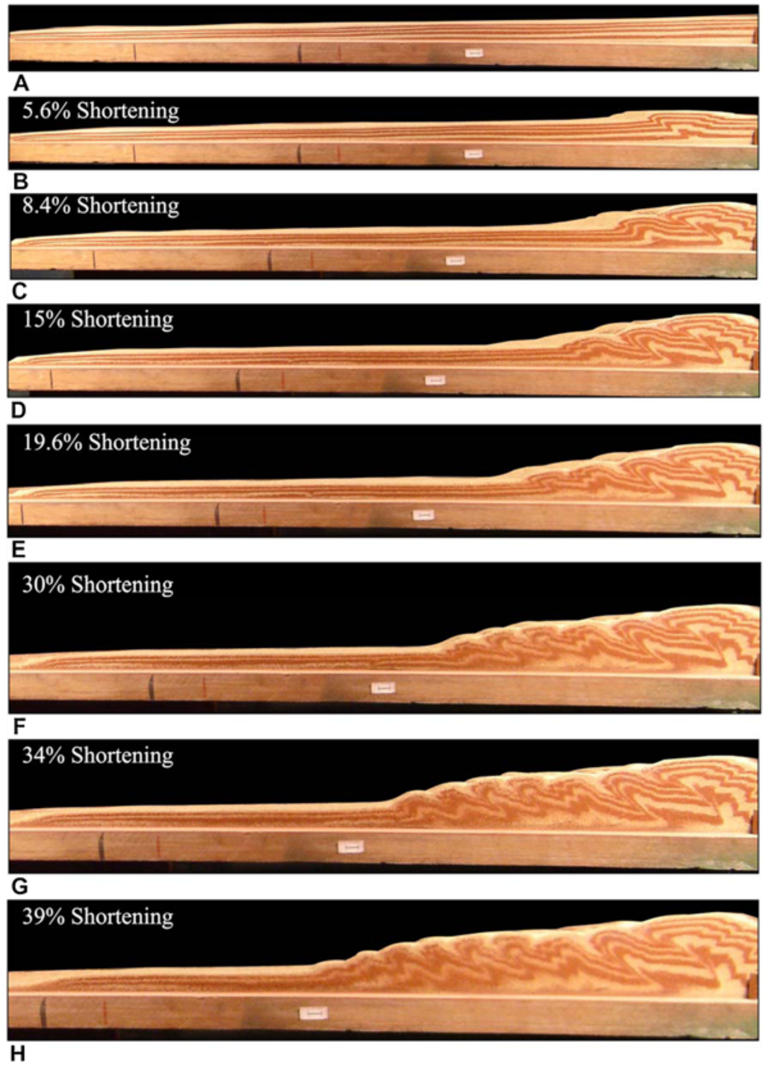

Figure 10(a). Style III thrust progression in sandbox model with low basal friction. $\alpha = 0$ and $\beta = 1°$.

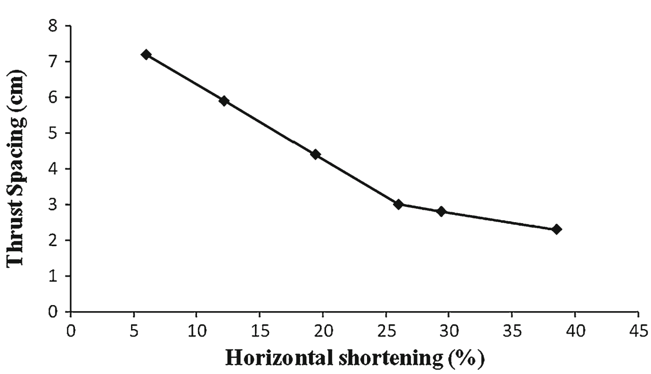

Figure 10(b). Graph showing continuous decrease in thrust spacing in forelandward direction. Scale bar: 1 cm.

spacing will be determined by a combined effect of the two parameters. For example, experiments with initial uniform bed thickness ($\delta H/\delta x = 0$) produced increasing thrust spacing in the high basal-friction condition. This increase in spacing was due to instantaneous increasing hinterland elevation of the wedge.

Based on experimental data, we can show fields of the three styles of thrust progression in a space defined by $\delta H/\delta x$ and $(\Delta H_e/H_e)$ (figure 14). For any positive value of $\delta H/\delta x$, thrust spacing will have a tendency to decrease in the foreland direction (Style III) as a result of decreasing bed thickness. A steady spacing (Style I) can develop only when the hinterland elevation of wedge $(\Delta H_e/H_e)$ grows at a critical rate. Hinterland growth exceeding the critical rate will cause thrust spacing to continuously increase, irrespective of forelandward decreasing bed thickness, and produce a Style II sequence (figure 14). It therefore appears that thrust sequences with uniform spacing (Style I) can develop at a very specific combination of

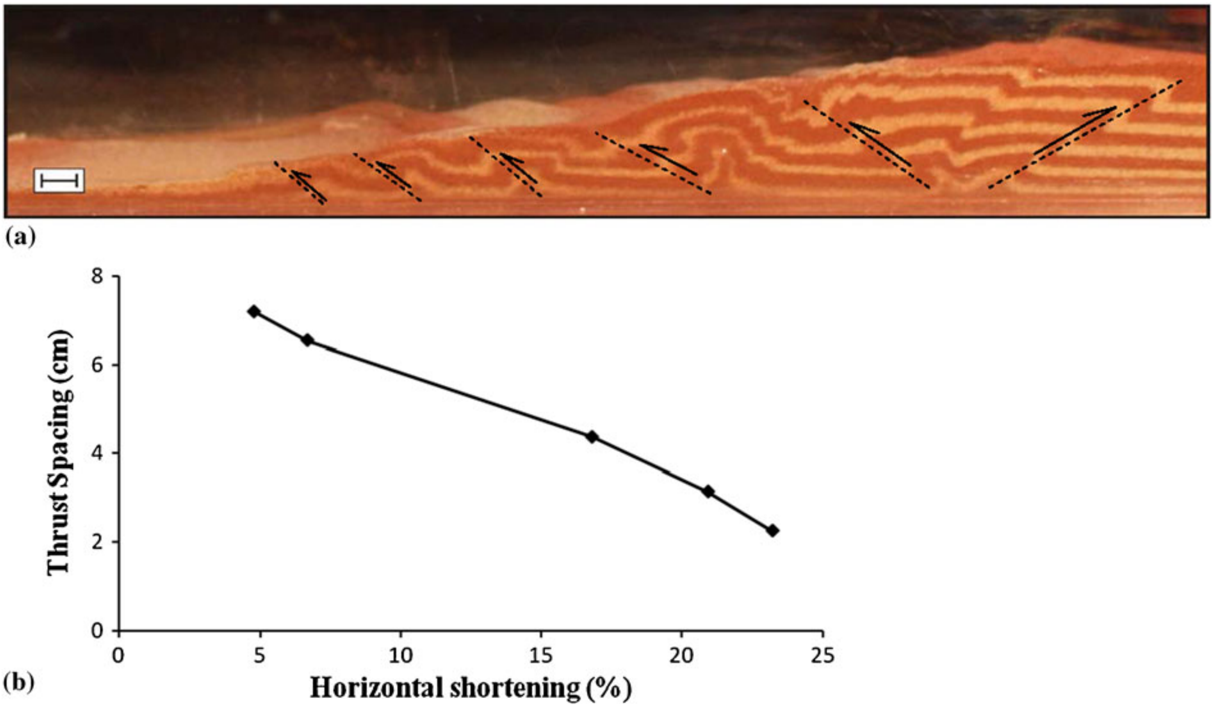

Figure 11. (**a**) Style III thrust sequence in sand model with low basal friction. $\alpha = 2°$ and $\beta = 0$. (**b**) Continuous decrease of thrust spacing with progressive bulk shortening. Scale bar: 1 cm.

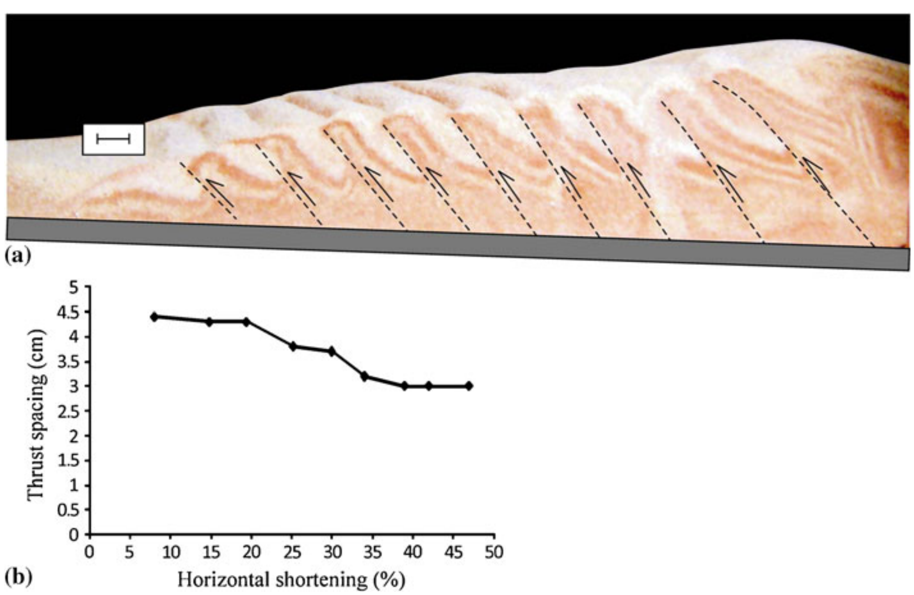

Figure 12. (**a**) Thrust sequences in sandbox model with high basal friction ($\mu_b = 0.46$). $\beta = 2°$, $\alpha = 0$. Note Style III progression in the model. (**b**) Variation of initial thrust spacing in experiments shown in (a). Scale bar: 1 cm.

varying bed thickness and hinterland wedge growth. The present experimental data show that Style II sequence can develop only when the basal slope is generally lower than 0.5°. Basal slopes exceeding this value produced Style III. This study is based on limited ranges of basal and surface slopes. Our analysis presented here is valid for low surface or basal slopes. The mode of frontal thrust progression can change dramatically, and it does not follow a typical style of sequential thrusting, as observed in monovergent wedges for large basal slopes. We address this issue separately elsewhere.

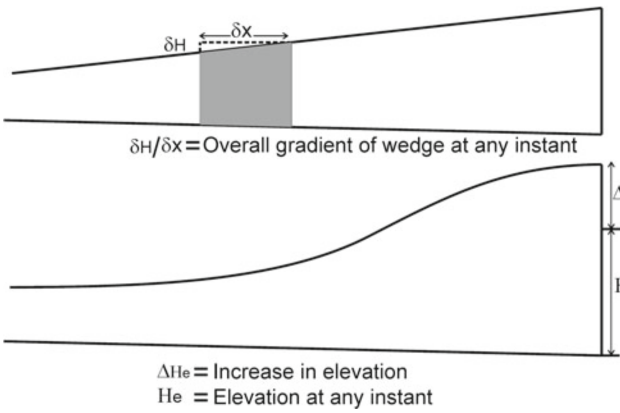

Figure 13. Consideration of wedge parameters for the analysis of thrust styles. $\delta H/\delta x$ is the forelandward gradient of bed thickness and $\Delta H_e/H_e$ is the normalized increase of hinterland thickness of the wedge at any instant.

4. Discussion

In thrust tectonics, it is of great importance to understand the role of physical, such as basal friction, basal velocity conditions (Mulugeta and Koyi 1987; Mandal *et al.* 1997; Willett 1999; Bose *et al.* 2009) and geometrical parameters, such as basal slope, surface slopes and backstop configuration (Persson and Sokoutis 2002). For example, earlier sandbox experiments show that low basal friction promotes formation of back thrusts, and reduces the taper of tectonic wedges (Mulugeta 1988; Liu *et al.* 1992; Mandal *et al.* 1997). It is thus possible to use thrust sequences with abundant back thrusts as an indicator of low basal friction (<0.36). Similarly, bivergent thrust wedges enable us to recognize the backstop geometry (Persson and Sokoutis 2002) or a singularity of the basal velocity condition (Willett 1999; Storti *et al.* 2000). Sandbox experiments show that vertical backstop produces monovergent wedges, which turn to be bivergent as the backstop verges towards the hinterland (Persson and Sokoutis 2002). Recent studies demonstrate that synorogenic surface erosion can promote out-of-sequence thrusting, resulting in localization of exhumation of deeper level rocks to the surface (Konstantinovskaia and Malavieille 2005). Such a geological setting one can use as an indicator of active erosion during the evolution of mountain belts. Along this line of study, we aim to demonstrate how one can use varying frontal thrust spacing as an additional parameter in estimating, at least qualitatively the geological factors mentioned above.

We have classified thrust sequences broadly into three styles, Style I: frontal thrust progression at constant spacing, and Style II and Style III: frontal thrust progression with increasing and decreasing thrust spacing, respectively. According to our experimental results, Style II sequences always develop in high basal friction conditions; even the bed maintains uniform thickness laterally (figure 7). The variation of thrust spacing in Style II becomes stronger with increasing basal friction (Liu *et al.* 1992; Mandal *et al.* 1997; Bose *et al.* 2009). We suggest that Style II thrust sequences can be used as an indicator of basal detachment with high basal friction. On the other hand, Style III thrust sequences developed in varied conditions, which are determined by a combined effect of basal friction and laterally varying bed thickness. Their interpretations demand additional geological information, such as basal slopes. In case of hinterland-dipping basal slopes, decreasing thickness can cause frontal thrusts to form at narrow spacing, as in Style III (cf. Panian and Wiltschko 2007). However, our experiments with small basal slopes (<0.5°) produced Style II if the basal friction was high (figure 14). Style III sequences can thus be used as indicator of low basal friction only when the basal slopes that are estimated independently

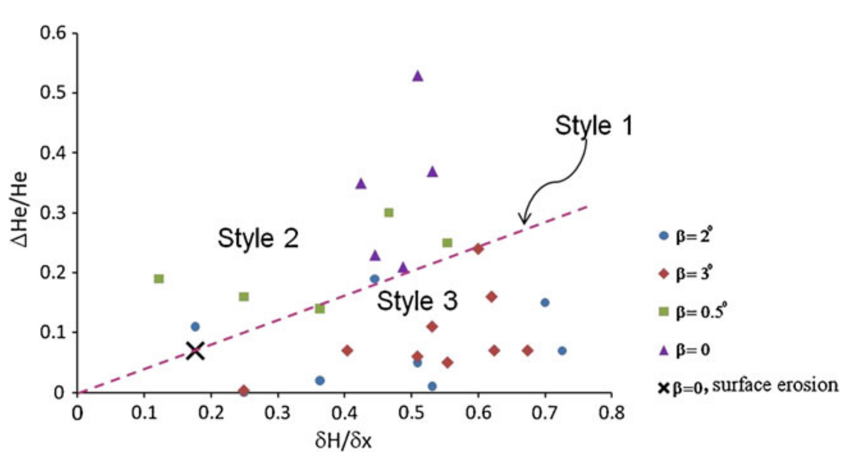

Figure 14. Plot of experimental data showing the fields of Style II and Style III thrust progression in a space defined by $\delta H/\delta x$ and $\Delta H_e/H_e$. The dashed line between the two fields represents the condition for Style I thrust progression.

from geological or seismic sections, are found to be low. This criterion will not apply for settings with large basal slopes.

Style I thrust progression was observed in earlier sandbox experiments (Mulugeta and Koyi 1987; Liu *et al.* 1992; Bose *et al.* 2009). Our experimental findings suggest that this style can develop in varied conditions, the interpretation of which is not straight forward. However, it can be shown useful to consider Style I thrust sequences as a potential proxy of specific geological conditions. For example, orogenic belts with little or no basal and surface slopes can show Style I progression under both low and high basal friction (figures 4 and 5). We can, however, recognize low basal friction conditions, considering back thrusts in the sequence. Their absence would indicate high basal friction. Style I can develop in high basal friction only when there is synorogenic surface erosion, the effects of which need to be recognized independently by using some geological criteria, such as localization of exhumation of deep crustal materials (Beaumont *et al.* 2001; Konstantinovskaia and Malavieille 2005).

Several natural fold-and-thrust belts occur on a ductile base, such as evaporites (Philippe 1994). In such settings, the mechanical coupling between the overlying brittle layer and the ductile base is the most crucial factor in controlling the progression behaviour of thrusts (Smit *et al.* 2003). However, the effect of brittle–ductile coupling differs from that of frictional base considered in this study. Frontal thrust progression in case of frictional base always occurs steadily in the foreland direction unless there is a concomitant erosional activity. On the other hand, the progression behaviour would be much more complex when the basal resistance is controlled by brittle–ductile coupling. Strong brittle-coupling can only give rise to a regular forelandward thrust progression, as in the case of frictional base. The progression turns to be oscillatory as the coupling becomes weak (Smit *et al.* 2003).

We used models with a uniform surface slope to investigate how the style of thrust progression can change depending upon the inherent topographic slopes in convergent zones. However, the surface topography can be much more complex in natural situations, exerting an additional effect on location of frontal thrust and their subsequent propagation (Marques and Cobbold 2002). In a recent study, Panian and Wiltschko (2004) have shown that the location of thrusting is also guided by the topography formed by earlier thrust ramping. Thus, the spacing of successive thrusts may be controlled not only by the overall slope, but their local variations, such as basal friction, synorogenic erosion and possibly, also due to variations in pore fluid pressure which we have not tested. Further, experimental investigations are required to study the style of frontal thrust progression as a function of laterally varying surface topography. The present result gives a first hand idea about the effect of surface slope on thrust progression. We have considered basal slope as another parameter in the experiments, which was varied between 0 and 2°. Natural fold-and-thrust belts can have much large basal slopes (Leech *et al.* 2005; Bollinger *et al.* 2006). The results of our study are, thus, applicable to tectonic wedges with very low basal slopes.

There are some other limitations in this study.

- Models considered in the experiments were rheologically homogeneous laterally as well as depthwise. On the other hand, the crustal rheology can vary significantly spatially, and influence location of thrust (e.g., Beaumont *et al.* 2001).
- All the experiments were conducted with a vertical buttress. However, thrust styles, particularly those localize in the hinterland part can vary depending upon buttress geometry (Persson and Sokoutis 2002).
- Fluid pressure may have significant control in development of thrust wedges (Cobbold and Castro 1999; Mourgues and Cobbold 2006), which has not been considered in our experiments.

5. Conclusions

- Frontal thrusts in orogenic wedges can progress in three styles: Style I – progression with uniform thrust spacing; Style II and III – progression with increasing and decreasing thrust spacing, respectively.
- Style II thrust progression occurs only when the basal friction is high. It can be used as an indicator of high basal friction.
- Thrust progression takes place in Style III if the convergent belts have significant basal slopes, irrespective of basal friction.
- Style I thrust sequences are indicators of the following initial conditions: (1) horizontal basal decollement with low friction without any initial surface slope and surface erosion, or (2) horizontal basal decollement with high basal friction and surface erosion.
- Surface erosion causes unsteadiness in frontal thrust progression, involving out-of-sequence thrusting when the basal friction is low.

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