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Discussion

Experimental insights on the geometry and kinematics of fold-and-thrust belts above weak, viscous evaporitic décollement; a discussion

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Costa and Vendeville (2002) report the results of four sand models shortened above a viscous detachment, to study external edge effects on the development of thrust belts. Costa and Vendeville (2002) miss the focus of an article by Cotton and Koyi (2000) when they write "The experiments we present in this article suggest that the pattern of forward fold-and-thrust propagation observed in Cotton and Koyi's experiments does not occur in plain-stress, plain-strain models, where the influence of lateral friction has been reduced by lubricating the models lateral boundaries". We think that the results of Costa and Vendeville's models are not relevant to our work (Cotton and Koyi, 2000), which studies the effect of an in-built boundary and lateral change in the mechanics of a décollement on the style of deformation. The critique that Costa and Vendeville (2002) have furnished is out of place and far from being an in-depth evaluation of Cotton and Koyi's (2000) work. It seems that Costa and Vendeville (2002) have not appreciated the main conclusion of our work. Below, we will explain why.

Cotton and Koyi (2000) use results of scaled sandbox models shortened from one end to explain the variation in structural development between areas with a viscous detachment and areas without. Their models simulate a natural example in Pakistan; the southern Potwar plateau and Salt Range on one side and the Surghar Range on the other. In this region, similar stratigraphic units are shortened, in the southern Potwar plateau and Salt Range, above a layer of salt (Salt Range Formation) acting as a viscous décollement and, in the Surghar Range, above a reduced salt section or a crystalline basement providing higher friction. Both of these areas were simultaneously shortened from north to south.

In a lecture in 1854, the French scientist and the father of modern medicine, Louis Pasteur said "In the field of observation, chance favours only the prepared mind". During deformation of 16 models, which were shortened partly above a viscous silicone décollement and partly above a frictional sand décollement, one common feature could not escape Cotton and Koyi's (2000) observation; the part of the model that was shortened above the viscous décollement propagated further and faster than the part that was shortened above the frictional décollement. The difference in deformation style above frictional and viscous décollements have been known and acknowledged before (e.g. Davis and Engelder, 1985). However, in our models, since the two décollement types were in the same model, the effect of the differential propagation was more profoundly displayed; it resulted in formation of a deflection zone between the two areas. Cotton and Koyi's model results anticipate the generation of inflection zones within fronts of fold–thrust belts as a result of lateral changes in detachment rheology. In Cotton and Koyi's models, the external boundary effect was limited to the areas immediately adjacent to the side of the models, whereas their conclusions were based on observations from the middle of the models furthest from the lateral boundary effect (Fig. 1). Hence, formation of the deflection zone between model viscous and frictional décollement domains was not affected by the friction along model side-boundaries, which, judging from the deformed surface markers, only affected 1/10th to, at most, 1/7th of the model which was 30 cm wide and on average 3 cm thick.

Costa and Vendeville's (2002) inference that Cotton and Koyi's (2000) finding would be affected by friction along the side walls of the wide models is demonstrably untrue.

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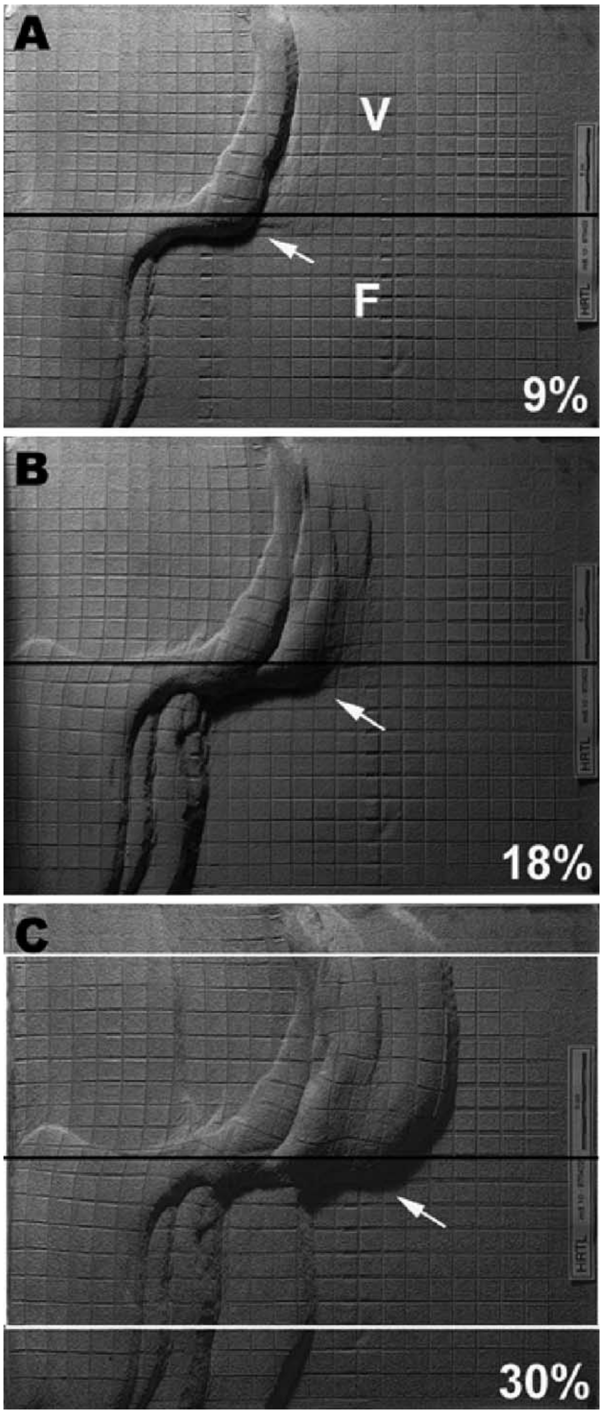

Fig. 1. Top views of three different stages of a model shortened, from left to right, above adjacent viscous (V) and frictional (F) décollements. The black line marks the initial boundary between viscous–brittle décollements. The white lines in C indicate the extent of the affect of the external lateral boundary. Note that the deflection zone (arrowed) is in the middle of the model along the ductile–brittle boundary and unaffected by friction along the external lateral boundary of the experiment. The scale bar is 6 cm.

Since 2000, wider models (60 cm), where the friction from the external lateral boundaries is even less significant on the middle part of the model, have been prepared and shortened partly above a viscous décollement and partly above a frictional décollement (Bahroudi and Koyi, 2003). Similar to Cotton and Koyi's (2000) models, these wider models also show that deflection zones develop between the two areas of different décollement types (Figure 4 in Bahroudi and Koyi, 2003).

Many natural 'viscous' detachments change gradually or abruptly to a frictional or less viscous décollement due to facies and/or simply thickness change (e.g. Zagros, Salt Range and Potwar Plateau). When present, such internal boundaries play a significant role in the deformation style of an area. The deflection zone formed in our models is known from the Salt Range in Pakistan and is also expected to have developed in the Zagros fold–thrust belt, where part of the belt is shortened above a thick layer of Hormuz salt, which pinches out northwestward from an internal boundary, resulting in shortening on two décollement types along the belt (Kent, 1979; Koyi et al., 2000; Bahroudi and Koyi, 2003). In our models, described in detail in Cotton and Koyi (2000), we simulated such an internal boundary, which *was* located in the middle of the models far from the influence of any external lateral boundary, given the thickness of the deformed layers.

During shortening of our models, the push from the rear was transmitted unevenly between the low-friction area represented by the viscous décollement and the high-friction area, resulting in differential propagation of the deformation front (Fig. 1). This differential propagation was obvious even at the early stages of model deformation (Fig. 1A). With continued shortening, the deformation fronts propagated further as new imbricates formed, but maintained the difference in their propagation (Fig. 1C).

Costa and Vendeville (2002) should be given credit for re-emphasising the effect of external lateral boundaries and we congratulate them for demonstrating how to minimise the boundary effect in models. However, in the process of emphasising the effect of unwanted and unrealistic external lateral boundary, Costa and Vendeville (2002) seem to have ignored the fact that temporal and spatial boundaries *do* exist in nature and play a significant role in the deformation style of an area. It is fair also to underline that the effect of lateral boundaries is rather well known and understood by most modellers. It is a common practice that analysis is made in the part of the model not affected by the external boundaries. Most deformation rigs allow preparing wide 1g models where the effect of lateral boundary is limited to the area adjacent to it. In centrifuge (i.e. high g) models, lateral boundaries are 'lubricated' to minimise the effect of the external lateral boundary (e.g. Harris and Koyi, 2003).

Had Costa and Vendeville (2002) repeated one of our models with no external lateral friction, they could then justifiably compare their results with those presented in Cotton and Koyi (2000). Had they done so, they would have learnt that the external lateral boundary does not affect the outcome of such a wide model. They too would have observed a deflection zone formed above the boundary between the frictional and viscous décollements, which is one of the main conclusions of Cotton and Koyi (2000).

Latin lyric poet and satirist Horace has said "In serious works and ones which promise great things; one or two purple patches are often stitched in, to glitter far and wide". Cotton and Koyi's (2000) observation that adjacent décollements with two entirely different mechanical characteristics result in formation of a complicated deflection zone was a 'purple patch' of that article which Costa and Vendeville (2002), unfortunately, seem to have missed.

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Experimental insights on the geometry and kinematics of fold-and-thrust belts above weak, viscous evaporitic décollement: reply to comments by Hemin Koyi and James Cotton☆

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In their comment on Costa and Vendeville (2002), Koyi and Cotton contest some of our statements dealing with their article (Cotton and Koyi, 2000).

Our sentence "The experiments we present in this article suggest that the pattern of forward fold-and-thrust propagation observed in Cotton and Koyi's experiments does not occur in plain-stress, plain-strain models, where the influence of lateral friction has been reduced by lubricating the model's lateral boundaries", regarded by Cotton and Koyi as an 'out-of-place critique', was not written as a demeaning criticism of their work, but was intended merely to explain why and illustrate how folds and thrusts in our models had a drastically different propagation sequence and kinematic history.

The taper and the propagation modes of thrusts in fold-and-thrust belts are controlled by stresses resisting forward advance of the brittle cover. These resisting shear stresses are of two types. The first type of shear stresses are the horizontal shear stresses acting at the base of the cover and associated with sliding above a frictional detachment or gliding above a viscous décollement. The effect of such stresses can be predicted using 2-D computer simulations in dip-oriented cross-sections. The brittle cover responds to shortening by forming a wedge whose width and surface slope angle depends on the magnitude of the basal shear stress. Provided that the length of the décollement/detachment is infinite or very large, folds and thrusts are expected to propagate forward, with younger structures forming in front of older ones. The second type of stresses resisting the advance of the deformation front is related to the third dimension. These are shear stresses acting along any boundaries (whether located within or along the lateral sides of the fold belt) oriented parallel to the direction of transport. Like basal shear stresses, lateral shear stresses resist forward advance of the brittle cover; therefore, their impact on fold-belt evolution is similar: high lateral friction leads to steeper wedge tapers and shorter fold belts.

In numerical models, the influence of lateral shear

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