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Use of fault cut-offs and bed travel distance in balanced cross-sections: Discussion 1

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CRANE (1987), in his short note on section construction in foreland thrust belts, has presented a simple rule that can be used easily and quickly to generate cross-sections. This principle states that, for any bed offset by a thrust fault, the cut-off angles and cut-off lengths are equal in both the footwall and hangingwall. Our concern, and the motivation for writing this Discussion, is two-fold: first, that assumptions inherent in the rule are in most cases contradicted by the available evidence and thus inappropriate; and second, that many geologists do not understand the basic assumptions and limitations, and therefore view any section not conforming to the rule as incorrect. Perfectly balanced and retro-deformable sections can and generally should be drawn with unequal cut-off lengths and angles (Fig. 1), yet will inevitably be criticized as invalid by some geologists.

Crane's method should generally be applied only where faults run parallel to bedding between two ramps, i.e. when the cut-off angle equals zero. Assuming no differential shortening between the hangingwall and footwall due to pressure solution, detachment folds, etc., the length of the footwall flat must be matched in the corresponding hangingwall flat. Failure to honor this condition, which is essentially the stipulation of constant line length, can lead to the construction of unbalanced and incorrect cross-sections. In the case of ramps, however, the actual cut-off angles and lengths need not be equal (Fig. 1a & b). Different values merely represent different amounts of net angular shear strain in the footwall and hangingwall. As noted by De Paor (1987), if bed thickness is kept constant (a basic assumption in both Crane's and our discussion), then the following relationship must hold (where L is the cut-off length, θ is the cut-off angle, and F and H refer to the footwall and hangingwall, respectively; Fig. 1a):

$$L_F \sin \theta_F = L_H \sin \theta_H.$$

There are two assertions in Crane's paper which we feel require discussion: (1) application of his rule minimizes the total amount of bedding-parallel slip in a fold, resulting in net interbed slippage approaching zero (p. 244); and (2) cross-sections which obey his rule are usually balanced.

Bedding-parallel slip

Crane suggests that as layers move through a ramp system, the sequence of folding and unfolding results in the net interbed slip approaching zero. It is important to distinguish, however, between different portions of the ramp anticline. If the forelimb has no net slip, as is required when cut-off angles and lengths are kept fixed, then the remaining portions of the fold must be sheared. In fact, significant bedding-parallel shear is clearly shown by the originally layer-perpendicular loose line marked with black boxes in Crane's fig. 1. Near bedding-perpendicularity for his dotted axial-plane marker lines has apparently been interpreted to indicate the presence

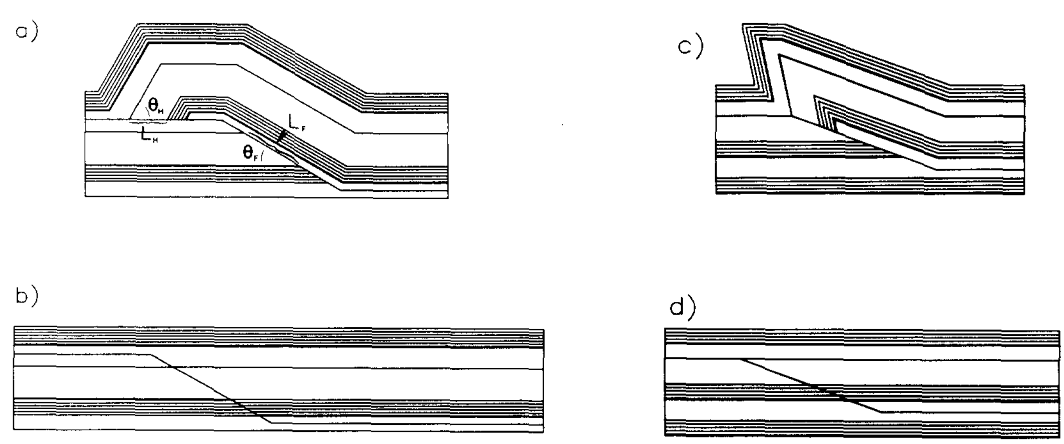

Fig. 1. Examples of balanced structures with unequal cut-off lengths (L) and angles (θ): (a) fault-bend fold (after Suppe 1983) and (b) its restoration; (c) fault-propagation fold (after Suppe 1985) and (d) its restoration. Figures drawn and restored using GEOSEC-20(TM).

of only small shear strains. However, these markers did not initiate as layer-perpendicular loose lines in the undeformed state: since each axial-plane marker originated at an angle to bedding, their eventual near perpendicularity requires sizeable layer-parallel shear.

That flexural flow is necessary in the hangingwall if bed thickness and area are to be maintained is not in itself a detraction from Crane's model. Although he suggests interbed slippage is uncommon in those portions of thrust belts where alternating competent and incompetent units occur (i.e. the major portions of thrust belts), this does not appear to be the case. Evidence for significant bedding-parallel shear, usually accommodated by slip on mesoscopically discrete planes, is virtually ubiquitous in folds within the portions of thrust belts under consideration (e.g. Price 1967, Chapple & Spang 1974, Mitra *et al.* 1984, Casas & Munoz 1987 and many others). Nonetheless, the implicit assumption that net interbed slip in forelimbs approaches zero is a critical postulate, and one which is difficult to reconcile with the observation that anticline forelimbs are often the most intensely deformed limbs (e.g. Allmendinger 1981, Evans & Craddock 1985, Marshak & Engelder 1985, Mitra & Yonkee 1985).

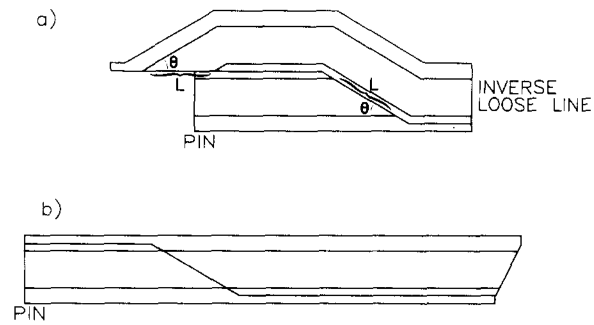

Fig. 2. Restoration of fold with equal cut-off lengths and angles: (a) deformed state (from Crane 1987, fig. 1d); (b) computer-drawn (GEOSEC-20(TM)) restoration showing that the inverse loose line restores to an angle of about 27° from the perpendicular (the inverse shear strain profile).

Cross-section balancing

One of Crane's fundamental arguments for using his rule is that it facilitates the construction of balanced cross-sections. Yet this is not generally true. In addition to significant shear strains within the fold itself, the hindward hangingwall flat experiences a net layer-parallel shear in his model. Figure 2 is a replication of Crane's fig. 1 and its computer-drawn line-length restoration, showing that it is *not* balanced according to the imposed restrictions: an inverse loose line does not restore to perpendicularity. In other words, layer-parallel simple shear must be applied to the hindward hangingwall flat during thrusting in order to achieve this geometry. This is in direct contradiction of Crane's basic assertion of minimal interbed slip, although it should be noted that it is possible such a simple-shear component can be imposed on the thrust sheet and carried through the hangingwall ramp (e.g. Elliott 1977, Coward & Kim 1981, Fischer & Coward 1982, Suppe 1983).

Crane's rule also assumes conservation of displacement along faults, a commonly misapplied section construction technique (see Elliott 1977). As Crane acknowledges, this is clearly impossible for a blind thrust, where displacement must decrease towards the tip, at which point shortening is wholly accommodated by folding or other mechanisms (e.g. Dahlstrom 1969, Chapman & Williams 1984, 1985, Evans & Spang 1984). For example, the fault-propagation fold model of Suppe (1985) shows unequal cut-off lengths and angles, yet by definition is perfectly balanced (Fig. 1c & d). Displacement variation is also inherent in ramp-flat geometries; the problems which arise in section balancing when displacement is preserved have been discussed by Woodward *et al.* (1985, pp. 89–91).

DISCUSSION

Assuming horizontal footwall strata, Crane's rule equates anticlinal forelimb dip with the footwall cut-off angle. Because mechanical arguments generally constrain this angle to be less than about 30–35° (e.g. Dahlen *et al.* 1984), the model's applicability is severely limited. Furthermore, the rule generally produces symmetrical ramp-anticlines, which are uncommon and have been shown to be accompanied by either imposed simple shear or thinning of beds in the forelimb (Suppe 1983, Jamison 1987, Usdansky & Groshong in revision). These limitations are critical, as differences in forelimb dips (which are scale independent) greatly affect the geometry and viability of the section.

While certainly allowing a quick interpretation, Crane's rule would appear to force geometric constraints on cross-sections which are not supported by field evidence. We do not agree that errors resulting from use of the rule are "much less than other possible errors in interpretation" (Crane 1987, p. 244). Although the balancing errors generated in applying Crane's rule to an individual structure may be arguably small, such errors propagate to adjacent structures and are cumulative.

Finally, it must be stressed that cross-sections that do not obey Crane's rule are not necessarily incorrect (Fig. 1). Only a complete line-length or area restoration of a cross-section will show whether or not the section is balanced and viable, and thus a potentially correct interpretation.

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