Use of fault cut-offs and bed travel distance in balanced cross-sections: Discussion 2

DAVID A. FERRILL

Department of Geology, The University of Alabama, Tuscaloosa, AL 35487, U.S.A.

CRANE (1987) raises some important points about balanced cross-section construction including the usefulness of applying geometric models and simplifying assumptions for constructing restorable sections. However, he makes some assumptions which are untenable with regard to many documented fold-thrust belts: for example, the generalizations that "in fold-belts with alternating competent and incompetent rocks, ramp-flat geometry works as a basic assumption", and that "when applied with geometrical precision, nearly all of a thrust belt can be satisfactorily interpreted". Crane's discussion of faults with ramp-flat geometries and the resulting fault-bend folds proceeds without acknowledging the occurrence of other fold types in fold-thrust belts.

Macroscopic folds in fold-thrust belts can generally be included in one of three categories: (1) fault-bend folds (Suppe 1983); (2) fault-propagation folds (Suppe 1985); and (3) buckle folds (Nickelsen 1963, Laubscher 1977). Documentation by previous work on folding in fold-thrust belts indicates that folds cannot simply be assumed to be related to faults with ramp-flat geometries.

Crane states that "ramp-flat geometry requires that three basic principles be applied in interpretation". Principles 1 (thrust faults cut up-section in the direction of transport) and 2 (thrust faults place older beds on younger beds) describe widely recognized and extensively documented characteristics of thin-skinned fold-thrust belts (see references in Boyer & Elliott 1982), although there are exceptions. However, principle 3, which states that "the cutoff angle on hangingwall and footwall and the distance a fault travels within a bed will not change during thrusting", is neither a requirement for a ramp-flat fault geometry nor a requirement for cross-section restoration (Suppe 1983, Williams & Chapman 1983). The statement by Boyer & Elliott (1982, p. 1225) that "in the undeformed state, the footwall and hangingwall cutoff must coincide" is more general and allows for modification of the hangingwall and footwall.

The assumption for principle 3 of "no interbed slippage or significant strains" is unreasonable because layer-parallel simple shear (e.g. interbed slippage, flexural-slip or flexural-flow) and/or some other internal strain mechanism are necessary to produce any tectonic fold (e.g. Sanderson 1982, Ramsay & Huber 1987, and references within). Additional strains are common in most fold-thrust belts (e.g. Alvarez *et al.* 1978, Mitra & Yonkee 1985, Morley 1986, Woodward *et al.* 1986). One noteworthy example is the Central Appalachian Valley and Ridge Province of West Virginia where layer-parallel shortening strains of 15–20% (Ferrill & Dunne 1986) have been determined for exposed Siluro-Devonian strata within the Hanging Rock–Cacapon Mountain Anticlinorium. The Broadtop Synclinorium, adjacent to and west of the Hanging Rock Anticlinorium, contains gas fields producing from the same Siluro-Devonian stratigraphy (Jacobeen & Kanes 1975), illustrating the occurrence of significant strains in a hydrocarbon producing foreland fold-thrust belt. This and other examples (e.g. Herman & Geiser 1985) show that balancing cross-sections through the Central Appalachian Valley and Ridge Province requires the incorporation of strain data.

Crane violates his assumption for principle 3 of "no interbed slippage or significant strains" three times within the text by: (1) describing the fault-bend folding process as occurring with "accompanying bedding-plane slippage"; (2) stating that "interbed slippage necessarily

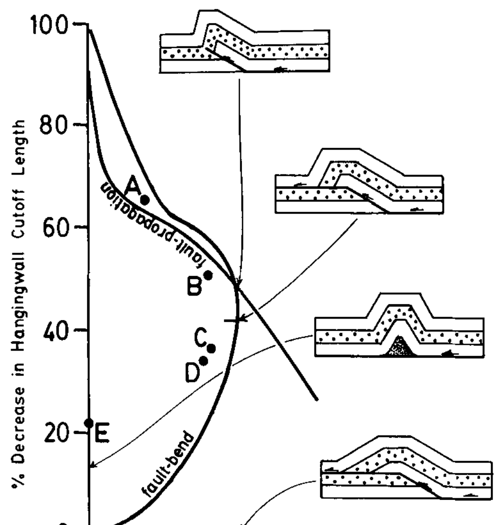

Fig. 1. The per cent decrease in hangingwall cutoff length is plotted vs the footwall cutoff angle to compare Crane's model with Suppe's models for fault-bend (Suppe 1983) and fault-propagation (Suppe 1985) folding, as well as some documented well-exposed natural examples of anticlines in foreland fold-thrust belts. Crane's model plots along the horizontal axis at 0% decrease in hangingwall cutoff length. Suppe's models plot in the field of the graph and are labelled fault-bend (representing fault-bend folds where the footwall cutoff angle equals the change in fault dip at the top of the ramp; mode 1 fault-bend folds plot below 42% decrease in hangingwall cutoff length, mode 2 folds plot above 42%) and fault-propagation. The natural examples are from the Idaho–Wyoming thrust belt, the Southern Appalachians, the Variscan of England and the Jura. A = fig. 6(b) in Boyer (1986). B = fig. 2(c) in Chapman & Williams (1985), after Lageson (1984). C = fig. 1 in Chapman & Williams (1984). D = fig. 7 in Williams & Chapman (1983). E = fig. 24.7 in Ramsay & Huber (1987), after Laubscher (1962).

occurs as the beds move through the system from syncline to anticline to anticline to syncline"; and (3) stating that "the literature is replete with examples which demonstrate that bed slippage occurs in nearly all fold structures and certainly occurs when beds move up over ramps". As Crane emphasized, and is documented in the literature (e.g. Chapple & Spang 1974), interbed slippage and strain certainly accompany fold development. Therefore, the assumption of "no interbed slippage or significant strain" is neither a necessary nor valid assumption for fault-bend folding.

Crane presents a model for fault-bend folding where the hangingwall and footwall cutoff angles and lengths (bed travel distance) are retained. This model produces a ramp anticline with a forelimb dip equal to the hangingwall cutoff angle, and a backlimb dip equal to the footwall cutoff angle. Crane's fig. 1(b) violates the description of the model in the text, and principle 3, because the cutoff angles in the hangingwall and footwall are not equal. The ramp-anticline forelimb is dipping at 45°, reflecting a 45° hangingwall cutoff angle, and the backlimb dip is 30°, reflecting a footwall cutoff angle of 30°.

An alternative to Crane's model is a fault-bend fold model presented by Suppe (1983) which allows bedding plane slip and is constrained by (a) preservation of layer thickness, (b) no net distortion of horizontal layers and (c) conservation of bed lengths. The fold is the product of moving the hangingwall over a non-planar fault surface. The resulting fault-bend fold is asymmetric (e.g. 60° forelimb dip and 30° backlimb dip for a fault-bend anticline with 0° flat segments and a 30° footwall cutoff angle). The hangingwall cutoff angle is dependent upon the footwall cutoff angle, the fault bend angle, and the axial angle. Figure 1 is a graph showing the per cent decrease in hangingwall cutoff length plotted versus footwall cutoff angles for Crane's model, Suppe's models for fault-bend and fault-propagation folding (Suppe 1983, 1985), and five natural examples of thrust fault related folds. Crane's model plots along the horizontal axis at 0% decrease in hangingwall cutoff length, and Suppe's models and the natural examples plot in the field of the graph. This figure illustrates that (a) some real examples of thrust-fault related folds in foreland fold-thrust belts (examples from the Variscan of England, the Southern Appalachians, the Idaho–Wyoming fold-thrust belt and the Jura) are not consistent with Crane's model, and (b) Crane's principle 3, and consequently his model, strongly disagrees with Suppe's model which has been successfully used in the construction of cross-sections for Taiwan (e.g. Suppe 1983) and the Appalachians (e.g. Mitra 1986). These observations indicate that retaining cutoff angles and lengths is not a necessity for the construction of viable and admissible cross-sections.

Use of fault cut-offs and bed travel distance in balanced cross-sections: Consolidated reply

RONALD C. CRANE

Chevron Overseas Petroleum Inc., San Ramon, CA 94583-0946, U.S.A.

DISCUSSIONS by both Rowan & Ratliff and by Ferrill of the short note on section construction by keeping fault angle cut-offs and lengths equal (Crane 1987) raise some valid objections about the universal applicability of the method when evaluating the structural style of a specific structure.

The proposed model should *not* be used to explain the details of development of a particular fold. The model is the limiting simplest case as has been pointed out by De Paor (1987), Boyer & Elliott (1982), p. 1225), Rowan & Ratliff and others. This simplest case is critical because it serves as the standard for thrust belt analysis. As is shown by Ferrill (fig. 1), other models can be constructed which fit specific thrust-fold shapes and can be valid for different strains and stratigraphy. These models will plot on Ferrill's graph in different positions, are unique, and thus cannot serve as a worldwide standard.

The advantage of the proposed model is that it allows predictions. The following criteria are fulfilled:

(1) the number of assumptions is limited;

(2) sections are capable of rapid geometrical restorations;

(3) subsurface conditions can be predicted where no primary data exist;

(4) it is widely applicable to all foreland thrust belts;

(5) it allows rapid construction of required numerous cross-sections;

(6) it serves as a standard by which other variables can be investigated to explain departures in form from the ideal norm.

The model predicts subsurface configuration of cutoffs, the placement of faults and existence of potential structures. Because the model is a standard, any deviations from this standard can be instantly recognized.