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SHORT NOTES

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

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Abstract—Successful hydrocarbon exploration in foreland fold-thrust belts requires the preparation of numerous fully balanced cross-sections. Each section must be compatible with neighboring sections. Line balancing on many sections is preferable to balancing on single sections. A series of balanced sections must also be volume balanced if constructed properly. An often overlooked basic principle is that the fault cut-off angle on both hangingwall and footwall, and the angle and distance that a fault travels within a bed will not change significantly during thrusting under simple shear motion assuming no significant interbed slippage. The section must be geometrically correct if it is to have a chance of being geologically correct.

INTRODUCTION

THE CONSTRUCTION of balanced cross-sections in foreland thrust belts is a powerful interpretive tool. It is essential that geometric techniques should be used as the guiding principle and that only valid balanced cross-sections (Elliott 1983) are ultimately acceptable. Restorable and admissible cross-sections can be rapidly constructed if a simple assumption is made in the initial interpretation.

Hydrocarbon exploration in thrust belts requires three-dimensional balancing of extensive surface and subsurface data, both stratigraphical and structural. Within the frontal portions of thrust belts, where hydrocarbon exploration is concentrated, plane strain can be assumed as a first approximation and the effects of strain hardening, minor shearing, bed flowage, etc., can be essentially ignored. Many simplifying assumptions can be used when thrusting post-dates both sedimentation and lithification. Sophisticated area and volume balancing techniques and detailed palinspastic restorations are required when sedimentation is contemporaneous with thrusting and synorogenic sediments are a significant part of the total section, and where interbed slippage is significant.

Successful hydrocarbon exploration requires the preparation of closely spaced (~5–10 km) sections across the entire length of a thrust belt from foreland to hinterland. Each section must be structurally compatible with adjacent sections and all surface and subsurface data should be integrated into a restorable geologic framework. The preparation of tens to hundreds of balanced sections is a monumental task for all but the most experienced interpreter and usually must be accomplished by teams of geologists. Adequate data is usually not available for every section and projections of data from other sections are common. The advantage of a number of sections is that *all* surface and paleontological data must be considered, explained, and integrated into a consistent interpretation.

Balancing methods

Line balancing techniques, when used on numerous adjacent and parallel sections essentially supplant area balancing techniques applied only to a single section. When a large number of sections are prepared and each is constructed to be compatible with adjoining sections, the final series of sections should be volumetrically balanced. The number of constraints on interpretation is increased because the geologist is forced to examine *all* available data. Within limited areas (tens to a few hundred square kilometers), many potentially valid geological interpretations are possible. Only a limited number are permissible when considering the entire thrust belt. A series of individually balanced, compatible sections should be both areally and volumetrically balanced, when completed. Strike sections should be routinely prepared as a check on the validity of the sections. Sea-level geologic maps, or a similar elevation-based map, constructed from the sections to remove topographic effects will identify problem areas.

Structural style

For hydrocarbon exploration, thrust belts can be simplistically divided into types with two end members: one where competent rocks form most of the section with a minimum number of zones of weakness; and the other where incompetent rocks predominate with extensive slippage planes. Both end members of the stratigraphic spectrum are characterized by a style wherein folding and thrusting proceeds simultaneously with extensive interbed slippage. This structural style (defined by Dahlstrom 1969) is not common in parts of major continental thrust belts where alternating competent and incompetent units occur. The style does occur during deformation of thick incompetent wedges of sediments on marine margins, deltas, or continental slope sediments, at depth in thrust belts, and in the near surface where faults die out into folds. Special care in balancing is required (Williams & Chapman 1983).

Ramp-flat geometry

In fold-belts with alternating competent and incompetent rocks, ramp-flat geometry works as a basic assumption. When applied with geometrical precision, nearly all of a thrust belt can be satisfactorily interpreted. Ramp-flat geometry requires that three basic principles be applied in interpretation. Two of these are well known, but the significance of the third has been overlooked in the literature and is responsible for many published geological implausibilities on cross-sections.

Principle 1. Thrust faults cut up-section in the direction of tectonic transport of the hangingwall. Exceptions have been noted in the field and can be explained by several different mechanisms, which may differ depending on original stratigraphy or changing direction of stress fields. The direction of easiest relief determines the actual fault location and not age relationships. Exceptions must be considered and explained during interpretation.

Principle 2. Older beds are thrust over younger beds. This is normal behavior. Examples are documented (e.g. Platt & Leggett 1986) where younger beds can be emplaced over older beds. As in Principle 1, many valid mechanisms can explain these relationships. The basic principle is fundamental to thrust interpretation and exceptions should be documented and explained.

Principle 3. The cut-off angle on hangingwall and footwall and the distance a fault travels within a bed will not change during thrusting. This assumes no interbed slippage, or significant strain.

APPLICATION OF FAULT CUT-OFF

Figure 1(a) shows the future location of a fault trajectory ramping from an incompetent section, up through a competent bed, into another bedding plane thrust. If the development of the folding associated with the ramp is traced in detail during movement, a continuous readjustment of every particle occurs as each part of the bed is first folded and subsequently unfolded with accompanying bedding-plane slippage.

Figure 1(b) shows the initial movement with a synclinal fold (A) forming above the position where the fault flattens into bedding. This fold will migrate forward with little change in shape as thrust movement continues. The original anticlinal fold (B) will unfold, flatten and disappear with additional movement and new migrating anticlinal hinges will form. With additional movement both the synclinal hinge (A) and the anticlinal hinge (B) will migrate forward away from the footwall cut-off ramp position and the distance between the folds will increase to a constant distance and then both hinges migrate as a pair. These are termed the migrating fold pairs of the system (Dahlstrom 1986 personal communication). Fold A will define the hangingwall fault cut-off of the top of the competent member, while fold B will be close to the fault cut-off at the base of the competent member in the hangingwall, when the axial planes of the migrating fold pair have reached a constant distance. An estimate of competent bed thickness can be derived from geometrical principles if the fault cut-off angle, flank dip and distance between hinges is known. A fixed-fold pair (Dahlstrom 1986 personal communication) will form simultaneously. A synclinal hinge (D) will form at the position where the fault begins to cut up through the competent section. This remains fixed in spatial position relative to the footwall ramp cut-off of the base of the competent section and defines the approximate position in the hangingwall of the base of the competent section in the footwall ramp. An initial anticlinal hinge (C) initially forms slightly forward of the syncline and migrates forward until it reaches a position above the top of the competent bed footwall cut-off. It remains fixed and equidistant from the syncline as movement continues. The two hinges define in the hangingwall the footwall cut-offs of the competent bed. The thickness of the competent unit can also be estimated if the distance between hinges, the fault cut-off angle and the dip between the hinges is known.

Figures 1(c) and 1(d) show further development of the system. Interbed slippage necessarily occurs as the beds move through the system from syncline to anticline to anticline to syncline. The curved dotted axial planes reflect earlier positions which have folded and unfolded. A complex series of movements of individual particles occurs but in general the upper part of the section moves forward in the absolute sense slightly more than the lower part within the hangingwall. This must occur when the original cut-off angle rotates from 30° to 0°. All movements have the effect of retaining the original fault cut-off angles and fault travel distance within the competent section. The folding and unfolding sequence minimizes the total amount of interbed slippage. The existence of paired folds contributes to the net interbed slippage approaching zero. It is probable that the fault cut-off angles and fault length within a bed change slightly during thrusting. These changes will depend upon many factors including original stratigraphy, the angle at which the competent bed is cut by the fault, the thickness of the incompetent beds, minor shearing and folding parallel to the major thrust, travel distance of the thrust in bedding below and above the competent member, formation of a ductile bead and other potential modifications. The total effect of slippage, while real, has not been found to be a significant factor in terms of interpreting the section on a larger scale. The assumption error is much less than other possible errors in interpretation.

If the assumption of limited or no change in fault cut-off angles and length of fault travel within a bed is followed, a powerful interpretation tool exists which would not be possible under a rigorous application of bed slippage effects and precise geometry. If the cut-off angles and length are known in the hangingwall, these values can be projected into the subsurface to the foot-

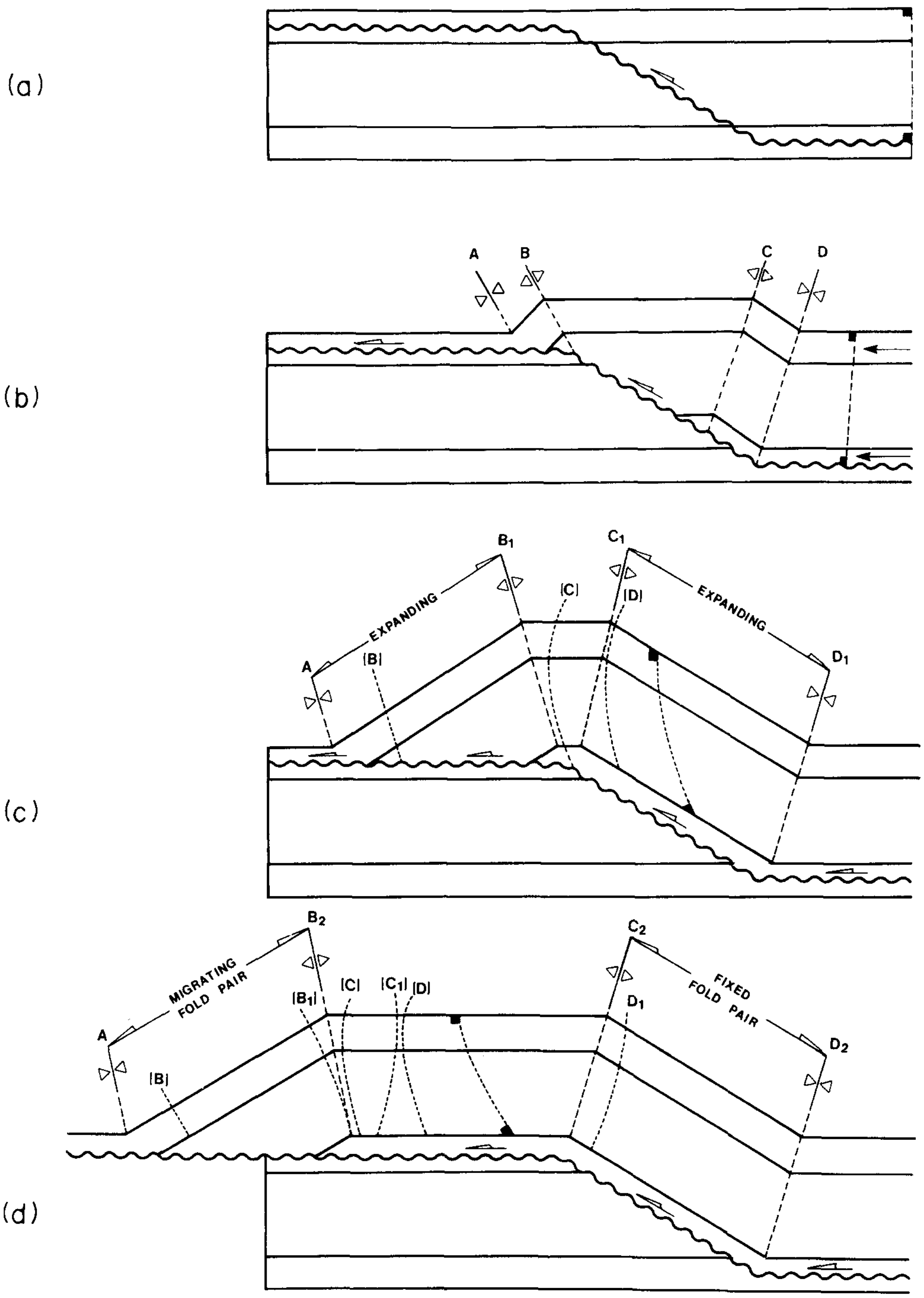

Fig. 1. Ramp-fold development.

wall. If the displacement is known at the surface, then the identical displacement can be used on each unit down section, as long as no further complications such as imbrications or folding occur in a hindward direction on the hangingwall between the fold pairs. As fault cut-off angles and length are matched in the footwall, a unique placement of the fault in the cross-section is achieved. This procedure severely constrains an interpretation. As a first approximation technique, it resolves balancing problems quickly and easily and allows rapid construction of balanced cross-sections. Application of this principle often leads to unexpected interpretations, giving insight into the hidden geology of an area. Because the interpretation is a unique solution, care must be taken not to 'believe' it entirely. The two cardinal axioms must be (1) if the section is geometrically incorrect, it is geologically wrong, and (2) if the section is geometrically correct, it *could* be geologically correct. The advantage of the procedure is that precise predictions can be made which can then be rigorously field checked.

Many difficulties arise when constructing cross-sections across complex thrust belts. The predictability of occurrence of horses, duplexes, overturned slivers under major thrusts, etc., is not possible at the present time. In order to isolate the remaining problems, conscientious application of Principle 3 as a first approximation in constructing sections, along with other standard techniques, will resolve many of the geometric problems of thrust behavior when used in conjunction with an adequate number of sections. Discussions of thrust structures and behavior in the literature indicates that this principle is not often followed. Recent examples are Chapman & Williams (1984, figs. 1 and 2), Tippett *et al.* (1985, fig. 1 from Dahlstrom 1969), etc.

Utilizing bed cut-off angles and fault length matching as a first approximation resolves balancing problems quickly and allows rapid cross-section construction. The major drawback to its widespread application is that interbed slippage cannot be significant. In many thrust belts, not enough real field data is available to determine the extent of bed slippage. 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. The question is whether slippage is of major importance and must be accounted for or whether it can be safely neglected in a first pass interpretation in order to examine the broad structure of the whole thrust belt before returning to the first approximation sections for modification.

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