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The terminology of structures in thrust belts*

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Abstract—A review of structures and geometric relationships recognized in thrust belts is presented. A thrust is defined as any contractional fault, a corollary being that thrusts must cut up-section in their transport direction. 'Flats' are those portions of a thrust surface which were parallel to an arbitrary datum surface at the time of displacement and 'ramps' are those portions of thrusts which cut across datum surfaces. Ramps are classified on the basis of their orientation relative to the thrust transport direction and whether they are cut offs in the hangingwall or footwall of the thrust. Lateral variations in the form of staircase trajectories are joined by oblique or lateral ramps which have a component of strike-slip movement.

An array of thrusts which diverge in their transport direction may form by either of two propagation models. These are termed 'piggy-back' propagation, which is foreland-directed, and 'overstep' propagation which is opposed to the thrust transport direction. An array of thrust surfaces is termed an 'imbricate stack' and should these surfaces anastamose upwards a 'duplex' will result; the fault-bounded blocks are termed 'horses'. A duplex is bounded by a higher, 'roof' thrust and a lower, 'floor' thrust. The intersection of any two thrust planes is termed a 'branch line'.

Thrusts can be classified on the basis of their relationship to asymmetric fold limbs which they cut. A further classification arises from whether a particular thrust lies in the hangingwall or footwall of another one.

The movement of thrust sheets over corrugated surfaces, or the local development of thrust structures beneath, will fold higher thrust sheets. These folds are termed 'culminations' and their limbs are termed 'culmination walls'. Accommodation of this folding may require movement on surfaces within the hangingwall of the active thrust. These accommodation surfaces are termed 'hangingwall detachments' and they need not root down into the active thrust. This category of detachment includes dip-slip 'hangingwall drop faults' which are developed by differential uplift of duplex roofs, and 'out-of-the-syncline' thrusts which develop from overtightened fold hinges. Back thrusts, as well as forming as hangingwall detachments, may also form due to layer-parallel shortening above a sticking thrust or by rotation of the hangingwall above a ramp.

INTRODUCTION

ALTHOUGH the study of thrust belts is by no means a recent activity, there has been a steady increase in interest in thin-skinned tectonics spurred on by work in the foothills of the North American Rocky Mountains. Pioneering research by Bally *et al.* (1966) and other workers was reviewed by Dahlstrom (1970). Drawing on examples largely taken from the Rocky Mountains, Dahlstrom produced a synthesis of the then recognized structures of thrust belts. Since that time these models of thrusting have been applied to numerous other belts and with this has come a plethora of descriptions of structures, such that there no longer exists a commonly used terminology.

This short paper has been prepared in order to initiate discussion of the problem. A recent review by McClay (1981), although not exhaustive, provided some useful definitions. In accordance with McClay's proposal, a thrust is considered to be any contractional fault (Norris 1958) and the rock mass carried upon it is called a thrust sheet. The somewhat broader term 'slide', meaning a synmetamorphic detachment surface or zone, carries no implication of displacement sense. This paper is concerned only with contractional systems, structures resulting from extensional tectonics are not considered.

THE THRUST SURFACE

The process of thrusting moves one body of rock over another along a thrust surface. Thrusts are contractional faults, a term defined by Norris (1958) in the Rocky Mountains, for faults that shorten datum surfaces (e.g. bedding). Those rocks which overlie a particular thrust surface are said to occur in the *hangingwall*, the rocks below in the *footwall*. In order to satisfy Norris's (1958) definition of contractional faults, thrusts must cut up-section in the transport direction (Dahlstrom 1970, p. 342) but they rarely do so as a smooth plane; in most cases they follow *a staircase trajectory* (see Rich 1934) made up of *ramps* and *flats* (Douglas 1950, p. 384; see Fig. 1). A flat is that part of a thrust surface which was horizontal at the time of fault initiation. It follows that when a thrust sheet is transported over a previously undeformed sedimentary sequence a flat will be parallel to bedding. This definition of a flat being parallel to an arbitrary datum surface differs from common usage which defines a flat as being layer- or bedding-parallel

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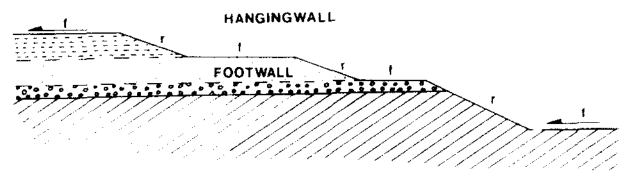


Fig. 1. A typical staircase trajectory in the footwall of a thrust composed of ramps (r) and flats (f).

(e.g. Elliott & Johnson 1980). The new definition is suggested since it extends the concept of staircase trajectories to thrusts which cut through previously folded strata or crystalline basement. Flats are connected by relatively steep ramps (originally termed 'steeps' by Douglas 1950, p. 84) along which thrusts climb up-section in the transport direction. Therefore, ramps cut off arbitrary datum surfaces. Ramps are classified not only by their orientation (Dahlstrom 1970, p. 345, Hossack personal communication) but also by whether they are cut offs in the hangingwall or footwall of a thrust surface. Those ramps which are cut offs in the hangingwall are termed *hangingwall ramps*, those cut offs in the footwall are *footwall ramps* (Fig. 2). The orientation of a ramp relative to the transport direction allows further classification (Fig. 3). Ramps which strike normal to the thrust transport direction are termed *frontal ramps* and are characterized by dominantly reverse dip-slip displacements. Should a ramp strike parallel to the transport direction it is termed a *lateral ramp* and is characterized by dominantly strike-slip displacement. Lateral footwall ramps have previously been known as sidewalls or sidewall ramps (e.g. Hossack 1981). However, the term 'lateral ramp' is preferred since 'sidewalls' have no meaning when related to cut offs in the hangingwall of a thrust. Ramps with a strike that is oblique to the transport direction are termed *oblique ramps* (Dahlstrom 1970, p. 345) and are characterized by elements of both strike-slip and reverse dip-slip.

It should be realised that although thrusts climb up-section in the transport direction they can migrate both to higher and lower levels across the transport direction (e.g. Dahlstrom 1970, p. 343, Elliott & Johnson 1980, p. 70). A thrust surface behaving in this manner will have a corrugated profile composed of a series of flats joined by a corresponding series of lateral or oblique ramps.

When thrusts do not project up to the topographic surface they are referred to as *blind thrusts* (Thompson 1981, p. 452). In some situations we can infer that a blind thrust must exist as a basal décollement for deformation which occurs below the lowest thrust in outcrop. Presumably these can be considered as very long flats.

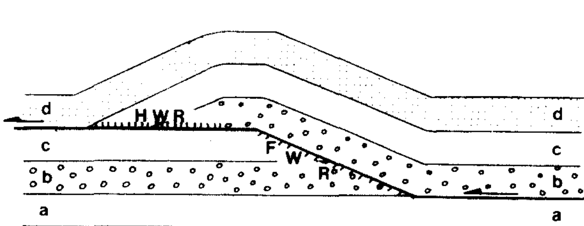


Fig. 2. The relationship between frontal hangingwall (HWR) and footwall (FWR) ramps. Beds are lettered a–d in ascending order.

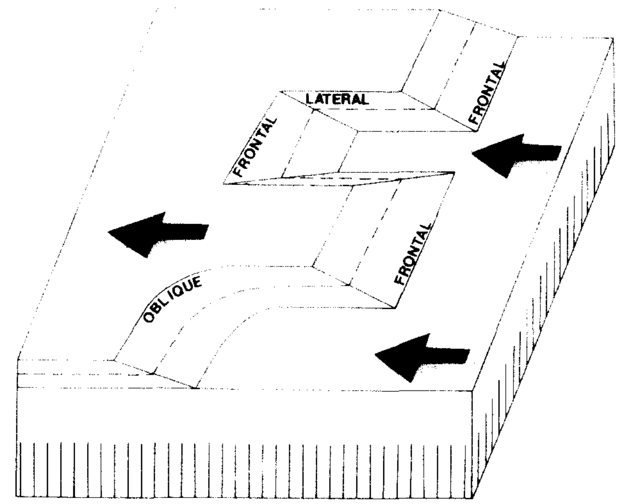


Fig. 3. Block diagram of footwall topography. The thrust transport direction is indicated by arrows.

Commonly, thrusts show a decrease in displacement both in and across the transport direction, displacement generally being accommodated by folding. The line which defines the limit of thrust displacement is known as a *tip* (Elliott 1976, p. 299; see Figs. 7 and 16). Beyond the latest-developed ramp system, at the leading edge of thrust surfaces, displacement may be difficult to detect because stratigraphic separation need not occur. As tips mark the limit of displacement rather than the limit of stratigraphic separation, commonly their detection is problematic.

THRUST SEQUENCES

There are two possible propagation and displacement sequences to explain the development of an array of thrust surfaces which diverge in the direction of tectonic transport. One arises if a younger thrust develops in the footwall of an older thrust, the other arises if a younger thrust develops in the hangingwall of an older thrust. In the first situation the older movement plane will be carried by further displacement on the lower, new thrust. This is termed *piggy-back* thrust propagation (Dahlstrom 1970, p. 349; see Fig. 4) and in an array of thrusts the highest will represent the earliest displacements, the lower ones representing the last displacements (Dahlstrom 1970, p. 354, Cooper 1981, p. 228). The thrusts propagate towards the foreland in the transport direction, and footwall rocks are progressively accreted onto the moving thrust sheet.

If a new thrust surface is developed in the hangingwall of an older thrust an *overstep* (Elliott & Johnson 1980, p. 90, Boyer & Elliott in press, fig. 4.4.3) or *overlap* sequence results (Peach *et al.* 1907, p. 494; see Fig. 5). Thrusts propagate towards the hinterland in a sense opposite to the transport direction; higher thrusts will represent the later movements across the array of faults.

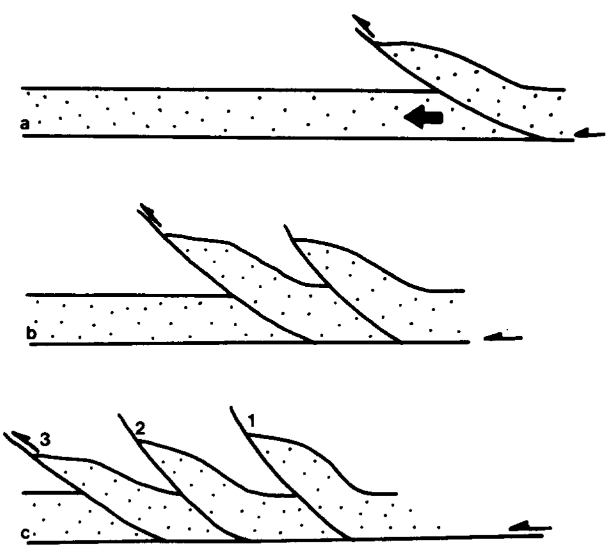


Fig. 4. Sequential development (a–c in time) of a piggy-back thrust sequence, the propagation direction is indicated by a large arrow. Thrusts are numbered 1–3 in order of development.

STRUCTURES RELATED TO THRUST SEQUENCES

Piggy-back thrust sequences result from new thrusts being developed in the footwall of what was previously the active thrust. Apparently, this occurs by progressive failure of footwall ramps (Cooper 1981, p. 228) and the abandonment of part of the old thrust surface. Should this failure continue an *imbricate stack* or *schuppen struktur* (Peach *et al.* 1907, p. 463) will develop. The displaced rocks between the thrusts are termed imbricate *slices* and the whole structure of faults and slices is called an imbricate *stack* or imbricate *zone* (also Dahlstrom 1970, p. 354).

A series of imbricate faults may be asymptotic and rejoin the earlier thrust surface at a higher level. If this occurs, the fault-bounded blocks (called 'parcels' by Bailey 1935, p. 161) are now termed *horses* (Elliott & Johnson 1980, p. 73), and a series of horses together with their bounding thrusts are collectively known as a *duplex* (Dahlstrom 1970, p. 353; see Fig. 6). The highest, shared thrust surface is termed the *roof thrust*, the lowest retaining thrust forms the *floor thrust* (Dahlstrom 1970, p. 357). Roof and floor thrusts meet at the front (*leading edge*) and rear (*trailing edge*) of the duplex (Dahlstrom 1970, p. 341). The term *sole thrust* (Peach *et al.* 1907, p. 472) was used in place of floor thrust by Dahlstrom (1970) but here it is recommended that the term be reserved for the lowest regional thrust surface (Elliott & Johnson 1980, p. 73). Both the floor and roof thrusts must be identified for a duplex to be defined. If a roof thrust cannot be recognized the structure should be termed an imbricate stack.

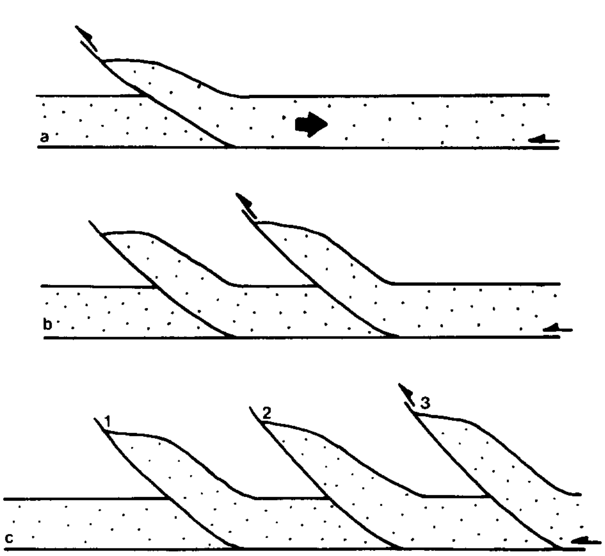


Fig. 5. Sequential development (a–c in time) of an overstep thrust sequence, the propagation direction is indicated by a large arrow. Thrusts are numbered 1–3 in order of development.

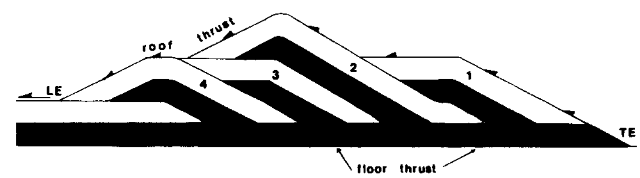


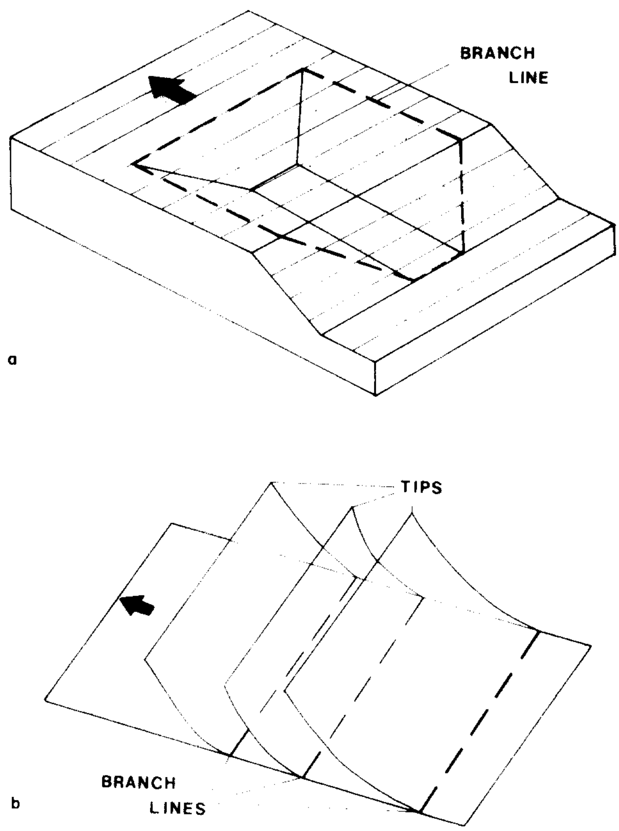
Fig. 6. Cross section through a duplex drawn parallel to the thrust transport direction. TE. trailing edge, LE. leading edge. Horses are numbered 1–4 in order of development.

The cross-sectional shape of a particular duplex will be controlled by the geometry of its constituent horses. Their geometry is governed by the relative spacing, staircase trajectory and displacement of the imbricate thrusts. Figure 6 shows an aspect of these geometric controls. Horse 2 is somewhat larger than the other horses and has a basal thrust which shows a greater displacement than the other imbricates. As a result of this geometry, the duplex roof is folded. Actual duplexes with locally complex horse geometries could locally develop highly-folded roof thrusts.

The intersection of two thrust surfaces is termed a *branch line* (Boyer & Elliott in press; see Fig. 7). The simple example of a horse, which is bounded by a roof and a floor thrust (Fig. 7a), exhibits a single branch line at the intersection of the two thrusts. Hossack (in preparation) classifies branch lines with respect to the intersection of a lower thrust with a higher one. Thus a horse is bounded by a *leading branch line* at its leading edge and a *trailing branch line* at its trailing edge, the two commonly connected by *lateral branch lines.* For the situation of a series of imbricate slices where the individual thrusts do not anastamose, an imbricate thrust is enclosed by a trailing branch line and a tip line at its leading edge (Fig. 7b).

Overstep thrust sequences are rarely recognized and, hence, the geometry of such thrust splays is not well described. A theoretical consideration of this type of thrust propagation by Boyer & Elliott (in press, fig. 4.4.3.) shows a somewhat chaotic imbricate geometry. It seems probable that overstep sequences can only produce imbricate stacks because thrust surfaces are unlikely to anastomose at a roof.

Dahlstrom (1970, p. 340; see Fig. 8) has classified



7. Block diagrams of branch lines. (a) At the intersection of the roof and floor thrusts of a horse (stippled). (b) At the trailing edge of imbricate slices. Note that the leading edge of the imbricate thrusts is a tip. The thrust transport direction is indicated by a large arrow.

thrusts on the basis of their relationship to asymmetric folds produced during the thrusting process. The development of asymmetric folds during thrusting is also discussed by Berger & Johnson (1980) who propose a shear mechanism acting on hangingwall ramps. Thus they consider the folds to develop after the propagation of the thrust ramp, a view which is contested by Fischer & Coward (in press) who argue for folding prior to ramp development. Dahlstrom (1970, p. 341) termed thrusts which cut the steep forelimb of a fold *forelimb thrusts* and those which cut the shallower backlimb *backlimb thrusts* (Fig. 8). However, Dahlstrom implied a structural sequence whereby thrusts cross-cut previously-folded rocks. It is conceivable that a thrust surface may climb across the backlimb and then, at a higher level, the forelimb of a fold (Fig. 9). Furthermore, after displacement, a backlimb in the hangingwall may be directly above a forelimb in the footwall and vice versa (Fig. 10). Thus, Dahlstrom's classification can only be used to describe local geometrical relationships between folds

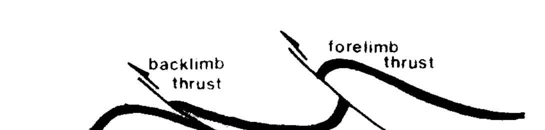


Fig. 8. Classification of thrusts on the basis of their relationships to asymmetric folds which verge in the direction of thrust transport.

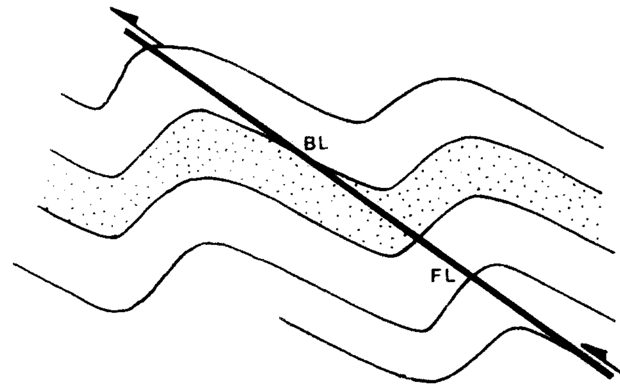


Fig. 9. A thrust migrating from a forelimb (FL) to a backlimb (BL).

and thrusts rather than embracing entire thrusts as originally envisaged by Dahlstrom.

Imbricate thrusts have been classified by Dahlstrom (1970, p. 351) according to whether they occur in the hangingwall or footwall of the main thrust. In general, the main thrust will display a larger displacement than that shown by individual faults in the imbricate stack. Faults which are found above a major thrust are termed *hangingwall imbricates*, those found below a major thrust are termed *footwall imbricates*. As the latter can be readily interpreted as forming a duplex, Dahlstrom (1970) could demonstrate a piggy-back propagation model for them. However, he could not demonstrate such a model for hangingwall imbricates although Hossack (1981) has since shown the same propagation style also applies to them.

The classification of imbricate thrusts in this way seems useful and the problem of propagation can be readily considered in terms of a simple duplex structure. The minor thrusts within the duplex form hangingwall imbricates with respect to the floor, and footwall imbricates with respect to the roof. The problem then becomes one of relative displacement on the bounding thrusts.

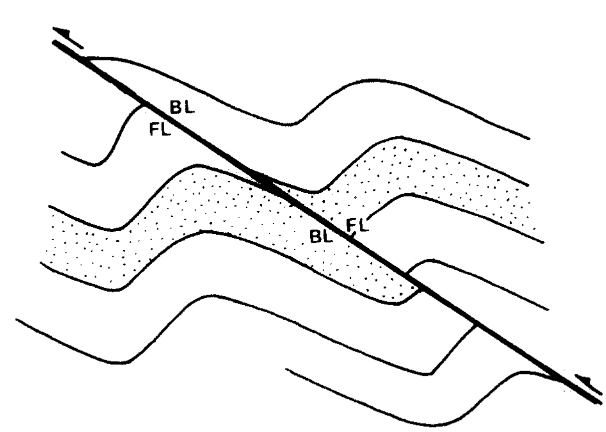


Fig. 10. Displacement on the configuration of thrusts and folds shown in Fig. 9 with a forelimb in the hangingwall directly over a backlimb in the footwall (and vice versa).

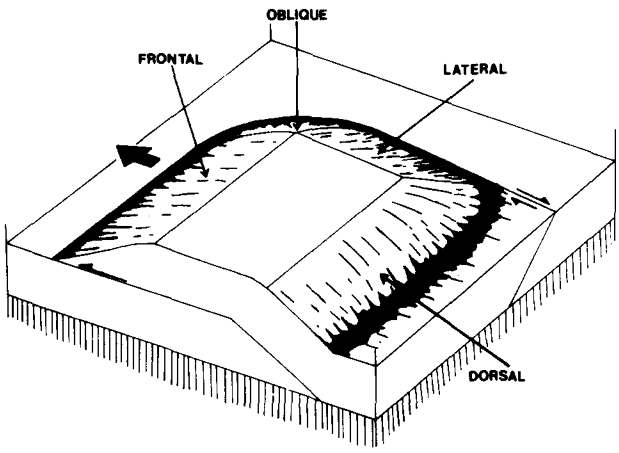


Fig. 11. Block diagram showing orientations of culmination walls relative to a thrust transport direction (large arrow).

STRUCTURES IN THE HANGINGWALL OF A THRUST

Rich (1934) recognised that as a thrust sheet moves over a corrugated surface it is folded above footwall and hangingwall ramps. Typically these folds are spaced monoclines which collectively may form flat-topped anticlines or domes (e.g. Rich 1934, fig. 5). These structures are termed *culminations* (Dahlstrom 1970, p. 358) and the limbs form *culmination walls* (Butler in press) which may be classified in the same manner as ramps (Fig. 11). Thus if a culmination wall strikes parallel to the thrust tranport direction it is termed a *lateral culmination wall*, because it will develop above either a footwall or hangingwall ramp (Fig. 12). A rock mass above a frontal hangingwall ramp dips in the transport direction and is termed a *frontal culmination wall.* A *dorsal culmination wall* develops above a frontal footwall ramp so it will dip against the transport direction. Any intermediate orientations will be shown by *oblique culmination walls*.

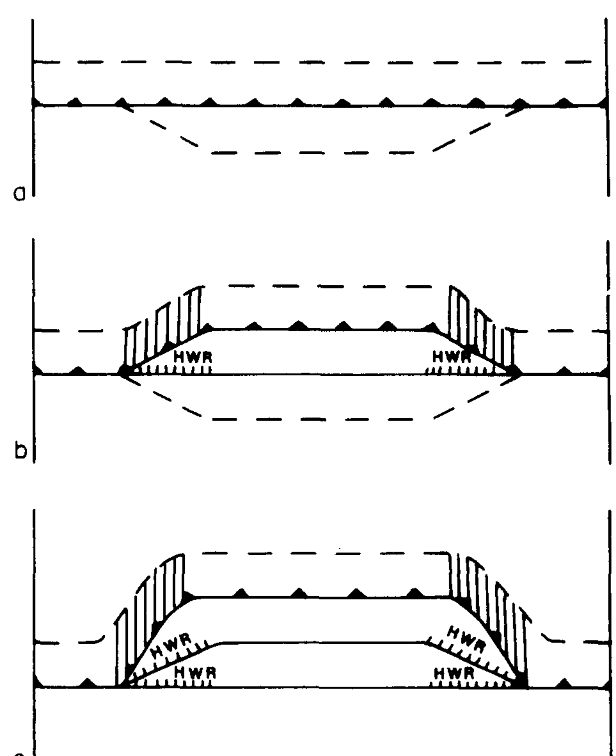


Fig. 12. Hangingwall sequence (a–c) diagrams (see Elliott & Johnson 1980) showing the relationship of lateral hangingwall ramps (HWR) to lateral culmination walls (shaded). Note that the thrust transport direction is out of the page.

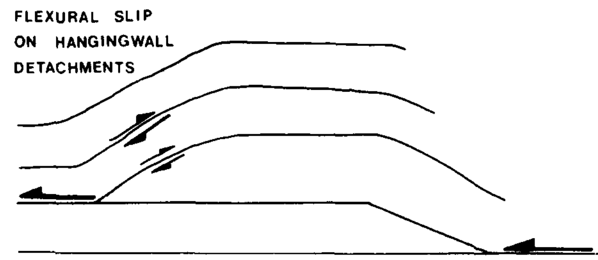


Fig. 13. Flexural-slip on hangingwall detachments in a frontal culmination wall (after Fischer & Coward in press, fig. 18).

Accommodation of folds in the hangingwall of a particular thrust may require slip on surfaces which need not root down into a thrust. These secondary slip zones are termed *hangingwall detachments* (Thompson 1981, p. 454). One type of detachment may be the flexural-slip surfaces which develop in the frontal culmination wall of an imbricate slice (Fischer & Coward in press; see Fig. 13). Dahlstrom (1970, p. 341) described arrays of low-angle faults which root down into the cores of synclines developed at the base of frontal culmination walls. Steepening of the frontal walls will tighten these synclines. Should folding be accommodated by tangential longitudinal strain, any such tightening of the interlimb angle may cause the fold to fail as a thrust-sense fault (Fig. 14). These faults are termed *out-of-the-syncline thrusts*. (Dahlstrom 1970, p. 341).

During piggy-back thrusting, local duplex development may result in laterally-variable thicknesses between the roof and floor thrusts. Elliott & Johnson (1980, p. 76) show a series of cross faults which strike parallel to the thrust transport direction. The faults only offset the roof thrust without affecting the floor of the duplex (Fig. 15), and it is suggested that these detachments are termed *hangingwall drop faults*. They do not represent differential thrust displacement of sheets in the hangingwall of the duplex roof thrust but merely differential uplift caused by variable duplex thicknesses. Thus, these faults differ from lateral ramps and wrench faults by having only a normal, dip-slip displacement.

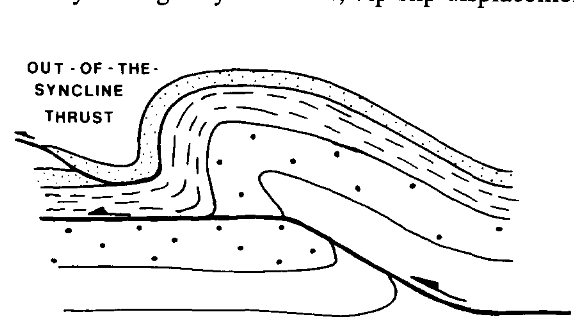


Fig. 14. An out-of-the-syncline thrust.

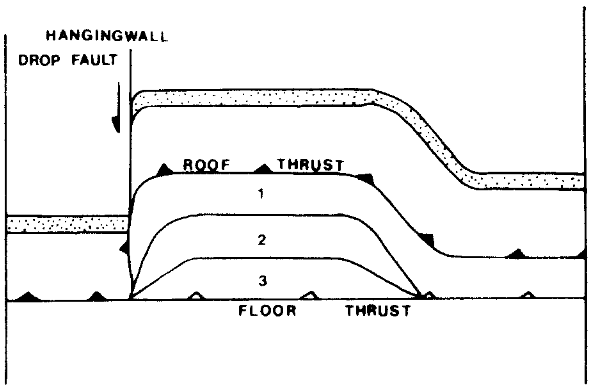


Fig. 15. Location of a hangingwall drop fault in a vertical lateral culmination wall. The thrust transport direction is out of the page.

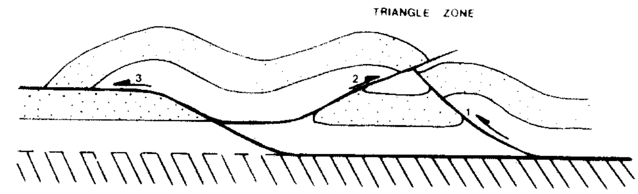


Fig. 17. Development of a triangle zone where a pop up back thrust (2) and a forward-directed imbricate thrust (1) converge. The thrusts are numbered in order of their relative displacement and the sequence continues with the development of a frontal ramp (3) at the leading edge of the pop up.

Fischer & Coward (in press) postulate that prior to a propagating thrust climbing a frontal ramp a period of layer-parallel shortening may occur. It is conceivable that this shortening zone will result in failure producing either a frontal ramp or a back thrust. When a frontal ramp is eventually formed the hangingwall will possess a box fold geometry. Large-scale examples of this geometry have been described from numerous locations including the Jura Mountains (Laubscher 1961, p. 233–234). Back thrusts which are developed by layer-parallel shortening prior to frontal ramp formation are termed *pop up back thrusts*. The uplifted hangingwall block between the back thrust and the frontal ramp is the *pop up* (Elliott 1981, see Fig. 16). Should such a back thrust meet or truncate an earlier thrust the area which is bounded by thrusts converging upwards is termed a *triangle zone* (Elliott 1981; see Fig. 17).

An alternative model for the development of back thrusts (Mandl & Crans 1981; see Fig. 18) is that they are structures associated with frontal ramp climb. These *antithetic back thrusts* are considered to result from the rotation of the hangingwall above the frontal footwall ramp. Although they can accommodate strains induced in the hangingwall during ramp climb, the rotational component would seem to inhibit the movement of the thrust sheet onto the higher flat. The model varies from pop-up development since it does not require a pre-existing ramp. Mandl & Crans (1981) additionally predict that these antithetic faults will steepen with depth which may allow them to be distinguished from pop-up back thrusts. However, it may often be difficult to distinguish these two back thrusting mechanisms. A further problem in identification can arise if back thrusts are developed in response to folding in the hangingwall to a lower thrust, in which situation they are hangingwall detachments and need not be associated with displacement processes on those forward-directed thrusts which they intersect. Should there be uncertainty about their interpretation it is probably better to use the general term 'back thrust'.

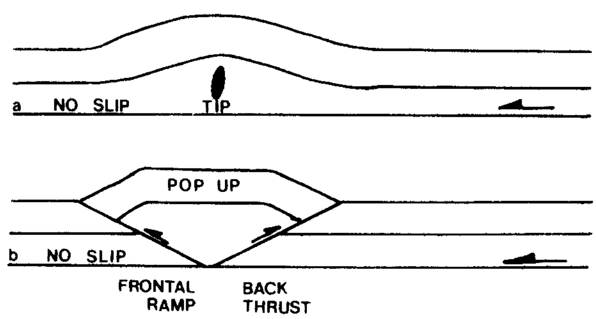


Fig. 16. Development of a pop up. (a) Layer-parallel shortening at a tip in front of a propagating thrust. (b) The developed pop up after thrusting.

DISCUSSION

It is perhaps appropriate to appraise the suggested terminology. The classification of the geometry of an individual thrust surface is relatively well established and provided that it is accepted that thrusts, by definition, do not cut down section in their transport direction, this classification of ramps and flats can account for all possible thrust to wall rock relationships. The more rigorous definition of a 'flat' suggested here, that is datum-parallel rather than necessarily bedding-parallel, allows the concept of staircase trajectories to be applied to thrusts which cut through previously deformed rocks. The two definitions coincide when thrusts cut through undeformed sediments marginal to the developing thrust belt since in these situations bedding is likely to be a datum surface.

Obviously, thrust sequences can theoretically be more

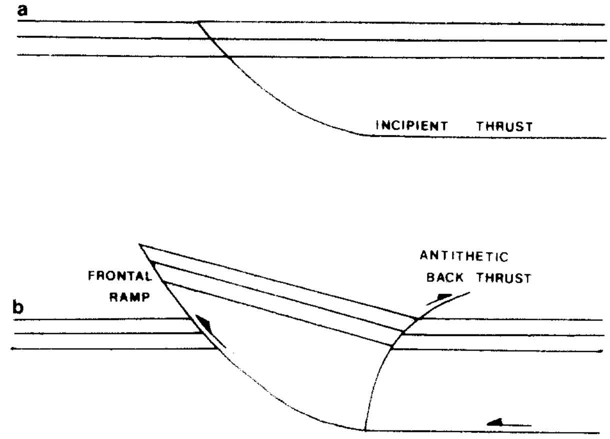


Fig. 18. The development of an antithetic back thrust (after Mandl & Crans 1981, fig. 13). (a) Before displacement, (b) After displacement.

complicated than the models reported here and structures resulting from less systematic propagation models are likely to be more complicated than the simple imbricate stack or duplex (see Boyer & Elliott in press). There are no well documented accounts of actual overstep thrust sequences and indeed, only the piggy-back model is being widely applied. That this model of thrust propagation dominates current work in thrust belts is well illustrated by the classification of 'hangingwall structures'. Many of these features require foreland-directed thrusting to fold or fault the hangingwall of duplexes. Obviously, many of the structures described here may be folded as a consequence of continued thrusting which may complicate their recognition in the field. Therefore, it is not surprising that many features remain to be described within the overall category of 'hangingwall structures'; the ideas contained in this short review can only serve as an introduction and stimulus to the further study of a potentially complex aspect of thrust tectonics.

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