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Thrust-surface geometry: implications for thrust-belt evolution and section-balancing techniques

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Abstract—The application of modern concepts of thrust tectonics to orogenic belts has yielded many detailed restorable sections. Thrusts generally restore with a staircase geometry onto the undeformed stratigraphic template. Since the work of Rich (1934) it has been generally assumed that thrusts have propagated with a staircase trajectory and that hangingwall structures result from the movement of the thrust sheet up footwall ramps. However, thrusts often cut through previously folded strata with a smooth trajectory. Smooth-trajectory thrusts can be identified from footwall geometry and strain state. Once a smooth-trajectory thrust has been identified it is insufficient to produce a balanced deformed section and its restored counterpart. Sequential balanced sections must be constructed reversing the deformation history. The restoration of thrusts to a staircase trajectory has no mechanical significance as the thrust is merely acting as a marker if restored back beyond the time at which it propagated. Thrust ramps are not necessarily actual steps in the thrust surface, they are often just zones where the thrust cuts through bedding in a smoothly curving trajectory. Ductile deformation in thrust belts can reduce bed length at depth thus removing the need for structures which are necessary to preserve constant bed lengths. Ductile deformation in the internal zones of orogenic belts renders the construction of balanced sections in these zones highly problematical.

INTRODUCTION

SINCE the classic work of Rich (1934) the concept of generating rootless folds simply by translation of the hangingwall block up a thrust with a staircase trajectory has gradually gained widespread acceptance. The principle has been successfully applied to many of the fold and thrust belts in North America, including the Valley and Ridge (Wilson & Stearns 1958, Gwinn 1970, Harris & Milici 1977, Roeder *et al.* 1978, Harris *et al.* 1981, Boyer & Elliott 1982), the Idaho–Wyoming overthrust belt (Armstrong & Oriel 1965, Royse *et al.* 1975), the Canadian Rockies (Douglas 1950, Bally *et al.* 1966, Dahlstrom 1970, Price & Mountjoy 1970, Price 1981, Thompson 1981) and in recent years many other orogenic belts (e.g. McClay & Coward 1981, Boyer & Elliott 1982, Hossack *et al.* in press).

The concept of the staircase-trajectory thrust as originally envisaged by Rich (1934) required that the whole system of staircase thrust geometry existed before movement of the hangingwall block commenced. At present the staircase trajectory is the accepted geometry for all thrust belts, and has been used to produce balanced cross-sections. As a result we now have available far more detailed and realistic cross-sections of thrust belts than hitherto.

The Rich model has in our opinion been overused and can lead to a misleading view of thrust belt evolution. In this paper we suggest the staircase-trajectory thrusts are less common than implied by that literature and that smooth-trajectory thrusts are equally likely to develop, particularly where thrust propagation is preceded by a ductile bead of deformation. The range of possible thrust surface geometries is large and kinematic models for the orogenic sector being studied must be developed and utilized to construct good quality sections.

THE GEOMETRY OF THRUST SURFACES

A staircase-trajectory thrust is a thrust which propagates through a sedimentary sequence as a long bed-parallel décollement, before climbing-up section as a short steep reverse fault to a higher level bed-parallel décollement, thereby producing the classic ramp and flat geometry (Fig. 1a; Royse *et al.* 1975, Elliott 1977). This definition closely follows Rich's description of the thrust beneath the Cumberland overthrust block where the result of thrust-sheet motion is to produce rootless hangingwall anticlines (e.g. the Cumberland overthrust block, Rich 1934, Harris & Milici 1977). The staircase

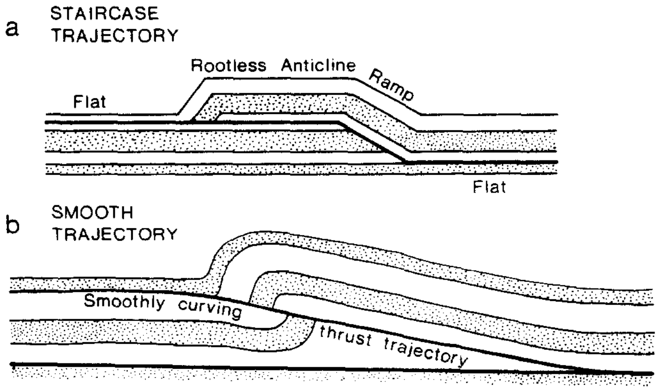

Fig. 1. (a) A staircase trajectory thrust based on the classic Rich mode. (b) A smooth trajectory thrust cutting through previously folded beds.

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trajectory is one of the 'rules of thrusting' proposed by Royse *et al.* (1975) and Elliott & Johnson (1980), and is implicit in the papers of Elliott (1977) and Butler (1982) who have refined the nomenclature of ramps, flats and their consequent structures. It is not surprising, therefore, that many workers have adopted and applied these geometric concepts in many fold and thrust belts with great success. It is important to appreciate, however, that whilst thrusts may appear to have a staircase trajectory on restored sections they will not necessarily have propagated with that geometry, a point also noted by Williams & Chapman (1983).

Detailed observations of thrusts in the field suggest that they do not all have this staircase profile (e.g. Brown & Spang 1978, Fischer & Coward 1982, Williams & Chapman 1983). The thrusts cut through strata, often folded, with a smooth curved trajectory; where the thrust climbs stratigraphy from one décollement to a higher one, it displays a smooth sigmoidal geometry (Fig. 1b).

The staircase-trajectory and smooth-trajectory thrusts are two end members of a continuous range of possible thrust profiles. Most natural examples will fall between the two end members, but to date the staircase trajectory has received considerable overemphasis in studies of thrust belts.

STRUCTURES IN THE FOOTWALLS AND HANGING WALLS OF THRUSTS

In the Rich model the cut-off relationships between the thrust and bedding in the footwall will depend on the angle between the thrust ramp and bedding. This angular relationship will be the same in the deformed and the restored states; it is difficult to smooth out a staircase trajectory in the footwall during thrust sheet motion. Footwall 'shortcuts' may reduce ramp angles, but this should be recognizable by thin accreted horses in the hangingwall. Many published sections show different footwall cut-off angles in the deformed and restored states (e.g. Thompson 1981, fig. 9, Williams & Chapman 1983, fig. 9, Cooper *et al.* 1984, fig. 2). A particularly common footwall cut-off relationship is the footwall syncline (e.g. Williams & Chapman 1983, fig. 9a), which is incompatible with the Rich model but is compatible with a smooth-trajectory thrust (Fisher & Coward 1982). We do not consider that the footwall syncline is the result of drag during thrust motion (see also Serra 1977).

There have been a number of attempts to model experimentally the development of fold and thrust belts. The majority of these models (e.g. Willis 1893, Bucher 1956, Davis *et al.* 1983) tend to produce folds ahead of propagating thrusts. Those that have 'successfully' modelled ramp and flat geometries and rootless anticlines (e.g. Morse 1977, House & Gray 1982) have incorporated the ramp in the initial model design. To our knowledge no-one has convincingly modelled the formation of a staircase-trajectory thrust. There are, however, many balanced cross-sections which display the 'ideal' footwall geometry of Fig. 1 (e.g. Roeder *et al.* 1978, fig. 10, Suppe & Namson 1979, figs. 6–8, Boyer & Elliott 1982, fig. 29), reflecting the interdependence of the Rich model and section balancing techniques.

The development of lower later thrusts can result in folding of the earlier formed thrust sheets into rootless anticlines (Hake *et al.* 1942, Jones 1971) and formation of cleavage in higher thrust sheets (e.g. Dahlstrom 1970, Gwinn 1970, Roeder *et al.* 1978, Elliott & Johnson 1980, Mitra & Elliott 1980, House & Gray 1982).

The hangingwall of the thrust can show a wide range of minor structures. In discussing the style of the rootless anticline Rich (1934) states that "if the forward movement is slight, a narrow anticline is formed, whereas greater movement produces a broad, flat-topped anticline". Although many subsequent workers have applied the Rich model it is clear from examining balanced cross-sections that there is considerable variation in the fold style (see sections of Dahlstrom 1970, Royse *et al.* 1975, Roeder *et al.* 1978, Cooper *et al.* 1984, Coward 1984). The Rich model would not appear to allow for such variability, as the folding is essentially a passive process, in which fold geometry is a function of ramp angle, ramp height and thrust sheet displacement (see also Harris & Milici 1977, fig. 8). The 'fault-bend' origin of these folds and their controlling factors have been discussed at length by Suppe (1983). Berger & Johnson (1980) modelled fold development during motion up a ramp and incorporated a component of drag on the ramp to produce asymmetric folds, and Sanderson (1982) suggests asymmetric ramp folds can be produced by flexural flow folding. The detailed work of Serra (1977) on well-exposed small-scale thrust ramps concluded that the hangingwall does not passively climb a footwall ramp, but deforms by one of three possible mechanisms (Serra 1977, fig. 10). These are (1) migration of the active ramp fault into the hangingwall, effectively reducing the gradient of the ramp; (2) ductile thickening of the unit in contact with the ramp region and (3) the development of antithetic splays (backthrusts) in the hangingwall above the ramp (see Mandl & Crans 1981).

The theoretical development of fabrics in the hangingwall has been considered by Sanderson (1982), who notes that the folding and subsequent unfolding of beds as they pass over a ramp should leave a crenulated fabric. If a footwall becomes a hangingwall as a new lower thrust develops, this can also cause the development of several superposed fabrics (Mitra & Elliott 1980). There is little data available on the detailed relationship between thrusts and fabrics, which are rarely shown on sections.

The ideal staircase-trajectory thrust should preserve an undeformed footwall. Hangingwall rocks should record only those strains due to the formation of the rootless anticline which depend largely on the preferred mechanism of folding. Strain studies in thrust belts contradict the idea of passive fold development (e.g. Spratt 1981, Fischer & Coward 1982, House & Gray 1982, Simon & Gray 1982), suggesting that deformation other than thrusting has occurred. To differentiate be-

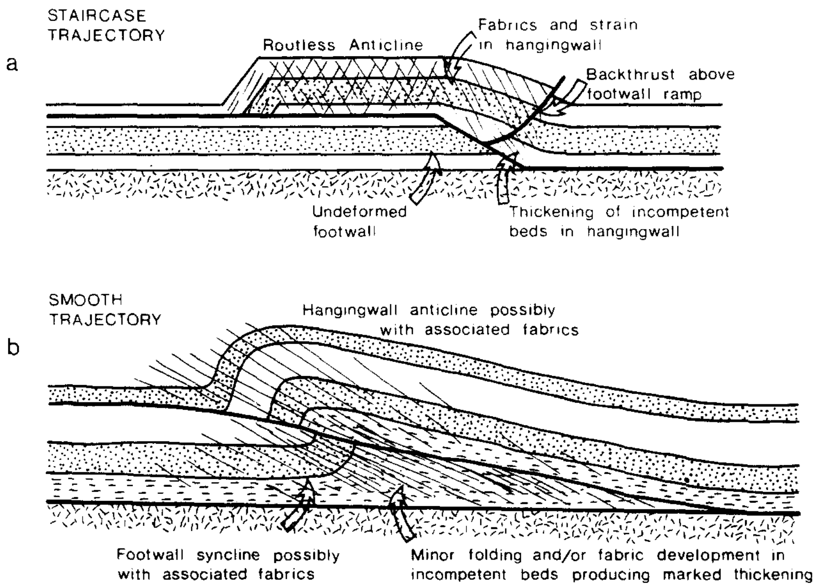

Fig. 2. The main characteristic features of (a) staircase trajectory and (b) smooth trajectory thrusts.

tween staircase- and smooth-trajectory thrusts, we believe that the critical area for detailed examination is the footwall ramp. In its footwall, an ideal staircase trajectory thrust should show no fabric or strain developed during the propagation of that thrust and the staircase geometry should be preserved; the beds in the footwall should be planar and unfolded (Fig. 2a). In the case of an ideal smooth trajectory thrust the footwall displays strain and/or fabrics developed prior to and during thrust propagation and the thrust maintains its orientation during transition from footwall flat to footwall ramp. An important characteristic of the smooth-trajectory thrust is the footwall syncline (Fig. 2b).

EVIDENCE FOR DEFORMATION PRECEDING THRUST PROPAGATION

The concept of a ductile bead of deformation ahead of a propagating thrust tip was first proposed by Elliott (1976, p. 299), and has been developed by Hossack (1983) and Williams & Chapman (1983) who treat thrust surfaces as Somigliana dislocations (Eshelby 1973). There is a considerable amount of information now available which suggests that a ductile deformation bead developing ahead of and being faulted by a propagating thrust is the rule rather than the exception (Mountjoy 1959, Nickleson 1966, Ollerenshaw 1968, Elliott 1976, Brown & Spang 1978, Mitra & Elliott 1979, Coward & Kim 1981, Fischer & Coward 1982, Cooper *et. al.* 1983, p. 148, Cooper *et. al.* 1984).

A point of critical importance is whether the ductile bead has existed throughout the propagation history of the thrust or has become significant only as the thrust died out. The data at present are incomplete, but detailed strain studies in the Canadian Rockies (Spratt 1981) suggest that the ductile bead has existed throughout the active propagation of a thrust; we will term this the constant ductile bead. Evidence for the passage of the ductile bead should, therefore, exist in the hangingwall and footwall of all thrusts (cf. Williams & Chapman 1983, p. 564). The situation is probably more complex and there will be a close link between thrust propagation rate and the strain rate of the ductile bead; an increase in the thrust propagation rate could temporarily 'overtake' the ductile bead. The constant ductile-bead model fits well with data from experimental rock deformation studies which generally reveal some degree of internal deformation prior to failure of the sample (e.g. Heard 1963, Heard & Raleigh 1972). Obviously, the environmental conditions under which the rocks are stressed is critical but in many fold and thrust belts conditions will be such as to facilitate some 'ductile' deformation.

There are apparent footwall space problems with the constant ductile bead model (Fig. 3a). In Fig. 3(b) the problem is solved by folds developing above a lower thrust and in Fig. 3(c) the folding dies out at depth. In both cases we are pushing the problem downwards and not finding a true solution. These models, in common with those of Chapman & Williams (1984, fig. 2a), also have the disadvantage that they will not allow the development of an imbricate sequence of thrusts above a common décollement. In using these models we 'kill off' that particular horizon as a décollement for future use. In Fig. 3(d) the footwall beds beneath the stippled marker bed thicken up by ductile deformation processes allowing continued development of the décollement and generation of imbricate thrusts; for this reason we prefer the latter model (cf. Serra 1977, fig. 9).

SECTION BALANCING METHODOLOGY

The constant ductile-bead model has important implications for the methods by which we balance cross-sections and requires revision of the conventional approach of simultaneously constructing the deformed section and its restored counterpart. Virtually all thrusts

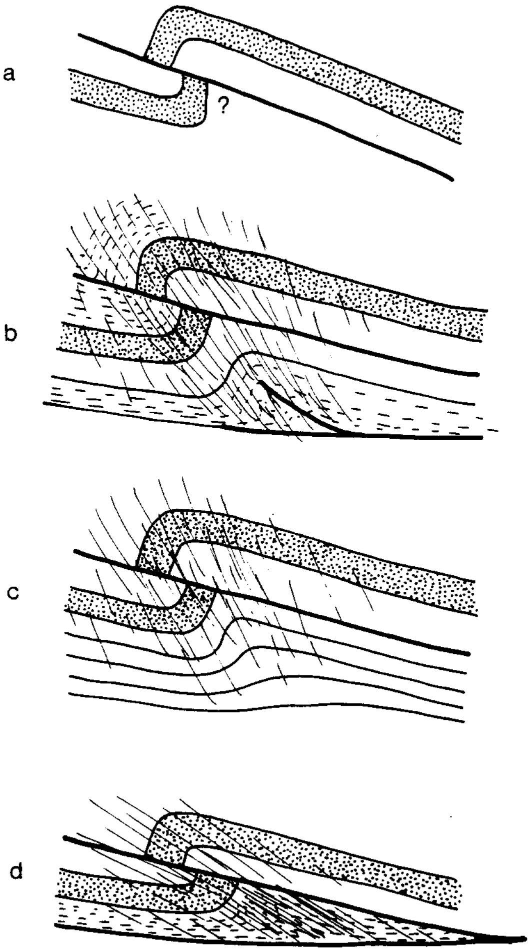

Fig. 3. (a) The space problem in the footwall of a smooth trajectory thrust. (b) Accommodation by a lower décollement with a splay thrust in the core of the footwall fold. (c) Accommodation by folding gradually dying out at depth. (d) Accommodation by ductile deformation in the beds immediately above the décollement.

will appear as staircase trajectories when restored onto the stratigraphic template (Williams & Chapman 1983). Unfortunately, many workers have related these geometric properties to mechanistic concepts of thrust and hangingwall fold development. As discussed earlier it is the geometry in the deformed state that is critical, not the geometry displayed in a restored section. We must, therefore, consider the results of a variety of deformation effects produced by the constant ductile bead on the geometry of restored thrusts.

The original stratigraphy is deformed by the constant ductile bead and subsequently cut by propagating thrusts. Figure 4 shows the effect of different types of ductile deformation on the restoration of a thrust ramp onto the stratigrapic template. The restoration of non-brittle deformation has no geometric or mechanical significance for thrust propagation. The position of thrust surfaces on restored sections has, however, held a peculiar fascination for many workers. Elliott (1977) used such restorations to calculate statistics on average ramp spacing and to characterize lithologies which were more likely to develop ramps than others. This implicitly assumes that the thrust propagates through undeformed strata. On the undeformed stratigraphic template the restored thrusts can only be used for calculating shortening and displacement. They are material marker lines of no mechanical significance.

In order to restore a thrust belt correctly we must make some assumptions about the sequence of deformation based on field observations. Structures may then be restored by reversing the deformation sequence. The thrusts should only be restored back to the point at which the thrust propagated. On any further restoration the thrust should be clearly designated as material marker lines. To illustrate the principle we have taken a simple example of a propagating thrust which sticks at point Y

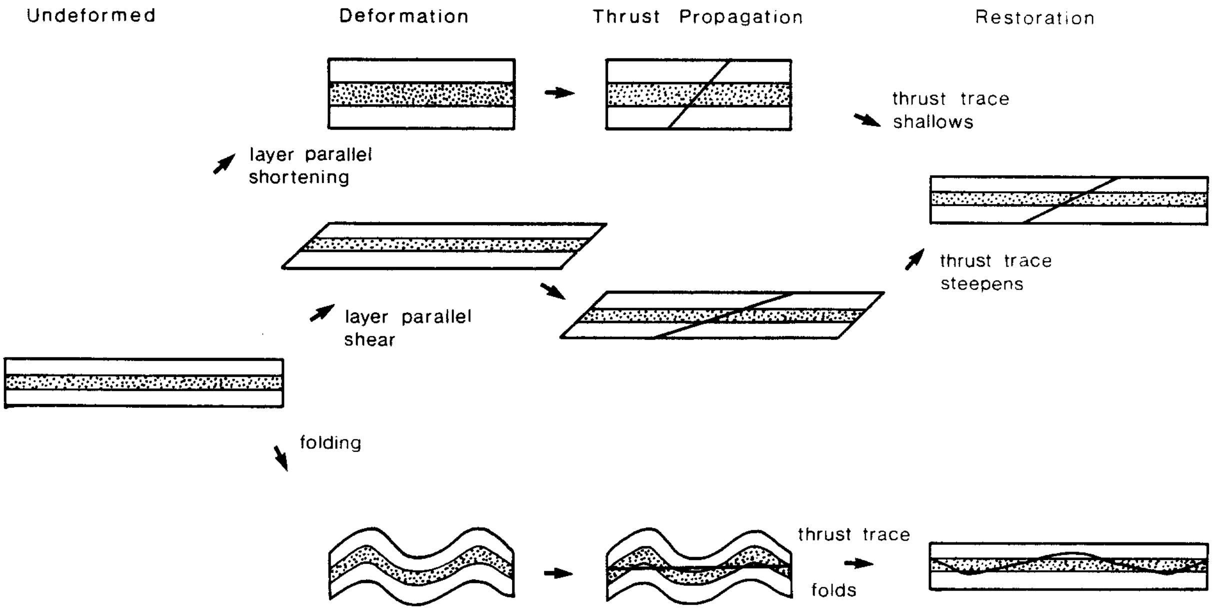

Fig. 4. The effect of various types of deformation preceding thrust propagation on the restoration of thrusts in sections. Note how in each case the restored thrust has a different geometry to the actual thrust geometry developed at the time of propagation.

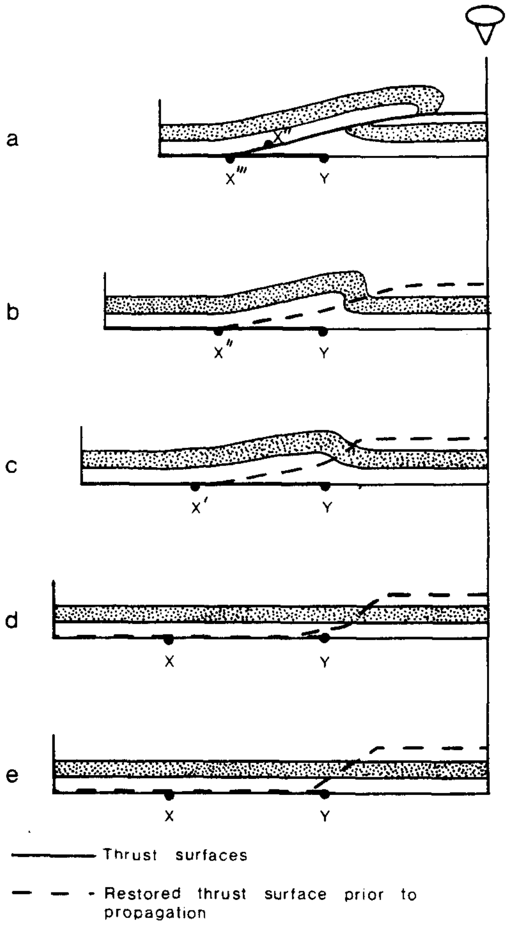

Fig. 5. The sequential restoration of a simple fold and thrust structure. (a) The deformed state, (b) immediately prior to propagation of the thrust splay from the decollement, (c) fold development above the sticking point of the propagating décollement. (d) An accurate restoration of the thrust trace onto the stratigraphic template. (e) The ideal restoration of the thrust trace based on the Rich model.

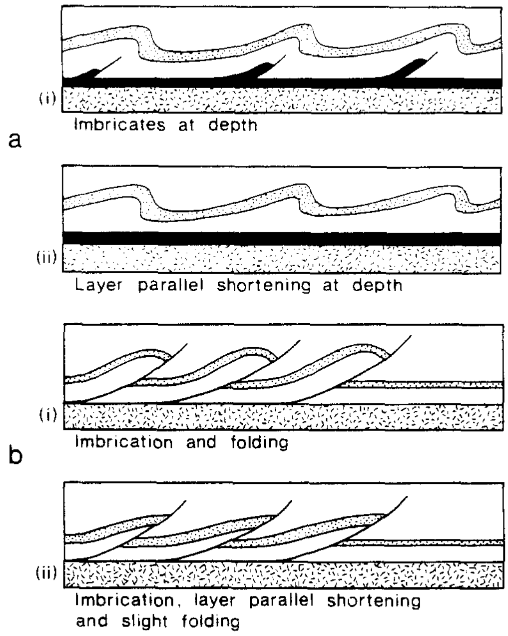

Fig. 6. Common methods of generating 'necessary' bed length at depth. In (a)(i) the black bed has been inferred to be imbricated. (a)(ii) shows how layer parallel shortening can reduce bed length whilst thickening the bed. In (b)(i) the stippled bed is strongly sigmoidal between the imbricates. (b)(ii) shows how the same shortening could be accomplished by less folding and a component of layer parallel shortening.

(Fig. 5c). X will move towards Y as the beds above the décollement shorten by folding and/or layer parallel shortening (Figs. 5b & c). Eventually an imbricate thrust propagates from the décollement and through the fold with a smooth trajectory (Figs. 5a & b). Restoration proceeds in the reverse sequence, but beyond the initiation of the thrust it is shown as a dotted line. In the total restoration (Fig. 5d) the thrust has a shallow take-off angle, then steepens abruptly. At this stage, many workers might question their balance and rework it until they arrive at the classic geometry (Fig. 5e). The restoration (Fig. 5d), however, is merely a geometric consequence of restoring the smooth-trajectory thrust, and hence its 'unrealistic' geometry is of no significance.

A common problem in section balancing is lack of bed-length at depth (Carey 1962). With line-length balancing insufficient bed length produces a progressive steepening of the thrusts on the restored template. However, ductile deformation, e.g. layer parallel shortening, can reduce bed length and hence its measurement in the deformed section may severely underestimate the undeformed bed length. At present balanced sections tend to contain 'convenience structures' to create the missing bed length at depth (e.g. Harris *et al.* 1981, fig. 3, Boyer & Elliott 1982, fig. 26, which is redrawn and balanced from Perry 1978, fig. 10, with additional splay thrusts). The commonest form of these structures are small splays climbing for a limited distance from the sole thrust (Fig. 6a) and excessively sigmoidal beds between successive thrusts (Fig. 6b). An area balance suffers from similar problems once ductile deformation is occurring as material may move into or out of the section plane.

How can such problems be avoided? The best solution is to incorporate strain data into the balanced section and to consider the time relationships of the ductile strain and the brittle thrusting. However, very few balanced sections so far constructed have attempted to include strain data (see Hossack 1978 and Cooper *et al.* 1983).

We propose that a rather different process of section balancing be adopted, as follows.

(1) Collect strain data along the proposed line of section. This may be quantitative or semi-quantitative; for example, an assessment of the amount of material removed during the development of spaced cleavages.

(2) Choose relatively competent beds for bed-length balancing which will have suffered least ductile deformation; for example, sandstones and carbonates.

(3) Pay close attention to the minor structures associated with the thrusts, in particular to cut-off relationships, footwall geometry, splay faults and fold structures. A kinematic model should be evolved for the section based on this data.

(4) Produce a provisional template for restoration based on available stratigraphic and geophysical data. In the case of thickness variations (e.g. Cooper *et al.* 1984),

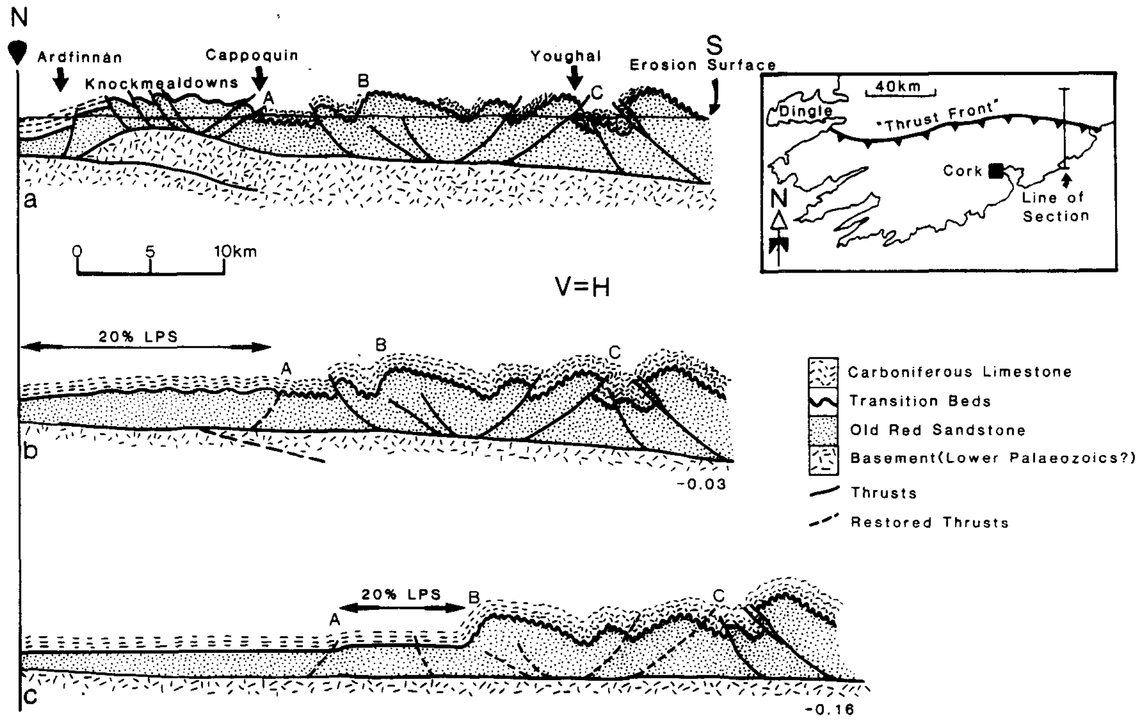

Fig. 7. An example of the use of step-wise restoration from the Variscan fold and thrust belt in southern Ireland. (a) is the deformed section drawn from Ardfinnan to Youghal (see inset map). In (b) thrust displacements are restored as far south as thrust A. In (c) folding and 20% layer parallel shortening (LPS) are restored back to A, folds and thrusts are restored back to B and thrusts are restored back to C. This reverses the sequence of deformation established from field observations in the area. The step-wise process is continued until the section is completely restored.

the template must be divided into segments each of which approximates to a wedge. Each template segment must be given an assumed percentage shortening which can be iteratively modified as the balancing process continues.

(5) Commence the balance from the pin-line reversing the kinematic model for the deformation. In some cases (e.g. Hossack 1978, Cooper *et al.* 1983) a simple sequence will require only one intermediate template. In many situations, however, a series of deformed templates will be required to restore the section. In this case, the deformed section, restored section and all intermediate sections must be produced simultaneously. It is critical to appreciate that bed-length and area will not be consistent from the deformed to the restored section. The inconsistencies and their causes will, however, be shown on intermediate sections.

The conventional balancing procedure can either under- or overestimate the true shortening, depending on whether the bed lengths and areas have been reduced or increased during the ductile component of deformation. Our method requires more data and makes assumptions (based on observations) regarding the kinematics of the deformation. However, we feel that the result is inevitably more meaningful and will highlight those areas with most problems. Figure 7 shows the application of this technique to the Irish Variscan producing a significantly improved section from our earlier version constructed by conventional methods (Cooper *et al.* 1984, fig. 1).

The balancing technique has been used extensively in many orogenic belts, primarily to assess the degree of shortening and to restore palinspastically the sediments to their original site of deposition (e.g. Price 1981, Butler 1983, Cooper *et al.* 1984). This has been a valuable exercise, but some of the results must be questioned. We must reconsider conventional methodology and rework sections incorporating data on the ductile component of deformation. We cannot necessarily assume that we will obtain a 'minimum answer' (Hossack 1979).

The degree of ductile deformation seen in the internal zones of an orogenic belt render even area-balancing highly dubious, as it is often difficult to assess material loss or gain in the section plane. To use the result to restore the individual units of the internal zone to their 'original' positions then makes the implicit assumption that the transport direction parallels the section. Any oblique subduction offers the potential for the accretion of suspect and exotic terranes (e.g. the Canadian Cordillera, Davis *et al.* 1978). The result of balancing a section through such regions is to restore units at an angle to the true transport direction, thus producing meaningless palaeogeographic reconstructions.

CONCLUSIONS

(1) Thrust surfaces will commonly restore as staircase trajectories onto the stratigraphic template; it does not follow that they propagated with that geometry.

(2) Thrusts can propagate through strata with a smoothly curving trajectory; this possibility is enhanced if the propagating thrust is preceded by a ductile bead of deformation, producing folds, for example.

(3) Field observations indicate that staircase trajectories for thrust surfaces are not as ubiquitous as suggested in the literature. Ramps are thus areas where a thrust surface cuts through strata, but do not necessarily constitute a mechanical step in the thrust surface.

(4) The propagation of thrusts through previously deformed rocks means that when thrusts are restored onto the stratigraphic template, geometric distortions are introduced and the thrusts have significance only as material marker lines.

(5)The normal practice in producing balanced sections is to include structures at depth to satisfy the requirement of constant bed length. However, ductile deformation of beds at depth can significantly reduce bed lengths and such structures may be largely imaginary.

(6) The improved method of balancing cross-sections proposed in this paper requires the understanding of all deformation processes and the reversal of the kinematic sequence by constructing a series of balanced sections.

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