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Including strain data in balanced cross-sections

NICHOLAS B. WOODWARD

Department of Geological Sciences, University of Tennessee, Knoxville, TN 37996, U.S.A.

DAVID R. GRAY

Department of Earth Sciences, Monash University, Clayton, Victoria, 3168, Australia

DAVID B. SPEARS

Chevron U.S.A., Inc., 935 Gravier Street, New Orleans, LA 70112, U.S.A.

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Abstract—Almost all published balanced cross-sections include cleaved and/or strained rocks and may therefore violate the requirement that bed-lengths and formation areas are preserved between undeformed and deformed states. Knowledge of distortions, presence and type of cleavage, and overprinting relations in poly-deformed segments are necessary to define area changes related to volume loss, strike elongation, and poly-deformation. Work in the Southern and Central Appalachians has shown variation in structural complexity and changing deformation styles both along and across the thrust-belt. This necessitates separate treatment of individual sheets during balancing. Regions of little or no interstratal slip (pinning points) should be chosen for each thrust sheet and each fold strain in the sheet. In external sheets, where deformation intensity increases towards thrusts, pin-points should be back-limb inflection points. In intermediate and internal sheets where cleavage is approximately coeval with folding, pin-points should be at fold hinges.

Where cleavage and strain are heterogeneously developed throughout a stratigraphic sequence, a line-length balance using massive relatively uncleaved beds (e.g. Knox Group, Southern Appalachians) can be used as a basis for restoring the section. Unstraining of deformed layers, given strain data and cleavage trajectories for individual thrust sheets, provides line lengths and formation areas which can be fitted to the key-bed of the undeformed section. Cleavages which partially or fully postdate folding indicate continued shortening in the thrust wedge, and modify earlier pinning points in upper sheets. These cleavages, and poly-deformed segments, are difficult to restore as strain data are generally scarce in the metamorphosed internal thrust sheets.

INTRODUCTION

BALANCED cross-sections were developed primarily in the petroleum industry to provide guidance for structural interpretations in areas of insufficient seismic and well data (Dahlstrom 1969). As such, they rely on a restrictive set of empirical groundrules regarding a limited set of expected possible structures (Dahlstrom 1970, Boyer & Elliott 1982). Their use has been most important in foreland fold- and thrust-belt areas where seismic data gives an outline, but not a conclusive picture, of the structural styles. Balanced sections move from the large-scale thrust geometries down to constrain the smaller-scale exploration targets.

Strain analysis (Ramsay & Huber 1983, and references therein) goes in the opposite direction. The methods build up an overall kinematic and geometric picture of an area's deformation history by considering how the smaller pieces fit together. Since they rely on individual measurements of markers over large areas, studies which unstrain parts of orogenic belts (e.g. Hossack 1978) rely on an opposite approach to that used in balanced sections. Instead of a lack of data, they rely on an overabundance of data. The two approaches were designed to meet different needs in different parts of mountain chains.

Price & Mountjoy (1970), Roeder *et al.* (1978), Hossack (1979) and Elliott & Johnson (1980) extended the concept of section balancing into penetratively deformed areas because of the power of the geometric concepts. Elliott & Johnson (1980) especially demonstrated that the geometric principles developed for the most external parts of orogenic zones, could be applied to penetratively deformed rocks to explain thrust development sequences in internal zones. Restorable cross-sections of the Canadian Rockies (Price & Mountjoy 1970, Price 1981) and the Appalachians (Roeder *et al.* 1978) have provided revealing glimpses of how different parts of orogenic belts must fit together.

The assumptions of balanced sections (Dahlstrom 1969, Hossack 1979, Elliott & Johnson 1980, Price 1981), which include plane strain, preservation of bed-lengths and areas, and parallel folding, are all more or less violated in internal parts of mountain belts. The fundamental geometric concept, that it should be possible to restore sections using a set of logical rules, is just as powerful in these internal zones, however. To generate more realistic balanced sections, we need to develop systematic ways to expand the simple balancing rules to deal with more penetratively deformed rocks.

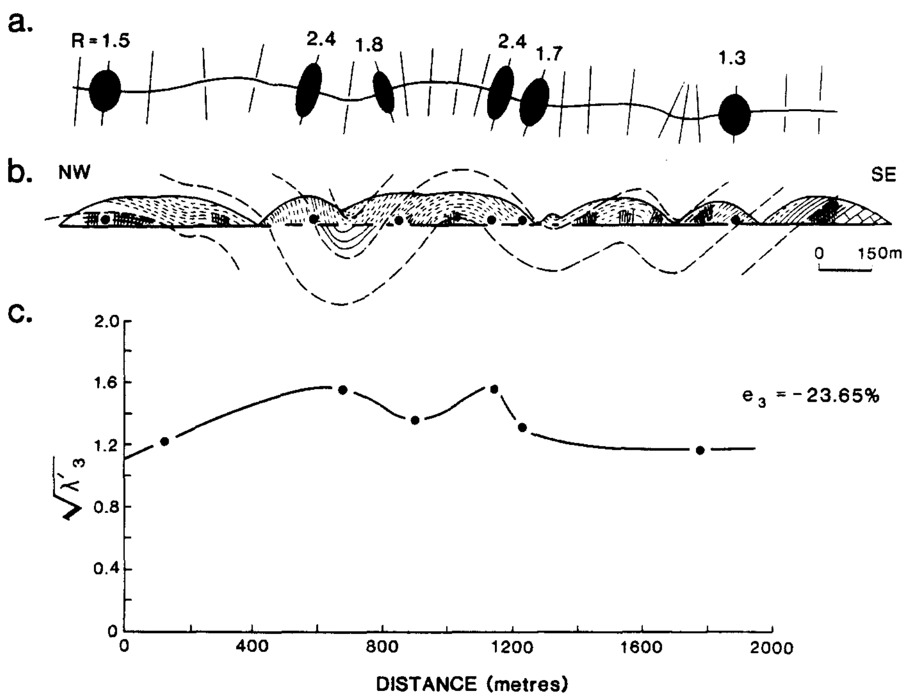

Fig. 1. Finite-strain trajectory integration (after Hossack 1979). (a) X and Z trajectories drawn from orientations of XZ strain ellipses determined from pencil structure and/or pressure-fringes on pyrite in mudrock, Knobs Formation, southwest Virginia. (b) Plot of $\sqrt{\lambda'_3}$ vs distance along the trajectory. Area under the curve equals the original length of the strain trajectory (23.7% shortening) (modified from Reks & Gray 1983).

INCLUDING STRAIN DATA

The types of strains we expect in any thrust belt are summarized in Table 1. For section balancing we need to worry about strains related to the formation of thrusts and folds, and superimposed strains because of subsequent deformation. Thrust-zone strains and cleavage in the external zones are usually restricted to the lower 30–70 m of thrust sheets, so that they are negligible (<1% area) for practical purposes. Therefore, in most sections we are primarily concerned with how to unfold folds and measure bed lengths and areas. More internal parts, such as the Blue Ridge and Smoky Mountains of the Southern Appalachians and the Helvetic nappes of the Alps, have more complicated deformation histories which make them difficult to restore. Due to the inherent limitations in the input data for balanced sections, especially irregular or uncertain stratigraphic thicknesses, strain of less than 5% cannot presently be dealt with either. This means that the small (5% range) but consistent pre-thrusting layer parallel shortening strains in the Central Appalachians (Geiser in press) can be ignored.

Table 1. Expected strain geometries in thrust-belts

(a)	Thrust zone strains
(b)	Folding strains
	(1) Thrust-tip folds
	(2) Hangingwall ramp anticlines
	(3) Footwall-folding during thrust motion
(c)	Superimposed strains
	(1) Strain related to emplacement of lower thrusts, or to folding within lower sheets
	(2) General shortening within the wedge

Why include strain data in regional cross-sections? The main benefit is to aid section restoration by determining the pre-tectonic shape of cleaved and/or strained lithotectonic units. The strains also provide information about the kinematics and internal deformation of individual thrust-sheets and help establish the mechanics of folding within them. In other words, they provide geometric constraints which aid section-balancing.

Despite these advantages there are problems and limitations in applying strain reversal techniques to regional cross-sections. Suitable strain markers are rare and can never be found for all points of interest in deformed sections. Volume changes are generally unknown as well. This means that the strains are at best estimates, and that most cross-sections will not have a continuous picture of strains for any one lithotectonic unit across the entire section. At best, we can only unstrain portions of sheets. The measured strains are, however, an aid to understanding thrust-sheet emplacement and fold formation, which can be useful in selecting positions of local pin-lines for individual thrust sheets. The importance of this is discussed later in the paper.

Two techniques incorporating strain data have applications to section balancing. These are strain integration (Hossack 1978) and strain reversal (Oertel 1974, 1980, Schwerdtner 1977, Oertel & Ernst 1978, Hossack 1978, Cobbold 1979, Cobbold & Percevault 1983). Both require orientation and magnitudes of principal strains.

(1) *Strain integration* computes the undeformed length of a strain trajectory by simple integration of the reciprocal stretch along the trajectory in the deformed state (Cobbold 1979). It can be used to give an estimate of the regional strain and the component of shortening due to

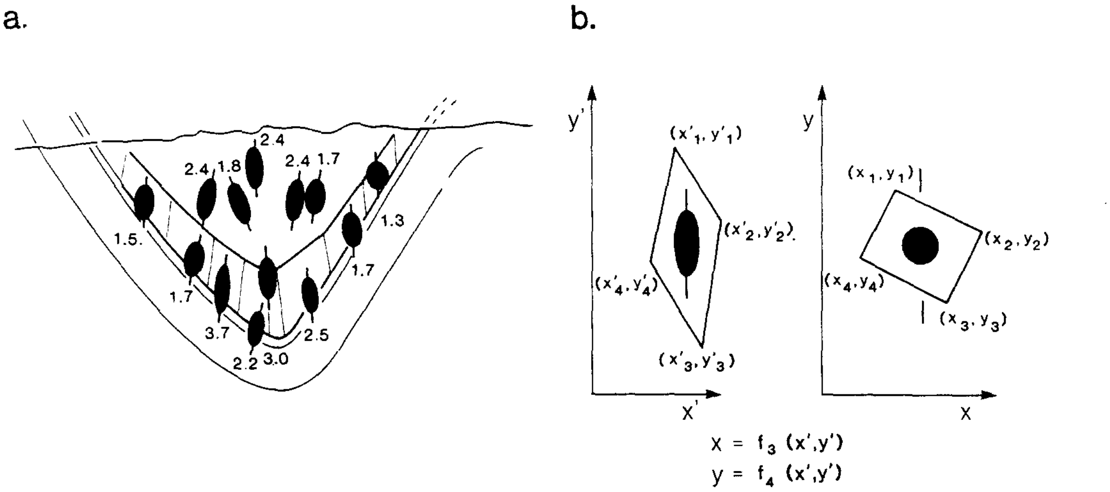

Fig. 2. Aspects of strain reversal. (a) Fold profile with total strains and finite elements selected for unstraining. (b) Eulerian transformation of deformed element (left) to undeformed element (right) using corner coordinates of the element and a reference system parallel to the X strain direction.

penetrative strain. A generalized strain trajectory is drawn parallel to Z axes of a series of varying strain ellipses (Fig. 1a). The reciprocal stretch, expressed as $\sqrt{\lambda'_3}$, is calculated for each locality along the trajectory and plotted versus distance (Fig. 1b). The original length (L_0) of the trajectory equals the area under the curve and is equivalent to the integral

$$L_0 = \int \sqrt{\lambda'}\, \mathrm{d}l.$$

The original length (L_0) and the final deformed length (L) gives the percentage shortening

$$e_3 = [(L_1 - L_0)/L_0] \times 100.$$

This value is a minimum as body rotation and volume strain are not considered (Hossack 1979).

(2) *Strain reversal* removes the effects of finite deformation given the principal values and orientations of strain at a number of points throughout a deformed body. The aim is to restore the rocks to their pre-deformational state. The section to be unstrained is subdivided into a series of finite elements bounded by lines paralleling the principal X strain trajectories and the folded bedding surfaces (Fig. 2a). Each element contains a strain observation which is taken to be representative and homogeneous across it. Elements are then individually unstrained by applying an Eulerian transformation of the form $x = f_3(x',y')$ and $y = f_4(x',y')$, derived from their total strain ellipses, to the coordinates of their corners (Fig. 2b). Elements are then put back together with voids and overlaps minimized by matching face centres of adjacent elements, without changing orientations of the strain axes. A useful discussion of the coordinate transformation equations and strain and reciprocal strain matrices involved in these manipulations is given by Ramsay & Huber (1983, Appendix B). Restored shapes can then be utilized in cross-sections, and original lengths (L_0) and percentage shortening calculated for the units which were unstrained.

Examples

Strain markers in the Southern Appalachians (southwest Virginia and northeast Tennessee) are uncommon, generally restricted to Middle Ordovician mudrocks, and are unevenly distributed over the area. Examples are pencil structure (Reks & Gray 1982, 1983), reduction spots (Simon & Gray 1983), pyrite pressure-fringes (Reks & Gray 1983) and mudcracks (House & Gray 1983). Measurements in most instances are minimum estimates of the strain, but are all that is available. Volume changes have occurred during deformation, but magnitudes are unknown. At best they show a relative variation in strain through the region. Values generally increase (<5 to 24%) from external to internal sheets, but in an irregular fashion and suggest a more complex history than perhaps would be inferred from the cross-sections themselves (Fig. 3). Due to the limited nature of the strain data it must be emphasized that we are not trying to unstrain all parts of our balanced sections in detail.

An example is taken from southwest Virginia (see Reks & Gray 1983), where strain magnitudes and orientations are available from pencil structure and pyrite pressure fringes in the Middle Ordovician Knobs Formation and Paperville Shale (Fig. 4). These units occupy the cores of five plunging synclines. This allows the construction of regional fold profiles, with strains superimposed by down plunge projection of map strain data (Fig. 4a). Strain integration and reversal techniques were applied to each regional profile and are discussed in detail in Reks & Gray (1983, pp. 113–121). Strain reversal of the regional folds (Fig. 5) allows the calculation of total shortenings (e_t) for the mudrock, using L_0 = arc length of the unstrained layer, and L_1 = deformed length of the layer. Values for these folds are −39.2% (A–A′), −27.0% (B–B′) and −63.0% (C–C′). The discontinuous nature of the mudrock in the section (Fig. 4b), even after down-plunge projection, precludes any useful contribution of the strain data to the restored

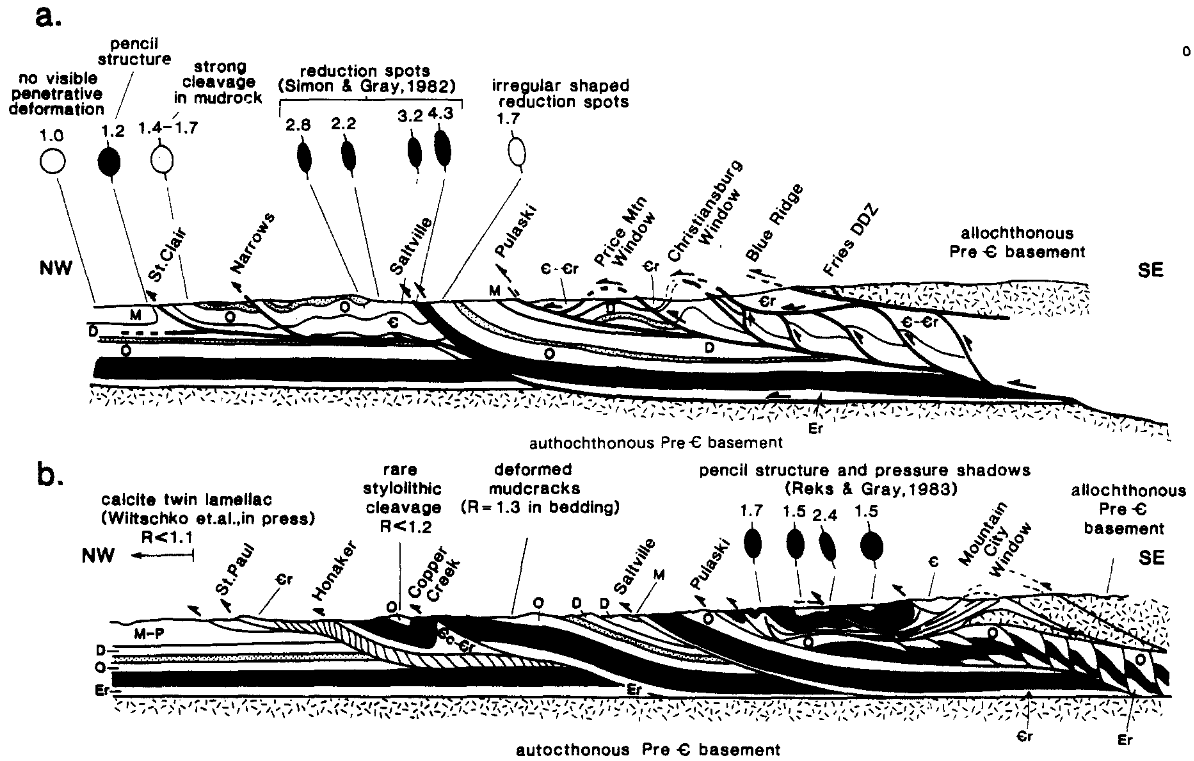

Fig. 3. Balanced sections across the Valley and Ridge in southwestern Virginia showing irregular patterns of strain. Locations for these sections are shown by dotted lines ② and ③, respectively in Fig. 10. M, Missippian; D, Devonian; C, Cambro-Ordovician carbonates (black): Cr, Cambrian Rome Formation.

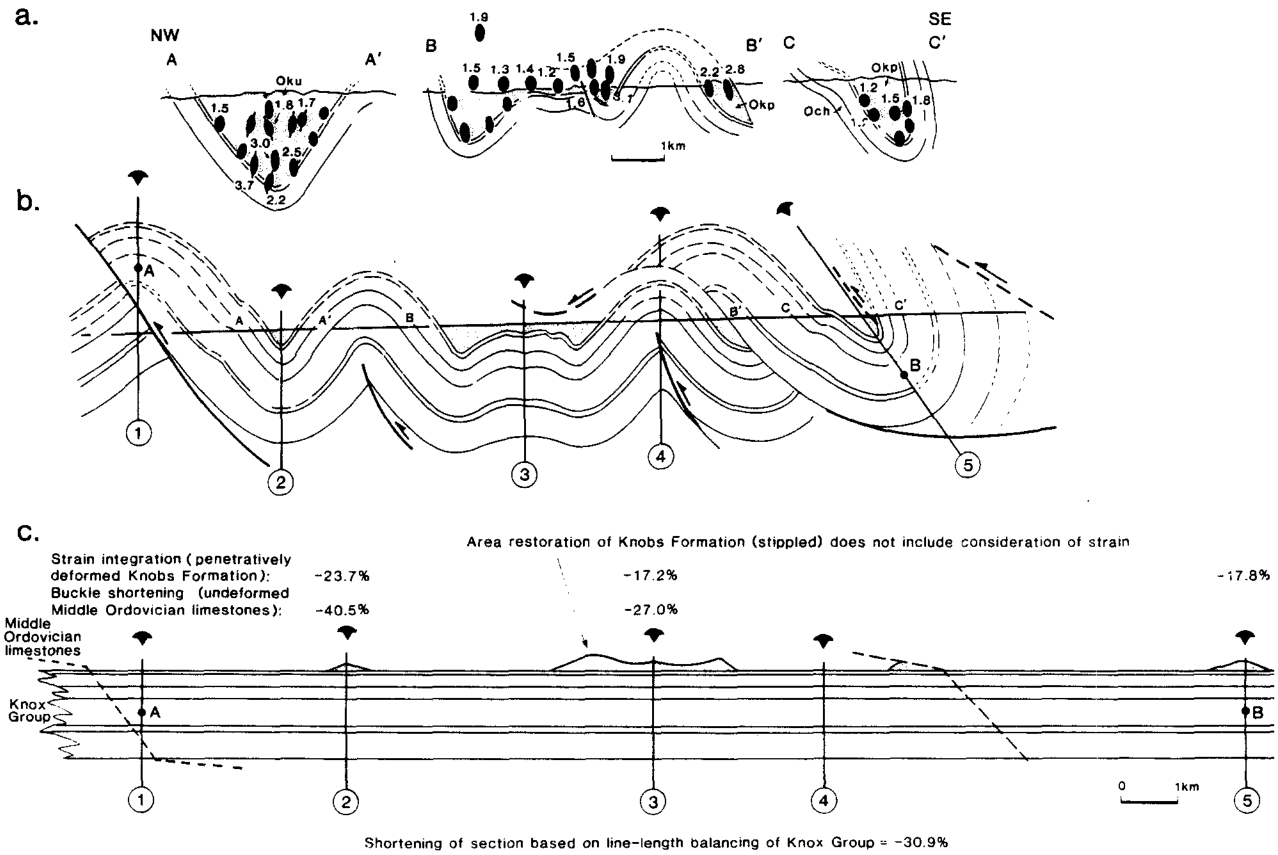

Fig. 4. Balanced-section reconstruction using strain data from Knobs Formation, southwest Virginia (modified from Reks & Gray 1983). (a) Regional fold profiles with strain data. (b) Deformed section showing local pin-line positions. (c) Reconstructed section, showing apparent fault trajectories and pin-line positions.

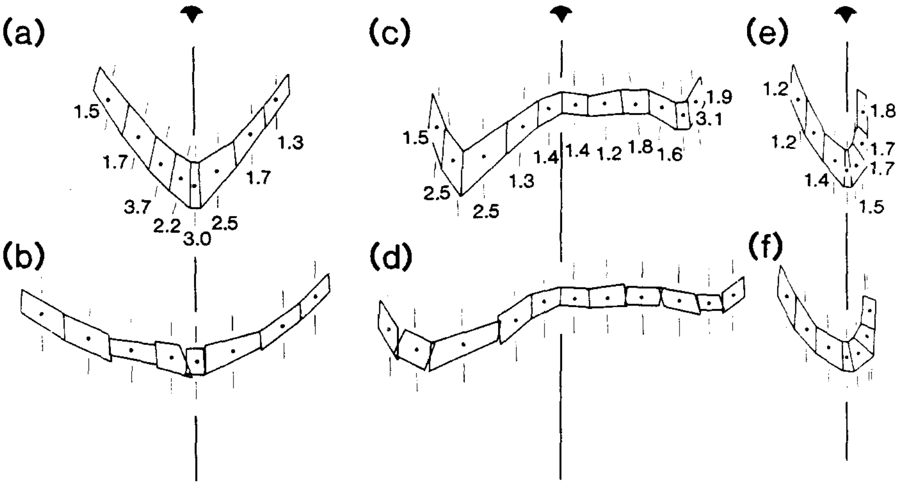

Fig. 5. Strain reversal of finite elements for the folds depicted in Fig. 4(a). Unstrained elements at the bottom.

section (Fig. 4c). Section restoration was based on line-length balancing of the undeformed Knox Group using local pin-lines at fold hinges.

In the Central Appalachians total strains have been calculated from chlorite pressure-fringes on framboidal pyrite in Ordovician and Devonian shales across the Massanutten synclinorium (Fig. 6). The depicted strains are once again minimum values, since volume changes are unknown (Gray & Wright 1984). Strain integration of Z trajectories (Fig. 7) for the Ordovician (Martinsburg Formation) gives shortening values of 41.3% (A–A′) and 43.1% (B–B′). Devonian shales give values of 42.5% (A–A′) and 39.0% (B–B′). Although the average for the Martinsburg (42.2%) is slightly higher than the average for the Devonian (40.8%), this difference is probably well within the. error limitations of the technique.

Strain integration of the Martinsburg shales in both sections (Fig. 8) give total shortenings (e_t) of −40.7% (A–A′) and −39.4% (B–B′), where again L_0 = arc length of the unstrained layer, and L_1 = deformed length of the layer.

Both techniques therefore yield approximately 40% shortening for shales in the Massanutten synclinorium. Once again, due to the discontinuous nature of the shales in the cross-sections (Fig. 6), it is difficult to incorporate these data fully in a restored section. A balanced section has not been attempted, as in contrast to the Southern Appalachians the Cambro-Ordovician dolomite package is penetratively strained (Cloos 1947). There is no unstrained marker bed within the Little North Mountain thrust-sheet that can be used for a line-length balance. Unstraining of all units is impossible since the regional folds are non-plunging, so that strain

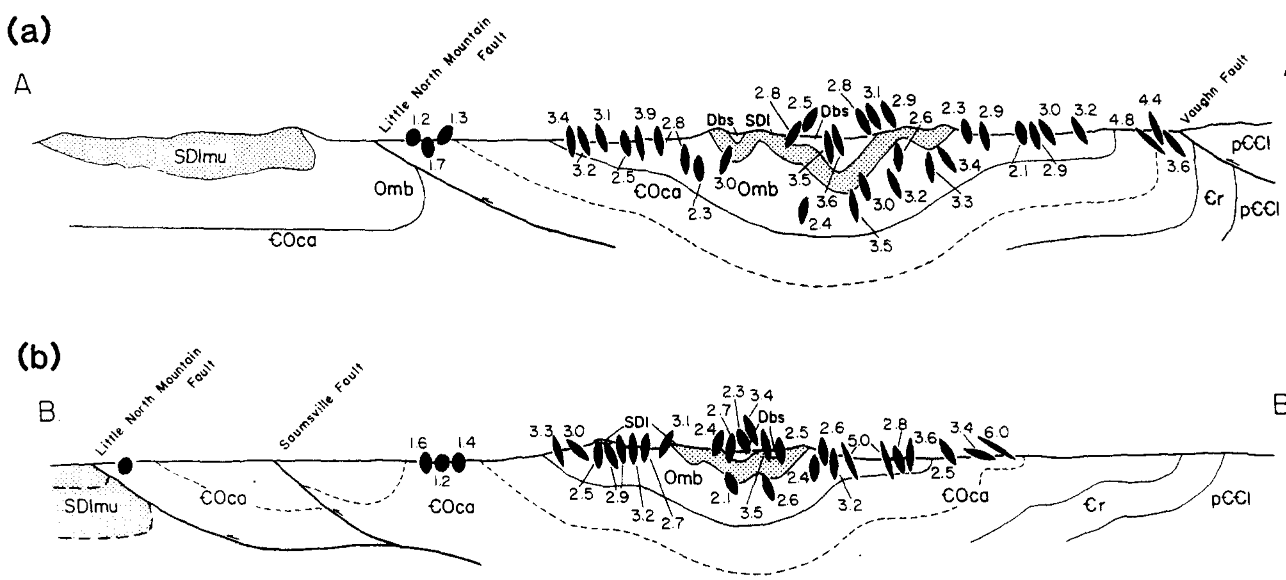

Fig. 6. Regional cross-sections across the Massanutten synclinorium, northern Virginia. Section locations are designated by dotted line (1) on Fig. 10. Ellipses show magnitudes and orientations of X/Z strains calculated from chlorite pressure-fringes on pyrite in Ordovician and Devonian mudrock. Dbs, Devonian black shale; SD, Silurian and Devonian undivided (stippled); Omb, Ordovician Martinsburg Formation; Coca, Cambro-Ordovician carbonates; Cr, Cambrian Rome (Waynesboro) Formation; Pccl, Precambrian and Cambrian undivided. Strains in carbonates are from Cloos (1971).

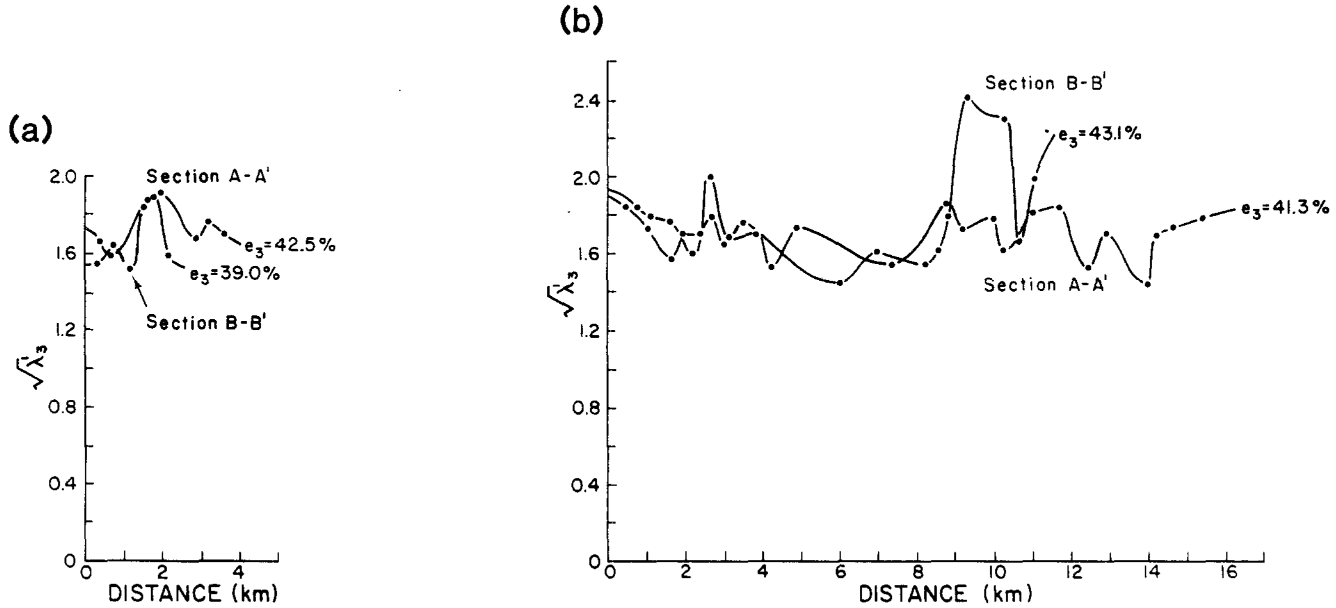

Fig. 7. Strain integration to calculate average strains in sections A–A′ and B–B′ (Fig. 6). Reciprocal quadratic elongation ($\sqrt{\lambda_3'}$) is plotted against distance along minimum principal strain trajectory (Hossack 1978). e_3 – average shortening due to penetrative strain. (a) Ordovician Martinsburg Formation. (b) Devonian shales.

measurements from Cambro-Ordovician rocks in the keel of the synclinorium are lacking. An unbalanced cross-section (Fig. 9) is included to show the relations of the synclinorium to the South Mountain anticlinorium, where Cloos did his pioneering strain work.

BALANCING STRAINED SECTIONS

The first question in modifying our geometrical techniques is which of them need to change, and by how much.

The assumption of plane strain

Balanced sections assume that the pieces of the jigsaw puzzle can be taken apart in order to recreate the predeformational geometry. Thus any section should be parallel to the transport direction and there should be no motion of material into or out of the section plane. Price (1981) suggested that section lines within 30° of the transport direction are close enough for most purposes (less than 15% error). This is probably true for individual sections, or pairs of sections, across an entire orogenic belt, such as those of Price & Mountjoy (1970) and Thompson (1981). If this degree of error is acceptable, most strains in the Valley and Ridge could be ignored in Southern Appalachian sections. In sets of serial sections across a thrust belt (e.g. Roeder *et al.* 1978, Dixon 1982, and Woodward 1985) a 30° error is very serious, whereas an error of ±5° is more reasonable. Cooper (1983) discusses this problem in more detail than the treatment here.

When many individual serial sections are produced, they cannot cross (see Dixon 1982 and Roeder *et al.* 1978 for crossing sections) and they should remain uniformly spaced throughout their lengths (Fig. 10). Balanced sections are restorable and admissible (Elliott 1983), but are not necessarily correct. Sets of restorable and admissible sections are much more likely to be correct, because adjacent section lines provide longitudinal constraints otherwise lacking in an individual section. The critical basis for evaluating how close section lines need to be to the true transport direction to remain restorable, is the scale of the observed structures. Detailed (1:24,000) sections need to be closer to the true transport direction than do 1:250,000 sections.

What does the regional strain distribution have to say about the accuracy of the plane-strain assumption? Given the curved nature of many orogenic belts, there will probably be some movement of material into or out of section planes. Again, as long as this is less than 5% it easily falls within our error limits on true stratigraphic thicknesses, and thus is negligible. Although strike elongations up to 10% have been reported in the Plateau of the Central Appalachians (Nickelsen 1966, Engelder & Engelder 1977), quartz fibres in pressure-shadows on framboidal pyrite in Ordovician shales suggest plane-strain deformation elsewhere (Gray, unpublished data). However, cleavage perpendicular to strike in the Southern Appalachians (Monz & Glover 1984) indicates significant contraction along strike; and some extensional strains parallel to strike may also exist in some units. Elliott (1981 pers. comm.) calculated that the Pine Mountain thrust sheet extended by 10% during motion, dominantly by minor brittle faults and fractures of the type described by Wojtal (1982).

The plane-strain assumption is a reasonable first premise, given our other inherent errors in section construction. The best solution to the plane-strain question is the construction of sets of serial balanced sections at a reasonable scale (1:50,000 or less) to match our section accuracy to our map accuracy.

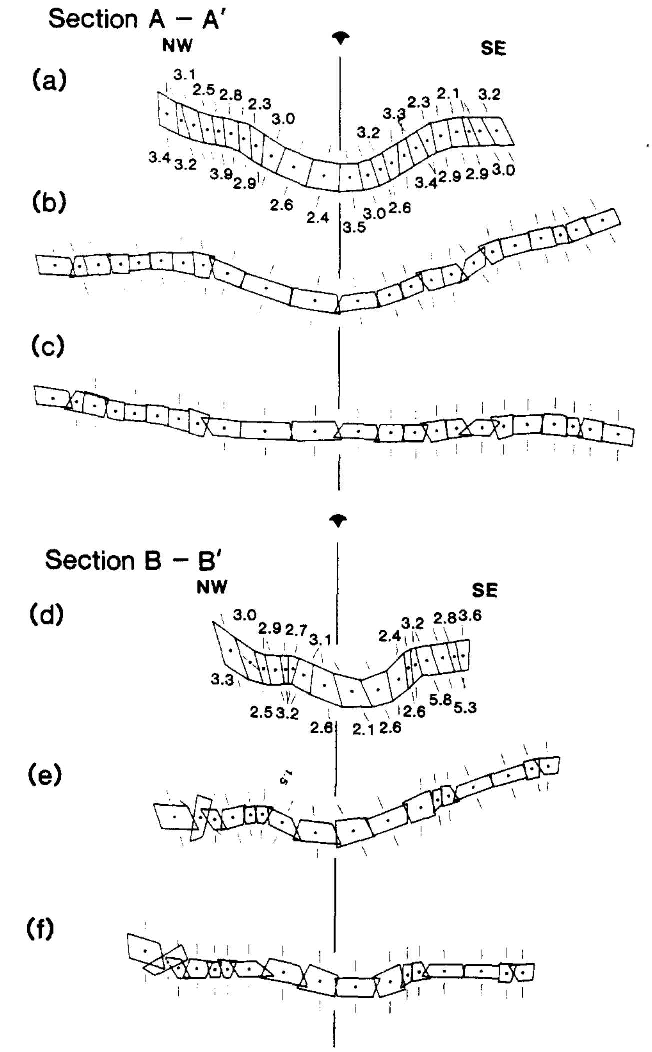

Fig. 8. Strain reversal for cross-sections A–A' and B–B' (see Fig. 6) in the Massanutten synclinorium as delineated by the boundaries of the Martinsburg Formation. (a) and (d) represent the deformed state with selected finite elements, measured strain values and principal elongation directions. (b) and (e) depict fold geometries after reversal of penetrative strains. (c) and (f) represent folds after rotation of all X strain trajectories to vertical.

Parallel folding

The geometric changes across a thrust-belt that most affect the restoration of cross-sections are changes in folding styles and mechanisms. The preservation of section area presupposes parallel folding and preservation of bed lengths. When non-parallel or non-flexural slip folding occurs because of cleavage formation, then our geometric requirements for those units must be relaxed. Fortunately, some stratigraphic units in almost any section (the Cambro-Ordovician Knox Group dolomites in the Southern Appalachians) preserve the parallel geometries despite measurable strains in other units.

Assuming parallel folding there are a number of approaches to unfolding folded rocks, each dependent on selection of a pinning point (Fig. 11). The most common way of unstraining folds has been to pin the fold at the hinge (Fig. 11a) and undeform the layer (Oertel 1974, 1980, Oertel & Ernst 1978). In contrast, sinuous bed-balancing (Dahlstrom 1969) of regional cross-sections, requires line-lengths to be pinned onto the footwall (FW) fault trajectory, as constructed from subsurface information if available, and then the structures in each sheet are unfolded back from the fault. In effect, this pins the forelimb inflection point of the thrust-related folds (Fig. 11c). Suppe (1980, 1983) and Suppe & Namson (1979) unfold their kink-folded sheets by the sinuous bed method. The kink geometry requires beds both within the kink bands at the leading edge of the hangingwall (HW) ramp anticline, and over the FW ramp, to undergo bedding-parallel slip. Beds outside these two kink band regions remain unslipped. The leading HW kinkband boundary (axial plane) is therefore a pin-line, as is the backlimb or the part which has not been over the FW ramp. In Dahlstrom's method, and in fault-bend fold models with asymmetric folds or unequal fault-bend fold angles, the main body of the

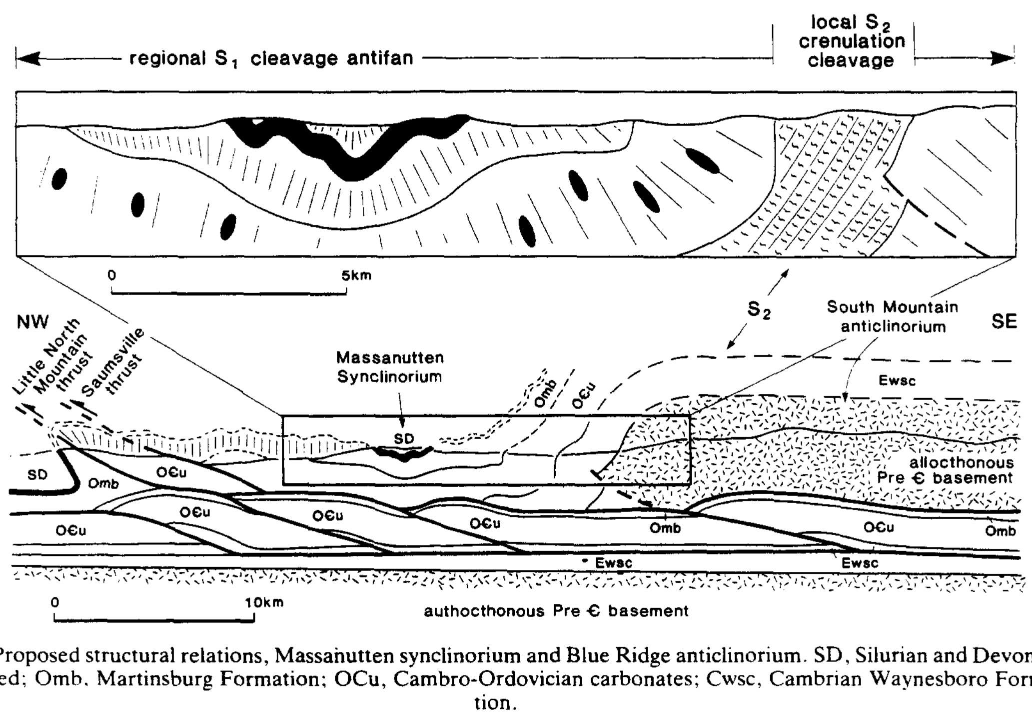

Fig. 9. Proposed structural relations, Massanutten synclinorium and Blue Ridge anticlinorium. SD, Silurian and Devonian undivided; Omb, Martinsburg Formation; OCu, Cambro-Ordovician carbonates; Cwsc, Cambrian Waynesboro Formation.

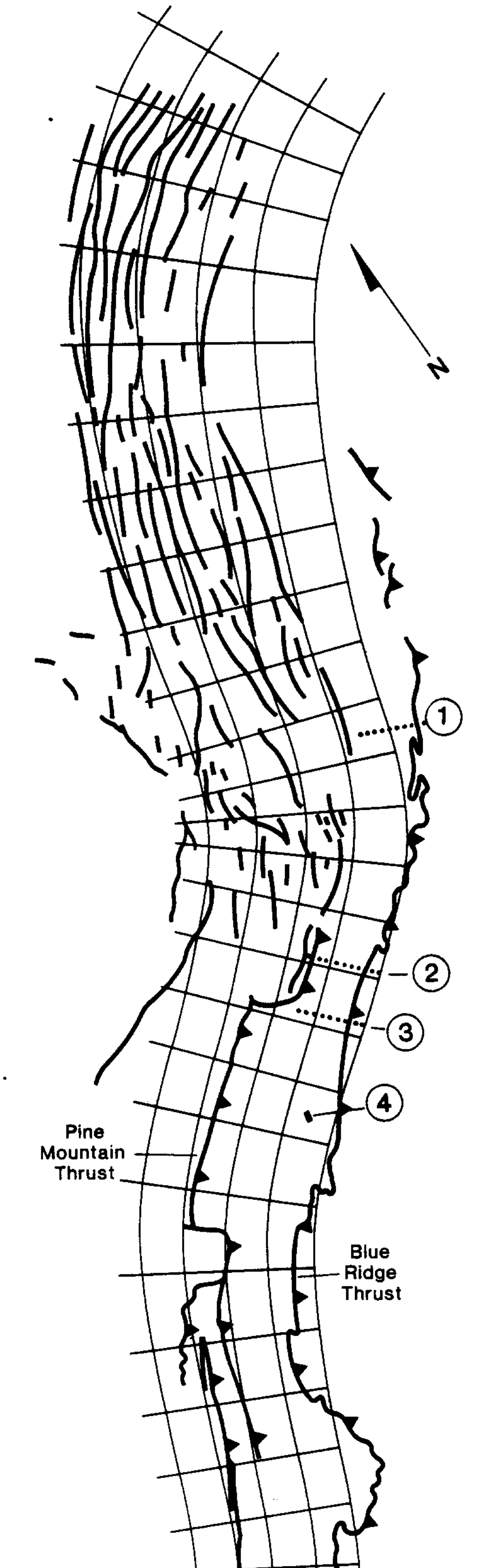

Fig. 10. Regional thrusts and fold axial-surface traces for the central and southern Appalachians with superposed orthogonal grid constructed parallel to the structure grain. Serial cross-section lines, shown by grid lines normal to the grain, must converge and diverge if transport is perpendicular to these trends. Locations of cross-sections used in the paper (Figs. 3, 4 and 6) and the map (Fig. 10) are shown.

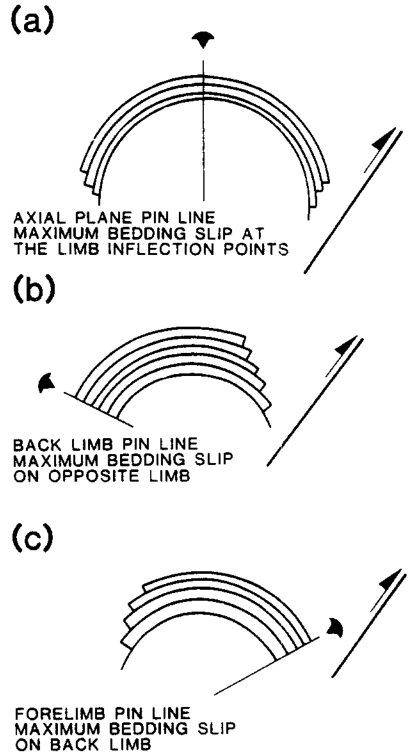

Fig. 11. Possible pin-line positions for general unfolding of folds (see text for details).

thrust sheet must undergo simple-shear by bedding-parallel slip.

A third possibility is that the main body of a thrust sheet undergoes a minimum amount of interbed slip, and that folding and bedding-parallel slip increases towards a thrust. This is the case where the folds are pinned on the backlimb inflection points and both forelimbs and hinges undergo bedding-parallel slip to accommodate parallel folding (Fig. 11b).

Our goal is to pick geometric constraints that most realistically model real rock behaviour as observed in the field. Woodward (1981, 1986) had substantial balancing problems in Wyoming sections that increased away from the foreland pin-line. Even when thrust paths still dipped hindwards, they became very steep in internal thrust sheets. The shapes of restored internal thrust sheets were not representative of the same sheets observed on the surface. Local pin-lines were therefore needed for each internal sheet to preserve the observed surface geometries. In the Southern Appalachians (Fig. 3) few hangingwall cutoffs are preserved, and consequently local pin-lines are again needed in each thrust sheet (Woodward 1985). For consistency and simplicity, the Pine Mountain and St. Clair sheets are also unfolded using internal pin-lines (pinned backlimb inflection-points). These backlimb pin-lines run contrary to the card-deck model of Elliott (1976), which suggested simple shear in thrust sheets and required a thrust to gain slip forward. In line-length balancing however, position of the local pin-line may not be that crucial, as its effects on the restored section are generally within the error limits of measurement. Where possible

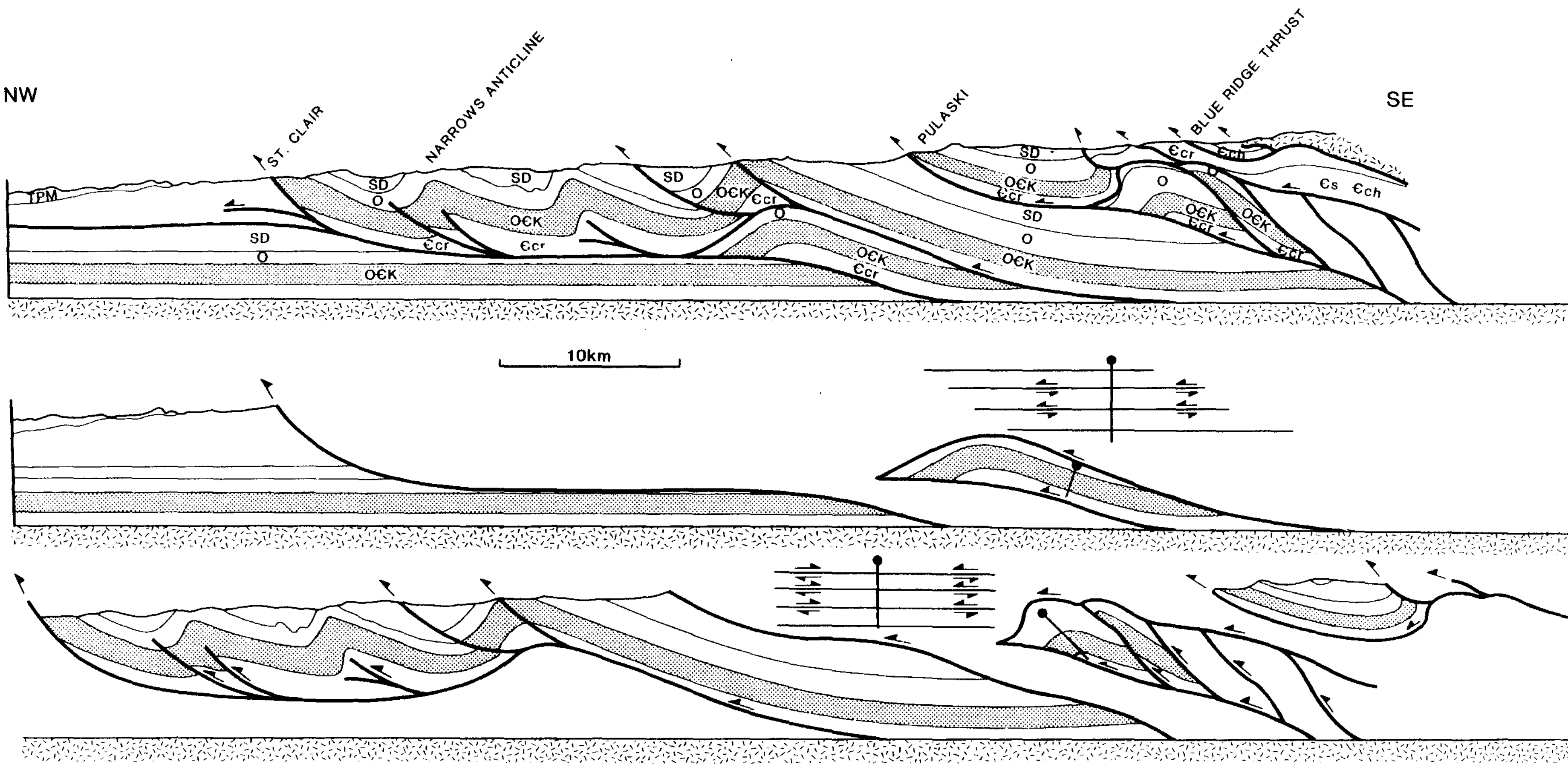

Fig. 12. Partial section restoration for a Valley and Ridge cross-section through Roanoke, Virginia; for the complete restoration see Section 15 (Woodward & Gray 1985, p. 40). The section is taken apart piece by piece, with each part restored using a somewhat different assumption. The external horse is unfolded with a back-limb pin-point, whereas the Saltville and Pulaski sheets are *pinned at the major fold hinges*. The Knox Group (stippled) shows parallel folding, although the middle Ordovician above it and the Rome Formation and Conasauga beneath it are both cleaved. The Pulaski sheet is reconstructed in the final version based on unfolding of the Knox.

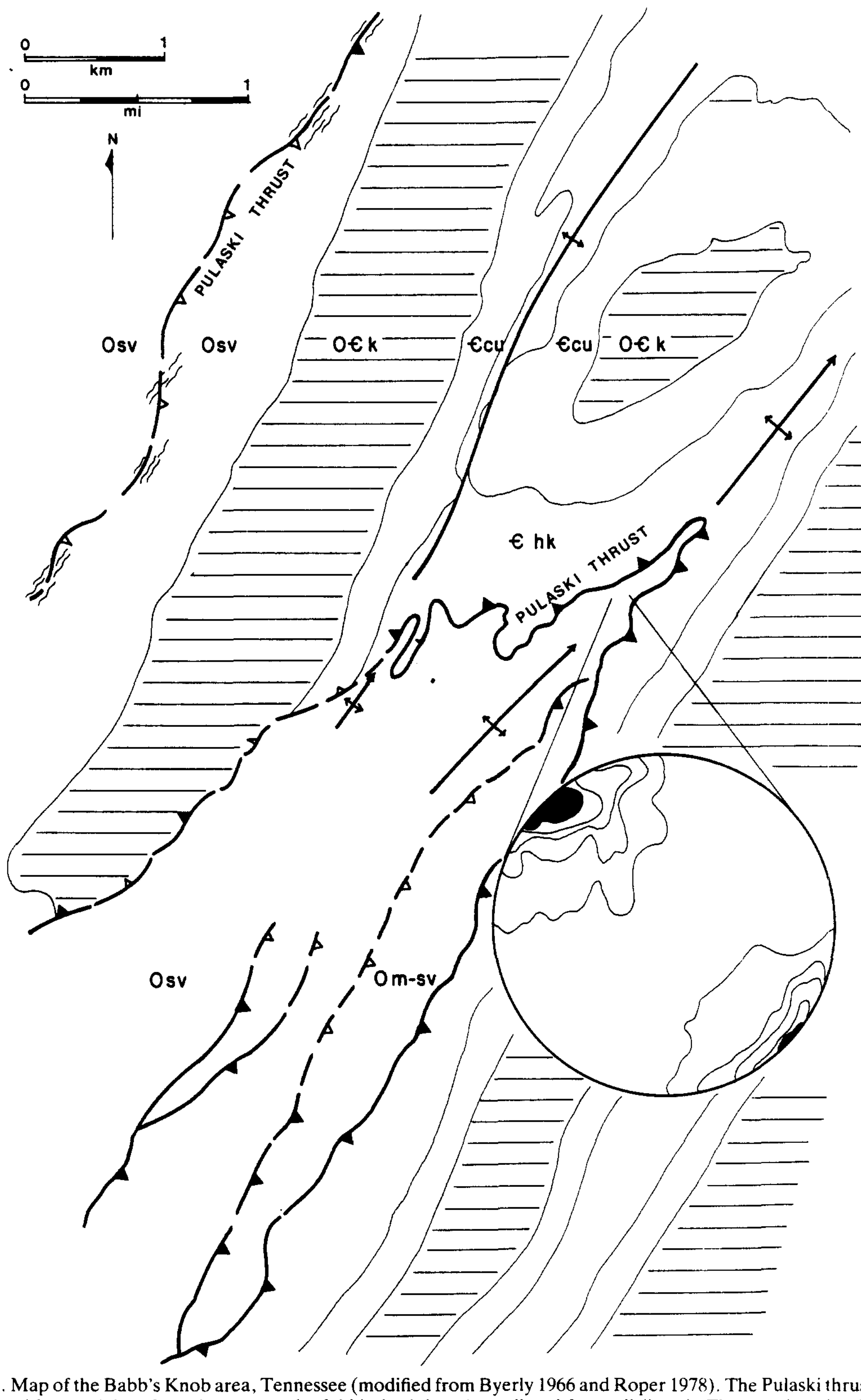

Fig. 13. Map of the Babb's Knob area, Tennessee (modified from Byerly 1966 and Roper 1978). The Pulaski thrust is tightly folded, with an axial-surface cleavage to the fold in both hangingwall and footwall (inset). The map location is given by position 4 in Fig. 10.

pin-line positions should be selected on the basis of fabrics within the main body of the thrust sheet. Another complicating factor is that in a layer undergoing folding pinning positions can change through time.

Our approach is to choose a backlimb (mid-sheet) local pin-line to use in restoring parallel folds in external thrust sheets where penetrative strains are low (Fig. 12). This results in rolling or migrating hinges as folds tighten during thrust motion. As penetrative deformation increases the pinning point migrates from the body of the sheet to the hinge regions of folds, as noted by Fischer & Coward (1982). A concurrent change in folding style is expected from pure flexural-slip in external thrust sheets to flattened flexural-flow folds, or cleavage-modified flattened folds, in internal sheets. A logical intermediate step should be folds with hinges that migrate by some flexural-slip, even after the initiation of significant cleavage formation (see Gray 1981b).

Preservation of lengths and areas

Once cleavage becomes prominent in some units (e.g. Ordovician shales of the Appalachians; Figs. 3 and 6), but not in others (e.g. the Knox Group dolomites of the Southern Appalachians), length and area balancing of all units becomes a problem. The fold geometries suggest that parallel-folding with kink-like form continues to occur in the Knox Group dolomites across the Valley and Ridge, even where the middle Ordovician rocks show major strains. The cleaved units have suffered volume loss (Gray 1981a, Wright & Platt 1982), whereas the Knox did not. Shape changes with no volume loss are what area balancing is designed to accommodate, but it cannot deal with volume losses. Our geometric reconstructions in internal thrust-sheets rely on unfolding and unfaulting the Knox Group which has best preserved its bed length and cross-sectional area. Parallel folding of such massive units is permitted locally by the higher strains in the mudrocks and shales above and beneath it. A comparison of the areas of overlying strained middle Ordovician rocks with the areas reconstructed, based on what should overlie the unfolded Knox, can give some indication of the volume loss. When volume loss occurs the balanced section will show a gap above or beneath the massive units which is otherwise not permitted in balanced sections. It is important to recognize that these gaps are real reflections of penetrative deformation and not 'errors' in balancing.

Superimposed strains

So far, all folding and strain features have been assumed to be related to thrust sheet emplacement onto an undeformed footwall. Reks & Gray (1983) reported several instances of anomalous strain patterns where some high strains were not located in the tightest folds, and others where after removal of the penetrative strains significant folds remained (Figs. 4 and 5). Perhaps the most anomalous result was that adjacent to the tightest syncline and the largest thrust. The strains were not only low, but also not geometrically related to either structure. At Babb's Knob in northeast Tennessee (Fig. 13) the Pulaski thrust sheet is folded tightly over a lower imbricate thrust (Byerly 1966, Roper 1978). Cleavage is present in both the hangingwall and the footwall and is axial-planar to the folded thrust. Our conclusion is that significant components of the total strains within the Pulaski sheet are a result of its folding and straining during piggyback imbrication of its footwall. This general shortening within the sheet can only be traced to its source where both the hangingwall and the footwall can be simultaneously studied. Similar superimposed fabrics were suggested by Mitra & Elliott (1979) for the Virginia Blue Ridge thrusts. Even where apparently simple relationships occur, the possibility of several incremental strains, each related to a different part of the emplacement and later piggyback transport of a thrust sheet, must be considered.

CONCLUSIONS

What steps are needed to systematically include strain data in the geometric rules for restorable, admissible 'balanced sections'? Each thrust sheet will probably show different degrees of penetrative strains and therefore the way each is reconstructed will differ. This is in contrast to simply using sinuous-bed and area balancing on all sections. External sheets are balanced using both sinuous-bed and area method for all stratigraphic units. We would suggest unfolding external sheets using local pin-lines for each sheet. More internal sheets are reconstructed using the sinuous-bed method on massive key-beds which are closest to the 'parallel' geometry and which have preserved their lengths and areas best. Area balancing cleaved units is the best method for other formations in internal sheets (see also Cooper *et al.* 1983). Folds in internal sheets are unfolded from pinned hinges in the key beds. Where severe penetrative deformation affects all stratigraphic units, any balancing of line lengths and areas can only give a rough outline of geometric forms and cannot be relied on without a detailed strain analysis approach. We cannot at this stage obtain the precision in balanced sections that is expected from strain analysis of local areas, because by their scale the balanced sections are based on more general measurements over much larger areas.

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