Geological Society of America
Special Paper 222
1988

The role of kinematics in the construction and analysis of geological cross sections in deformed terranes

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ABSTRACT

This chapter explores the critical role that kinematics plays in the construction and analysis of geological cross sections. The structures on any admissible cross section must arise from relative displacements that are consistent with reasonable deformation kinematics. Sections that violate this constraint are physically impossible. The deformation kinematics can be derived from a displacement field, but the scale at which the displacement field is analyzed affects our perceptions of the movement of rocks in the cross section. Microscopic displacement fields associated with grain-scale deformation may be derived by the standard techniques of finite strain analysis, while macroscopic displacement fields may be derived from the geometry of map-scale cross sections in those regions that have undergone uniform area strain.

Physical compatibility requires that the two scales be linked. In regions of uniform area strain, the displacement fields at the two levels may be linked through elementary vector analysis. Finite strain data indicate that the central Appalachians suffered uniform area strain. Elementary vector analysis of a blind autochthonous roof duplex in the central Appalachians shows that: (1) the faulted stiff layer and its overlying roof layer have separate displacement fields; and (2) restoration of structure sections across regions of uniform area strain requires that sections be constructed approximately parallel to the finite strain trajectory of maximum shortening.

Another way to link the microscopic and macroscopic deformation kinematics is the use of "loose lines" in the deformed and undeformed states. Loose lines drawn on geological cross sections predict the shear strains at any point within a thrust sheet. These shear strains, derived solely from the geometry of structures in the cross section, are independent data that can be compared to measured strains, providing an additional constraint for a cross section. Loose line analysis can also offer insight to the sequence of faulting in a cross section and the geometry of subsurface structures.

Macroscopic kinematic analysis, using vector analysis and loose lines, shows that the "excess section" technique for predicting depth to detachment and finding the initial section length contains implicit assumptions about the kinematics of deformation. Use of this technique without examining the boundary conditions may lead to inadmissible or incorrect cross sections. The problem is perhaps most acute in blind thrust terranes where use of the excess section technique has led to significant underestimates in the amount of shortening in these terranes.

Kinematic analysis suggests that "kinematic admissibility" is an additional criterion that can constrain geological cross sections. Since lines drawn on a section have kinematic significance, it is possible to test a section for kinematic admissibility by attempting to pass from its undeformed state, produced by "balancing" the section, to the deformed state by the process of "forward modeling." This test is applied to several examples from the literature, and it is demonstrated that the proposed solutions can be rejected because they fail to meet the test of kinematic admissibility.

INTRODUCTION

The purpose of this chapter is to illustrate the importance of kinematics in the structural analysis of mountain belts, particularly in the construction and balancing of geological cross sections and in palinspastic restoration. The kinematic history of geologic structures can be determined by linking regional and local finite strain analysis with section construction. Failure to consider the kinematics can lead to serious errors in sections, while knowledge of the kinematics provides an important additional constraint in the section construction process.

The term kinematics refers to an analysis of the movements of component parts of a body during its transformation from the undeformed to deformed states. The movement of component parts in the deforming body is best described with a displacement field. A critical element here is the spacing between the component parts used to analyze the deformation. As the spacing between components changes, and we shift from one scale to another, important qualitative changes arise in our perception of the relative movement of components parts of a deforming rock.

For example, if the spacing between component parts is on the order of tens of meters or greater (macroscopic scale of observation), we focus on the movement of separate horses or thrust sheets. If, on the other hand, the spacing is on the order of a centimeter or less (microscopic scale of observation), we focus on the displacements that accompany the development of rock fabrics. Ultimately, the requirement of physical compatibility dictate that the kinematics at all scales be linked. One of the aims of this chapter is to suggest ways in which this may be done.

Macroscopic kinematics are critical to methods of section balancing and testing for admissibility. As will be seen, the standard methods of area and bed-length balancing (cf. Dahlstrom, 1969; Gwinn, 1970; Elliott, 1979) contain implicit assumptions of the macroscopic kinematic boundary conditions. Unwitting use of these methods leads to significant errors in calculating the depth to detachment in, and determining initial length of, faulted strata. Such errors are easily avoided by applying simple concepts of fault kinematics. Another area affected by the assumptions in implicit areas and bed-length balancing is palinspastic reconstruction. Applying a technique that ignores the presence of a component of shear within a thrust sheet can cause serious errors in the local palinspastic restoration of points within the sheet, although at the regional scale the effects are significantly diminished.

Recently, considerable attention has been focused on the use of balancing and restoration techniques as an aid to unraveling the structural complexity of fold-thrust belts. The aim of these techniques is to use constraints derived from the physical laws to produce balanced sections, where a balanced section is defined as one which is both restorable and admissible (Elliott, 1980). As is well known, however, several different balanced sections may be drawn along a given line of section. The number of possible cross-section solutions can be reduced, and the accuracy of those cross sections improved, by increasing the number of constraints applied to the section. Regional finite strain analyses (Hossack, 1979) and elementary vector analyses of macroscopic kinematics (described in this chapter) are two constraints that have been little utilized in analyzing cross sections of fold-thrust belts. They provide previously unassessed data on the mechanisms of deformation in fold-thrust belts. Although the two data sets are closely related (e.g., information on the state of strain within a thrust sheet is required to determine the macroscopic displacement field), the data sets are determined independently of each other. In this way, these data can be used to check assumptions used during section construction or to constrain possible cross-section solutions.

Strain data are critical to the construction of geologic cross sections. A major goal in structural geology, first attempted by John Suppe (1983), is the derivation of a section construction methodology which guarantees that sections so constructed will be "balanced" and "retrodeformable" by virtue of the construction technique itself. By assuming that rocks above a hanging wall flat undergo no shape change (there are no local displacement gradients), Suppe (1983) was able to derive an analytical method for section construction. Field work by Suppe and Namson (1982) in Taiwan and by Wojtal (1986) in the Appalachians provide evidence supporting this critical assumption for the most external part of the foreland. However, Mitra and others (1988) find evidence of a significant component of simple shear in the Idaho-Wyoming thrust belt. Data supporting similar conclusions exist for basement massifs in the Helvetics (Ramsay and others, 1983) and the Appalachians (Cloos, 1971). As both massifs are mechanically coupled to the foreland, it is probable that a significant shear component extends into the foreland of these belts as well. Thus, knowledge about the state of strain within thrust sheets is critical if one wishes to confidently apply an analytical method like Suppe's (1983) as an aid to determining the structural geometry of a thrust belt.

DETERMINING DISPLACEMENT FIELDS FROM MAPS

The displacement field for any heterogenous strain is unique, and there is no simple relation between the finite strain and the displacement field associated with that strain. Given only the deformed state, the displacement field for a body of rock may be determined only if there are features whose initial and final positions are known (Ramsay and Huber, 1983, p. 58–61). Naturally occurring features of this type are very rare (Means, 1976). However, by analyzing in two dimensions rocks subjected to uniform area strains, it is possible to determine the displacement field directly from finite strains.

Cutler and Elliott (1983) demonstrate that under uniform area strain the orientation of two principal directions and the magnitude of one principal value of the finite strain ellipse remain constant (Fig. 1). As a result, all particles moving in the principal plane containing the constant axis must move in straight lines

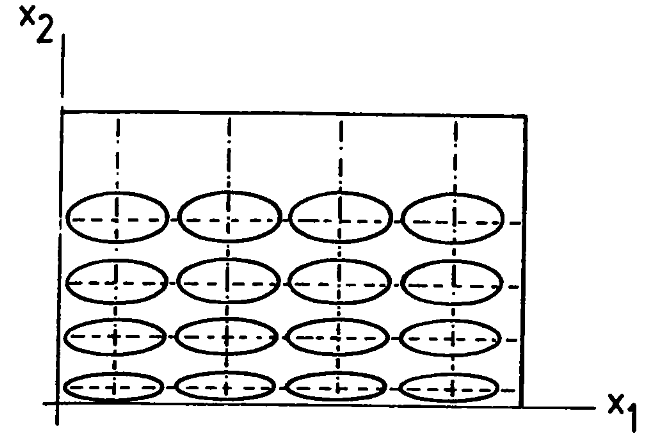


Figure 1. Schematic diagram showing geometric properties of uniform area strain (after Cutler and Elliott, 1983).

normal to it. In other words, the displacement paths of material particles are normal to the constant axis, and thus the trajectory of this axis can be used to determine the displacement field. How common in this type of strain in orogenic belts, and how is it manifested?

With regard to extensional belts, there are virtually no finite strain studies other than those of a regional and generalized nature, and these questions cannot be answered for this type of terrane. In compressional belts, however, it is well known that uniform area strains are not common in the internal parts of these regions where deformation occurred at greenschist grade and higher. Although most regional finite strain analyses have been done in the higher-grade terranes, in recent years more strain data have been gathered in external parts of compressional belts. These data show that, like other parts of orogenic belts, the total strain in foreland fold-thrust belts is partitioned among three mechanisms: faulting, folding, and layer parallel shortening (LPS).

Many of the finite strain data available for foreland fold-thrust belts come from the Appalachians. Finite strain measurements from the central Appalachian foreland (Geiser, 1988a; Fig. 2) show that the characteristic LPS deformation of late Paleozoic strata above duplexes of Cambro-Ordovician carbonates is irrotational flattening. Strains lie in the flattening field with the $1 + e_1 > 1 + e_2 \approx 1.00 > 1 + e_3$. The fold axes are approximately parallel to $1 + e_2$, and $1 + e_1$ is approximately normal to bedding.

These data suggest that deformation in the external part of the central Appalachian fold-thrust belt was a uniform area strain. Cutler and Elliott (1983) and Cutler and Cobbold (1985) demonstrate that the curvature of the strain trajectories is a function of the strain gradients and/or the strain axial ratios. For uniform area strains in particular, the ratio of the curvatures of the strain trajectories equals the axial ratio (Cutler and Elliott, 1983). Thus, if one of the trajectories is straight, the other must also be. Their work suggests that examination of principal strain trajectories of the central Appalachian foreland can provide additional insight into the nature of the strain field.

Finite strains measured in the Valley and Ridge Province include a component due to folding and faulting, and their effects must be removed to ascertain the LPS component. In the New York Plateau of the central Appalachian foreland, however, this problem does not exist. Here, the LPS strain component in rocks exposed at the surface is three orders of magnitude larger than that due to folding and faulting (Geiser, 1988b). As a result, it is possible to examine the LPS strain behavior in this region without having to remove folding and faulting strains.

The finite strain data from the New York Plateau, derived from the widely developed cleavage, penciling, and twinned crinoid ossicles and calcite grains (Engelder, 1979; Engelder and Geiser, 1979; Slaughter, 1982), are shown in Figures 3 and 4. The principal strain trajectories are generally parallel in the regions where $(1 + e_3)^{-1} > 1.10$; they curve gently and diverge as $1 + e_3 \rightarrow 1.00$. In accordance with the prediction of the compatibility equations, the trajectory divergence is most pronounced in the regions with the greatest variability in area strain, namely those regions where $1 + e_3 \rightarrow 1.00$.

How significant is the divergence of trajectories if we wish to use them to determine the displacement field? The effect is negligible since the scale of the principal trajectories we are considering is many orders of magnitude greater than the scale at which the deformation occurred. For example, the data cover a region whose dimensions are on the order of 10^{10} m^2, whereas the deformation mechanisms, operating at the level of grains or hand specimens, affected areas on the order of 10^{-2} to 10^{-3} m. Moreover, the maximum strains only reach values of $(1 + e_3)^{-1} \approx 1.09$ (Geiser, 1988b). Curvature of the trajectories is ~0.3°/km. Given these values, the assumption of uniform area strain is a good approximation, and the following method may be used to find the displacement field for the region. This method can be applied to any region where the strain field has the characteristics outlined above.

The first step is to prepare an iso-strain map using finite strain data from the region of interest (Fig. 3). Plots of $1 + e_3$ values versus distance show that where data exist, the strain gradients are approximately linear parallel to this axis (Geiser, 1988b). The deformed state iso-strain map (Fig. 5) was constructed by assuming that strains parallel to the $1 + e_3$ trajectory vary linearly with distance across the region. Finite strain values at any point can be found by interpolation.

A relative displacement field for the region is determined by finding the original locations of the material lines that now coincide with the iso-strain contours. It is necessary to integrate strain values along any strain trajectory (Hossack, 1979); the strain integration method used here is shown schematically in Figure 6. For any point, the direction of the displacement vector is given by the principal strain trajectories, while its magnitude is given by interpolation between the iso-strain contours.

Local displacement vectors are found by drawing an orthogonal grid on the deformed central Appalachian Plateau, and

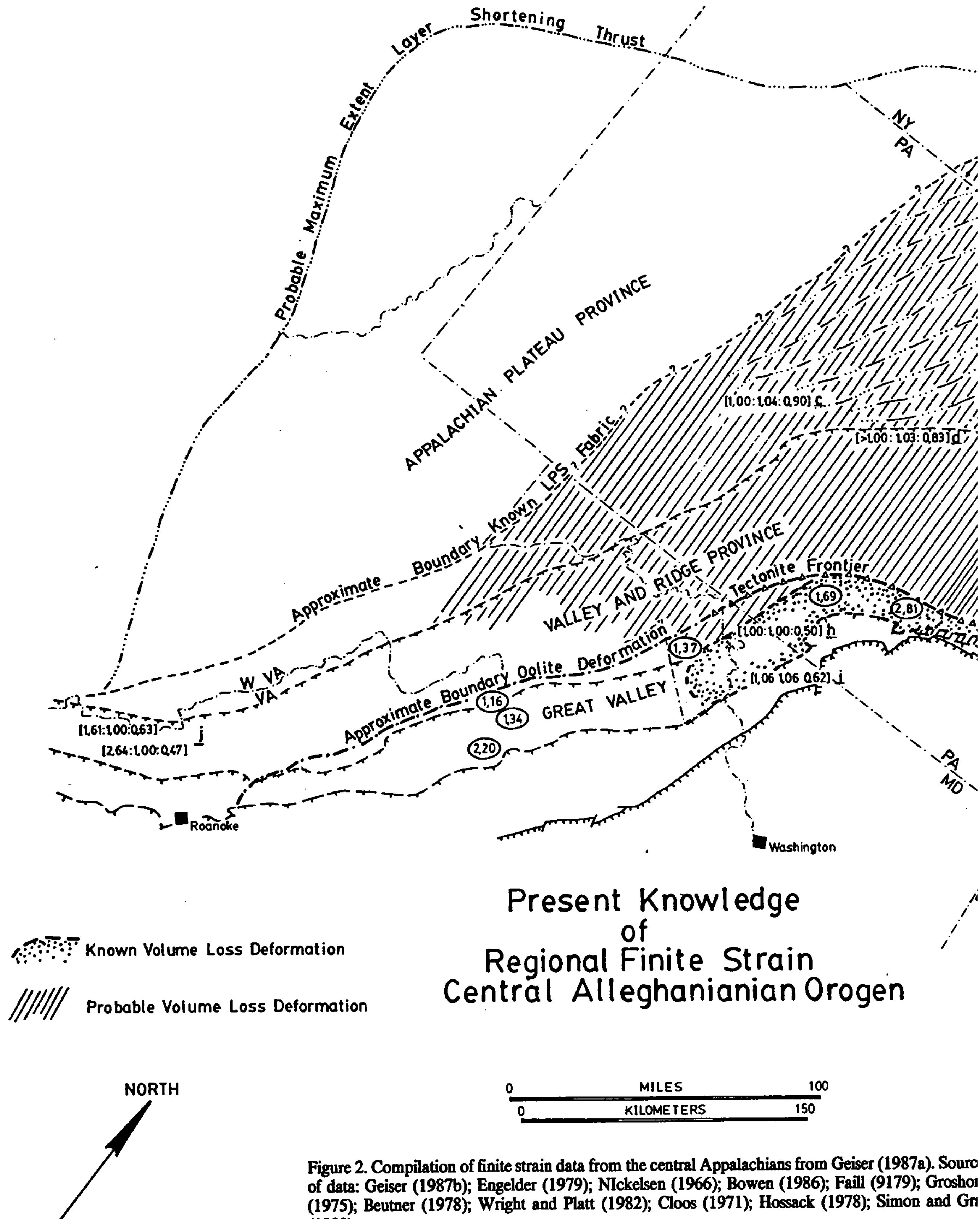
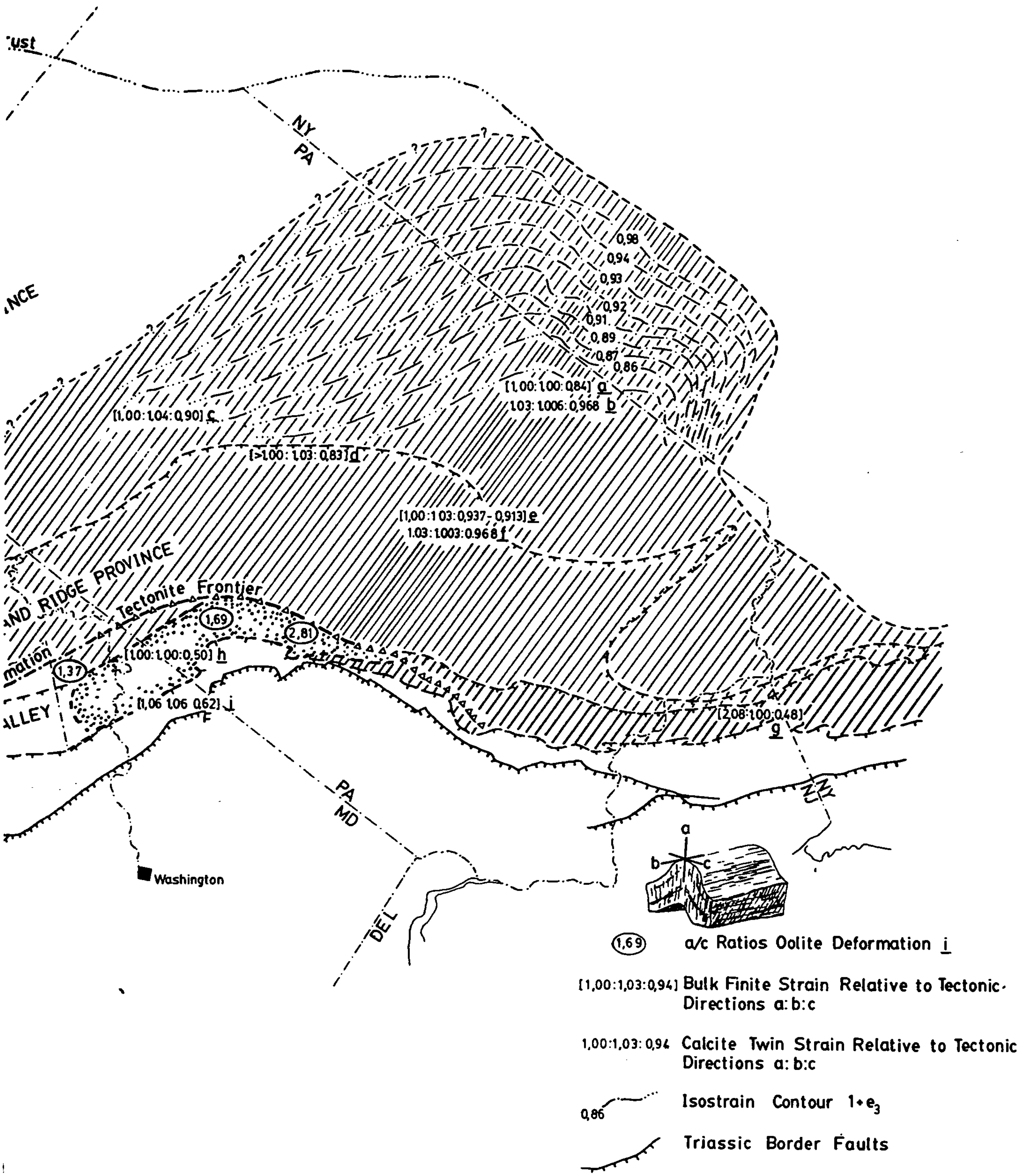


Figure 2. Compilation of finite strain data from the central Appalachians from Geiser (1987a). Sourc of data: Geiser (1987b); Engelder (1979); NIckelsen (1966); Bowen (1986); Faill (9179); Grosho (1975); Beutner (1978); Wright and Platt (1982); Cloos (1971); Hossack (1978); Simon and Gr (1982).


NY
PA
0,98
0,94
0,93
0,92
0,91
0,89
0,87
0,86
[1,00:1,00:0,84] a
1,03:1,006:0,968 b
[1,00:1,04:0,90] c
[>1,00:1,03:0,83] d
[1,00:1 03:0,937-0,913] e
1,03:1,003:0,968 f
RIDGE PROVINCE
Tectonite Frontier
1,69
2,81
1,37
[1,00:1,00:0,50] h
[1,06 1,06 0,62] i
[2,08:1,00:0,48] g
PA
MD
NY
NJ
DEL
Washington
a
b
c
1,69 a/c Ratios Oolite Deformation i
[1,00:1,03:0,94] Bulk Finite Strain Relative to Tectonic Directions a:b:c
1,00:1,03:0,94 Calcite Twin Strain Relative to Tectonic Directions a:b:c
0,86 Isostrain Contour 1+e3
Triassic Border Faults

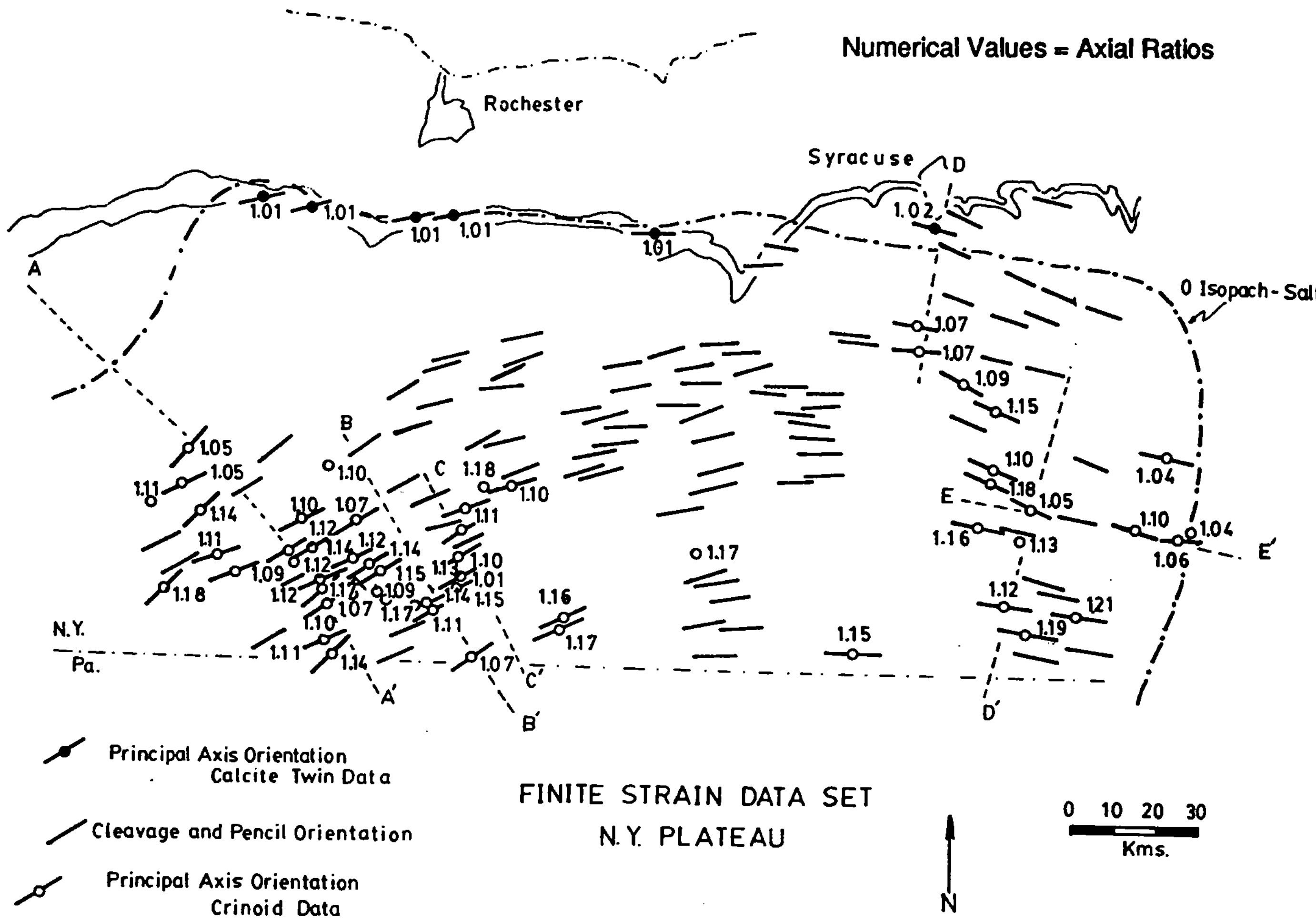


Figure 3. Finite strain data showing layer parallel shortening in the New York Plateau.

using the measured strains to determine an Eulerian specification of each point on the grid. The reciprocal strain matrix for each grid element is then determined by comparing the original shape of any element in the grid with its image in the deformed state (Fig. 7).

DISPLACEMENT FIELDS FROM GEOLOGICAL CROSS SECTIONS

Duplexes are common structures in fold-thrust belts (Boyer and Elliott, 1982). The portion of the stratigraphic section shortened by imbricates between the floor and roof thrusts in the duplex is here called the stiff layer; the strata above the duplex are here called the roof layer of the duplex. The roof layer strata in a "typical" duplex are allochthonous, that is they are translated by movement on an *active* roof thrust. Banks and Warburton (1986) showed that the cover strata above some duplexes are not displaced with the stiff layer and that these relatively autochthonous strata are passively uplifted as the stiff layer is shortened. Shortening of cover strata in such a "passive roof" may occur by movement on an emergent antithetic thrust, forming a triangle zone (Banks and Warburton, 1986; Fig. 8). Passive roof duplexes occur in the central Appalachians (Perry, 1978; Herman, 1984; Herman and Geiser, 1985), but there are no antithetic thrusts at the front of the duplex. Shortening in the cover strata occurs by body deformation and minor thrust faults restricted to the cover (Fig. 8). I will refer to duplexes like those in the central Appalachian Plateau described by Herman (1984) and Herman and Geiser (1985) as blind autochthonous roof duplexes, those describes by Banks and Warburton (1986) as emergent autochthonous roof duplexes, and the type described by Boyer and Elliott (1982) as allochthonous roof duplexes.

For purposes of analysis, I assume that the roof layer and stiff layer were initially the same length (bed-length balance; see Fig. 8), that is, deformation occurred after the deposition of both layers. I will show later that this assumption can be tested independently. The contact between the cover and the stiff layer

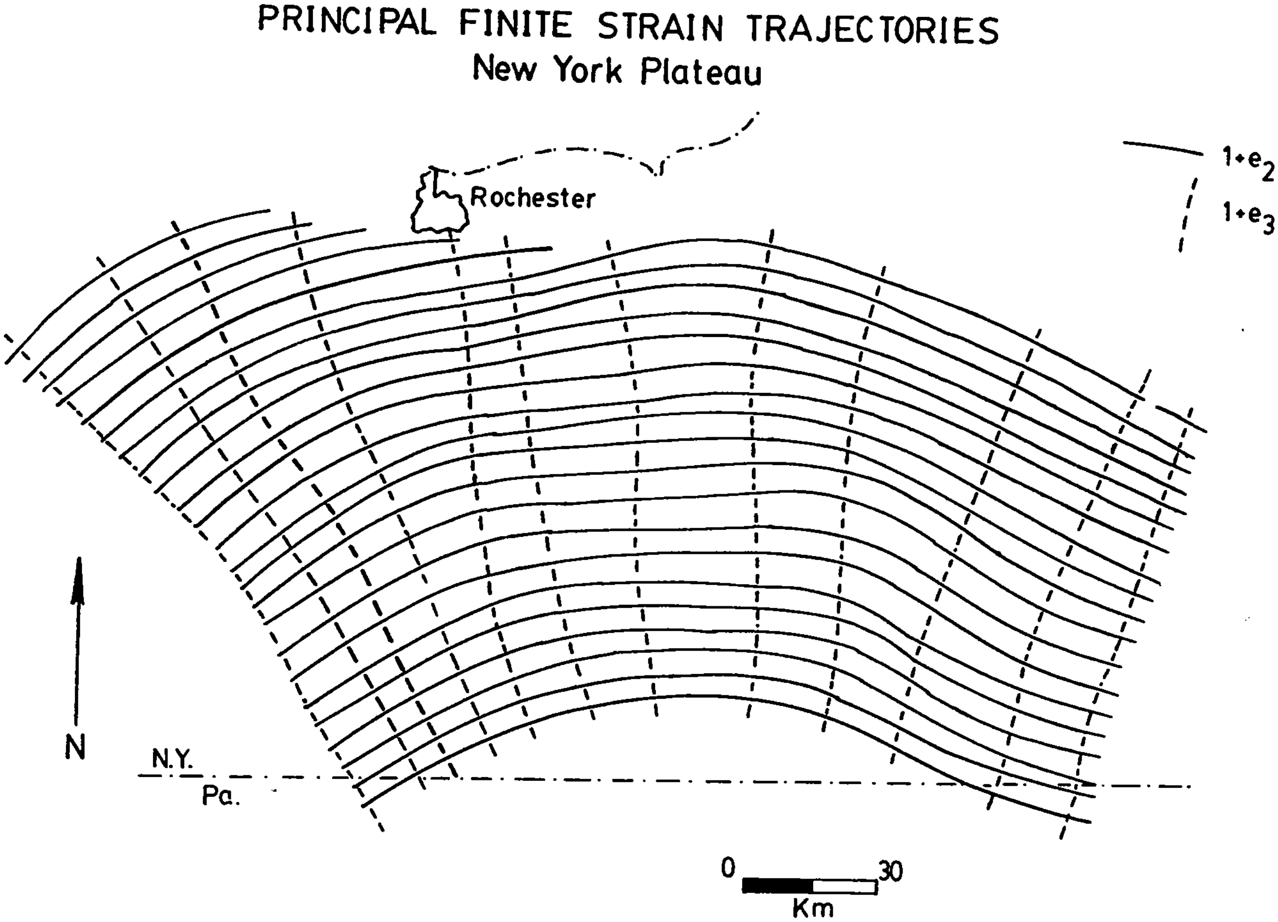


Figure 4. Finite strain trajectories for layer parallel shortening in the New York Plateau.

consists of two boundaries: the base of the cover strata and the top of the stiff layer (Fig. 8a). I also assume that the deformation of the stiff layer is restricted to flexural flow or slip, and thus preserves bed length. This assumption can be relaxed later.

Consider a small material region P, which straddles the roof thrust, partly in the stiff layer and partly in the cover (Fig. 9A). After movement on a single imbricate in the stiff layer, one portion of P is attached to the base of the roof (Pc_1 in Fig. 9-B1), and the other portion is attached to the top of the stiff layer (Psl_1 in Fig. 9-B1). While these two points had identical initial positions, their displacements during deformation were not the same. This occurs because deformation mechanisms other than faulting and flexural slip folding may occur in the cover layer. The net displacement of the roof layer during the emplacement of horses in the stiff layer will be the sum of the following components, where the subscript i denotes the contribution during the emplacement of the ith horse:

(1) U_{cAi} = the displacement component of the roof layer due to area constant strains, e.g., contraction and extension faulting, minor folding, etc., which produce plane strain thickening or thinning of the section.

(2) U_{cDi} = the displacement component of the roof layer due to dilational strains, e.g., pressure solution.

(3) U_{cTi} = the component of the total translation of the roof layer relative to its footwall due to the motion of any given assemblage of horses where bed length is preserved, e.g., rigid body translation and rotation, faulting, and fault bend folding (Fig. 9).

Note that U_{cAi} and U_{cTi} will have the same signs in compressional terranes, and opposite signs in extensional terranes. U_{cDi} will always have the same sign as U_{cTi} in compressional terranes, since no significant volume increases are known to occur in orogenic belts.

Let us now examine how the displacement of the entire thrust system is partitioned between the stiff layer and roof layer. To do this, I define (see Fig. 9):

U_{Ti} = the increment of displacement of the thrust system with respect to the "basement", where $U_{Ti} = n_{sli} - n_{bi}$. For the

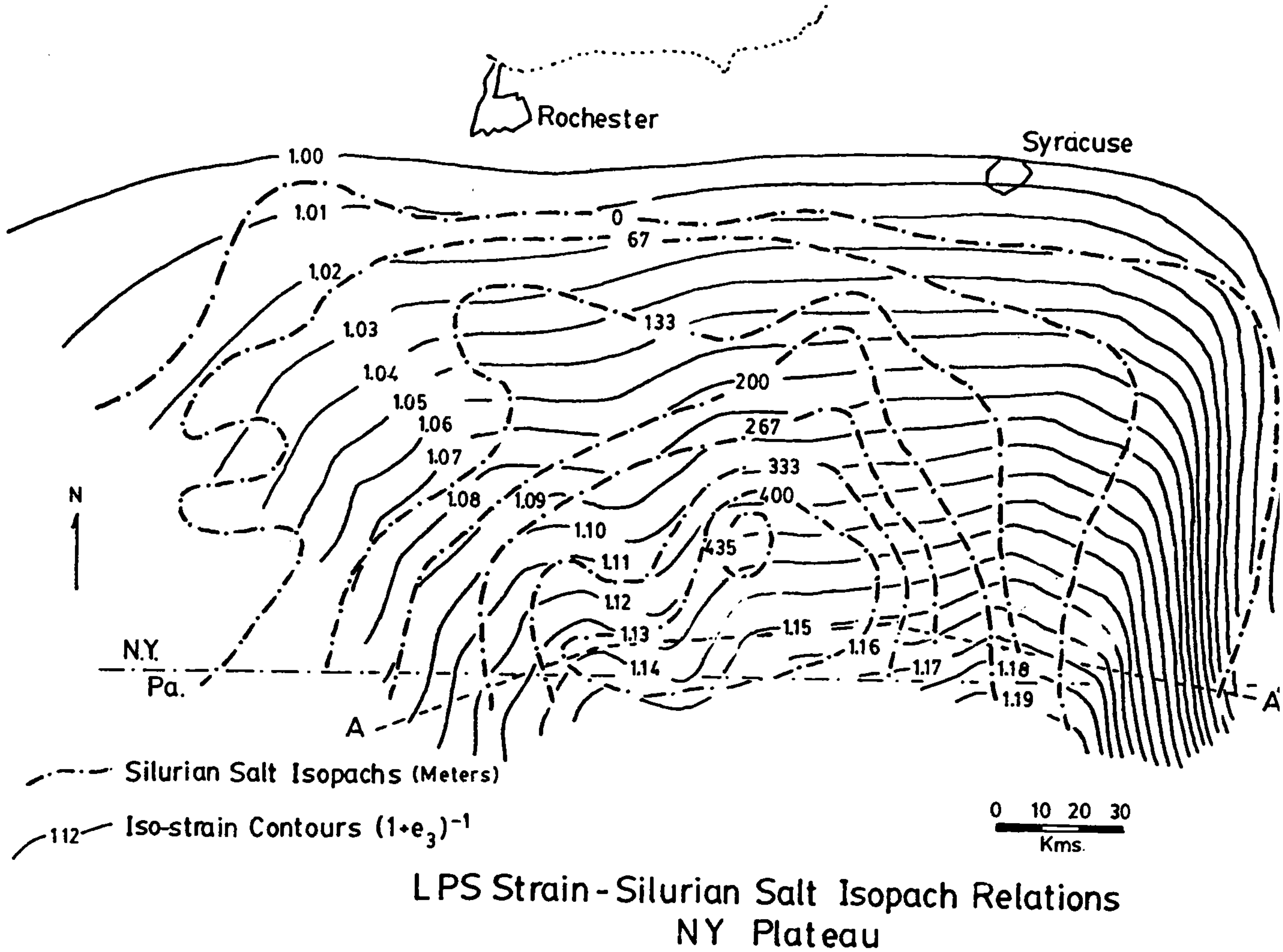


Figure 5. Iso-strain map prepared from finite strain data shown in Figure 3.

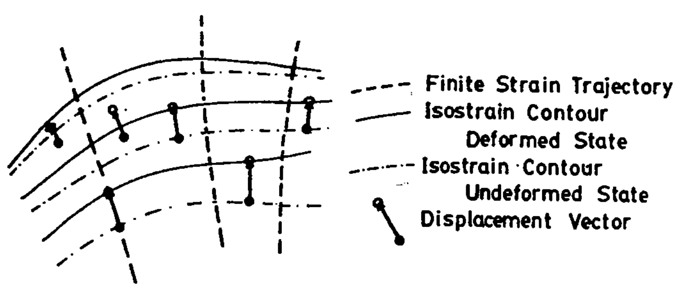


Figure 6. Method of calculating two-dimensional displacement field. Iso-strain contours for deformed state established from field data. Iso-strain contours for undeformed state given by integrating the inverse of finite strain data for the deformed state along the principal finite strain trajectories (Geiser, 1987b).

purposes of this example, I assume that the stiff layer suffers no shear strains as long as it has its original dip. If the shear component is $\alpha > 0$, then the error due to ignoring shear strains $\Delta U_{Ti} = \alpha t_{sl}$, where t_{sl} is the thickness of the stiff layer.

U_{fi} = the increment of slip lost or gained due to folding of an assemblage of i horses where $i \geq 1$, where U_{fi} may be either positive or negative.

U_i = the displacement of the hanging wall cutoff of the top of the leading horse relative to its footwall cutoff.

Using these definitions, the following equations describe the motions of the duplex and its cover.

$$U_{cTi} = U_{Ti} + U_{fi} = U_i \quad (1)$$

The displacement U_{cTi} must be absorbed by the roof layer during the motion of the ith horse. I assume that the stiff layer undergoes only constant area strain and thus preserved bed length. This

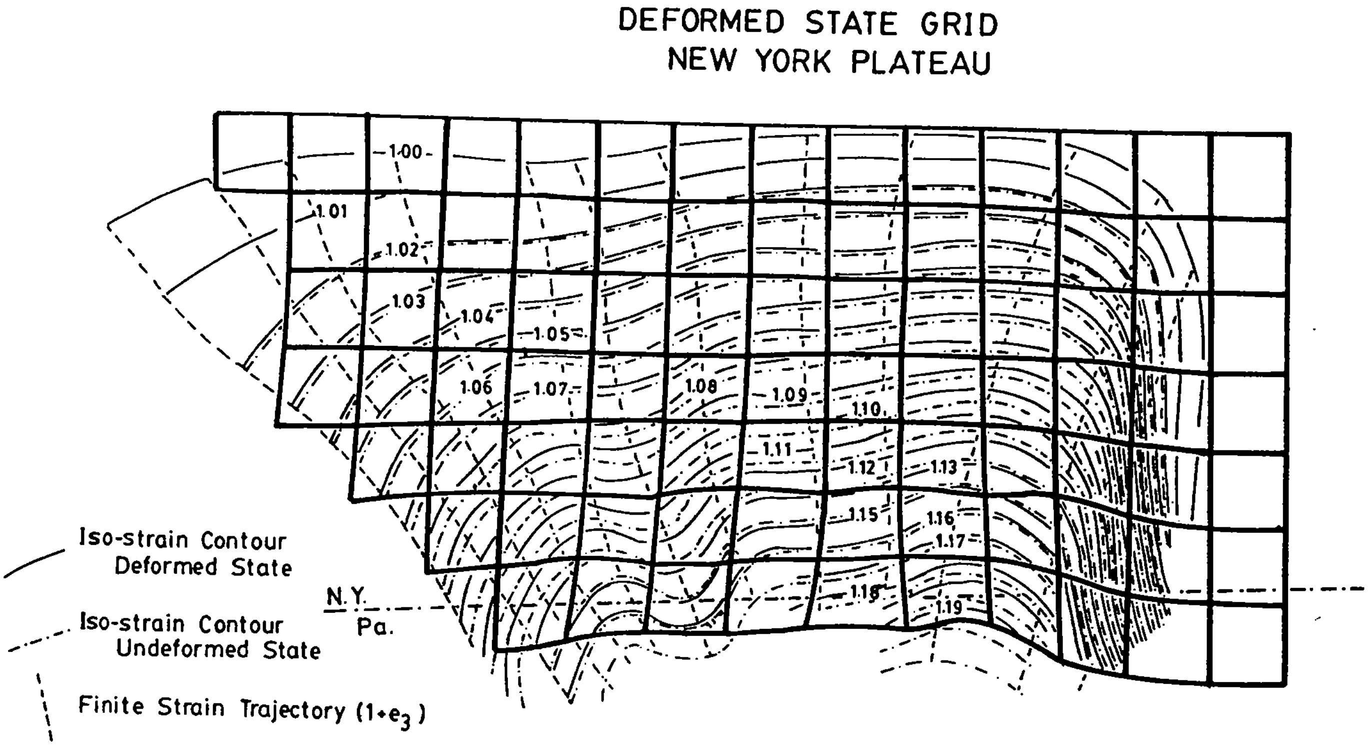


Figure 7. Deformed state grid given by displacement field determined from data set shown in Figure 3. Initial length of each grid element is 20 km.

ondition can be relaxed by simply adding a term to equation 1 to nclude the integrated area strains for the stiff layer as well.

To include the area strains in the roof layer in the calcula- ion, let U_{ci} be the displacement of the cover:

$$U_{ci} = U_{cAi} + U_{cDi} + U_{cTi} \tag{2}$$

vhen $U_{cAi} = U_{cDi} = 0$,

$$U_{ci} = U_{cTi} = U_i \tag{3}$$

The relation between the displacement of the roof layer, U_{ci}, nd any increment of displacement of the entire thrust system, U_{Ti}, can be found by substituting the value of U_{cTi} from equation into equation 2.

$$U_{ci} = U_{cAi} + U_{cDi} + U_{Ti} + U_{fi} \tag{4}$$

Equation 2 and Figure 9 illustrate how the motion of points the roof layer is related to the motion of points in the stiff layer. he area constant and dilational strains, U_{cAi} and U_{cDi}, can be easured directly in the field. This is not true for the translation the roof layer due to the motion of the stiff layer U_{cTi}. In general, it cannot be independently determined whether the roof layer strata are pinned relative to the horse (Fig. 9-B1-B2) or to the footwall of the stiff layer (Fig. 9C). Figure 9, in which $U_{cAi} = U_{cDi} = 0$, shows that there are three possible final positions relative to the underlying horse for a point initially attached to the cover, P_c. It may (1) move forward due to motion imparted to it from a more internal horse (Fig. 9B$_1$, point Pc_2), (2) move backward by "insertion" or "delamination" (Fig. 9C, point Pc_1), or (3) remain pinned at the top of the HW cutoff (Fig. 9B$_1$, point Pc_1). To further complicate matters, it is conceivable that any given point in the duplex cover may move in different directions at different times during the deformation history. How then may we determine the initial position of any point in the cover with respect to its initial position above the stiff layer?

One approach to a solution (Fig. 10) is to take advantage of the relationship between the total displacement of the duplex thrust system relative to the footwall of the sole fault, U_T, and the total displacement of the roof layer relative to the stiff layer, U_c. The total displacement of the cover at any point where $U_c = \Sigma U_{ci}$ is the sum of each of the terms in equations 1 and 4, where $U_{cA} = \Sigma U_{cAi}$, $U_{cD} = \Sigma U_{cDi}$, $U_{cT} = \Sigma U_{cTi}$.

$$U_c = U_{cA} + U_{cd} = U_{cT} \tag{5}$$

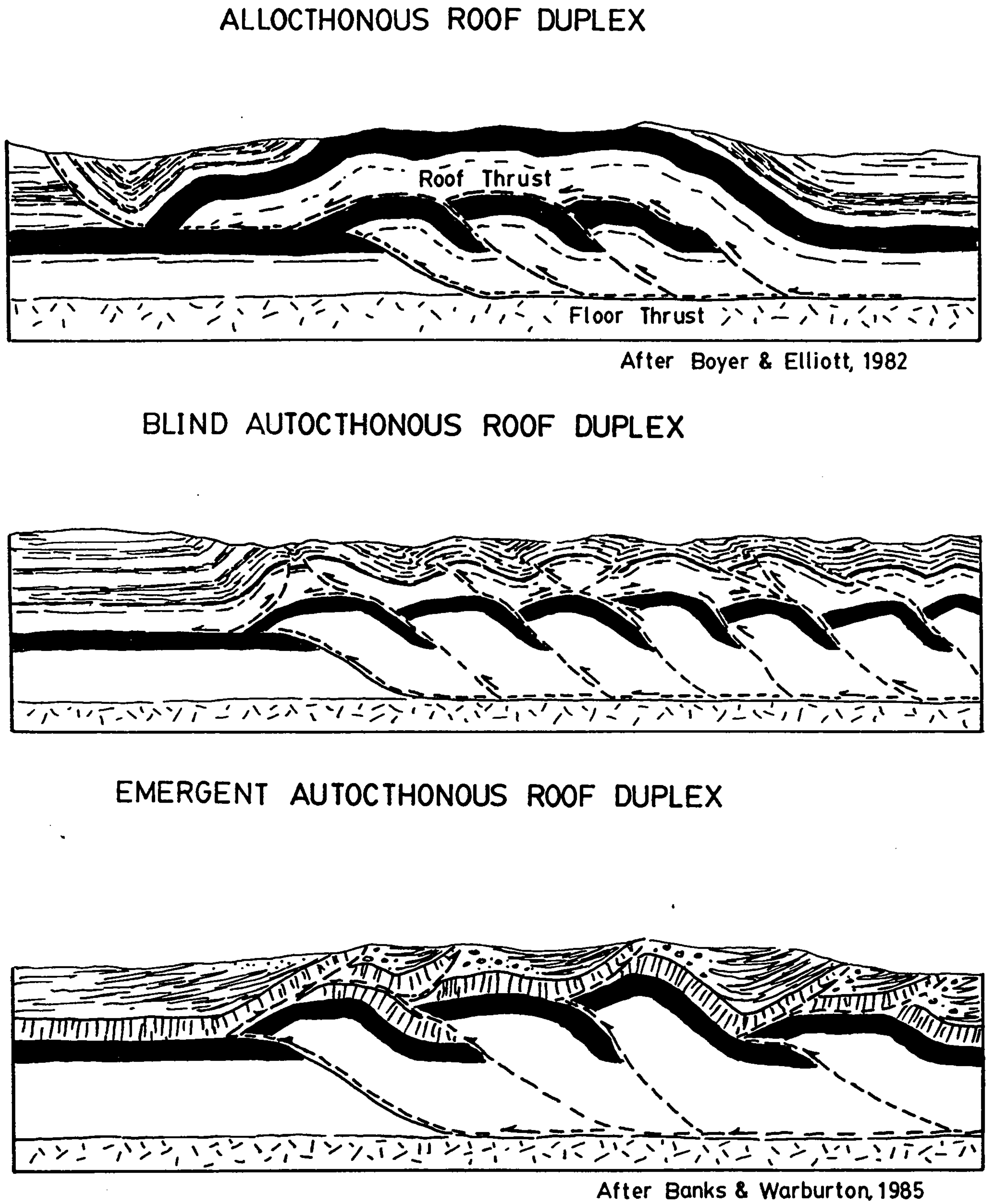


Figure 8. Schematic diagram illustrating the contrasts between allochthonous roof and autochthonous roof duplexes. Note that an allochthonous roof duplex is equivalent to a flat-on-flat structure while an autochthonous roof duplex is a ramp-on-flat structure.

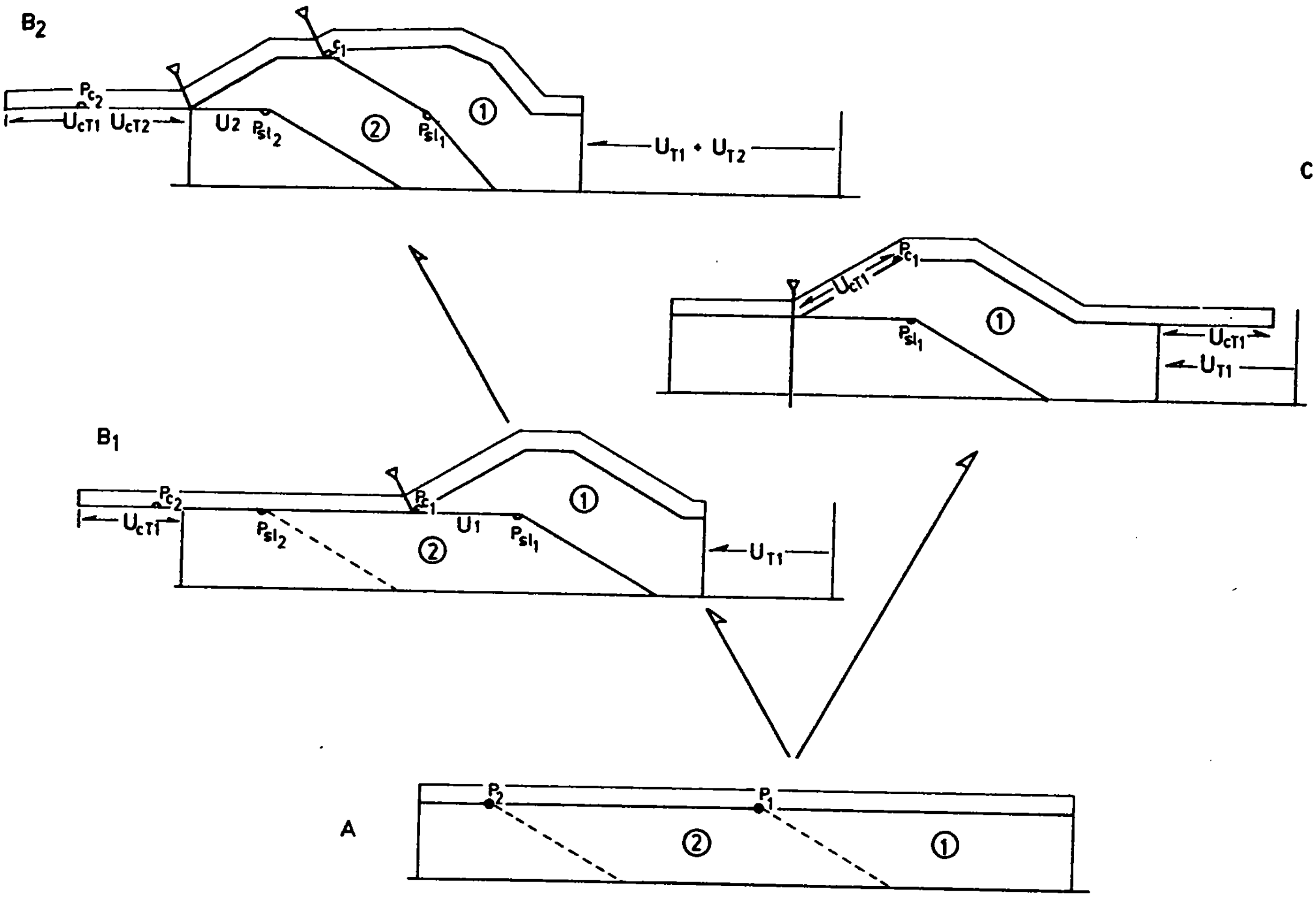


Figure 9. Schematic diagram of the three possible displacements that the roof layer may have relative to its associated horse. The case illustrated shows only the effects of rigid body translation of the roof layer, i.e., $U_{cA} = U_{cD} = 0$. 9A shows the undeformed state with points P_1 and P_2 located at the boundary between the roof layer and the stiff layer. 9B_1 shows the case in which the roof layer is pinned to its horse (Point Pc_1, horse 1). This causes translation of the part of point P_2 that is attached to the roof layer (point Pc_2) by the amount U_{cT1}, where $U_{cT1} = U_{T1} + U_{fl}$ and U_{fl} is the displacement gained or lost due to folding. 9B_2 shows the effect of repeating this process for the motion of the next horse. 9C shows the relative motion of the roof layer and horse due to delamination.

Equation 5 expresses the relationship between the displacement of the roof layer relative to the stiff layer for a duplex of n horses, where U_{cA} and U_{cD} are integrated uniform area strains (see Hossack, 1978; Woodward and others, 1986, for discussion of strain integration techniques). Since these are vector sums, the value of the term U_c gives the translational component of the roof layer at any point, regardless of its deformation history. Thus, given the correct values for U_{cA} and U_{cD}, we can find the values of U_c at this point. Note that for a blind autochthonous roof duplex, the value of U_c will decrease to zero at the tip of the roof thrust. Given these properties and the location of the tip of the roof thrust, the following method can be used to find the value of the term U_c at any point in a blind autochthonous roof duplex:

(1) In the deformed state, chose an arbitrary point at the boundary between the stiff layer and the roof layer (Fig. 10a, points P_{ci} – P_{s11}). (2) Remove the strains due to map-scale folding and faulting by bed-length balancing the section (Fig. 10b). (3) Remove the LPS strains by using the values for U_{cA} and U_{cD} (Fig. 10c). Once this is done there are three possible results (Fig. 10c).

(1) If there has been backthrusting (delamination or insertion), the portion of the deformed-state point P_{ci} attached to the roof layer will now be located ahead of (i.e., in the direction of) thrust motion, its apparent image point (p_{s11}) in the stiff layer (Fig. 10c1).

(2) If the point P_{ci} had initially been moved forward with the entire roof layer due to movement on a more internal thrust,

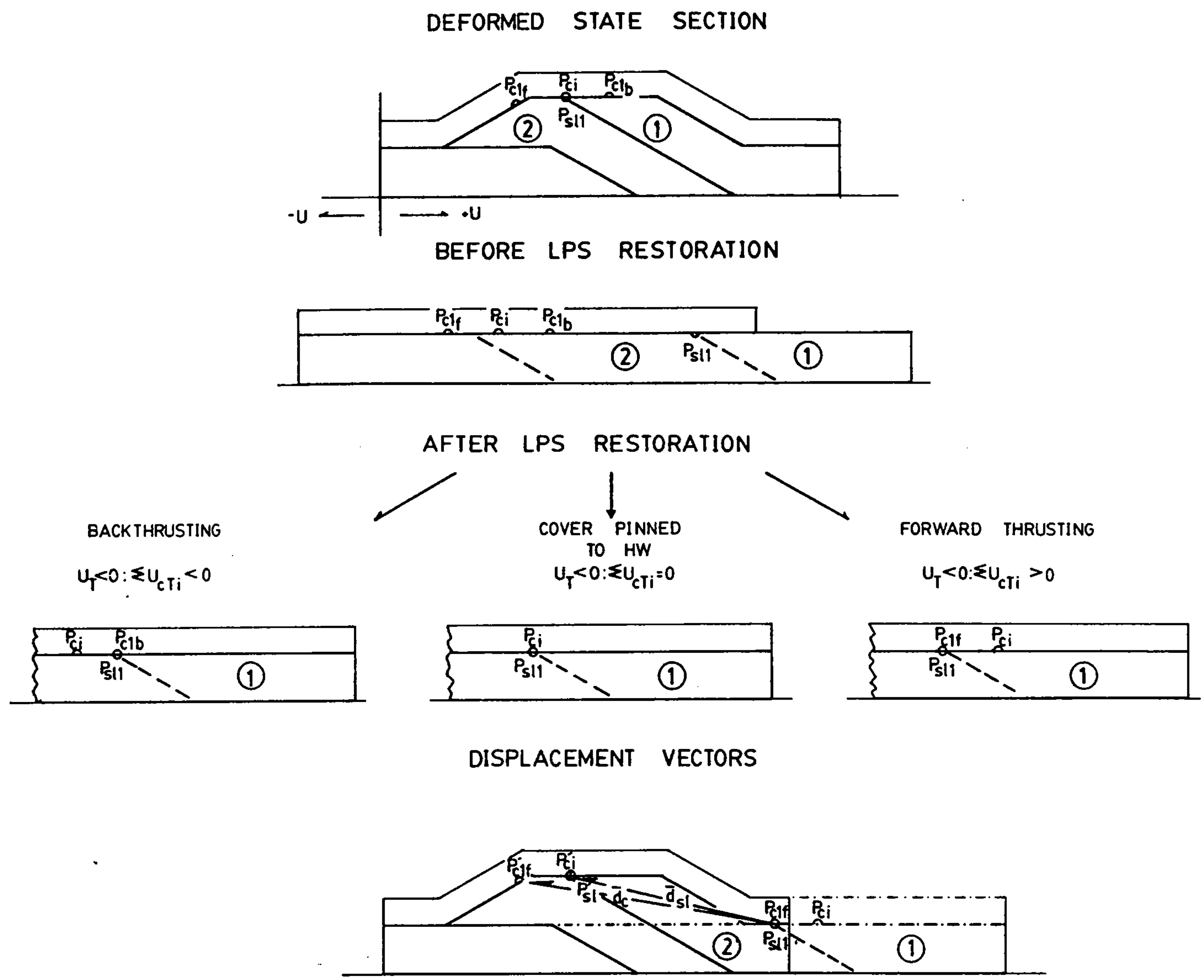


Figure 10. Illustration of how the three possible final positions of an arbitrarily chosen point (P_{ci}) at the roof layer–stiff layer interface may be used to determine the relative motions of the roof layer and the stiff layer. In the first step, before LPS restoration, all faulting and folding strains are removed. In the second step a correction factor is applied to the roof layer by integrating the finite LPS strains measured in the roof layer and extending or contracting the roof layer accordingly. After this LPS restoration the points of contact between the roof layer and the stiff layer are now in their initial positions. If backthrusting or delamination has occurred, the point P_{ci} appears to have moved in the same direction as the stiff layer. For the pinned case, P_{ci} has undergone no motion relative to the stiff layer, while in the forward-thrusting case the point P_{ci} appears to have moved backwards relative to the stiff layer. Since the initial position of all points in the undeformed state is now known relative to the initial, it is possible to find their positions in the deformed state and identify the associated displacement vectors.

then the restored position of the point, p'c, will be located behind (i.e., in the direction opposite) thrust motion, its apparent image point p_{s11} (Fig. 10c3).

(3) If the roof and stiff layers were either pinned to each other or the deformation history such that the sum of the translations cancel each other out, then the point p_c will coincide with the point p_{s11} (Fig 10c2).

With the true position of the point P_c found, a displacement vector for the roof layer can be constructed (Fig. 10d). The displacement vectors for the stiff layer and roof layer coincide only where the roof layer is pinned to the top of the hanging wall ramp.

The conclusions drawn from this analysis are: (A) In general, a blind autochthonous roof duplex will have two different displacement fields: one for the roof layer and a second for the stiff layer. (B) Proper restoration of structure sections across any terrane subjected to a uniform area strain requires the sections be constructed approximately parallel to the direction of maximum shortening.

HISTORICAL DEVELOPMENT OF THE CONCEPTS OF SECTION BALANCING

Some concept of the kinematics of the deformation process is a sine qua non for any method of constructing a balanced cross ecction. The truth of this statement is evident from the inception of the methodology. Chamberlin (1910), who first used the idea of constant area deformation to calculate the depth of folding, issumed that the deformation reflected the folding of shells of various thicknesses. This kinematic model, decidedly thick kinned, was suggested to him by a set of fracture experiments onducted by Daubre. Interestingly, the experimental conditions hat Chamberlin referred to were uniaxial shortening.

In 1933, Bucher re-examined Chamberlin's work in light of Bailey Willis's (1894) experimental results and pointed out that, lthough the conceptual framework of area preservation was ound, the details of the methodology were not. Their application o the deformed sections produced by Bailey Willis did not return he depth to detachment observed in the experiment. Bucher oted that when one used what is now known as area balancing Fig. 11), the results were in good agreement with Willis's xperiments.

The reason Bucher's method works, whereas that of Chamberlin does not, is that the geometric relations between the deformed and undeformed state for the "excess section" calculations e precisely those of Willis's experiments, i.e., volume-constant lane strain with physical boundaries that constrain the ends of e deforming body *with no net angular shear strain* (Fig. 12). hus, the integrated strain of the *entire* body is that of pure shear. hamberlin, on the other hand, based his calculations on a different set of geometric boundary conditions, that of the folding of a t of shells of unequal thickness. Since Willis's experiments were much better approximation of the actual global kinematics of reland fold-thrust belts than Chamberlin's conception, the methodology developed by Bucher is much more successful than that of Chamberlin. This contrast in the results produced by two different kinematic models for area balancing serves to illustrate the important role that kinematic models play in structural analysis. I use the term "global pure shear" to refer to this set of general or global boundary conditions in which the boundaries of the entire body under consideration undergo no net angular shear. If the physical boundaries of a body deformed under similar conditions have a non-zero but constant displacement gradient, I use the term "global simple shear." Use of the term "global" refers to the entire body under consideration (see Fig. 13).

Bucher's (1933) methodology has carried down over the years with only minor modifications (Goguel, 1962; Laubscher, 1961; Dennison and Woodward, 1963; De Sitter, 1964; Dahlstrom, 1969; Gwinn, 1970; Hossack, 1979; Woodward and others, 1985). This technique, outlined in Figure 11, consists of defining a stratigraphic horizon, typically one about which the most trustworthy data exist, as an enveloping surface. Points are chosen where, on structural grounds, it is believed that there has been no significant movement between the enveloping surface and the underlying beds (vertical lines through these points are pin lines). The excess section between the enveloping surface and its inferred base is used to calculate either the depth to detachment or the shortening of the section, depending on which variables in the equation shown in Figure 11 are known.

A critical question that must be answered concerns how the kinematics of Wilis's experiments relate to the mechanism of shortening thrust sheets in foreland fold-thrust belts. There are three possible ways a thrust sheet may shorten (Geiser, 1988b): faulting of strata, folding of the section, and differential layer-parallel shortening (Fig. 14). As Figures 11 and 12 show, Willis's experiment and the excess section method treat only folded strata under global pure shear. What happens when we try to apply this method to other structural settings? Is it possible to get correct results? What happens if we change the global boundary conditions?

PALINSPASTIC RESTORATION AND THE ROLE OF LOOSE LINES

In order to answer these questions, it is necessary to make a clear distinction between palinspastic restoration and the calculation of the shortening of a thrust sheet by the excess section method. A very useful and important concept is that of a "loose line" (Elliott, 1980). A loose line, as defined by Elliott, is a line orthogonal to the sliding surfaces in the deformed state whose shape is allowed to change when returned to the undeformed state (Fig. 15). Pin lines, on the other hand, remain normal to the sliding surface directions in both the deformed and undeformed state, i.e., there is no net angular shear strain across them.

Loose lines inserted into a section provide information on bedding parallel slip during deformation. Loose lines can be inserted in a deformed or undeformed section. I call loose lines inserted in the deformed state "deformed state loose lines" (line

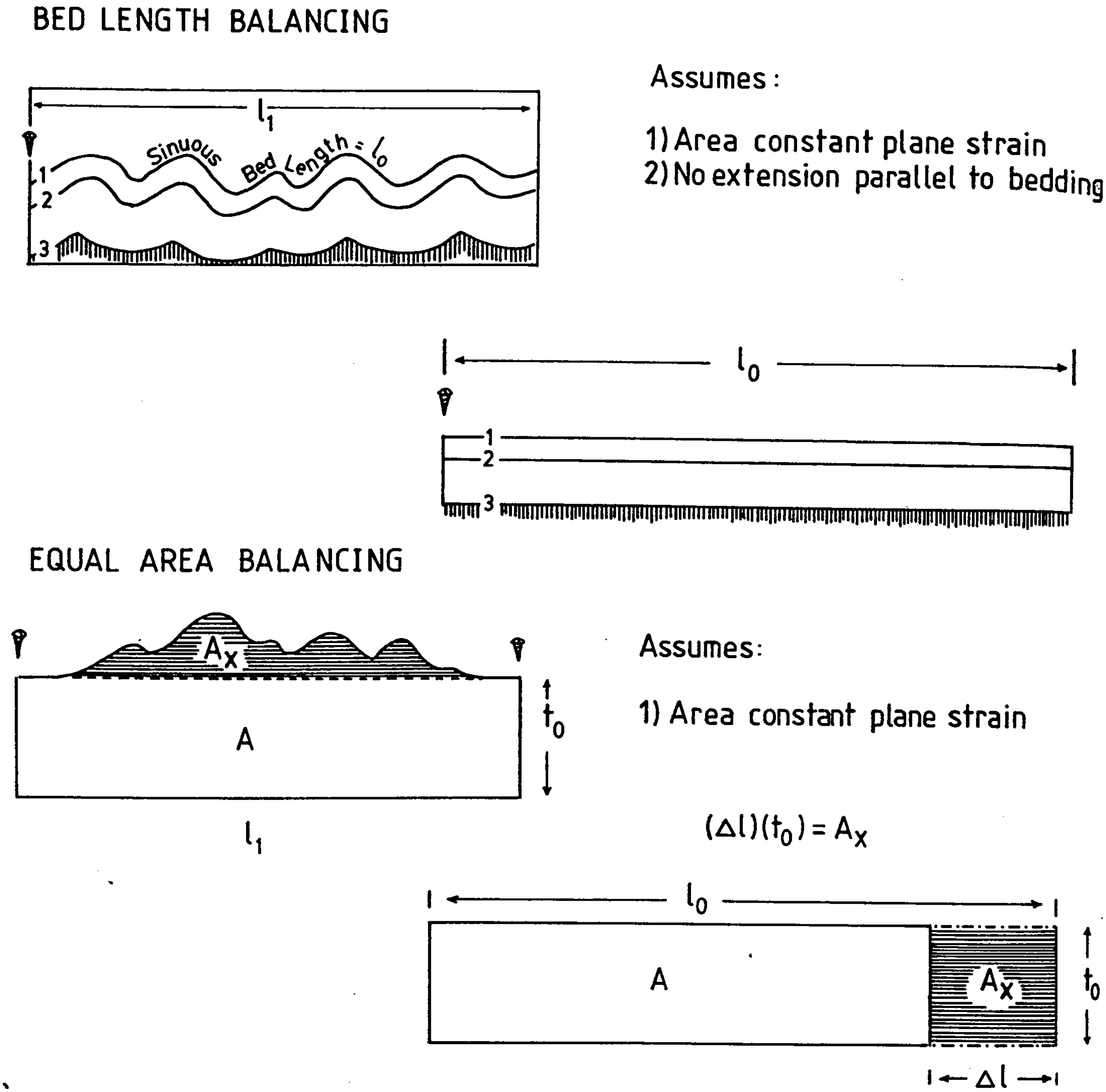


Figure 11. Fundamental principles of bed length and area balancing, and their use in the construction of a geological section.

A′B′, Fig. 15), and call those that are orthogonal to the sliding surfaces in the undeformed state "undeformed state loose lines" (AO, Fig. 15). In order to use loose lines, bed length must be conserved during deformation.

Returning a deformed state loose line to its undeformed position gives the palinspastic location of the line in the undeformed state as well as information on the shear strain within the sheet (Fig. 15). A deformed state loose line inserted above a flat deformed under global pure shear will restore to a line normal to the sliding surfaces, whereas such a line under global simple shear will not.

An undeformed state loose line creates a displacement pro-

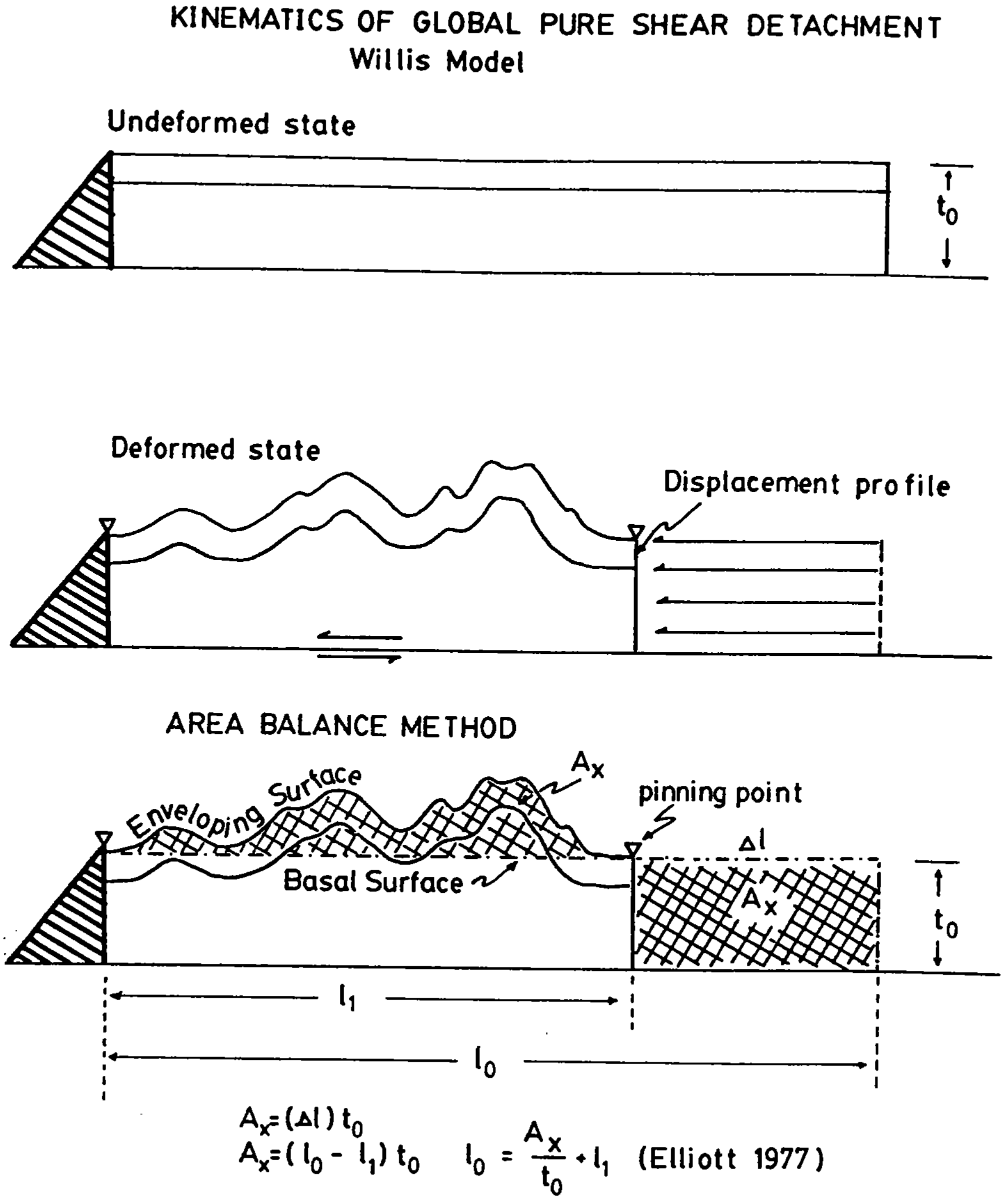


Figure 12. Figure illustrating the relationship between the Willis (1894) squeeze box experiments and the excess section, area balance method. Note that kinematic boundary conditions are those of global pure shear and that the kinematics are those of folding of shells (see Fig. 14).

: (line A′O′, Fig. 15), which gives information on the state of ıin within the sheet. For a region subjected to pure shear, an leformed state loose line remains normal to the sliding surfaces ɜr deformation. For nonhomogenous strain within the sheet or the boundaries of a section under global nonhomogeneous ıple shear, the initially orthogonal line will have a curved iectory like line AB in Figure 15. The tangent of the angle ween the undeformed state loose line and the sliding surfaces the deformed state is the angular shear strain. The displacents and strains of a deformed state loose line are the reciprocals hose of an undeformed state loose line.

EXCESS SECTION ANALYSIS OF COVER STRATA DEFORMED BY LPS

The excess section technique cannot be applied to sheets deformed by LPS because they have not suffered constant area deformation. The depth to the detachment beneath a thrust sheet shortened by LPS must be determined independently. Shortening of the thrust sheet, on the other hand, can be calculated by directly measuring finite strains in the sheet and applying strain integration techniques (Hossack, 1979; Geiser, 1988b). One problem with strain integration techniques is that strain data are

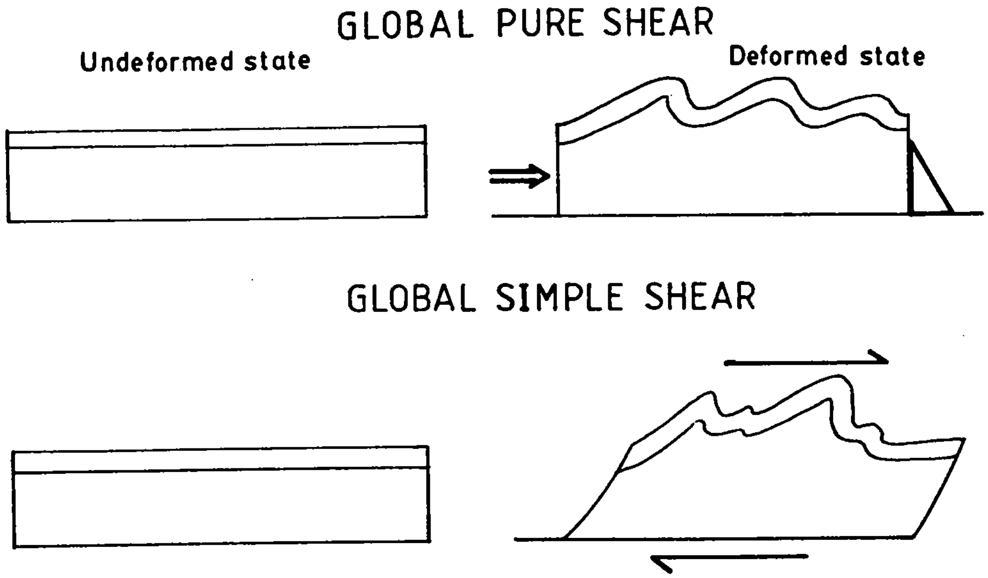


Figure 13. Schematic diagram illustrating the concept of global strains. Note that the case of global simple shear requires that the basal decollement has not been reoriented relative to the global principal directions.

typically restricted to a single horizon. In order to calculate the shortening in the entire thrust sheet, one is forced to project this data to depth, assuming that the vertical strain gradient is zero, a condition that is physically unlikely.

Figure 16 shows the difference between the palinspastic positions of lines determined using Hossack's (1978) method, where the vertical strain gradient is assumed to be zero (global pure shear) and the depth to the detachment is assumed, and those determined by assuming that there was a non-zero strain gradient (global simple shear). The difference arises because the excess area must restore to a rectangle under global pure shear, whereas the actual undeformed shape is the triangle AA′C given by the restored deformed state loose line A′C (Fig. 16).

This difference in the restored shape of the region defined by the deformed state loose line, in contrast to the rectangle of the excess section method, produces an error $1/1_0 = \alpha t/1_1$ in the calculation of the initial section length, where t is the depth to detachment and α is the average shear strain (Mugnier and Vialon, 1986). The misidentification of the global kinematics can produce either an overestimate or an underestimate of the shortening, depending on the sense of shear. As the expression for the error shows, the longer the section the smaller the error.

EXCESS SECTION ANALYSIS OF FOLDED SHEETS

Figure 17 is an area-balanced section of folded strata above a detachment horizon. This computer-generated section illustrates pitfalls inherent in the excess section method. The deformed state section was constructed using an area-constant flexural-flow model. An arbitrary depth to detachment has been used, creating a cushion of subfold material (Laubscher, 1977). This cushion of material is analogous to that caused by underflow of the ductile material into anticlinal cores in the New York Plateau (Wiltschko and Chapple, 1977) and the Jura (Laubscher, 1977).

As noted earlier (Figs. 11 and 12), the excess section method assumes no flow of material from outside the boundaries of the region in which the calculation is being made (lines ℓd1, m-n, Fig. 17). Moreover, the method requires that at least one of the boundaries is pinned to the detachment as well, i.e., it is a regional pin line (see Woodward and others, 1985). To see why this is so, we must carefully consider the kinematics of Figure 17. The following discussion considers only the consequences of a purely geometric analysis and does not incorporate finite strain data on LPS.

The first step in the analysis is to construct pin lines ℓd1 and m-n at the point where the folded strata return to their regional dips and define the excess section in the structure. Using this area and the depth to detachment we can find the initial length of the section, 1_o, shown as the line ℓ′b in Figure 17B. Comparing this to the sinuous bed length of the fold (portion ab of line ℓ-b, where ℓ_1 = ml; Fig. 17), we find that the initial length is greater than the sinuous bed length, implying LPS has occurred. From our initial conditions, flexural flow with a subfold cushion, we know that this is an error. However, if we apply the excess section method, which is based only on the geometric configuration of the deformed state, the error is unrecognizable. The method fails to produce the correct undeformed state because kinematic boundary conditions implicit in the excess sec-

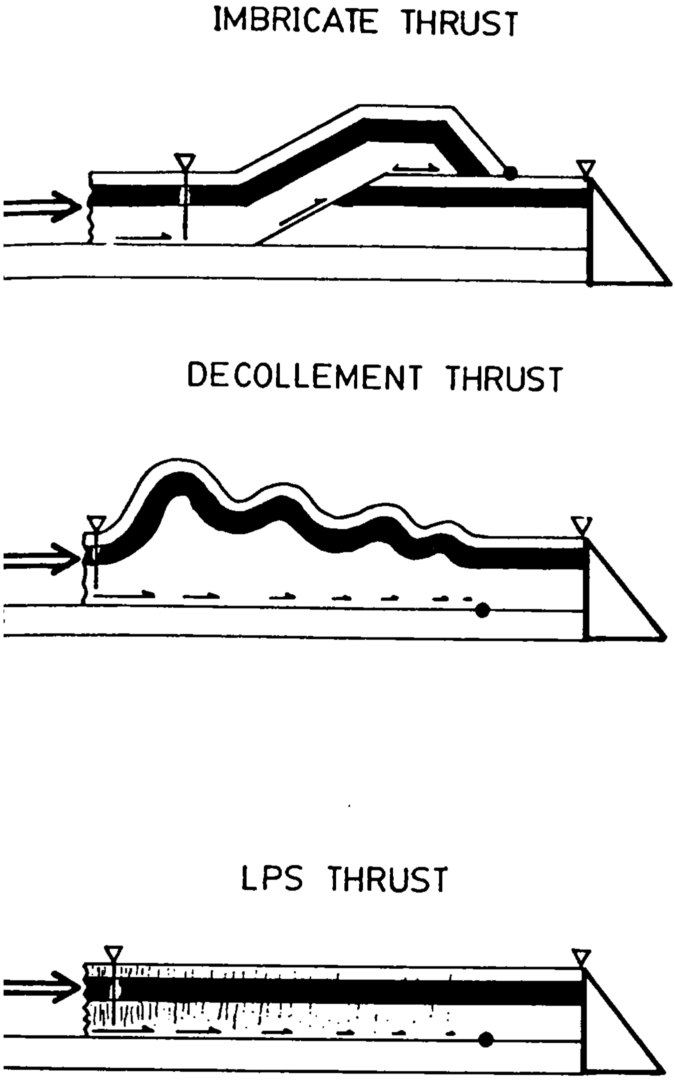


Figure 14. Modes of thrust sheet deformation (from Geiser, 1988b).

on method have not been maintained. There is a flow of ductile ıaterial beneath the fold, even if the line m-n is a pin line for the ıyers that deformed by flexural flow.

The excess section method also fails to give correct restored ositions for material lines in a section because it is based on the ssumption that one of the pin lines is fixed relative to the de- ıchment. To illustrate that this need not be true, we assume that ı-n again marks the return to regional dips, and we forward ıodel the undeformed body abcd (Fig. 17B) into two deformed ates. State I has boundaries a1-d1 and b1-c1, and State II has oundaries a2-d2 and b2c2. In State II, the entire body abcd has oth folded and been translated through line m-n, which we ssumed was pinned. The error produced by this assumption is ıown in Figure 17, where the bodies a2mnd2 and a1mnd1 are restored to the a1′bcd1′ and a2′bcd2′. The error is the difference between the line ℓ′-d1′ and the lines a2′-d2′ and a1-d1′, respectively. An error due to this boundary condition violation is clearly not restricted to folded sheets but is a general problem of all local pin lines (Woodward and others, 1985).

EXCESS SECTION ANALYSIS OF THRUSTED STRATA

Thrusts whose tips reach the surface are emergent thrusts (Boyer and Elliott, 1982), or erosion or surface thrusts (Hills, 1967) (Fig. 18). They consist of a fractured stiff layer only. Thrusts whose tips never reach the surface during deformation are blind thrusts (Thompson, 1979) and consist of a stiff layer and roof layer (Fig. 19). Both types of thrusts may form under conditions of either global simple shear or global pure shear. As can be seen in Figures 18 and 19, the general geometries of blind and emergent thrusts are similar. Despite this superficial geometric similarity, the method for area-balancing blind thrusts is different than that for emergent ones. The reason for this is evident from an inspection of the deformed and undeformed states of the two types of fracture thrusts.

Emergent thrusts

Consider the emergent thrust shown in Figure 18. The portion of the hanging wall displaced to a position above the ramp as the stiff layer shortens—the ramp anticline—is the "excess section" of the excess section method. If the boundary conditions for this sheet are global pure shear, the true shortening of the stiff layer can be calculated using this excess section and the known depth to the detachment. This cannot be done if the boundary conditions for this sheet were global simple shear, because simple shear within the sheet violates the conditions on which the excess section method is based. Restoring this section using the excess section method, we find that the line P′-O′ restores to a-b. If there were any bedding parallel simple shear in the sheet, the true restored position of line P′-O′ might be A-B.

A solution to the problem exists if it is possible to do bed-length balancing (see Woodward and others, 1985, for details on the methodology) along with the excess section calculation. This requires that three conditions be met: (1) the dominant deformation mechanism is flexural flow; (2) the hanging wall and footwall cutoffs can be identified; and (3) at least one pinning line can be found. If these conditions are met, then it is possible to examine the internal strain of the sheet using a deformed state loose line as previously outlined and adjust the boundaries of the section accordingly.

Blind thrusts and "kinematic admissibility"

For sections of blind thrusts, the possibility exists for an even larger error from the application of the standard area-balance

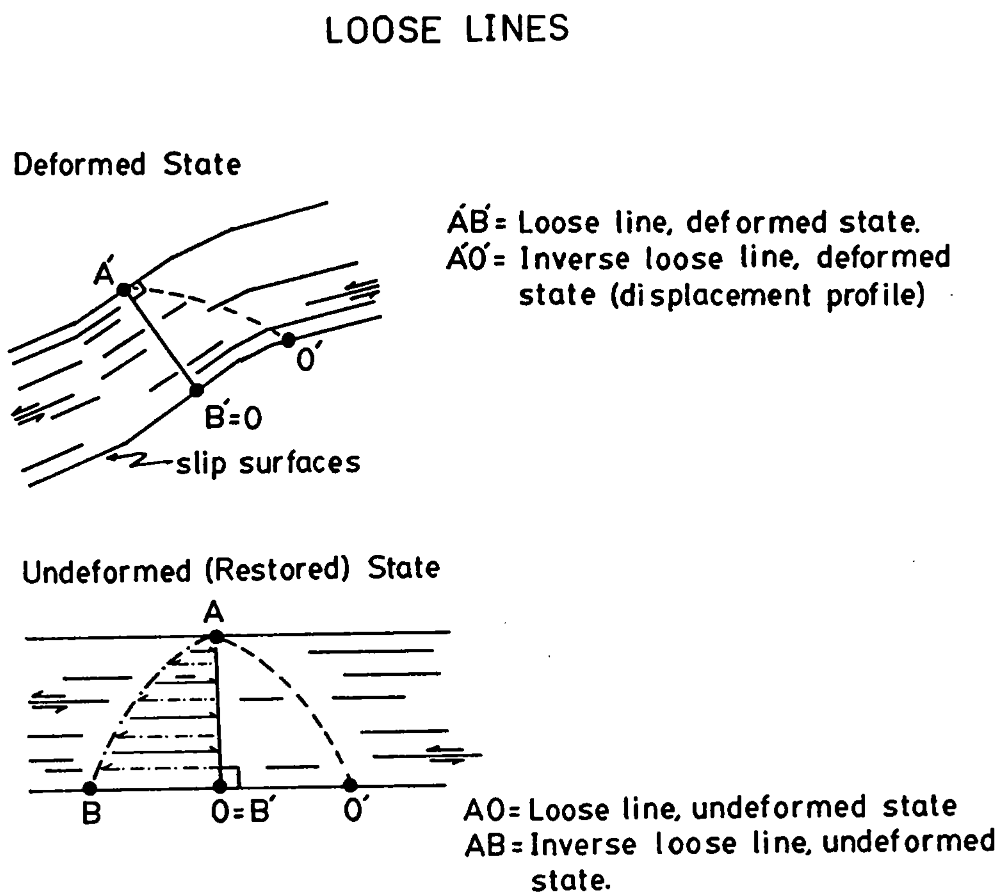


Figure 15. Illustration of the nature of deformed state loose lines and undeformed state loose lines.

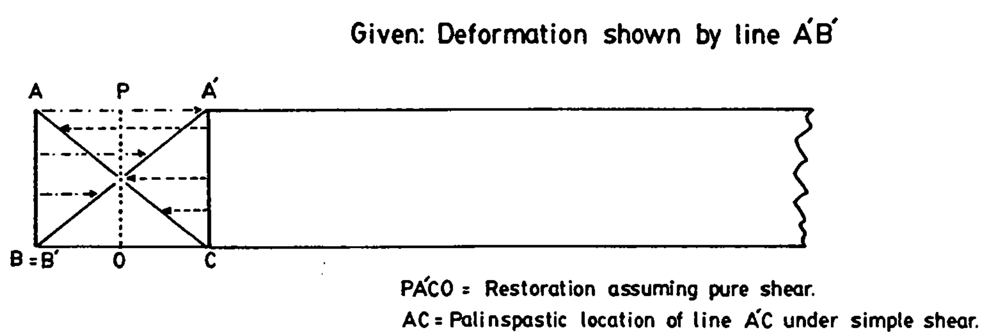


Figure 16. Illustration of the types of errors that can arise by the assumption of layer parallel shortening with a zero displacement gradient in terrane with a non-zero displacement gradient. In the case shown, an arbitrary deformation, indicated by line A′B′, has been applied to the sheet. The assumption that the displacement gradient is 0 results in the deformed state loose line, A′C′, being restored to the position PO, whereas its actual position is indicated by the line AC.

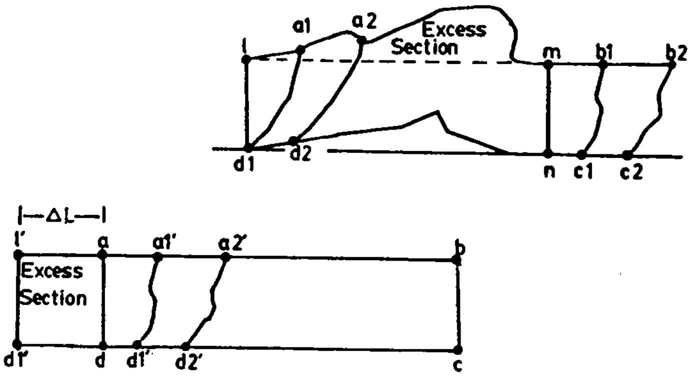


Figure 17. Errors in palinspastic reconstruction of a fold thrust due to the assumption of global pure shear. Under nonhomogeneous simple shear, a line initially normal to the slip surface does not remain normal after deformation. In effect material is moved beyond both the assumed pinning lines.

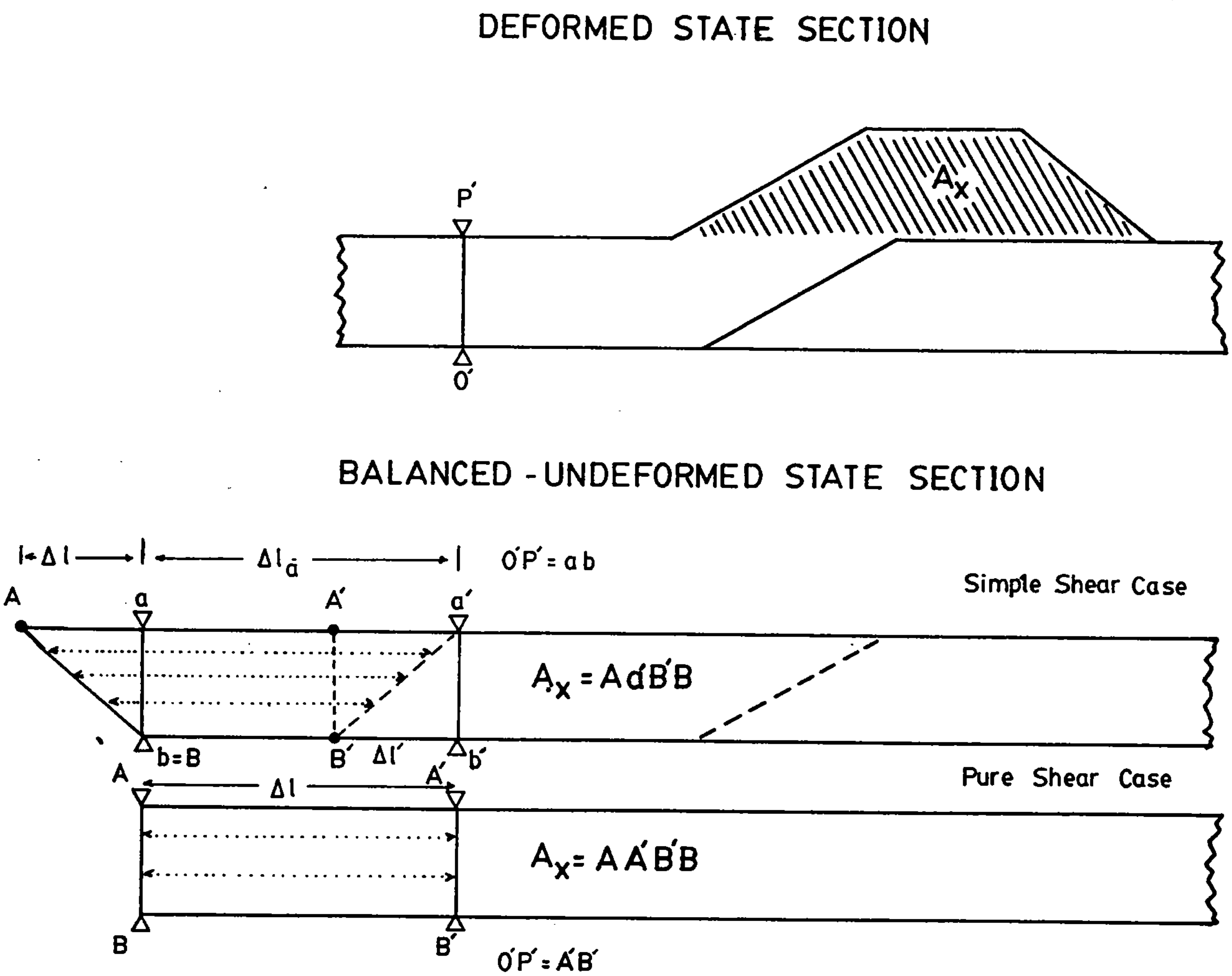


Figure 18. Illustration of problems of utilizing the excess section method to area balance in emergent thrust terranes where flexural flow is the dominant deformation mechanism. Application of the excess section method to a thrust sheet, subject to the shear gradient shown, produces the error. The actual palinspastically restored position (determined by bedlength balancing) of the deformed state loose line O'P' is AB rather than the position ab given by the pure shear assumption.

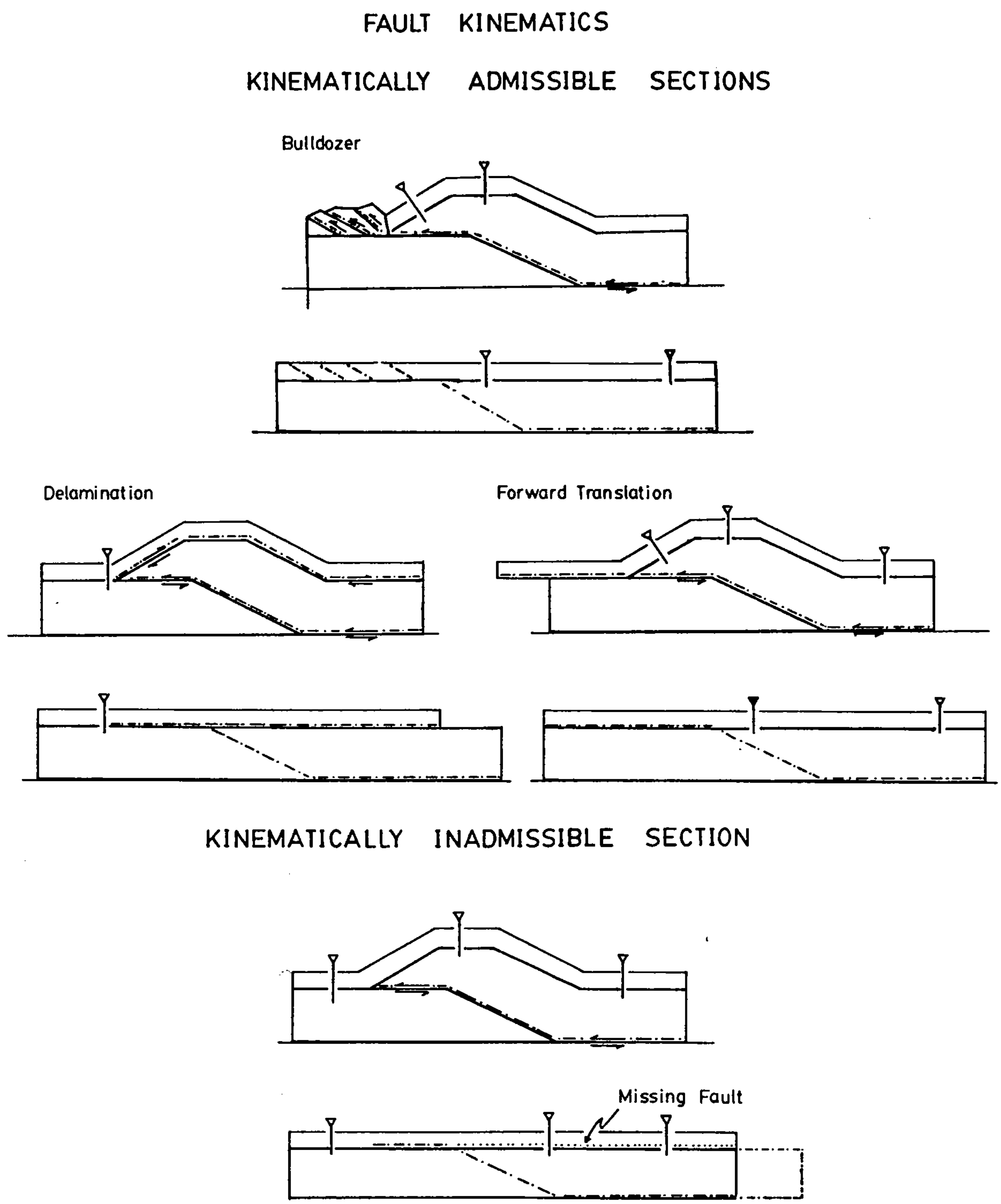


Figure 19. Application of macroscopic kinematics to the analysis of a geological cross section in blind thrust terrane. The three kinematically admissible sections show deformed state fault trajectories, which permit the components of the section to move from the undeformed state to the deformed state. The kinematically inadmissible section does not allow this, indicating that it is not a possible solution. Note that all sections are balanced (restorable and admissible). Figures 22 and 23 illustrate examples from the literature of kinematically inadmissible sections.

method. The error arises again from the nature of the macroscopic kinematics. From a purely geometric standpoint, the stiff layer shortens by doubling its thickness, whereas the roof layer can shorten only by draping over the ramp anticline of the stiff layer. Since much more shortening is accomplished by doubling thickness than by passive folding, there would appear to be a much larger shortening of the stiff layer than the roof layer.

Assuming area-constant plane strain and constant bedding thickness, there area only three ways that the shortening in the roof and stiff layers can be the same: (1) the stiff layer may insert itself beneath the roof layer, resulting in backthrusting over the top of the stiff layer (delamination, Fig. 19); (2) the floor thrust may climb section and join the roof thrust, with the displaced roof layer carried off the section (forward translation, Fig. 19); or (3) this displacement of the roof layer may be absorbed by imbrication or formation of folds in the roof layer in front of the duplex ("bulldozer", Fig. 19). An alternative here is to relax the area-constant condition and allow the displacement of the roof layer to be absorbed by LPS either in front of the forelimb, over the forelimb, or in some combination (Fig. 14). Obviously, all three deformation modes may accommodate some fraction of the displacement of the roof layer, but this does not affect the kinematic relations shown in Figure 19.

In any case, the faults that allow the motion must appear in both the deformed state section and the undeformed state section. I use the term "kinematically admissible" to describe those sections whose deformed state geometry is such as to allow those sections to reach the deformed state section by a physically possible route. Sections which do not have this property are kinematically inadmissible. The process whereby the kinematic admissiblity of a section is tested, by going from the undeformed to the deformed state, is referred to as "forward modeling." In Figure 19, constructed with area-constant plane strain and constant bedding thickness, the three kinematically admissible solutions for blind imbricate thrusts show that, depending upon which of the solutions is used, the stiff layer may be either initially longer than the roof layer or of the same length.

The critical point with regard to balancing these sections is that stiff and roof layers must be treated independently (Fig. 20). If the excess section method is used, with an arbitrary stratigraphic horizon, chosen as the enveloping surface, and if this horizon is part of the cover sequence, there is an overestimate of the thickness of the units deforming by similar macroscopic kinematics. The result is an underestimate of the total shortening of the section (Fig. 20). On the other hand, as long as the enveloping surface lies within the stiff layer and only the thickness of the units included within the enveloping surface is used, a correct answer will result.

Examples of this type of error are common in the literature. For example, Gwinn (1970, Fig. 3) chose the top of the Devonian Oriskany Sandstone as his datum for calculating the excess section in the western panel of his cross sections through the central Appalachian Valley and Ridge Province. The actual top of the stiff layer in this section is near the middle of the Ordovician Reedsville Formation. In his central panel, Gwinn restricts imbricate thrusts to the Ordovician Bald Eagle Formation through the Lower Devonian, but he places his enveloping surface at the top of the Middle Devonian Hamilton Formation. As a result, Gwinn's estimates of shortening for both panels is incorrect. The only panel without problem is the eastern one, as Gwinn chose a surface within the stiff layer for his enveloping surface (the top of the Cambrian Conococheague Limestone).

Palinspastic maps by Dennison and Woodward (1963) suffer from the same problem, for they chose the top of the Devonian Onesquethaw Limestone for their enveloping surface. Since this unit is well within the roof layer, their restoration almost certainly significantly underestimates the shortening of the central Appalachians. Unfortunately, Dennison and Woodward (1963) do not present sufficient data to allow recalculation, since they show only the form of the deformed roof layer and leave out the critical stiff layer geometry.

Gwinn's sections do contain this information. Consequently I have been able to use one of them (Fig. 3 in Gwinn, 1970) to illustrate how to recalculate the shortening using the stiff layer geometry. For the western panel of Gwinn's Figure 3, the true shortening is 16 miles, rather than Gwinn's estimate of 12 miles, an error of 22 percent. The problem is greater in the central panel wher the stiff layer thickness is grossly overestimated; here the shortening of the Ordovician Bald Eagle–lower Devonian interval is 3.9 miles, rather than Gwinn's estimate of 1 mile, resulting ina 74 percent underestimate of the shortening.

The displacement of the roof layer relative to the stiff layer means that there is no pinning line common to both roof and stiff layer. Thus, one of the requirements for the area balance method has been violated. In effect, part of the section that should be included in the excess area has been moved off the section in the direction of tectonic transport (assuming area-constant plane strain).

How then do we balance a section in a blind thrust terrane? The section can be balanced only if the stiff layer can be identified (Figs. 18 and 20). The identification of this layer can be made using prior stratigraphic knowledge. If the thrust tips are exposed on a map, stratigraphic separation diagrams can be used to differentiate between ramp-forming units (the stiff layer) and flat-forming units. If the stiff layer itself has undergone penetrative shortening, then this must be compensated for during balancing.

ANALYSIS OF GEOLOGICAL CROSS SECTION USING LOOSE LINES

A kinematically admissible section is one drawn with the macroscopic kinematics in mind. In addition, even if the strain history is not known, the section must also be compatible with independently measured strains, which constrain the mesoscopic and microscopic kinematics. Loose lines can be used to provide information about the deformation history and the state of strain at different positions within a thrust sheet.

To outline a method for using loose lines to analyze sections,

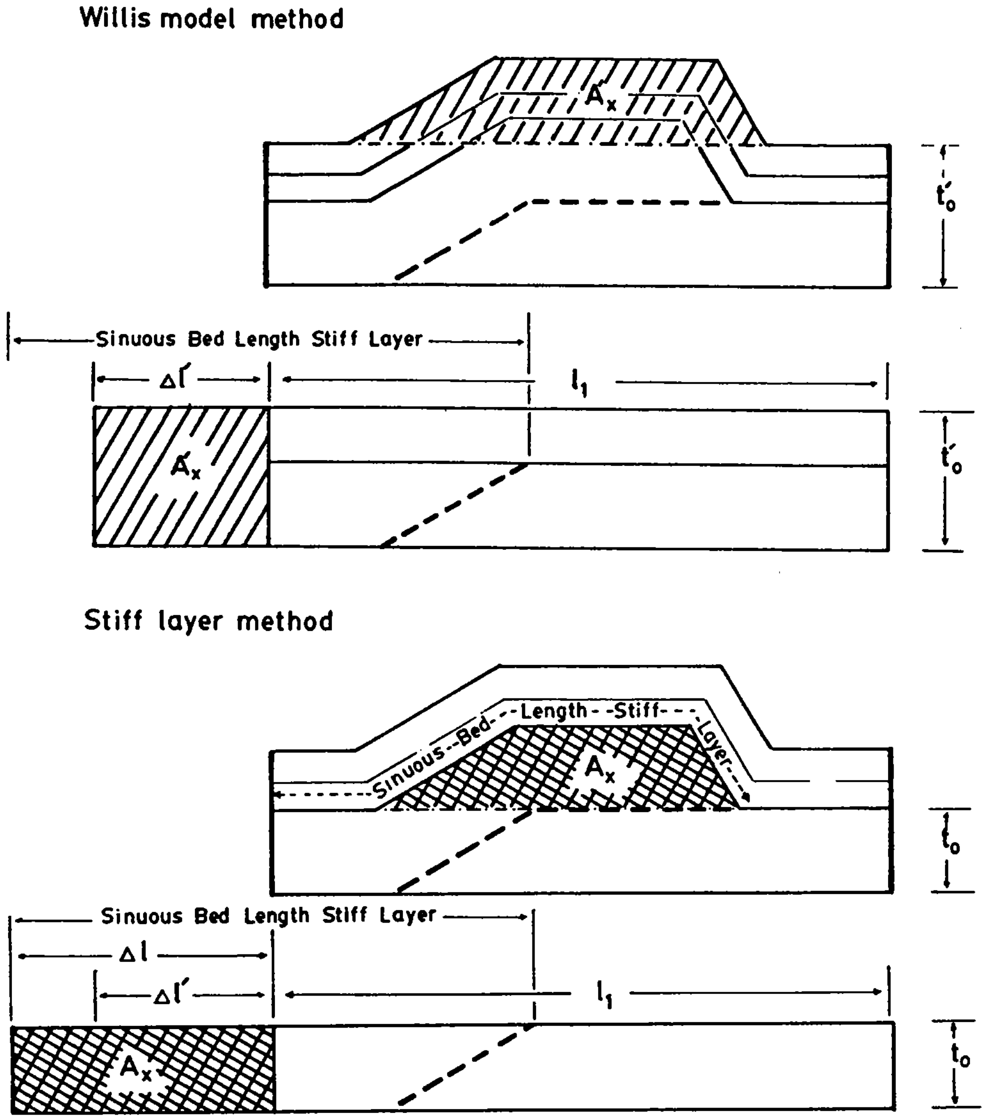


Figure 20. Schematic diagram showing how underestimation of shortening occurs if the excess section method based on the Willis folding model is used in blind imbricate thrust terrane.

I will examine the cross section in the central Appalachian Valley and Ridge Province in western Virginia constructed by Perry (1978). This analysis is directed at answering the following questions: (1) Is the geometry of the section correct? (2) What is the sequence of faulting: break back or break forward? (3) What is the state of strain implied by the section geometry? Perry's section is an acceptible solution if it is both restorable and admissible (Elliott, 1980).

I begin by drawing a loose line above the hanging wall flat in the most internal horse since it has remained approximately horizontal. Any bedding segment that departs from horizontality experiences bedding parallel simple shear, regardless of the global strain state (cf. Suppe, 1983). Thus, the best position for a loose line to test the state of strain is above a hanging wall flat that has not traveled over a footwall ramp. This loose line can be used to provide information on the state of the global strain as well as to check the kinematic admissibility of the section.

The undeformed fracture array, created by laying off bed lengths measured in the deformed state onto the area-balanced stiff layer, is shown in Figure 21 as the uncorrected fracture array. Faults 1-2 and 3-4 are admissible as break forward structures. Fault 5-6 is not, however, as its geometry is concave in the direction of tectonic transport. The section is still admissible if the faults formed in a break-back sequence, where fault 5-6 propa-

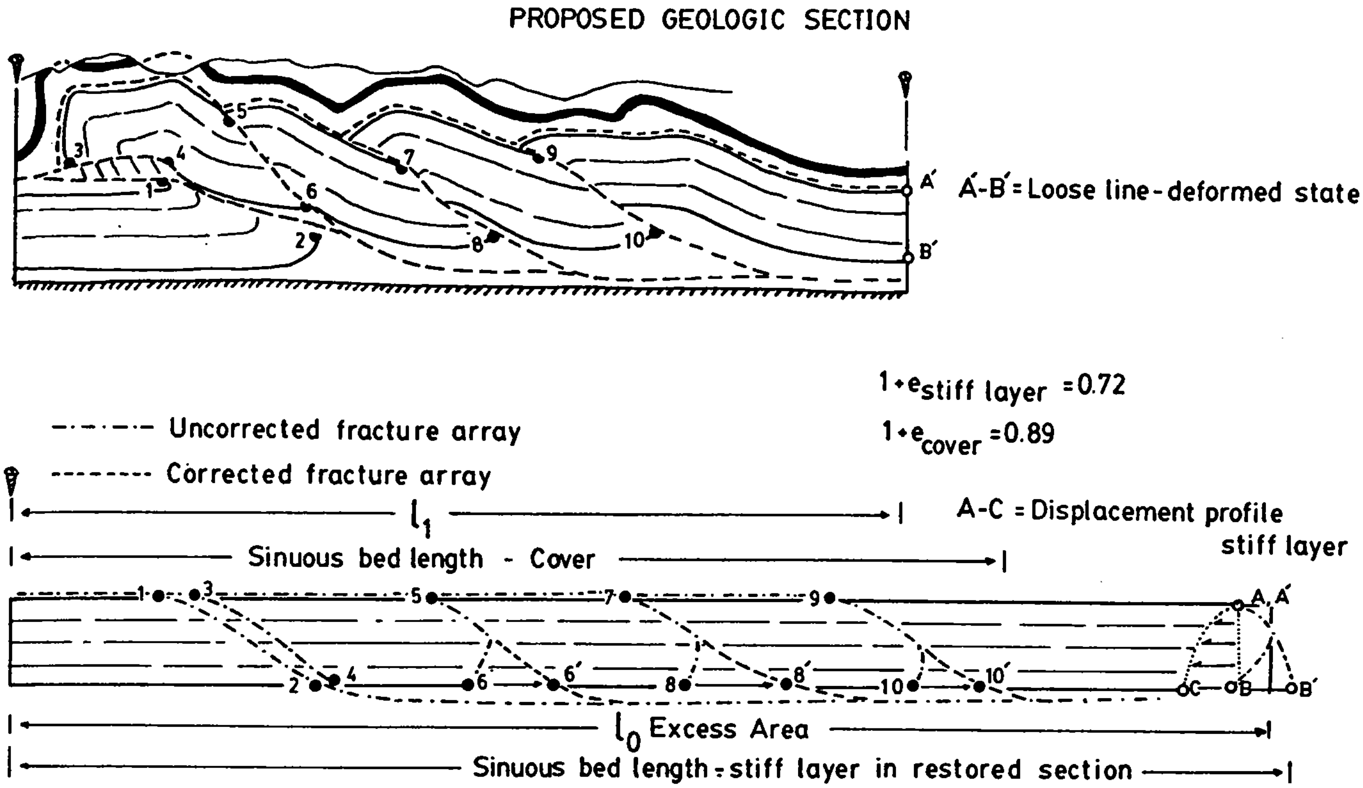


Figure 21. Analysis of geological cross section using the stiff layer method. This section (from Perry, 1978) illustrates some of the problems encountered in balancing autochthonous roof duplexes. Roof and stiff layer do not have equal line lengths. Restoration of the stiff layer and use of loose lines provide evidence that the fault with cutoffs 5 and 6 is part of a break-forward sequence. An admissible section is created by adding bed length to the most external horse. Note that the final displacement profile (A-C) indicates nonhomogeneous simple shear in hanging wall flat.

gated across a fault-propagation fold (Suppe, 1985) or formed as a break thrust (Willis, 1894). As constructed, the section shows the thrust as a break thrust, since the horses were lifted off the detachment and material was injected beneath the horses. The problem is to find some additional information that will allow us to determine which solution has a higher probability of being correct.

The bedlengths to the remaining faults and the loose line, A′-B′) are laid off as well without attempting any correction. The uncorrected fracture array shows that the remaining horses have the same problem (if it is a problem) as fault 5-6, i.e., they are concave in the direction of tectonic transport. Moreover, the undeformed image of the loose line (AB, dash-dot line in Fig. 21) indicates that bedding parallel shear must have occurred within the stiff layer, and that this simple shear reverses its sense through the strata in the stiff layer. Intuition suggests that such a deformation is unlikely, but this fault sequence cannot be rejected a priori.

If we correct the undeformed fault array so that it is admissible as a break-forward sequence, we get an interesting result. The correction is made by adding bed length to the horse bounded by faults 3-4 and 5-6 in both the deformed state and undeformed state sections (Fig. 21). Bedlength is added to the base of the horses since there is less hard data on the deep subsurface configuration of the horses. This correction changes the restored image of the loose line to A-B′, eliminating the shear sense reversal. The displacement profile that results is still questionable since it indicates a dextral shear sense rather than a sinistral shear sense, which might be expected given the direction of tectonic transport.

If one were using Elliott's original concept of admissibility, utilizing only the undeformed fracture array, there would be no other place to go at this point and the section would be considered balanced. Using the loose lines to generate displacement profiles, it is possible to test the geometry of the deformed state section to see if it is compatible with other strain states. Displacement profiles, whether derived from rock structures or from a proposed cross-section solution, must be admissible. Constructing a cross section with an admissible displacement profile is simply carrying the notion of admissibility one step further. The use of kinematics here adds to the concept of admissibility as well as providing a further constraint in section construction.

To conclude, this brief illustration shows that loose lines are useful kinematic indicators. Since loose line analysis provides a means to investigate whether a given deformed state geometry is compatible with finite strains, it can help determine if a section is admissible.

ANALYSIS OF GEOLOGICAL CROSS SECTIONS USING MACROSCOPIC KINEMATICS

Central Appalachian Valley and Ridge: The Juniata Culmination

A common problem encountered in constructing cross sections in blind thrust terranes is how to fill space in structural culminations, where the thickness of the stiff layer is often doubled. There are two ways that this may be accomplished: (1) where the proportion of hanging wall flat on footwall flat is large (i.e., ->1.00), as in an allochthonous roof duplex shown in Figure 8 (a "flat-on-flat" solution); and (2) where the proportion of hanging wall ramp on footwall flat is ->1.00, as in the autochthonous roof duplex of Figure 8 (a ramp-on-flat solution).

Since both types of solutions can be successfully balanced (i.e., restorable and admissible), it is impossible to find an error in the solution by balancing alone. Only by considering the macroscopic kinematics and its consequences in terms of the resulting finite strains can one find the error. Perhaps the most critical observation for this analysis is that a geological cross section represents a slice through physical reality, and as such, every line in a section has physical meaning. Any fault shown in a section represents a boundary along which significant motion occurred. Conversely, the absence of a fault or other structure indicating differential motion, such as a folding or layer parallel shortening, means that no motion occurred between adjacent rock masses.

In pratice, then, every kinematically significant structure must be shown on the section. Behind this seemingly trivial statement is an important reality. Considering the kinematic significance of each line on the section forces one to consider the kinematic significance of structures in the rocks. The kinematic significance of lines on the section are most easily understood by forward modeling. In forward modeling, one often encounters new information which indicates: (1) the section could or could not have formed in the manner implicit in the geometry of deformed section, (2) the section requires a geologic history that is either incompatible with or different from that suggested by other geologic data, or (3) the section requires that structures be added or subtracted to make it kinematically admissible. These predictions may be tested either by direct field observation or reinterpretation of existing geologic data.

The section shown in Figure 22 was published by the Pennsylvania Geological Survey (Berg and others, 1980) and represents a possible solution to the problem of space filling beneath structural culminations. Other examples of sections that use a solution similar to that shown in Figure 21 can be found in Roeder and others (1978), sections V1–V4; Woodward (1985), sections 3–8; and Lash and others (1984). If we examine the deformed section in Figure 22 and its area-balanced undeformed image, we find two problems characteristic of most sections through autochthonous roof duplexes. First, the restored length of the roof layer is much less than that of the stiff layer; i.e., the section does not bedlength balance. Second, what are the macroscopic kinematics that might explain this imbalance?

The problem of the missing section in the roof layer can be resolved by a combination of rigid body translation of the roof strata off the stiff layer with layer parallel shortening in the roof (Herman and Geiser, 1985; Herman, 1984; Bowen, 1986; Geiser, 1988b). The problem of the macroscopic kinematics is more difficult to resolve. Berg and others (1980) proposed a "flat-on-flat" solution. To determine whether or not the section is kinematically admissible, we must be able to find a physically possible method of placing one 50-km-long section of stiff layer on top of another. Moreover, the deformation history predicted by the model must be compatible with existing finite strain data as well as the structural geometry.

The deformed state section (Fig. 22) shows no significant faults separating the roof layer from the underlying horses. The absence of a fault means there can be no delamination, either by rigid body translation or layer parallel shortening of the roof. As there is no evidence for imbrication of the roof layer, we are apparently dealing with layer parallel shortening. If so, then all of the missing roof layer (about 95 km in length; Herman, 1984) must be absorbed in deformation of cover strata off the section to the west, in the New York and Pennsylvania Plateaus. This hypothesis requires that: (1) the deformed state fracture array makes it possible to move the missing 95 km off the section; (2) the geology of the section to the west be compatible with absorbing the missing section; (3) the deformation predicted for the rest of the section be compatible with the geology of the culmination and the more internal parts of the section.

Examination of the area-balanced undeformed section (Fig. 22) reveals that there are serious problems in meeting these requirements. Although the roof strata are assumed to be pinned to the stiff layer, restoration of the horse above fault 4 requires a separation of almost 12 km, opening a gap (BB′) in the roof layer. Two other such gaps (C′C′ and D′D′), about 10 and 15 km in length respectively, are also created. The deformed state section does not have a fault array that allows the missing section to be moved to the west (even if the section had such an array, there is no means of accommodating more than 40 km of shortening in the plateau, most of which must be accommodated by layer parallel shortening) (Nickelsen, 1966; Geiser, 1988b). Moreover, since the roof layer is supposed to be pinned to the stiff layer, layer shortening must begin at the Allegheny front. This too is incompatible with the finite strain data, which show the LPS strain continues across the Allegheny front into the Juniata Culmination (Faill, 1977; Bowen, 1986).

There are three possible ways to account for the missing material: (1) emergent backthrusts of the type described by Banks and Warburton (1986); (2) highly inhomogeneous pressure solu-

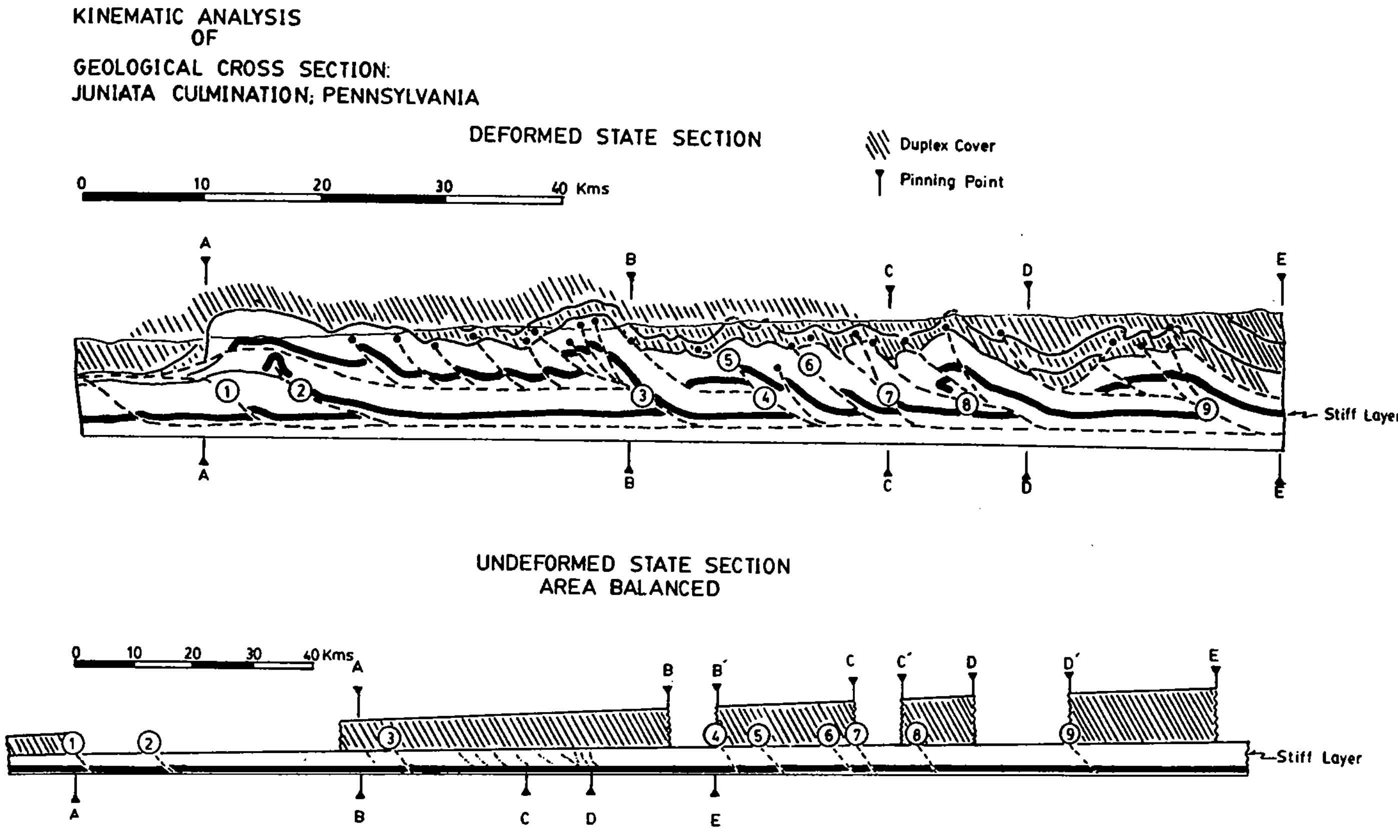


Figure 22. Proposed flat-on-flat solution for Juniata culmination of the central Appalachian Valley and Ridge Province (Berg and others, 1980). Kinematic analysis utilizing deformed state and undeformed state sections illustrates the types of problems that show the section to be kinematically inadmissible.

tion similar to that observed in the Umbrian Apennines (Geiser, 1988b); or (3) having a significant part of the deformation occur prior to the deposition of the roof layer.

Surface mapping shows no evidence for emergent backthrusts with displacements of 10 to 15 km. Using Elliott's (1976) 7 percent "bow-and-arrow" rule, such backthrusts would have map lengths of 130 to 150 km and would be difficult to miss in the field. The second mechanism requires an enormous volume loss—the 10 to 15 km of missing bed length now occupies a region 1 to 5 km in length. Not only would this be an unprecedented phenomenon, this hypothesis conflicts with finite strain data from the Juniata Culmination (Bowen, 1986) and the Valley and Ridge Province. Other strain measurements in the Valley and Ridge Province (Faill and Nickelsen, 1973; Geiser, 1974; Faill, 1977; Geiser and Engelder, 1983) show that, although strains are not homogeneously distributed, they are pervasive, and volume loss is nowhere greater than 27 percent. Because there is no physically possible route from the restored section to the deformed section that is inconsistent with map and finite strain data, the cross section is kinematically inadmissible.

Herman (1984) and Herman and Geiser (1985) have proposed a kinematically admissible solution for this region. Their solution uses a "ramp-on-flat" geometry for the duplex. The missing section is accounted for by having approximately 40 km absorbed by LPS in the Appalachian Plateau and the remaining 40 to 50 km absorbed by a system of local backthrusts with associated layer parallel shortening and folding as described by Geiser (1988b).

Southern Appalachian Valley and Ridge

Roeder and others (1978, section V4) proposed a flat-on-flat solution for the southern Appalachian Valley and Ridge (Fig. 23). The geometry of this section differs only slightly from Figure 22, and the restored section has problems similar to those noted for the Juniata Culmination section and for blind thrust culminations in general. Here, the duplex consists of faults 1 to 10, and the entire stratigraphic sequence is the stiff layer. This eliminates both the delamination and imbrication models from consideration and requires that the missing section be accounted for off section, in the direction of tectonic transport.

In contrast to the example from the Juniata culmination, the tip of the sole thrust is placed in the section. This makes the kinematic consequences more dramatic than in the Juniata cul-

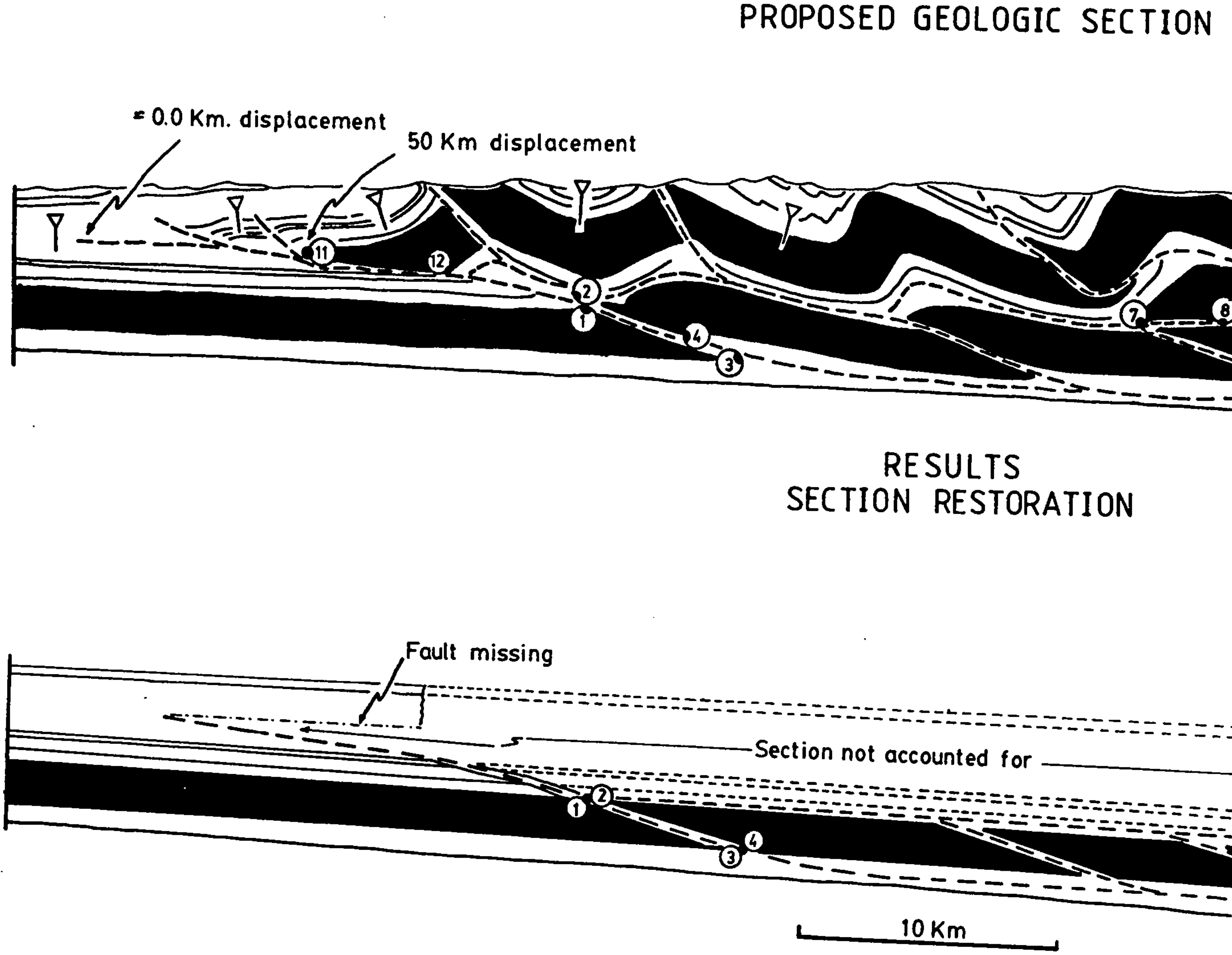
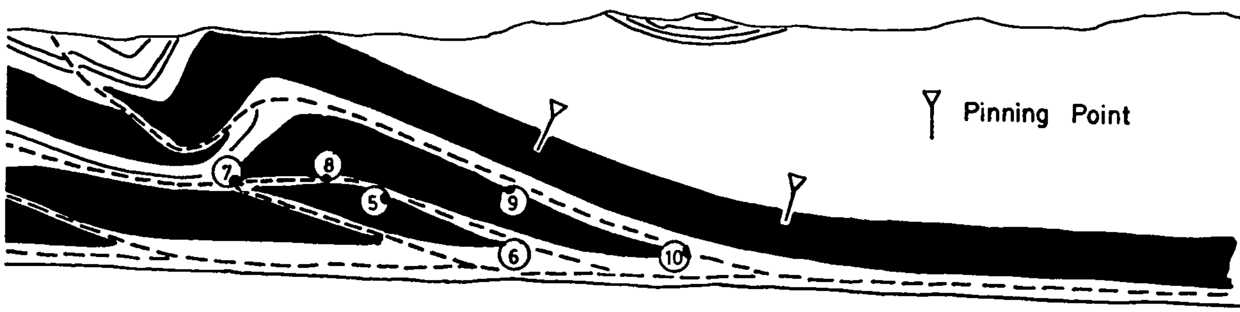


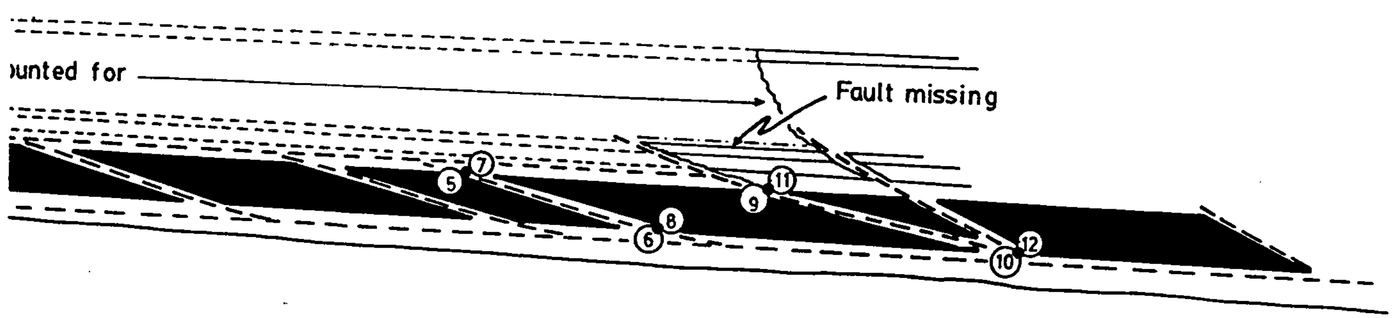
Figure 23. Analysis of proposed flat-on-flat solution for section V (Roeder and others, 1978) located in the southern end of the central Appalachian Valley and Ridge Province. Kinematic analysis utilizing deformed state and undeformed state sections shows that the proposed solution has problems similar to those shown in Figure 22.

mination. In this case, assuming that the roof layer is pinned to the hanging wall requires all of the displaced cover stripped from the footwall flat (about 50 km of section) to undergo extreme volume loss and collapse into the tiny area bounded by the tip of the sole thrust and the most external splay. Similar comments can be made with regard to sections V1, V2, and V3 in Roeder and others (1978).

One possible explanation is that Roeder and others (1978) located the tip of the sole thrust in the wrong place and that this portion of the Appalachian Plateau suffered layer parallel shortening like that observed in Pennsylvania and New York. Field work by D. Wiltschko and students (personal communication, 1986) and my own field reconnaissance shows that layer shortening cannot account for all of the missing bed length. Only small amounts of LPS has occurred in this region. Surface mapping indicates that emergent thrusts cannot account for the missing bed length either. I conclude that this section is kinematically inadmissible and that an alternative solution is required for the region.

An autochthonous roof ramp-on-flat duplex (Figs. 8 and 22; Perry, 1978; Herman, 1984) is again a viable alternative. A question that arises in examining these two examples is whether a flat-on-flat solution is possible in *any* blind thrust terrane in which the cover strata are essentially unfaulted. In such cases, the only plausible mechanisms for emplacing a horse with a low thickness-to-length ratio (<<1.0) are: (1) delamination, (2) a system of emergent thrusts, or (3) layer parallel shortening in the roof layer





to accommodate the movement of the stiff layer. Although delamination has been well documented elsewhere (cf. Price, 1986), the wedging body always has a relatively large thickness-to-length ratio (>1.0). If the deformation occurred by area-constant plane strain, delamination requires that the original length of the stiff layer be greater than the original length of the roof layers. This condition can exist only if there was syntectonic sedimentation or if the thrusts were buried by later sedimentation.

From the standpoint of mechanics, the insertion of a horse beneath roof-layer strata by delamination essentially doubles the amount of fault surface. Both the energy expended in fault propagation and that expended in fault sliding are directly proportional to total fault length in a duplex (Mitra and Boyer, 1986). The energy expended in fault sliding is also directly proportional to the total fault displacement. Increasing the total length of faults and the total fault displacement in a duplex by an order of magnitude increases the energy required to form the duplex by several orders of magnitude. Work requirements predict that the emplacement of horses with a small thickness-to-length ratio by delamination is unlikely.

The macroscopic kinematics of a flat-on-flat solution for blind structural culminations is, at best, unlikely, and can be shown to be physically impossible in many cases. The most probable alternative solution is an autochthonous roof duplex (Fig. 8) in which the displacement on the individual horses of the stiff layer is absorbed by combinations of layer parallel shortening and folding of the roof layer strata (see Fig. 8 and Geiser, 1988b). Boyer and Elliott suggested that the "corrugated iron" pattern of the central Appalachian Valley and Ridge Province could be applied to the rest of the Appalachians. Herman (1984) and Bowen (1986) have found evidence supporting this interpretation, and the mechanical model proposed by Geiser (1988b), in the Juniata culmination. A similar interpretation may apply to structures in other parts of the Appalachian Valley and Ridge Province (personal reconnaissance; Dunn, personal communication, 1986).

CONCLUSIONS

Although kinematics is an important tool for examining deformation, it has not previously been considered in constructing geological cross sections. In this chapter, I have shown that kinematic analysis is as significant a consideration in section construction as it is in orogenic processes. Kinematic concepts can be applied to the construction of geological cross sections in deformed terranes in the following ways:

(1) In analyzing map-scale structures, it is imperative to recognize that the pattern of faulting and cutoffs in the restored section dictates the kinematic history of the deformed state section. The elementary concept of forward modeling, and its finite strain consequences, allows one to eliminate entire classes of possible structural solutions from consideration. Kinematic admissibility is a powerful addition to constraints on cross-section construction.

(2) Macroscopic strain states, whether global pure shear or global simple shear, can be investigated through the use of loose lines. The nature of the boundary conditions is an additional attribute of the concept of admissibility. As such, information given by loose lines can be used to suggest changes in the geometry of the deformed state section.

(3) Analysis of the excess section method of area balancing using macroscopic kinematics demonstrates that ignoring the implications of the boundary conditions can lead to serious errors in palinspastic restoration of geological cross sections. The problem is particularly acute in blind thrust terranes, where passively deformed roof-layer strata must be distinguished from stiff-layer strata deformed by imbricate thrusts, or where the stiff layer must be distinguished from the layer containing the tips of the imbricates.

(4) The link between the microscopic kinematics of grain-scale deformation and the macroscopic kinematics of horses and thrust sheets can be made in two ways: (a) Macroscopic loose lines can be used to predict strains and strain gradients in the deforming thrust sheets. The predicted strains can then be compared to field data on deformation fabrics. Disparities between the two data sets require the geometry of the deformed state section or the interpretation of the material properties of different strata to be altered. (b) In regions of blind thrusting, it is possible to define separate displacement fields for the passively deformed roof-layer strata and the faulted stiff layer. The displacement fields for the two components need not be identical. Since the decomposition of the total displacement vector is known, and its components can be measured independently, the two sets of data can act as independent checks on each other. The link between different scales occurs because the grain-scale deformation is one of the components of the decomposition of the total displacement vector. Consequently, predicted microscopic kinematics must be compatible with measured finite strains.

(5) Regional microscopic finite strain analysis can be combined with macroscopic kinematics, derived from the restoration of serial geological cross sections, to determine a unique displacement field for an orogen. In doing so, it should be possible to resolve such problems as the origin of salients (the "salient paradox" of Bally and others, 1966) and lead to a clearer understanding of the three-dimensional kinematics of orogenesis.

ACKNOWLEDGMENTS

Much of the original inspiration for this work is owed to Dave Elliott and Ernst Cloos; to Dave for his re-invigoration of thinking about the construction of geological cross sections and to Ernst Cloos for his pioneering work in regional finite strain analysis. Fred Diegle's scientific and editorial comments provided invaluable help in clarifying and focusing many of the ideas in this paper. I would also like to express my gratitude to the graduate students in my advanced structural analysis classes whose support and interest helped me to refine and formulate my own thinking. Finally I would like to thank my colleagues, Walter Alvarez, Terry Engelder, Dave Wiltschko, and Norman Gray, whose sympathetic help and criticism over the years were critical to making this work a reality.

Financial support for much of the field work from which these concepts were derived was provided by NSF grants EAR 77-14431, EAR 79-11085, and EAR 82-07355.

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Manuscript Accepted by the Society October 29, 1987

Printed in U.S.A.