Journal of Structural Geology, Vol. 11, No. 8, pp. 1011 to 1019, 1989
Printed in Great Britain

0191-8141/89 $03.00+0.00
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Description and analysis of early faults based on geometry of fault–bed intersections

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(*Received* 1 *February* 1988; *accepted in revised form* 17 *April* 1989)

Abstract—The cross-sectional configuration of dip-slip faults in stratified rocks can be characterized in terms of sense of displacement, relative age of faulted strata, polarity, hangingwall ramp/flat type, footwall ramp/flat type, hangingwall younging direction and footwall younging direction. Together, these variables provide a descriptive framework for observations at single outcrops, and a tool for kinematic analysis of deformed early faults. Contractional and extensional faults cutting strata that were flat-lying when faulted can produce only 20 initial fault configurations. Including derivative configurations that result from fault-propagation folding and post-fault deformations, as many as 120 fault configurations might be encountered in early faults. Application of these concepts is demonstrated through analysis of a major premetamorphic fault in the Acadian Orogen in Maine, which is reinterpreted as a contractional rather than an extensional structure.

INTRODUCTION

DESPITE STEADY progress in the theory and practice of section balancing in foreland thrust belts (e.g. Dahlstrom 1970, Suppe 1983), geologists in hinterland terranes are commonly faced with folded and faulted sections where existing procedures fail. Ironically, early hinterland faults are often more relevant to plate tectonic analyses of orogenic belts than the prominent but straightforward foreland thrusts that have received so much recent attention. This paper is concerned with early faults, such as normal faults formed in rifts or outer trench slopes, gravity-driven slump detachments along passive margins, and thrusts related to subduction–accretion or early stages of collision. Owing to their original tectonic settings, such faults tend to end up in collisional orogens. Yet in strongly tectonized sedimentary sequences, it often is a major accomplishment just to recognize a premetamorphic fault, much less to identify the original hangingwall and footwall, or to determine the sense of motion. The problem is compounded when a fault cannot be traced beyond one outcrop, so any conclusions must be drawn from a single set of observations.

Fault classification schemes in common usage (e.g. Billings 1972, pp. 191–198) have evolved out of decades of debate over the merits of genetic vs descriptive, and observed vs inferred criteria (e.g. Reid *et al.* 1913, Crowell 1959). The popular three-fold Andersonian classification scheme (thrust, normal and strike-slip faults; Anderson 1942) is one descriptive scheme, in which the classes have a tectonically meaningful basis. A problem with most fault nomenclature is that it breaks down when a fault has been sufficiently deformed that its initial and final attitudes differ significantly. Description and interpretation of early faults requires an understanding of the possible effects of faulting on stratified rocks, and of deformation on faults. Outcrop-scale properties that facilitate description of early faults include: relative age of hangingwall and footwall strata, ramp/flat type of hangingwall and footwall beds, younging directions in faulted bedding, fault polarity and sense of displacement in a variety of reference frames. While the number of hypothetical combinations of these binary or trinary variables is bewilderingly large, relatively few combinations are likely to be encountered in nature. This paper shows how these variables facilitate both the description and kinematic analysis of early faults.

The term *early fault* is used informally here for a fault cutting strata that were flat-lying at the onset of faulting. Thrusts that cut their own fault-propagation folds are borderline cases, and these are considered early faults for present purposes. However, faults that have been reactivated with opposite displacement sense are not considered in the present study, even if they did originate as early faults. Early faults in orogenic belts are generally recognized on the basis of structural sequence. Figure 1 illustrates an example of an early, slump-related fault exposed on a slaty cleavage face, in Devonian flysch in New Brunswick. Cleavage clearly post-dates faulting.

An additional criterion for recognition of early dip-slip faults is the test for coaxiality. A *coaxial fault* is defined here as one in which poles to bedding in both fault walls lie in the plane containing the slip direction and the pole to the fault, which is termed the *fault profile plane*. Ordinary thrusts with ramp/flat trajectories and fault-bend or fault-propagation folds are coaxial (Figs. 2a & b), as are ordinary normal faults with normal or reverse 'drag' (Fig. 2c). If the slip direction is unknown, the attitude of the fault profile plane is also unknown. Here the coaxiality test is not definitive, but coaxiality is suggested if the poles to the fault and bedding in both walls are coplanar. Figure 2 illustrates simple cases in which the fault profile planes dips vertically. Deformed

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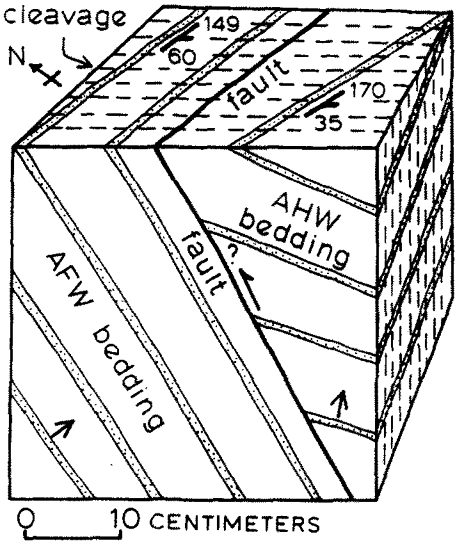

Fig. 1. Schematic block diagram of outcrop relations of an early, slump-related fault in the Temiscouata Formation (Lower Devonian), New Brunswick. These slates occur in a belt of tight to isoclinal regional folds attributed to mid-Devonian Acadian deformation. Cleavage (parallel to front face) is approximately axial planar to tectonic folds, and clearly post-dates faulting. The fault has a right-way-up flat in the apparent footwall (AFW) and a right-way-up ramp in the apparent hangingwall (AHW).

early faults that originated as dip-slip faults are also coaxial, but the attitude of the fault profile plane may be other than vertical, depending on the orientation of the post-faulting deformation axes. In general, strike-slip and oblique-slip faults are strongly non-coaxial. Faults that cut already deformed strata may or may not be coaxial, depending on the orientations of successive deformation axes.

The geometric relationships between a fault and the strata it cuts can be complex, and in general must be described in three dimensions (Crowell 1959). However, the concept of coaxiality provides a justification for the much simpler two-dimensional analysis of dip-slip faults and their deformed equivalents. The two-dimensional treatment is justifiable in all of the common tectonic settings mentioned above, but is unlikely to be useful in analysis of non-coaxial early faults in wrench tectonic settings.

FAULT NOMENCLATURE

It is important to distinguish between observed properties of faults in the present reference frame, and inferred properties in an original, unknown reference frame. Unfortunately, much of the deeply rooted fault nomenclature (e.g. Reid *et al.* 1913) does not draw this distinction. In the present paper, an *undeformed fault* is one which retains the attitude it had when it formed, while a *deformed fault* is one whose attitude and/or bedding cutoff angles have been substantially modified after faulting. A *restored fault* has been returned to an inferred attitude by removing the effects of post-fault deformation.

When applied to deformed faults, the terms thrust and normal fault are ambiguous. In the spirit of Hancock (1985), a *contractional fault* refers to a fault that shortened a datum that was horizontal at the onset of faulting (ordinary thrusts and reverse faults are contractional faults, but so are folded or otherwise rotated thrusts). *Thrust and reverse faults* are contractional faults on which the present-day hangingwall moved up with respect to the footwall. Similarly, an *extensional fault* is one that lengthened an originally horizontal datum, while *normal fault* applies only to contractional faults on which the present-day hangingwall moved down with respect to the footwall. In referring to various types of faults, slip rather than separation is implied (cf. Crowell 1959).

Hangingwall and *footwall* implicitly refer to present state. However, these terms lose their clarity when

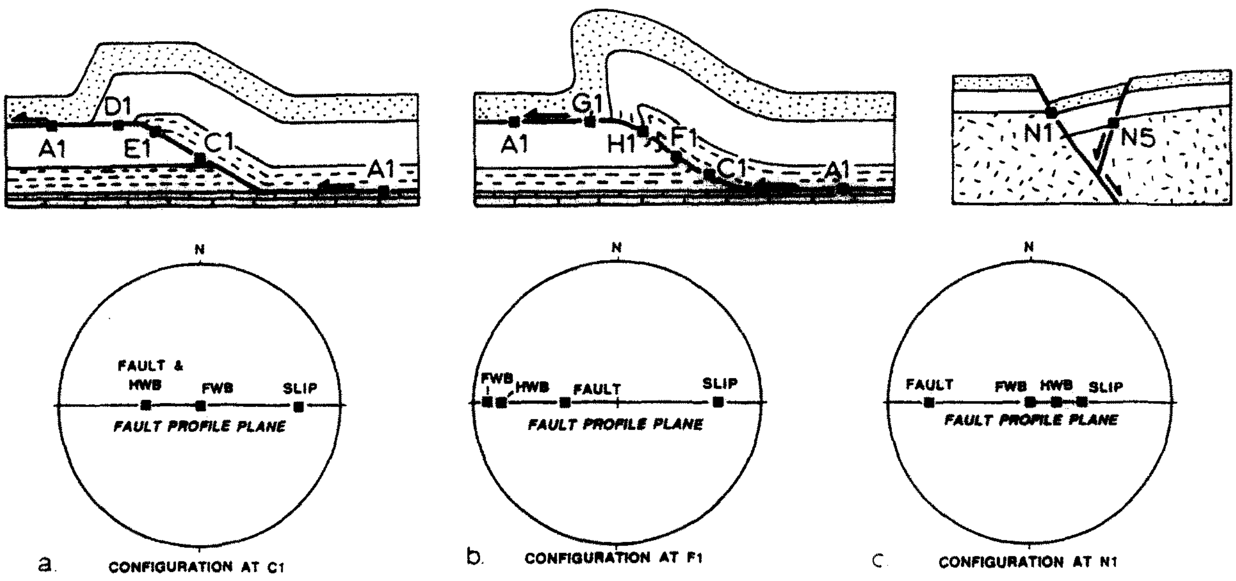

Fig. 2. Hypothetical E–W cross-sections of N-striking coaxial faults: (a) thrust with fault-bend folds; (b) thrust with fault-propagation folds in both walls; and (c) synthetic (right-dipping) and antithetic normal faults. Letter/number pairs along the faults identify configurations in Figs. 6 and 8. Corresponding stereographic projections show that poles to footwall (FWB) and hangingwall (HWB) bedding lie in the plane defined by the pole to the fault and the slip vector.

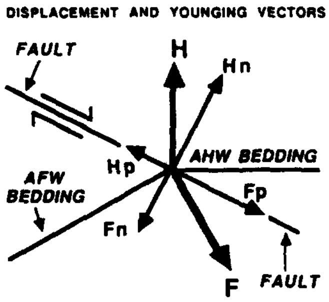

Fig. 3. Fault–bed relationships at a point on a dip-slip fault. In the apparent hangingwall, the younging vector **H** has unit length in a direction perpendicular to bedding, and can be resolved into perpendicular and normal components $\mathbf{H_p}$ and $\mathbf{H_n}$ parallel and perpendicular to the fault. In the apparent footwall, the younging vector **F** has unit length in a direction perpendicular to bedding, and can be resolved into components $\mathbf{F_p}$ and $\mathbf{F_n}$.

dealing with faults that have rotated through vertical: does one refer to the fault wall now overhead as the hangingwall, even if it was the footwall originally? To avoid confusion, the terms *apparent hangingwall* and *apparent footwall* are used where necessary to describe present state, while *paleohangingwall* and *paleofootwall* refer to an inferred initial state. *Apparent thrust* refers to a fault whose apparent hangingwall moved up the present-day fault dip; an *apparent normal fault* is one where the apparent hangingwall moved down the fault dip. Thus, it is possible for an extension fault also to be an apparent thrust (e.g. Jackson *et al.* 1982).

The younging direction of beds in a given fault wall can be expressed as the *younging vector* (**F** for beds in the apparent footwall, **H** for beds in the apparent hangingwall), with unit length perpendicular to bedding (Fig. 3). It is useful to resolve the younging vector into two components, parallel and normal to the fault (e.g. $\mathbf{F_p}$ and $\mathbf{F_n}$).

CRITERIA FOR DESCRIPTION OF COAXIAL FAULTS

A number of properties can be used to describe the cross-sectional geometry of coaxial faults in stratified rocks. None are scale-dependent, but illustrations in Figs. 4 and 5 are particularly applicable to mesoscale relationships at individual outcrops. The ensuing discussion will assume a vertical fault profile plane; the same concepts apply regardless of the dip of this plane, but convenient terminology is lacking.

Horizontal deformation effects

The most common and useful two-fold subdivision of dip-slip faults is based on their horizontal tectonic effects. Does the fault lengthen or shorten a horizontal datum in the present reference frame (Fig. 4a)? For simple ramp-on-ramp faults, an important related question is: does the fault lengthen or shorten bedding?

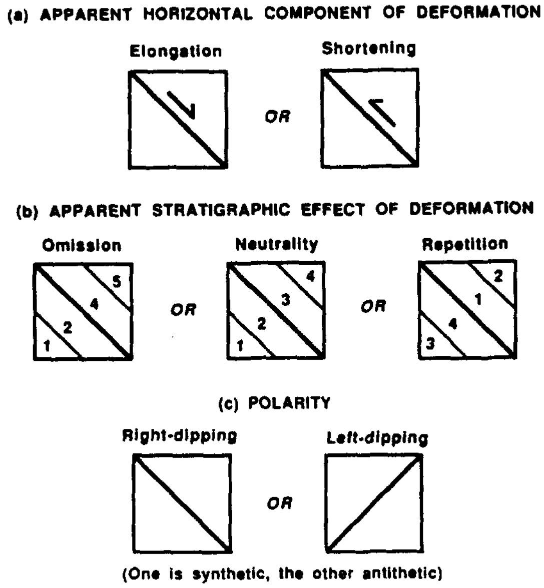

Fig. 4. Variables used in description of dip-slip faults. 'Repetition' includes all possible variations on old-over-young at a given point on the fault. Strata are numbered by relative age, starting with 1 at the base.

Vertical deformation effects

Relative age of hangingwall and footwall strata (Fig. 4b) is an indirect measure of a more fundamental parameter: the vertical component of relative motion. Where a fault cuts previously undeformed, layer-cake stratigraphy, stratigraphic age *does* reflect original position in a vertical column. On the other hand, there are some circumstances where more complex relationships hold. For example, strata in a deep sedimentary basin normally occur topographically below relatively older strata along the basin margin, which can give rise to young-on-old thrusts. Obviously, deformation of a stratified sequence prior to faulting can also produce anomalous age relationships across a fault, such as young-over-old thrusts. Dip-slip faulting can have one of three stratigraphic effects: (1) older over younger (repetition of section); (2) younger over older (omission of section); and (3) normal stratigraphic order (intact section). The third is not always a trivial case; rather, a common type of fault is stratigraphically neutral: the bedding-parallel detachment between beds on the limb of a flexural-slip fold.

Tectonic polarity

In contractional and extensional terranes with a consistent regional tectonic transport direction, faults can be classed as either synthetic (displacement in agreement with the regional direction) or antithetic (displacement in the opposite direction). In the case of deformed faults, the original polarity may be obscure. Accordingly, faults are more objectively described as right-dipping or left-dipping (Fig. 4c), one of the original dip directions being synthetic, the other antithetic.

Ramp/flat type and younging direction

Fault walls are commonly described as flats (essentially bedding-parallel in a given wall of a fault) and ramps (oblique to bedding). Despite common practice, it is wrong to simply characterize some portion of a fault as a ramp or flat. A fault has two walls, and a ramp in the footwall can be juxtaposed with a flat in the hangingwall. The terms ramp and flat have nothing to do with present-day attitude.

The younging direction of bedding in a fault wall is as important as the distinction between ramps and flats. Flats are of two fundamentally different types: bedding either youngs toward or away from a fault. Clearly, an inverted flat in the apparent hangingwall (Fig. 5a, bed 3) must have a very different origin from a right-way-up flat in the same wall (bed 4). Similarly, two fundamentally different types of ramps can be discriminated (bed 1 vs bed 2), based on the relationship between the parallel component of the younging vector ($\mathbf{F}_p$ and $\mathbf{H}_p$) and the fault dip. In bed 1, $\mathbf{H}_p$ points up the fault dip; in bed 2, $\mathbf{H}_p$ points downdip. Despite differences in ramp angle, beds 1a and 1c in Fig. 5(b) could be produced from one another by an appropriate shear deformation; the normal components of the younging vector ($\mathbf{H}_n$) differ in sign in the two cases, with $\mathbf{H}_n$ having zero length for bed 1b. Beds 2a–c comprise a similar set. It is impossible to produce beds 1a–c by deformation of beds 2a–c, because that would entail reversal of the younging direction.

APPLICATIONS TO FAULT PROBLEMS

Early contractional faults

The concepts outlined above have applications in the recognition of early contractional faults, such as might be encountered in tightly folded, metamorphosed flysch terranes. The discussion is based entirely on the types of observations that can be made at single outcrops, as opposed to relationships that might only become apparent from regional mapping. In real examples, the sense of motion and the relative age of faulted strata are not likely to be known, but the discussion begins with the assumption that all properties in Figs. 4 and 5 can be specified.

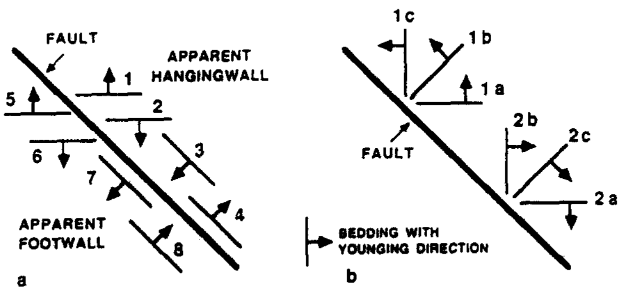

Fig. 5. (a) Four fundamentally different angular relationships between bedding and fault are illustrated in each fault wall. If hangingwall and footwall are treated independently, there are 16 possible combinations. (b) Further subdivision of fault–bed intersection types based on consideration of the normal component of younging vector. $\mathbf{H}_p$ in beds 1a, 1b and 1c is the same sign, but $\mathbf{H}_n$ points toward the fault in bed 1a, and away from the fault in bed 1c.

Figure 6 illustrates all of the fault–bed geometries that can result from contractional faulting of flat-lying strata. The fault types that initially dip to the right (rows A–I, column 1) have mirror images that initially dip to the left (column 5). Paired rows C/F, D/G and E/H differ in that the initial ramp geometry depends on whether faulting is accompanied by fault-bend or fault-propagation folding. In both types of ramps, $\mathbf{H}_p$ and $\mathbf{F}_p$ point up the fault dip. However, these faulting styles do produce differences in the normal components of the younging vectors, $\mathbf{H}_n$ and $\mathbf{F}_n$ (compare beds 1a and 1c in Fig. 5). Fault-bend folding produces right-way-up bedding attitudes in both faults walls. Fault-propagation folding tends to produce overturned bedding in one or both walls, depending on the trajectory of the fault through the fold; hence a configuration combining the hangingwall geometry of row H, column 1 with the footwall geometry of row E, column 1 is also possible (row I). Note the existence of two fundamentally different variations on the flat-on-flat geometry: bedding-parallel slip involving a single detachment and no stratigraphic throw (row 1, columns 1 and 5), and slip involving two detachments, such that the hangingwall flat of the lower detachment is juxtaposed against the footwall flat of the upper detachment (row 2, columns 1 and 5).

Each of the initial contractional fault configurations can be changed into three other configurations by simple rotation in the fault profile plane. A typical flat-on-ramp thrust is shown in Fig. 6, row C, column 1. The initial thrust dips to the right, has relatively older beds in the hangingwall, and right-way-up beds in both walls. A 90° clockwise rotation results in several major changes (row C, column 2). The dip direction is to the left, the apparent hangingwall has moved relatively down, the apparent hangingwall contains the relatively younger strata, the fault walls containing the ramp and flat have switched, and the apparent footwall beds are inverted. Changes of comparable magnitude are realized when any coaxial fault is rotated through vertical so that its dip direction changes. When a fault is rotated through horizontal so that its dip direction changes, the sense of displacement and polarity change, but the hangingwall and footwall do not (compare row C, columns 1 and 4 in Fig. 6).

The configurations that can be produced by simple or pure shear strains are comparable to those induced by rotations, but they are not so conveniently illustrated for all cases. Figure 7 shows how horizontal simple shear can cause several simultaneous changes in fault configuration. Initially (Fig. 7a), the fault is comparable to row C, column 1 in Fig. 6: a right-dipping, flat-on-ramp thrust. Following dextral simple shear of 1.2, the fault dips to the left, appears to omit section, has an inverted flat in the apparent footwall, and a right-way-up ramp in the apparent hangingwall. Moreover, the ramp angle has changed so that bedding that previously younged toward the fault now youngs away from it. This capacity

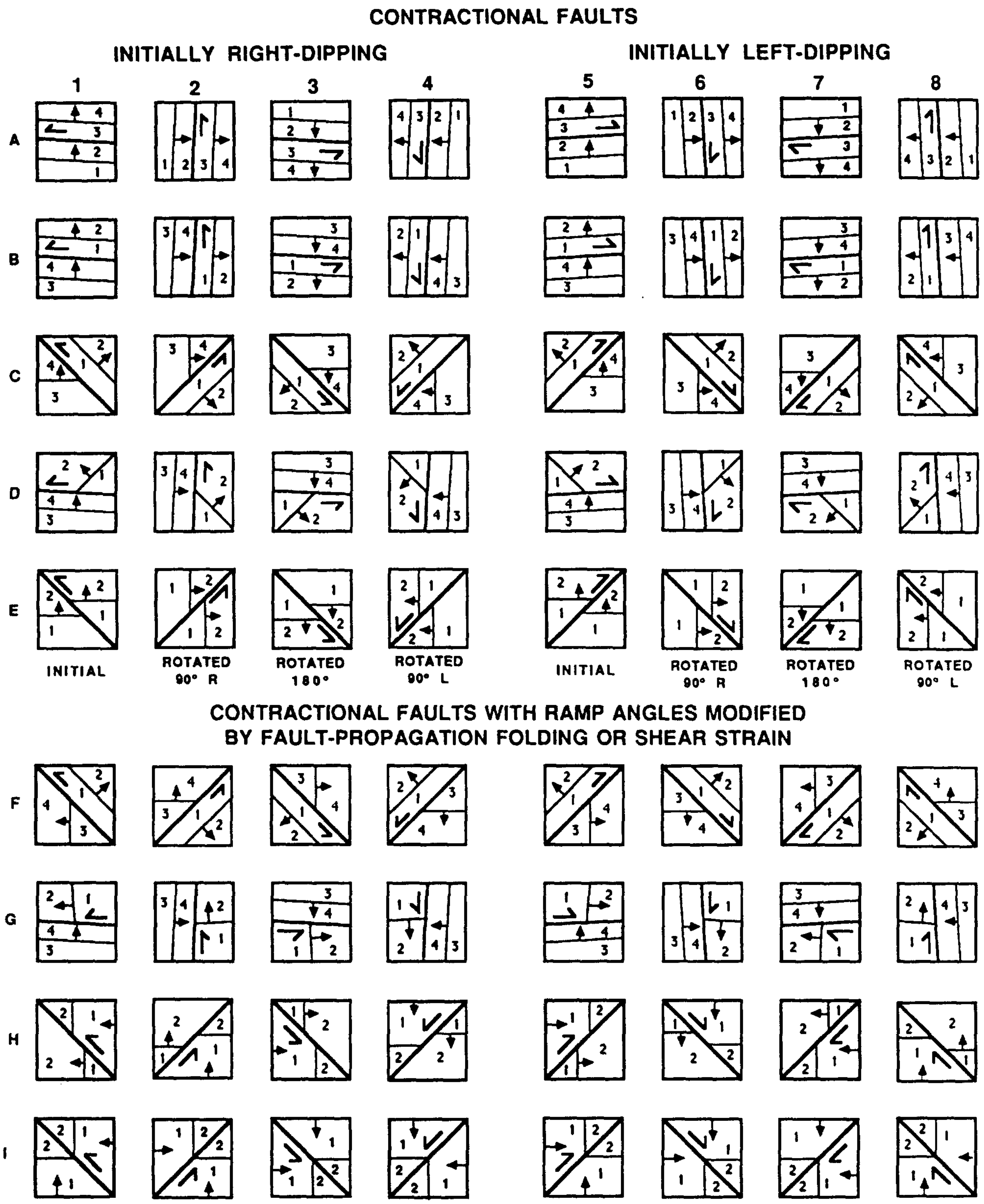

Fig. 6. The 72 possible cross-sectional fault configurations that can result from contractional faulting of flat-lying strata. Strata are numbered with 1 the oldest; full arrows show younging direction. Faults are shown by thick lines and displacement half-arrows. The eight fault types that initially dip to the right (column 1) have mirror images that initially dip to the left (column 5). Paired rows C/F, D/G and E/H are minor variations, which differ in terms of the sign of H_n and/or F_n.

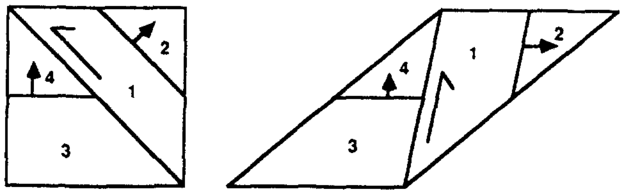

Fig. 7. Changes in fault configuration due to a horizontal simple shear. (a) Initially, the fault is comparable to row C, column 1 in Fig. 6. (b) Following dextral simple shear of 1.2, the paleohangingwall has become the apparent footwall, and the ramp angle has changed so that the younging direction in the paleofootwall now points away from the fault.

to alter ramp angles sets shear strain apart from rotation in the present context. A second way of generating the configurations in rows F–H in Fig. 6 is through shear-induced modifications of ramp angle.

Some contractional fault configurations in Fig. 6 are more likely than others. By definition, synthetic faults are more likely to be encountered than antithetic faults. Some post-faulting deformations are more likely than others, depending on tectonic setting. For example, clockwise rotations of older thrusts are commonly induced by footwall imbrication in right-dipping thrust systems. The results of severe rotations of 180° are shown in Fig. 6 to cover all possibilities, but such rotations should only be suspected in areas characterized by downward-facing folds.

Early extensional faults

Figure 8 illustrates all the fault–bed geometries that might conceivably result from extensional faulting of flat-lying strata, including staircase trajectories. Five fault configurations can be recognized that initially dip to the right (rows J–N, column 1), each with a mirror image with opposite dip (column 5). Ordinary normal faults with right-way-up ramps in both walls are shown in row N, columns 1 and 5, one being synthetic, the other antithetic for a given region.

Each of the 10 initial fault configurations can be changed into three other configurations by simple rotation about the pole to the fault profile plane. The most common rotations in extensional settings are those which tend to decrease the dip of synthetic faults, while steepening antithetic faults until, in the extreme, they are rotated through vertical and become apparent thrusts (row N, columns 5 and 6) (Jackson *et al.* 1982). The effects of shear strains on extensional fault configurations (rows O–Q) are comparable to those on contractional faults, except that there is no obvious mechanism to produce configurations analogous to those in row I of Fig. 6.

Practical considerations

Outcrop observations of a problematic fault at outcrop should include: relative age of the fault in the structural sequence; evidence of post-fault penetrative strain, fault attitude, sense and amount of slip; relative age of faulted strata; and bedding attitude, younging direction; and ramp/flat status in both fault walls. If a fault is non-coaxial (determine this stereographically) or late, the following discussion will be of limited help in working out the fault's origin or initial configuration. If the fault is coaxial and early, several different cases need to be considered, depending on the configuration of the fault in question, and on the availability of certain data. Finally, if the coaxiality test is not definitive (i.e. all three poles are coplanar but slip direction is unknown), any conclusions must be treated with caution.

A rapid, qualitative solution can be obtained when all information in Figs. 4 and 5 is available, shear strain is small, and the fault profile plane is vertical or nearly so. Figures 6 and 8 should be consulted to find a configuration that qualitatively matches the fault in question in terms of fault dip direction, sense of displacement, hangingwall younging direction and ramp/flat status, footwall younging direction and ramp/flat status, and relative age. If a match cannot be made, then either the fault cut already deformed strata, or relative age, sense of displacement, or younging direction were misinterpreted. If there is a match, the initial fault configuration can be readily found in column 1 or 5. In most cases, a unique configuration will be found in Fig. 6 or Fig. 8. However, comparison of rows H and N, and rows E and Q reveals that the same fault configurations can develop in contractional and extensional regimes, although their origins differ profoundly. To resolve this problem, compare the observed post-faulting deformation history of the area in question with the two very different implied deformation histories of the alternatives in Figs. 6 and 8, and select the initial fault geometry which is consistent with the structural setting.

A slightly different approach is appropriate when a quantitative solution is desired, or when the fault profile plane is non-vertical. (Shear strain is still assumed to be negligible.) The first objective is to identify the paleofootwall; the second objective, though not always feasible, is to restore its bedding to horizontal. Columns 1 and 5 in Figs. 6 and 8 show that paleofootwall flats always young toward the fault, and paleohangingwall flats always young away from the fault. Therefore, the paleofootwall can be unambiguously identified for any fault configuration involving at least one flat. Where both walls are ramps, the fault either belongs in row E, H, I, N or Q in Figs. 6 and 8. If both ramps young toward the fault, the configuration belongs in row I and the paleofootwall is the one containing right-way-up bedding when the fault is oriented such that its apparent sense of displacement is contractional. Otherwise, one is faced with the same ambiguity discussed in the previous paragraph: that paired rows H/N and E/Q contain identical configurations. As above, the implied deformation histories should lead to a unique solution.

Having identified the paleofootwall, these beds should be rotated to horizontal and right-way-up. The rotation axis or axes should be selected using the same criteria as should be applied in paleocurrent analysis, the

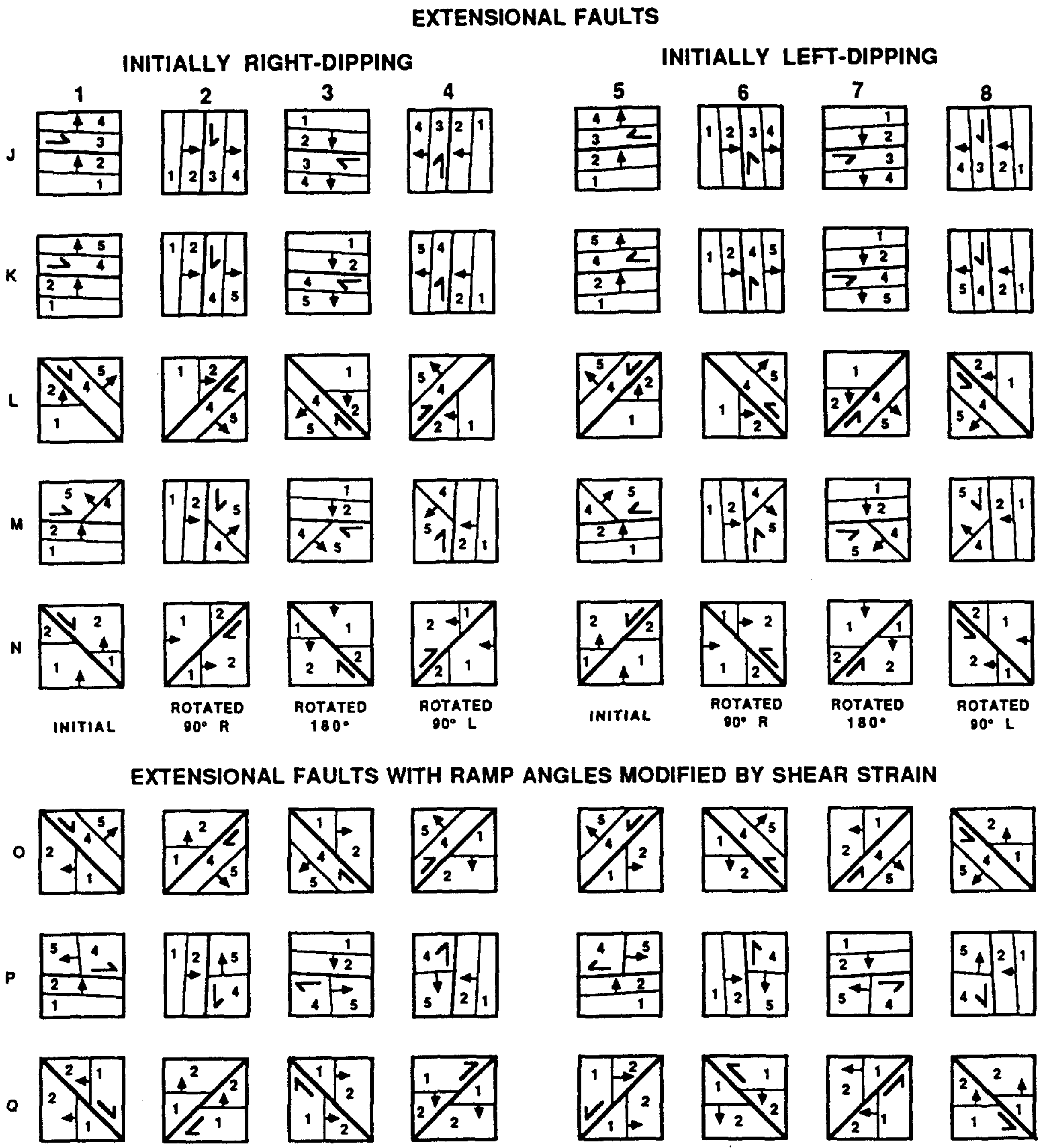

Fig. 8. The 64 possible cross-sectional fault configurations that can result from extensional faulting of flat-lying strata. See also caption for Fig. 6.

objective being to exactly reverse the path followed by paleofootwall during deformation. This operation yields the initial attitudes of the fault, slip direction and bedding in the paleohangingwall. Simultaneously, the fault profile plane is restored to vertical. If the fault configuration is in rows F or O, there is no suitable reference frame for tilt correction of the fault, either because paleofootwall beds were already inclined when the fault propagated through the deforming strata ahead of its tip line, or because shear strain modified the ramp angle. However, the initial fault dip direction can be determined, assuming that paleohangingwall strata were right-way-up after faulting. If the fault belongs in rows H/N or E/Q, two alternative tilt-corrections must be performed, and the initial fault geometry is selected as described above.

If the shear component of deformation was intense enough to have changed the dip direction of the fault and/or the sign of $\mathbf{F}_n$ or $\mathbf{H}_n$, the foregoing analysis should be postponed until after strain correction. Where the orientation and axial ratio of the strain ellipse in the fault profile plane are known, a simple orthographic construction (De Paor 1986) yields the strain-corrected fault configurations. Where the axial ratio is unknown but the principal strain directions are known, orthographic constructions can be performed for several plausible axial ratios, to see if any reasonable strains would have been capable of changing the fault configuration.

In most actual examples of early faults, sense of displacement is unknown or equivocal. Here, Figs. 6 and 8 aid in kinematic analysis. Without arrows to indicate relative motion, rows A and J would become identical, adding to the two identical pairs of rows discussed above. Otherwise, each fault configuration is unique, and the initial configuration and displacement sense of most faults can be inferred as outlined above. Another common unknown is relative age of strata, especially in seemingly monotonous metaturbidite and metapelite sequences. Without numbers indicating relative age of strata, rows A and B and rows J and K become exact replicas. Otherwise, each fault configuration is unique, and the initial configuration and relative stratigraphic age across of most faults can be inferred from Figs. 6 and 8. Cases where both sense of displacement and relative age are unknown are also common. In some cases, it should be possible to determine initial configuration and both unknowns; in other cases, the range of possible choices can be narrowed.

Application in a metasedimentary terrane

Several major strike-parallel premetamorphic faults cut deep-water Siluro-Devonian strata on the northwestern limb of the Kearsarge–Central Maine Synclinorium in the Northern Appalachians. The faults occur on the limbs of regional-scale, tight to isoclinal, right-way-up folds, and they predate regional metamorphism to andalusite grade. Any mesoscopic or microscopic kinematic indicators that might have once existed have probably been obliterated; in any case, no modern analyses of fault kinematics have been attempted. The Hill 2808 fault (Fig. 9) is such a fault. It dips steeply to the southeast, and seems to omit section in that the apparent hangingwall contains relatively younger strata. Moench (1970) interpreted it as a down-to-basin normal growth fault. On the other hand, Bradley (1983) speculated that the Hill 2808 and related faults might be rotated thrusts. These alternatives exemplify the important role of early faults in regional tectonic analysis, since Moench's (1970) interpretation implies an extensional setting immediately before the Acadian Orogeny, while Bradley's (1983) implies convergent tectonism.

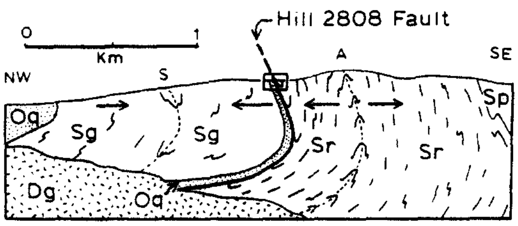

Fig. 9. Simplified structure section through the Hill 2808 fault, Rangeley quadrangle, western Maine (adapted from Moench 1970). In ascending order, formations are abbreviated as follows: Oq = Quimby Formation; Sg = Greenvale Cove Formation; Sr = Rangeley Formation; Sp = Perry Mountain Formation. Arrows show overall younging directions and S and A mark the axial traces of major syncline and anticline. Note that beds immediately adjacent to the fault in the apparent hangingwall young away from rather than toward the fault. Small rectangle is location of Fig. 10.

The present study provides a rational framework within which to consider all possible structural interpretations.

Figure 10(a) summarizes Moench's (1970) normal fault interpretation. The apparent hangingwall is a ramp with beds younging away from, and up the dip of the fault. The apparent footwall is a flat with beds younging away from the fault. The apparent hangingwall contains strata that are interpreted to be relatively younger; hence the fault seems to omit section. Comparing Figs. 6, 8 and 10(a), the Hill 2808 fault corresponds to one and only one configuration, in row F, column 8. Therefore, a provisional solution is that it is a contractional fault with a paleofootwall syncline (initially row F, column 5) that has been rotated counterclockwise through an angle sufficient to reverse the fault's dip direction. Strain determinations are unavailable from outcrops of the fault at Hill 2808; if shear strain was sufficient to rotate the ramp angle through the normal to the fault (considered unlikely), the initial configuration would have been row C, column 5. Examination of Fig. 8 seems to preclude a simple normal fault interpretation, as there are no matching configurations. The Hill 2808 could only be a SE-down normal fault if it cut strata that were already deformed to a far greater degree than implied by Moench (1970, p. 1489).

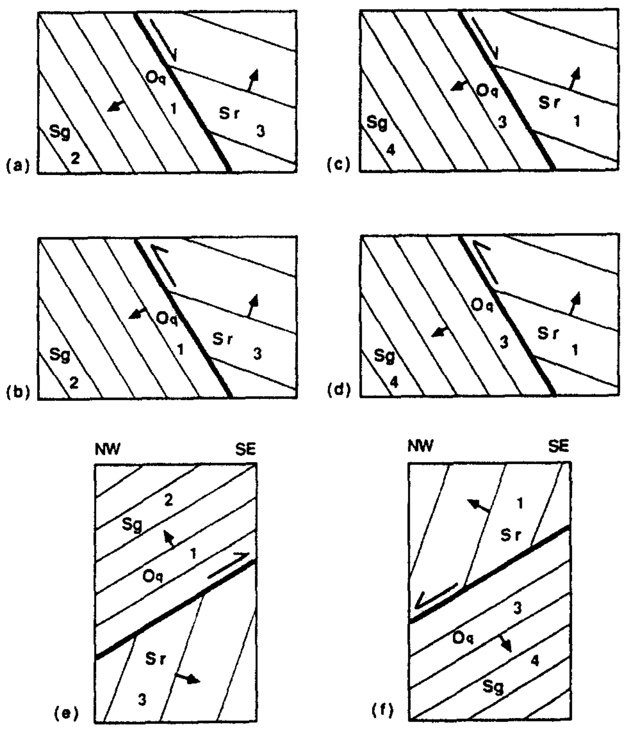

Fig. 10. Stylized cross-sections through the Hill 2808 fault. Numbers next to formation abbreviations stand for inferred relative ages with 1 being oldest. (a) Moench's (1970) interpretation that the fault is a normal fault, consistent with the presence of relatively younger strata in the apparent hangingwall. (b) Alternative hypothesis for the present fault geometry, assuming the fault is an apparent thrust. (c & d) Alternative hypotheses assuming that the relative ages of formations are reversed. (e) Preferred interpretation that the fault was originally a SE-directed thrust. A 90° counterclockwise rotation would transform the initial configuration to that observed at outcrop. (f) Less plausible alternative interpretation that the fault originated as a NW-down normal fault; this can only be the case if the established stratigraphy is wrong.

The (apparent) SE-down sense of displacement inferred by Moench (1970) and shown in Fig. 10(a) was based on the dip direction and relative age of faulted strata, and not on shear criteria. Therefore, the possibility that the sense of displacement was (apparent) SE-up must be considered. However, Figs. 6 and 8 contain no fault configurations that correspond to the hypothetical one in Fig. 10(b). This supports Moench's (1970) assessment of displacement sense.

Poor age control is a common problem in tectonized, deep-water, metasedimentary terranes such as the Kearsarge–Central Maine Synclinorium in Maine. Although the relative ages in Fig. 10(a) are generally accepted, fossil control is admittedly poor, suggesting the possibility that the relative ages are actually reversed. Figure 10(c), which depicts this hypothesis, is unlike any configuration found in Figs. 6 and 8, and can therefore be rejected. However, if both the stratigraphic sequence and the sense of motion were incorrectly interpreted by Moench (Fig. 10d), a match can be made with row O, column 8 in Fig. 8.

Of the two possible alternatives, both are qualitatively consistent with the structural setting of the Hill 2808 fault. The entire region was subject to Acadian folding on a much broader scale than the outcrops where the fault is observed (Fig. 9). Judging from the position of the fault on the shared limb of an anticline–syncline pair, a clockwise sense of rotation would be required to correct for folding. A broad range of clockwise rotations (from 30° to 120°) are sufficient to produce an initially NW-dipping fault with a hangingwall flat and footwall ramp. Figure 10(e) is a flat-on-ramp geometry which is commonly produced by thrusting where fault-propagation folding produces a footwall syncline. On the other hand, Fig. 10(f) implies an initial staircase trajectory which is uncommon in extensional settings, and requires a strain-induced change in ramp angle of at least 50°. Since Fig. 10(f) can only be correct if the well-accepted stratigraphic sequence is wrong, the most reasonable conclusion is that Fig. 10(e) is a qualitatively correct starting configuration for the Hill 2808 fault.

CONCLUSIONS

Early faults in orogenic belts are often significant to regional tectonic interpretations because they record deformation regimes that may be quite unrelated to terminal orogenic events. Post-faulting deformations tend to obscure the original configuration of a fault in many ways. A rotation sufficient to change the dip direction of a fault simultaneously reverses the apparent sense of displacement. In some cases, such rotations also cause a switch in the identity of the apparent hangingwall and footwall, and a corresponding switch in the identity of the fault wall containing the relatively older strata. However, in the reference frame corresponding to the fault profile plane, with the fault trace as one coordinate axis and an immaterial line normal to the fault as the other, flats remain flats, ramps remain ramps, relative age of strata across the fault is immutable, and displacement direction is constant. The interpretation of a deformed early fault is contingent on recognition of the paleofootwall, so that the rest of the properties of the fault can be viewed in the correct reference frame.

Contractional and extensional faults cutting strata that were flat-lying when faulted can produce 20 initial fault configurations (rows A–E and J–N in Figs. 6 and 8). Additional configurations associated with fault-propagation folding, plus others resulting from rotation and penetrative deformation, minus repeats, yield a total of 120 coaxial early fault configurations. Daunting as this array may seem, it is dwarfed by the 432 hypothetical combinations which could conceivably exist, if all eight variables in Figs. 4 and 5 are allowed to vary independently. Some of the 312 'complex' configurations might occur in rocks that were deformed prior to faulting, for example, as a result of out-of-sequence thrusting (Morley 1988, p. 541). Others might arise on paper during construction of a cross-section, calling attention to possible errors.

Acknowledgements—P. Geiser provided a thoughtful review which vastly improved the manuscript. I also benefited from comments by L. Bradley, T. Kusky and G. Fisher. My collaborative research with L. Hanson on slump-related faulting in Maine has been supported by NSF grant EAR-8803233. I thank the U.S. Geological Survey, Branch of Alaskan Geology, for the opportunity to complete and revise the manuscript.

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