Paleoslope Analysis of Slump Folds in the Devonian Flysch of Maine[1]

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ABSTRACT

Ancient submarine slide and slump deposits in the Devonian flysch of central and northern Maine show considerable variation in fold style, from symmetric to asymmetric to sheath geometries. Building on earlier work by Farrell and Eaton, we suggest that the spectrum of fold styles reflects the degree of simple shear within each slump deposit. We present a stereographic approach to paleoslope analysis that exploits fold hinge attitudes, axial surface attitudes, sheath axes, vergence, S- and Z-asymmetry—depending on the style of slump folding. Our paleoslope determinations from widely scattered locations across the Devonian foreland basin in Maine show a regionally consistent pattern of westerly to northwesterly slopes.

Introduction

In the interval between the Taconic and Acadian orogenies, turbidites were deposited across much of Maine (figure 1). Many previous workers (Moench and Boudette 1970, p. A-1-17; Griffin and Lindsley-Griffin 1974; Hall et al. 1976, p. 61; Ludman 1977, p. 12; Pankiwskyj 1979, p. 40; Hanson and Bradley 1989; Roy et al. 1991) have interpreted chaotic rock bodies within these Silurian-Devonian turbidites as slump deposits formed as a result of downslope mass wasting. The slump deposits have proven useful for paleogeographic studies, because they suggest the presence of submarine slopes steep enough to fail. Although slump folds can also reveal paleoslope *directions*, little effort has been made in Maine to glean this sort of quantitative information. Among the papers cited above, the only one to report an actual paleoslope direction is that by Hall et al. (1976), for a slump at Grand Lake Matagamon (figure 1).

In this paper, we present paleoslope determinations for six inferred slump deposits in the Devonian flysch of Maine. We came across these slumps during the course of a regional paleocurrent study, which focused on large, riverbank exposures in structurally simple, homoclinal sections. Out of dozens of inferred slump deposits we encountered, only the six described here have yielded paleoslope directions we deem reliable enough to report. Among the others, the most common problem was that the lower and upper contacts of a supposed slump horizon were not exposed, making it difficult to rule out a tectonic origin for the deformation and impossible to restore the slump folds to paleohorizontal. Slump deformation in some of the giant outcrops was so chaotic that kinematic analysis was not even attempted. At small outcrops, slump horizons were found that contained only one or two folds, which, we will argue below, is not enough to be very meaningful. All of these problems eroded what might have been a much larger data set.

The final difficulty, which we address here, is that even among the most tractable slump deposits, there is considerable variation in structural style and a corresponding variation in stereonet patterns of fold hinges and axial surfaces. At one extreme, fold hinges are clustered and poles to axial surfaces lie on a great circle; at the opposite extreme, hinges lie along a great circle while poles to axial surfaces are clustered. The problem is how systematically to treat these data, without resorting to *ad hoc* approaches that work on some slump deposits but not others.

Geologic Setting of Devonian Flysch in the Acadian Orogen of Maine

The slump deposits are from three depositional belts of Devonian flysch in the Maine Appalachians

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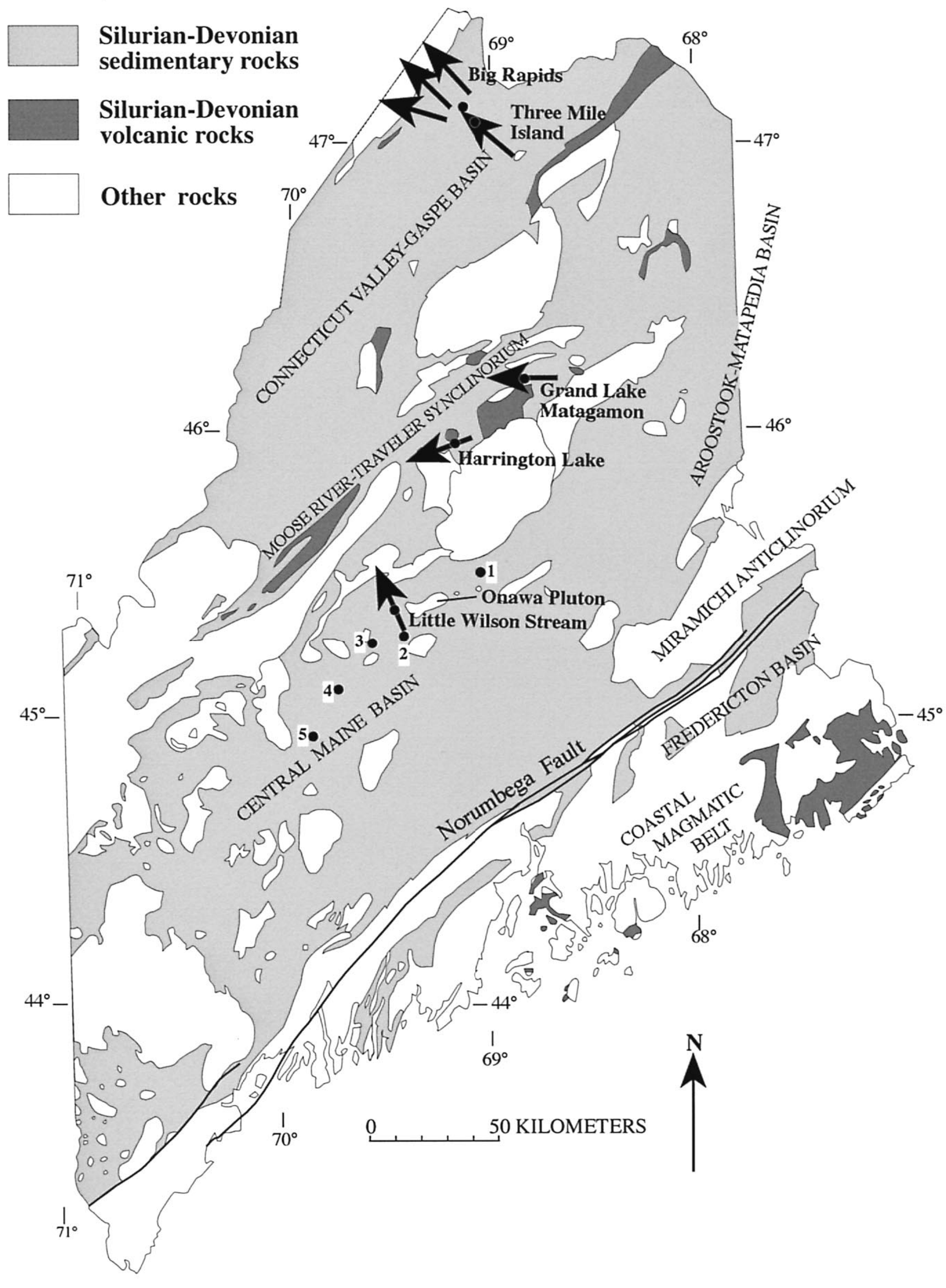


Figure 1. Map of Maine showing major Silurian-Devonian paleogeographic belts, and locations of the main slumps discussed in the text. Additional locations are as follows: 1—Gauntlet Falls; 2—Tobey Falls, 3—Barrows Falls; 4—Coles Corners; 5—Arnolds Landing; and 6—Greenville Junction. Large arrows show inferred paleoslope directions based on the present study, except at Grand Lake Matagamon, which is a generalized direction from Hall et al. (1976).

(figure 1): the Carrabassett Formation of the Central Maine basin, an undifferentiated part of the Seboomook Group along the Moose River–Traveler Synclinorium, and the St. John River Formation (of Roy et al. 1991) in the Connecticut Valley–Gaspe basin. These units contain variable proportions of slate and graywacke, and stratigraphic thicknesses are typically >1 km. The Devonian flysch of Maine has been interpreted as a foredeep succession, the deformed precursor to the classic Catskill delta of the Appalachian Basin (e.g., Bradley 1987; Hanson et al. 1993; Bradley 1997). In the areas of interest, the main affects of the Acadian orogeny were regional open- to tight-folding, development of a NE-striking cleavage, chlorite- and sub-chlorite-grade regional metamorphism, gabbroic and granitic plutonism, and cordierite- and andalusite-grade contact metamorphism in surrounding aureoles (e.g., Osberg et al. 1989).

Carrabassett Formation. The Carrabassett Formation, of probable Early Devonian age (e.g., Moench and Pankiwskyj 1988; Osberg et al. 1985), is the youngest regionally extensive rock unit in the Central Maine basin (Hanson and Bradley 1989). Although it has not yielded diagnostic fossils, its age can be inferred from: (1) its stratigraphic position about 1.5 km above an early Ludlovian graptolite in the Smalls Falls Formation; (2) lithologic similarity with the Lockhovian and Pragian Seboomook Group of the Moose River Synclinorium; and (3) the fact that it was deformed, regionally metamorphosed, and intruded by a number of plutons with early Emsian concordant U/Pb zircon ages of 404–408 Ma (Bradley et al. 1996). We have suggested that the Carrabassett Formation was deposited on the N-facing frontal slope of an advancing Acadian orogenic wedge (Hanson and Bradley 1989). This interpretation is based on its immediately pre-Acadian age, our recognition of slope facies, including slump deposits, and on the regional paleocurrent pattern.

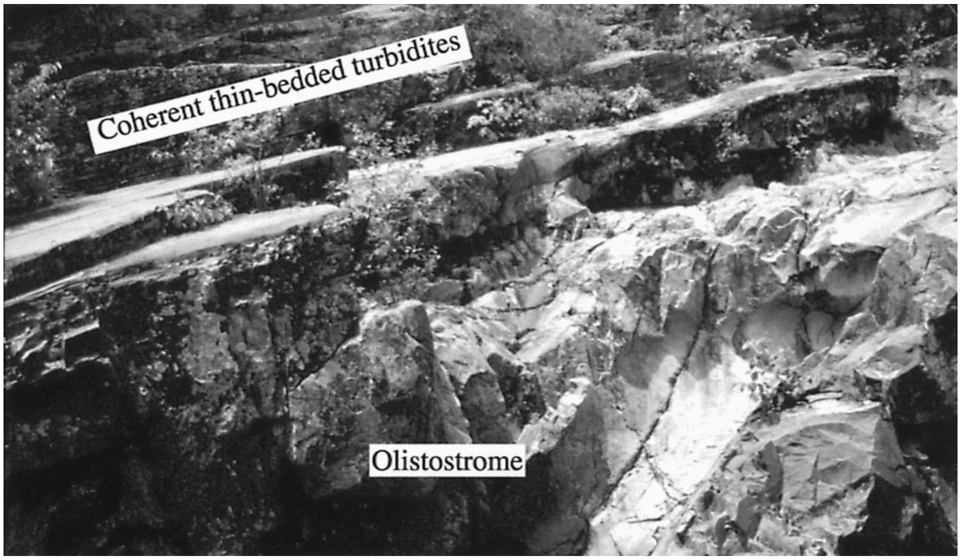
Chaotic deposits comprise about 75% of the formation (Hanson and Bradley 1989). Coherent turbidites are interlayered with the chaotic deposits, and in several key places it is clear that the two are interbedded rather than tectonically juxtaposed. The most revealing location is in the contact aureole of the Moxie pluton at Gauntlet Falls (figure 1; Hanson 1994), where gently dipping turbidites were laid down over the irregular surface of a >10-m-thick zone of disharmonically folded and dismembered thin-bedded turbidites (figure 2*A*). Chaotic and coherent strata alike were contact-metamorphosed before acquiring the prevasive regional cleavage ubiquitous outside the aureole. The contact is depositional, showing that the chaotic structure originated on the seafloor rather than at depth due to tectonism. Elsewhere in the region, many outcrops of Carrabassett Formation consist entirely of disrupted, fragmented thin-bedded turbidites; these rocks typically display a fragment foliation, and the relative importance of soft-sediment versus tectonic deformation is unknown. Coherent strata of the Carrabassett Formation include thin- and thick-bedded turbidites and massive sandstones, which we believe represent slope-basin and channel subenvironments, respectively (Hanson and Bradley 1989). Paleocurrent analysis at 16 sites in the Carrabassett Formation reveals that the dominant flow direction was toward the north, with a secondary component toward the east (Hanson et al. 1993, p. CC-14). The paleocurrents record a new paleogeographic regime; pre-Carrabassett strata in the Central Maine basin were deposited by paleocurrents flowing either toward the southeast or southwest (Hanson and Bradley 1994).

Seboomook Group. Devonian turbidites along the Moose River-Traveler Synclinorium (figure 1) are assigned to the Seboomook Group. Detailed studies at Grand Lake Matagamon (Hall et al. 1976; Pollock et al. 1988) have established that the Seboomook is a deep-water, base-of-slope turbidite succession associated with a west-prograding deltaic complex. Paleocurrent analysis of the Seboomook Group at 10 sites indicates flow toward the west (Hanson and Bradley 1994). Inferred slump deposits are present but are a relatively minor part of the Seboomook Group in this belt (Hall 1973; Hall et al. 1976).

St. John River Formation. In the Connecticut Valley–Gaspe deep-water basin of northernmost Maine, most of the Seboomook Group has been assigned to the informally named St. John River Formation (of Roy et al. 1991). About two-thirds of the strata belong to turbidite facies B, C, D, or mud turbidites, preserved in coherent, homoclinal stratal successions. Most of the remainder of the formation consists of siltstone-rich chaotically deformed strata inferred to represent slump deposits. Sheath folds are common (figure 2*b*). Paleocurrent data from three sites in the Connecticut Valley–Gaspe basin in Maine indicate flow toward the west (Hanson and Bradley 1994).

Analytical Techniques

Identification of Slump Deposits. The regional structure of our study area is simple and straightforward; in typical exposures one finds homoclinally dipping beds cut by a regional cleavage. The



A

B

Figure 2. *A*. Slump deposit at Gauntlet Falls. Outcrop is within the contact aureole of the Moxie Pluton, in andalusite-grade rocks. The strata were contact-metamorphosed prior to Acadian regional deformation, which left no imprint aside from the gentle bedding dip. Olistostrome below the bedded turbidites consists of steeply dippling, dismembered siltstone bed segments and a few rootless folds. Interbedded chaotic and coherent strata are also present in the Carrabassett Formation at Little Wilson Stream, Tobey Falls, Barrows Falls, and Coles Corners (figure 1). *B*. Sheath fold from a well-exposed slump horizon in the Temiscouata Formation (Seboomook equivalent), northwestern New Brunswick, a few tens of kilometers along strike from Big Rapids (figure 1). The movement was roughly toward or away from the observer. The three slump deposits from Big Rapids, analyzed here, display comparable folds, but are not as photogenic.

folded zones we identify as slump deposits are visually striking: anomalous, disharmonically folded layers enclosed in strata affected only by the regional folding (figure 3). The strata below and above face in the same direction. The six folded zones for which we quote paleoslope directions all include dismembered bed segments. Despite the intensity of deformation, there is no evidence of syn-deformational veining, for example, at fold hinges on the convex sides of competent beds. A slump should have a detachment at its base and a depositional contact at its top (Elliott and Williams 1988). Of the six folded zones for which we quote paleoslope directions, the upper contact is exposed at four and the lower contact is exposed at four. In all cases, the outcrop evidence is consistent with these criteria. In four instances, the folds demonstrably predate regional cleavage, and in no case is the reverse true (Hanson 1994; Kusky et al. 1994). In all six cases, the weight of evidence supports a slump origin. Alternatively, a tectonic explanation for any of the disharmonically folded zones would require special pleading.

Reference Frames and Retrodeformation. Two reference frames are normally used in analyzing slump folds in tectonically deformed rocks: (1) the present-day reference frame, in which folds are actually measured, and (2) the stratigraphic reference frame, in which the original attitudes of slump structures are interpreted. The stratigraphic reference frame is found by restoring to horizontal the host bedding that stratigraphically overlies or un-

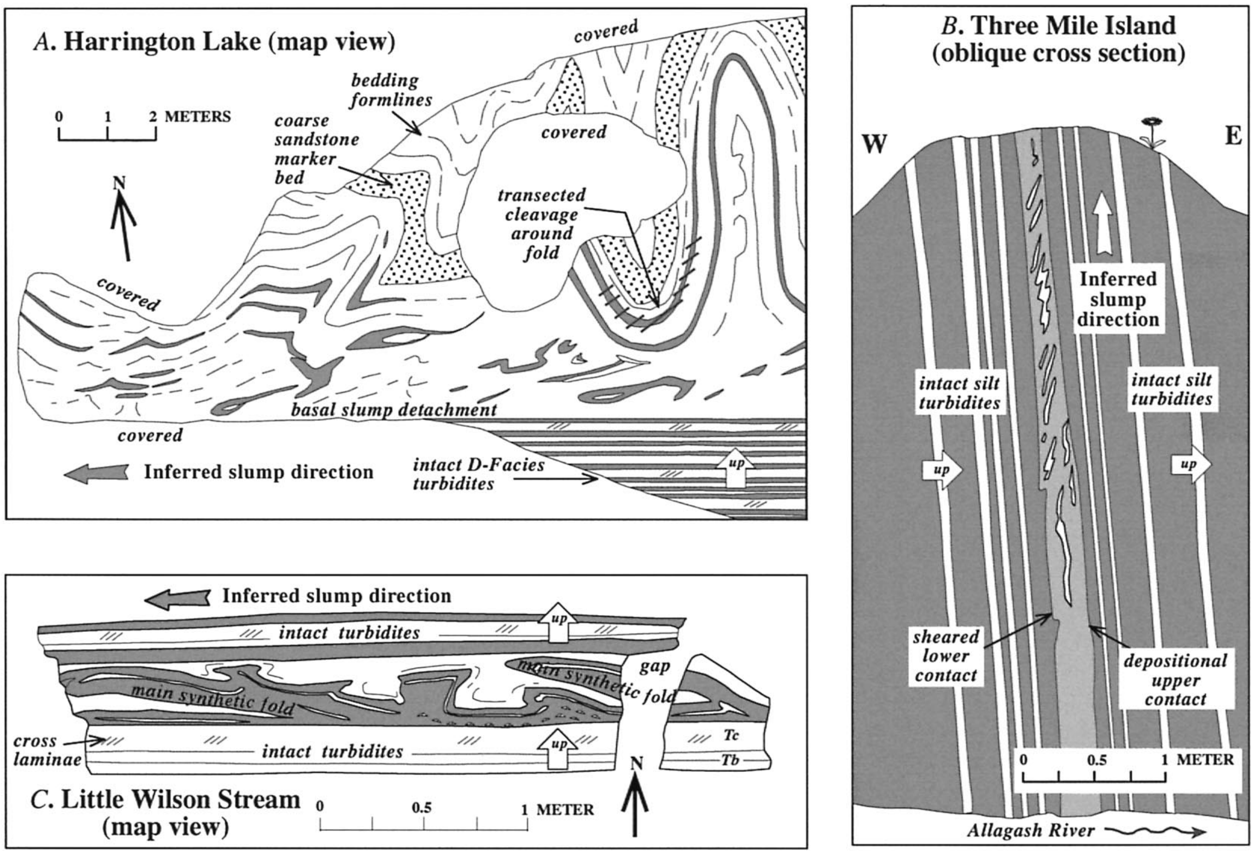


Figure 3. *A*. Tape-and-compass map of the stratabound slump horizon at Harrington Lake, showing upright, symmetric folds. *B*. Stratabound slump horizon showing asymmetric folds, from the Seboomook Group (St. John River Formation of Roy et al. 1991) near Three Mile Island, Allagash River. Sketch from a photograph. *C*. Tape-and-compass map of a stratabound slump horizon showing synthetic faults and folds, and antithetic folds, from Little Wilson Stream. Tb and Tc are the B and C divisions of the Bouma turbidite sequence.

derlies a slump. Ideally, this procedure should exactly reverse any changes in attitude due to deformation, just as in paleocurrent analysis. The possibility that strata hosting a slump may have originated on a slope with some initial dip is normally glossed over in studies of ancient rocks (figure 4). This is not an unreasonable simplification, since most submarine slopes dip less than 10°, but it does complicate the understanding S- and Z-fold asymmetry.

All but one of the slump deposits were restored to paleohorizontal by the standard single-tilt correction: host bedding and slump structures were rotated about an axis parallel to bedding strike through an angle equal to the bedding dip. This is appropriate for the Devonian flysch in central and northern Maine, which is affected by a single generation of upright, NE-trending, open-to-tight folds with a single axial-planar cleavage. (There are parts of the Acadian Orogen—for example, southwestern Maine, New Hampshire, and Massachusetts—where deformation was polyphase, and the single-tilt correction would be wholly inappropriate.) A two-step rotation was used for one slump (Little Wilson Stream; see below), where regional bedding strike was deflected during emplacement of a nearby pluton. For want of mesoscopic strain markers, we did not account for the minor effects of penetrative tectonic strain in the paleoslope analysis that follows. Where we were able to measure and correct for strain in our regional paleocurrent studies, it turned out to have a negligible impact. Specifically, in the Madrid Formation at Arnolds Landing (figure 1), 26 cross laminae in subvertical beds yielded a mean paleocurrent direction of 254°, subject to single-tilt correction only, compared to 249°, subject also to orthographic strain correction (Hanson et al. 1993).

Style of Slump Folding and Stereographic Methods. Farrell and Eaton (1987, 1988) presented an elegant model that accounts for much of the variation in structural style of slump folds (figure 5). In

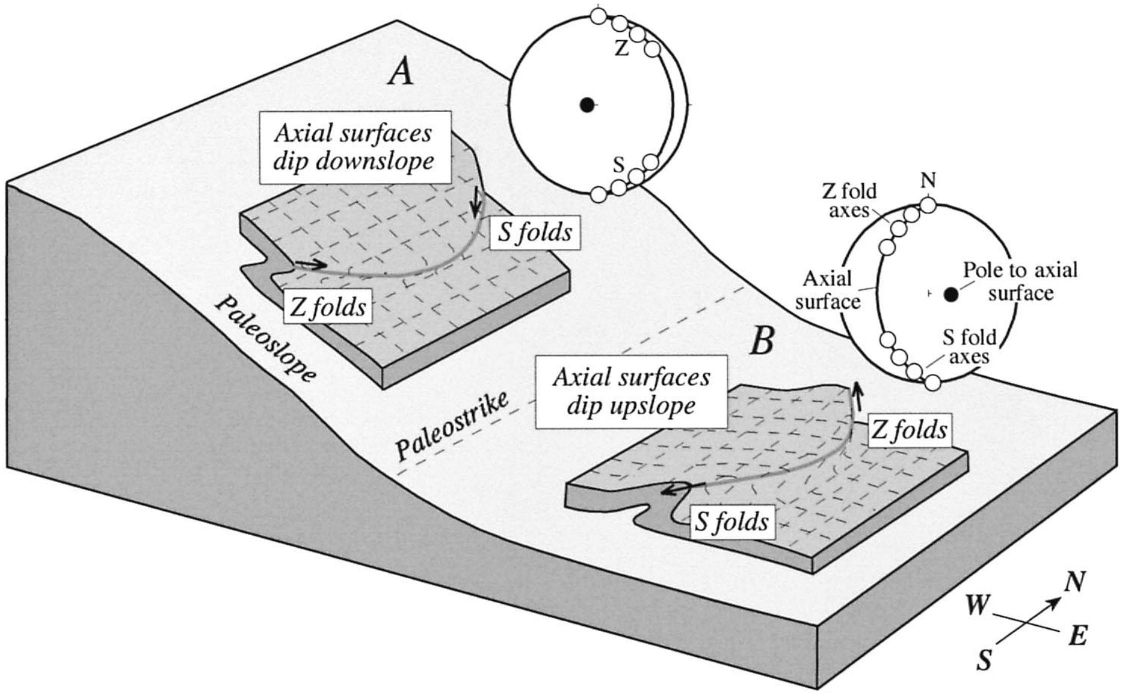


Figure 4. Vertically exaggerated block diagram showing idealized slump folds on a slope and at its base. Corresponding stereonets illustrate orientations of poles to axial surfaces (filled circles) and fold axes (open circles). The paleoslope direction could be determined by the separation arc method from either fold, but note that the right-hand limb of the slump would be transformed from an S to a Z were the slump to travel from the slope out onto the basin plain. This property of slump-fold asymmetry has not been mentioned in previous discussions of the separation-arc method, but fortunately, it does not make much practical difference because ancient slump deposits are restored to an inferred paleohorizontal.

their model, slump deposits that have undergone only short translations tend to display upright, parallel folds, the product of bedding-parallel contraction. Slumps translated further experience a superimposed simple shear, which produces inclined asymmetric folds, then recumbent similar folds, and in the extreme, sheath folds.

Since the pioneering work of Jones (e.g., 1940), many paleoslope determinations from slump folds have relied heavily, or even exclusively, on the orientation of fold axes. The oldest and most widely applied method is based on the supposition that the trend of fold axes formed by downslope movement should be normal to the paleoslope (e.g., Jones 1940). Woodcock (1979) called this the *alongslope mean-axis method*. The idealized slump folds in figure 6*A* are amenable to the alongslope mean-axis method. Stereoplots of fold axes alone, however, yield two equally viable choices of paleoslope direction, i.e., either east or west in figure 6*A*. The correct choice can be made from a combination of other paleogeographic information (e.g., Jones 1940), and (or) the vergence of slump folds.

Woodcock (1979) has shown that in many slump deposits, fold axes cluster in the paleoslope direction, rather than normal to it. Here, the *downslope mean-axis method* is useful. In the model shown in figure 6, slump folds originate with their axes parallel to the slope; with moderate downslope movement, fold axes begin to spread along a girdle, and with continued movement they begin to cluster in the transport direction. In the extreme (figure 6*C*), fold axes cluster in the downslope direction, parallel to sheath axes, and the girdle disappears. Fold axes are reoriented as a result of simple shear during downslope movement; the only folds to escape reorientation are those with initial orientations exactly parallel or exactly perpendicular to the strike of the slope.

The *separation-arc method* of Hansen (1971) also accounts for downslope rotation of fold axes, but it is better suited for slump folds with axes distributed along great circles rather than in clusters. Natural folds similar to the one in figure 4*A* have been described from a tundra slide by Hansen (1971), and from a snow slide by Lajoie (1972). Hansen (1971) showed that the downslope direction bisects the angle (Hansen's ‘‘separation angle’’) be-

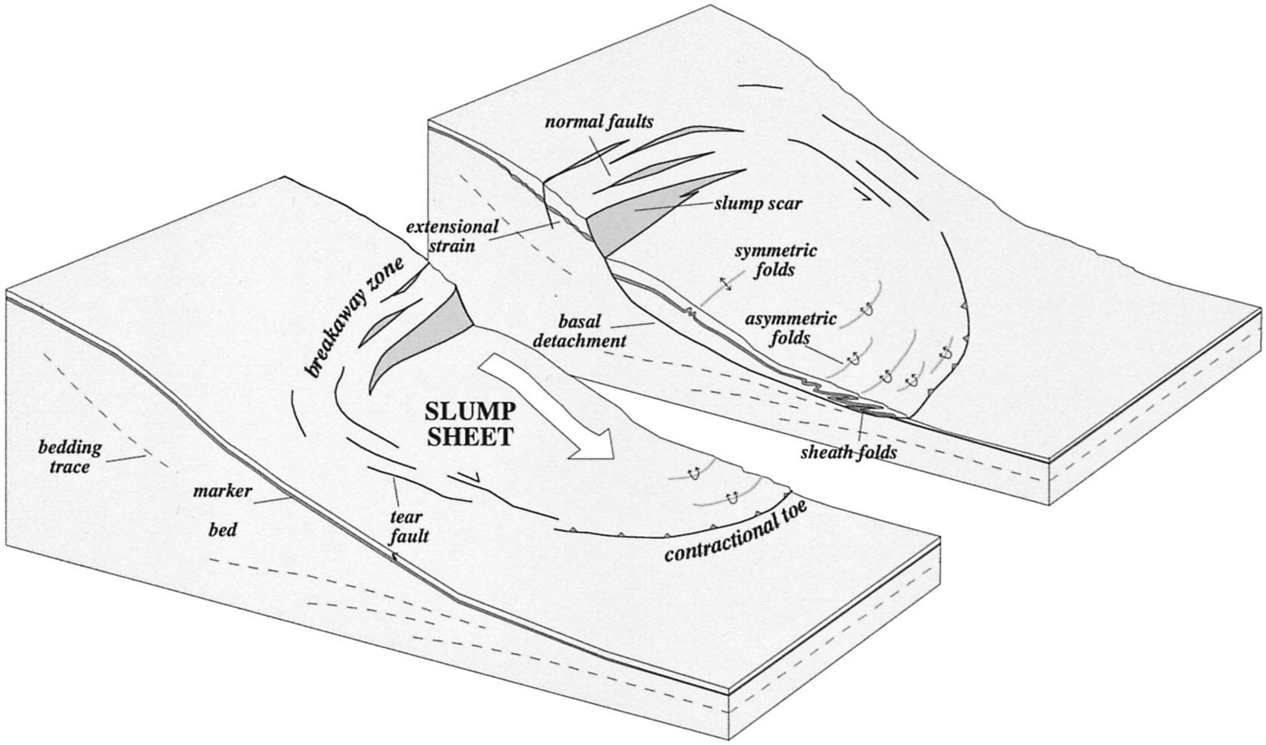


Figure 5. Block diagram of an idealized slump, with slight vertical exaggeration. Modified, in part, from Farrell (1984) and Farrell and Eaton (1988).

tween two fields of slump fold axes of opposite sense of asymmetry, S's (counterclockwise sense of rotation) on one side, Z's on the other (clockwise sense). The fold axes define a great circle that Hansen (1971) called the ''slip plane.'' Stereoplots from the tundra and snow slumps are similar to the plot in figure 4*A:* the slip plane dips downslope and the slip direction bisects the separation arc. The slip plane defined by axes of slump folds from the base of a slope (figure 4*B*), however, should dip in the *upslope* direction. Fold axes from slump deposits restored in the stratigraphic reference frame should plot as in figure 4*B*, regardless of whether the slump actually came to rest on the slope or the base of the slope.

The two folds in figure 4 differ in a superficially troubling way that merits discussion but is less of a problem than might first appear. Folds formed along the right-hand limb of the slump, while on the slope, are Z folds, but they become S folds after transport all the way to the base. This results from the universal convention in structural geology of classifying an asymmetric fold as an S or Z when the fold is viewed in the downplunge direction (figure 7). In figure 4*A* and 4*B*, the change from Z to S is due to a 180° flip in the *trend*, which itself is the result of a change of only a few degrees in the *amount* of fold plunge. This phenomenon may be responsible for some of the overlap of S and Z fields in some of our examples from Maine, as well as the considerable overlap that Woodcock (1979) found in published descriptions of slump folds. In gently plunging folds (e.g., figure 7), S and Z are not very robust properties at all. Clearly, the main difference between the two folds in figure 7 is that one verges toward the observer whereas the other verges away, yet both folds have S portions and Z portions. Another shortcoming of the separation-arc method is an inability to deal with folds that cannot be classified as either S or Z, such as symmetric folds, some disharmonic folds, most isolated fold hooks, and sheath folds. This is ironic, because sheath folds are the ultimate product of the simple shear that makes the separation arc method succeed in the first place.

In some cases, *slump vergence,* as determined from the fold axial surface, is a more reliable paleoslope indicator than fold axes. The vergence of an asymmetric slump fold is here defined as the trend, in the stratigraphic reference frame, of the pole to the axial surface. (A more cumbersome definition would need to be contrived to also account for refolded slump folds that face downward in the stratigraphic frame.)

The distinction between the present-day and stratigraphic reference frames is essential, even in

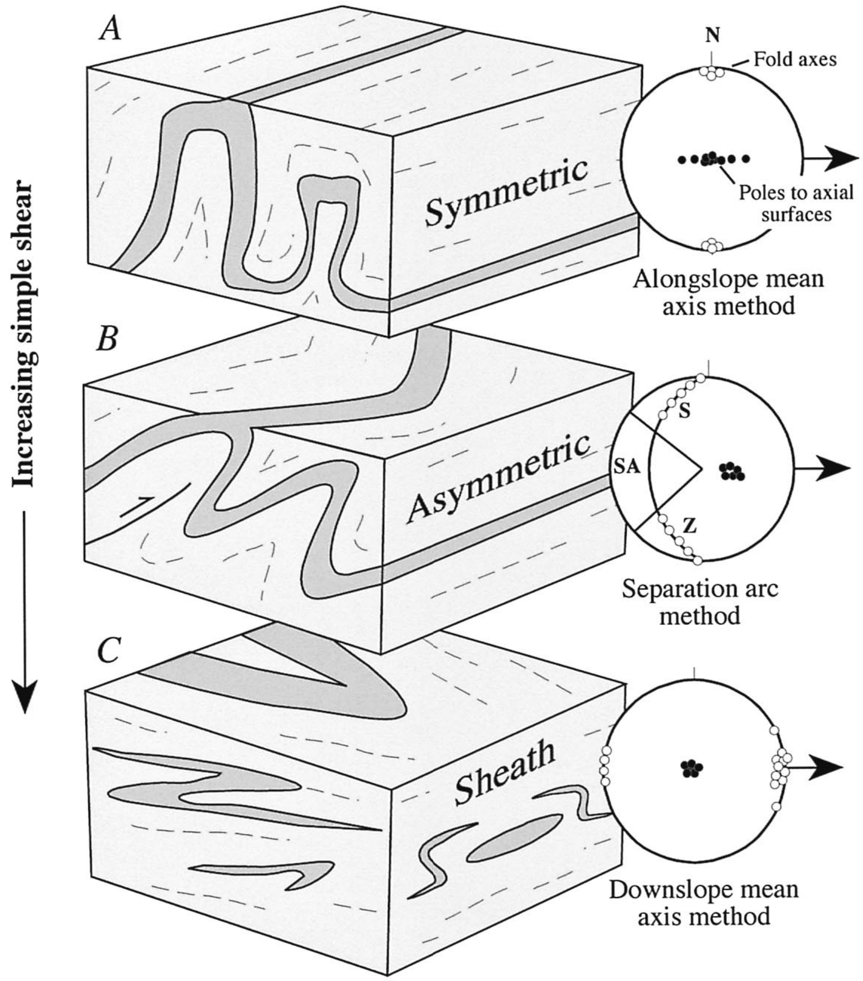


Figure 6. Three structural styles of slump folds stacked from the top down in order of increasing simple shear. Arrows in stereonets show slope direction. *A*. Initially, fold axes show tight clustering normal to slope. Alongslope mean-axis method gives the paleoslope direction. *B*. With moderate downslope rotation, fold axes acquire S and Z asymmetry and define two fields along a great circle corresponding to the slope. SA is the separation arc, which gives the paleoslope direction. *C*. With continued downslope rotation, the separation arc narrows and then disappears completely, as fold axes are reoriented toward the downslope direction. Downslope mean-axis method (or better yet, sheath axes) gives the paleoslope direction.

the case of a tectonically undeformed slope like the one in figure 4. In the present-day reference frame, asymmetric folds at the base of a slope have axial surfaces that dip upslope (figure 4*B*). Axial surfaces of folds on a slope may either dip gently downslope (figure 4*A*), or gently upslope. In the stratigraphic reference frame, however, *axial surfaces of synthetic folds dip upslope.* Consequently, in analyzing slump folds from dipping strata, which will be subject to structural tilt-correction, it doesn't matter whether the folds came to rest on a slope, or at the base of a slope: the relationship between fold axial surfaces and the paleoslope direction is the same.

Paleoslope Determinations

In the foregoing discussion, the various idealized stereographic patterns were based on many measurements around a single fold. In all the stereoplots that follow, however, the structural data are from different folds—generally one hinge line and one axial surface per fold. By necessity, we use measurements from several folds to build a composite picture of the fold geometry.

Slump Deposits with Upright, Symmetric Folds. We report a single example of a slump dominated by pure-shear deformation, a spectacular horizon that resembles a rumpled rug (figure 3*A*). The folded zone crops out along the shore of Harrington Lake (figure 1; for details see stop 3 of Hanson et al. 1993, or stop 9 Kusky et al. 1994). The folded zone overlies a moderately dipping (average dip is 48°), homoclinal section of thin-bedded turbidites; a mean paleocurrent direction of 265° was obtained from 55 cross laminae (Hanson et al. 1993, p. CC-13). The basal contact of the folded zone is a detachment that parallels the underlying bedding; disrupted beds just above the detachment are discordant to it. The upper contact is not exposed, but coherent turbidites occur a few meters farther upsection. The exposed part of the slump is about 8.5 m thick. One large fold is overprinted by, and hence is older than, the regional cleavage that makes a ~60° angle with the axial surface (figure 3*A*).

The largest folds are upright and symmetric.

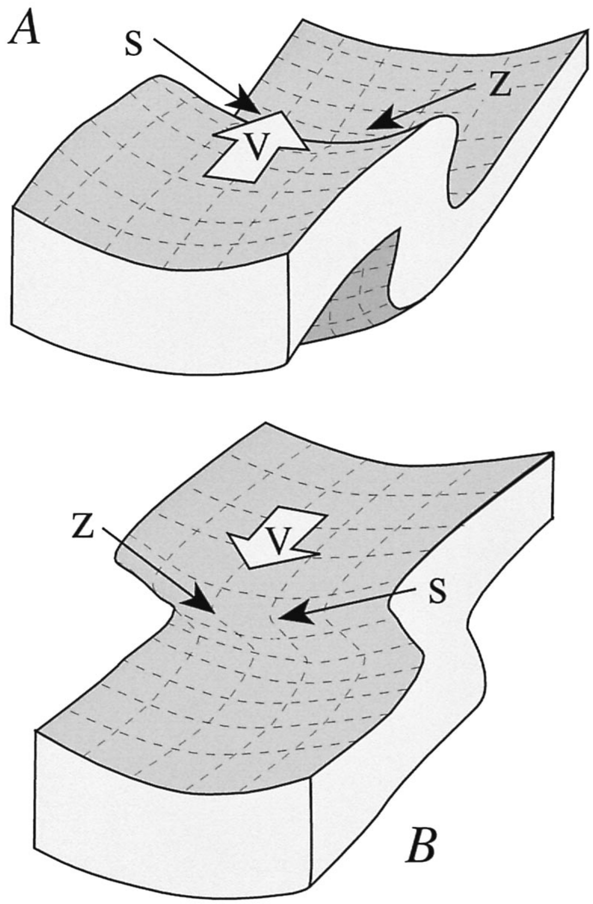


Figure 7. Two folds with opposite vergence (V arrows), each having portions that have S asymmetry, and portions having Z asymmetry. A minor change in the amount of plunge can change the sense of asymmetry of these folds, but not their vergence. Vergence is therefore a much more robust and useful property than S or Z asymmetry.

Near the base, some of the small folds are asymmetric. Fold axes form a loose cluster on the stereoplot (figure 8*A*) but are nondiagnostic because the alongslope mean-axis method yields a paleoslope of either 070° or 250°, whereas the downslope mean-axis method yields a paleoslope of either 160° or 340°. About half the folds are asymmetric and can be described as S's or Z's. The S and Z fields overlap, however, so the separation-arc method doesn't work. In contrast with the other slump folds in figure 8, poles to axial surfaces are distributed about a vertical great circle, which strikes about 250°. The folds show no preferential vergence. However, given the style of the large folds (figure 3*A*) and the tight clustering of axial plane strikes, the best solution is a slope of either 070° or 250°. In light of the paleocurrent data and regional relations, which indicate that the Seboomook is the deep-water facies of a deltaic sequence farther east (Hall et al. 1976), the best choice is 250°. In hindsight, then, the alongslope mean-axis method would have yielded the correct result.

Slump Deposits with Asymmetric Folds. Two slump deposits in our study display asymmetric folds with inclined axial surfaces. These are broadly similar to the slump illustrated by Farrell (1984, his figure 2*B*). The first is in the St. John River Formation (of Roy et al. 1991) near Three Mile Island on the Allagash River (figure 1). The folded zone is 20–30 cm thick and sandwiched between thin-bedded, silt turbidites (figure 3*B*). Upright bedding dips 71° E. The younging direction in underlying beds is evident from subtle grading. The base of the folded zone is marked by a throughgoing bed of siltstone deformed by two small folds that are recumbent in the stratigraphic reference frame (figure 3*B*). The folded zone itself consists mostly of dark, chloritic slate, but within it are dismembered beds of siltstone, which outline tight, asymmetric, nearly recumbent folds with thickened hinges. The immediately overlying siltstone bed, which youngs in the same direction as beds below the folded zone, shows no evidence of bedding disruption or outcrop-scale folding. This bed everywhere overlies slate, in which bedding cannot be seen, but it truncates the projections of axial surfaces defined by the folded siltstones a few centimeters stratigraphically below. A well-developed regional slaty cleavage affects both the folded zone and beds above and below. Dihedral angles between fold axial surfaces and cleavage range from nearly parallel to 14°. The folded zone is most readily interpreted as a slump accumulation, although a tectonic origin cannot be ruled out. The upper contact appears to be depositional; the lower contact sheared. Quartz veins are notably absent around the fold hinge areas. In contrast, at a nearby stratabound duplex of undoubted tectonic origin, such veins are abundant and clearly indicate that duplexing post-dated lithification (Bradley and Bradley 1994). After single-tilt restoration of enclosing beds, a well-defined separation arc of S- and Z-fold axes indicates a paleoslope to the northwest (figure 8*B*). Poles to fold axial surfaces also cluster tightly and indicate the same slope direction (310°, combined visual mean). This is similar to the westerly paleocurrent directions mentioned above.

A slump in the Carrabassett Formation (figure 3*C*) illustrates some complications. The 30 cm thick folded zone occurs within a homoclinal, well-bedded succession along Little Wilson Stream (figure 1). Sedimentary structures are remarkably well preserved; tectonic strain is negligible. The folded

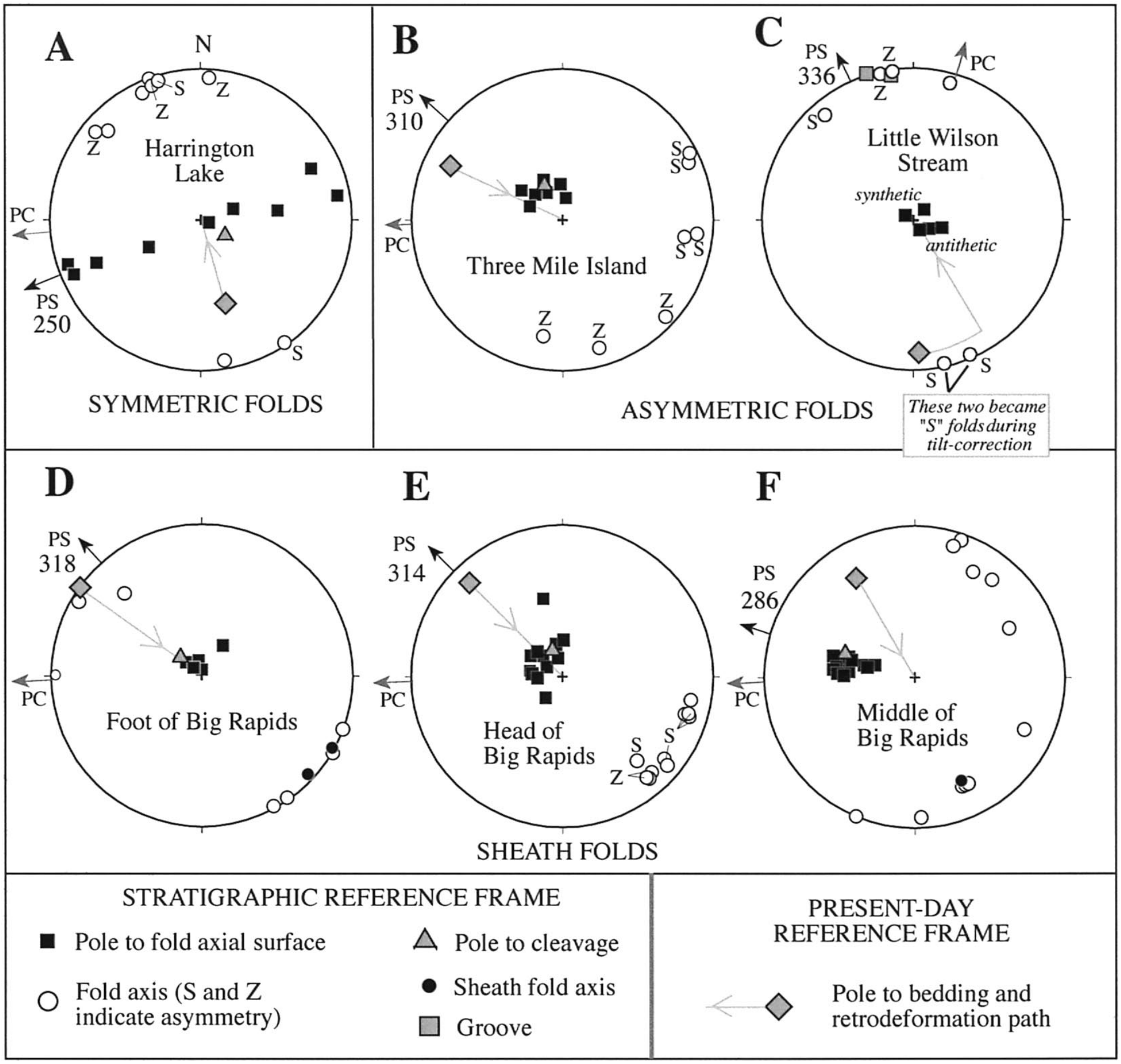


Figure 8. Lower hemisphere equal-area projections of structural data from slump horizons in Maine. Each plot shows the pole to bedding, as measured, and the tilt-correction path along which bedding was restored to paleohorizontal. To facilitate comparisons between different slump deposits and with hypothetical models, all other data have been plotted only in the stratigraphic reference frame, subject to the same rotation(s) as bedding. Poles to cleavage are plotted in the stratigraphic reference frame to aid comparison between cleavage and fold axial surfaces. PC is paleocurrent direction as determined from nearby strata (see text for references). PS is the inferred paleoslope direction, with azimuth in degrees.

zone is about 40 cm thick and is sandwiched between medium-bedded sandstone turbidites displaying the Bouma B and C divisions. Bedding dips 79° N; graded bedding in both underlying and overlying beds shows that the section is upright. The base of the folded zone is a detachment surface (figure 3*C*). The folded zone consists of interlayered dark metapelite, cross-laminated siltstone, and sandstone. The largest folds in the outcrop have sheared lower limbs recumbent in the stratigraphic reference frame; these repeat the section within the folded zone and are labeled as ''main synthetic folds'' in figure 3*C*. The smaller folds are both antithetic and synthetic. The Little Wilson Stream exposure lies in the contact aureole of the Onawa Pluton where the strike of bedding is nearly E-W, about 33° clockwise of the regional bedding strike; the deflection of bedding strike either came during or after the pluton was emplaced. Structural correction involved (1) a 33° counterclockwise vertical-axis rotation to correct for the deflection around the pluton, and (2) single-tilt correction of bedding to horizontal. Fold axes within the slump horizon are fairly tightly clustered (figure 8*C*), but it is not obvious, from the fold axes alone, whether they trend in the paleoslope direction, or normal to it. The separation-arc method is useless because S and Z folds do not form distinct groupings. (Two of the fold axes were classified in the field as Z folds, but during tilt-correction, they crossed the primitive circle and thus had to be reclassified to S folds.) Axial surfaces of the synthetic folds dip south, the antithetic ones dip north. The axial surfaces suggest a paleoslope of about 336°, corrected for Onawa pluton deflection. The fold axes, therefore, trend roughly parallel to the inferred slope direction. For comparison, a mean paleocurrent direction of 037°, corrected for Onawa pluton deflection, was determined from 56 directional indicators along Little Wilson Stream (Hanson and Bradley 1994).

Slump Deposits with Sheath Folds. We analyzed three slump deposits characterized by sheath folds along a 2-km section of the St. John River known as Big Rapids, near the town of Allagash (figure 1). All three slump deposits are in the St. John River Formation (of Roy et al. 1991). The best-developed sheath folds are in an outcrop at the foot of Big Rapids. The folded zone is several tens of meters thick and consists of folded bed segments of sandstone (figure 9*A* and *B*), enclosed in a black slate matrix. An intact, throughgoing upright bed which dips 89° E underlies the folded zone; the upper contact is not exposed. Folding clearly predated cleavage, as indicated (1) by the trace of folded bedding shown in figure 9*A*, exposed on a planar cleavage surface, (2) by a 180° distribution of bedding-cleavage intersection lineations along a girdle (figure 9*A*), and (3) by several folds whose axial surfaces are strongly oblique to the regional cleavage. Fold axes show a fairly tight clustering along a NW-SE trend (figure 8*D*), and given the sheath style of folding, the downslope mean-axis method is applicable. Two sheath axes also trend NW-SE. Together, these data suggest a slope toward either 318° or 138°; in light of the regional paleocurrent direction, 318° is the clear choice. The poles to fold axial surfaces cluster in the northwestern quadrant, which would tend to confirm the 318° paleoslope. The separation-arc method does not work for this slump deposit because none of the folds have a clear sense of asymmetry.

A second zone with sheath folds is located at the head of Big Rapids. Its lower contact is not exposed; it is overlain along what appears to be a depositional contact by thin-bedded silt turbidites, which in turn are overlain by thick-bedded graywacke turbidites. Upright bedding dips 75°E. All of the folds within the slump horizon appear to be rootless. The axial surfaces of some folds are cut obliquely by the regional cleavage. Some bed fragments are in the shape of asymmetric S- or Z-folds; others have eye-like patterns in plan view. Fold axes cluster fairly tightly (figure 8*E*) and, given the sheath-style of folding, the downslope mean-axis method is deemed appropriate, yielding a paleoslope of either 314° or 134°. In light of the paleocurrent data, 314° is the best choice. Poles to axial surfaces cluster in the northwestern quadrant, supporting the northwesterly paleoslope. Because S and Z fold axes overlap, a separation arc cannot be defined.

A third slump, several tens of meters thick, was measured in the middle of Big Rapids (figures 1 and 9*C*). Its lower contact is not exposed; it is depositionally overlain by thick-bedded graywacke turbidites, which in turn are overlain by a fragmented olistostromal horizon. Upright bedding dips 65°E. The slump folds are defined by rootless sandstone bed segments set in a slate matrix; the axial surfaces of some of the folds are cut obliquely by the regional cleavage. None of the measured fold axes have a clear sense of asymmetry; hence the separation-arc method is not applicable. Furthermore, in contrast with the other sheath-folded slump deposits, fold axes here display a 180° spread along a great circle (figure 8*F*). Neither the normal mean-axis, downslope mean-axis, nor separation-arc methods are applicable. Poles to axial surfaces tightly cluster about a westerly trend. A single sheath axis trends NW-SE. Together, these data suggest a paleoslope toward about 286°.

Many other large outcrops in the St. John River Formation (of Roy et al. 1991), and in the correlative Temiscouata Formation in nearby New Brunswick (figure 2*B*), consist entirely of chaotically deformed, silt-rich turbidites that resemble the three slump deposits at Big Rapids. Ductile-looking sheath folds are abundant, despite the very low grade of regional metamorphism (prehnite-pumpellyite; Osberg et al. 1985). Unfortunately, because overlying or underlying beds are not exposed, the stratigraphic reference frame is unknown for these probable slump deposits.

Recommended Procedures

Slump folds are so variable in geometry that a flexible approach is required in paleoslope analysis: no

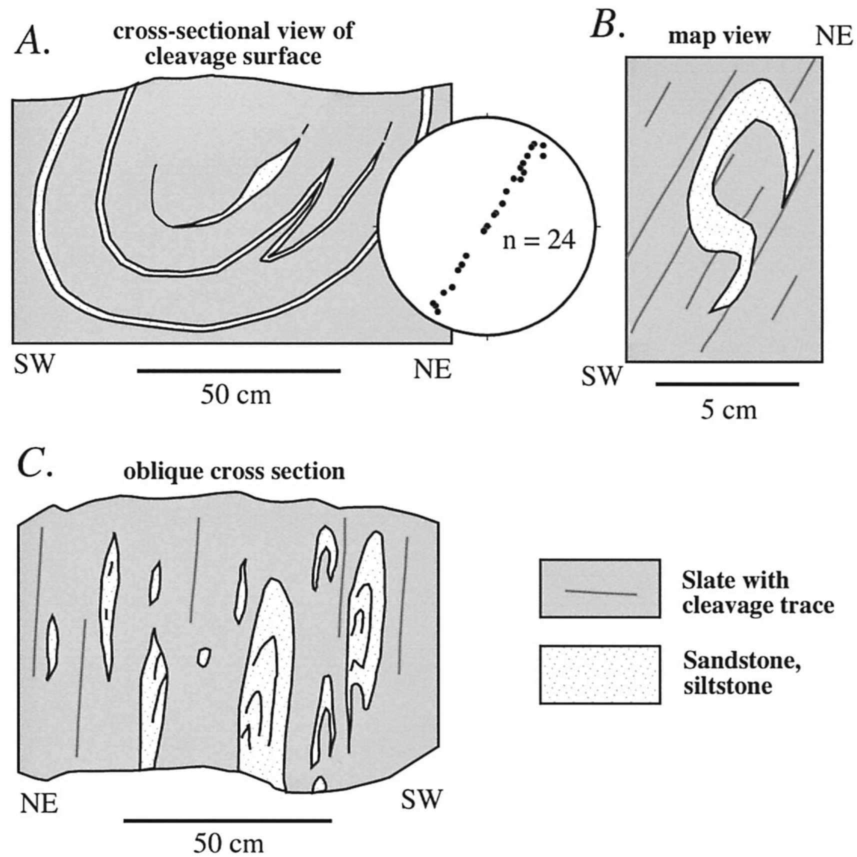


Figure 9. *A*. Sketch of a pre-cleavage slump fold at the foot of Big Rapids, exposed on a cleavage face. Stereonet shows a great-circle distribution of bedding-cleavage intersections from this outcrop, which confirms that folding predated the regional cleavage. *B*. Fold fragment whose axial surface is transected by the regional cleavage, from the foot of Big Rapids. *C*. Dismembered beds and rootless folds from the slump horizon in the middle of Big Rapids.

single method will work for every slump deposit. The first order of business is to assess the evidence that a particular folded zone is, indeed, a slump. Elliott and Williams (1988) reviewed the diagnostic value of various criteria for slump versus tectonic folding; their paper, however, stresses exceptions and caveats to the admittedly imperfect, but still handy, guidelines for recognizing slumps (e.g., Helwig 1970). Careful, detailed observations within a suspected slump are a must—especially evidence for a depositional upper contact.

The second order of business is to measure the attitude and observe the way-up direction of coherent strata that overlie or underlie the slump. Without this information, there isn't much point in continuing because it will be impossible to correct for tectonic deformation.

For folds within the slump, the axis and axial surface should be measured, and the sense of asymmetry—S, Z, or neither—observed in the present reference frame. For asymmetric folds, the vergence in the stratigraphic reference frame should also be assessed, and each fold classified accordingly as either synthetic or antithetic. For sheath folds, the direction of most interest is the sheath's long axis, and not the various local orientations of the curved fold axis. Many fold axis measurements could be made around a fold like that in figure 6*C*, but the results would only lead in a roundabout way to the same conclusion as could be drawn from a single measurement of the sheath axis. Slump faults and any associated slip lineations, if present, should also be measured.

The attitudes of any tectonic folds (axis and axial surface axis), cleavage, and mesoscopic strain markers are needed to retrace the deformation path and thus restore the slump to paleohorizontal. Stereographic techniques for retrodeformation are the same as for paleocurrent analysis; the pitfalls are likewise the same. During retrodeformation, if a slump-fold axis crosses the primitive circle, its sense of asymmetry will flip from S to Z, and vice-versa.

The interpretation of paleoslope from the structural data begins with classification of the slump according to the overall geometric style of folds within it. For slump deposits containing at least some *upright, symmetric folds*, we offer the following guidelines. (1) Axial surfaces are likely to have fairly constant strikes but may show scatter in their dip and dip direction, with no preferential vergence among the whole population. If poles to axial surfaces show enough variation in attitude to define a great circle, it will strike in the paleoslope direction. (2) In our single example at Harrington Lake, fold axes are fairly tightly clustered normal to flow direction. Hence, the alongslope mean-axis method provides essentially the same paleoslope direction as the axial surfaces. (3) Both axial surfaces and fold axes are bidirectional paleoslope indicators in this case. Regional facies relations and (or) paleocurrent data must be relied on to choose between the two possibilities.

For paleoslope analysis of *asymmetric folds:* (1) Axial surfaces of the main, synthetic folds dip upslope, as do any associated contractional faults. (2) Axial surfaces of antithetic folds, as well as any associated contractional faults, dip in the opposite direction. (Obviously, it is essential to decide in the field whether a fold is synthetic, antithetic, or perhaps, neither.) (3) Fold axes are more problematic. In one of our examples, S and Z fold axes have a great-circle distribution and define a beautiful separation arc. In the other example, however, S and Z fold axes are fairly tightly clustered in the inferred paleoslope direction, and the fields of S and Z folds completely overlap. In this second case, the downslope mean-axis method yields the same result as the fold axial surfaces and slip lineations, and therefore seems applicable.

For paleoslope analysis of *sheath folds,* we suggest the following guidelines: (1) The most useful measurements are sheath axes, which, unfortunately, are bidirectional indicators. (2) The downslope mean-axis method is applicable but the result is only bidirectional. (3) The fields of any S and Z folds are likely to overlap; S and Z folds may be rare if, as in our examples, the slump folds are rootless.

Discussion and Regional Significance

Paleoslope directions deduced from slumps in the Devonian flysch of Maine show a consistent map pattern across a wide region (figure 1). This pattern would seem to assuage various concerns about potential pitfalls, and thus about the significance of the results. The first of these, already discussed at length, is whether the disharmonically folded zones are of slump or tectonic origin. Inappropriate structural corrections may have been applied, perhaps leading to errors of up to a few tens of degrees in the quoted paleoslope directions. It is also plausible that some or all of the slumps formed due to local slope failure in a submarine fan setting—for example, the collapse of a levee into a channel—rather than on a slope of regional scale. Finally, because each slump must be interpreted from a single exposure, it is possible that the results are not representative of the whole slump sheet.

We conclude from the results summarized in figure 1 that the regional topographic grain was roughly parallel to present structural grain, and the slopes were down toward the craton. Paleocurrent from the same rock units show a similar regional pattern (Hanson and Bradley 1994). The paleoslope and paleocurrent data together reinforce the interpretation of the Devonian flysch as a foredeep succession that was deposited in front of a cratonward-advancing orogenic wedge (Bradley 1987, 1997).

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