

Volume loss during cleavage formation in the Meguma Group, Nova Scotia, Canada

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Abstract—Diffusive mass transfer (pressure solution) is a widely recognized cleavage-forming mechanism under low-grade conditions. The amount of accompanying volume change during cleavage development, however, is difficult to quantify and remains controversial. The distance between sites of mineral dissolution and reprecipitation and transport mechanisms also are controversial. The structural history of the Cambrian–Ordovician Meguma Group, Nova Scotia, Canada, is well known and abundant strain markers provide an opportunity to assess geometrically volume changes accompanying cleavage development. During diagenesis about 70% compaction in muds and 15% in silts and sands occurred. The pelitic-to-psammitic Meguma Group was cleaved prior to being folded. Pressure solution was the dominant cleavage-forming deformation mechanism under chlorite-grade metamorphic conditions during the early Devonian Acadian orogeny. Measurement of tectonic strain in principal directions ($X > Y > Z$) shows that bedding-parallel coaxial shortening (Z) is 60%, and there is no evidence of fold-hinge parallel extension (Y). Estimation of tectonic vertical extension (X) in the cleavage plane is complicated by diagenetic compaction corrections to primary strain markers, but is insufficient to compensate for the observed 60% shortening in Z , indicating 40–60% volume loss during cleavage formation. Because cleavage formed at least 50 Ma after deposition and under approximately 6 km of Silurian to early Devonian strata, porosity of the sediments upon onset of cleavage was likely less than 15%. Pore-space reduction therefore cannot account for the apparent volume loss during cleavage formation. Cleavage-related volume loss applies regionally and to a stratigraphic thickness of several thousand meters, implying that a large amount of material was removed and transported large distances. When combined with 50% shortening by folding, a bulk tectonic shortening of 80% is estimated for the Meguma Group during the Acadian orogeny.

INTRODUCTION

PRESSURE solution is widely recognized as the principal mechanism of continuous (slaty) and spaced cleavage formation at low temperature (e.g. Siddans 1972, Alvarez *et al.* 1976, McClay 1977, Rutter 1983, Groschong 1988). Controversy exists however regarding the migration of mineralizing fluids during the pressure-solution process, and in particular whether significant volume loss occurs on the scale of formations tens of kilometers in lateral and vertical extent. For example, Ramsay & Wood (1973) assigned no more than 20% volume loss to slaty cleavage formation whereas Wright & Platt (1982), and Beutner & Charles (1985) showed geometric evidence for large (50%) volume loss during pressure-solution cleavage formation. Working on similar lithologies, but using a chemical mass balance approach, Erslev & Mann (1984) and Wintsch *et al.* (1991) concluded that little or no volume loss occurred during slaty cleavage formation. Engelder (1984) raised the point that large volume loss requires fluid flows many times larger than the rock volume, which appears to be inconsistent with evidence suggesting little permeability below about 5 km depth: at least with respect to convective circulation of meteoric waters.

Due to the presence of a number of different strain

markers, and a well understood deformation history, the Meguma Group of Nova Scotia offers a site where large volume loss associated with pressure solution accompanying slaty and spaced cleavage formation can be documented, and its regional extent estimated.

REGIONAL BACKGROUND

The Cambrian–Ordovician Meguma Group consists of the Goldenville Formation, a sandy turbiditic flysch, and the overlying Halifax Formation, a shaly turbiditic flysch. The Group is considered to be a continental rise prism at least 13 km thick, and the base of the Goldenville Formation is not exposed (Schenk *et al.* 1980). The Meguma Group is overlain conformably by about 6 km of Silurian to early Devonian strata (Smitheringale 1973). Strain data used in this study were gathered primarily in two regions along the Atlantic coast of Nova Scotia (Fig. 1): the Ecum Secum region provided strain data from the Goldenville Formation (Henderson *et al.* 1986), and the Lunenburg Bay region provided strain data from the Halifax Formation. In both areas upright folds and a strongly developed cleavage are attributed to the early Devonian Acadian orogeny.

In the study areas, metamorphic grade is low-

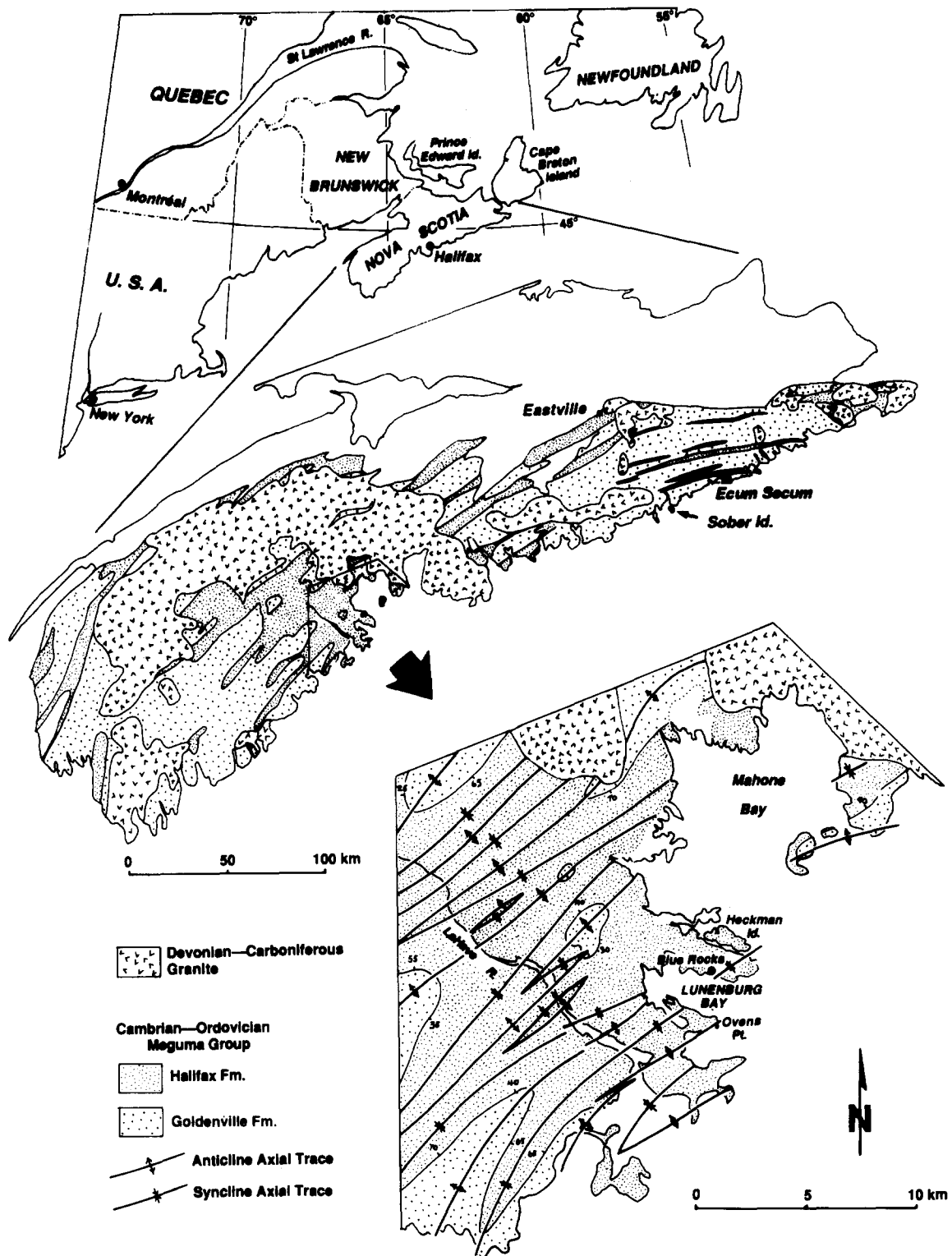


Fig. 1. Location of the study area in Nova Scotia, Canada. Geology of the Lunenburg Bay area modified from Taylor (1962).

greenschist facies (chlorite grade). Despite strong distortion by cleavage and folding, primary sedimentary features are recognizable and can be used to track strain accumulation in the rocks. Sand volcanoes, dewatering pipes and silt-filled worm burrows provide originally circular markers formed on bedding surfaces on the sea floor, and sand-filled dewatering pipes and silt-filled

worm tubes provide paleoplumbines across the beds. Sand dikes provide planar reference surfaces originally at high angles to bedding. Early diagenetic carbonate-cemented concretions allow estimates of pore-volume loss due to sedimentary compaction, and these estimates were used to account for pre-cleavage (compactional) strain. Buckled early tectonic, bedding-parallel veins

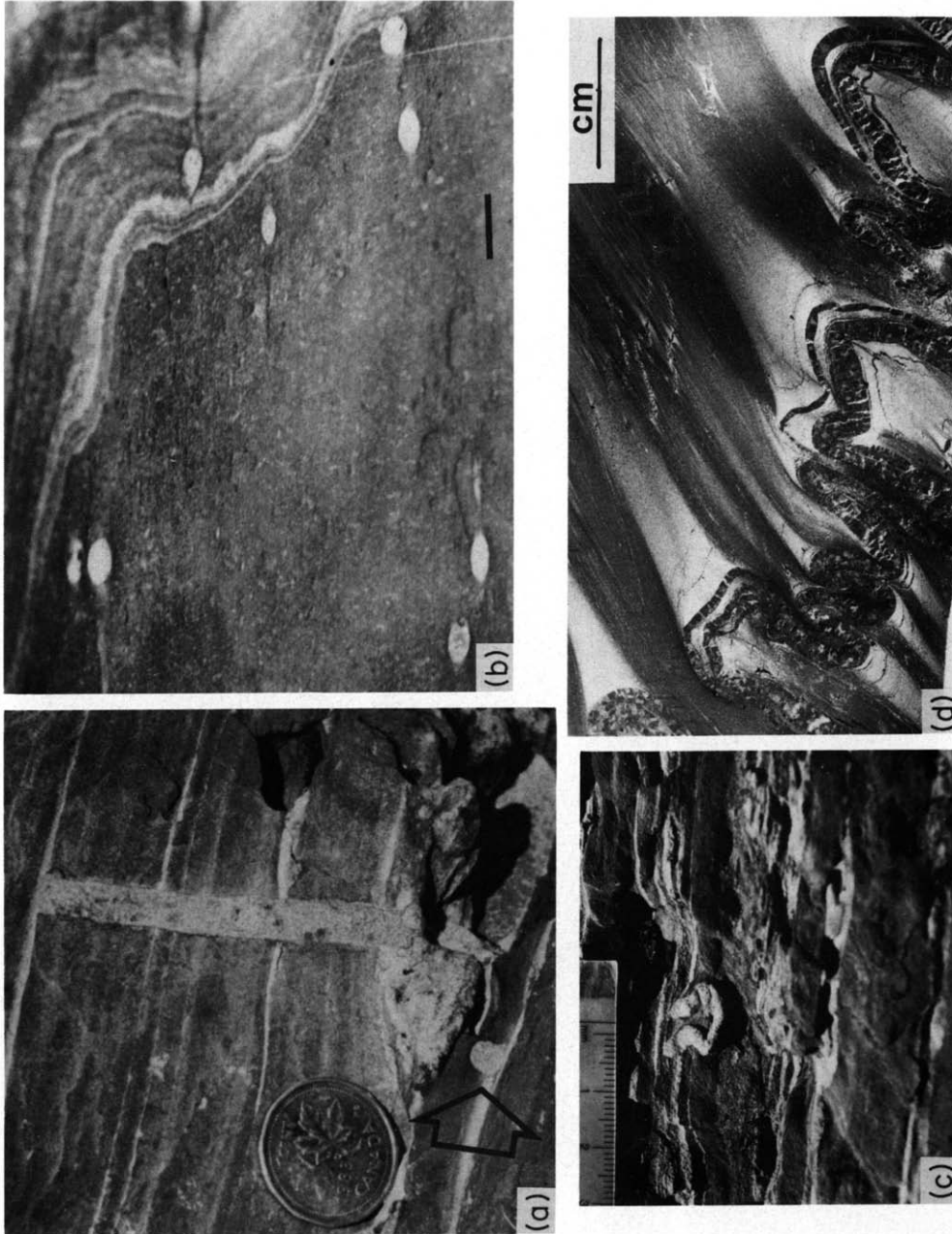


Fig. 2. (a) Photograph of worm burrow (*Arenicolites variabilis*) showing burrow on cleavage. Bedding and cleavage are not perpendicular. Arrow points to circular cross-section of horizontal part of burrow on cleavage. Coin diameter is 1.9 cm. Located at Felzen South, on Lunenburg Bay. (b) Photograph of elliptical sections of worm burrows exposed on a horizontal bedding surface. Trace of vertical cleavage is parallel to 1 cm scale bar. Located at Blue Rocks. (c) Photograph of the U-shaped join of paired silt-filled burrows formed by *Arenicolites variabilis*. Located at Blue Rocks. (d) Photomicrograph showing intrafolial concentric folds in a carbonate bed within a slate bed. Scale bar is 10 mm. Drill core from the Goldenville-Halifax transition zone near Eastville, Nova Scotia. (Specimen from A. Sangster collection, Geological Survey of Canada.)

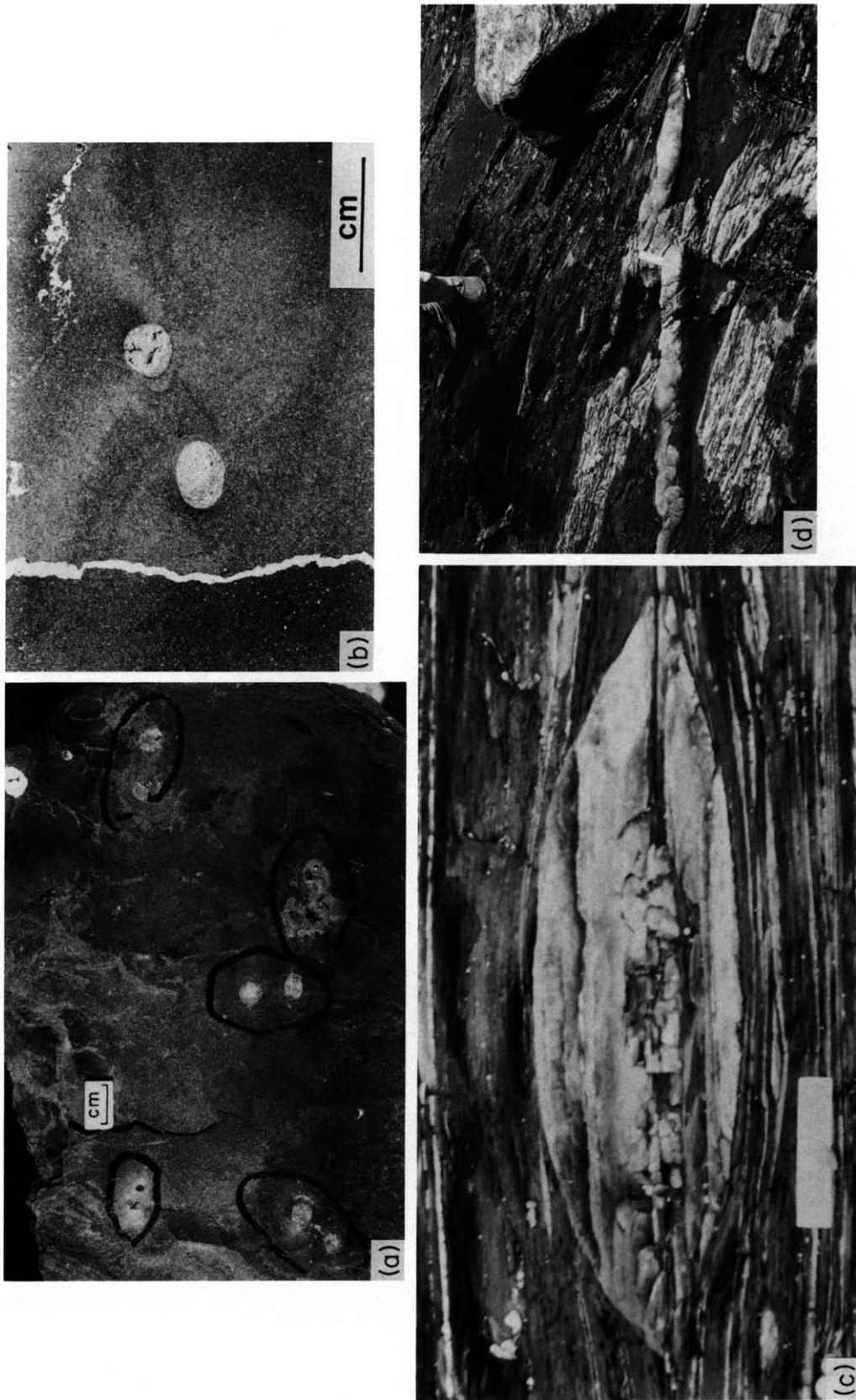


Fig. 3. (a) Photomicrograph showing paired worm burrows (circled) exposed on a cleavage surface. Specimen collected from a slump-folded horizon on Heckman Island. (b) Photomicrograph showing a pair of burrow sections on cleavage. Specimen collected from a slump-folded horizon on Heckman Island. (c) Photomicrograph showing bedding laminations passing through a cone-in-cone concretion demonstrating the extent of pre-cleavage sediment compaction. Located at Owens Point. (d) Sandstone dike showing two branches nearly parallel with cleavage and a third (which is folded) crossed by cleavage. Scale bar at the join of the branches is 10 cm.

and carbonate laminae in slate beds provide additional estimates of layer-parallel shortening due to pressure-resolution cleavage formation.

SEQUENCE OF CLEAVAGE AND FOLDING

Previously, Henderson *et al.* (1986) (see also Henderson *et al.* 1988 and Treagus 1988) developed a model for the deformation of the Goldenville Formation in the Ecum Secum region involving cleavage formation followed by flexural folding. A similar scenario is shown for the Halifax Formation in the Lunenburg Bay region. The two essential points of the argument for the sequence of cleavage and folding are that (1) paleoplumb-lines in Meguma Group rocks lie in cleavage planes regardless of the present cleavage-bedding angle, and (2) distortion of primary circular markers on bedding surfaces is uniform regardless of position on the major folds. Both observations are consistent with folding following cleavage development, but not with cleavage formed during or after folding. However, there may be some overlap in cleavage and folding that is undetected; cleavage and folding are regarded as successive stages in a single progressive event. Different opinions do exist on aspects of the structural history of the Meguma Group, particularly on the origin and timing of gold mineralization and associated quartz veining (Graves & Zentilli 1982, Haynes 1986, Mawer 1987, 1989, Henderson *et al.* 1989, 1990, 1991, Kontak *et al.* 1990, 1991, Williams & Hy 1990). Although important from a regional tectonic and metallogenic point of view, these conflicting interpretations do not materially affect the analysis of volume changes accompanying cleavage development. Based on cross-sections drawn by Fairbault (1911), the Meguma strata are shortened about 50% by folding alone. In this paper we restrict our arguments to cleavage-related strain estimation.

Henderson *et al.* (1986) used dewatering pipes (elutriation tubes) in graded metaturbidite beds as paleoplumb-lines; in the Lunenburg Bay area silt-filled worm burrows in metasilstones and slate beds are used as paleoplumb-lines (Fig. 2a). Worm burrows invariably lie in the plane of cleavage (except in soft-sediment slumped horizons, discussed below), and the angle measured within the cleavage plane between bedding traces and worm burrows averages 90° (Fig. 4), confirming the validity of the latter as paleoplumb-lines. Silt-filled worm burrows refract along with cleavage across inclined, graded sandy metagreywacke-slate beds.

Figure 5 shows that worm-burrow axial ratios measured on bedding surfaces are uniform and independent of bedding dip, supporting the argument of Henderson *et al.* (1986) that bedding-plane distortion accompanying cleavage formation preceded flexural folding. It is evident that in the region where bedding and cleavage are still at right angles, the co-axial layer-parallel cleavage formation was unaffected by subsequent folding, unlike positions on fold limbs where non-coaxial strain

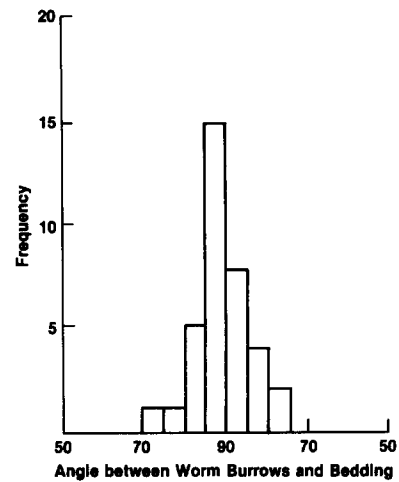


Fig. 4. Histogram showing the angle between worm burrows and bedding as measured on the cleavage plane (5° class intervals), from the Lunenburg Bay area.

due to folding was superimposed. Further discussion is limited to these hinge regions of coaxial deformation.

ESTIMATION OF STRAIN IN PRINCIPAL PLANES

Evidence leading to an argument for volume change during cleavage formation in the Meguma Group came from the hinges of several large folds in the Halifax Formation exposed near Lunenburg, Nova Scotia, where abundant silt-filled worm burrows occur. The burrows are commonly paired, and are connected at the bottom by a 'U' (Fig. 2c). On bedding surfaces the silt-filled burrows present elliptical sections with the long axis of the ellipse invariably parallel to the trace of cleavage (*Y* direction) (Fig. 2b). Burrow cross-sectional long axes average 5 mm, and aspect ratios measured on bedding surfaces average more than 2:1, regardless of

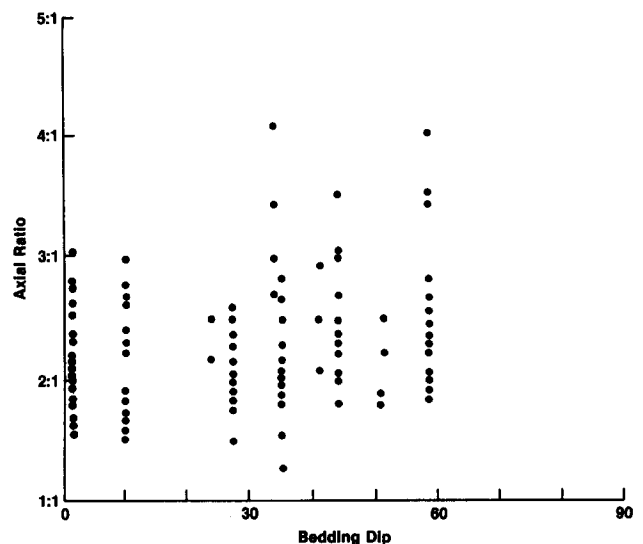


Fig. 5. Graph of worm-burrow axial ratios on bedding vs dip of bedding.

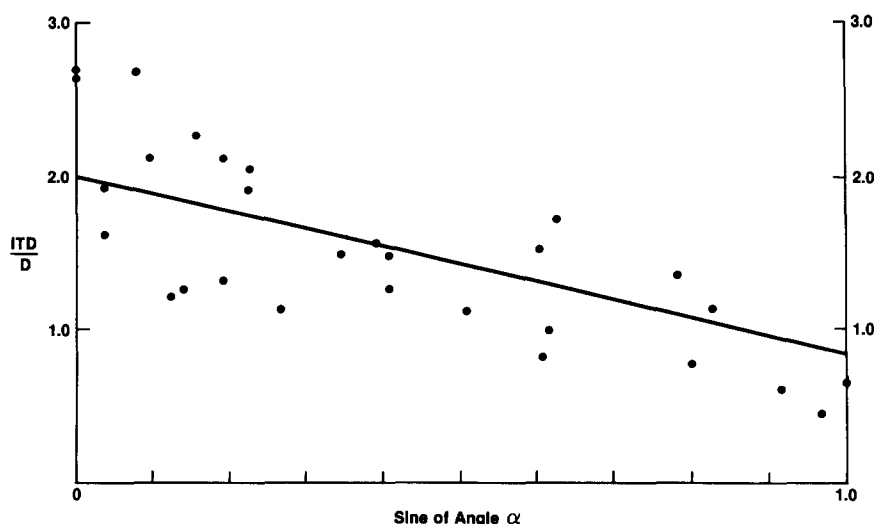


Fig. 6. Graph showing normalized center-to-center distances between paired worm burrows (ITD/D , where ITD = center to center distance between worm burrow pairs and D = long dimension of burrow cross-section on bedding) vs sine of the angle (α) between the connecting centerlines and cleavage traces. The slope of the linear regression line is 2.1.

bedding dip (Fig. 5). Burrows up to 1 m were observed crossing several beds of slate and siltstone.

It is assumed that when formed, the burrows were vertical (except where they are joined) and were circular in transverse sections. For freshly deposited sediment, fluid-filled space can be as high as 60–70% for muds and 25–35% for silts and sands. Vertical compaction and fluid expulsion are thought to proceed rapidly, commonly resulting in half the fluid being removed within the first few tens of meters of burial (Powers 1967, Burst 1969), until 10–15% fluid-filled void space remains at 5000 m, a porosity typical of shale and slate. The presence in the Meguma Group of abundant sand volcanoes, sand dikes and the slumped horizons attest to near sea-floor compaction processes. Also present in the Halifax Formation are limey concretions (Fig. 3c) that incorporate silt beds in more abundant slate. Around the margins of the concretions are cone-in-cone structures, typically formed during diagenesis by calcite cement growth during vertical compaction. By comparing slate thickness between silt marker beds inside the concretion to thickness between these same beds outside the concretion, a 70% compaction in the slate was measured. The silt beds, however, record no more than 10–15% thickness change due to compaction. Cleavage refracts across the concretion, indicating that cleavage is a post-compaction feature. Because of the evidence for near sea-floor compaction, it is not possible to know the amount of fluid-filled void space at the time when the worms made their burrows in the mud, but reasonable estimates lie between 35 and 70%. Diagenetic compaction acted vertically with no detectable lateral dimensional changes because burrow axes are presently normal to bedding on fold hinges, and the angle between worm burrows and bedding–cleavage intersection lineations remains near 90° on fold limbs. Lateral differential compaction such as that discussed by Plessmann (1966) could not be detected. Therefore a direct comparison between the assumed original circular outline of worm

burrows on bedding and the present shape is a measure of tectonic cleavage-related strain.

It appears that the deformed worm burrows record somewhat less than the total tectonic strain imposed on the rock because slaty cleavage in the micaceous matrix is partly deflected around quartz-rich burrows. A more correct estimate of bedding-plane strain is obtained by assuming that the original separation of paired burrows was linearly related to the burrow diameter. Figure 6 shows a graph of center-to-center distances between paired burrows, normalized by the long diameter of the burrow, and plotted against the sine of the angle between the line connecting the burrow centers and the cleavage trace. The normalized center-to-center values indicate 60% bedding parallel shortening, or $Z = 0.4$.

Where bedding is regionally horizontal, strain estimates in the Z direction can also be estimated using buckled carbonate beds (Fig. 2d) and buckled pre-cleavage, bedding-parallel quartz veins (Fig. 7) (e.g. Henderson *et al.* 1986) within slate beds. Comparison of initial and final bed lengths (assuming no homogeneous layer-parallel shortening of carbonate beds or the quartz veins) give Z values between 0.4 and 0.6. The ratio of initial fold wavelength to layer thickness following Biot (1961), Sherwin & Chapple (1968) and Holst (1987) suggests an effective viscosity contrast between carbonate beds and quartz veins and slate matrix of about 60. Because the layer-parallel shortening (Z) observed in the carbonate beds and worm tubes is the same as that recorded in the quartz veins, it is deduced that the veins were present before the cleavage formation.

Strain in the Y direction can be estimated by consideration of the behavior of carbonate beds, bedding-parallel veins and worm burrow sections on cleavage planes. The beds and quartz veins buckled in the XZ plane show no evidence of boudinage in the Y direction. If extension in Y occurred during the shortening in Z , boudinage of the vein should also have occurred because of the demonstrated high viscosity contrast between the

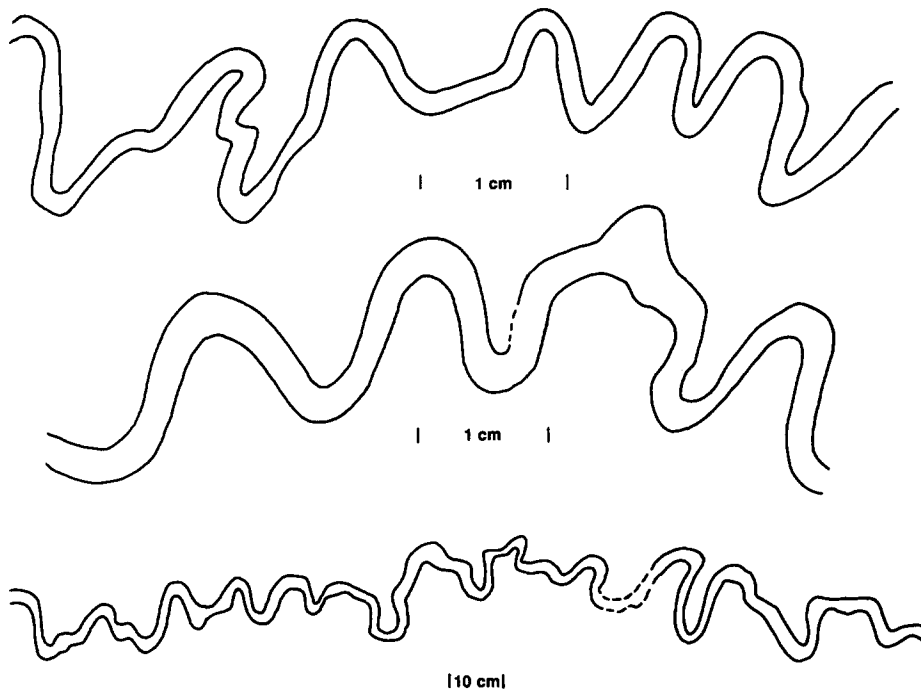


Fig. 7. Line drawing showing intrafolial concentric folds in bedding-parallel quartz veins within slate beds on the crest of the anticline at Ovens Point.

matrix and the vein. The absence of visible boudinage limits extension in Y to small values and also limits cleavage-related strain mainly to the ZX plane.

The conclusion of only small values of strain in the Y direction is supported by consideration of the deformation of a sandstone dike (Fig. 3d) exposed on Sober Island (Fig. 1), on the axis of the Sober Island anticline. The sandstone dike has three branches, arranged with two nearly parallel with cleavage and the other lying oblique to cleavage. All dip steeply and are nearly 90° to bedding. The cleavage-parallel branches are straight and extend for several meters with no evidence of boudinage. However the oblique branch is buckled with vertical fold hinges and axial planar cleavage. This geometry would be expected if no extension in Y accompanied shortening in Z . If there was significant extension in Y , thinning and boudinage would occur in the cleavage-parallel branches and little or no folding would result in the oblique branch. Thus the conclusion that little or no strain in Y is supported.

Strain in the X direction is more difficult to quantify primarily because of the scarcity of suitable markers in this orientation. However, there are no down-dip lineations on cleavage surfaces nor are there visible extension fibers on cleavage around pyrite framboids that would require significant strain in X . Additional evidence for or against extension in the cleavage plane is found in a well-exposed beach section along a synclinal axis on Heckman Island (Fig. 1) where several soft-sediment slump horizons are present. Nearly horizontal beds bound these units above and below. Within the slumped horizons are non-cylindrical folds, commonly with wavelengths of 5–15 m. Cleavage, however, is regular and co-planar with cleavage in the beds outside the disrupted section, resulting in transection of the slump

folds. In the soft sediment slump horizon, worm burrows locally lost their paleoplumbline orientation during slumping, and in places worm burrows are found nearly normal to the vertical cleavage and bedding plane. Although worm burrows are found at all angles to cleavage in the slump horizon, further discussion focuses on burrows normal to cleavage. Of particular interest are observations that burrow cross-section outlines on cleavage are nearly circular, and the distances between tubes of a pair are nearly the same regardless of orientation direction on the cleavage (Fig. 3a). In addition, elsewhere the horizontal bottom parts of the U-shaped burrows appear to have a circular cross-section (Fig. 2a). Before these features can be used to estimate tectonic strain (in particular to assess down-dip changes), the effects of diagenetic compaction on the original worm burrow shape must be evaluated.

Because these burrows were rotated from vertical to horizontal by slumping, any post-slump compaction will vertically flatten the burrow, and also vertically compact the matrix material between the burrows. This diagenetic strain must be removed from the total strain recorded by the burrows in order to estimate the tectonic strain. (Note that, unlike the case here, vertical compaction did not affect the shape of the burrows in normal living position, so for those burrows the present burrow cross-sectional shape could be compared directly to a circle without a compaction correction.) Again assuming that the worm burrows in the slumped horizon were originally circular in cross-section, and that the distance between tubes of a pair is related to burrow diameter, diagenetic effects can be modeled (Fig. 8). For this analysis, diagenetic compaction of 70% for clays and 15% for silt and sand caused by pore water expulsion are used as reasonable values for the Meguma Group. There

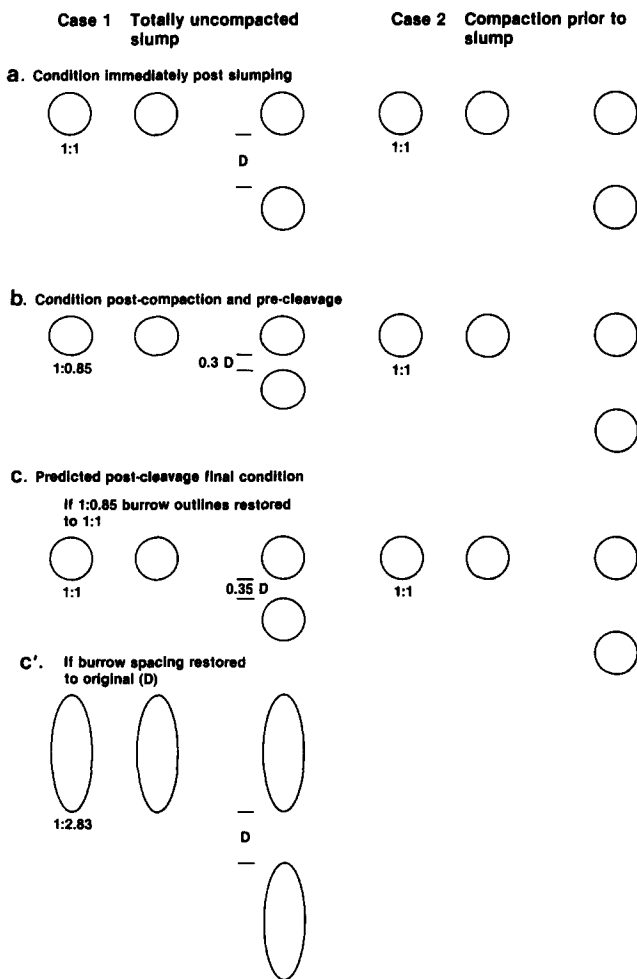


Fig. 8. Two compaction scenarios: Case 1 in which sediments remain uncompacted during slumping and Case 2 in which compaction occurred prior to slumping. All diagrams show a horizontal view normal to bedding and (future) cleavage and parallel with the long axis of burrows. Case 1a shows uniformly spaced burrows with circular cross-sections in uncompacted sediment. Case 2a shows uniformly spaced burrows with circular cross-sections in previously compacted sediment. Case 1b shows expected compacted version of Case 1a in which silt-filled burrows have compacted 15% and matrix mud has compacted 70%. Case 2b shows no change from Case 2a since compaction was completed earlier. Case 1c shows the final post-cleavage condition predicted by the model if the elliptical burrow outlines in Case 1b are extended along with the matrix to duplicate the observed circular outline. Note that the down-dip distance (D) between burrow pairs is not restored to the observed distances. Case 1c' shows the model predictions of the post-cleavage condition if the distances between burrow pairs shown in Case 1b are restored by down-dip extension of the burrows and the matrix. Note that the model predicts that the burrows are extended to 3:1 ellipses with down-dip elongation, contrary to the actually observed final geometry. Case 2c shows that the Case 2 model requires no deformation to duplicate the actually observed geometry (Fig. 3a).

are two scenarios to consider before the effect of compaction in the slumped beds can be applied to the observed worm burrow geometries. If the sediments were uncompacted when they were burrowed, infilled and then underwent slumping and came to rest still totally uncompacted, then the enclosing sediment and the worm burrows would undergo the full diagenetic compaction, and the resulting distortion must be removed from their present shape to estimate the tectonic strain (Case 1). However, if the sediments had undergone extensive compaction before burrowing,

infilling and slumping, only the remaining diagenetic compaction would distort the worm burrows and require removal (Case 2).

For Case 1, the horizontal circular silt-infilled worm tubes (oriented horizontal and normal to the future cleavage) would diagenetically compact to a 1:0.85 ellipse with the long axis horizontal (Fig. 8a). At the same time, the distance between burrows of a pair lying in the horizontal plane would not change, while the distance between burrows of a horizontal pair oriented so that one lies above the other vertically would reduce to 30% of the original separation (Fig. 8b). For Case 2, no diagenetic compaction correction need be applied and worm burrows would have circular cross-sections and orientation-independent burrow spacings prior to cleavage formation.

Figure 3(a) shows burrows from the slumped horizon that are normal to cleavage. The burrow outlines are nearly circular, and the distance between paired burrows does not vary with orientation. These final geometries represent total strain and the portion attributable to tectonic strain will depend on the amount of diagenetic strain. Starting with the post-diagenetic geometry shown in Fig. 8(b), tectonic extension in X is required to restore the elliptical burrow outline to a circle (18% stretch) and also restore the original spacing between the two tubes of a pair, thus requiring a 333% stretch in slate in order to arrive at the observed final geometry (Figs. 8c & c'). Such a differential extension between silt and slate in response to tectonic extension is in conflict with evidence that both lithologies responded similarly to tectonic shortening in Z . (If the same stretch occurred in both lithologies, the silt-infilled tubes should be 3:1 ellipses with the long axis vertical if the distance between burrows was restored, Fig. 8c'.) Additionally it is difficult to reconcile a 333% stretch in slate with the lack of observable down-dip lineations, fibers, or strain-shadow effects around the silt-filled tubes (Fig. 3b). Following Case 2, the observed geometry matches the pre-cleavage geometry, leading to the conclusion of no extension in X . It seems unlikely, however, that all compaction occurred before slumping, because only a few tens of meters are involved during slumping, so some cryptic extension in X cannot be precluded by the data. We think it is very unlikely to be as much as 50%.

CONSTANT VOLUME VS VOLUME LOSS DURING DEFORMATION: DISCUSSION

Tectonic bedding-parallel flattening of approximately 60% in Z is established both by worm-tube data and by data on buckled carbonate lamellae and bedding-parallel quartz veins. No significant extension in Y is indicated by the absence of carbonate bed or vein boudinage and behavior of the sand dikes. This results in a 60% loss of area on the bedding plane. Any volume-compensating extension must be in the down-dip or (X) direction, and although diagenetic compaction complicates quantification of extension in X , we conclude that

the simplest explanation of our observations and data is that there was little or no tectonic extension in *X*. Thus a 60% volume loss results. If cryptic down-dip extension of 50% is allowed, a 40% volume loss is indicated. Because expected pore spaces of shale at the onset of cleavage and resulting slate have similar values (10–15%), the volume loss represents primarily material loss.

These conclusions have several implications for the deformation of cleaved rocks, mechanically and chemically. A paradox arises, for example, in considering the apparently homogeneous layer-parallel shortening of approximately 60% and the subsequent macroscopic buckle folding of the strata (Fig. 1). The former implies no or low competence contrast between layers of different compositions while the latter requires a reasonably high competence contrast between effective members of the sequence. However, these may not be incompatible. Assuming that convergence rates between the plates that are driving the deformation remain constant and that the layered sequence has a reasonable competence contrast between the effective strong and weak members, then the following could occur as deformation proceeds. At first elastic strain accumulates in all layers as stress accumulates. With further build-up in stress the layers have two possibilities. If the stress build-up has exceeded the buckling instability then the small perturbations, required by theory and presumably present, will be activated and buckling would proceed. If, on the other hand, pressure solution-driven volume loss operates at a lower stress level than the buckling instability level and dissipates the stress build-up fast enough to keep the stress level below that required to initiate buckles, then the rocks would shorten but not fold, despite high competency differences between the effective strong and weak members. As long as this stress dissipation by volume loss can keep up with the external strain rate, then only cleavage-related shortening would occur. If it becomes increasingly difficult to remove more material by pressure solution, or if some other factor changed, stress could then build to the point where buckling occurred. Once initiated, further fold amplification could then progress if it was energetically favored over continued pressure solution. Thus, conceptually at least, the apparent paradox could be resolved; but it does require that pressure solution volume loss operate effectively at lower stress levels than that required to initiate buckle folds and to continue to do so long enough to remove 60% of the rock. The sequence of events in the tectonic model presented here and in Henderson *et al.* (1989) implies that this has been the case in the deformation of the Meguma Group.

From a chemical perspective, the proposed removal of 60% of the rock is perplexing as well. If it was possible to know the specific shape, size and composition of the original block of rock that resulted in the block of deformed rock under study, it would be a simple matter to determine changes in volume and composition. Removal of material in an aqueous phase may be accomplished by either fluid flow or by diffusion, but large volume loss should be accompanied by significant bulk

chemical changes due to the different solubilities of constituent minerals, reactions during deformation and different diffusion coefficients for dissolved species. However, recent attempts to assess volume changes during cleavage development using ratios between elements have failed to detect significant volume loss (Erslev & Mann 1984, Wintsch *et al.* 1991). Both studies were conducted in part on the same units in which previous studies determined large volume loss by geometric methods (Wright & Platt 1982, Beutner & Charles 1985). The study areas are separated by approximately 150 km along strike, so one possibility is that a major change in cleavage mechanism occurs in the interval. More likely, however, is the possibility that the geometric and/or the chemical methods have flawed assumptions about starting materials to which the final material should be compared.

Wintsch *et al.* (1991) indicated that the geometric result of 50% volume loss determined by Wright & Platt (1982) probably applied to their area, but was flawed because the analysis included compactional strain as well as any cleavage related strain. Since argillaceous sediments can have large porosities upon deposition (50–70%), the implication is that no volume loss during cleavage is required by the data used in Wright & Platt (1982). However Wright and Platt accounted for compaction strain, noting that the graptolites used as strain markers were flattened in the bedding plane and that graptolite dimensions measured parallel to the bedding–cleavage intersection were undeformed relative to known dimensions of the same species from undeformed strata. Vertical dewatering of sediment by normal compaction within a few thousand meters of the sea floor does not distort marker dimensions on the bedding plane, and therefore compaction strain is not a component in the 50% volume loss reported by Wright & Platt (1982), so resolution of the discrepancy in results must lie elsewhere.

Just as assumptions about the shape and size of strain markers affect geometric methods, assumptions about original compositions of starting materials affect the geochemical approach. The approach taken by Erslev & Mann (1984) and Wintsch *et al.* (1991) can only measure present compositions of deformed material and relies on one or more elements being immobile to provide a means of determining the original composition. The measured low relative differential mobility of the 'immobile' elements is equated to actual immobility. If, alternatively, these elements are removed from the starting material at an equal rate during cleavage development, an undetectable bias will enter their conclusions, and the volume loss will be underestimated.

This analysis of volume change in the Meguma Group is based on geometric relationships in two relatively small areas. However a number of the same features used are observed widely, both stratigraphically and spatially, within other parts of the Group. Buckled quartz veins in slate beds exposed in a number of mines (Henderson *et al.* 1989) commonly display 60–70% buckle shortening on major fold hinges. Extensive pressure-shadows around isolated starved ripple trains

and buckle-shortened carbonate beds in slate are common. Abundant evidence consistent with major dissolution are seen in corroded grains, seams of insoluble residues and the presence of pressure shadows that preserve protected material adjacent to hard objects. Absence of macroscopic or microscopic veins (cf. Cox & Etheridge 1989) related to cleavage which might act as local sinks implies that dissolved material was transported from the Meguma rocks. Cleavage surfaces of the Meguma rocks seldom show stretching lineations except rarely near plutons. Quartz fibers around pyrite framboids are restricted to steep bedding dips and their presence is related to bedding-parallel shearing during the subsequent folding. These observations and the remarkably uniform appearance of cleavage indicate that cleavage was developed homogeneously throughout the Meguma Group, at least on the scale of observation of several tens of kilometers. While it is possible that there may be lateral and vertical variations in the amount of associated volume change, we are not aware of evidence of variable compensating extension to the regionally observed uniform shortening.

CONCLUSION

Unless evidence documenting significant extension can be found, we conclude that approximately 60% of the rock originally present in the Meguma Group has been entirely lost during cleavage formation. Further, the material was removed by dissolution and transported out of the Group presumably in an aqueous phase, either by fluid flow or by diffusion. This estimate of cleavage-related shortening combined with an additional conservative estimate of 50% shortening by later folding, jointly results in 80% total bulk shortening of the Meguma Group during the Acadian orogeny.

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