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Bundled slaty cleavage in laminated argillite, north-central Minnesota

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Abstract—Exceptional bundled slaty cleavage (defined herein) has been found in drill cores of laminated, folded, weakly metamorphosed argillite at several localities in the early Proterozoic Animikie basin of north-central Minnesota. The cleavage domains are more closely spaced within the cleavage bundles than outside them, the mean tectosilicate grain size of siltstone layers, measured normal to cleavage, is less in the cleavage bundles than outside them, and the cleavage bundles are enriched in opaque phases and phyllosilicates relative to extra-bundle segments. These facts suggest that pressure solution was a major factor in bundle development. If it is assumed that opaque phases have been conserved during pressure solution, the modal differences in composition between intra-bundle and extra-bundle segments of beds provide a means for estimating bulk material shortening normal to cleavage. Argillite samples from the central part of the Animikie basin have been shortened a minimum of about 22%, as estimated by this method. These estimates are similar to the shortening values derived from other strain markers in other rock types interbedded with the argillite, and are also consistent with the regional pattern of deformation.

INTRODUCTION

DIAMOND DRILLING at several localities in the central and western parts of the Animikie basin, Minnesota (Fig. 1) has intersected cleaved argillite with strikingly developed cleavage fans or cleavage bundles. The terms 'cleavage bundles' and 'bundled cleavage' are introduced here to describe zones in which cleavage films are more frequent and more prominent than elsewhere in the rock (Figs. 2a & b). These bundles resemble the zonal cleavage described by Gray (1978), and are similar in most respects to the 'discrete crenulation surfaces' described by Powell *et al.* (1982). They differ from the latter, however, by having formed in rocks lacking a strong pre-cleavage fabric, and in being significantly narrower where crossing silty layers than where crossing pelitic layers. Thus, where the zones traverse a bedding triplet of pelite–siltstone–pelite they have cross-sectional forms analogous to sheaves or bundles of grain, and hence are named cleavage bundles. Cleavage bundles have been observed in argillitic rocks of the Rabbit Lake, Thomson and Virginia Formations, which are broadly correlative turbidite units that collectively form the bulk of the Animikie Group, and also in rocks provisionally assigned to the Little Falls Formation of the stratigraphically older Mille Lacs Group (Morey 1978, 1983a). All these rocks are of early Proterozoic age.

Regionally, the rocks with bundled cleavage occur in a broad belt across the central part of the Animikie basin (area B of Fig. 1). This belt and the pervasively cleaved belt south of it (area C) are both within a zone of more or less open and upright folding, broadly of 'foreland' style, between an intensely deformed zone of nappe-like structural geometry in the southeast (area D) and a virtually undeformed continental platform in the northwest (area A; also Morey 1983a,b, Sims & Peterman 1983, Holst 1982, 1984). No data are available on the detailed distribution of bundled cleavage domains within individual meter-scale folds, owing to the nearly complete burial of the terrain by Quaternary glacial deposits. Outcrops are lacking except in the vicinity of Thomson (Fig. 1) where the rocks are pervasively cleaved, without bundle development.

The Animikie basin was deformed in the Penokean orogeny, which culminated about 1850 Ma ago (Goldich *et al.* 1961, Van Schmus 1976). Although the orogeny was apparently complex and long-lived, and its tectonic details are subject to continuing debate and reinterpretation (e.g. LaRue 1983, Sims & Peterman 1983, Hoffman 1987), it is clear in Minnesota that the compressional phase involved two periods of folding and cleavage formation (Holst 1982, 1984). The first folding event, which affected only the southern part of the basin, produced N-verging recumbent structures and a regional phyllitic cleavage that is nearly bedding-parallel (Holst 1985). The second event refolded the early recumbent folds into upright folds having a steeply inclined crenulation cleavage parallel to their axial surfaces. This folding extended northward well beyond the limit of early recumbent structures, producing folds with a single steeply dipping slaty cleavage in the central part of the Animikie basin (Fig. 1). It is the cleavage associated with this upright folding that locally shows the bundled morphology described herein. Lithologically and structurally the singly cleaved Animikie rocks are similar to the Siamo and Michigamme 'slates' of northern Michigan, the cleavage in which has been described and debated by Powell (1972) and Beutner (1980).

DETAILED DESCRIPTION OF ARGILLITES WITH CLEAVAGE BUNDLES

Bundled cleavage is best developed in laminated argillite composed of alternating pelite and silt layers about

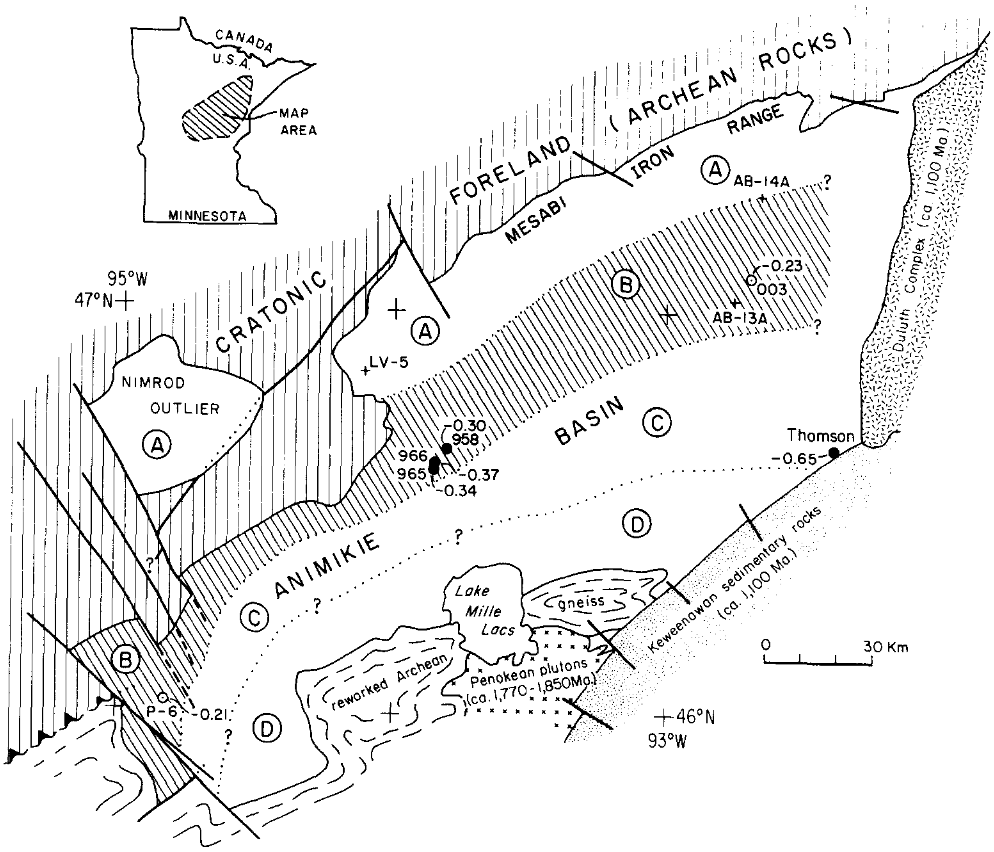

Fig. 1. Regional geologic sketch map of the Animikie basin, Minnesota showing approximate distribution of cleavage morphologies. Area A: rocks dip homoclinally about 10°SSE; no cleavage. Area B: open, upright to inclined folds; single slaty cleavage; bundles common. Area C: open to moderately tight, upright and inclined folds; single, pervasive, slaty cleavage; bundles rare (absent?). Area D: refolded recumbent folds; two cleavages; bundles absent. Negative numbers are values of shortening (e_3) normal to cleavage. Circled points are shortening determinations by the bundle method (see text); solid circles are shortening determinations by other methods. Crosses denote other samples discussed or illustrated in the text.

4–10 mm thick (Fig. 2a & b). The bundle-like morphology of regular, subparallel, gently fanning cleavage films is observed in sections cut approximately normal to the bedding–cleavage intersection. Sections cut parallel to bedding and subnormal to cleavage show curving and anastomosing cleavage films and the clustering of cleavage films into discrete but somewhat irregular zones (Fig. 2c). The three-dimensional form of the bundles, therefore, is approximately that sketched in Fig. 4.

The silty layers contain original clastic grains of quartz and feldspar that have survived lower greenschist-facies metamorphism, smaller quantities of fine-grained, metamorphically recrystallized chlorite and white mica, and opaque phases (graphite, amorphous carbon, pyrite, leucoxene). The pelitic layers contain the same mineral assemblage, but the ratio of phyllosilicates to tectosilicates is higher, reflecting differences in original proportions of clay and silt. Many of the silty layers are micro-graded and have sharply defined, scoured basal contacts.

Table 1 presents modal analyses determined on four layers of sample P-6 within the area of a single thin-section (Fig. 2b). Modal compositions of silty layers 3 and 8 were determined both between and within cleav-

Table 1. Modal analyses (volume per cent) of four sedimentary layers in sample P-6, see Fig. 2(b)

	Silty layers				Pelitic layers	
	3	3cb	8	8cb	4	7
Phyllosilicates (chlorite + white mica)	39	52	44	59	65	80
Tectosilicates (quartz + minor feldspar)	51	20	50	15	22	16
Granular opaques (amorphous C, leucoxene)	9	24	6	25	7	4
Graphite	1	4	tr	1	6	—
Tourmaline	tr	tr	—	—	tr	—
No. of points	372	119	315	130	319	375

Notes: cb = segment within cleavage bundle.

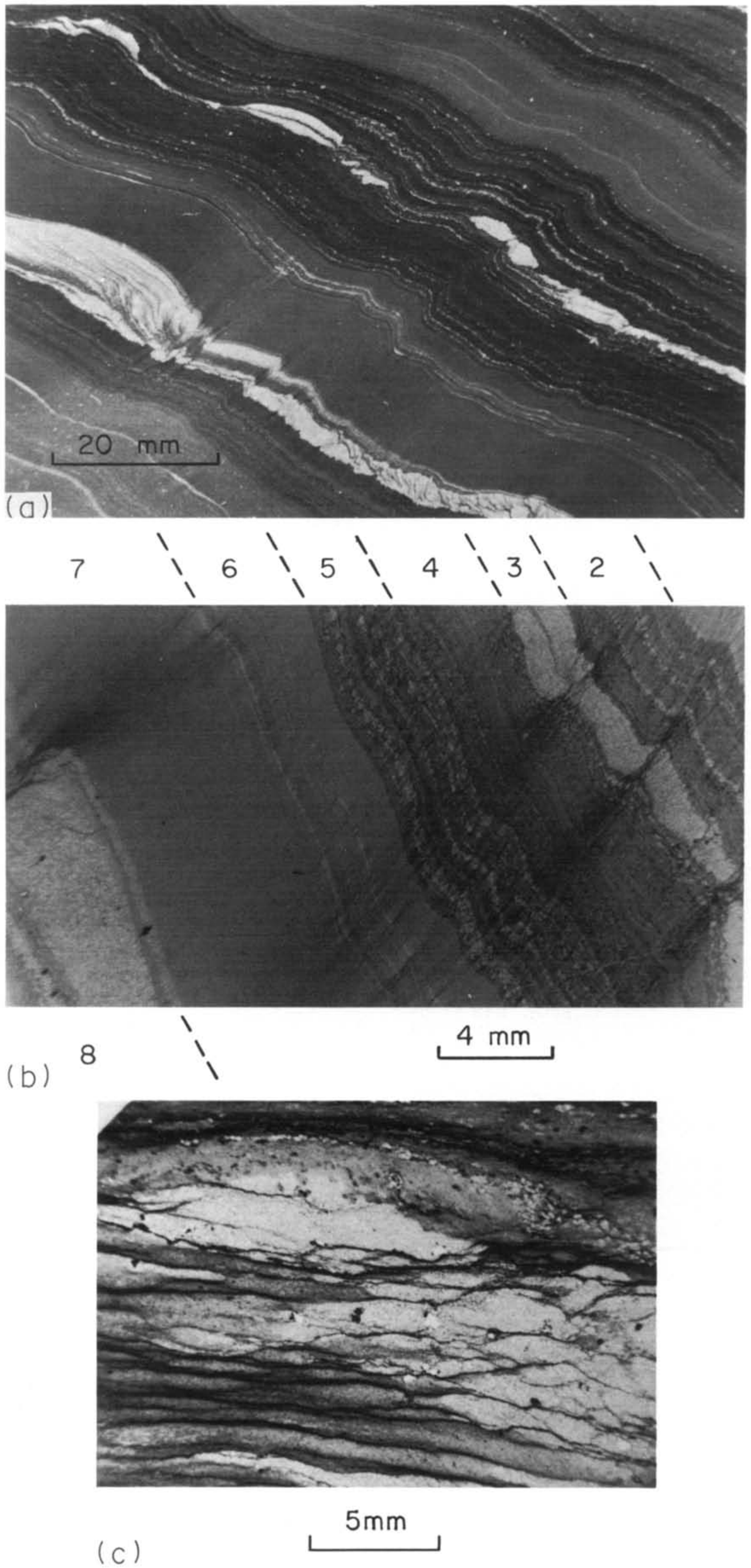

Fig. 2. (a) Sawed surface of cleaved, laminated argillite, cut normal to cleavage and approximately normal to cleavage–bedding intersection of sample P-6. Light layers are silty. Bar scale = 20 mm. (b) Photomicrograph showing cleavage bundles and inter-bundle segments in sample P-6. Thin section cut normal to cleavage–bedding intersection. Numbers indicate layers discussed in text. (c) Photomicrograph showing anastomosing form of bundled cleavage in section approximately parallel to bedding, sample P-6.

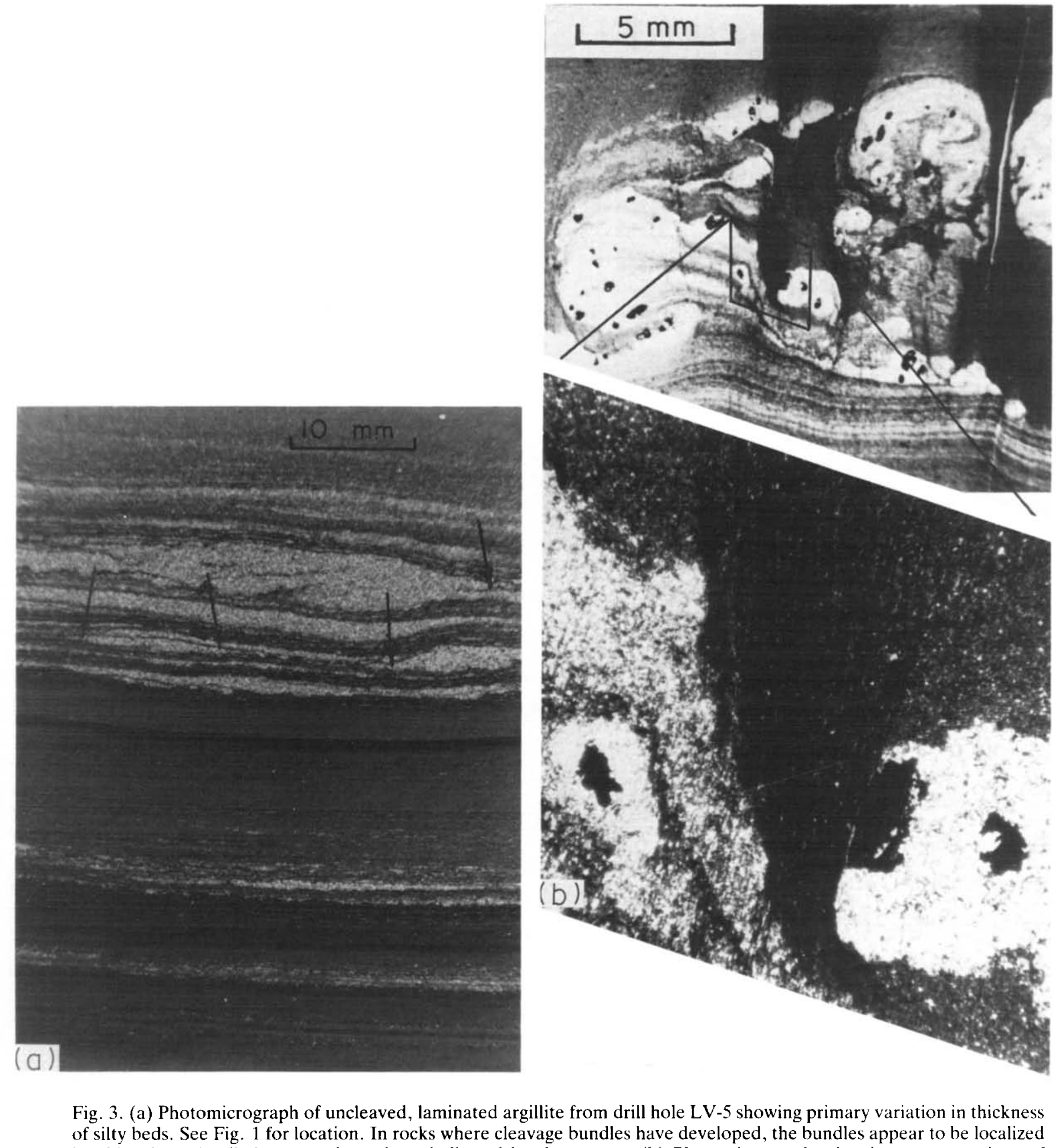

Fig. 3. (a) Photomicrograph of uncleaved, laminated argillite from drill hole LV-5 showing primary variation in thickness of silty beds. See Fig. 1 for location. In rocks where cleavage bundles have developed, the bundles appear to be localized by thin places in silt layers such as those indicated by the arrows. (b) Photomicrographs showing concentrations of opaque-rich cleavage films at the tips of silty compaction lobes. Note, in the enlarged view, the discrete opaque-rich cleavage films within the bundle and the flat facet on the right-hand lobe adjacent to the bundle. Drill core AB-13A (Fig. 1).

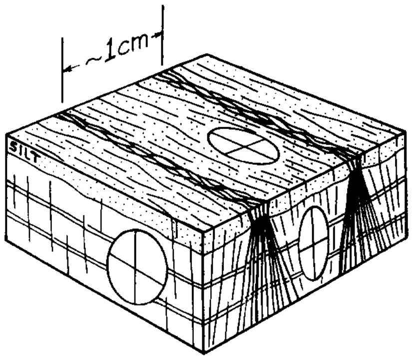

Fig. 4. Sketch illustrating the general three-dimensional form of bundled cleavage. A finite-strain ellipsoid is shown schematically.

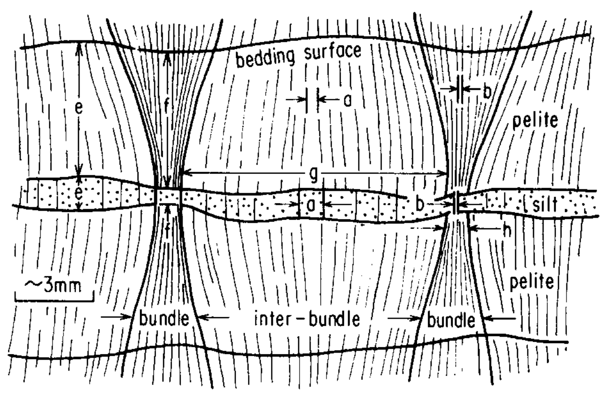

Fig. 5. Diagram of cleavage measurements reported in Table 2 and discussed in text.

age bundles. Reproducible modes could not be measured within the cleavage bundles in pelitic layers 4 and 7, owing to the fine size and indistinct boundaries of mineral grains near the closely spaced cleavage films.

Table 2 (columns a and b) contains data on the spacing of cleavage domains (or microlithon widths) in the seven layers of sample P-6 shown in Fig. 2(b) (see Fig. 5 for definitions of the measurements). Also presented are the mean sizes of tectosilicate grains, measured normal to the cleavage films, between the bundles in these layers (column c), and within the cleavage bundles in silty layers 3 and 8 (column d). The mean tectosilicate grain sizes of microlaminated layers 5 and 6 were determined indirectly by a weighting procedure. In each, the stratigraphic fraction of siltstone and pelite was first determined, and these fractions were multiplied by the mean grain size of tectosilicates in adjacent thicker layers. For example, the mean tectosilicate grain size of layer 5, which is 34% siltstone laminae and 66% pelite laminae, is estimated as 0.34 × grain size of layer 3 + 0.66 × grain size of layer 4.

The width of microlithons in the between-bundle segments of bundle-cleaved rocks is strongly dependent on tectosilicate grain size, and tends toward a small multiple of the mean diameter of tectosilicate grains in a particular cleaved layer. This relationship, noted previously in other slaty rocks (e.g. Nickelsen 1979, Gray 1978, 1979), is illustrated by the linear array of between-bundle data points on a plot of microlithon width vs grain size for sample P-6 (Fig. 6). Some of the scatter about the best-fit line on this plot is undoubtedly due to measurement error, but a component of it may be due to the real influences of varying layer thickness and varying quartz/phyllosilicate ratios from layer to layer. The intra-bundle data points, in contrast, exhibit no tendency toward a linear distribution.

The spatial correlation of reduced grain dimensions of tectosilicates with regions of decreased microlithon width in the cleavage bundles of layers 3 and 8 (Table 2, columns c and d) suggests that the change in grain size may have resulted from tectosilicate dissolution in sites of high stress. Inasmuch as the microlithons within the cleavage bundles are narrower in all layers than they are outside the bundles (Table 2, columns a and b), it is

Table 2. Dimensional data measured by eyepiece micrometer in thin section of sample P-6. Thicknesses and spacing values are means of 10–30 measurements

Layers			(c)							
(see Fig. 3)	(a)	(b)	*m*	*σ*	*n*	(d)	(e)	(f)	(g)	(h)
2	0.06	0.027	0.027	0.010	32	—	3.10	3.20	3.3	—
3 (silty)	0.15	0.029	0.051	0.012	32	0.021	1.43	1.05	3.7	0.45
4	0.05	0.029	0.022	0.009	43	—	3.80	4.40	4.1	—
5	0.05	0.023	0.032	—	(x)	—	3.02	3.02	3.6	—
6	0.03	0.022	0.022	—	(x)	—	1.50	1.50	—	—
7	0.016	0.016	0.019	0.006	38	—	6.80	8.10	—	—
8 (silty)	0.11	0.029	0.049	0.010	35	0.019	4.70	4.10	11.8	1.4

Explanation of data (all dimensions in mm)
(a) Microlithon width in inter-bundle segments (mean).
(b) Microlithon width within cleavage bundles (mean).
(c) Tectosilicate grain size in interbundle segments, measured normal to cleavage: m = mean, σ = standard deviation, n = number of measurements.
(d) Tectosilicate grain size within cleavage bundles, silty beds only, measured normal to cleavage.
(e) Bed thickness in inter-bundle segments.
(f) Bed thickness within cleavage bundles.
(g) Mean width of inter-bundle segments, measured perpendicular to cleavage.
(h) Mean width of bundles, measured perpendicular to cleavage.
(x) The mean grain sizes for microlaminated layers 5 and 6 were obtained by weighted averaging; see text for details. Layer 5 = 34% layer 3 + 66% layer 4. Layer 6 = 10% layer 8 + 90% layer 4.

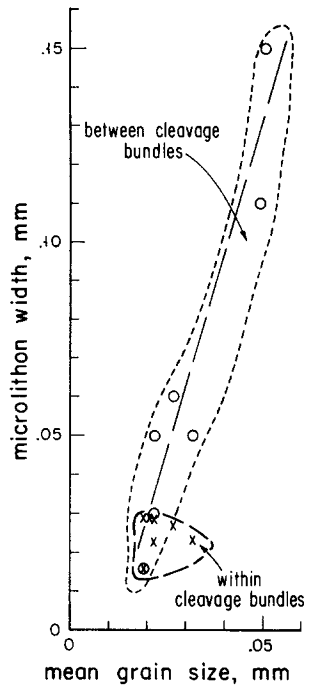

Fig. 6. Plot of microlithon width vs mean tectosilicate grain size (measured normal to cleavage) for several contiguous layers in sample P-6. The slope of the regression line for between-bundle data is 3.4 (correlation coefficient = 0.95). Thus the microlithon width is about 3 times the mean tectosilicate grain diameter in this sample.

likely that the grain size of the pelitic layers may also be finer in the bundles than outside of them. This could not be confirmed by optical means.

The cleavage films and cleavage bundles in these slaty argillites are enriched in phyllosilicates and opaque phases relative to the inter-cleavage and inter-bundle domains, an observation that has been made repeatedly on cleaved rocks from many areas (see, for example, Gray 1978). If the silty layers 3 and 8 were mineralogically uniform along their length before the cleavage formed, the modal data of Table 1 clearly show that major mineralogical adjustments accompanied cleavage development. The removal of quartz and the net gain of phyllosilicates and opaque phases in the bundles are consistent with the pressure dissolution mechanism of cleavage formation, as discussed by Gray (1978, 1979), Beutner (1980), Woodland (1982, 1985) and Wright & Platt (1982).

The contention that pressure solution played a dominant role in cleavage development is further supported by the observation that the cleavage bundles are localized by, and radiate from, anomalously thin segments of silty beds (Fig. 2b; Table 2, columns e and f). The thin segments of the silt layers are interpreted as primary sedimentary phenomena caused either by sedimentation of silt on slightly irregular scoured surfaces of mud (Fig. 3a), or by differential compaction. If a silt layer of varying thickness were subjected to layer-parallel stress, and if it were mechanically stiff relative to its surroundings, the stress concentration and the tendency for pressure solution to occur, would be greatest where the layer is thinnest. Thus, the growth of cleavage bundles may have initiated at the thinnest parts of silt layers.

The inferred importance of stress concentrations in localizing cleavage bundles is further indicated by Fig. 3(b), which shows pronounced concentrations of opaque-rich cleavage films at the tips of small compaction lobes in a thin layer of silt. The compaction-generated lobes are clearly of pre-cleavage origin, and acted as relatively rigid bodies in less rigid matrix during bulk layer-parallel shortening. It appears from the flat terminations of some lobes against the opaque-rich cleavage bundles that material has been removed from the lobe tips by dissolution, and that the lobes have been somewhat shortened normal to cleavage.

Dissolution effects may have been augmented to some extent by the flow of fluids expelled from pelitic layers as they were dewatered during compaction, deformation and metamorphism (e.g. Powell 1972; see also discussions in Borradaile *et al.* 1982, pp. 17–31 and Beutner 1980), and were probably augmented by metamorphic reorientation and recrystallization of phyllosilicate grains in the cleavage films. Dewatering is thought to have been a minor process because there is no clear evidence that the bundles have propagated toward the stratigraphic top of the sedimentary section, the most likely direction of fluid release. Instead, the splaying cleavage is about equally developed both upward and downward from a given silty layer (Fig. 2a).

REGIONAL VARIATION IN CLEAVAGE MORPHOLOGY

Although control is poor, owing to the spotty distribution of core holes and outcrops, it appears that the morphology of slaty cleavage changes systematically from north to south across the Animikie basin. There is no slaty cleavage developed in the rocks within about 15 km of the northern rim of the basin (area A, Fig. 1). The first cleavage to appear south of that position, as, for example, at site AB–14A of Fig. 1, is distinctly spaced, tends toward bundled morphology, and is emphasized by a concentration of opaque material along the cleavage films. The bundles seemingly initiated in triplets or larger multiples of sub-millimeter-thick laminae of fine silt and graphitic argillite, and fan across a very limited thickness of adjacent strata before dying out. Farther south, the cleavage is stronger in two ways. The early-formed bundles are longer (cross more layers) and darker, as more opaque material is concentrated in them. More or less concomitantly, very fine cleavage films developed in the inter-bundle areas. The inter-bundle cleavage continues to strengthen to the south, and eventually becomes pervasive enough to vitiate the distinction between bundles and inter-bundle regions (area C, Fig. 1). This is the situation at Thomson.

The correlation of the north-to-south change in cleavage morphology with a north-to-south tightening of folds strongly implies that cleavage morphology is related to a regional gradient in bulk shortening strain. Holst (1983) has measured a N–S shortening of about 65% across the cleavage at Thomson, which is probably typical of the southern margin of the belt. Shortening within 15 km of the Mesabi range has been effectively nil. It is reasonable to infer that the intervening area, where bundled cleavage has developed, underwent bulk shortening of an intermediate amount.

ESTIMATES OF BULK SHORTENING NORMAL TO CLEAVAGE

If it is assumed that the changes in modal mineralogy in the cleavage bundles are due entirely to open-system dissolution of silicates (Durney 1976), and also assumed that opaque minerals have been perfectly conserved, the bulk shortening within the bundles normal to the cleavage can be estimated from a comparison of modal compositions within and outside cleavage bundles in a particular layer. One can also estimate the relative removal of phyllosilicates and tectosilicates from the plane of observation (again presuming conservation of opaque phases). Finally, the modal data can be combined with dimensional data of the sort presented in Table 2, columns (g) and (h), to produce estimates of bulk shortening across the cleavage, exclusive of any buckling of layers and assuming complete removal of dissolved components from the cross section under consideration. The reasoning involved is illustrated by Fig. 7, utilizing data for layer 8 of sample P-6 (Tables 1 and 2).

The uppermost bar of Fig. 7 is divided into segments that are proportional to the modal abundances of tectosilicates (Q), phyllosilicates (P) and opaque phases (O) in layer 8 outside the cleavage bundles. The center bar similarly represents the modal composition of layer 8 inside the cleavage bundles. The opaque content of the layer is 4.33 times greater inside the cleavage bundles than outside them, implying that an original length of bed 4.33 times as long as the observed bundle width has been partially dissolved. This length of bed, which would have had modal proportions of the bed between the bundles, is shown schematically as the bottom bar of Fig. 7. The overall shortening within cleavage bundles, e_o, is readily calculated:

$$e_o = \frac{l_d - l_u}{l_u} = -0.77\ (77\%).$$

The shortening (or loss) of tectosilicates and phyllosilicates (e_Q and e_P, respectively) is obtained in the same way:

$$e_Q = -0.93\ (93\%)$$
$$e_P = -0.69\ (69\%).$$

The observed mean bundle width in layer 8 is 1.4 mm (Table 2, column h), which, prior to cleavage formation, would have represented a layer length of 6.1 mm (1.4 mm × 4.33). The mean spacing between bundles in layer 8 (Table 2, column g) is 11.8 mm. If the interbundle segments were not shortened at all (clearly untrue because of the occurrence of cleavage films, but they probably were shortened much less than the bundles), the original length of a bundle–inter-bundle pair would have been 17.9 mm as compared to a present length of 13.2 mm. The bulk shortening, therefore, is

$$e_B = \frac{13.2 - 17.9}{17.9} = -0.26\ (26\%),$$

which must be a minimum value.

The same procedures for layer 3 in sample P-6 give $e_o = -0.64$, $e_Q = -0.86$, $e_P = -0.52$ and $e_B = -0.16$, the e_B value suggesting a difference of 10% in bulk shortening between two layers only about 1.5 cm apart. Some of the difference could be real, because the layers differ slightly in thickness, mean tectosilicate grain size and modal composition, and therefore in bulk mechanical properties. Measurement errors undoubtedly have contributed to the disparity, however, inasmuch as the technique involves several determinations of length, each having an associated error, and two estimates of modal composition, each having statistical error that is strongly dependent on sample size. The largest uncertainty is associated with the modal analyses of layer segments within cleavage bundles, which are based on small thin section areas and thus present statistical sampling problems.

An independent test of the bundle method for estimating bulk shortening is obviously desirable, and would be most convincing if provided by independent strain markers within bundle-cleaved argillite samples. No such markers have been found. However, shortening data have been obtained from a buckled layer of recrystallized chert (thickness 1 cm) in a meter-thick bed of argillaceous, hematitic iron-formation interbedded with bundle-cleaved argillite, and from two occurrences of deformed accretionary lapilli in 10–20 cm thick beds of

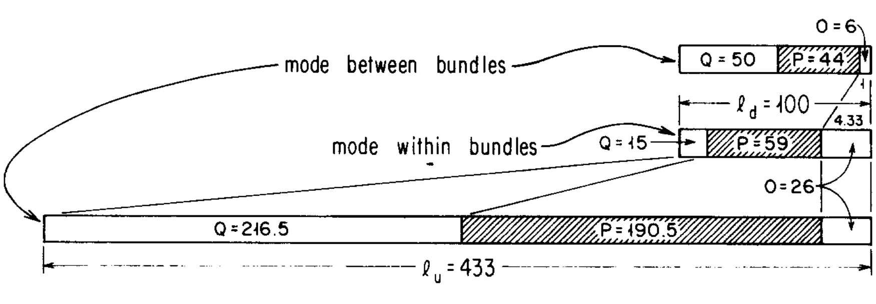

Fig. 7. Schematic representation of modal data as used for computation of shortening. Q = tectosilicates (mainly quartz), P = phyllosilicates (chlorite and white mica), O = opaque phases (mainly Fe oxides and graphite). See text for details.

volcanic ash within thick sections of cleaved graphitic argillite and argillaceous iron-formation. The shortening estimates from these closely associated rocks are regionally compatible with those obtained from the bundle-cleaved argillite, as discussed below.

Shortening of the buckled chert layer (site 958 on Fig. 1) was determined by comparing its original length along bedding, as measured around the folds in profile section, with its deformed length as measured perpendicular to the axial surfaces. The layer has been shortened about 30%. Axial ratios of the ellipsoidal lapilli (sites 965 and 966 on Fig. 1) were measured in three sections cut nearly coincident with their principal planes, and the three-dimensional finite strain (including compactional strain) was calculated. Both samples had undergone flattening, yielding *K*-values on the Flinn diagram of 0.232 and 0.452 (Flinn 1962). In both cases the *XY* plane of these flattened ellipsoids corresponds with the plane of cleavage in the bulk sample; $(1 + e_3)$ is normal to the cleavage and has values of 0.627 (sample 966) and 0.663 (sample 965). The shortening normal to cleavage, therefore, has been about 37 and 34%, respectively, for samples 966 and 965.

Although these results from iron-formation and lapilli tuff are not directly comparable with strains determined by the bundle method in cleaved argillite because of material differences among the several rock types and their probable influence on strain intensity, it appears that the shortening estimates from the bundle method are within reasonable range of those provided by other indicators when considered from the regional perspective. According to Gray (1979, p. 115), values of shortening due to solution along first-generation slaty cleavages range as high as 70% and average around 30%. The minimum bulk shortening of about 20–40% calculated for the central Minnesota samples therefore appears reasonable.

Finally, it is of some interest to consider the changes in phyllosilicate abundance that have accompanied the formation of cleavage bundles. Taking the data for layer 8 of Fig. 2(b) as an example, and comparing equal areas of layer inside and outside bundle domains (comparing the top and center bars of Fig. 7), there has been an increase of 15 units of phyllosilicate accompanying an increase of 20 units of opaque material and a decrease of 35 units of tectosilicate. Therefore the bundle-forming process has 'concentrated' micaceous minerals in the cleavage films of this rock, which one can see at a glance petrographically without recourse to laborious point counting. If, however, layer lengths now within bundle domains are compared with those calculated for the pre-bundle state, assuming conservation of opaque phases (i.e. comparing the middle and bottom bars of Fig. 7), a 'shortening' of 69% is inferred in the phyllosilicate content. These seemingly contradictory findings may mean that both tectosilicates and phyllosilicates were removed from the rock relative to opaque phases, but that tectosilicates were more rapidly or efficiently removed. Alternatively, the areal proportion of phyllosilicate grains in planes normal to cleavage may have changed in complex ways as the micaceous minerals reoriented and grew metamorphically in the cleavage films.

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