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Résumé de l'article

L'accroieseaent de l'inegalite' et la baisse des fluctuations des longs axes des grains de quartz, des lithons jusqu'aux zones de clivage, dans les metagrauwackes du groupe Heguma, indique une haueae de tension. Cette hausse de tension est attribute £ la solution de pression pgne'trante dans laquelle les grains de quartz sont tallies et donnent des sections presque rectangulaires dans les zones de clivage, compart a leur profile irregulier dans les lithons. Le raccourcissement, calculi a partlr d'un modele de pression unidimensionnel, atteint des valeurs entre 60 et 702 dans les zones de clivage. Des valeurs comparables du raccourcissement sont calcul£es a partlr d'analyses mocales, et d'analyses chimiques des clivages et des lithons-

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Formation of Spaced Cleavage and Concurrent Mass Removal of SiO_2, Meguma Goup Metagreywackes, Goldenville, Nova Scotia

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Increasing inequancy and decreasing fluctuation of long axes of quartz grains from lithons to cleavage zones in Meguma Group metagreywackes indicate an increase in strain. This strain increase is best ascribed to pervasive pressure solution in which quartz grains are trimmed to yield nearly rectangular sections in cleavage zones, as compared to their irregular outlines in lithons. Shortening calculated from a one-dimensional strain model reaches 60-70% in cleavage zones. Comparable values of shortening are calculated from modal analyses, and from chemical analyses of cleavages and lithons.

The implication of such shortening is that about ten percent of all the quartz in the original rock has been removed from the immediate system. This demands volumes of water about one order of magnitude greater than any likely content of connate water. The transport system was a dynamic one, involving most of the rock volume.

L'accroissement de l'inégalité et la baisse des fluctuations des longs axes des grains de quartz, des lithons jusqu'aux zones de clivage, dans les métagrauwackes du groupe Meguma, indique une hausse de tension. Cette hausse de tension est attribuée à la solution de pression pénétrante dans laquelle les grains de quartz sont taillés et donnent des sections presque rectangulaires dans les zones de clivage, comparé à leur profile irrégulier dans les lithons. Le raccourcissement, calculé à partir d'un modèle de pression unidimensionnel, atteint des valeurs entre 60 et 70% dans les zones de clivage. Des valeurs comparables du raccourcissement sont calculées à partir d'analyses modales, et d'analyses chimiques des clivages et des lithons.

L'implication de ce raccourcissement est qu'environ dix pourcent de tout le quartz de la roche originaire, a été supprimé du système immediat. Cela exige des volumes d'eau d'un ordre de grandeur plus important que n'importe quel système inné d'eau vraissembable. Ce système de transport était un système dynamique qui comprenait la majorité du volume des roches.

INTRODUCTION

An earlier report (Clifford et al.) suggested that a cleavage in metagreywackes of the Meguma Group, Nova Scotia, has been formed by pressure solution processes. New data sustain that interpretation and permit estimates of shortening in directions normal to cleavage. These in turn have implications for transport of quartz and gold.

The metagreywackes which we have examined are part of the Goldenville Formation, which is the lower division of the Cambro-Ordovician Meguma Group of Nova Scotia. Mapping in the Ecum Secum area (Fig. 1) shows that these rocks have been deformed into a series of gently, but doubly, plunging folds, commonly arranged en échelon. Axial surfaces are roughly upright and strike almost east-west. Associated with these folds is a very obvious spaced cleavage, marked by zones of high concentration of phyllosilicates. Other structures include quartz veins (see Henderson, 1983), faults which trend about 130°, and kink folds. We deal here only with the cleavage and its generation, as revealed by petrography, geometric analysis and chemistry.

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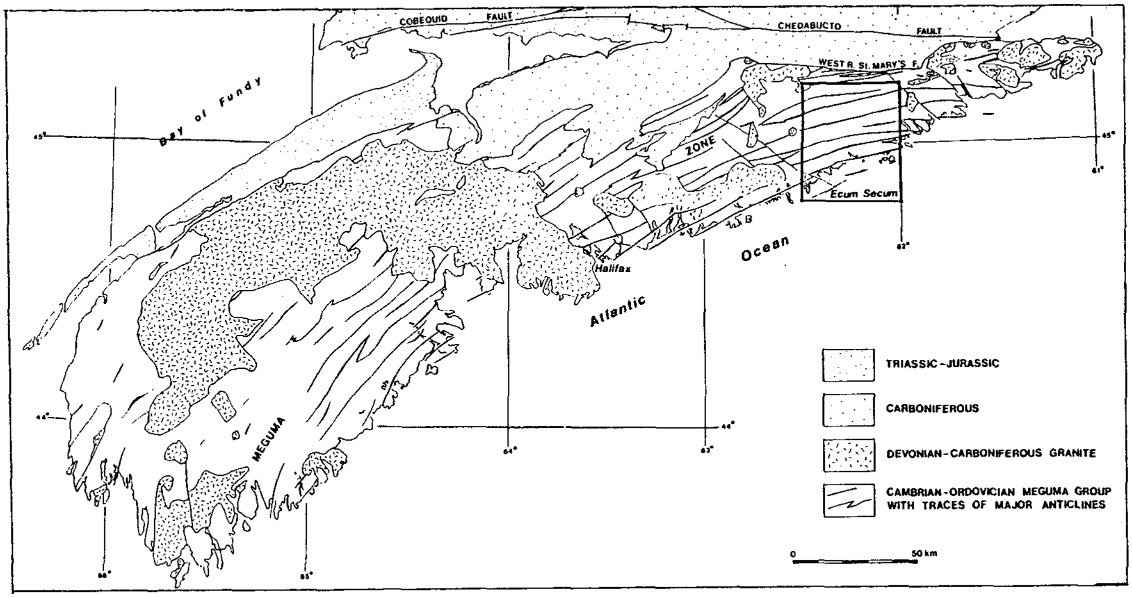


Figure 1 - Simplified geological map of Nova Scotia: Ecum Secum area is outlined. G = Goldenville.

METAGREYWACKE

The Goldenville metagreywackes occur as beds about 1-2 m thick, mainly massive, with Bouma divisions discernible in some beds. Such beds are separated by thin (ca. 10 cm) layers of meta-argillite which are recessive in most outcrops. Cleavage in the metagreywackes is widely spaced compared to a closely packed slaty cleavage in the meta-argillites. Goldenville metagreywackes are typically medium grained micaceous arenites. Quartz is the dominant mineral phase, followed by phyllosilicates. Modal analyses show that these minerals form about 95% of the rock. Other species include feldspar, carbonate and opaques.

Quartz occurs as obviously detrital grains, and also in polycrystalline aggregates which may be quartzite clasts (cf. Graves, 1976). Virtually all grains show some undulatory extinction. Most grains in lithons are irregularly sutured; but in cleavage zones (CZ), quartz grain boundaries are mainly straight and many grains are rectangular in section. Some 50% of grains have beard overgrowths of quartz and white mica.

White Mica occurs overwhelmingly as well-developed subhedral inequant crystals throughout the rock; crystals in CZ are generally a little larger than those in lithons. Small amounts of white mica are part of the beard overgrowths on quartz grains in both CZ and lithons.

Biotite occurs as anhedral crystals, usually associated with carbonate or opaque minerals in lithons. In CZ biotite crystals are larger and of better form than those of the lithons.

Taylor and Schiller (1966) noted that the regional metamorphism here is greenschist facies and this latter mineral assemblage is compatible with this metamorphic grade.

Table 1 gives modal analyses for eight thin sections, with over 2000 points per section. These include both lithons and cleavage zones. In carrying out the modal analyses, traverse lines were oriented parallel to cleavage zones and spaced 0.3 mm apart. The count "track" was recorded on a photo-map of the section, and zones of different mineralogic abundances were easily defined. Because quartz and mica comprise 95% of these rocks, we ignore other components in subsequent physical analysis, with no great loss of

Table 1

MODAL ANALYSES, TWO SECTIONS FOR EACH OF FOUR SAMPLES, OF GOLDENVILLE METEGREYWACKES. OVER 2000 POINTS PER SECTION

	Quartz	White Mica	Dark Mica	Opaques	Carbonate	Feldspar
G20 753 AC	67.0	23.5	4.9	1.6	1.4	1.4
G20 753 BC	73.2	17.7	4.5	1.3	2.1	1.1
G26 415 AC	68.6	26.0	1.4	2.0	1.7	0.3
G26 415 BC	58.8	34.0	2.2	1.9	2.2	0.9
G19 354 AC	68.3	23.0	2.7	1.0	3.6	1.3
G19 354 BC	68.0	20.4	6.2	0.8	3.5	1.0
G26 353 AC	68.1	24.9	2.9	1.1	1.7	1.2
G26 353 BC	68.7	23.6	3.3	1.3	2.5	0.6
Overall Averages	68%	24%	4%	1%	2%	2%

accuracy.

PHYLLOSILICATES

Figure 2 gives the trans-cleavage variation in phyllosilicate content for a range of cleavage development, from mediocre [G20-753 AC] to exceptionally wide and sharply defined [G26-415 AC]. CZ are best defined in terms of phyllosilicate contents. Even in poorly-developed CZ, phyllosilicate content exceeds 30%, and the gradient in mica content from lithon to CZ is invariably steep. In well-developed CZ, mica content exceeds 60% and the CZ margin is very well defined. Lithons by contrast, always have phyllosilicate contents of 20% or less; the phyllosilicate grains seem to be distributed more or less uniformly throughout lithons.

Throughout the lithons, white mica and biotite are about equally abundant. But in CZ, white mica content increases sharply whereas biotite content remains unchanged, relative to the modal abundances of these minerals in lithons (Fig. 3). A simple concentration of phyllosilicates should appear as an equal rise in modal abundances of both phases in CZ. This is obviously not the case. One possible conclusion is that, in addition to simple concentration,

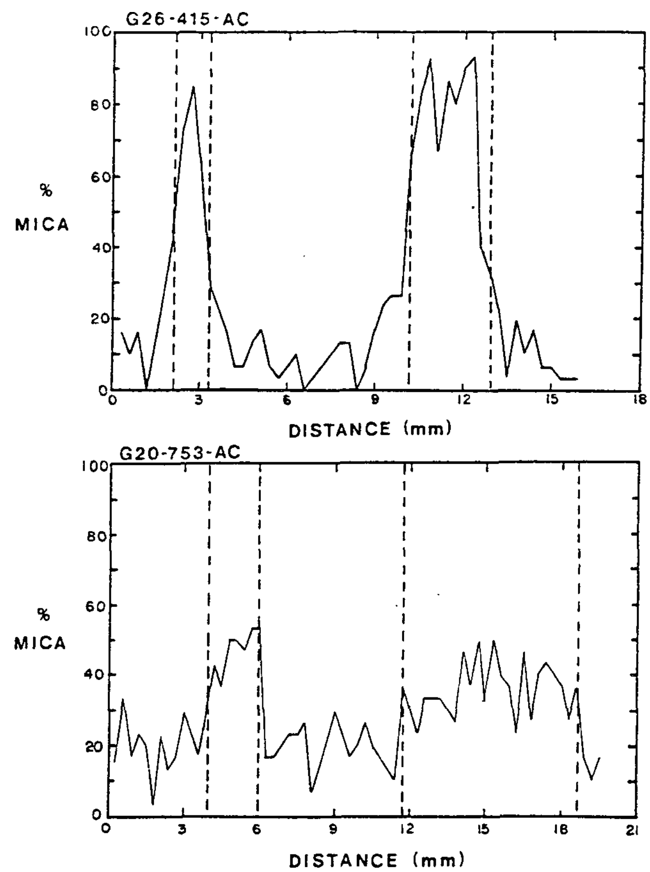


Figure 2 - Variation in phyllosilicate content across section # G26 - 415 AC, # G20 - 753 AC. Note marked changes which help define cleavage (CZ).

there has also occurred a production of some white mica as a new phase, presumably at the expense of other phyllosilicates. The process also involved removal of carbonate; there is little carbonate in the rock as a whole and none in CZ.

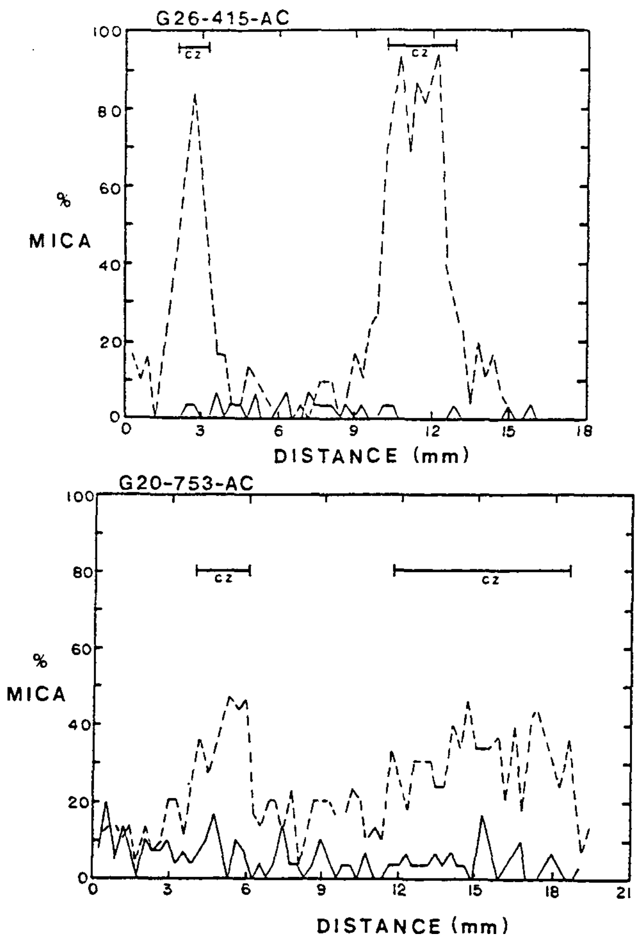


Figure 3 - Change in modal abundances of dark (continuous line) and light (dashed line) micas, sections # G26 - 415 AC, # G20 - 753 AC.

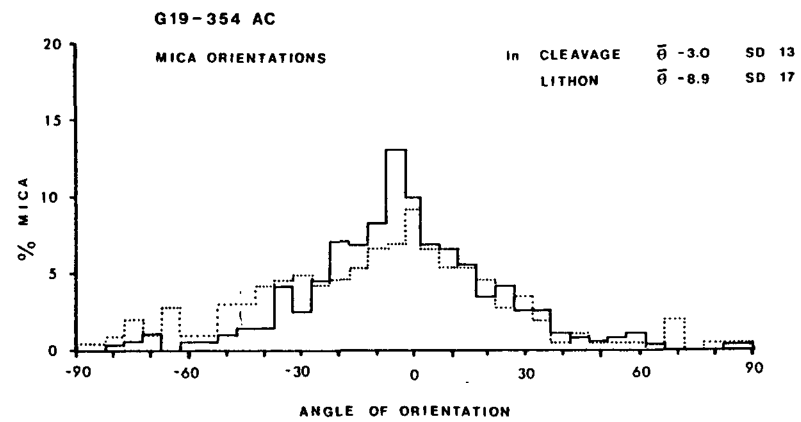
Orientation patterns of phyllosilicate grains in CZ and lithons are very similar (Fig. 4). Standard deviations of orientations in CZ are a little smaller than in lithons (Table 2), suggesting a slightly better degree of preferred orientation in CZ. However, the differences are not profound, and the mean orientations for the two kinds of sites are nearly identical, coinciding approximately with the general orientation of CZ. Better developed CZ show smaller standard deviations. One possible implication of this is that the process of cleavage formation, as it affected the orientation of phyllosilicate grains, was little more powerful in CZ than in lithons of the same sample, though the process does lead to a better degree of preferred orientation with better development of cleavage.

QUARTZ GRAIN SHAPES AND ORIENTATIONS

For the analysis of grain shape variation, we have identified three kinds of domain in each sample. Lithons (ML) have apparently undergone least deformation. They contain more than 60% detrital quartz grains, of highly variable size and shape. Axial ratios are low, shapes range from angular to subrounded. There is a very weak preferred orientation of such grains. Intermediate zones (IM) possess a well-defined grain cleavage. Quartz exceeds 50%; quartz grains are eye-shaped with tapered ends, defining the cleavage though not very powerfully. Cleavage zones (CZ) are zones of high abundance of phyllosilicates, mainly white mica, and of straight-sided quartz grains. Micas exceed 30% and may reach 80% of the volume of the CZ. Boundaries between these domains vary from sharp to diffuse. Two examples are given in Figure 5.

For each domain, we have measured long and short axes of quartz grains, and also measured the orientation of long axes relative to an arbitrary datum (fluctuation angle, θ) for mutually perpendicular sections: (ac) sections are normal to fold axis, and (bc) sections are normal to cleavage but parallel to fold axis.

Results are plotted as "fluctuation plots" of axial ratio, A_T, versus fluctuation angle θ, for (ac) and (bc) sections (Fig. 6) (Ramsay,1967). From these plots, it is apparent that (i) quartz grains become progressively more inequant, ML → IM → CZ. (ii) long axis fluctuation is progressively more restricted ML → IM → CZ. Accompanying these changes, grain boundary geometries change from largely irregular to commonly straight-sided. In addition, there is no marked



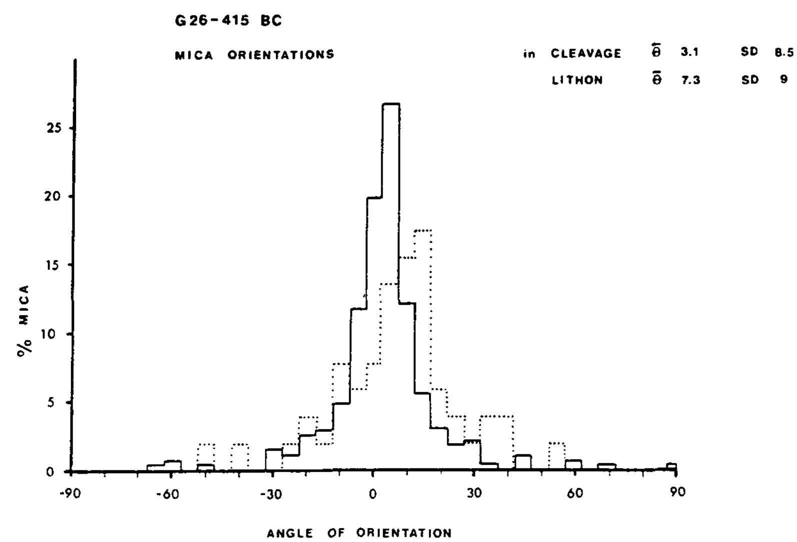


Figure 4 - Histograms of orientation of basal cleavage planes of mica (Zero = orientation of CZ). Solid line = CZ; Dotted line = Lithon. (a) Section # G19 - 354 AC; poorly defined, poorly developed CZ. Micas show highest standard deviation about mean orientation for all samples analyzed, and lowest calculated shortening -- 51%. (b) Section # G26 - 415 BC; sharply defined, well developed CZ. Micas show lowest standard deviation about mean orientations, greatest contrast between CZ and lithon for all samples analyzed, and highest calculated shortening -- 83%.

distinction in long-axis dimensions from ML to CZ, nor is there any marked increase in such things as undulatory extinction, which suggests that the changes in grain shape are not dominated by crystal plasticity.

VOLUME CHANGES

We have attempted to estimate the dimensional changes associated with this quartz grain shape change. From each fluctuation plot, we can calculate the axial ratio of the strain ellipse for that section, or a version of it where the section plane may not be exactly parallel to a plane of principal strain. This tectonic axial ratio we refer to subsequently as A_t for any given section. From such data for the mutually perpendicular sections, we calculate the axial ratio of the strain ellipsoid for each site, following the method which was outlined by Ramsay (1967) and subsequently modified by others (e.g. Dunnet, 1969). Results are given in Table 3, and illustrated in a logarithmic Flinn-type plot in Figure 7. With one exception (G26-415 lithon), all calculated strain ellipsoids suggest volume loss. The trends for all data are to greater apparent flattening from ML to CZ.

If we assume that the progression ML

Table 2.

ORIENTATION OF BASAL CLEAVAGE IN GOLDENVILLE METAGREYWACKES

Sample Number	Cleavage (CZ)	Lithon (ML)	
G19 - 354 AC	355	263	N
	- 3	- 9	M
	13	17	SD
G19 - 354 BC	357	202	N
	- 2	- 3	M
	11	11	SD
G20 - 753 AC	367	188	N
	0	0	M
	10	17	SD
G20 - 753 BC	141	192	N
	- 2	- 3	M
	11	9	SD
G26 - 353 AC	214	189	N
	- 1	- 1	M
	8	11	SD
G26 - 353 BC	224	194	N
	- 4	- 3	M
	10	9	SD
G26 - 415 AC	310	127	N
	- 2	5	M
	9	13	SD
G26 - 415 AC	273	52	N
	3	7	M
	9	9	SD

Cleavage trace is zero

N = number of observations;
M = mean orientation relative to cleavage;
SD = standard derivation

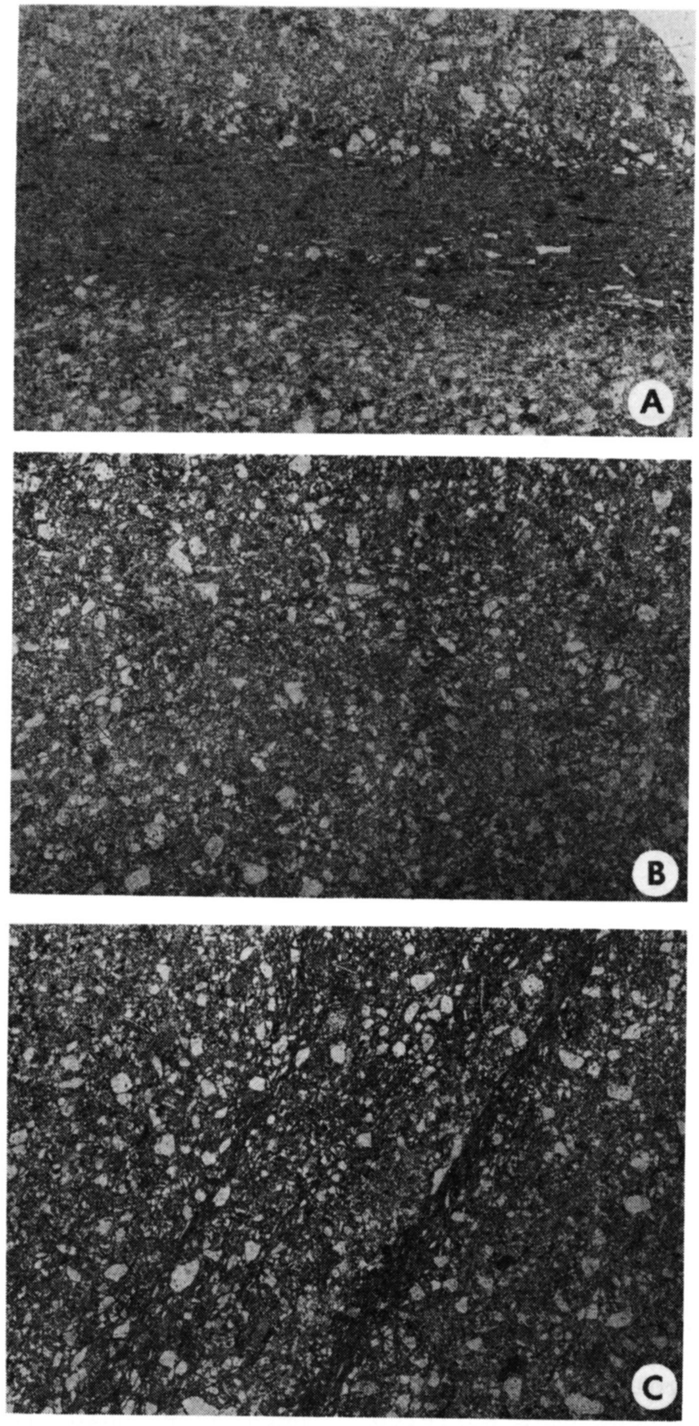


Figure 5 - Photomicrographs of (a) cleavage zone, sample # G26 - 415, (b) lithon, sample # G26 - 415, (c) sample # G20 - 753. Note differences in shapes and margins of quartz between the two domains.

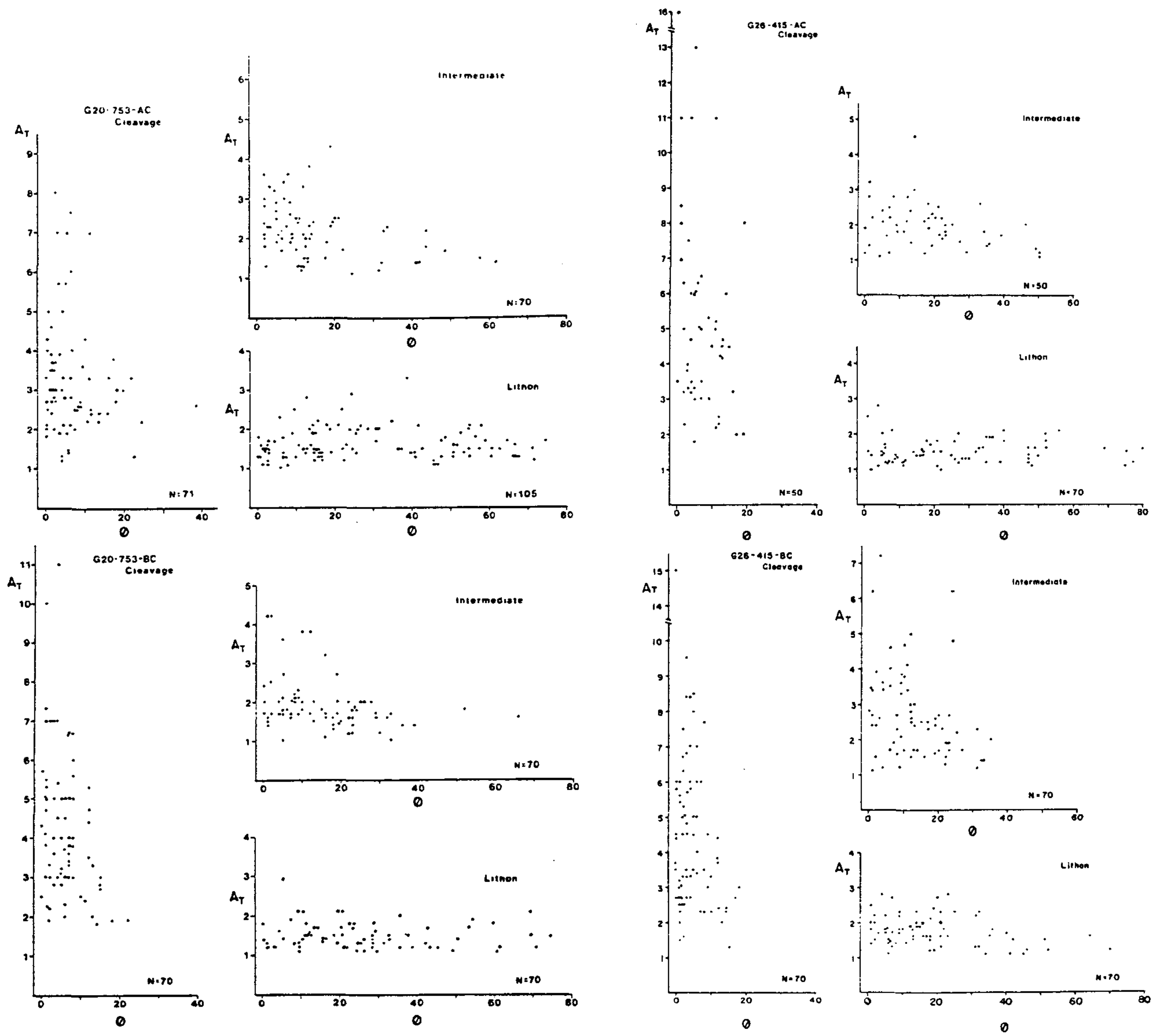


Figure 6 - Fluctuation plots: actual axial ratio, A_T, versus fluctuation angle, θ. Sample # G26 - 415 has the best defined cleavage and the highest calculated shortening. Sample # G20 - 753 has less well-defined cleavage, least calculated shortening. θ is measured from the cleavage. Diagrams should be symmetrical about zero but points have been reflected across zero to better define the distribution.

→ IM ↔ CZ is a genuinely evolutionary one, then the deformation paths all have low k values. Following Ramsay and Wood (1973), we superimpose on Figure 7, lines of equal volume loss. These suggest that even lithons have suffered some loss of volume, up to 27%; that the loss is greater in intermediate areas; and is uniformly highest in CZ. As it happens, the highest volume losses, 71% from G26-353 and G26-415 cleavage, occurred in the anticlinal core. The least volume loss, 58% from G20-753 cleavage, occurred in the fold limb. Ranges of ΔV are least for CZ, most for ML.

A second, crude estimate of ΔV has been made, using the ratio of A_t for CZ to A_t for ML in each sample. This ratio is equivalent to the fraction of a grain, having the original dimensions of a strain ellipse for the lithon, that remains after experiencing a material volume loss accomplished by a change in one dimension only, and which

Table 3.

AXIAL RATIOS OF STRAIN ELLIPSOIDS, CALCULATED AFTER RAMSEY (1967) AND DUNNET (1969)

Sample #, Site		Axial Ratio, X_t	Strain Y_t	Ellipsoid Z_t
G26 - 353				
	CZ	1.08	1.0	0.27
	IM	1.03	1.0	0.56
	ML	1.05	1.0	0.70
G26 - 415				
	CZ	1.15	1.0	0.25
	IM	1.31	1.0	0.53
	ML	1.30	1.0	0.81
G20 - 753				
	CZ	1.27	1.0	0.33
	IM	1.15	1.0	0.56
	ML	1.03	1.0	0.80
G19 - 354				
	CZ	1.07	1.0	0.30
	IM	1.01	1.0	0.45
	ML	1.03	1.0	0.71

CZ -- Cleavage zone; IM -- Intermediate zone, ML -- Lithon

yields a strain ellipse equivalent to that found in the CZ. The equation for the elliptical case is:

$$\left[\frac{A_t\ (\text{lithon})}{A_t\ (\text{cleavage})} - 1\right] \times 100 = \text{percent area loss} \quad [\text{Eq. 1}]$$

This calculation has been carried out for (ac) and (bc) sections of each sample, and the values averaged to give a volume loss; results are listed in Table 4 alongside results from Figure 7. The numbers are remarkably similar, agreeing to within 10%. We conclude from this that the essential process of cleavage formation in these rocks involved loss of quartz by diffusional mass transfer, with the change of dimension being accomplished overwhelmingly in directions normal to the cleavage. This is supported, in our view, by the change in axial ratios in (ac) and (bc) sections without marked changes in the actual dimensions of quartz grains as measured parallel to cleavage, and by the straight margins ("neatly trimmed") of quartz grains in CZ as compared to the margins in ML.

For this second calculation, there are several assumptions:

(a) the lithons are representative of the original rock prior to deformation.

(b) volume loss affected only the Z dimension of the evolving strain ellipse; in geological terms, material was removed along axes normal to cleavage.

(c) volume loss is due solely to loss of quartz.

Of these, (c) is approximately

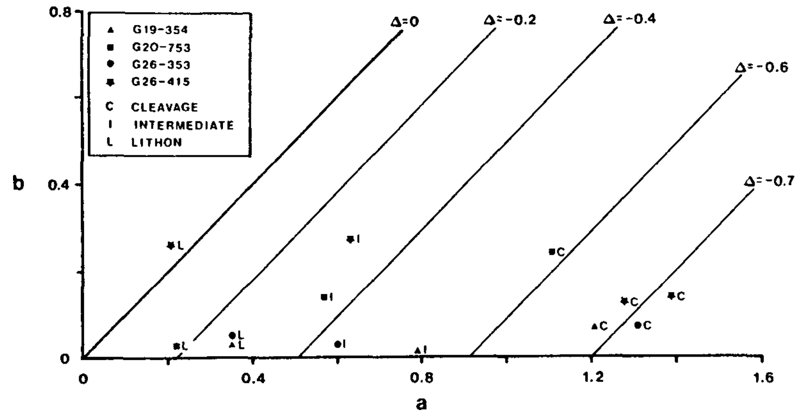


Figure 7 - Logarithmic Flinn-type plot of

$$\ln\left[\frac{1+e}{1+e_2}\right] = a \quad \underline{\text{versus}} \quad \ln\left[\frac{1+e_2}{1+e_3}\right] = b$$

for calculated strain ellipsoids in three domains in each of four samples. Lines of $\Delta = n$ are lines of implied volume loss (c.f. Ramsay and Wood, 1973). Points plot above b = 0, suggesting that deformation is not exclusively two-dimensional.

correct (ignoring any effects during compaction), because there is little of anything else but phyllosilicate in the rock. Removal of all material other than quartz and phyllosilicates would alter the numbers by, at most, ten per cent of their calculated value. Assumption (b) is probably not correct everywhere; there are some signs of crystal plasticity and preliminary calculations suggest that, in the core of the anticline, there may have been changes in both X_t and Z_t, due to constant-volume deformation. More work is to be done on this aspect. (a) is most contentious. We have no certain means of deciding what is unaltered. pristine Meguma metagreywacke. In our samples, lithons must be most nearly like the original material. However, Figure 7 implies a volume loss from lithons. This must imply that our second crude calculation is on the low side.

An alternative approach to this problem is to assume that CZ represent zones in which has accumulated phyllosilicate material, as a residue after the loss of quartz, treating lithons as unaffected. This gives a shortening across CZ only, according to the equation:

$$\left[\frac{\%\ \text{mica in lithon}}{\%\ \text{mica in cleavage}} - 1\right] \times 100 = \%\ \text{shortening} \qquad \text{[Eq. 2]}$$

Results range from 51% to 83%. This approach, dependent upon viewing lithons as original, suffers from the same drawback as mentioned above. It assumes also that all mineral phases, other than phyllosilicates, could have been involved in the volume loss episode; this is probably a safer assumption than (c) above. This calculation is unaffected by plastic deformation.

CHEMICAL ANALYSIS

Yet another approach to this problem is by chemical analysis of cleavage zones and lithons separately. Five samples of core, each approximately ten centimetres long, were selected for analysis. Each piece of core yielded one sample set, consisting of five to six cleavage planes and five to six lithons. Each cleavage and each lithon was then analysed individually, for a total of 55 samples analysed.

Table 4.

CALCULATED VOLUME CHANGES, ΔV AFTER RAMSEY AND WOOD (1973) AND ΔV_p USING EQUATION 1

Sample #, Site		ΔV	ΔV_p	$\Delta V - \Delta V_p$
G26 - 353				
	CZ	-0.71	-0.62	+0.09
	IM	-0.40		
	ML	-0.26		
G26 - 415				
	CZ	-0.71	-0.67	+0.04
	IM	-0.31		
	ML	+0.05		
G20 - 753				
	CZ	-0.58	-0.62	-0.04
	IM	-0.36		
	ML	-0.18		
G19 - 354				
	CZ	-0.68	-0.59	+0.09
	IM	-0.54		
	ML	-0.27		

CZ -- Cleavage zone; IM -- Intermediate zone; ML -- Lithon

Figure 8a shows the results of the analysis of five individual lithons of sample G26-415. As can be seen, there is a minor fluctuation in the CaO content, which probably reflects an equally minor variation in the carbonate content of the lithons of this sample. Overall, however, there is no significant variation in the major element chemistry of the lithons of individual sample sets. Other sample sets show similar agreements.

Figure 8b depicts the results of the analysis of five individual cleavage planes of sample G26-415. The chemical composition of the cleavage planes is distinctly different from that of the lithons. However, the compositions of the five different cleavage planes agree quite closely amongst themselves.

In order to determine how much the major element chemistry of cleavages and lithons of different beds varies, the average of each, cleavages and lithons, were calculated for every sample set. It is apparent from Figure 8c that the main variation in composition of the lithon average lies in their MgO content. This variation is between 0.01 wt% and 1 wt% and is likely to be due to differences in amounts of original Mg-bearing detrital phases. The bulk of the Mg may be originally derived from detrital clays; alternatively, the carbonate may have been magnesium-rich. The minor fluctuation in K_2O also can be explained by differences in the content of original K-bearing detrital phases. Overall, the chemical variation between the lithons of the five beds is quite small. The average compositions of the cleavage planes of all sample sets (Figure 8d) are also very similar to each other, especially when we consider that not every cleavage plane is

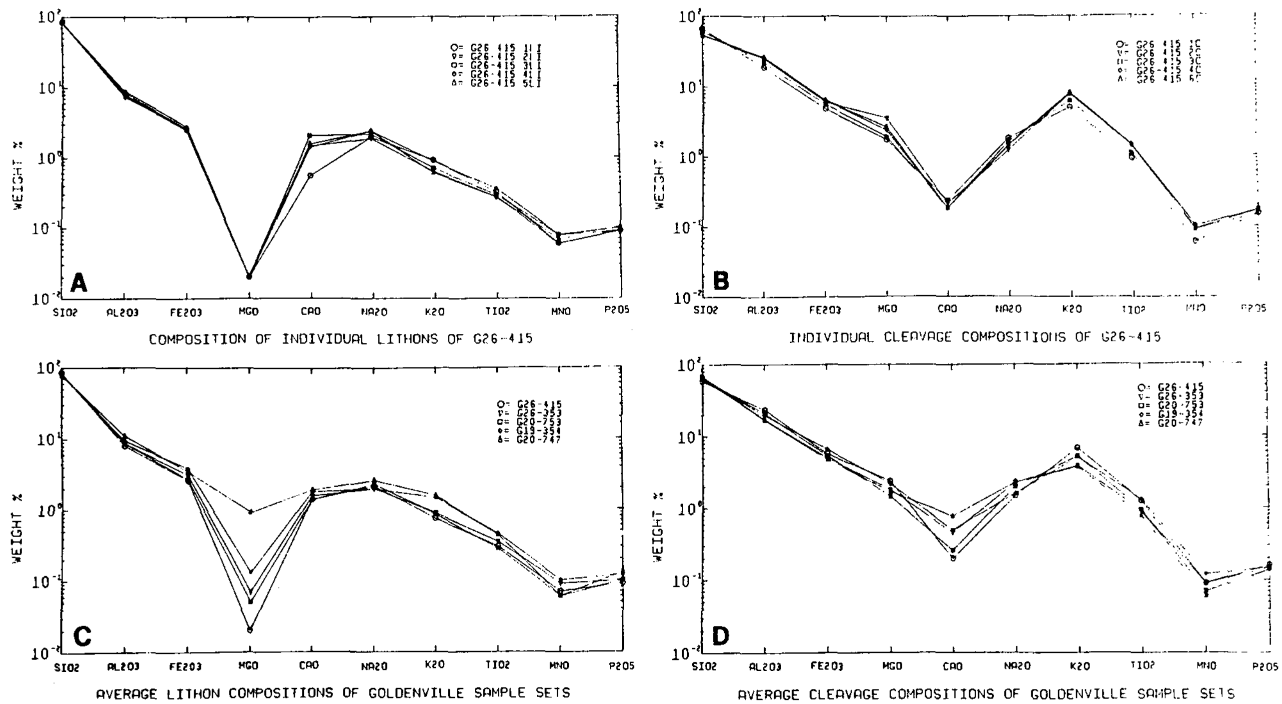


Figure 8 - Chemistry of lithons and CZ. (A) 5 lithons, sample # G26 - 415; (B) 5 CZ, sample # G26 - 415; (C) average composition of all lithons in each sample; (D) average composition of all CZ in each sample. Vertical axis has logarithmic scale.

equally well developed. Differences in the degree of development of the cleavage planes, indicated by variations in their mica content, cannot help but be reflected in their major element chemistry. The chemical composition of the lithons and cleavage planes are quite consistent and lend themselves to further investigation.

Figure 9 compares the average lithon and cleavage compositions of sample set G26-415, and indicates the following changes. The cleavage, with respect to the lithon is 26 wt% lower in SiO_2, 15 wt% higher in Al_2O_3, 3.2 wt% higher in Fe_2O_3, 2.4 wt% higher in MgO, 1.4 wt% lower in CaO, 0.6 wt% lower in Na_2O, 6.1 wt% higher in K_2O and 0.9 wt% higher in TiO_2. The amounts of MnO and P_2O_5 present and the errors associated with the XRF analysis in these oxides do not allow them to be used for quantitative results. They will therefore be ignored in the following discussion. The most interesting difference between the lithons and the cleavages is the large percentage difference in MgO and K_2O. Comparisons of other sample sets show similar results.

In an effort to determine the true losses and gains associated with the cleavage formation, the standard Gresens (1967) approach was taken. The Gresens equation is :

$$100 \left[f_v \left(\frac{g_c}{g_L}\right) C_n^c - C_n^L \right] = X_n \qquad \text{[Eq. 3]}$$

where f_v is volume factor; g_c, g_L are the densities of cleavage and lithon respectively; C_n^c, C_n^L are the amounts of any component, n, in cleavage and lithon respectively; and X_n is the actual amount of component n, lost or gained. Measurements of the densities of the cleavages and lithons showed that the differences in densities between the two was within the limits of accuracy of measurement. The density ratio used in the Gresens equation was therefore taken to be equal to one. Figure 10 shows the average volume factors for the oxides in all sample sets, assuming no loss or gain to or from the cleavage, ie. setting X_n to

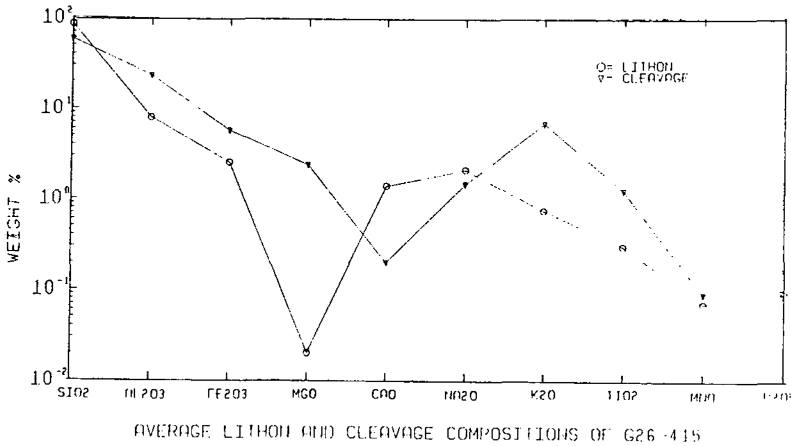


Figure 9 - Composition of the chemistry of lithons and CZ in sample # G26 - 415.

zero. Since the Gresens equation is applied to each component individually, the volume factor for each component is completely independent of the volume factor for any other component. This allows one to determine the true volume factor for the system, giving the overall bulk loss or gain the system has experienced. The criteria used to choose the true volume factor (Gresens, 1969) are as follow: one is a clustering of volume factors of several oxides, which would indicate that these oxides had been gained or lost to the same degree, or more likely, that they had been relatively immobile components; the other involves consistent component ratios of two or more oxides. If the ratios of two or more oxides is roughly the same in the lithon and in the cleavage, this indicates that these oxides were gained or lost to the same degree, or very little at all. Even though clustering may not be immediately apparent in Figure 9, TiO_2, Al_2O_3, and Fe_2O_3 are the only oxides in all five cases that are relatively close to each other. TiO_2, Al_2O_3 and Fe_2O_3 are also the only oxides that maintain relatively consistent component ratios. We therefore regard these oxides as least mobile components in this system. As the true volume factor for this system, we choose Al_2O_3, because it is located in the centre of the three relatively immobile oxides, but also because it shows the highest wt% of the three considered and is therefore least influenced by minor internal losses or gains. The true volume factors for the five cases presented here range from between 0.4 and 0.6. This implies that the cleavage represents a forty (volume factor = 0.6) to sixty (volume factor = 0.4) percent volume loss, with respect to its parental rock volume.

With the use of a true volume factor one can then use Figure 10 to determine what has been lost from or introduced to the cleavage during its formation. Any oxides to the right of the true volume factor have been lost from the cleavage during its formation, whereas oxides to the left of the volume factor were introduced to the cleavage during its formation. The distance from the true volume factor gives an indication of the degree to which this loss or gain has taken place. In all cases the results show remarkable similarities. In all cases CaO has been lost to the greatest extent during cleavage formation. It should be noted that this does not imply that the bulk of the material lost during cleavage formation was CaO but rather that this component has suffered the greatest loss with respect to its "original" lithon composition. SiO_2 shows the second greatest loss. The losses in these two components have been demonstrated in thin section by the lack of carbonate and the depletion of quartz in the cleavage plane (see above). The loss of silica is also the largest bulk loss from the cleavage plane. Other oxides

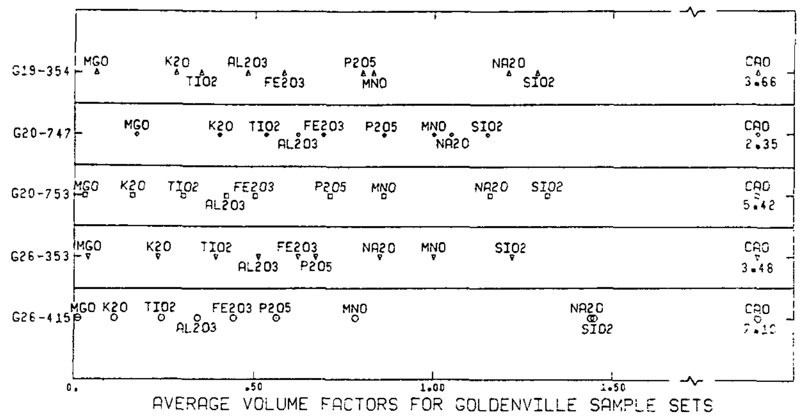


Figure 10 - Volume factor plot of Goldenville samples, using Gresens (1967) equation.

lost during the cleavage formation, in decreasing amounts, are Na_2O, MnO and P_2O_5. The sources for these oxides are likely to have been detrital clays which eventually formed the micas of the cleavage. MgO and K_2O were introduced into the cleavage plane and probably absorbed by forming micas.

These chemical changes imply that phyllosilicates [biotite, muscovite, chlorite] were actively recrystallizing during the cleavage formation period and that the chemical migrations observed took place during that period. The micas in the cleavage are different from those in the lithon as a result of these migrations. This is demonstrated by the petrography and reflected in the variations in the mica content between lithons and cleavage mentioned earlier. The similarity in the order with which the oxides plot on Figure 10, i.e. MgO on the left side to CaO on the right side, demonstrates how remarkably consistent the processes were that led to the chemical evolution of the cleavage. Furthermore, the degree to which the oxides are spaced out amongst themselves along the volume factor axis of Figure 10 is dependent upon the volume loss that has occurred. Sample G20-747, which shows the highest volume factor and therefore represents the smallest volume loss also displays the smallest spread amongst the oxides. On the other hand, sample G26-415 which shows the largest volume loss also displays the largest spread of the oxides. This demonstrates that the chemical movements that take place during the cleavage formation are not spurious and erratic, but are well controlled and follow certain definite patterns.

The fundamental assumption here is that the lithon represents the original source rock; the same assumption was used in the manipulation of the modal data earlier. Though there is a small quantity of "new" material in the lithons, in the form of beard overgrowths, this cannot alter the essential conclusion that the lithon is closer to original composition, or that it has suffered material loss. Deposition in the lithon would mean that the volume losses from CZ calculated from the chemistry are overestimates, while removal of material from lithons would lead to underestimation of losses from CZ. The close agreement of loss estimates from chemistry with loss estimates based on grain shape analysis suggests that lithons represent nearly "undiluted" source rock. This implies that material corresponding to the shortening was totally expelled from the greywackes, the bulk of this material being SiO_2.

DISCUSSION

The regional structure pattern, and the nature and geometry of quartz veins have been dealt with elsewhere (Henderson, 1983). We have concentrated on the documentation of a particular process for the two reasons: (i) we think the process is responsible for the generation of a pervasive spaced cleavage; (ii) the process involves transfer of substantial quantities of SiO_2 from the local rocks.

Several different approaches to the problem of general mechanism of cleavage formation in these greywackes by different analyses converge on the same process, namely, pressure solution. This has produced essentially a one dimensional shortening along axes normal to CZ. Each CZ represents a shortening of at least 50% of its parent rock volume, with concurrent removal of SiO_2. Carbonate has also been removed, but is a trivial portion of the migrant material.

Our calculations of volume loss for CZ can be translated into a mass loss of SiO_2 from the system as a whole. We take the volume loss for CZ to be 50%; the lithon/CZ ratio is taken as 10:1, and the modal proportion of quartz and mica in lithon as 80 to 17. All loss is ascribed to transfer of SiO_2. These are either average figures, or, in the case of volume loss for CZ, at the low end of our range.

This converts to a mass loss of about 200 kg SiO_2 per cubic metre of dense rock. For metamorphic fluids, solubility of quartz has been put at levels of 0.1% to at most 2% by weight (Eugster, 1982). This implies rather large volumes of water to accomplish the removal of the SiO_2. For a high solubility of 2%, this works out at about 10 cubic metres of water for every cubic metre of rock affected. Naturally, this number will vary because of any or all of the following: different levels of volume loss across CZ, different lithon/cleavage ratios, different modal compositions, and variations in solubility accompanying changes in water temperature, pH, etc. The most influential of these are probably water properties and lithon/cleavage ratio. Nonetheless, even if we have overestimated by an order of magnitude, there still is a need for quantities of fluid well in excess of any plausible connate water content. The transfer system appears to have a dynamic one, involving either multiple recycling of water, or a steady supply of water from some other source (? interbedded mudstones, now slates).

This water must have circulated in such a way as to involve most of the rock volume. There is no record of a highly localized conduit or conduits with attendant alteration, such as is typical of a geothermal system. It seems probable that fluids moved mainly along all the lithons. Some redeposition in the form of straight-fibre beard overgrowths is found in the lithons, and could represent the declining stages of the process.

CONCLUSIONS

Spaced cleavage in metagreywackes of the Goldenville Formation was produced at Goldenville, Nova Scotia, primarily by removal of SiO_2 from zones in the rock as a result of pressure solution. Cleavage zones record a shortening normal to cleavage of at least 50% in the Goldenville area. This represents a loss of about 10% of the original quartz content of the total rock, equivalent to a bulk volume loss of roughly 8%, at a conservative estimate.

The removal of such a large quantity of SiO_2 appears to demand substantial quantities of water, which can be made available only by a steady recycling of water, or an equally steady supply of water from an external source. Such large quantities of water are vital for the transport of gold in amounts likely to prove exploitable.

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