Transmission Electron Microscope Study of Bedding-Cleavage Relations in the Vassalboro Formation, East-Central Maine

Beth Z. Lincoln
Department of Geological Sciences
Albion College
Albion, Michigan 49224

ABSTRACT

Transmission electron microscope study of a suite of samples from the Ordovician-Silurian-aged Vassalboro Formation, east-central Maine, provides evidence bearing on the origin of cleavage. Transmission electron microscopy is essential to this study because the fine grain size of these rocks makes textural details impossible to resolve with the petrographic microscope. These rocks are characterized by a spaced cleavage consisting of alternating cleavage zones and uncleaved microlithons. The mineral assemblage in the cleavage zones differs from that in the microlithons, notably in the lack of quartz in the cleavage zones. Phyllosilicates in the cleavage zones occur in two habits: as platy grains, and as blocky grains. Typically, the blocky grains are elongated perpendicular to their (001) planes and parallel to the rock cleavage. The cleavage zones and microlithons also have different average chemical compositions. The cleavage zones are depleted strongly in most major oxides, especially SiO$_2$ and Na$_2$O, relative to the microlithons. It is proposed that the cleavage zones formed by the partial, or, in some cases, complete, dissolution and removal of minerals, especially quartz, chlorite, and white mica, and by the growth of chlorite and white mica.

INTRODUCTION

Since at least the time of Sharpe (1849) and Sorby (1853; 1856a; 1856b), geologists have been intrigued by the deformation of micaceous rocks, and especially by the formation of slaty cleavage. The relationship of cleavage to the stress and strain ellipsoids, the mechanism by which a preferred mineral orientation originates, and the relationship of slaty cleavage to other forms of cleavage are among the problems which have been examined. Many of these problems remain controversial, and fundamental questions on the origin of cleavage remain unanswered. This study documents the textures of cleaved rocks and thus presents key evidence bearing on the origin of slaty cleavage.

A suite of phyllites from the Vassalboro Formation, east-central Maine, was examined using optical and transmission electron microscopy. Transmission electron microscopy is an essential component of this work, because the grain size of these rocks is too fine to allow textural details to be resolved adequately with the petrographic microscope. The transmission electron microscope is capable of extremely high magnification, and so is a powerful tool in the study of textures of fine-grained rocks. One drawback, however, is that only very small areas (approximately several grain diameters across) can be examined. Much preliminary work with the optical microscope is necessary to ensure that representative areas of the samples are selected for the transmission electron microscope, or a biased view of the samples will result.

This suite was chosen for study because it contains a spaced cleavage defined by alternating zones of relatively uncleaved and strongly cleaved rock. Elsewhere in the Vassalboro Formation, this spaced cleavage grades into a well-developed slaty cleavage (Schwartz, 1976). Assuming that this spaced cleavage represents the early stages of the development of a penetrative slaty cleavage, then the transition from uncleaved to strongly cleaved rock is preserved in these rocks. Such rocks can provide more information on the mechanism of cleavage formation than can rocks containing one well-developed cleavage, because one can compare directly the uncleaved and cleaved zones, and so gain information on the progressive de-
Development of cleavage.

GEOL O G IC SET T I NG

The Vassalboro Formation has been described by several previous workers, including Osberg (1968) and Griffin and Lindsley-Griffin (1974). It is dominantly a thick-bedded, slightly calcareous metasandstone with thin interbeds of phyllite. It is described as being similar to the Siluro-Devonian-aged Madrid Formation (Ludman and Griffin, 1974), and early work suggested that these units were correlative (Osberg et al., 1968; Griffin, 1973; Ludman and Griffin, 1974), but later work suggests that the Vassalboro Formation is Ordovician-Silurian in age (Osberg et al., 1985). It has been metamorphosed to the chlorite and biotite grades of greenschist metamorphism, and several episodes of tectonic folding and faulting have affected these rocks. Sedimentary and slump features still can be recognized, however. The cleavage described in this paper is the earliest and, in these samples, shows no evidence of overprinting by younger events.

The samples examined in this study are from the portion of the formation informally referred to by Griffin (1973) as the “Kenduskeag formation”, a name no longer in use. These samples lie in the chlorite zone of the greenschist facies of metamorphism. Several generations of cleavages are contained in this outcrop, as are original depositional features such as graded bedding, cross laminae, slump folds, and sedimentary breccias. Samples were chosen in which bedding and the earliest cleavage are both pronounced and at a high angle to each other. Here, this early cleavage is a spaced cleavage; elsewhere in the region it has been described as a penetrative slaty cleavage and as a crenulation cleavage (Schwartz, 1976). Schwartz (1976) concluded that the cleavage began as a spaced cleavage, and that in some areas the spacing between the cleavage zones decreased as the deformation progressed, resulting in a penetrative slaty cleavage. The goal of this present study is to use textural evidence to document the processes by which cleavage development progresses.

OBSERVATIONS

Compositional variation in the samples permits the study of compositional influences on cleavage formation. Some of the beds are quartz-rich or psammitic, some are phyllosilicate-rich or pelitic, and some are graded from psammitic to pelitic.

In hand sample and thin section, discrete cleavage zones cut across and disrupt bedding (Figs. 1 and 2). The spacing between these zones varies between a centimeter in psammitic beds and a fraction of a millimeter in pelitic beds. The areas in which sedimentary structures are preserved between the cleavage zones are referred to as microlithons in this study. It is believed that

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*The samples were collected by H. R. Burger III at Stop #4 of field trip A-3, 1974 New England Intercollegiate Geological Conference (Griffin and Lindsley-Griffin, 1974).
Bedding-cleavage relations

Figure 3. Detail in plane-polarized light of one microlithon in the psammitic layer shown in Figure 1. The white grains are dominantly quartz. White mica lies along quartz grain boundaries, and can be found in many orientations. Sparse stringers of opaque material lie parallel to the rock cleavage.

Figure 4. Detail in plane-polarized light of one cleavage zone in a psammitic layer. The cleavage zone at the bottom is dominated by the dark trails of iron oxides and iron-titanium oxides parallel to the plane of the cleavage. Both the flake-like and the blocky habits of the phyllosilicate grains occur within the cleavage zone. While some flake-like phyllosilicate grains have their long dimensions parallel to the rock cleavage, many do not. The blocky grains tend to have their (001) planes at high angles to the rock cleavage. Those that are elongated perpendicular to their (001) planes thus have their long dimensions approximately parallel to the rock cleavage. A comparison of the microlithon at the top of the photograph with the cleavage zone on the bottom reveals that quartz (which appears as equant white grains in the microlithon) is much less abundant in the cleavage zone than in the microlithon.

and feldspar occur as equidimensional grains and are subrounded to subangular in shape, and thus are interpreted to be detrital. Grain diameters in the microlithons equal 60 micrometers or less. Quartz does not exhibit undulose extinction. The phyllosilicates occur as isolated grains along quartz grain boundaries and do not form mica beards. There is a tendency for the white mica to lie parallel to the plane of the cleavage zones, but some white mica lies parallel to the bedding plane and some in all orientations between bedding and cleavage. The phyllosilicates commonly are lath-like in cross-section, with their long axes parallel to the traces of their (001) planes. The lengths of these long axes are roughly the same as the diameters of the quartz grains. The chlorite occurs as coarse grains, commonly interlayered with white mica.

In contrast to the microlithons, the cleavage zones contain very sparse quartz. Instead, cleavage zones are composed of white mica, with lesser amounts of chlorite, brown iron oxides, and iron-titanium oxides. The phyllosilicates commonly are oriented with neither their long axes nor the traces of their basal planes parallel to the rock cleavage direction (Fig. 4). The white mica exists in two habits. It occurs as flake-like grains which have the trace of their (001) planes parallel to their long dimensions. Some of these grains lie with (001) parallel to the cleavage zones, but many lie with (001) at a high angle to the zones. In a noteworthy difference from the microlithons, white mica also occurs in these zones as more nearly equant grains (Fig. 4). The traces of the (001) planes of most grains with this habit lie at a high angle to the rock cleavage, although the long dimensions of some lie roughly parallel to it. Chlorite exists only in this second habit. This observation is confirmed by an analysis of transmission electron microscope diffraction patterns; the (001) planes of white mica grains lack a strong preferred orientation, while the (001) planes of chlorite grains are oriented at a high angle to the rock cleavage. Many of the chlorite grains are elongated perpendicular to their (001) planes (Figs. 4 and 7). The phyllosilicates with this habit commonly abut iron-stained zones defining the cleavage. No phyllosilicates with this habit exist in the microlithons.

Iron oxides and iron-titanium oxides are concentrated in the cleavage zones. Many of the phyllosilicates are iron-stained, and wavy dark brown seams of oxides extend along the cleavage traces (Fig. 4). As mentioned above, the blocky phyllosilicate grains commonly abut against these oxide seams.

In the pelitic beds, the cleavage zones are thinner and more closely spaced than those in the psammitic beds (Fig. 2), but otherwise are identical. Pelitic microlithons contain less quartz and feldspar and more phyllosilicates than the psammitic microlithons, reflecting their original compositional difference (Fig. 5). The textural relationships are the same as in the psammitic layers already described. Boundaries between microlithons and cleavage zones are sharp, and grains do not bend from one orientation into another. Some isolated grains parallel to the cleavage direction are present in the microlithons. These are surrounded by grains parallel to the bedding plane (Fig. 6); perhaps these represent incipient cleavage zones.

In summary, the microlithons differ from the cleavage zones in both mineralogy and texture. The cleavage zones contain significantly less quartz and feldspar than the microlithons. It is especially noteworthy that the nearly equant phyllosilicates are found only in the cleavage zones (Fig. 7). The phyllosilicates lack a strong preferred orientation of their (001) planes in both
The high concentration of phyllosilicate grains is typical; in this sample quartz is scarce. In contrast to the phyllosilicates in the microlithons of the psammitic sample, the phyllosilicates in the pelitic sample tend to have their long dimensions and their (001) planes parallel to the bedding plane.

Figure 5. Transmission electron micrograph illustrating phyllosilicates in one of the microlithons in the pelitic sample shown in Figure 2. The high concentration of phyllosilicate grains is typical; in this sample quartz is scarce. In contrast to the phyllosilicates in the microlithons of the psammitic sample, the phyllosilicates in the pelitic sample tend to have their long dimensions and their (001) planes parallel to the bedding plane.

Figure 6. Transmission electron micrograph illustrating examples of isolated grains within the microlithon of a pelitic sample which lie parallel to the cleavage direction and may represent incipient cleavage zones. Note the sharp boundaries between grains of different orientations.

zones, although there is a tendency for white mica (001) planes to lie parallel to the cleavage zones within the zones themselves.

CHEMISTRY

Optical and electron microscopy reveal definite differences between the mineral assemblages in the microlithons and cleavage zones. The main difference is the scarcity of quartz, a major constituent of the microlithons, in the cleavage zones. The fine grain size of the rocks makes modal analysis impossible, so in an effort to quantify the differences between the two zones, each was analyzed for major oxides with an electron microprobe. Five areas in the microlithons and four in the cleavage zones of a psammitic sample were analyzed, each at four or five spots, using a wide beam (40 micrometers in the cleavage zones and 70 micrometers in the bedding zones) to give average compositions. These are given in Table 1.

Overall averages for the cleavage and bedding zones are given in the first two columns of Table 2. Before meaningful comparisons between these two zones can be made, the composition of the original uncleaved rock must be known. In these rocks, this composition cannot be determined directly. However, it is possible to infer what it might have been. There are two extreme cases to consider. In the first, the rock behaves as a closed system and all the material removed from the cleavage zones is deposited in the areas between the cleavage zones. The original rock is differentiated into quartz-rich and phyllosilicate-rich domains; the composition of the original rock thus would be intermediate between those of the two domains. The case documented by Marlowe and Etheridge (1977) approaches this extreme. They studied a crenulation cleavage composed of alternating quartz-rich and mica-rich domains which they could trace into uncrenulated rock, and found that the composition of the uncrenulated rock indeed did lie between that of the quartz-rich and mica-rich domains for many of the components. Only MgO and FeO had been removed in significant quantities from these rocks (Marlowe and Etheridge, 1977).

In the second extreme case, the rock behaves as an open system and all the material removed from the cleavage zones leaves the rock. Some of the material that is dissolved may be reprecipitated elsewhere within the cleavage zone, but the microlithons between the cleavage zones retain their original composition. Cleavage described by Glasson and Keays (1978) exemplifies this case. This cleavage, like that described in this study, is defined by zones of phyllosilicates and titanium oxides that cut
Bedding-cleavage relations

TABLE 1. AVERAGE ANALYSES OF FIVE BEDDING AND FOUR CLEAVAGE ZONES, PSAMMITIC SAMPLE, VASSALBORO FORMATION (WEIGHT PERCENT).

<table>
<thead>
<tr>
<th></th>
<th>Microlithons*</th>
<th>Cleavage zones**</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>80.85</td>
<td>70.69</td>
</tr>
<tr>
<td>K₂O</td>
<td>1.54</td>
<td>2.17</td>
</tr>
<tr>
<td>CaO</td>
<td>0.08</td>
<td>0.63</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.38</td>
<td>0.50</td>
</tr>
<tr>
<td>MnO</td>
<td>0.03</td>
<td>0.06</td>
</tr>
<tr>
<td>FeO</td>
<td>2.62</td>
<td>6.88</td>
</tr>
<tr>
<td>Na₂O</td>
<td>2.77</td>
<td>1.27</td>
</tr>
<tr>
<td>MgO</td>
<td>1.19</td>
<td>2.91</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>9.21</td>
<td>12.06</td>
</tr>
<tr>
<td>Total</td>
<td>98.66</td>
<td>96.77</td>
</tr>
</tbody>
</table>

*Each column represents the average of five spot analyses.
**Each column represents the average of four or five spot analyses.

TABLE 2. COMPARISON OF AVERAGE CLEAVAGE ZONES AND MICROLITHONS, VASSALBORO FORMATION.

<table>
<thead>
<tr>
<th></th>
<th>Cleavage (Weight percent)</th>
<th>Microlithon</th>
<th>Clvg-microlithon/ micro lithon</th>
<th>Net Change assuming immobile TiO₂</th>
<th>% Change assuming immobile TiO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>80.85</td>
<td>70.69</td>
<td>46.19</td>
<td>-70.67</td>
<td>-93</td>
</tr>
<tr>
<td>K₂O</td>
<td>1.54</td>
<td>2.17</td>
<td>1.09</td>
<td>-6.37</td>
<td>-38</td>
</tr>
<tr>
<td>CaO</td>
<td>0.08</td>
<td>0.63</td>
<td>0.11</td>
<td>-1.49</td>
<td>-65</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.38</td>
<td>0.50</td>
<td>0.43</td>
<td>-0.25</td>
<td>0</td>
</tr>
<tr>
<td>MnO</td>
<td>0.03</td>
<td>0.06</td>
<td>0.07</td>
<td>-0.03</td>
<td>-75</td>
</tr>
<tr>
<td>FeO</td>
<td>2.62</td>
<td>6.88</td>
<td>7.13</td>
<td>-3.62</td>
<td>-80</td>
</tr>
<tr>
<td>Na₂O</td>
<td>2.77</td>
<td>1.27</td>
<td>2.48</td>
<td>-2.25</td>
<td>-97</td>
</tr>
<tr>
<td>MgO</td>
<td>1.19</td>
<td>2.91</td>
<td>3.19</td>
<td>-1.42</td>
<td>-74</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>9.21</td>
<td>12.06</td>
<td>14.45</td>
<td>-6.94</td>
<td>-67</td>
</tr>
</tbody>
</table>

Net change calculations are based on the assumption that material was neither added nor removed from the microlithons. This may not be strictly true; however, for reasons outlined above, it is thought that any additions must have been minor. In the event that material in fact was transferred from the cleavage zones to the bedding zones, the net changes would be less than the maximum values calculated here.

TABLE 2 shows apparent enrichments and depletions of components in the cleavage zones relative to the microlithons. SiO₂ and Na₂O show an apparent depletion in the cleavage zones; all other components show an apparent enrichment, with TiO₂ showing the greatest apparent enrichment. It is unlikely that TiO₂ actually was added to the cleavage zones, and previous workers have demonstrated that it is immobile under a wide range of conditions (e.g. Glasson and Keays, 1978). Thus TiO₂ is assumed to have been immobile, and its apparent enrichment is attributed to passive concentration upon removal of more mobile constituents. Assuming immobility of TiO₂, net changes for the other constituents were calculated. These changes are given in column 4 of Table 2, and percent changes are given in column 5. Marked depletion of all components except TiO₂ occurred in the cleavage zones. This is consistent with the petrographic observation that quartz and feldspar, abundant phases in the microlithons, are lacking in the cleavage zones.
DISCUSSION

The petrographic and chemical observations cited above support a solution-precipitation model for the formation of the cleavage zones. The textures in these zones appear to have resulted from three processes: 1) The dissolution of quartz, feldspar, and to a lesser extent, chlorite and white mica resulted in the concentration of the remaining phyllosilicates, iron oxides, and iron-titanium oxides. This dissolution is the process of pressure solution, in which under a differential stress, there is an enhanced tendency for material from the higher stressed sides of grains to dissolve in the thin film of water found along grain boundaries (Rutter, 1976, 1978; Schmid, 1983). The dissolution is evidenced by the lack of quartz and feldspar in the cleavage zones, by the nearly equant phyllosilicate grains which abut the brown zones parallel to the rock cleavage, and by the marked depletion of all components except TiO₂ in the cleavage zones. 2) Although some of this dissolved material was removed from the rock, some remained to form new flake-like white mica grains and chlorite and chlorite-white mica grains which are elongate perpendicular to their (001) planes. This is evidenced by the different habits of the phyllosilicate grains in the cleavage zones compared to the microlithons. The blocky shape of the grains in the cleavage zones results from a combination of shortening perpendicular to the trace of the cleavage zone caused by solution and grain growth parallel to the trace of the cleavage zone caused by precipitation. 3) Recrystallization of preexisting micas occurred in both the cleavage zones and microlithons as a response to the temperatures and pressures of regional metamorphism. Evidence for this is the absence of any bent or deformed grains.

Evidence for any rotation of grains may have been masked by the metamorphic recrystallization. Certainly bedding has been transposed toward the cleavage direction near the cleavage zones (Fig. 1), and there must have been collapse of sedimentary structures upon dissolution and removal of large volumes of material from the cleavage zones. Additional disruption would have occurred if unequal volumes of material were removed from adjacent pelitic and psammitic layers, as seems likely (Steuer and Platt, 1980). This collapse could have caused the rotation of platy phyllosilicate grains into the cleavage direction. However, the existence of relatively coarse, early-formed chlorite crystals lying at high angles to the cleavage zones and which were affected by the cleavage-forming processes, argues against rotation as a significant factor in these rocks.

Several other workers (e.g. Bell, 1978; Woodland, 1982) have invoked a combination of dissolution and new grain growth to explain the formation of discrete cleavage zones. In particular, the works of Glasson and Keays (1978) and Stephens et al. (1979) are relevant to this study. They postulate a similar sequence of chemical reactions to explain the development of cleavage zones in a sequence of sandstones, siltstones, and graywackes. Marlowe and Etheridge (1977) also have called on a combination of modification of existing grains and crystallization of new ones to explain the differentiation into quartz-rich and mica-rich domains which define a crenulation cleavage.

The cleavage zones described in this study differ in the degree of phyllosilicate preferred orientation from many of the spaced cleavages found elsewhere. The white mica grains in the cleavage zones described here have a tendency to lie with their (001) planes parallel to the rock cleavage, but white mica also lies in off-cleavage orientations. This is in contrast to cleavage zones in, for example, the Martinsburg Formation of Pennsylvania. Transmission electron microscopy confirms that the white mica grains in the cleavage zones of the Martinsburg Formation have a strong preferred orientation parallel to the rock cleavage (Lincoln, 1980, 1985). In other respects, these two cleavages are similar and are believed to have formed by the same processes. These processes are driven by stress and by such chemical factors as partial pressure of fluids and temperature gradients (Marlowe and Etheridge, 1977; Stephens et al., 1979; Piqué, 1982). It is possible that in these samples from the Vassalboro Formation the chemical factors played a greater role, while in the Martinsburg Formation the stress was more important, resulting in the differences in preferred orientation.

The original composition of the rock influenced the development of the cleavage. As noted earlier, the cleavage zones in the psammitic layers are farther apart than those in the pelitic layers, although individual zones are wider in the psammitic layers than are their counterparts in the pelitic layers. Robin (1979) states that micas promote silica diffusion. This is in accord with the above observation that the cleavage zones are better developed in mica-rich than in mica-poor layers. It is possible that the cleavage zones began to develop first in portions of the pelitic layers with higher concentrations of white mica.

CONCLUSIONS

The textures in this suite from the Vassalboro Formation provide evidence bearing on the origin of spaced cleavage. The cleavage zones contain a different mineral assemblage than do the intervening zones. The cleavage zones consist of phyllosilicate grains and opaque material and lack quartz, which is an important constituent of these rocks in their uncleaved state. It is assumed in this study that the microlithons are close in composition to the whole rock prior to cleavage development. The process of cleavage development created the differences between the cleavage zones and the microlithons.

Textures observed in this study provide evidence bearing on the nature of this process. The lack of quartz in the cleavage zones and the presence of truncated white mica and chlorite grains evidence the complete or partial dissolution of these minerals. Dissolution occurred along planes parallel to the cleavage zones, and also perpendicular to the maximum shortening direction in these rocks. As a consequence of this dissolution, relatively insoluble material, such as iron oxides, was concentrated.

Along with dissolution, crystallization of new grains occurred.
The shapes of the chlorite and chlorite-white mica grains in the cleavage zones suggest that these grains underwent what might be termed classic pressure solution, dissolving along planes parallel to the cleavage zones and growing along planes perpendicular to these zones. There was also the growth of some new platy white mica grains. Studies of similar zones in other rocks have shown this new white mica to have a different composition than the preexisting white mica (e.g. Stephens et al., 1979), whereas studies of still other rocks have shown no difference in composition between the two populations (e.g. Gray, 1977). Accompanying this crystallization was metamorphic recrystallization due to the temperatures and pressures of regional metamorphism.

The cleavage is better developed and more penetrative in the more pelitic portions of the samples than in the more psammitic. This suggests that original composition is important in cleavage development.

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REFERENCES CITED


Sorby, H. C., 1856a, On slaty cleavage, as exhibited in the Devonian limestones of Devonshire: Phil. Mag. and Jour. of Sci., 4th Ser., v. 11, p. 20-37.


