PRESSURE SOLUTION AND CLEAVAGE DEVELOPMENT IN THE BARABOO QUARTZITE

by

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ABSTRACT

This study demonstrates two main points. The first is that the shape of the quartz grains makes a significant contribution to the development of penetrative cleavage in both quartzite and phyllite. The second is that the penetrative cleavage becomes more defined and the spaced cleavage becomes more common with increasing phyllosilicate content. Samples from two localities on the south limb of the Baraboo Syncline were sectioned at right angles to the bedding cleavage intersection. The length to width ratio of the quartz grains and the orientation of the long axes were recorded as a function of the phyllosilicate content. The spacing of the spaced cleavage was also measured as a function of the phyllosilicate content. In quartz-rich horizons the grains have low axial ratios and exhibit a long-axis orientation close to bedding. With increasing phyllosilicate content the axial ratio increases and a long-axis orientation distinct from bedding is observed. The latter is parallel to the spaced cleavage where this is present. The long axes of the grains and the spaced cleavage both curve toward the bedding (refraction) as the phyllosilicate content increases, and the distinction between bedding parallel orientation and cleavage parallel orientation of the quartz grains becomes difficult to measure.

In an analogy with the development of pressure solution in sedimentary rock it is suggested that the increase in the length to width ratio of quartz grains and the spacing of spaced cleavage with the increase in phyllosilicate content supports the origin of the cleavage by pressure solution. The presence of truncated grains, pressure shadows, and interpenetrative grains provides additional support. The concentration of sulphide and zircon in the spaced cleavage planes suggests that they too are related to a process of selective solution transfer.

INTRODUCTION

The Baraboo Quartzite of Wisconsin is a relatively small outcrop of Proterozoic quartzite deposited sometime between 1,760 Ma and 1,630 Ma (Van Schmus and Bickford, 1981). It is isolated from other Proterozoic rocks by Paleozoic cover (fig. 1). Correlation, age relationships, and tectonic setting of the quartzite are obscure, but the structures have been of interest for geologists since the last century (Van Hise, 1893). The descriptive classification of cleavages into slaty, fracture and strain slip (penetrative, spaced and crenulation cleavage in modern usage) was well demonstrated here, and continued investigations have attempted to determine the mechanism of cleavage formation using rock from this locality (Dalziel and Dott, 1970; Dalziel and Stirewalt, 1975). The cleavage investigated in this study consists of a penetrative structure controlled by tectonically flattened quartz grains and aligned phyllosilicates, S_1' (Dalziel and Dott, 1970) and a spaced cleavage, often referred to as a fracture cleavage (Irving, 1877; Steidtman, 1910; Leith, 1913, 1923) which consists of closely spaced, but nonetheless discrete, surfaces formed by concentrations of aligned phyllosilicates (S_1' of Dalziel and Dott, 1970). The phyllosilicates consist of pyrophyllite and muscovite (Dalziel and Dott, 1970).

The concept of pressure solution is an old one (Thomson, 1862a,b) and in some of the older geologic literature it was referred to as the Riecke Principle (Riecke, 1912). Sorby applied the concept of pressure solution to several of his geologic observations. His studies still form the basis of many of the more modern concepts (Sorby, 1879; Kerrich, 1977). In general, it is thought that a body of rock in a state of non-hydrostatic stress will preferentially undergo solution on surfaces normal to the maximum principle stress direction (σ_1) even without precipitation of the dissolved material on the surfaces of the grains which are normal to the minimum principle stress direction (σ_3); the grains would tend to become more elongate in the σ_3 direction (fig. 2). If precipitation does occur, then the effect is enhanced and structures which are commonly called pressure shadows are formed (fig. 2). Such a mechanism could be responsible for the development of penetrative cleavage in a variety of lithologies. While it is a theoretically sound mechanism it is difficult to test its role in a natural situation. An alternative mechanism might be termed strain solution. As stress builds up at the grain contacts normal to the σ_1 direction, the points of contact will become regions of potentially high strain. If the strain is in the form of increased dislocation density, then the potential for an increased rate of dissolution exists at these points. The two mechanisms could be distinguished by using the transmission electron microscope to look for the distribution of dislocations. However, the dislocations have

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a tendency to anneal and recrystallize under the conditions thought to exist during metamorphism. There is also the possibility that the grain shape variation may be due to homogeneous distortion of the grains. It would be hard to explain the increase in the axial ratio of the grains in areas of high phyllosilicate content if this were the case. The correlation between grain shape and phyllosilicate content and spacing of spaced cleavage and phyllosilicate content suggests to us that pressure solution has played an important role in the production of spaced and penetrative cleavage in the Baraboo Quartzite.

It has been proposed that the presence of clay minerals increases the potential for pressure solution (Heald, 1956; Weyl, 1959; Thompson, 1959; Greseno, 1966; Durney, 1972b; Sibley and Blatt, 1975; Kerrich and others, 1975; Bosworth, 1981). These authors based their ideas on petrographic observations of the concentration of clay minerals in rock containing structures which they thought might be formed by pressure solution. The theoretical basis for the observations is difficult to test but several suggestions have been made. It is generally thought that the migration of the dissolved components is the rate controlling factor in the process. With this in mind it has been proposed that the presence of clay films might provide pathways for transport (Weyl, 1959; Sibley and Blatt, 1975). Clay could also be responsible for local chemical variations such as a high pH (Thompson, 1959) or act as catalysts (Heald, 1956). Hydrolytic weakening of quartz as a result of the water associated with the clay has also been suggested (Weyl, 1959; Jones, 1975; Hobbs, 1981). A good review of the role of pressure solution in geologic processes can be found in Kerrich (1977).

The association of pressure solution with phyllosilicate and the development of cleavage in greenschist-facies metamorphic rock is the focus of this paper. The length to width ratio and the orientation of the long axes of the phyllosilicate were recorded together with the phyllosilicate content. In addition the spacing of the spaced cleavage was recorded. The hypothesis to be tested is that if pressure solution is a function of phyllosilicate content then the length to width ratios should increase, the long axis orientation should become better defined, and the spaced cleaving should become more dense with an increase in phyllosilicate content. The success of this test does not mean that pressure solution is the operative mechanism, only that it could be under the conditions described here.

There are petrographic features which also suggest selective removal and precipitation of quartz. Quartz grains which are adjacent to the spaced cleavage bands commonly have flat margins facing the band and a more rounded shape on the side facing away from the band (fig. 3a). In the area between the spaced cleavage the quartz grains have delicate finger-like overgrowths of quartz extending from the grains in the direction of the longest dimension (fig. 3b). These pressure shadows do not extend from surfaces which are parallel to the cleavage; such surfaces tend to be smooth. Finally, there is a higher concentration of opaque minerals in the spaced-cleavage zones compared with the rest of the rock.

The data were plotted using SURFACE II GRAPHICS SYSTEM of the Kansas Geological Survey (Sampson, 1978), a licensed package of software.

PROCEDURE

Large, oriented specimens were collected from two localities--one set from the LaRue quarry (SW¼NW¼ sec. 22, T. 11 N., R. 5 E.) and the other set from an outcrop near Lake Jerdean (SW¼SW¼SE¼ sec. 15, T. 11 N., R. 5 E.) (fig. 1). The samples contain a complete cross section of a bed which grades from a phyllite at the base to a quartzite in the center and back to a phyllite at the top. The phyllitic horizons exhibit a well developed penetrative foliation lying close to the bedding. The quartzite shows a well developed spaced cleavage consisting of narrow seams of phyllosilicate which are at a high angle to the bedding in the quartz-rich parts and progressively approach parallelism with the bedding as the quartz content decreases toward the top and bottom of the layer.

Several sections were cut from each bed form in order to obtain a complete cross section of the bed. The sections were cut at right angles to the bedding-cleavage intersection. This was done on the assumption that the same cross section of the finite strain ellipsoid was being examined in each case. The Baraboo Syncline has an essentially horizontal hinge line at the localities chosen, and the bedding cleavage intersection is parallel to it. It is assumed for the purpose of this study that the sections are close to the X-Z plane of the finite-strain ellipsoid and therefore exhibit the maximum strain ratio. It is realized that this is not always the case, but the simple nature of the Baraboo Syncline justifies the assumption for the purpose of this study. A more complete three-dimensional study to determine strain variation is now underway.

Point counts were made on each thin section to determine the ratio of quartz to phyllosilicate (1000 points per section). In addition the length to width ratio of the quartz grains was measured together with the orientation of the long axis (150 grains per section). The spacing of the spaced cleavages was measured for the same specimens. These results are plotted on figures 4 through 13. Sixteen samples were measured; for consideration of space only eight are shown in detail on figures 6 through 13. The interchange of stress and strain terms does not mean that we have proved any geometric similarities; on the other hand, we were not able to define any differences.

RESULTS AND CONCLUSIONS

The simplest measurement to make is the spacing of the spaced cleavage as a function of lithology. It is obvious in the field that the spaced cleavage is less common in the quartz-rich centers of the beds than in the phyllitic margins. Although there is a wide spread in the data, the spaced cleavage in the LaRue quarry varies from zero to five per centimetre over the range of phyllosilicate content recorded (fig. 4) with a correlation coefficient of 0.709 ($p<0.01$, df = 74). Fewer measurements were made at Lake Jerdean but a similar trend was found with a correlation coefficient of 0.894 ($p<0.01$, dfn= 7) (fig. 4b). The spaced cleavage consists of phyllosilicate seams varying in width from 0.1 to 1 millimetre. Concentrations of opaque and heavy minerals are found in these seams. This last mentioned feature is independent evidence in support of the idea of pressure solution. It is proposed that the quartz has been selectively removed during deformation leaving behind the phyllosilicate, the opaque and heavy minerals. This process was more effective in the phyllosilicate-rich horizons for reasons outlined in the introduction.

The shape of the quartz grains shows a progressive increase in length to width ratio with increasing phyllosilicate content (fig. 5). The long axes of the quartz grains change from a bedding-parallel orientation to one which becomes increasingly parallel to that of the spaced cleavage. It is interesting to note that it is still common in introductory books to state that penetrative (slaty) cleavage is only common in rocks rich in phyllosilicates and is due to the alignment of the phyllosilicate cleavage (Press and Siever, 1982). This study clearly shows that the shape of the quartz grains makes a major contribution to the penetrative cleavage in the Baraboo Quartzite. The easiest way to represent these results is by plotting the axial ratio against the orientation of the long axis with respect to bedding (figs. 6b through 13b) and the

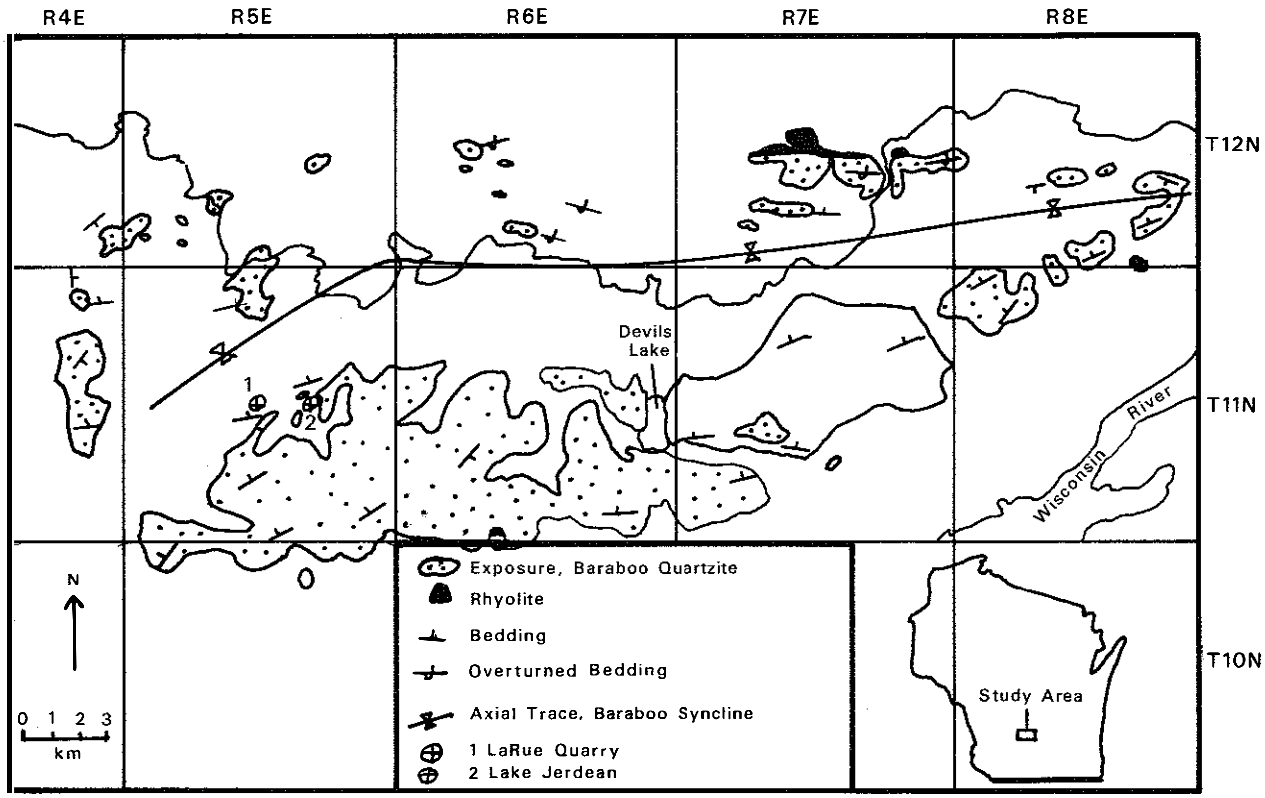


Figure 1.--Map of Baraboo Quartzite (after Dalziel and Dott, 1970).

frequency of a given angular relationship (fig. 5a through 12b). The series of block diagrams (figs. 6c through 13c) show the same data in pictorial form. On each diagram bedding is the 0° orientation for reference. The series of thin sections representing the LaRue quarry show that for a low phyllosilicate content, 5.8 percent, there is a strong concentration of long axes parallel to the bedding (fig. 6a). The plot of the distribution of axial ratios as a function of orientation shows that there is a broad distribution of grains with axial ratios between 1 (circular) and 2, and that there is a small maximum of grains with larger axial ratios close to the bedding orientation (fig. 6b). The main features of this sample are grains with low axial ratios, a preferred orientation of long axes in the bedding plane, and a tendency for the more elongate grains to lie in the bedding plane. The specimen containing 38.6 percent phyllosilicate shows a concentration of long axes distinct from the bedding orientation (fig. 7a). The ratioplot (fig. 7b) illustrates the change in orientation of the long axes and the increase in axial ratio of grains with this orientation. In addition, the mean orientation of the spaced cleavage and its range are plotted. It can be seen that the spaced cleavage and the orientation of the long axes of the quartz grains have similar trends. These observations are further illustrated in the block diagram (fig. 7c). The specimen with 47.7 percent phyllosilicate (fig. 8) shows a more distinct concentration of quartz-grain long axes separate from the bedding and again subparallel to the spaced cleavage. The increase in axial ratio of grains with this orientation is also more clearly defined. The specimen with the highest phyllosilicate content at the LaRue Quarry, 70.6 percent (fig. 9) shows the largest axial ratios. The orientation of quartz-grain long axes still shows a distinct maximum parallel to the spaced cleavage. However, because of the refraction of the cleavage, the bedding and cleavage are almost parallel at this point. The samples analyzed from the Lake Jerdean locality were taken from one large specimen. They show the same pattern of quartz-grain long-axis orientations and axial ratios in relation to the bedding and spaced cleavage. The sample with the lowest phyllosilicate content, 27.5 percent, shows a broad distribution of long axes and low ratios (fig. 10). There is a weak maximum close to, but not parallel to, the bedding. There is also a well developed spaced cleavage in the specimen almost at right angles to bedding. The section containing 38.1 percent phyllosilicate (fig. 11) shows a marked change; there

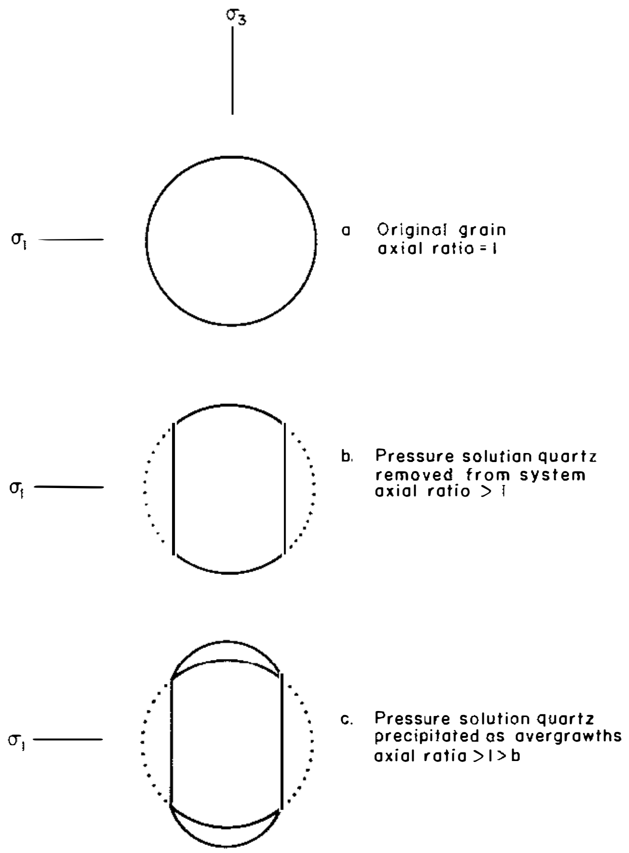


Figure 2.--Effect of pressure solution when quartz is removed from the system (b) or stays within the system (c).

is a concentration of long axes parallel to the spaced cleavage and an increase in axial ratio of grains with this orientation. In the sample containing 56.1 percent phyllosilicate (fig. 12) the maximum orientation of the grains with the largest axial ratio is still parallel to the spaced cleavage though the pattern is more diffuse. At the margins of the bed where the phyllosilicate content reaches 84.0 percent (fig. 13), the axial ratios show a further increase with a strong concentration of the long axes parallel to the spaced cleavage which at this point has been refracted so that it lies close to the bedding.

The main conclusions are that both the penetrative and the spaced cleavages in the Baraboo Quartzite become stronger with increasing phyllosilicate content (fig. 4 and fig. 5). This supports the concept of pressure solution as a mechanism for the origin of both cleavages by analogy with the studies of pressure solution in sedimentary rock. The penetrative cleavage is formed by a mixture of quartz grain-shape and phyllosilicate cleavage orientation. The spaced cleavage is

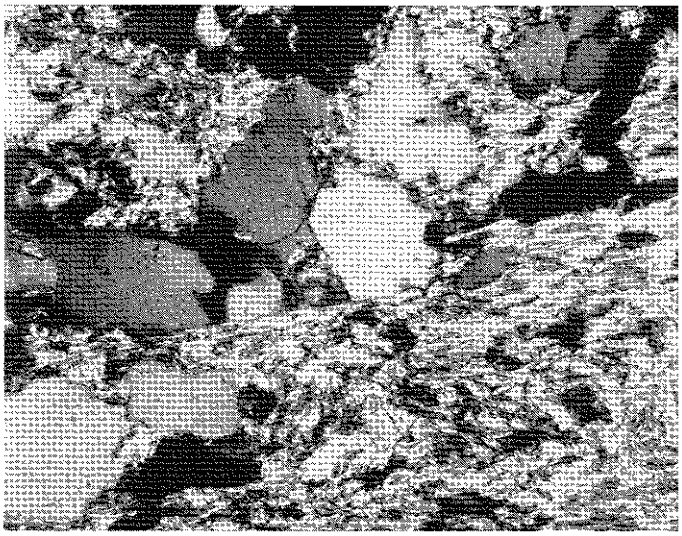


Figure 3a.--Straight-sided quartz grains abutting against spaced cleavage surface (lower left of photo). Note the irregular surfaces on parts of quartz grains not abutting against the spaced cleavage. (magnification x 160).

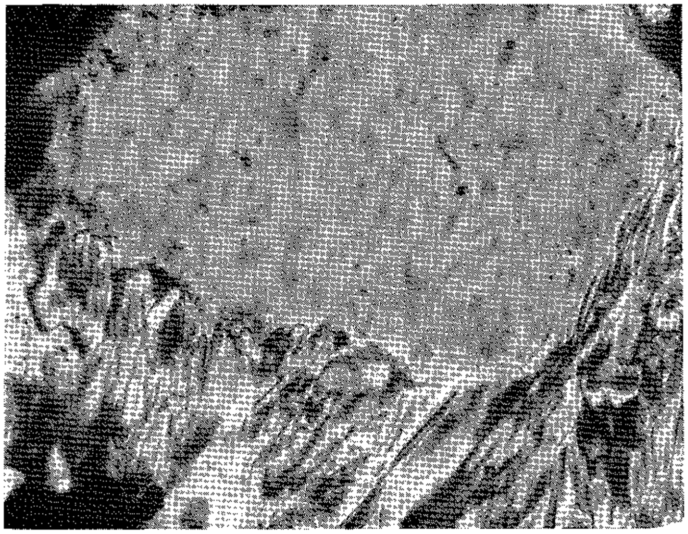


Figure 3b.--Fine overgrowths on quartz grain running parallel to the penetrative cleavage (bottom left to top right), (magnification x 620).

formed by selective removal of quartz along bands which form at regular intervals. It also demonstrates large strain variations within a single layer. There seems to be a critical level of about 20 percent present phyllosilicate content below which no spaced cleavage forms. The penetrative cleavage formed by the elongation of the quartz grains is also difficult to detect below this level.

There remains the possibility that the phyllosilicate content we have measured is entirely due to the strain. If we are to argue that the rock has deformed by removal of quartz as a result of pressure solution, then it is equally true to state that the high strain regions will inevitably become proportionally richer in phyllosilicate. We have not attempted to resolve this dilemma in the present study. If pressure solution was an important mechanism in inducing strain in the rock, then it is possible that the phyllosilicate-rich regions developed higher strain for the reasons suggested above and that in the course of this deformation became even more phyllosilicate rich.

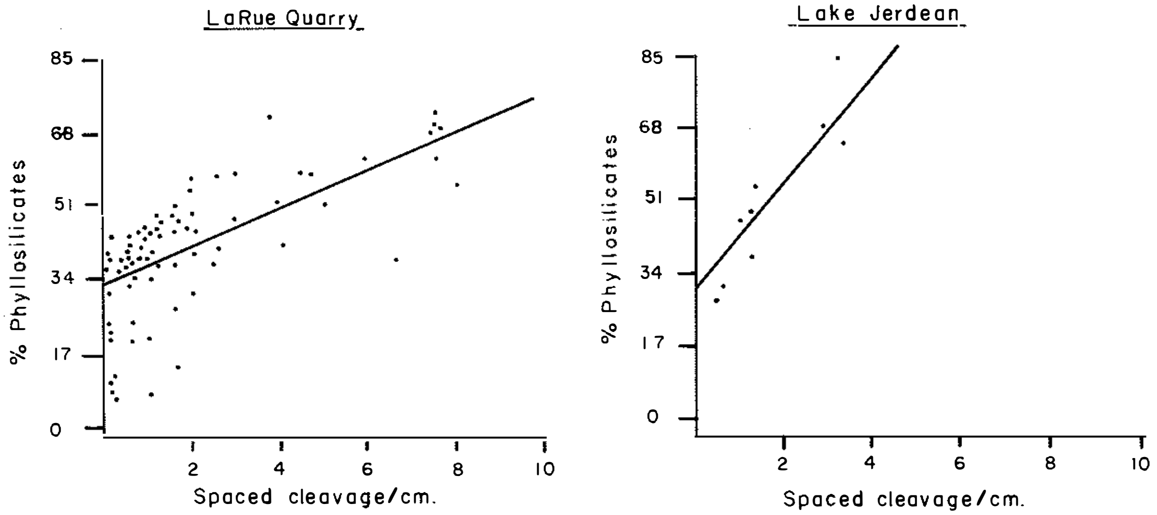


Figure 4.--Relationship between phyllosilicate content and spacing of spaced cleavage for the LaRue quarry (a) and the Lake Jerdean outcrop (b).

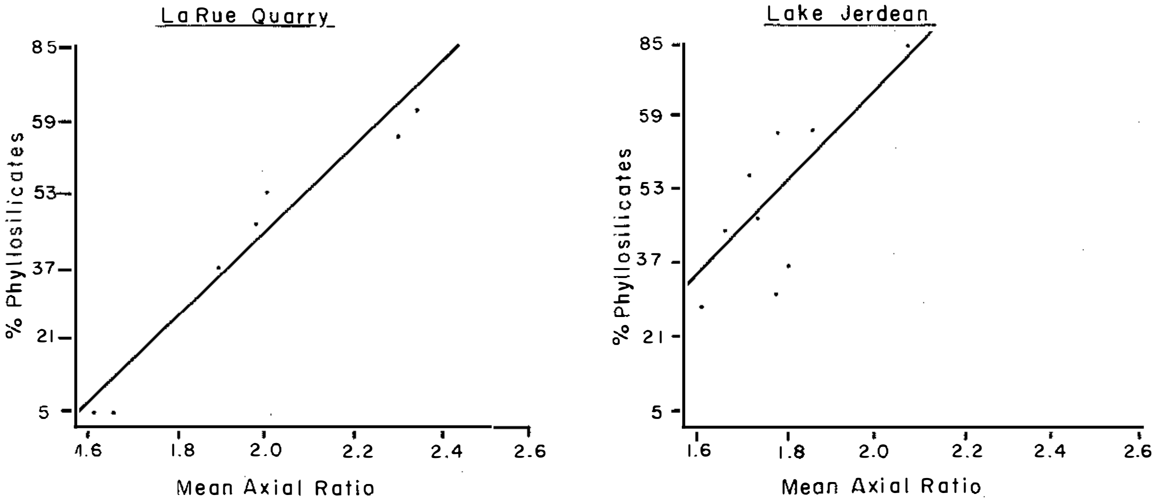


Figure 5.--The relationship between phyllosilicate content and mean axial ratio of quartz grains for the LaRue quarry (a) and the Lake Jerdean outcrop (b).

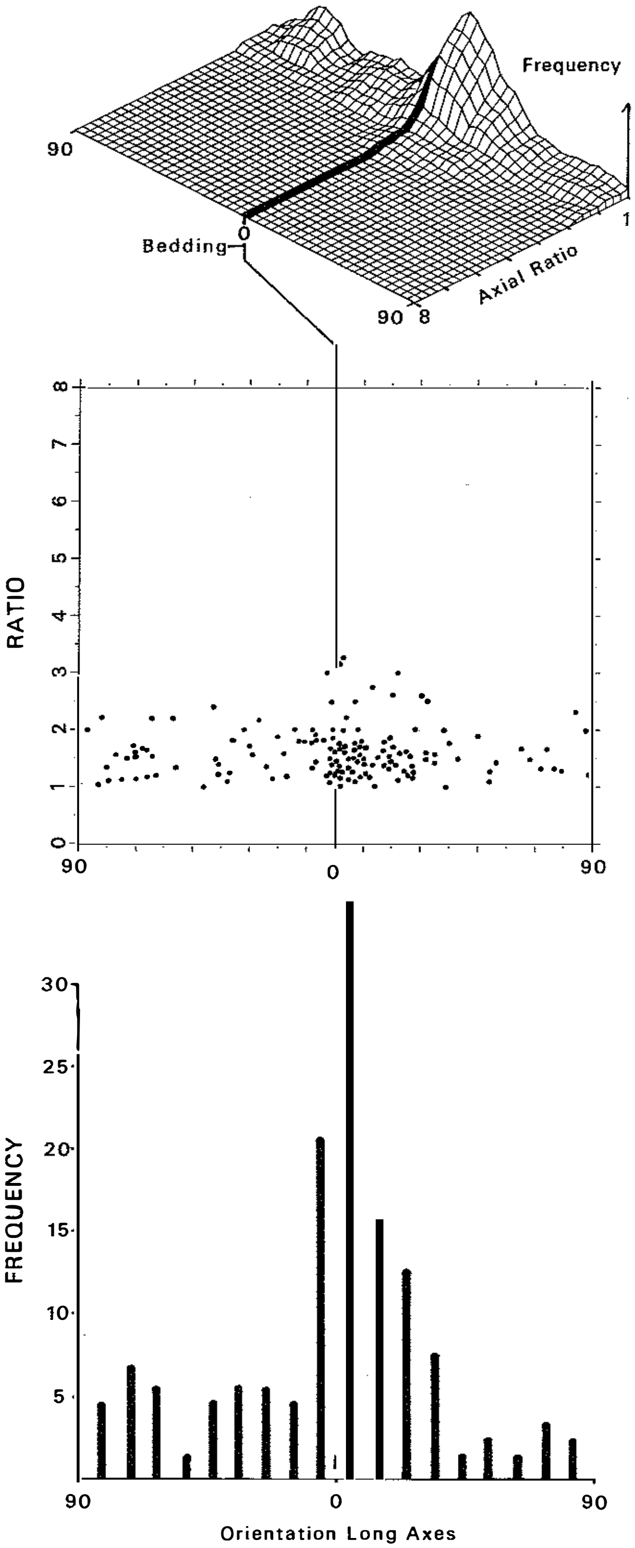


Figure 6.--Plot of axial ratio and orientation of long axis to bedding for LaRue Quarry (5.8 percent phyllosilicate): a) histogram of orientation; b) orientation to axial ratio; c) block diagram of a and b.

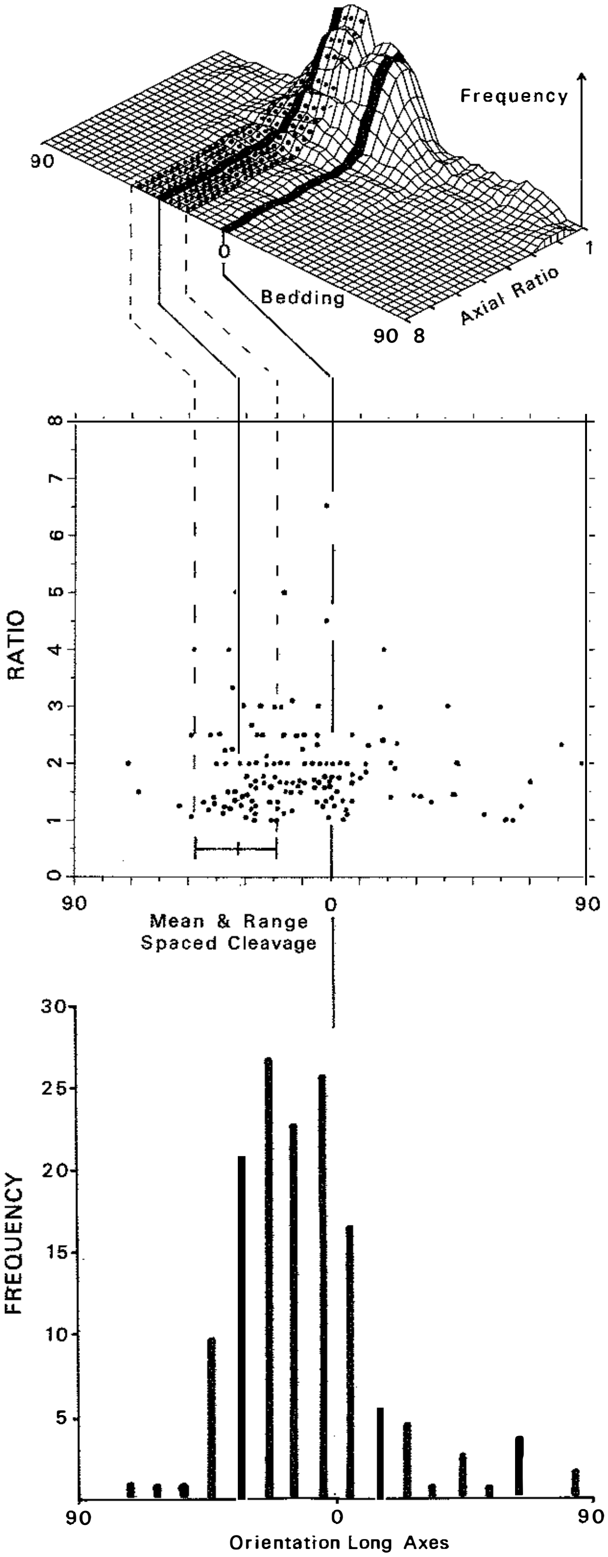


Figure 7.--Plot of axial ratio and orientation of long axis to bedding for LaRue Quarry (38.6 percent phyllosilicate): a) histogram of orientation; b) orientation to axial ratio; c) block diagram of a and b.

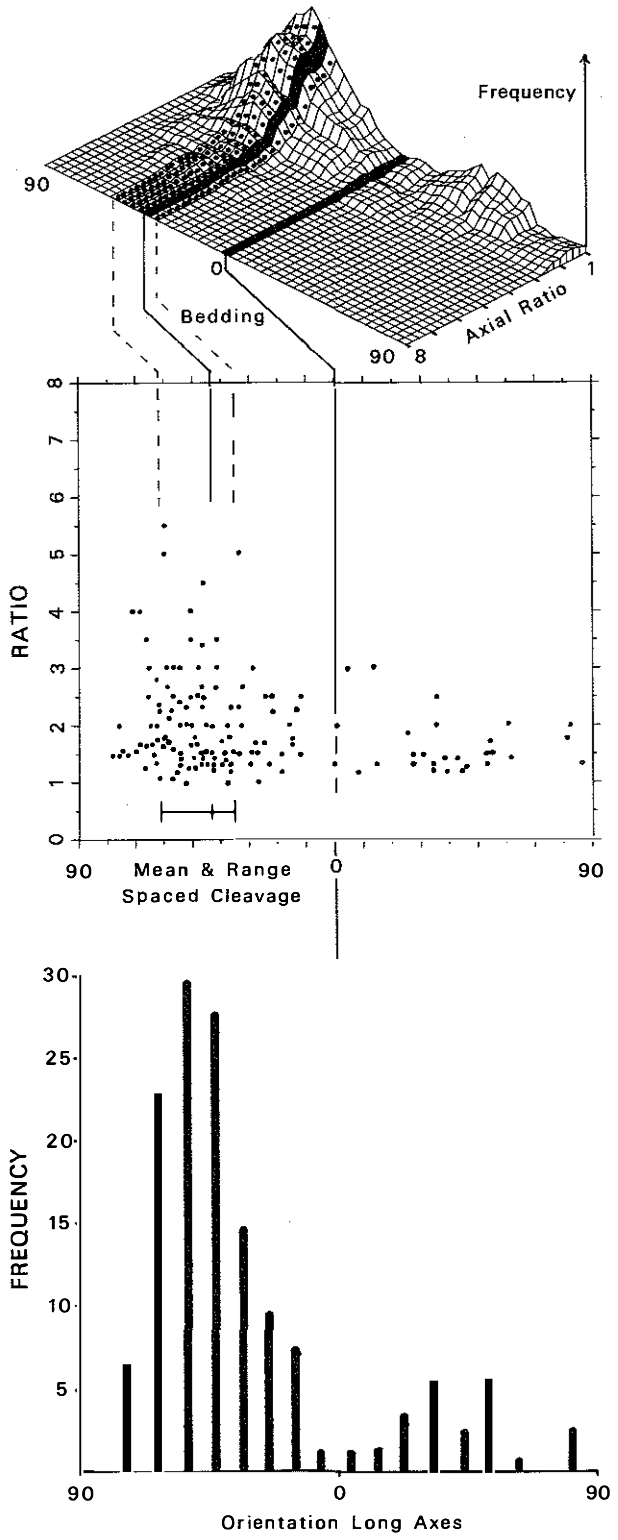


Figure 8.--Plot of axial ratio and orientation of long axis to bedding for LaRue Quarry (47.7% phyllosilicate): a) histogram of orientation; b) orientation to axial ratio; c) block diagram of a and b.

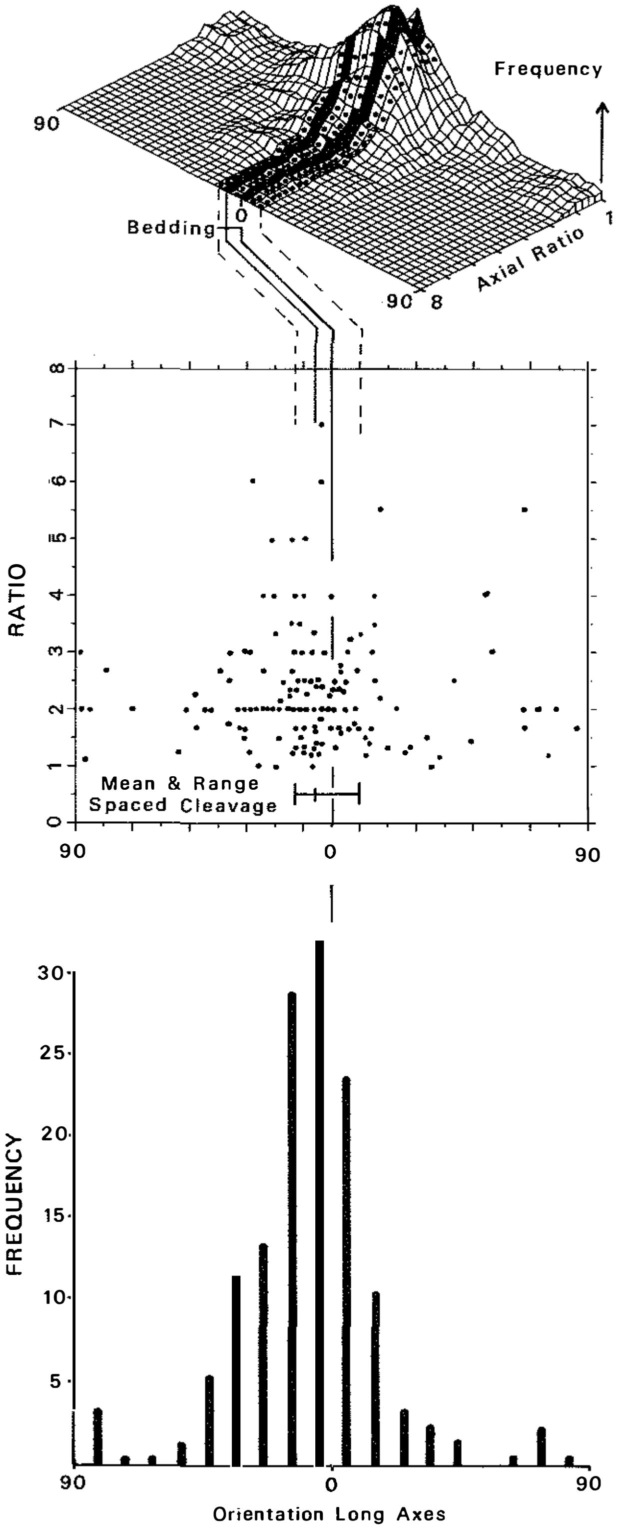
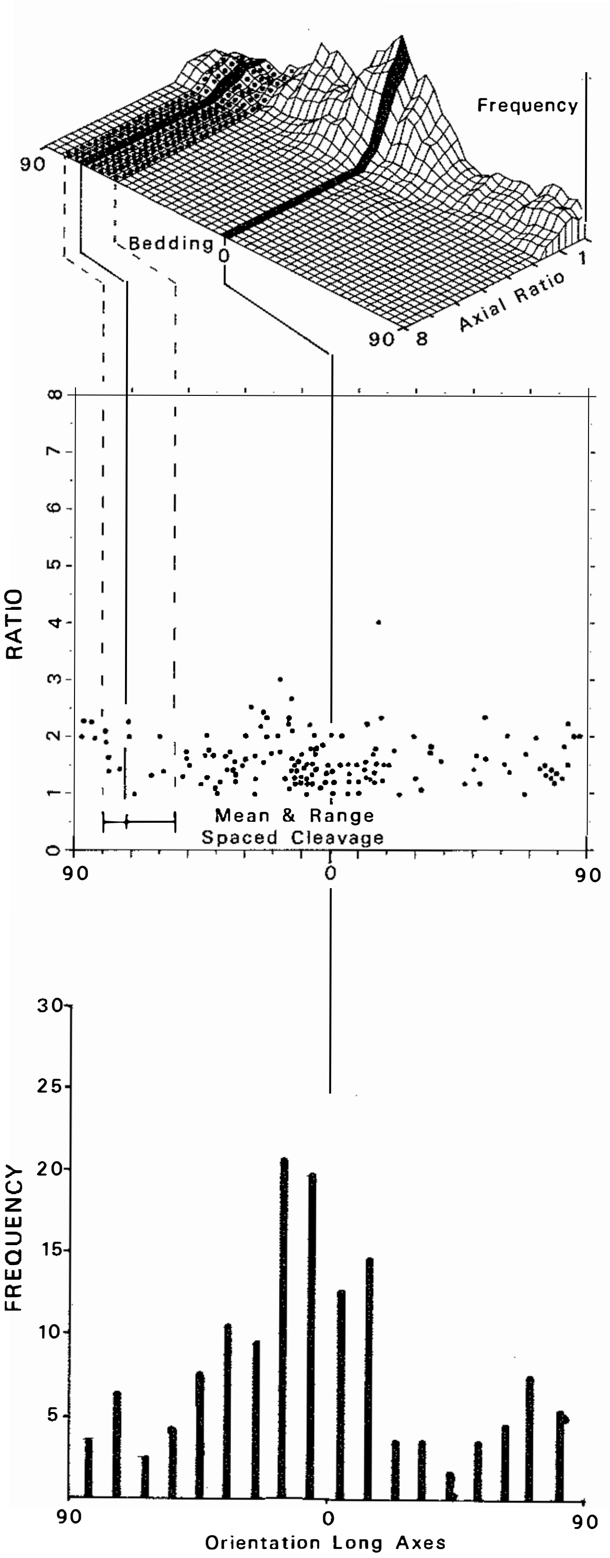


Figure 9.--Plot of axial ratio and orientation of long axis to bedding for LaRue Quarry (70.6 percent phyllosilicate): a) histogram of orientation; b) orientation to axial ratio; c) block diagram of a and b.



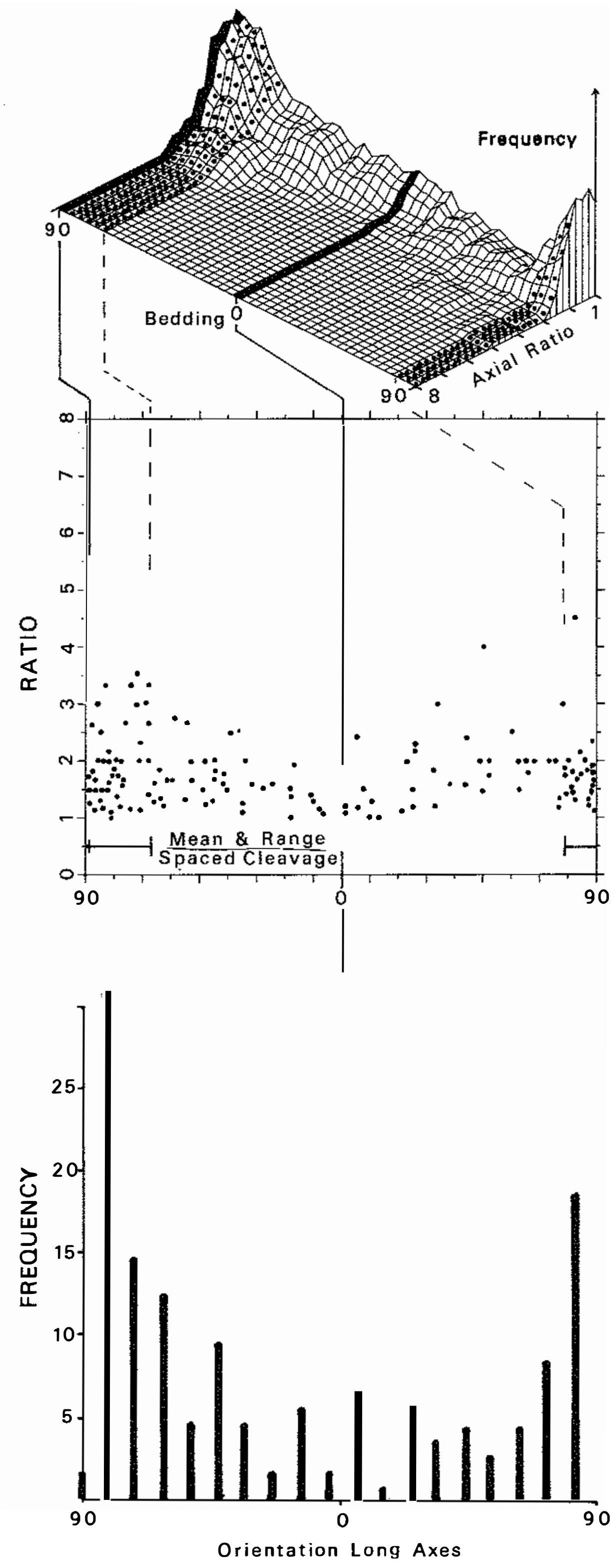


Figure 10.--Plot of axial ratio and orientation of long axis to bedding for LaRue Quarry (27.5 percent phyllosilicate): a) histogram of orientation; b) orientation to axial ratio; c) block diagram of a and b.

Figure 11.--Plot of axial ratio and orientation of long axis to bedding of LaRue Quarry (38.1 percent phyllosilicate): a) histogram of orientation; b) orientation to axial ratio; c) block diagram of a and b.

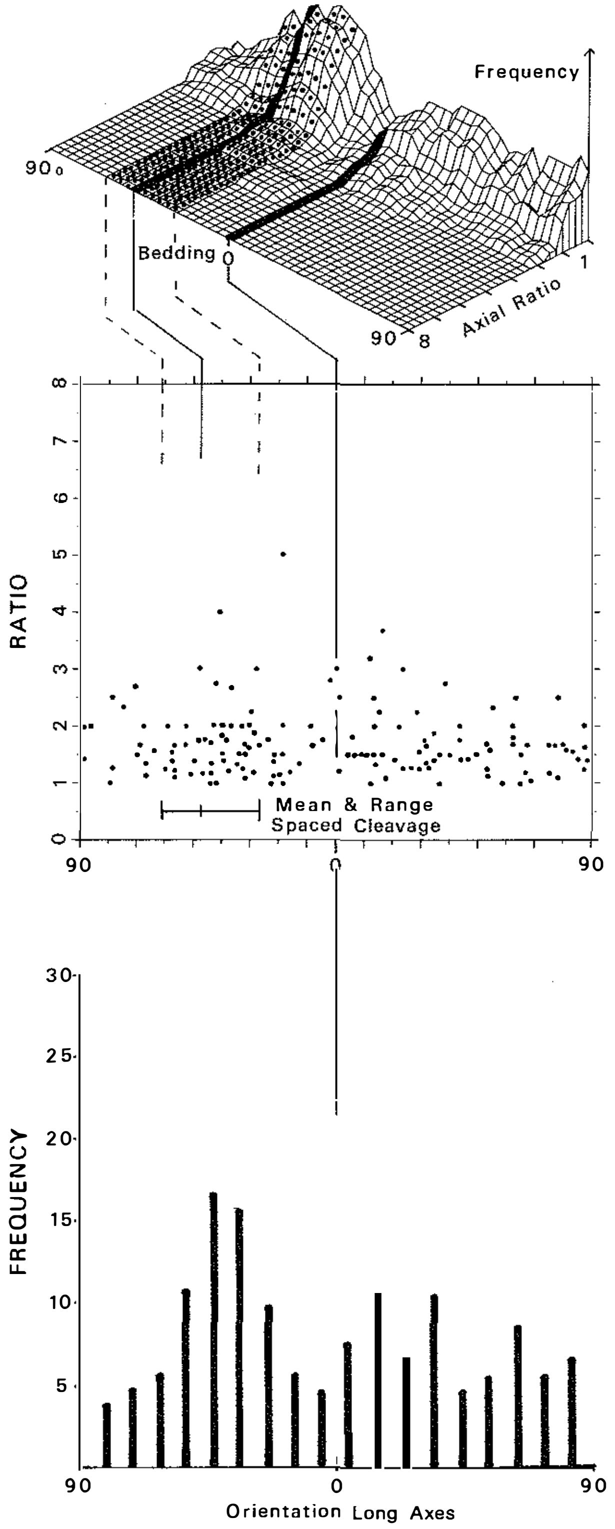


Figure 12.--Plot of axial ratio and orientation of long axis to bedding for LaRue Quarry (56.1 percent phyllosilicate): a) histogram of orientation; b) orientation to axial ratio; c) block diagram of a and b.

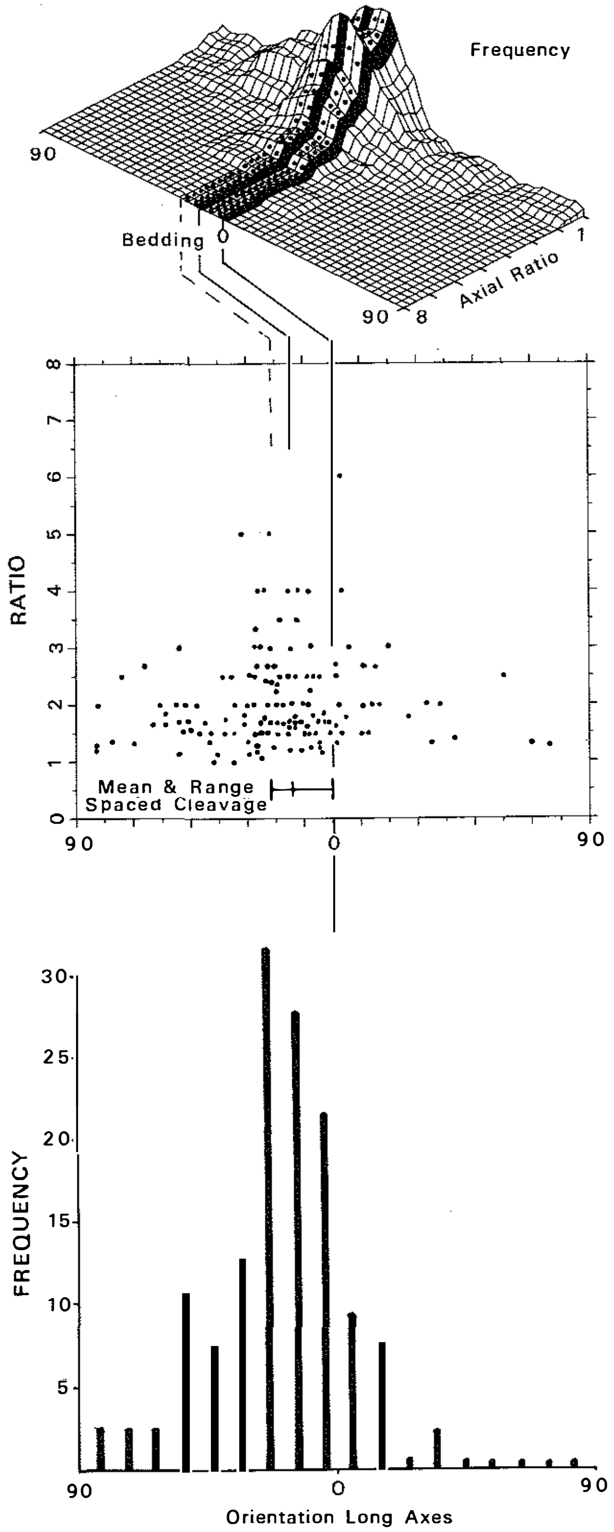


Figure 13.--Plot of axial ratio and orientation of long axis to bedding for LaRue Quarry (84.0 percent phyllosilicate): a) histogram of orientation; b) orientation to axial ratio; c) block diagram of a and b.

ACKNOWLEDGMENTS

The authors acknowledge invaluable discussions with students and faculty of the Department of Geological Sciences at MSU. In particular, one of us (FWC) would like to express thanks to Bill Monaghan for writing a computer program which made it possible to produce the block diagrams, and to John Wilband for general help in data reduction.

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