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Static recrystallization and preferred orientation of phyllosilicates: Michigamme Formation, northern Michigan, USA

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Abstract

The Michigamme Formation of the Marquette District in Michigan's Upper Peninsula comprises a sequence of cleaved rocks of increasing metamorphic grade. Because metamorphism in the area occurred after cleavage formation, the rocks provide an opportunity to study preferred orientation development of phyllosilicates under conditions of static recrystallization.

X-ray texture goniometry on samples from the greenschist-facies zone that were collected at varying distances from the bounding biotite-in and garnet-in isograds, shows that: (1) the preferred orientation of phyllosilicates is always parallel to the mesoscopic cleavage, and (2) the degree of preferred orientation of phyllosilicates improves as a function of increasing metamorphic grade (from <4 to >9 m.r.d.). Scanning electron microscopy on these samples shows that: (1) the length/width ratio increases with increasing grade, and (2) grain shapes are better defined with increasing grade.

Previous work on slates showed mechanical processes dominate at very low-grade metamorphism, whereas chemical processes are favored at higher grades. The Michigamme samples show that improvement of preferred orientation occurrred by grain dissolution and crystallization. Noncleavage-parallel phyllosilicate grains were preferentially dissolved, probably facilitated by internal strain energy from mineral defects, aided by chemical energy, whereas cleavage-parallel phyllosilicates were hosts for new growth along their basal planes. These results show that significant fabric strengthening can be achieved by grain dissolution and crystallization in the absence of tectonic stress.

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1. Introduction

In a burial/diagenetic environment, like that of the Gulf Coast of southern North America, the development of (bedding-parallel) preferred orientation of phyllosilicates is largely affected by the mineralogical transformation from imperfect, wavy smectite layers to straight, defect-free illite packets (Ho et al., 1999). As clay-rich sediments undergo very low-grade metamorphism in the presence of tectonic stress, the orientations of phyllosilicates are modified by the effects of temperature and strain, resulting in the formation of a cleavage; however, different phyllosilicate populations in these deformed rocks behave differently. Large (tens of μm) grains of detrital to early diagenetic origin display evidence for mechanical deformation processes such as grain rotation and kinking. Authigenic, fine-grained (tens of nm) phyllosilicates are primarily affected by chemical processes such as grain dissolution and new growth (Ho et al., 1996). Our studies in contrasting geologic environments show that mechanical processes are favored at very low metamorphic grade and low strain, whereas chemical processes are favored in relatively high-grade and high-strain environments (van der Pluijm et al., 1998). This suggests that the dominant slaty cleavage forming mechanism is a function of the combined effects of thermal and strain energy in rocks. The contribution of either source to the total energy of the system is complementary and fully interchangeable, with chemical processes favored at higher temperature and/or higher strain.

At low-grade metamorphic conditions (greenschist facies), phyllosilicate-rich rocks typically show changes in mineral assemblage, and new foliations may form in response to the presence of tectonic stress (dynamic recrystallization). However, the behavior of phyllosilicates under conditions where metamorphism postdates foliation development (static recrystallization) is poorly known. This study of slates in northern Michigan was designed to examine changes in microstructure and preferred orientation of phyllosilicates at greenschist facies metamorphic conditions in an area where the last metamorphism postdates regional cleavage development, representing conditions of static recrystallization.

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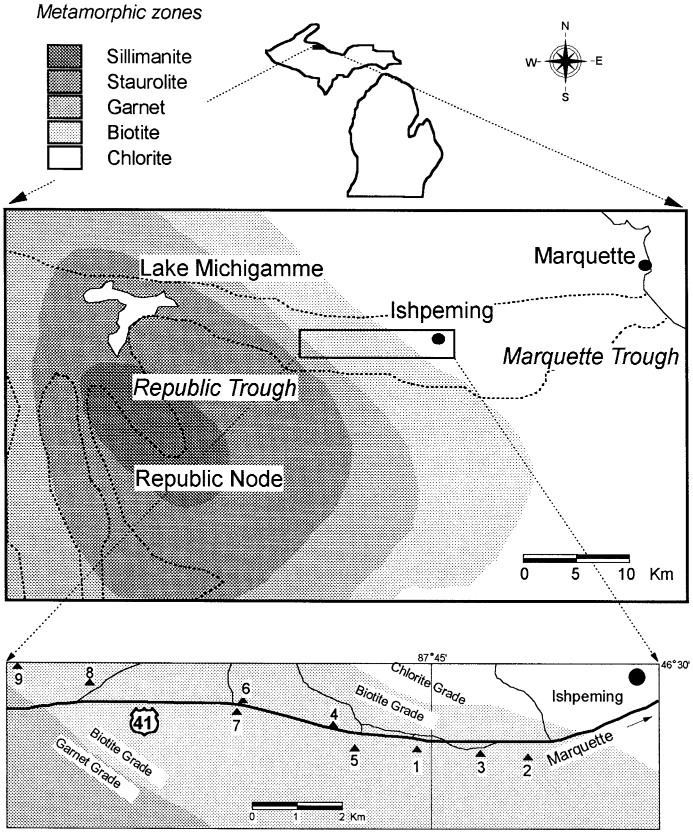


Fig. 1. Metamorphism of the Marquette District of northern Michigan, and locations of samples collected for this study. The dotted line on the metamorphic map indicates the boundary of metasedimentary rocks (after James, 1955).

2. Geological setting and sample collection

The study area is located in the Marquette District of Michigan's Upper Peninsula (Fig. 1). The Marquette District, extending from south of Marquette at Lake Superior to west of Lake Michigamme, is part of the east–west trending Marquette Trough and contains deformed and metamorphosed Early Proterozoic sedimentary and volcanic rocks (Gair and Thaden, 1968; Cambray, 1977, 1978). These metasedimentary rocks are collectively named the Marquette Supergroup, and are thought to have been deposited on a passive continental margin before 1.85 Ga (Barovich et al., 1989). The deformation and metamorphism preserved today are the results of several deformation events and at least one metamorphic event during the Penokean orogeny (approximately 1.9–1.7 Ga; Klasner et al., 1988; Barovich et al., 1989).

The Marquette Supergroup is divided, from older to younger, into the Chocolay, Menominee and Baraga Groups (Cannon and Gair, 1970). Samples collected for this study belong to the Michigamme Formation (also known as the Michigamme Slate) in the bottom part of the Baraga Group, which is interpreted as a deep-water sequence with turbidites and mafic volcanic rocks. The regional cleavage in the Michigamme Formation is believed to have formed in the first stage of deformation of the Penokean Orogeny (e.g., Klasner et al., 1988; Stahl et al., 1988). Metamorphic isograds in the area are centered around the Republic node (Fig. 1), one of four metamorphic aureoles originally identified by James (1955) in northern Michigan and northern Wisconsin. These nodes are delineated by chlorite, biotite, garnet, staurolite and sillimanite isograds. The detailed relation between deformation events and regional metamorphic events has been under some debate. Early studies suggested that metamorphism postdates all deformation events (e.g., James, 1955; Powell, 1969, 1972), although, later studies (e.g., Klasner, 1978) suggested that

Table 1
Sample IDs and locations, and bedding/cleavage orientations (strike/dip)

Sample ID	Field ID	Bedding	Cleavage	Reference[a]	Distance[b]
1	UP-4	12/85E	276/80N	C	2.5
2	UP-1	270/60N	320/70N	B	3
3	UP-2	20/50S	10/30W	C	3.5
4	UP-8	N/A	291/76N	C	5.5
5	UP-7	20/85E	108/75N	C	6
6	UP-5	242/38S	308/90	C	8
7	UP-6	242/38S	308/90	B	8.1
8	UP-10	264/60N	336/60W	C	12.7
9	UP-9	300/60N	306/80S	C	14.5

[a] C: cleavage; B: bedding.

[b] Distance from biotite/chlorite (biotite-in) isograd (km).

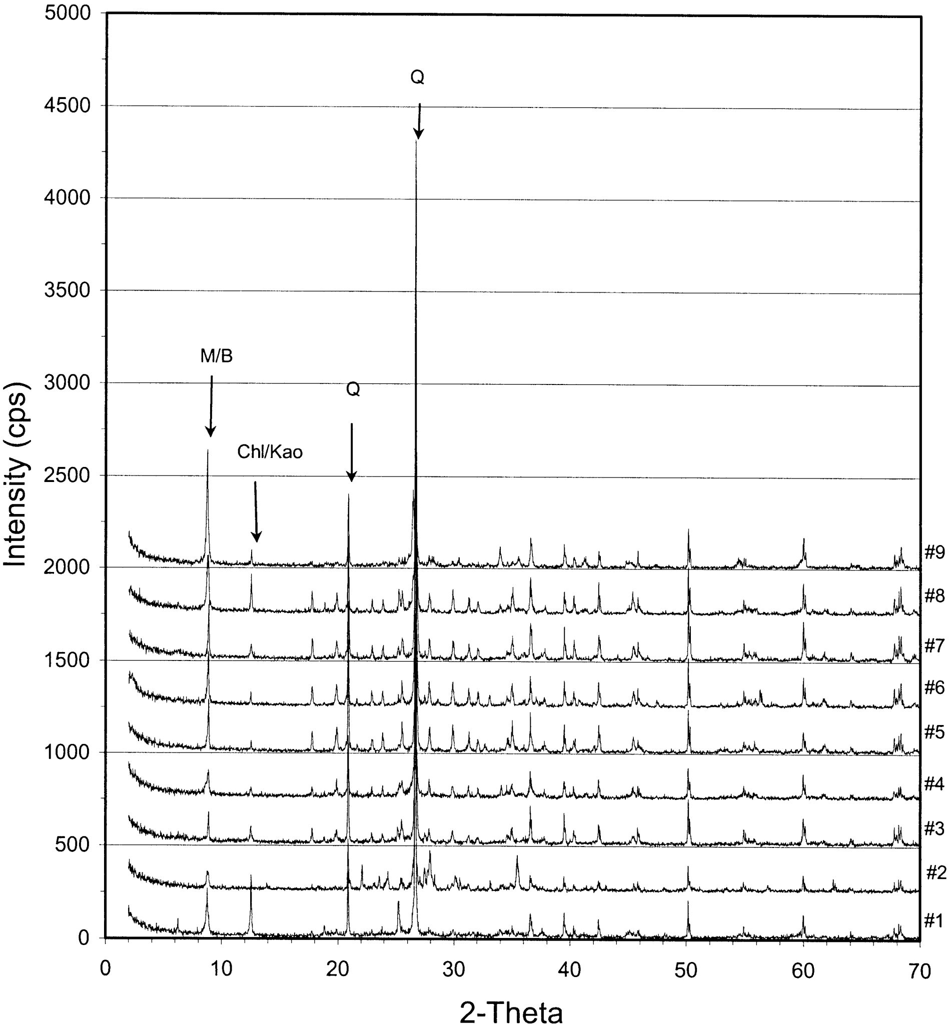


Fig. 2. Representative bulk powder X-ray diffraction data for all samples. Data are stacked with increasing distance from the biotite-in isograd, corresponding to a relative increase in metamorphic grade. Curves are plotted on the same vertical scale but offset by 250 cps for clarity. Labeled peaks are from: muscovite (M), biotite (B), chlorite (Chl), kaolinite (Kao) and quartz (Q).

metamorphism may have started immediately after the first deformation event, and reached a peak during the later stage of the uplift of the Lower Precambrian basement. Although the exact timing of metamorphism is not clear, all workers agree that the formation of the regional cleavage predates final metamorphism (e.g., Klasner et al., 1988; Stahl et al., 1988; Matty et al., 1990). Based on this temporal relationship between cleavage formation and metamorphism, the Michigamme Formation in the Marquette District provides an opportunity to study changes in preferred orientation of phyllosilicates in the absence of tectonic stress (static recrystallization).

Nine oriented samples were collected from exposures of the Michigamme Formation along Highway 41, between Ishpeming and Clarksburg (Fig. 1). Bedding and cleavage orientations at each sample site are listed in Table 1. The regional metamorphic grade increases toward the southwest. The study area is bound on the eastern side by the chlorite/biotite (biotite-in) isograd and on the western side by the biotite/garnet (garnet-in) isograd that roughly parallels the chlorite/biotite isograd. Thus, all samples lie in the biotite zone of the greenschist facies, but represent a prograde sequence.

3. Methods

3.1. X-ray analysis

The bulk mineral assemblage for each sample was identified by powder X-ray diffraction (XRD), using a Scintag X1 theta–theta X-ray diffractometer, equipped with a Cu radiation source and a solid state detector. Preferred orientation data of phyllosilicates were obtained with an Enraf–Nonius CAD4 automated single-crystal diffractometer with a Mo radiation source, equipped with a custom-built X-ray pole-figure stage (XTG).

The preferred orientation data of phyllosilicates were collected in the transmission mode in view of the low diffraction angle of the (001) plane ($d = 10$ Å). In the transmission mode, X-rays passing through the specimen reach a detector that is pre-set for receiving diffracted X-rays for a given *d*-value. The specimen is rotated so that diffracted X-ray intensities in different orientations can be measured. In addition, measured X-ray intensity data were corrected for background and absorption effects, and then normalized so that the results are independent of mineral concentration. Detailed procedures are described in van der Pluijm et al. (1994). Normalized intensity data are expressed in multiples of random distribution (m.r.d.; Wenk, 1985).

3.2. Scanning electron microscopy

Microscopic observations were made using a Hitachi S 3200N scanning electron microscope (SEM), equipped with a Noran Voyager energy dispersive spectrometer. Mineral assemblages were identified by semi-quantitative EDS analysis. All observations were made in the backscattered electron (BSE) image mode, where differences in gray level (contrast) reflect differences in atomic number.

3.3. Sample preparation

Specimens for XRD were powdered rock chips that received no further treatment. Two matching specimens were prepared from each sample. For goniometry and optical examination, the optimal specimen surface is perpendicular to cleavage and bedding. For the XTG study, we prepared a rock slice with a thickness of ca. 0.2 mm that was mounted on a square aluminum holder with a circular opening for X-rays to pass through. For SEM observations, a diamond-polished thin section of standard thickness of the same rock slice was prepared. These samples are immediately adjacent to the XTG samples, so that the results from these sample pairs are directly comparable.

4. Results

The results of this study are organized as a function of sample distance from the biotite/chlorite (biotite-in) isograd, which is defined as the perpendicular distance between the sample location and the isograd in map view. We equate a larger distance from this isograd with a higher grade, but do not necessarily assume that grade increases linearly or continuously with distance. Moreover, we have no independent control on the dip of the isogradic surface.

4.1. X-ray analysis

XRD patterns (CuKα $2\theta = 2$–$70°$) from powdered samples for all nine sites are shown in Fig. 2. Except for sample 2, excellent agreement between samples indicates that bulk mineral assemblages are similar. However, changes in relative mineral contents, as indicated by relative peak intensities, are noticeable. The relative intensities of quartz and mica peaks, for example, vary between samples. Except for sample 1, the ratio of the intensity of the quartz 20.6° peak to that of the mica 8.8° peak shows a general decreasing trend with grade, suggesting a relative increase in the total mica (muscovite and biotite) to quartz content with increasing metamorphic grade.

The preferred orientations of phyllosilicates were measured at $d = 10$ Å (1 nm). At this position, orientations of both muscovite and biotite are measured collectively. The XTG results in Fig. 3 (as pole figures) show contoured X-ray intensity diagrams in equal-area, lower-hemisphere projection. The maxima for each sample have been rotated to the center of the projection to show the shape and the intensity of the contours, which, after normalization, represent the degree of preferred orientation. A higher intensity (given in m.r.d.) represents a greater degree of preferred orientation (better grains alignment). The orientation of the fabric elements relative to bedding or cleavage and maximum intensities are listed in Table 2. The maximum intensity of each sample is plotted as a function of distance in Fig. 4.

Fig. 3 shows that the preferred orientation for all samples, except sample 2, is parallel to the cleavage orientation. Sample 2 shows an orientation fabric that is close to bedding, and this sample has a composition that is different from that of the other samples. There is a general trend of

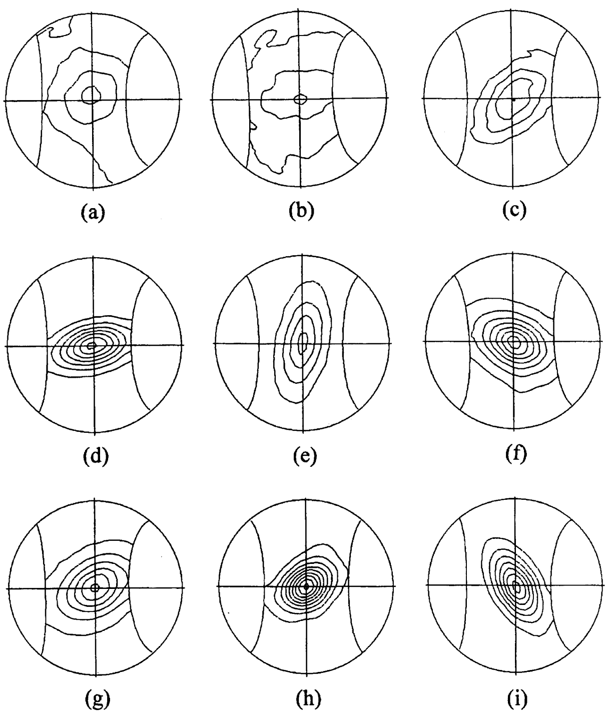


Fig. 3. Equal-area, lower-hemisphere projections of X-ray texture goniometry data from samples 1–9 (a–i). The center of each plot represents the pole to cleavage, except for pole to bedding in sample 2 (b). Plots are contoured in multiples of random distribution (m.r.d.), using a contour interval of 1 m.r.d. Peak maximum and maximum contour level for each sample are listed in Table 2.

Table 2
Results from X-ray texture goniometry measurements

Sample ID	Preferred orientation[a]	Max. intensity (m.r.d.)	Max. contour[b]
1	C	3.49	3.25
2	~B	3.38	3.10
3	C	4.62	4.60
4	C	7.87	7.50
5	C	4.75	4.50
6	C	7.52	7.00
7	C	6.11	6.00
8	C	9.83	9.50
9	C	7.71	7.50

[a] C: cleavage; B: bedding.

[b] Same contour interval of 1 m.r.d. is used to plot all the samples.

increasing degree of preferred orientation with distance from the biotite-in isograd (= grade), although the maximum intensities vary significantly (Fig. 4). Sample 4 has a relatively high degree of preferred orientation (as large as sample 9) despite a relatively low grade. Sample 8 has the highest degree of preferred orientation, although the location of sample 9 would suggest a higher metamorphic grade based on proximity to the garnet-in isograd.

4.2. SEM observations

Representative SEM images of the samples are shown in Fig. 5. All images were acquired in the BSE mode and are shown at the same magnification of 500×, with the cleavage orientation parallel to the short side of the image.

The microstructure of samples 4 and 7 (Fig. 5a and b) is very different from that of samples 8 and 9 (Fig. 5c and d). In samples 4 and 7, grains generally have irregular boundaries with rounded corners and smooth surfaces. Fine-grained material that occupies space between grains is widely observed. Biotite commonly occurs near large quartz grains approximately parallel to cleavage, or at the rim of quartz grains (e.g., Fig. 5a). As indicated by SEM images and supported by XRD, the mineral assemblages in these samples are dominated by quartz, with considerable amounts of muscovite, biotite and chlorite.

In samples 8 and 9 (Fig. 5c and d, respectively), the outlines of individual grains are much better defined, especially in sample 9. The contacts between grains are generally straighter, and there is less of the fine-grained material that is common in samples 4 and 7. Aggregates of phyllosilicates are commonly observed. Although most of the phyllosilicate grains are oriented with their basal planes (long dimension in cross-section) approximately parallel to the cleavage direction (N–S on the image), some phyllosilicate grains are oriented with (001) at a high angle to the cleavage orientation. This is especially true in samples near the biotite-in isograd, where grains are uniform in size and have a larger aspect ratio (length to width ratio) than those in samples 4 and 7. Finally, semi-quantitative EDS analysis shows that the biotite in samples 1 and 9 has a relatively high Fe-content.

5. Discussion and conclusions

The ratio of total phyllosilicate to quartz shows an increasing trend with grade, as indicated by XRD results and SEM observations, with the exception of sample 1, which has a high mica content. Biotite can form by reaction of muscovite with iron oxide, which occurs widespread in iron formations in the area. Alternatively, biotite can form by reaction between muscovite, quartz, chlorite and/or Kfeldspar (e.g., Guidotti, 1984). Whereas chlorite was detected by XRD only in samples 1 and 8, its presence in other samples is indicated by EDS analysis. These two reactions have distinctly different effects on preferred

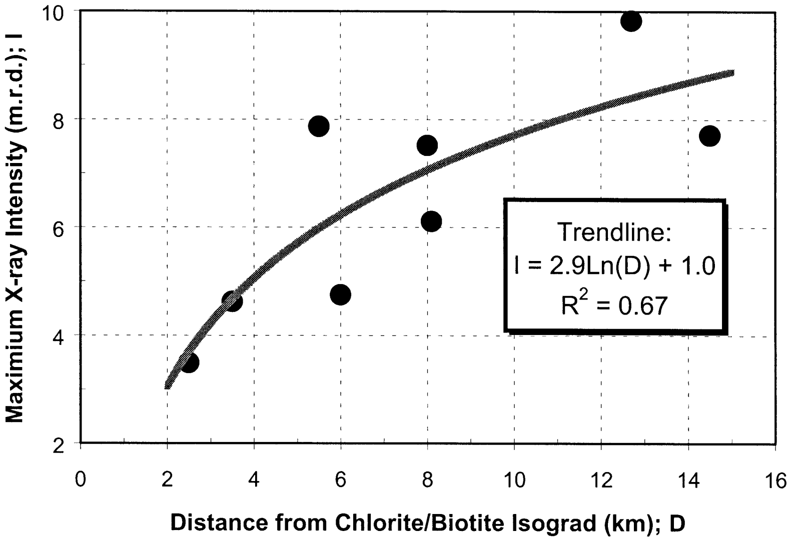
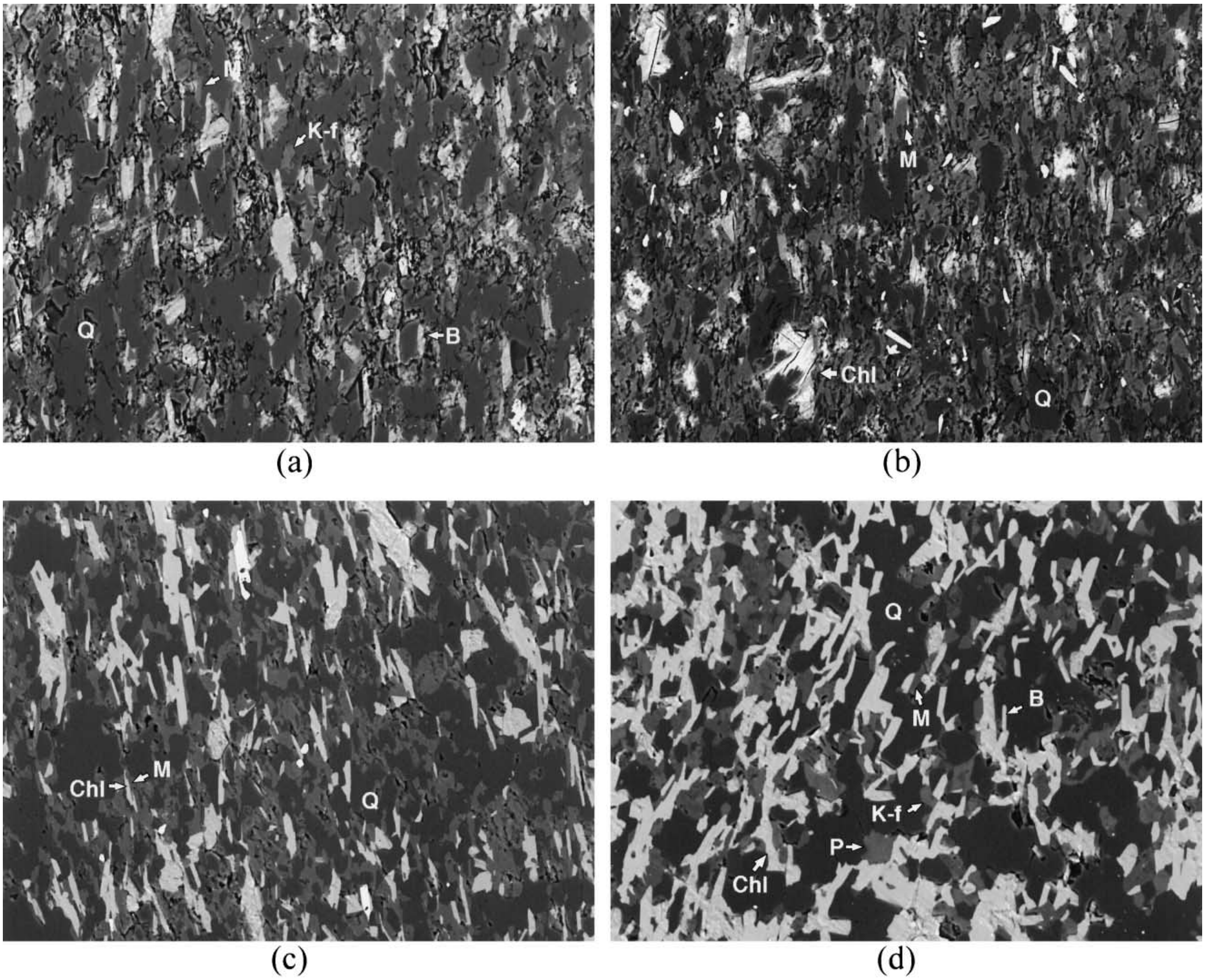


Fig. 4. Maximum X-ray intensities (in m.r.d) for all samples plotted as a function of distance from the chlorite/biotite (biotite-in) isograd (km).



(a) (b) (c) (d)

Fig. 5. Back-scattered electron micrographs of (a) sample 4, (b) sample 7, (c) sample 8, (d) sample 9; muscovite (M), biotite (B), chlorite (Chl), quartz (Q), plagioclase (P) and feldspar (K-f). Width of view is 20 nm.

orientation development. The reaction of muscovite with iron oxide would produce a phyllosilicate preferred orientation that is probably at least as good as that of preexisting muscovite, because newly-formed biotite inherits the orientation of preexisting muscovite (e.g., Oertel, 1970; Etheridge et al., 1974). On the other hand, if biotite were formed by the second reaction in a tectonic stress-free environment, newly-formed phyllosilicates would probably have variable orientations with relatively low preferred orientations. Quantitative XTG is able to distinguish between these two possibilities.

The XTG results from this study show that: (1) the preferred orientations of phyllosilicates are parallel to the cleavage orientation, and (2) the degree of preferred orientation generally increases with metamorphic grade. Assuming that the lowest grade samples are representative of the regional cleavage fabric before metamorphism, the results require that the preferred orientation of phyllosilicates improved during post-kinematic metamorphism.

Preferred orientation of phyllosilicates develops by a combination of two end-member processes: (1) mechanical reorientation of grains into a common direction, and (2) growth of grains in a common direction at the expense of dissolving grains in less favorable directions (e.g., Ho et al., 1995, 1996). Evidence for mechanical processes, such as kinking or bending of grains, is largely absent from our samples of the Michigamme Formation. Rather, it is seen that: (1) phyllosilicates (mostly biotite) occur either along the grain boundaries of quartz and muscovite, or at a high angle to quartz or feldspar grains, (2) irregular grain contacts are sharper and straighter as the metamorphic grade increases, and (3) fine-grained material is progressively removed in higher grade samples.

SEM images of phyllosilicate grains show better-defined shapes, straighter boundaries and increasingly larger length-to-thickness ratios with increasing grade. Combining this information with stronger preferred orientation as a function of increasing metamorphic grade, we conclude that crystallization of phyllosilicates occurred through: (1) dissolution of fine-grained material, (2) dissolution of phyllosilicate grains in noncleavage-parallel orientations, and (3) growth on pre-existing, cleavage-parallel phyllosilicates. We surmise that phyllosilicate grains with their basal planes at an angle to the cleavage orientation preserved relatively high internal strain energy from earlier cleavage formation, in the form of line and stacking defects. The defect state of these grains lowered their resistance to dissolution, with the result that they were preferentially dissolved. Chemical energy may have further contributed to the dissolution of these grains in response to changing metamorphic conditions (e.g., Etheridge and Hobbs, 1974). Crystallization of dissolved phyllosilicates occurred along the basal plane of cleavage parallel grains, which represents the easy growth direction of mica (Oertel, 1970). This produced a stronger preferred orientation of phyllosilicates by post-deformational growth than that of the pre-metamorphic cleavage.

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