SOME ASPECTS OF THE PETROLOGIC AND TECTONIC HISTORY OF THE PRECAMBRIAN ROCKS OF WATERLOO, WISCONSIN

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ABSTRACT

Study of the highly aluminous pelitic schists interbedded with the Waterloo Quartzite of southern Wisconsin suggests at least two periods of deformation followed by two separate metamorphic events (M_1 and M_2). Both metamorphisms occurred in a static environment and although both probably took place under amphibolite facies conditions, M_1 probably represents somewhat higher temperature conditions than M_2. Arguments are presented which suggest that M_1 occurred at P_{H_2O} < 3.8kb and T between 350°C and 550°C.

M_1 and M_2 clearly represent post-Penokean metamorphic events which may have occurred on a regional scale throughout much of southern Wisconsin. An age of near 1,630 m.y. seems most reasonable for these metamorphic events.

INTRODUCTION

The Waterloo Quartzite crops out about 35 kilometers northeast of Madison near the town of Waterloo (Fig. 1). These outcrops are part of the complex Precambrian bedrock terrane of Wisconsin. This report discusses the metamorphic and tectonic history of the southernmost exposures of Precambrian rocks in Wisconsin. Although the focus is on a single locality, the data obtained have implication for all of the middle Proterozoic geology of southern Wisconsin.

Most of the rocks at Waterloo are massive red to gray quartzites with lesser amounts of interbedded pelitic schist, quartzose schist, and minor amphibolites and pegmatites. The pelitic schists were studied because they provide the best mineralogic and textural indicators of the metamorphic history of the Precambrian in a part of Wisconsin that is otherwise covered by Paleozoic strata. Due to limited exposures, ten core samples were studied in addition to six samples collected from outcrops. Only the core samples (each 10-20 cm in length from 4.0 cm diameter cores) were studied in detail (Table 1). They came from depths of 19.2 m to 333.45 m.

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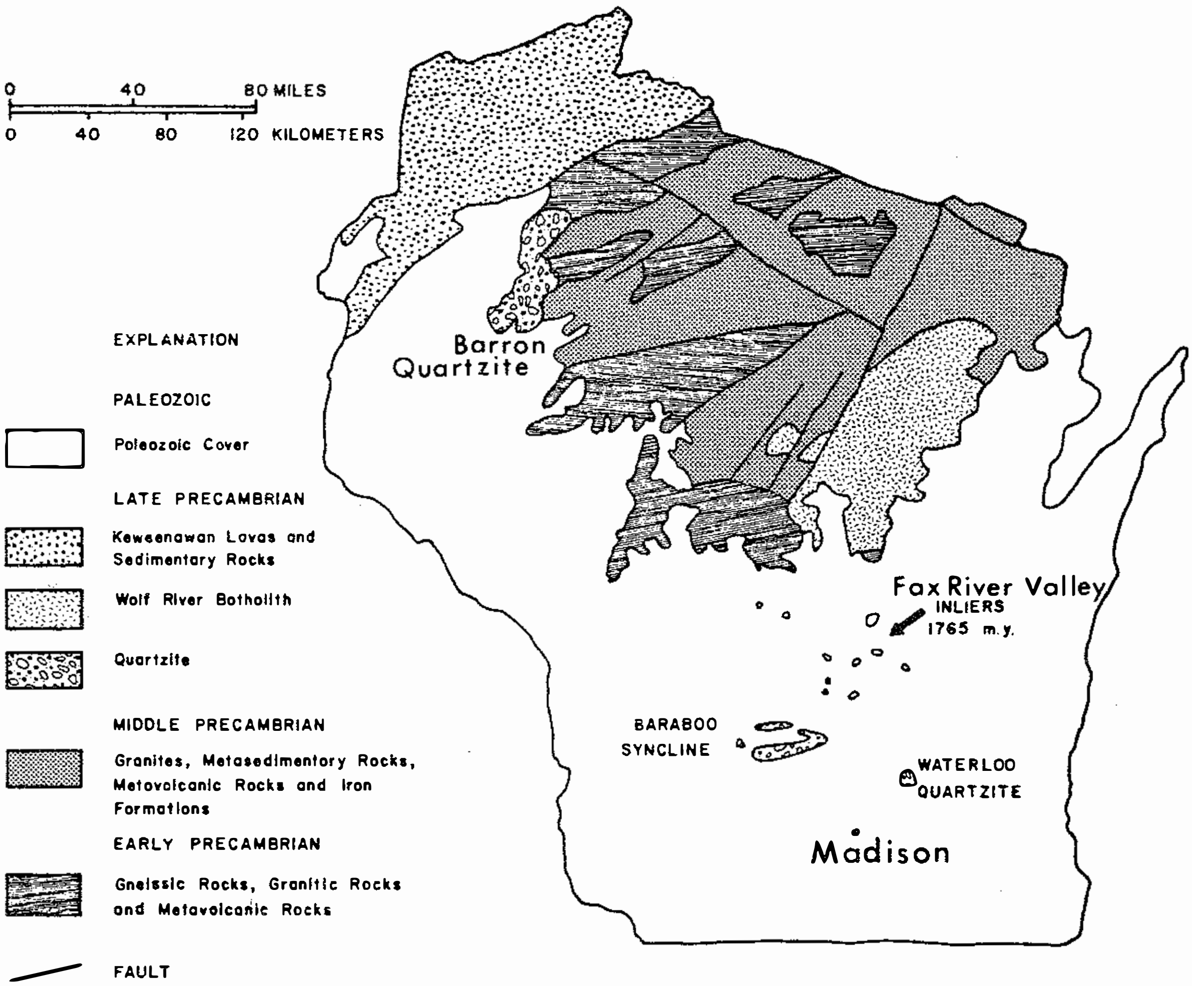

Figure 1. Location of the Waterloo, Baraboo, and Barron Quartzites relative to other major Precambrian features in Wisconsin. Diagram modified slightly from Smith (1978b).

GEOLOGIC SETTING

The Waterloo Quartzite is one of several Precambrian quartzites in Wisconsin. It is lithologically similar and probably stratigraphically equivalent to the Baraboo and Barron Quartzites (Dott and Dalziel, 1972). According to Smith (1978c), the Baraboo Quartzite lies stratigraphically above granites and rhyolites that are chemically similar to rhyolites in the Fox River Valley which have been dated at 1,765 m.y. U-Pb dating of zircons by Banks and Cain (1969) and Van Schmus (1976; 1981), indicate that the main igneous episode of the Penokean Orogeny in Wisconsin occurred far to the north of Waterloo about 1850 to 1900 m.y. ago. Anderson and others (1975) and Smith (1978a) suggested that the rhyolites of the Fox River Valley represent a waning stage of the Penokean Orogeny. More recently, Anderson and others (1978) and Smith (1980) have suggested that the rhyolites were extruded in an anorogenic episode possibly related to crustal extension.

Thus, it would appear that at some time after the last stages of the Penokean Orogeny the Baraboo Quartzite and its stratigraphically equivalent Waterloo Quartzite were deposited. Because of the similarity and proximity (Fig. 1) of the southern Wisconsin quartzites, many workers have concluded that they were part of a sand sheet that was deposited on a major erosional surface of the Penokean granites and the 1,765 m.y. old rhyolites (Dott and Dalziel, 1972; Van Schmus, 1976; Smith, 1978b). Dott and Dalziel (1972) present a brief interpretation of the sedimentologic history of Wisconsin during this time. They suggest that the Waterloo and Baraboo Quartzites represent only a small portion of a thick accumulation of quartz sand deposited on a subsiding, shallow-water continental shelf. More recently, Dott (verbal communication, 1980) has suggested that the lower half of this thick accumulation may be braided river deposits. This thick layer of sand (the Baraboo Quartzite alone is over 1,219 meters thick) (Dott and Dalziel, 1972) extended at least from present Lake Michigan to western South Dakota. According to these authors, most of this thick blanket of quartz sand has subsequently been removed by erosion. The only presently known remnants would be scattered outcrops such as the Baraboo, Waterloo, and Barron Quartzites in Wisconsin and the Sioux Quartzite of South Dakota and Minnesota. The source of this originally large volume of fairly pure quartz sand has never been identified. However, several petrologic factors discussed below enable one to make some reasonable speculations on the source of the clays that formed the schists, and thus the quartz that formed the quartzites.

For the outcrops at Waterloo, the very large modal amounts of muscovite, andalusite, chlorite, and hematite in the pelitic schists, as well as the presence of chloritoid, indicates that these rocks are rich in Al_2O_3 and Fe_2O_3 and to a lesser extent FeO and K_2O. The source for the original sediment may be the extensive area of Penokean and older granitic and metamorphic rocks that are present in northern Wisconsin and Michigan. Weathering and erosion of such rocks could serve as a source for the varying amounts of clays, K_2O, iron oxides, and detrital quartz required to produce the assortment of rocks found at the Waterloo locality. Such a northerly source area would agree with the paleocurrent analyses on the Waterloo Quartzite by Dott and Dalziel (1972). In the case of the Baraboo locality, the shaly interbeds consist mainly of pyrophyllite and presumably are formed by metamorphism of sediment derived from a source producing abundant kaolinite. Thwaites (1931) has presented evidence that significant amounts of kaolinite did form on the Penokean granitic rocks of northern Wisconsin and Michigan. He noted that kaolinite clay horizons, formed on Precambrian rocks and subsequently overlain by Paleozoic strata, were once exploited to a considerable extent for making bricks. Figure 4 of Thwaites' report shows one of these horizons developed at Nekoosa, Wisconsin.

The Waterloo Quartzite presently occurs in a broad, easterly plunging syncline (Buell, 1892; Warner, 1904; and Sumner, 1955), that is folded into a basement of late Penokean granites and 1,765 m.y. old rhyolites. On this structural basis and from the implications of the above discussed correlation of the Baraboo and Waterloo Quartzites, it appears fairly certain that the Waterloo Quartzite is younger than both the Penokean granites and the 1,765 m.y. old rhyolites. Because our observations bear on the events that have affected the rocks since the time of deposition and hence, how these rocks are related to the broader-scale post 1,765 m.y. old events in Wisconsin, further discussion of their geologic history and age will be deferred to the end of this report.

METHODS OF STUDY

Each sample was slabbed and inspected visually in order to observe the megascopic interrelations among foliations, megacrysts and/or pseudomorphs. Subsequently, thin sections and polished sections of each sample were studied by means of transmitted and reflected light. X-ray diffraction scans were run on mica separates in order to ascertain if more than one type of white mica was present. The white mica and opaque minerals were chemically analyzed by means of the University of Wisconsin-Madison ARL Microprobe. The details of these chemical data and its petrologic implications will be presented in a subsequent report.

For the present, emphasis is given to those observations and data which bear more on geologic rather than petrologic aspects. Specifically, these will include features such as cross-cutting relations among foliations, overprinting by megacrysts, and pseudomorphing of megacrysts. The interrelationships among such features enables one to ascertain the relative order of tectonic and metamorphic events.

PETROGRAPHY AND MINERALOGY

Only two essential mineral assemblages have been recognized in the pelitic schists (see Table 1). One of these consists of muscovite, quartz, chlorite, hematite, $\pm$ plagioclase with minor amounts of tourmaline, apatite, rutile, zircon, and a high relief, high birefringence mineral which is probably in the epidote group. The other assemblage is similar but also contains andalusite, chloritoid, and plagioclase.

In both assemblages, the modal amounts of each mineral vary considerably from specimen to specimen. Moreover, in many samples the presence of two types of pseudomorphs suggests that other assemblages were previously present. The lack of biotite in all samples is presumably due to bulk composition (too high Al_2O_3) rather than to metamorphic conditions.

Table 1. Mineralogy of specimens from Waterloo, Wisconsin.

	CVG-B55	CVG-B56	CVG-B57	CVG-B58	CVG-B59	CVG-B60	CVG-B61	CVG-B62	CVG-B63	CVG-B64	CVG-B65
<u>Mineral</u>											
Quartz	√	√	√	√	√	√	A	√	√	√	A
Plagioclase	√	√	?	√	√	?	M	√	√	√	M
Muscovite	√	√	√	√	√	√	P	√	√	√	P
Chlorite	√	√	√	√	?	√	H	√		√	H
Andalusite	√				√	√	I		?		I
Chloritoid	√				?		B				B
Opaques (Hem+Mag)	√	√	√	√	√	√	O	√	√	√	O
Rutile	?	√	√	√	√	√	L		√	√	L
							I				I
<u>Alteration Minerals</u>							T				T
Kaolinite	√				√	√	E				E
Hematite "Dust"	√	√			√	√			√		
<u>Accessory Minerals</u>											
Tourmaline	√	√	√	√	√	√		√	√		
Apatite	√	√	√	√	√	√		√	√	√	
Zircon	√	√	√					√			
Epidote Mineral	?	√			√	√		?	√	√	

√ = mineral present; ?=question if present; blank = not seen.

All specimens display a strong foliation of the groundmass minerals (muscovite, quartz, plagioclase, hematite, and to a minor extent chlorite) with highly-oriented muscovite laths providing the main foliation. This strong foliation appears to be the earliest and, following the classification of Spry (1969), is designated as S_1. It is present in all specimens and usually is the only foliation that is easily recognized in hand specimen. Two later strain-slip cleavages (Ayrton and Ramsey, 1974), defined by the alignment and kink banding of muscovite, can also be recognized and are designated as S_2 and S_3. All three S surfaces are shown in Figure 2. As seen on this Figure, S_3 which is only weakly and sporadically developed, is recognizable mainly in terms of minor kinking of some of the coarser muscovite plates which overprint the groundmass matrix. S_2 can be recognized in about half of the specimens. In at least three samples it is readily apparent even in hand specimen (especially sample WTL-1). The spacing of the strain-slip planes of S_2 is on the scale of a few mm. However, any bending of muscovite laths which may have occurred during the slip-cleaving event has now been obscured by recrustallization. The resulting straight laths of groundmass muscovite produces a polygonal texture (Zwart, 1962) which is apparent when viewed with crossed nicols. Typically S_2 occurs at approximately 90° to S_1 (See Fig. 2).

Muscovite

Although muscovite is dominantly a groundmass mineral, it also occurs as coarser laths that crosscut and overprint the groundmass foliations, S_1 and S_2. In some cases the coarser muscovite laths are oriented parallel to S_2. Figures 2, 3, and 5 show some of these features. The groundmass laths are usually less than 0.1 mm in length whereas the larger laths are up to 0.3 mm by 1.2 mm in size.

X-ray diffraction scans indicate that muscovite is the only "white mica" in the pelitic schists. No peaks of paragonite, margarite, or pyrophyllite were detected. The modal amount of muscovite ranges from less than 10 percent in the quartzose schists to as high as 85 percent in the mica-rich samples.

Quartz and Plagioclase

Quartz and plagioclase are restricted to the groundmass. The plagioclase is untwinned, contains various inclusions, and has rather indistinct grain boundaries. It appears to be present in minor amounts in most specimens (usually less than 2 percent), but because of its indistinct appearance it could not be recognized in some specimens. In no cases could rigorous estimates of its abundance be made. Quartz occurs in several different textural types. Normal (that is, unstrained) quartz is most abundant, but in some samples quartz has undulose extinction or a "cross hatching," which is indicative of strain in the crystal structure (Spry, 1969). In a few cases, quartz grains occur in thin, 0.5 mm wide veinlets that crosscut all other features in the specimens. Apparently these veinlets were formed very late in the tectonic and metamorphic history of the Waterloo Quartzite. The modal amounts of quartz range from a few percent in highly micaceous specimens to as much as 90 percent in some of the quartzose schists.

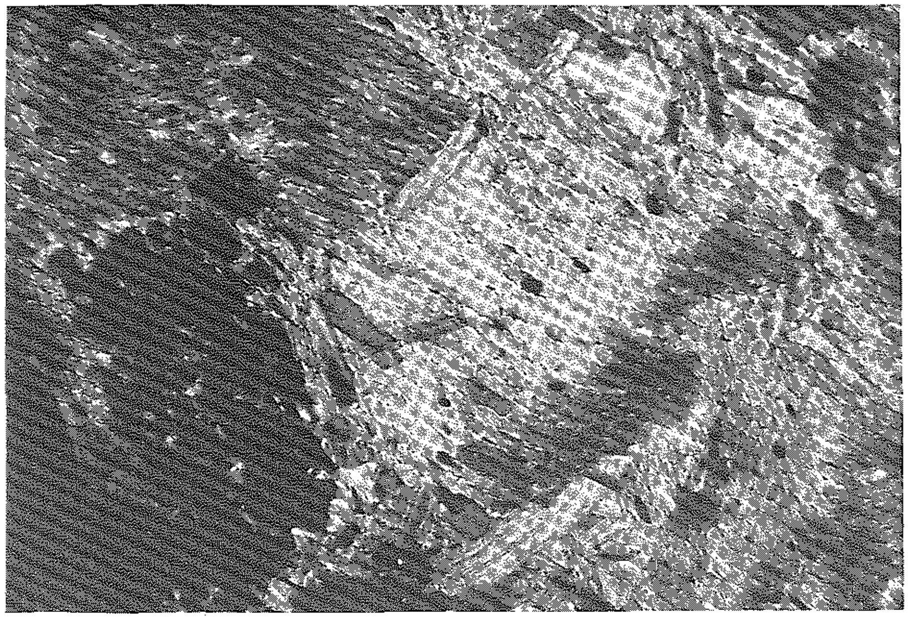

Figure 2. S_1 foliation (trending from upper left to lower right) and annealed slip cleavage S_2 (trending from lower left to upper right and shown by the bands of extinguished and non-extinguished muscovite). Large muscovite lath in the lower center overprints S_1 and S_2 and has been kinked by a subsequent slip cleavage, S_3 which is nearly parallel to S_1. Mineral in lower left is andalusite. Specimen: CVG-B55. Photo taken with nicols crossed; long direction is 2.4 mm.

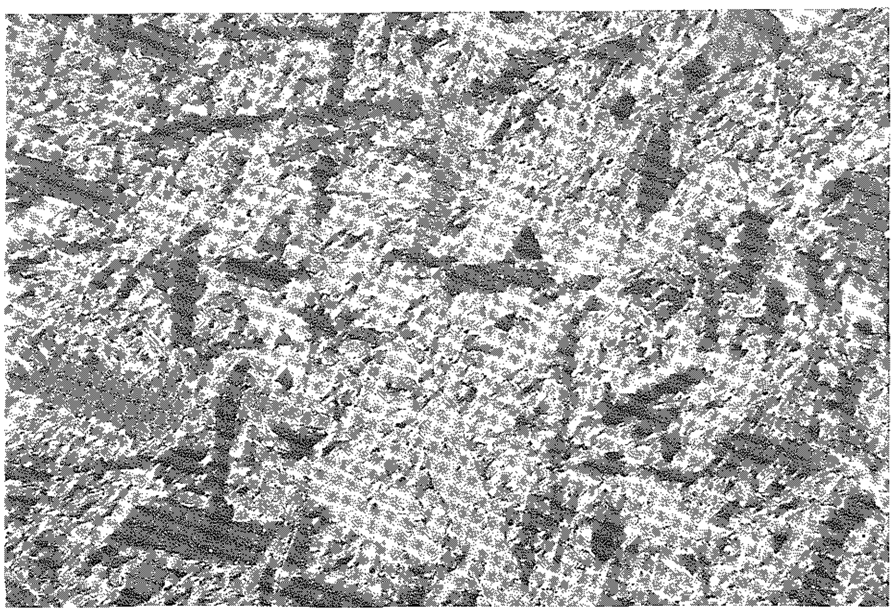

Figure 3. Large muscovite laths overprinting groundmass foliation to produce a "Herringbone" pattern. Specimen: CVG-B58; nicols crossed; long direction is 2.4 mm.

Chlorite

Chlorite is present in modal amounts ranging up to 10 percent. Under crossed nicols it varies in color from anomalous blue in some specimens to anomalous brown in others. According to the criteria developed by Albee (1962), the blue chlorite is Fe-rich and the brown chlorite is Mg-rich. Texturally chlorite occurs in three different varieties: (1) fine-grained laths in the groundmass foliation; (2) coarse laths or plates (to 1.5 mm) or both which crosscut and overprint the groundmass; and (3) coarse plates and laths intimately associated with the two different types of pseudomorphs.

Andalusite

Andalusite occurs as euhedral megacrysts up to 0.5 cm in width. In hand specimen, it occurs as reddish-colored, square prisms which are more deeply colored in the outer portions. In thin section, the megacrysts are seen to contain abundant poikilitic inclusions and to truncate and overprint both S_1 and S_2 (Fig. 2). In most cases, the andalusite-bearing samples do not contain any of the pseudomorphs mentioned above. However, some exceptions do occur, and in one specimen (WTL-2), andalusite megacrysts are included within the larger of the two pseudomorph types. In some cases, the core portion of andalusite contains much greater amounts of fine-grained inclusions which form patterns simulating those in the groundmass (Fig. 7 and 9).

Two different types of partial pseudomorphs (after andalusite) have formed. The extent of this pseudomorphing varies from specimen to specimen as well as from grain to grain in a given specimen. One type consists of small, cross-cutting veinlets of moderately fine-grained muscovite (Fig. 9). These veinlets continue into the groundmass and may represent cracks along which andalusite has been converted to muscovite. The other type of pseudomorph after andalusite is restricted to the outer few mm of some of the megacrysts (Fig. 7 and 8). It consists of kaolinite as indicated by its optical properties and the presence of a 7.35 °A peak on one of the diffractometer scans. The kaolinite is intimately intergrown with very fine grained hematite and possibly results from a late hydration reaction such as:

$$Al_2SiO_5 + 2H_2O + SiO_2 \rightleftharpoons Al_2(Si_2O_5)(OH)_4$$

The concentration of hematite in these kaolinite rims may be responsible for the red color mentioned above.

Chloritoid

Chloritoid is present in some of the andalusite-bearing specimens. It occurs as prisms approximately 0.05 mm to 0.3 mm in length and occasionally as large as 0.5 mm. Commonly, the prisms form bundles or radiating clusters. At the most, chloritoid accounts for about 2 modal percent of a given specimen. Typically it has a weakly pleochroic green color, high relief, and prominent polysynthetic twinning. In some samples the chloritoid has been partially to totally altered to hematite and possibly other unidentified iron oxide minerals. Although no unequivocal textural evidence is present, the chloritoid appears to have grown contemporaneously with andalusite. According to Winkler (1979), the presence of chloritoid suggests bulk compositions with a relatively high Fe/Fe+Mg ratio, high Al_2O_3, and low total alkalies.

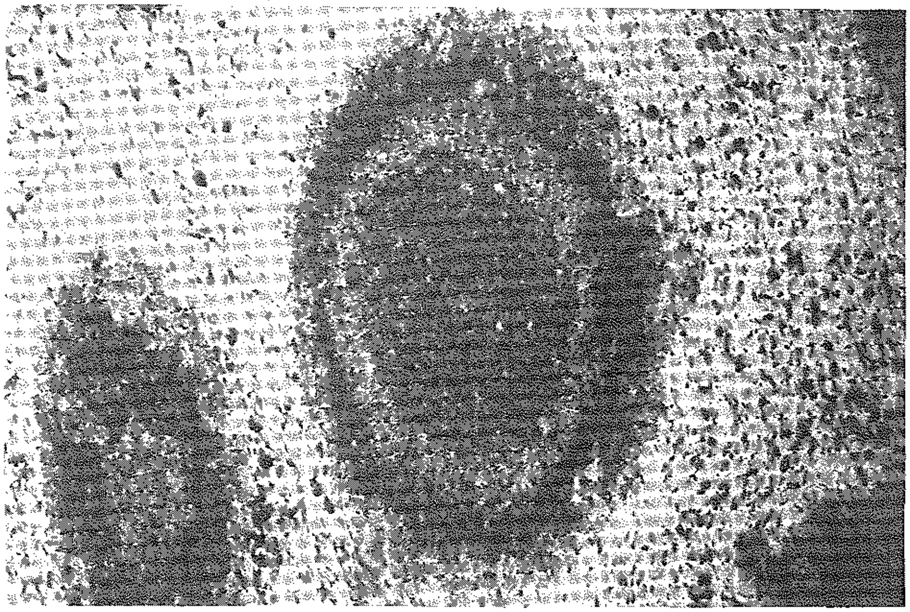

Figure 4. Type I pseudomorph. showing concentric banding. Specimen: CVG-B62; nicols crossed; long direction is 6.0 mm.

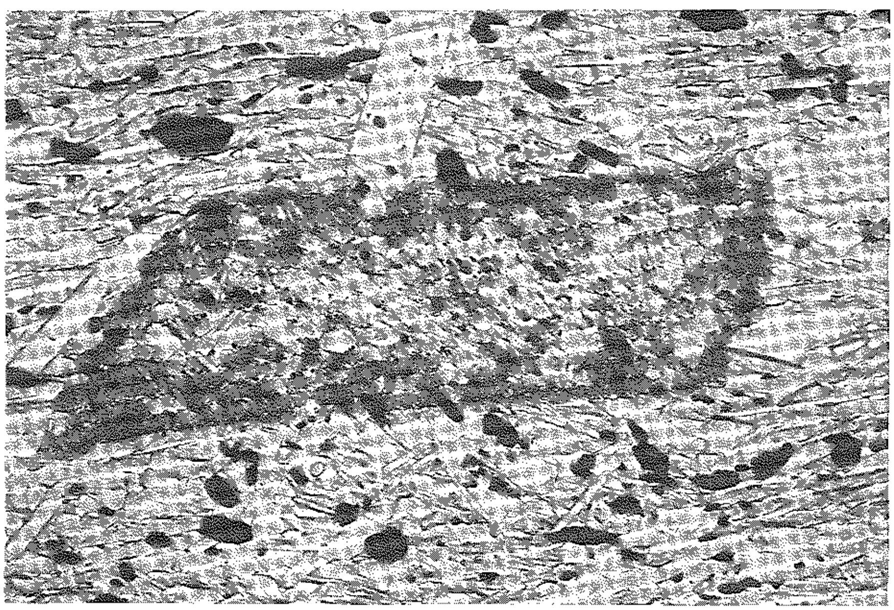

Figure 5. Type II pseudomorph. Outer dark rim is mainly chlorite. S_2 is parallel to the coarse muscovite laths and S_1 parallel to the groundmass muscovite laths. Specimen: CVG-B57; Plane light; long direction is 1.0 mm.

Iron Oxides

Hematite and magnetite are the only opaque minerals that have been identified. Because the thin sections were cut perpendicular to foliation, the hematite appears as lath shaped subhedra. Most specimens contain as much as 20 modal percent of hematite and only minor magnetite. The magnetite occurs as small "island like" patches within the larger hematite laths.

Some of the hematite, as described in the discussion of andalusite, occurs as finely dispersed grains, at least some of which may be related to a later alteration event. However, most hematite is present as coarser laths (generally less than 0.1 mm long) which are parallel to S_1 but also follow the crinkles produced by S_2. In the andalusite + chloritoid-bearing specimens some of these laths are euhedral and up to 0.8 mm in length.

Cursory probe work indicates significant amounts of $FeTiO_3$ dissolved in the hematite laths that are 0.1 mm and smaller. According to Rumble (1976) these laths should be classified as titanhematites. In contrast, the coarsest laths (to 0.8 mm) and their associated magnetite do not appear to contain significant amounts of TiO_2.

Other Minerals

Except in one specimen, tourmaline is present only as an accessory mineral. In specimen CVG-B55 it amounts to about 10 modal percent and occurs as prisms ranging in length from 0.02 mm up to 0.8 mm. In the other specimens it occurs only as prisms less than 0.02 mm long. In all cases the tourmaline is blue-green. Apatite, epidote, rutile, and zircon are minor accessory minerals in virtually all specimens. However, in one specimen small needles and irregular grains of rutile make up about 3 modal percent. Zircon occurs as tiny grains in chlorite and is easily detected due to the development of pleochroic halos.

Pseudomorphs (non-andalusite)

In addition to the partial pseudomorphing of andalusite, two other types of pseudomorphs are present in several specimens. Unually both types are present together in a given specimen. Type I pseudomorphs are ovoid in shape and range from 0.5 to 1.0 cm in diameter. They consist mainly of moderately fine-grained chlorite, muscovite, quartz, and opaques (hematite?). Microscopically and megascopically these pseudomorphs display a complex concentric zonation. In hand specimen the zonation is defined by varying shades of green with a reddish core in some cases (due to finely disseminated hematite?). In thin section it is evident that these concentric, diffuse bands are due to variation in the relative amounts of the minerals that make up the pseudomorphs. As many as six bands of fairly uniform thickness (excluding the core) are present in some of them. Within the pseudomorphs, the chlorite, muscovite, and quartz are about as coarse-grained as they are in the groundmass, but in some cases the chlorite in the outer zone is coarser grained. This implies that the pseudomorphs probably formed at temperatures high enough to facilitate significant recrystallization. Figure 4 shows one of these pseudomorphs with at least three recognizable zones. Identification of the pseudomorph precursors has not been possible, but because of their ovoidal shape and abundance of chlorite, it is presumed that the original mineral was an equant, Fe-Mg phase

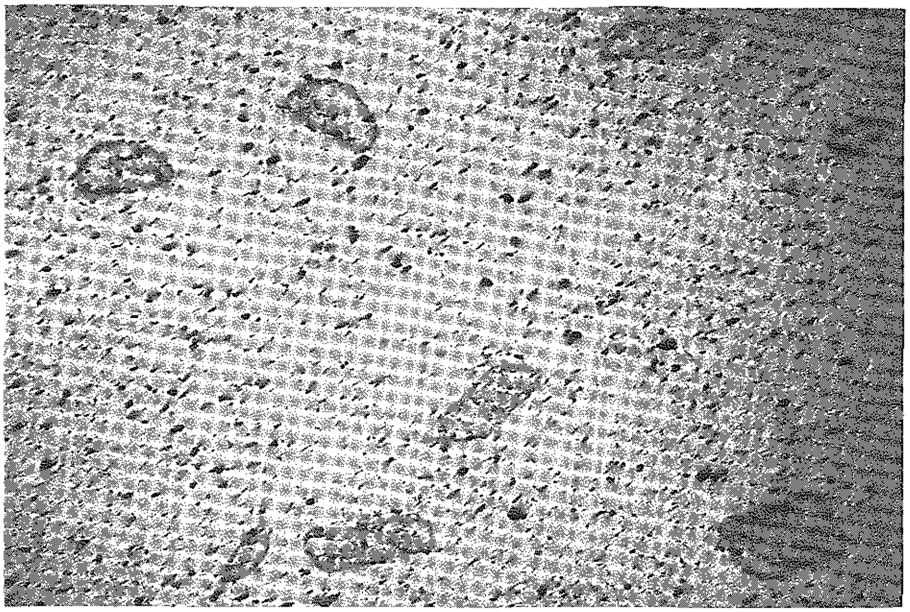

Figure 6. Type II pseudomorphs. Note how they overprint this groundmass.
Specimen: CVG-B57; Plane light; long direction is 6.0 mm.

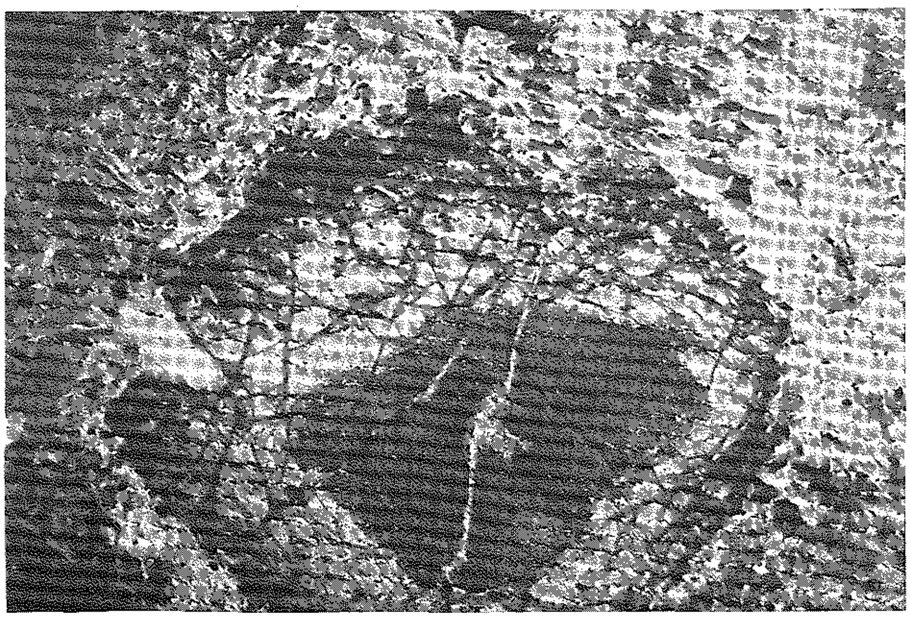

Figure 7. Andalusite megacryst. Outer dark zone is kaolinite replacing andalusite. The inner dark zone consists of andalusite plus abundant inclusions of quartz and muscovite. These inclusions outline an earlier fine-grained groundmass foliation which has been overprinted. Specimen CVG-B55; Crossed nicols; long direction is 6.0mm.

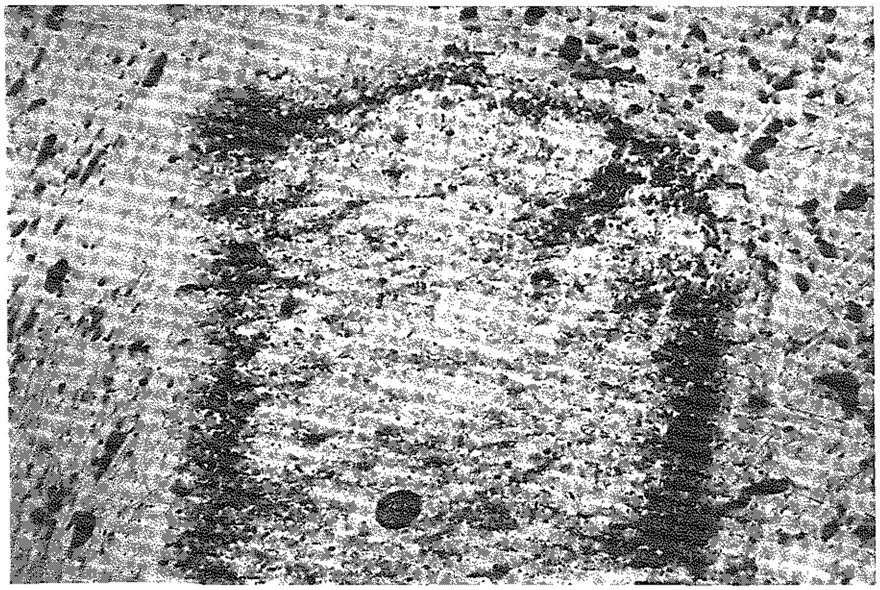

Figure 8. Partially altered andalusite megacryst. Outer dark rim is mainly hematite. Specimen: CVA-B59; Plane light; long direction is 2.4 mm.

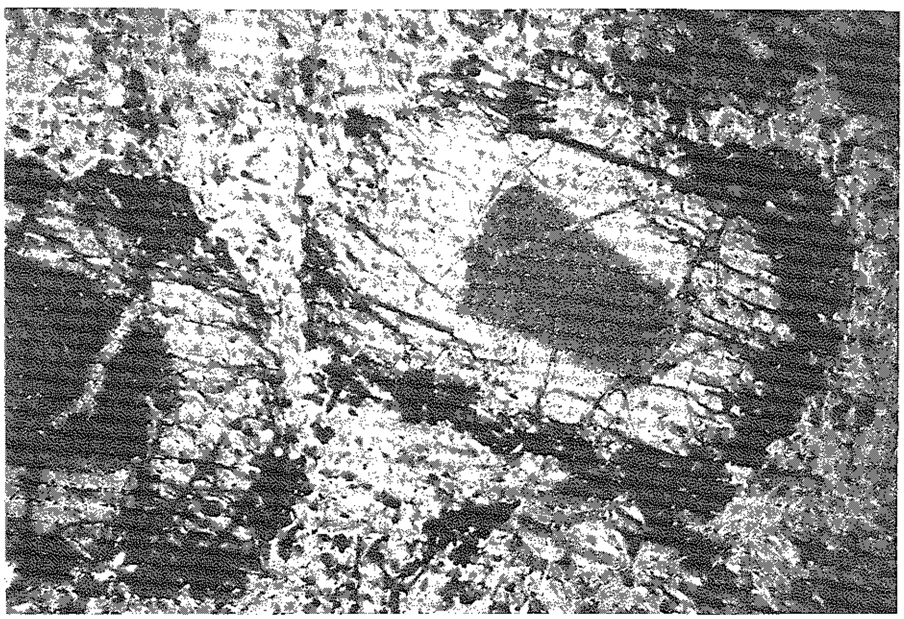

Figure 9. Andalusite megacrysts. Note late, crosscutting veinlets consisting of fine-grained muscovite-trending NE to SW in the central portion of the megacryst on the left. Specimen: CVG-B55; Crossed nicols; long direction is 6.0 mm.

such as garnet or cordierite. Moreover, it was not possible to determine whether the concentric bands reflect original zonation in the precursor mineral or some diffusion mechanism that occurred during formation of the pseudomorphs.

Type II pseudomorphs are much smaller (1.5 mm by 0.5 mm) and display a distinctly prismatic shape (Fig. 5 and 6). Their overall shape, in some cases involving twinning, suggests that they may have formed after staurolite. These pseudomorphs consist of relatively coarse-grained chlorite, muscovite, and quartz plus finely-dispersed opaque minerals. In most cases these minerals tend to concentrate in various combinations such that the pseudomorph displays some degree of concentric banding. However, in no cases are the bands as pronounced as in the case of the Type I pseudomorphs. In neither case does there appear to be a systematic pattern of zonation that persists from specimen to specimen.

Both types of pseudomorphs clearly truncate S_1 and S_2, thereby indicating that the original minerals also post-date the formation of S_1 and S_2. In one specimen the pattern or distribution of coarser opaque grains in the groundmass can be seen to persist in an undisturbed fashion completely through one of the Type I pseudomorphs. These latter observations plus the fact that both Type I and Type II pseudomorphs consist of fairly coarse, randomly oriented muscovite and chlorite, suggests that not only were two separate metamorphic events required to produce the original minerals and their subsequent pseudomorphs but that both were post-deformational events. Moreover, both must have involved fairly intensive crystallization but with the first being the more intense. The post-deformational nature of the first event is also suggested by the lack of any orientation of andalusite (or the two precursor minerals) with respect to S_1 or S_2.

TECTONIC AND METAMORPHIC HISTORY

The above-described interrelationships of minerals and textures tentatively suggest a sequence of metamorphic and structural events that have affected the Waterloo rocks. Because late, widely-spaced brittle shears which are unassociated with any recrystallization may not have any effect on textures, the suggested sequence of events may not include such activity. The sequence suggested below is based on the manner in which mineral grains, foliations, and pseudomorphs are interrelated. An attempt has been made to propose a sequence that is as simple as possible so as to avoid making assumptions not required by the data.

The proposed sequence of events is:

(1) The rocks were deformed (D_1) producing S_1, the main foliation as defined by the orientation of fine-grained muscovite laths. Probably this was mainly a tectonic event, but it may have been accompanied by low-grade crystallization such as during the formation of a slaty cleavage.

(2) Another deformation (D_2) occurred and produced a closely spaced strain slip cleavage, S_2. S_2, like S_1, is defined by the laths of fine-grained muscovite and typically is at a high angle to S_1. As with D_1, any metamorphism associated with D_2 must have been low-grade.

Depending upon whether the few amphibolites encountered in the core log are dikes or sills instead of lava flows, they could have been emplaced at any time through event #1. According to Haimson (1978) these mafic bodies are sills.

(3) The next event was a high-grade, largely static metamorphism which produced the euhedral megacrysts of andalusite and chloritoid. Because this was the first major thermal event, it is designated as M_1. It would seem likely that the two unidentified minerals which are now pseudomorphed also formed during this event. During M_1, any bending of the micas which may have occurred during formation of S_2, was probably eliminated due to recrystallization. The resulting straight mica laths form arches of a sort described by Zwart (1962) as polygonal texture. The amphibolites mentioned above may have formed during this event. This stage clearly postdated the two deformational events as the andalusite megacrysts overprint the S_1 and S_2 foliations. As discussed in the last section, this megacryst forming event is interpreted as a thermal culmination following the two deformations in a single thermo-tectonic event.

(4) The next event was another moderately high-grade, static metamorphism (M_2). This event produced the Types I and II pseudomorphs. Some partial pseudomorphing of chloritoid also occurred during this event. The muscovite which partially replaces some andalusite may be contemporaneous with M_2, and the coarse chlorite and muscovite that overprints the groundmass foliations probably formed at this time also.

As discussed in the next section, the P,T conditions for M_1 can be estimated roughly, but due to the lack of any indicator minerals, such estimates are less rigorous for M_2. However, it can be said that M_2 was a pervasive event that resulted in complete pseudomorphing of some presumably Fe-Mg mineral that was up to 1 cm in size. Moreover, it also involved sufficient recrystallization such that fairly coarse-grained chlorite and muscovite were produced.

(5) The last event (or events) caused only minor effects which are not evident in all specimens. It produced the kaolinite rims around some of the andalusite and the very minor kinking (S_3) that effects a few large chlorite and muscovite laths. The few thin quartz veinlets crosscutting some specimens probably formed during this event (or events). It seems likely that these various effects are due mainly to late, low-temperature, brittle fracturing. Moreover, one specimen, CVG-B64 which is highly sheared, may be related to a larger cataclastic zone.

METAMORPHIC CONDITIONS

Inasmuch as two of the minerals formed during M_1 are now completely pseudomorphed (and not rigorously identifiable), it is not possible to ascertain accurately the prevailing P,T conditions. Nonetheless, the presence of andalusite, muscovite, and chloritoid combined with the knowledge that the bulk composition is highly aluminous makes it possible to estimate the limiting P,T conditions during M_1. The aluminosilicate phase diagram of Holdaway (1971) was used in making these estimates. It was also assumed that $P_{fluid} = P_{Total} = P_{H_2O}$. This is a reasonable assumption because: (1) there are no C or CO_2-bearing phases present, (2) the high fO_2 implied by the presence of hematite would require that any H in the fluid be combined with O to form H_2O, and (3) the breakdown of the various clays (kaolinite, pyrophyllite) during M_1 would liberate abundant H_2O.

Figure 10 shows a P,T diagram with those experimental curves that are relevant to the Waterloo rocks. The presence of andalusite clearly implies that during M_1 these rocks recrystallized at a maximum of 3.8 kb pressure within the P,T field shown for andalusite on Figure 10.

Although no pyrophyllite has been observed in the Waterloo rocks, the high Al_2O_3 content implied by the abundance of andalusite and the absence of biotite, suggests that at the appropriate grade, this mineral would be present. Moreover, in the shaly interbeds of the supposedly stratigraphic equivalent Baraboo Quartzite, pyrophyllite is abundant. Hence, it would seem reasonable to suggest that the Waterloo rocks crystallized at some temperature (depending upon the pressure) above the pyrophyllite breakdown curve shown on Figure 10.

On the other hand, the presence of chloritoid in several specimens clearly suggests that the maximum temperature attained had to be below the upper stability limit of chloritoid in quartz + muscovite-bearing rocks. On Figure 10 the stability curves of Fe-chloritoid + quartz + O_2 and Fe-chloritoid + Al_2SiO_5 + O_2 are from Richardson (1968). Because of the Fe-rich aspect of the Waterloo rocks, use of these iron-end-member chloritoid stability curves probably provides a reasonable approximation of the bulk composition of the natural specimens. It is therefore evident that the occurrence of chloritoid + quartz in the Waterloo pelitic schists implies that these rocks formed at temperatures below those of the two chloritoid curves shown on Figure 10. According to Grieve and Fawcett (1974) and Hoschek (1969), variation of fO_2 will have some effect on the position of the chloritoid curves, but the effect will not be extreme. For the purposes of this paper this effect will be ignored.

In summary, based on the above discussion, it is possible to estimate roughly that during M_1, $P_{Total} = P_{H_2O} < 3.8$kb and temperatures were between 350 °C and 550 °C. Based on the degree of crystallization and thoroughly penetrative fabric, it would seem unlikely that these rocks formed in a near surface environment. Hence, it is assumed that the minimum pressure was at least greater than 1 kb (equivalent to a depth of 3.6 km). If the Type I and II pseudomorphs were originally minerals such as staurolite or cordierite, then the temperatures would have had to be at least high enough to be in the stability fields of these minerals. This would provide a more refined estimate of the lower temperature limit of M_1.

As mentioned previously, it is not feasible to say much about the metamorphic conditions during M_2. It seems likely that the T of M_2 was less than that of M_1. However, the thorough degree of recrystallization of the Type I and II pseudomorphs suggests that the T of M_2 must have been high enough to overcome any kinetic barriers to recrystallization of the original phases,

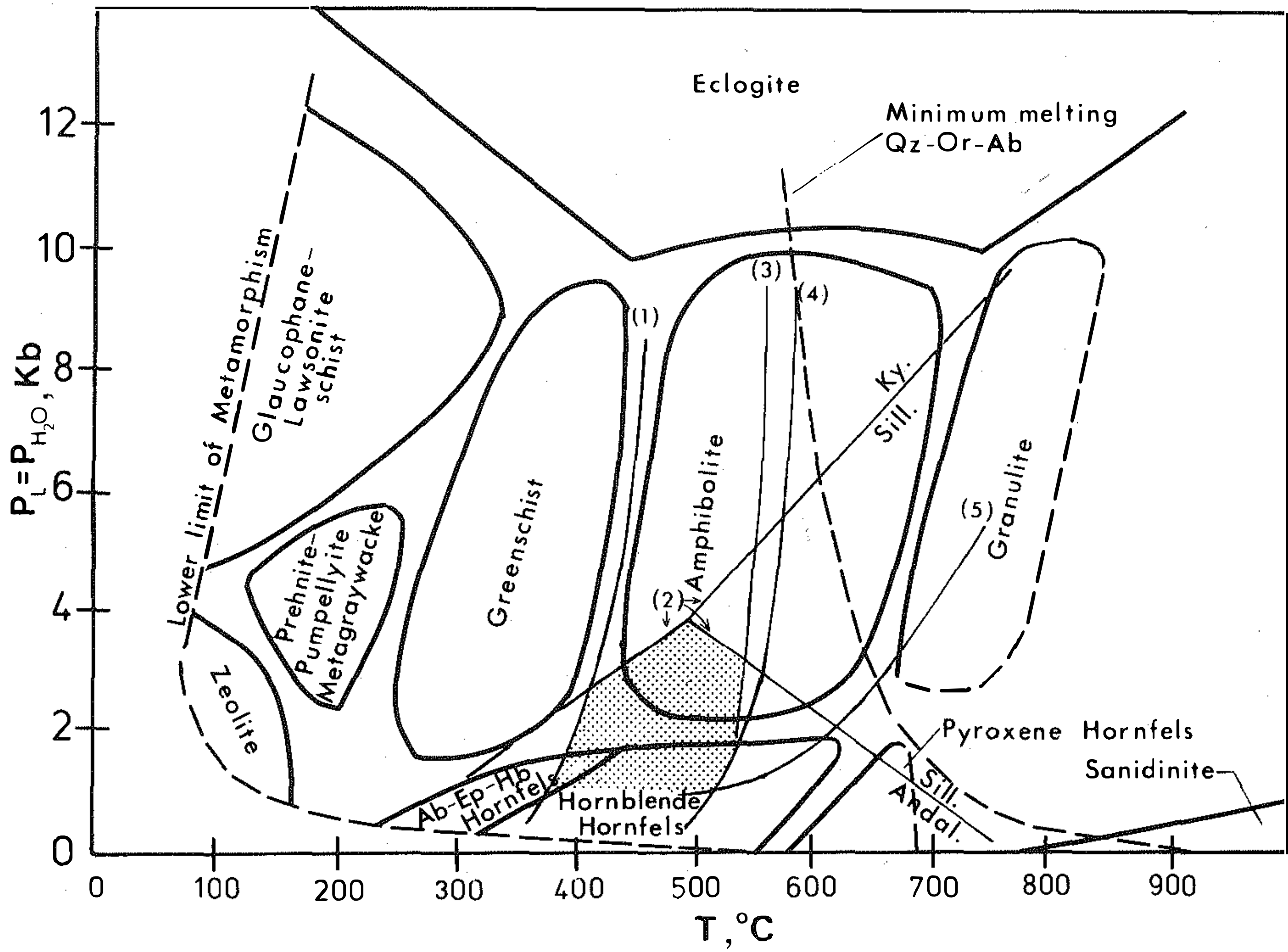

Figure 10. PT curves and facies zones bearing on the metamorphic conditions which have affected the rocks at Waterloo, Wisconsin. Source and identification of information shown include:

Curve (1). Upper stability limit of pyrophyllite in the presence of quartz, (Kerrick, 1968).
Curve (2). PT curves for the aluminosilicate polymorphs, (Holdaway, 1971).
Curve (3). Upper stability limit of the asemblage Fe-chloritoid + Al_2SiO_5+O_2, (Richardson, 1968).
Curve (4). Stability limit of Fe-chloritoid + SiO_2 + O_2, (Richardson, 1968).
Curve (5). Upper stability limit of muscovite + SiO_2, (Kerrick, 1972).

Facies Zones. Taken from Turner (1968).

Stippled area shows the metamorphic conditions that may have affected the Waterloo area.

including the diffusion required to form the present minerals in the pseudomorphs. If the assemblage andalusite ± chloritoid + muscovite + chlorite + quartz remained stable during M_2, then the broad range of P,T conditions discussed above for M_1 would also apply to M_2.

REGIONAL IMPLICATIONS

In this section discussion will focus on two points, (1) a comparison between the petrologic conditions which prevailed in the Waterloo and Baraboo areas, and (2) an attempt to relate the events listed above with the region wide events recognized or suggested by other workers.

Regarding the first point, it appears that the metamorphic conditions at Baraboo were significantly less intense than those at Waterloo. For example, andalusite has never been verified at Baraboo but pyrophyllite is quite abundant. Because of the pyrophyllite at Baraboo, Dalziel and Dott (1970) suggest metamorphic temperatures below 430 °C. These suggested lower temperatures in that area are fully consistent with the relatively minor recrystallization which has affected those rocks. Assuming that it was M_1 which affected both areas and that it was a large-scale regional event (see discussion below), then the temperatures of metamorphism for these stratigraphically equivalent rocks *may* have differed by as much as 120 °C -- for outcrops some 65 km apart.

As for the second point, arguments were advanced in an early section of this report which suggested that the deposition of the Baraboo and Waterloo Quartzites postdated both the Penokean Orogeny and the 1,765 m.y. old rhyolites. Hence, based on the observations on D_1, D_2, M_1, and M_2 which have been discussed in this paper, it would seem possible that significant (probably regional) tectonic and metamorphic events may have occurred in southern Wisconsin subsequent to the Penokean Orogeny and extrusion of the 1,765 m.y. old rhyolites (See also Van Schmus and others, 1975a).

Some of the events subsequent to the formation of the 1,765 m.y. old rhyolites that have been suggested for Wisconsin include:

(a) Smith (1978b) has suggested that the rhyolites were folded sometime between 1,765 m.y. and 1,650 m.y. ago. Subsequently, the sands that later became the Baraboo and Waterloo Quartzites were deposited over the folded rhyolites.

(b) Smith (1978b) also suggested that the Waterloo Quartzite was deformed to its present attitude during a regional metamorphic event 1,650 m.y. ago. This corresponds with a time of widespread regional resetting of Rb-Sr systems in much of Wisconsin (Van Schmus and others, 1975a). More recently, Van Schmus (1978), using new decay constants, has modified the time of this resetting to 1,630 m.y. ago.

(c) The Wolf River Batholith was intruded about 1,500 m.y. ago and the Keweenawan basalts were extruded and diabase dikes intruded 1,115 m.y. ago (Van Schmus and others, 1975B) (See Fig. 1 for locations).

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