MAGMATISM AND THE BARABOO INTERVAL: BRECCIA, METASOMATISM, AND INTRUSION

by

J.K. Greenberg[1]

ABSTRACT

Breccia consisting of quartzite fragments surrounded by white, vein quartz is known to occur in Wisconsin at several exposures of Baraboo-type metasedimentary rock. These quartzite breccias include those at Rock Springs on the north limb of the Baraboo Syncline, Hamilton Mound, Necedah, Battle Point, Vesper, Waterloo, and McCaslin Mountain. With the exception of McCaslin Mountain in the northeast, all the breccias occur in the central or south-central part of the state. Most of the brecciated quartzite has intrusive contact with plutonic rock. Various types of hydrothermal alteration (metasomatism) are apparent in the brecciated outcrop and other exposures of quartzite intruded by granitic or dioritic magma. The most common metasomatic features are quartz crystal-lined pockets and clay-mica segregations, feldspar porphyroblasts in altered quartzite, hematite segregations, and quartz-tourmaline veinlets.

A present interpretation of the breccias is that they are analogous to the stockwork of quartz veins produced around the upper levels of porphyry-copper mineralized plutons. During magma intrusion, the roof rock of quartzite was fractured and soaked in hydrous granitic fluids. The fluids and their particular effects vary with distance from source plutons. Thus, as in some Wisconsin examples quartz veins and breccia grade into pegmatite dikes as an intrusion is approached. Another possible analogue for the Wisconsin examples are explosive breccias developed in quartzite above volatile-rich appinite intrusions.

INTRODUCTION

Several exposures of quartzite deposited during the Proterozoic Baraboo tectonic interval (Dott, 1983; Greenberg and Brown, 1983, 1984) contain breccia with a white vein-quartz matrix. These exposures are widely distributed across central and northern Wisconsin (fig. 1). Intrusions and metamorphic effects of various types have also been observed in brecciated and some unbrecciated outcrops of Baraboo-type quartzite. Intrusive contact and the character of the affected sedimentary rock suggest that these features may be related to anorogenic magmatism which occurred 1,760 and 1,500 Ma. Intrusive bodies are viewed as sources of the combined heat, fluid mobility, and stress necessary to cause much of the observed metamorphism, commonly hydrothermal metasomatism and deformation. Evidence linking the various phenomena is at present mostly empirical. However, the volume of evidence is substantial and sufficient to warrant more comprehensive investigation.

Baraboo-type quartzite and associated metasedimentary rock in Wisconsin, Minnesota, Iowa, and South Dakota are considered to be a product of anorogenic, epicratonic deposition (Greenberg and Brown, 1984). The period of deposition, probably between 1,760 and 1,630 Ma, was preceded by orogenesis from 1,900 to 1,800 Ma, the Penokean orogeny. After 1,800 Ma, magmatism, sedimentation, and deformation in Wisconsin were apparently responses to epeirogenic subsidence and elevation of maturing continental crust (Greenberg and Brown, 1984; Rogers and others, 1984).

Intrusion, metamorphism, and brecciation appear to post-date most folding and associated cleavage in Baraboo interval rock. If, as several investigators have proposed, the quartzite and associated metasedimentary rock were folded about 1,630 Ma (Smith, 1978; Geiger and others, 1982; Dott, 1983; Greenberg and Brown, 1984), then this could be considered a maximum age of intrusion. At Rib Mountain, McCaslin Mountain, and Waterloo (fig. 1) quartzite was cut by granite about 1,500 Ma. However, a recently obtained U-Pb zircon age is anomalous; the granitic rocks intruding deformed quartzite at Hamilton Mound (fig. 1) are near 1,760 Ma (R. Van Schmus, unpublished data; Taylor and Montgomery, this volume). A tectonic sequence similar to Hamilton Mound is apparent at Baxter Hollow (Baraboo, fig. 1) where granitic magma intruded quartzite, possibly sometime between 1,760 and 1,630 Ma (Dott and Dalziel, 1972; Smith, 1983). A potential explanation for the apparent age discrepancies is that the broad, open folds at Hamilton Mound (Ostrander, 1931) and Baraboo (Dalziel and Dott, 1970) actually followed intrusion and imposed only minor, brittle strain on plutonic rock. Another possible explanation is that some folding occurred about 1,760 Ma as well as later. Because some foliated granitic rock in northern Wisconsin were recently

1. Geological and Natural History Survey, 3817 Mineral Point Road, Madison, Wisconsin 53705

determined to be about 1,760 Ma (Van Schmus, unpublished data), the folding at Hamilton Mound, Baraboo and elsewhere may also have taken place about the same time. There is, however, no direct evidence for this.

With the exception of Mancuso (1960) and Dalziel and Dott (1970, p. 29, 105), there has been little previous discussion of the quartzite breccia. Dalziel and Dott attributed the brecciation to some unspecified "explosive hydrothermal activity." Mancuso reported breccias associated with intrusive igneous activity at McCaslin Mountain. Other intrusive relationships have been recognized at Rib Mountain (mafic dike, LaBerge and Myers, 1983) which is itself a quartzite xenolith in syenite, Waterloo (granite pegmatite, Dott and Dalziel, 1972), Hamilton Mound (Greenberg and Brown, 1983; Taylor and Montgomery, this volume), Baxter Hollow (Gates, 1942; Petro, 1983), and most recently, Necedah (fig. 1, see below). Metasomatic alteration in the form of microcline intergrown with quartz in quartzite had previously been described by Ostrander (1931) at Hamilton Mound. Before quarrying exposed the intrusive contact, Ostrander speculated correctly that the Hamilton Mound quartzite may have been intruded. Gates (1942) also suggested that granitic veins in the Baraboo quartzite and the petrography of Baxter Hollow granite indicated intrusion-related hydrothermal activity. His interpretation has not been widely accepted, but reexamination of Baxter Hollow in this study provides additional evidence supporting many of the observations of Gates (1942).

DESCRIPTION AND INTERPRETATION OF LOCALITIES

Baraboo

There are three areas of interest in the Baraboo Quartzite, two on the south and one on the north limb of the Baraboo Syncline (fig. 1).

Rock Springs

In the Rock Springs area (sec. 28, 29, T. 12 N., R. 5 E.) well developed breccia zones were produced without any overt evidence of intrusion. White, vein quartz commonly first appears as bedding-parallel fracture filling near distinct contacts between conglomerate and finer-grained beds (fig. 2). The veins become more abundant and grade into breccia zones where there is much less planar preference of vein orientations. Dalziel and Dott (1970) concluded that the breccia was not fault phenomena in that neither quartzite within or on either side of the zone had been displaced. Typical breccia (fig. 3) consists of angular fragments of purplish quartzite surrounded by white to colorless, vein quartz. The veins possess pockets up to about a metre in diameter that are lined with quartz crystals. Other pocket constituents include interstitial dickite or kaolinite and well crystallized hematite (to 2 cm in diameter). S.W. Bailey of the University of Wisconsin reported that fluid inclusions in quartz crystals indicate temperature of formation near 106 °C (Dalziel and Dott, 1970, p. 105). Geiger (this volume) has determined by x-ray diffraction that some feldspar is also preserved in clay-rich quartzite pockets. Although intrusive rock is not exposed at Rock Springs or elsewhere on the syncline's north limb, gravity and magnetic anomaly maps (Hinze, 1957) indicate the possibility of plutons beneath the brecciated zones.

Highway 12 - South Bluff

On the east side of Highway 12 where it crosses the south limb of the syncline (sec. 34, T. 11 N., R. 6 E.) the presumably basal Baraboo quartzite is unusually fractured in a boxwork of joints and quartz veins (fig. 4). Most of the joints are coated with clay and secondary quartz. No displacement along any fracture surface is apparent. Quartz veining and the characteristic pockets are less well developed here than at Rock Springs, but the fracturing and quartz-clay concentrations are similar. Drill core from the area between Highway 12 and Baxter Hollow contains quartzite intruded by granitic rocks.

Baxter Hollow

Baxter Hollow designates an area with over 400 m of continuous outcrop along the south limb of the syncline (sec. 32, 33, T. 11 N., R. 6 E.). This area is of particular interest because of the controversial nature of the contact between granite and quartzite. Previous workers have ascribed the contact either to intrusion (Gates, 1942) or were uncertain as to the nature of the contact (Dott and Dalziel, 1972). Recent investigations by the Wisconsin Geological and Natural History Survey and Petro (1983) have concluded that the Baxter Hollow granite was a complex intrusive into quartzite.

An unusual zone of interaction varying from less than one to several metres in width separates relatively unaltered Baxter Hollow granite from unaltered quartzite and phyllite. Within this

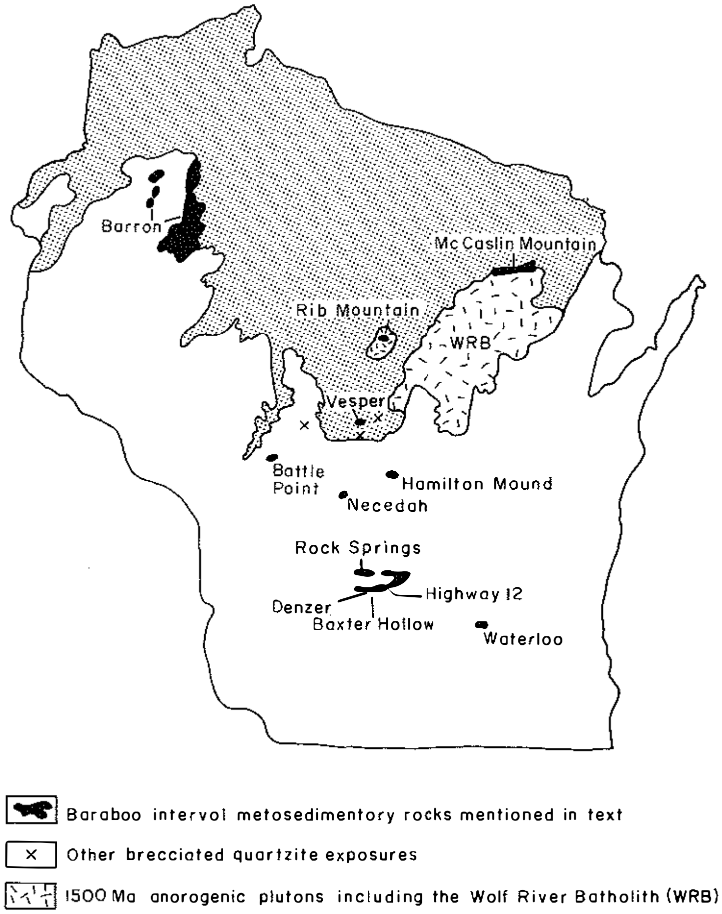

Figure 1.--Distribution of brecciated quartzite of the Baraboo interval. The unbrecciated Barron Quartzite is also shown. The northern region of Precambrian exposures is shaded.

zone the intrusion becomes albite rich, is granophyric in texture, and plagioclase becomes progressively sericitized toward the quartzite. Nearest the contact intense foliation developed in the altered granite led Gates (1942) to propose the existence of a shear zone. The foliation can also be explained mechanically as a result of forceful intrusion. The sericite-rich rock probably received ductile strain along the intrusive contact. Where observed, the foliation is parallel or subparallel to the contact. Above the contact within quartzite, laths of albite have been introduced into quartz-rich rocks (greater than 65 percent quartz). These laths are referred to as porphyroblasts by Gates (1942). The albitized and sericitized rocks are commonly green, perhaps due to the reduction of iron.

Hematite concentrations occur sporadically on both sides of and close to the contact. The granitic rock, especially where altered, contains as much as 60 percent hematite with quartz and sericitized plagioclase. Near the intrusion a unique quartzite breccia with highly strained angular rock fragments in a matrix of over 40 percent hematite (fig. 5) appears to be a brittlely deformed version of hematitic conglomerate. Some samples of undeformed conglomerate from the same area also contain hematite in high proportions as matrix, but surrounding more coherent quartz and phyllite pebbles. In most cases hematite is well crystallized, perhaps indicative of hydrothermal development. The iron oxide could have originally been sedimentary and was later mobilized by intrusion. Another possibility is that the iron was a metasomatic addition from a magmatic source (Hauck and Kimball, 1984). The sericite, hematite, and quartz mineralogy of altered rock at Baxter Hollow represent the same chemical mobility present in the more conventional Baraboo breccias.

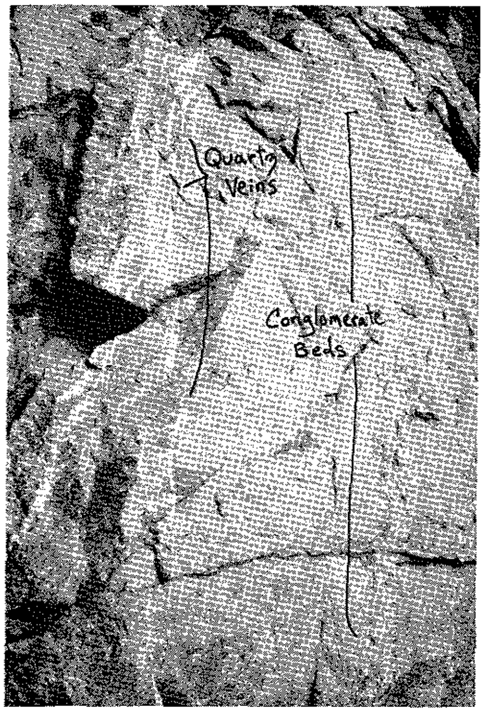

Figure 2.--Outcrop of Baraboo Quartzite at Rock Springs: White quartz veins are oriented parallel to bedding as shown by pebble conglomerate on right.

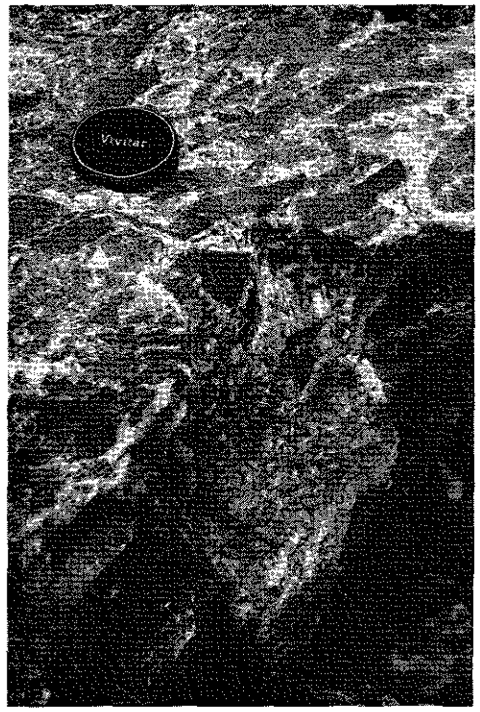

Figure 3.--Close up of typical Baraboo quartz breccia. Dark fragments are purplish quartzite.

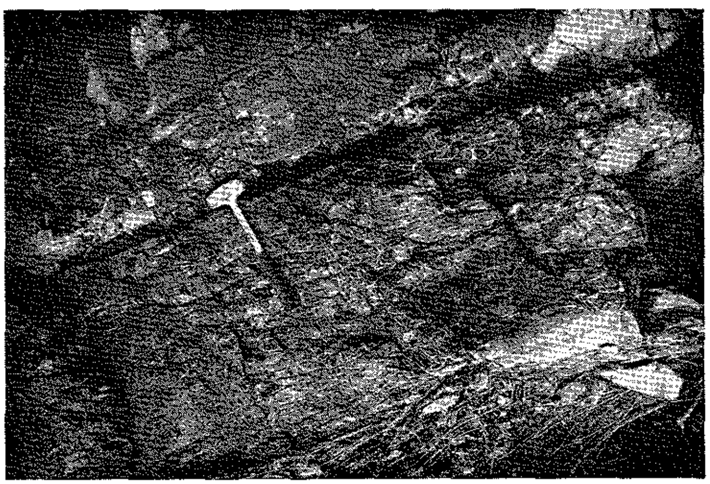

Figure 4.--Outcrop of Baraboo Quartzite on Highway 12 (south range). Note the network of thin fractures lined with clay minerals and some quartz.

Gates (1942) and Petro (1983) interpreted quartz-tourmaline veinlets as additional late-state hydrothermal phenomena in or near Baxter Hollow. The thin veins cut both altered intrusive rocks and quartzite.

Necedah

Quartzite exposures at Necedah (fig. 1) include a large quarry cut into a prominent ridge and two other smaller outcrop ridges. All of these are overlain by Cambrian sandstone which has been variably eroded. The quarry (sec. 24, T. 18 N., R. 3 E.) exposes ferruginous quartzite which is locally well brecciated (fig. 6). Many of the fragments and blocks in the breccia are metachert, red-gray to black or green in color (Greenberg and Brown, 1983) and are surrounded by networks of white vein quartz. Color is a function of the oxidation state of iron, grain size of recrystallized quartz, and fracturing. Quartz crystal pockets with partial to complete clay filling occur between fragments in the veins. Unlike Baraboo the pockets and fracture fillings at Necedah also contain well crystallized books of muscovite as large as 1 cm in diameter. The presence of coarsely crystalline muscovite in quartzite breccia at the quarry suggested the possibility of an unexposed intrusion (Greenberg and Brown, 1983). Recent quarry expansion at Necedah has confirmed this suspicion with the uncovering of breccia with granitic matrix and fragments. Water-well records also indicate that granite and diorite occur below the quartzite in the immediate area.

Deformation and alteration effects in the quartzite fragments developed before and perhaps during brecciation. Previously-foliated quartzite fragments are randomly oriented in the breccia. The typically dark green to black fragments are limited to the area where igneous material is exposed in the quarry. Reddish or lighter-colored quartzite occurs elsewhere at Necedah. At present there is no evidence to suggest any deformation of Necedah quartzite after brecciation.

The igneous breccia contains relatively few quartz veins compared with the quartzite breccia. Constituents of the igneous breccia include fragments of variably altered aplitic granite, dark colored quartzite and metachert, ferrugenous metaargillite, and quartz, perthite and plagioclase megacrysts. All these components range in size from several mm to blocks near 1 m in the longest dimension. The breccia matrix surrounds the large fragments with highly strained quartz, relatively unstrained microcline and sodic plagioclase, chlorite, muscovite-sericite, and hematite. Zircon occurs as a relatively abundant minor phase.

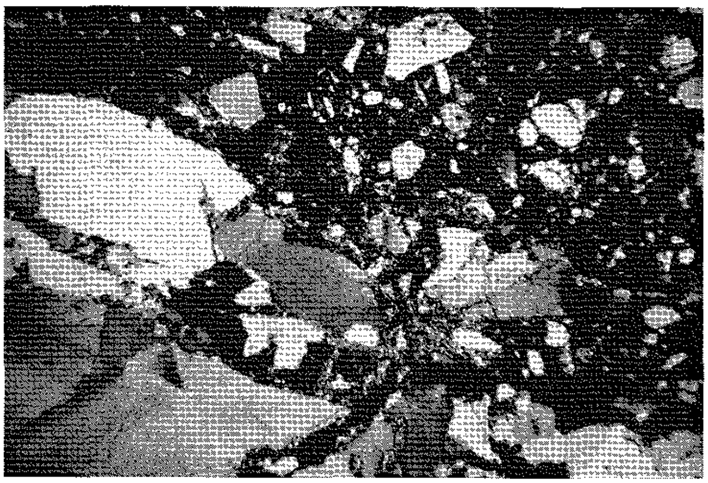

Figure 5.--Photomicrograph of brecciated quartzite from Baxter Hollow. Dark matrix is predominantly hematite crossed nicols. Long dimension about 8 mm.

Although mineral grains and rock fragments in this igneous breccia are variably strained, no uniform recrystallization is apparent in the rock as a whole. There is much evidence for the near solid-state reaction of various breccia components. Some of the large feldspar grains have been partially replaced by quartz and sericite. Radial clusters of chlorite occur in some samples as a boundary phase between argillaceous and granitic fragments. Well-crystallized muscovite has grown within irregular veinlets that transect feldspar megacrysts and continue into the matrix.

Another major Necedah outcrop is located southeast of the quarry (sec. 19, T. 18 N., R. 4 E.) and consists of a different, unbrecciated rock. The exposed ridge is glacially polished and is composed of a white to gray quartzite with recognizable, but contorted, cross beds (fig. 7). At Baraboo similar contorted structures have been interpreted as slumped cross beds oversteepened by synsedimentary deformation (Dalziel and Dott, 1970, p. 16, 154). This may be the correct interpretation at the exposure described by Dalziel and Dott, but the degree of strain and evidence of thermal metamorphism from intrusion at Necedah, Hamilton Mound (see below), and possibly Baraboo suggests the possibility of a tectonic origin for some of the contorted structures.

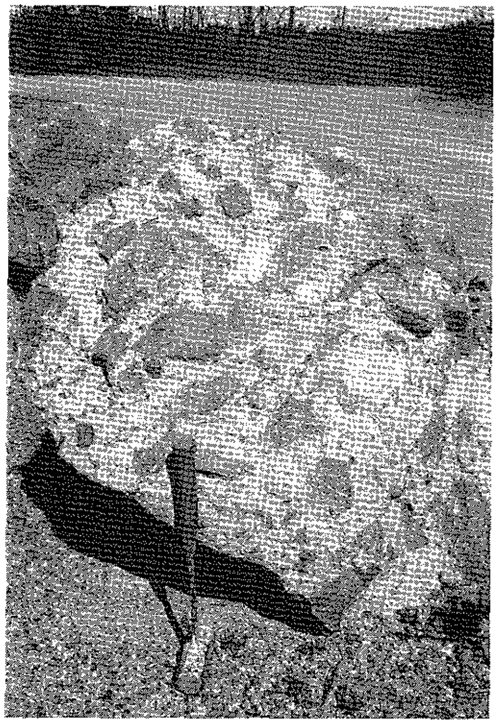

Figure 6.--Boulder of intrusion breccia at Necedah. Dark fragments are green to black quartzite and argillite. Lighter-colored materials are altered granitic rock and clay/quartz-rich matrix.

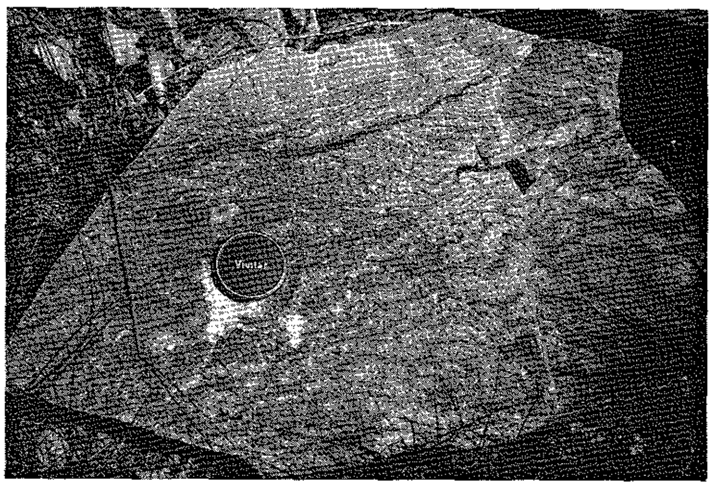

Figure 7.--Broken outcrop at Necedah showing contorted (distorted?) crossbedding.

In the unbrecciated Necedah outcrop quartz veins are present both parallel to and transecting bedding. Dark, chlorite and muscovite-coated fractures also transect bedding at high angles. Coarse-grained perthite with or without muscovite has been identified during detailed examination of some of the larger quartz veins. These veins are appropriately termed granite pegmatites.

Hamilton Mound

A cluster of quartzite ridges in northeast Adams County, Wisconsin (sec. 36, T. 20 N., R. 6 E. and sec. 31, T. 20 N., R. 7 E.) are collectively known as Hamilton Mound (fig. 1). Studies of the quartzite and intruding granitic rock (Greenberg and Brown, 1983; Taylor and Montgomery, this volume) have only recently taken place after initial description by Ostrander (1931). Granitic intrusion, quartz veins, breccia, and evidence of metasomatism, are exposed in one large quarry and are similar to corresponding features described for Baraboo.

The intrusion in the quarry is present as two discernable types, both apparently contaminated. One type is porphyritic with red microperthite and plagioclase phenocrysts in a matrix of chlorite and strained quartz. Alkali feldspar, plagioclase, and biotite are less abundant matrix phases. Taylor and Montgomery (this volume) determined little evidence for contamination of the porphyritic intrusion, but their chemical data alone is inconclusive. The nature of the other intrusive rock type points more conclusively to contamination. This second type occurs in an area within 40 m of the porphyritic variety, but is finer grained and otherwise different in appearance. The intrusive contact in this area is nearly horizontal with quartzite at the top of the quarry and magmatic rock exposed in a vertical surface for about 15 m below. Where exposed furthest below the contact, the intrusion appears least modified. Here the rock is an unusually quartz-rich medium- to fine-grained foliated granodiorite. Quartz content varies from about 40 percent to 65 percent at the contact. Even the most quartzose rocks contain sodic plagioclase, microcline, biotite, and hornblende in various proportions. Nearest the intrusive contact, rocks are greenish, some exhibiting an oddly distorted banding and inclusions composed of concentric zones rich in biotite, muscovite, chlorite, and quartz (fig. 8). The rock in the contact zone is certainly neither of unmodified sedimentary or magmatic origin. The green color is interpreted as a result of hydrothermal iron reduction. Undeformed, tourmaline-bearing pegmatite which cuts the hybrid contact-rock (fig. 9) indicate a later stage of magmatic activity.

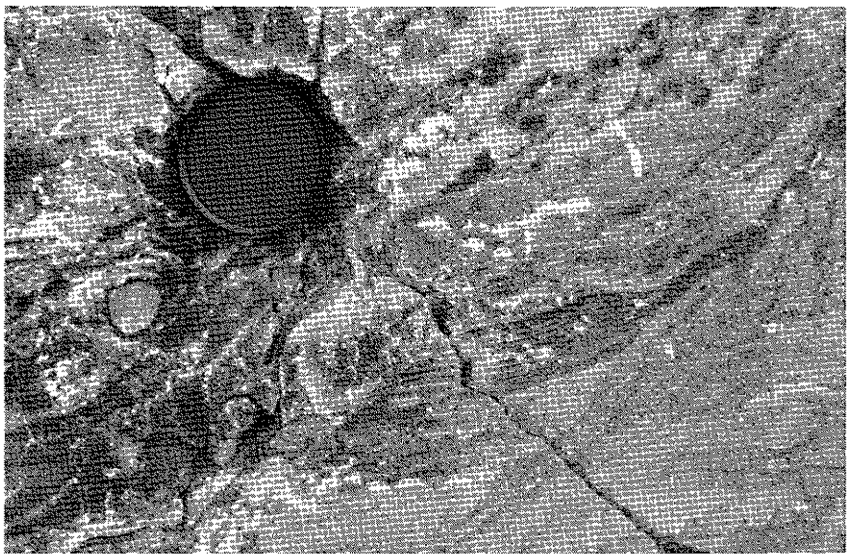

Figure 8.--Close up of outcrop at Hamilton Mound showing flow lamination (distorted cross beds?) and xenolith to upper right of lens cap. The rock shown is over 65 percent quartz.

Banding in the contact zone is not unlike the appearance of contorted cross-bedding preserved in the green quartzite above the contact (Greenberg and Brown, 1983). In another, smaller quarry away from the intrusion quartzite is purplish and contains only undeformed cross beds. This may be a specific analogue of the nature of bedding structures at Baxter Hollow and Necedah.

Silica mobility is evident at Hamilton Mound, especially within and above the porphyritic granite. The intrusion contains abundant quartz veins rich in chlorite and calcite. These veins increase in number and tend to merge with subhorizontal silicified faults and fractures which occur near the contact. Ductile and brittle strain is most intense near the contact. Small quartz veins that penetrate both altered granite and metasomatized quartzite have stylolites developed along quartz grain boundaries (fig. 10). Secondary silica, presumably mobilized by pressure solution, is observed as dark, fine-grained to cryptocrystalline matrix material in fractures, faults, and some hybrid rocks. The timing of the causal deformation is interpreted as late to post intrusion.

Brittle fracturing and brecciation occur respectively over 75 m horizontally and 25 m vertically from the porphyritic intrusion as it is now exposed. The fractures seen in one face of the quarry cut near vertical bedding at high angles (fig. 11). The fractures may represent either fold-related cleavage or jointing. Fillings of kaolin and doubly terminated quartz crystals also suggest that these fractures may be the result of magmatic hydrothermal activity.

Breccias at Hamilton Mound are present both in the larger quarry and in the smaller quarry, where there is no overt indication of intrusion. Above the intrusion the quartzite breccia appears virtually identical to most of the others described in this paper. As Taylor and Montgomery (this volume) described, some of the blocks surrounded by white vein-quartz are granite or are quartzite cut by pink granite aplite. All that this means for sure is that at least some distinctly magmatic activity preceded some hydrothermal activity. Hamilton Mound is one place where complex magmatic-hydrothermal relationships are amenable to further analysis. A temporal sequence of cross-cutting features could be derived from the well exposed and diverse types of evidence.

Waterloo

Quartzite and associated metapelite exposed near Waterloo, Wisconsin (fig. 1) are similar in composition and general appearance to rock 50 km to the northwest at Baraboo. Some of the Waterloo outcrops contain granite pegmatite dikes (fig. 12), sec. 27, T. 9 N., R. 13 E. and others (sec. 28, T. 9 N., R. 13 E.) contain andalusite-bearing, phyllitic beds (Geiger and others, 1982). Peak metamorphism and dikes are evidently the same age, about 1,500 Ma (Dott and Dalziel, 1972; C. Guidotti, unpublished data) and are interpreted as products of a major episode of anorogenic thermal activity (Greenberg and Brown, 1984; Greenberg and Brown, 1986) A penetrative foliation and cross-cutting crenulations in the phyllites predate peak metamorphism and may reflect 1,630 Ma tectonism.

The pegmatite dikes at Waterloo consist mostly of red microcline, perthitic orthoclase, muscovite, and quartz. Dike margins are sharp with only minor growth of microcline grains in the adjacent quartzite wall rock. No other metasomatic features were observed in these exposures.

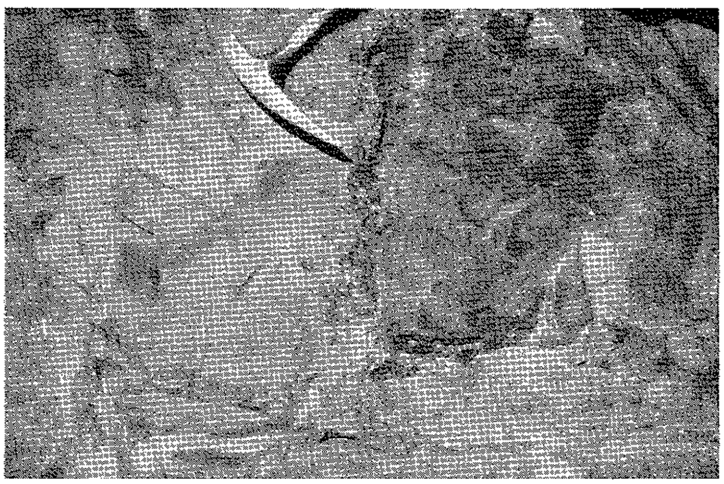

Figure 9.--The hammer points to a nearly vertical pegmatitic segregation in the quartz-rich Hamilton Mound exposure. Tourmaline crystals occur as black rods up to 2 cm in diameter.

A large outcrop area of brecciated quartzite occurs several kilometres north of the pegmatite (sec. 3, T. 9 N., R. 14 E.). Joints at high angles to bedding become vein-quartz filled as the zone of brecciation is approached. This zone is about 30 m wide along strike of bedding and perhaps twice as wide perpendicular to bedding. The breccia is well developed with dark gray quartzite fragments in white quartz matrix (fig. 13). Some quartz-crystal lined pockets are present, but no clay filling was in evidence. There is no direct evidence associating the breccia at Waterloo with intrusion.

McCaslin Mountain

McCaslin Mountain is a 40 km-long ridge of quartzite exposed along the northern margin of the intruding 1,500 Ma-old anorogenic Wolf River batholith in northeast Wisconsin (fig. 1). Studies have documented the intrusive and thermal metamorphic effects at different locations along the ridge. Chloritoid, andalusite, garnet, and sillimanite occur in various combinations in quartzose-pelitic rocks of appropriate composition at the main ridge and at other nearby exposures

Figure 10.--Photomicrograph of "shear zone" microstylolite in quartzite above granite at Hamilton Mound. Crossed nicols, long dimension about 3 mm.

Figure 11.--Well-developed fracture cleavage at high angles to bedding in Hamilton Mound quartzite. Long dimension about 20 cm.

to the north and east (Mancuso, 1960; Olson, 1984; Greenberg and Brown, 1986). The development of these metamorphic phases is attributed to contact with rock of the Wolf River batholith.

Mancuso (1960, p. 35) described outcrop including steep rock walls along the eastern end of the ridge which shows well developed brecciation. The breccia occurs above an intrusive contact where massive granite and granite dikes have been injected into fractures. Mancuso (1960) wrote that "a continuous transition exists from granite to quartzite invaded by large granite veins and dikes, to quartzite breccia healed by later secondary quartz" and "the white secondary quartz can be traced downward to an origin in a granite vein or stringer."

There has been some metasomatism of the quartzite near contact with the Hager porphyry and other granitic members of the Wolf River batholith. Pink microperthite and albite grains occur in McCaslin quartzite at various locations (Mancuso, 1960) but are particularly conspicuous in conglomeratic rocks cut by granitic dikes. The extent of metasomatic replacement at McCaslin Mountain, Waterloo, and Rib Mountain, where quartzite was intruded about 1,500 Ma, is not as great as Baxter Hollow and Hamilton Mound, where the intrusions are thought to be older. It is possible that the earlier magma was more fluid and volatile rich. It is also likely that the sedimentary rock would be more permeable and retained more of the original water of deposition 1,760 Ma than about 250 m.y. later.

Rib Mountain

Rib Mountain near Wausau, Wisconsin (secs. 7, 8, 9, 10, 15, 16, 17, T. 28 N., R. 7 E., fig. 1) is a 3.5 x 1 km quartzite xenolith in syenite of the 1,500 Ma-old Wausau granite-syenite complex

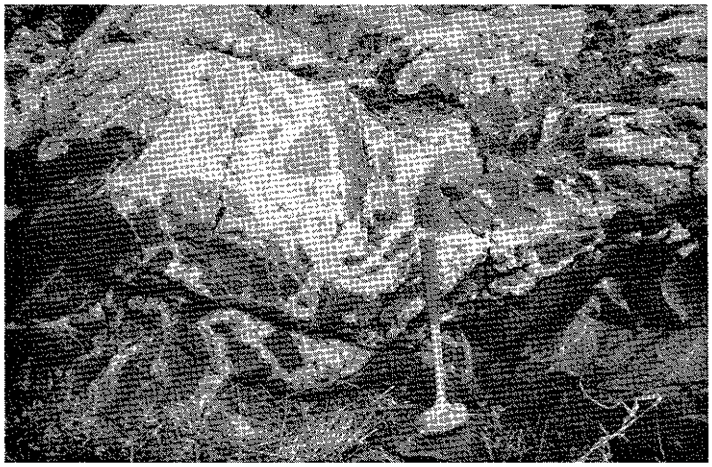

Figure 12.--Outcrop of 1,450 Ma pegmatite cutting Waterloo Quartzite. Quartzite is the darker, gray lithology along the bottom.

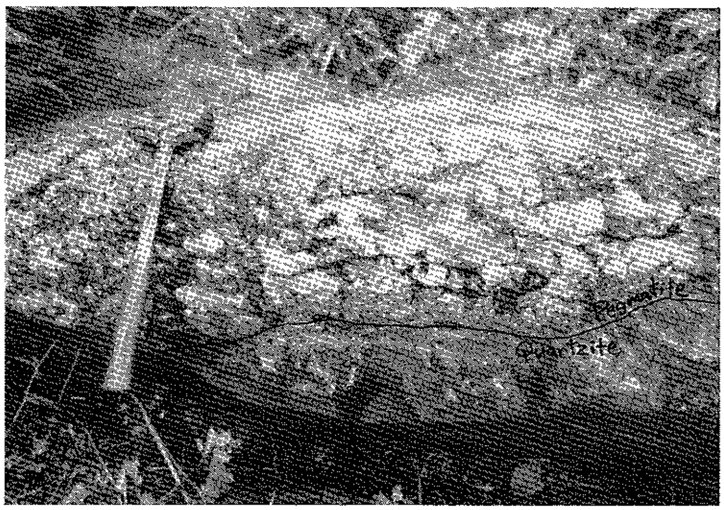

Figure 13.--Quartzite breccia outcrop at the far northern end of the Waterloo quartzite exposure area.

(LaBerge and Myers, 1983). Due to thermal metamorphism the quartzite is generally recrystallized to coarse grain sizes, and contains sillimanite in the more aluminous layers. The typical white to gray color of the quartzite may be a result of a metamorphic bleaching which mobilized iron, precipitating the iron along discrete fractures.

There is no direct evidence of granitic magma penetrating the quartzite at this location although a large, undeformed (Keweenewan-age?), basaltic dike occurs in the quarry atop Rib Mountain (sec. 8, T. 28 N., R. 7 E.). No breccias have been observed here, but large quartz veins and unusual zones of alteration exist in several areas of the quarry.

The quartz veins contain crystal pockets, some with large crystals of muscovite (to 2 cm) grown over quartz. The veins and alteration zones also contain 0.5 mm to 2 mm crystals of anatase and brookite (A. Falster, unpublished data). The exact nature of the alteration zones has not been determined. Detailed petrographic and chemical analysis will be necessary to determine the origin of the zones. The tabular geometry of the alteration which parallels some joint surfaces may imply dike or fracture control. As seen in thin section alteration consists of sericite and secondary quartz which have overgrown the preexisting rock fabric. In two samples the protolith appears to have contained pyroxene phenocrysts, possibly suggesting earlier dikes. As with other described exposures, the source of the distinctly aluminous and siliceous metasomatizing fluids is interpreted to be an intrusion acting on variably aluminous quartzite.

Battle Point

At Battle Point (sec. 9, T. 21 N., R. 2 W., fig. 1) a single outcrop of highly brecciated and fractured pink quartzite is exposed at the eastern end of a ridge oriented parallel to faint east-west bedding (Brown, 1983, p. 31). Major white quartz veins are subparallel to bedding. The general macro- and microscopic appearance of the angular rock fragments suggests a metachert. However, although all of the fragments appear to be similar, some are silicified felsic volcanic rock containing feldspar phenocryst laths replaced by sericite, clay, and quartz. These pseudomorphs were also observed in a clay-rich, quartz vein. This atypical breccia is another example of granitic magma-quartzite interaction.

Other Brecciated Quartzite

Several other quartzite breccias similar to those described here have been recognized during regional geologic mapping in northcentral Wisconsin. These other exposures include a small quarry near Vesper (Greenberg and Brown, 1983, p. 17-20), excavated farm ponds and road-side, ditch outcrops (fig. 1). None of these examples show any overt evidence of associated intrusive activity. Their one common attribute is geographic distribution in a region of extensive anorogenic magmatism.

Non-brecciated Quartzite

Among quartzite correlated with Baraboo interval rock, only the westernmost exposures (the Barron Quartzite in northwestern Wisconsin and the Sioux Quartzite in Minnesota, Iowa, and South Dakota) have experienced neither brecciation nor metasomatic alteration. One reason for the apparent absence may be the lack of detailed studies on the Barron exposures in particular. It is more likely that these only mildly deformed and metamorphosed western quartzites (Greenberg and Brown, 1984) were not in the main region of anorogenic intrusion. Keweenawan-age, diabase dikes which have been found in the Barron and Sioux contributed little more than minor contact thermal effects. Altered felsite known from subsurface data to occur in the Sioux Quartzite are possibly about 1,500 Ma (Lidiak, 1971), but these have not been well studied.

DISCUSSION

The above evidence strongly implies that brecciation and metasomatism of quartzite in central and northern Wisconsin originated with intrusion. The relationship between mostly thermal metamorphism of Baraboo interval rock and anorogenic magmatism has been previously discussed (Greenberg and Brown, 1984). The interaction between anorogenic plutons and quartzose cover rock is not well documented in the literature. Two pluton-cover rock relationships that may be pertinent to the association in Wisconsin are the nature of porphyry-copper mineralization and breccia zones developed around appinitic intrusions.

Burnham (1979) has provided a general physical-chemical framework for hydrothermal activity attending high-level granitic intrusions. His model shows in great detail how H_2O saturated melt ---> crystals + vapor produces brittle deformation, dike intrusion, and chemical alteration of wall rock. This scheme is well demonstrated around porphyry-copper host plutons. Complexities of magmatic crystallization and second boiling vapor release often develop multiple stages of hydrothermal activity and metallogenesis (Wallace and others, 1978). There can be several comagmatic generations of cross-cutting dikes and fracture-breccia systems (Burnham, 1979, fig. 3.5b). In Burnham's illustrations (p. 112, 113) and the Wisconsin examples breccia zones attain a vertical orientation from hydrothermal expansion and hydrofracting with a horizontal σ_3 (minimum stress axis).

During crystallization of volatile-rich plutons vapor build up and separation may cause fracturing of the wall rock and saturation of the fracture system in a silica-rich fluid. In porphyry-copper deposits the stockwork of quartz veins and fractures are sites of extensive sulfide mineralization. Distinctive zones of metasomatic alteration are also characteristic of porphyry systems (Lowell and Guilbert, 1970).

The quartzite-intruding magmas in Wisconsin produced physical effects similar to porphyry-copper systems, but they were chemically distinct. Neither porphyry-type mineralization nor metasomatic zonation have yet been identified in Wisconsin. Evidence of any chlorine or sulfur enrichment in the magmatic hydrothermal systems affecting the quartzites is also lacking. Other than silica, only feldspar (both K and Na varieties), phyllosilicates, iron oxide, tourmaline, calcite, and traces of fluorite were hydrothermally precipitated from mobile components within definable country rock.

There may be reasonable doubt as to the feasibility of granitic magma assimilating quartzite at Baxter Hollow or Hamilton Mound. Silica-saturated melt should not be capable of dissolving siliceous wall rocks, especially in any appreciable volume. However, the corrosive action of a volatile-rich intrusion on potentially hydrous country-rock involves vapor-rich fluid separated from the host magma (as described by Burnham, 1979) and not simply the magma itself. Chemical and petrographic data from Baxter Hollow and Hamilton Mound also suggest that the original uncontaminated magma may have been more dioritic than after intrusion. Some plagioclase laths at Baxter Hollow are zoned having cores as calcic as An_{32} with albitic rims. Textures and the crystalli- zation sequence of feldspar and mafic minerals apparent at Baxter Hollow are consistent with those in the Denzer diorite exposed 4 km to the west (fig. 1). Both diorite and granite display grano- phyric-diabasic textures with euhedral plagioclase. Smith (1983) has shown chemically that the diorite is a reasonable source of the Baxter Hollow granite. Large blocks of Denzer-type diorite are included in the granite near quartzite contacts (fig. 14). Burnham (1979, p. 104) specified that a moderately hydrous dioritic magma could crystallize plagioclase and pyroxene (also some hornblende) and enable the remaining melt fraction to dissolve relatively large amounts of quartz and potassium feldspar. These two phases are progressively incorporated into the residual melt and vapor involved in dike, vein, and hybrid-rock formation. Metasomatic quartz and microcline hybrids occur above the more mafic intrusive rock at Hamilton Mound.

Although porphyry-type mineralization may be absent from Wisconsin, the mobility of iron, fluorine, and CO_2 in the hydrothermal zone at Hamilton Mound, Baxter Hollow, and Necedah may be consistent with certain other ore-forming environments (Hauck and Kimball, 1984). Specific examples are associated with anorogenic iron-rich dioritic to granitic intrusion.

Explosion breccia (Wright and Bowes, 1968) or breccia pipe (Norton and Cathles, 1973) are phenomena related to the violent action of a water-rich vapor phase exsolved from a cooling magmatic body. The mechanism and force of vapor separation were discussed above with reference to Burnham (1979). Wright and Bowes (1968) mentioned several types of magmatic systems, including high-level granite, which may involve the development of explosion breccia. The common factor in all cases is the presence of ample volatiles. Caledonian appinite stocks from Scotland are described by Wright and Bowes (Bowes and McArthur, 1976) as classic, breccia-forming systems. The appinites are moderately alkaline dioritic rock with both quartzand amphibole-rich varieties. These compositions are similar in many respects to the more mafic varients proposed as members of the Wisconsin anorogenic suite.

The occurrence of Scottish appinite strongly implies particular structural controls (Wright and Bowes, 1968; Bowes and McArthur, 1976). The appinitic plutons and accompanying breccia are commonly exposed in antiformal structures of thick quartzite roof rock. The quartzite served as a nearly impermeable cap over the cooling magmas. In Scotland the quartzite was folded before and after intrusion (Bowes and McArthur, 1976). Folding may have allowed volatiles to collect in the hinges of antiforms and also provided fractured zones for escape of trapped fluids. In Wisconsin, the structural role of some Baraboo interval quartzite appears analogous to the appinite-suite environment. The timing of Wisconsin quartzite deformation relative to intrusion is not yet well understood, but brecciated rocks do occur in the eroded axial regions of large anticlines at Baraboo, Hamilton Mound, and perhaps elsewhere. The limited vertical exposure of the plutons associated with Wisconsin breccia typically does not allow an appreciation of the explosiveness envisioned by Bowes and McArthur (1976). At the present level of exposure, only Necedah, McCaslin Mountain, Hamilton Mound, and Battle Point breccia exhibit actual igneous fragments. Only the first two of these could be considered true magmatic breccia with igneous matrix material.

An idealized cross section through brecciated, metasomatized quartzite is depicted in figure 15. Two or more of the features shown have been observed at each of the Wisconsin exposures described above. An oversimplified sequence would place these features in the following progression from pluton outward: intrusion breccia, metasomatism, dikes, quartz veins, and quartzite breccia. There is some spatial overlap, especially with metasomatism and igneous dikes.

One additional implication can be drawn from the exposures of quartzite discussed above. It may seem strange that most areas of Baraboo-type metasedimentary rock contain quartz veins and vein quartz breccia. It has been shown that these veined exposures also commonly cap intruding granitic or dioritic plutons. The apparent coincidence suggests that intrusion-related hydrothermal quartz contributed to the preservation of some quartzite whereas other deformed but unintruded parts of the sedimentary pile were more easily eroded.

CONCLUSIONS

There is a previously unrecognized association of anorogenic intrusion with brecciated and metasomatized quartzite deposited during the Baraboo interval in central and northern Wisconsin. Specific exposures and characteristic features are summarized in table 1. Apparently the Barron Quartzite in western Wisconsin was the only major area of outcrop unaffected by overt hydrothermal activity.

The breccia is typically composed of recrystallized orthoquartzite or metachert surrounded by white, vein-quartz. The quartz-vein networks often contain open pockets of quartz crystals with or without clay and hematite. Fluid inclusion analysis from one quartzite exposure indicates a vein-quartz origin near 106 °C. With an average geothermal gradient (stable craton) this temperature would exist at pressures that may be too high to allow open crystal-pockets of sedimentary or origin groundwater. This suggests a hydrothermal origin for the quartz veins and breccia.

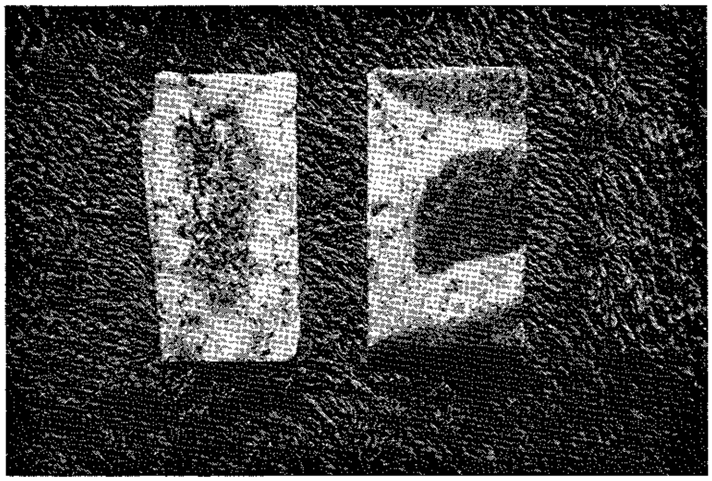

Figure 14.--Polished core samples of Denzer-type diorite inclusions in Baxter Hollow granite. Long dimensions about 12 cm.

Most of the brecciated exposures display complex metasomatic alteration of quartzite and intrusive rock. Hybrid-rock zones several metres wide span the contacts at Baxter Hollow and Hamilton Mound. Si, Al, Fe, K, and Na were the primary components mobilized in the hydrothermal systems. F, CO_2, and Ca were also present in metasomatizing fluids. The more extensive metasomatic changes described at Baxter Hollow, Hamilton Mound and Necedah were developed in conjunction with the anorogenic plutons of the older, 1,760 Ma, type. This may imply that the earlier magma was effectively wetter than the 1,500 Ma-old intrusions which generally produced less alteration. It is also possible that original water of deposition trapped in the Baraboo-type units contributed to alteration 1,760 Ma. Less water was probably available 1,500 Ma after deformation and thermal metamorphism.

Contorted bedding structures, including cross beds, appear in certain cases to be related to ductile deformation and recrystallization of metamorphosed quartzite. Similar structures had previously been attributed to synsedimentary processes, which may also be a correct interpretation in some exposures.

Two types of intrusion-country rock interaction have been evaluated for their similarity to the described features in Wisconsin. Each proves to be a reasonable model analogous to certain features. Both porphyry-copper host plutons and appinite intrusions produce well developed vein-breccia zones. Porphyry-copper deposits are also characterized by hydrothermal metasomatism. Folded quartzite roof rock appears to be especially important to the development of appinite brec- cias. Similarities to porphyry-copper magmatism and hydrothermal systems imply the possibility of economic mineralization in Wisconsin. Although sulfide enrichment has not been observed, the mo- bility of other volatiles and iron in magma intruding the quartzite is consistent with certain ore-forming environments.

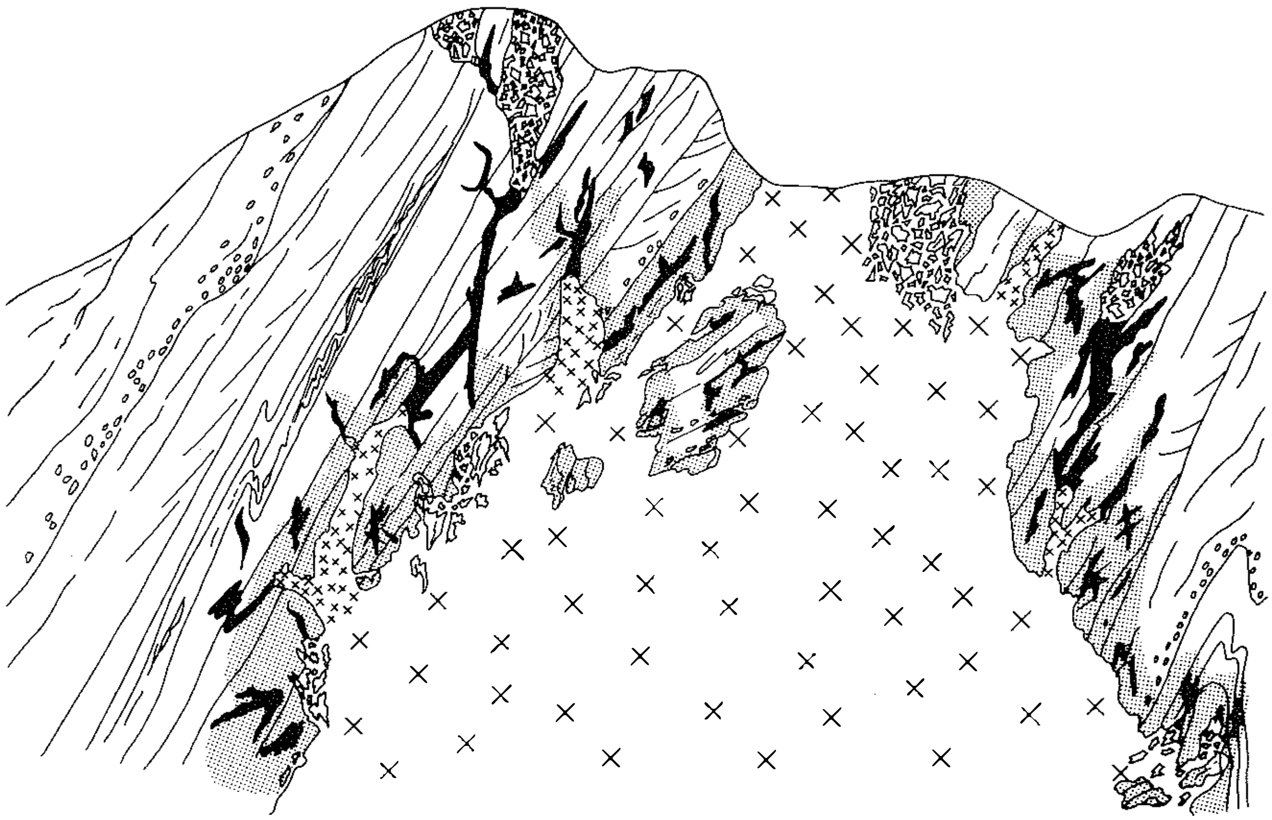

Figure 15.--Idealized cross section sketch representing the major features associated with intrusion of Baraboo-interval quartzite.

The coincidence of quartz-vein breccia with most Baraboo interval quartzite exposures is significant. Intrusions and silicification are considered to be at least partly responsible for outcrop preservation.

A final conclusion is that detailed investigations are needed to further study problems brought out in the present reconnaissance study. Metasomatism can be characterized by oxygen isotope and other geochemical analyses as well as by careful petrographic work. Trace element data would be particularly helpful to test models of hydrothermal processes and ore formation. Whenever possible, rocks intruding quartzite should be isotopically dated to provide adequate control for tectonic models.

Table 1. Features observed at various locations.

Wisconsin quartzite	Intrusion type (age)	Intrusion breccia	Quartz veins	Quartzite breccia	Hydrothermal metasomatic features	Other significant metamorphic phases
Baraboo	-	-	-	-	-	pyrophyllite
Baxter Hollow	granite-diorite (1,760 Ma?)	not observed	yes	hematite rich	sericitization, albite porphyroblasts-iron mobility, quartz-tourmaline	-
Rock Springs Area	subsurface?	-	abundant, bedding parallel near breccia	well developed	quartz-clay-hematite pockets	-
Highway 12 - South Bluff	subsurface granite	-	yes	-	clay-lined fractures	-
Necedah	granophyric granite (similar to 1,760 Ma) pegmatites, diorite(?) in subsurface	yes	bedding parallel and across bedding	yes	clay-muscovite pockets chlorite-muscovite lined fractures	-
Hamilton Mound	contaminated porphyritic granite,(1,760 Ma) foliated granodiorite, pegmatites containing tourmaline	not observed	abundant and varied, some include chlorite and calcite	contains granitic dikelets in quartzite	quartzite-intrusion hybrid rocks, Si mobility, quartz crystal clay lined fractures clasts	-
Waterloo	granite pegmatites (about 1,500 Ma) metabasalt(?) dike (1,430 Ma)	-	increase near breccias	yes	quartz crystal pockets feldspar grains in quartzite	andalusite chloritoid hornblende
McCaslin Mountain	granite and feldspar porphyry (about 1,500 Ma)	yes	grading into breccia	yes	feldspar grains in quartzite	sillimanite, andalusite, chloritoid, garnet
Rib Mountain	granite-syenite (1,500 Ma) altered mafic dike (?about 1,000 Ma?)	not observed	large and complex	(?) not observed	sericitic alteration, quartz-coarse grained muscovite pockets, anatase, brookite, tourmaline	sillimanite
Battle Point	?felsic porphyry inferred	?probably	yes	contains altered feldspar-rich clasts	sericite-clay-quartz pockets	-
Barron	basaltic dike (about 1000 Ma)	-	-	-	-	-
Others including Vesper	-	-	yes	yes, in various locations	quartz-clay pockets	-

REFERENCES CITED

Bowes, D.R., and McArthur, A.C., 1976, Nature and genesis of the appinite suite: Krystalinikum, v. 12, p. 31-46.

Brown, B.A., ed., 1983, Three billion years of geology: Wisconsin Geological and Natural History Survey Field Trip Guide Book 9, 51p.

Burnham, C.W., 1979, Magmas and hydrothermal fluids, in Barnes, H.L., ed., Geochemistry of hydrothermal ore deposits: New York, Wiley, p. 71-136.

Dalziel, I.W.D., and Dott, R.H. Jr., 1970, Geology of the Baraboo district, Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 14, 164p.

Dott, R.H., Jr., 1983, The Proterozoic red quartzite enigma in the north-central U.S.--resolved by plate collision? in Medaris, L.G., Jr., ed., Early Proterozoic geology of the Great Lakes Region: Geological Society of America Memoir 160, p. 129-141.

Dott, R.H., Jr., and Dalziel, I.W.D., 1972, Age and correlation of the Precambrian Baraboo Quartzite in Wisconsin: Journal of Geology, v. 80, p. 552-568.

Gates, R.M., 1942, Baxter Hollow granite cupola: American Mineralogist, v. 27, p. 699-711.

Geiger, C.A., 1985, A note regarding the mineralogy and sedimentology of rocks overlying the Baraboo Quartzite: Geoscience Wisconsin, v. 10.

Geiger, C.A., Guidotti, C.V., and Petro, W.L., 1982, Some aspects of the petrologic and tectonic history of the Precambrian rocks of Waterloo, Wisconsin: Geoscience Wisconsin, v. 6, p. 21-40.

Greenberg, J.K., and Brown, B.A., 1983, Middle Proterozoic to Cambrian rocks in central Wisconsin: anorogenic sedimentary and igneous activity: Wisconsin Geological and Natural History Survey Field Trip Guide Book 8, 50p.

Greenberg, J.K., and Brown, B.A., 1984, Cratonic sedimentation during the Proterozoic: an anorogenic connection in Wisconsin and the upper midwest: Journal of Geology, v. 92, p. 159-171.

Greenberg, J.K., and Brown, B.A., 1986, Deformational and metamorphic features associated with 1500 Ma anorogenic magmatism in Wisconsin: in The crust-- The significance of granites-gneisses in the lithosphere: Athens, Theophrastus Publications, S.A., p. 79-93.

Hauck, S.A., and Kendall, E.W., 1984, Comparison of Middle Proterozoic iron oxide-rich ore deposits, mid-continent U.S.A., South Australia, Sweden, and the Peoples Republic of China (abs.): Institute on Lake Superior Geology Proceedings and Abstracts, 30th (Wausau), p. 17-18.

Hinze, W.J., 1957, A gravity investigation of the Baraboo syncline region: Madison, University of Wisconsin, unpublished Ph.D. dissertation, 136p.

LaBerge, G.L., and Myers, P.E., 1983, Precambrian geology of Marathon County, Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 45, 88p.

Lidiak, E.G., 1971, Buried Precambrian rocks of South Dakota: Geological Society of America Bulletin, v. 82, p. 1411-1420.

Lowell, J.D., and Guilbert, J.M., 1970, Lateral and vertical alteration-mineralization zoning in porphyry ore deposits: Economic Geology, v. 65, p. 373-408.

Mancuso, J.J., 1960, Stratigraphy and structure of the McCaslin district, Wisconsin: East Lansing, Michigan State University, unpublished Ph.D. dissertation, 101p.

Norton, D.L., and Cathles, L.M., 1973, Breccia pipes--products of exsolved vapor from magmas: Economic Geology, v. 68, p. 540-546.

Olson, J.M., 1984, The geology of the lower Proterozoic McCaslin formation, northeastern Wisconsin: Geoscience Wisconsin, v. 9, p. 1-19.

Ostrander, A.R., 1931, Geology and structure of Hamilton Mounds, Adams County, Wisconsin: Madison, University of Wisconsin, unpublished M.S. thesis, 27 p.

Petro, W.L., 1983, Igneous rocks of the Baraboo district, Wisconsin (abs.): Institute on Lake Superior Geology Proceedings and Abstracts, 29th (Houghton), p. 33.

Rogers, J.J.W., Dabbagh, M., Olszewski, W.J., Jr., Gaudette, H.E., Greenberg, J.K., and Brown, B.A., 1984, Early poststabilization sedimentation and later growth of shields: Geology, v. 12, p. 607-609.

Smith, E.I., 1978, Precambrian rhyolites and granites in southcentral Wisconsin: Field relations and geochemistry: Geological Society of America Bulletin, v. 89, p. 875-890.

Smith, E.I., 1983, Geochemistry and evolution of the early Proterozoic, post-Penokean rhyolites, granites, and related rocks of south-central Wisconsin, U.S.A. in Medaris, L.G., Jr., ed., Early Proterozoic geology of the Great Lakes region: Geological Society of America Memoir 160, p. 113-128.

Taylor, S.M., and Montgomery, C.W., 1985, Petrology, geochemistry, and Rb-Sr systematics of the prophyritic granite at Hamilton Mound, Wisconsin: Geoscience Wisconsin, v. 10.

Wallace, S.R., McKenzie, W.B., Blair, R.G., and Muncaster, N.K., 1978, Geology of the Urad and Henderson molybdenite deposits, Clear Creek County, Colorado: Economic Geology, v. 73, p. 325-367.

Wright, A.E., and Bowes, D.R., 1968, Formation of Explosion-breccias: Bulletin Volcanologique, v. 32, p. 15-32.

Geoscience Wisconsin Editorial and Publication Policy

General Information

"Geoscience Wisconsin," a report series covering significant geoscience research pertaining to Wisconsin geology, is published by the Wisconsin Geological and Natural History Survey, University of Wisconsin—Extension. The purpose of the series is to provide increased awareness of the geoscience research done in Wisconsin and to provide a vehicle for the communication of scholarly geologic reresearch pertinent to Wisconsin. Although compilations and review papers will be considered for publication, the main object of the series is to publish high-quality, original research papers of general interest on all phases of the geology of Wisconsin.

Scope and Length of Papers

All phases of geoscience research done in Wisconsin or very closely related to Wisconsin interests will be considered for publication. All members of the professional geoscience community are encouraged to submit their scholarly papers for publication in "Geoscience Wisconsin." Students are also encouraged to submit papers on their completed thesis research.

Papers should be no longer than 25 pages including all figures, references, abstracts, nd so forth. Manuscripts exceeding 25 pages must have the approval of the editor before submission to "Geoscience Wisconsin." Draft copies for review will be double spaced with ample margins; this includes references cited. For final publication, camera-ready copy of all papers will be prepared by the Wisconsin Geological and Natural History Survey. Originals or photographs of all illustrations will be submitted at this time. Photocopies (xerographies) will not be accepted for printing. General style follows that of the U.S. Geological Survey and the Geological Society of America. Manuscripts not meeting style will be returned to the authors without review. There are no page charges.

Administrative Framework

Editor

Michael G. Mudrey, Jr., is the editor and is responsible for receiving manuscripts which are submitted. He will examine manuscripts for general style and length requirements, and he will make recommendation as to suitability for publication in "Geoscience Wisconsin." The recommendation will be submitted to the Director for a decision and the manuscript will either be rejected, returned to the author for modification, or sent to one of the associate editors for review.

After the manuscript has been reviewed by an associate editor and reviewers (specialists in the field addressed by the paper) a final decision on acceptance or rejection will be made by the editor. The manuscript, if accepted, will be returned to the author for modification, based on the recommendations of the associate editor and reviewers, and for preparation of the final copy. The final manuscript will then be submitted to the editor who will see the manuscript through its publication stages.

Associate Editors

Associate editors have been selected from a pool of geoscientists interested in Wisconsin geology. They are:

Richard A. Paull
University of Wisconsin-Milwaukee

Peter A. Nielsen
University of Wisconsin-Parkside

Kenneth R. Bradbury
Wisconsin Geological and
Natural History Survey

Lee Clayton
Wisconsin Geological and
Natural History Survey

Geoscience Wisconsin
Geological and Natural History Survey
University of Wisconsin -Extension
3817 Mineral Point Road
Madison, WI 53705
Phone: (608)262-1705

ISSN-0164-2049