Canadian Mineralogist
Vol. 12, pp. 469-474 (1974)

SUB-GREENSCHIST METAMORPHIC ASSEMBLAGES IN NORTHERN MAINE

DOROTHY A. RICHTER* AND DAVID C. ROY**

Abstract

Prehnite-pumpellyite facies mineral assemblages have been recognized in Ordovician and Silurian rocks in northern Maine. Systematic variation of the mineral assemblages permits the mapping of three zones of increasing grade within the prehnite-pumpellyite facies: a prehnite-analcime zone, a prehnite-pumpellyite zone, and a pumpellyite-epidote-actinolite zone. Local variations in μ_{CO_2} are suggested to explain the erratic distribution of chlorite-calcite assemblages. Acadian metamorphism did not exceed the prehnite-pumpellyite facies. However, the presence of lithic clasts showing prehnite-pumpellyite assemblages in Silurian greywackes suggests the possibility of Taconian metamorphism to the same grade.

Introduction

Several areas of sub-greenschist metamorphism have recently been described in the northern Appalachians. The first report of the prehnite-pumpellyite facies in lower Paleozoic rocks of the northern Appalachians region is that of Coombs *et al.* (1970) in which they describe the facies in the Big Machias Lake region of Aroostook County, Maine (Fig. 1). They found diagnostic metamorphic assemblages in intermediate to mafic volcanic rocks and greywackes ranging in age from Middle Ordovician to Early Devonian. Zen (in press), Mossman & Bachinski (1972), and Papezik (1972) have reported other occurrences of sub-greenschist facies mineral assemblages in Pennsylvania, New York, Quebec, New Brunswick, and Newfoundland.

This report summarizes the results of a petrographic study of rocks, from a large region to the north and east of the area studied by Coombs *et al.* (1970), which are discussed in more detail in Richter & Roy (MS submitted 1974). Included in our study were thin sections examined by Coombs *et al.* which were kindly provided to us by R. Horodyski; these samples allowed us to incorporate their assemblage information on the map shown in Figure 2. Our purpose was to determine the extent of the prehnite-pumpellyite facies in a region already extensively mapped by Roy & Mencher (in press) and shown to contain rocks of suitable composition to support mineral assemblages indicative of sub-greenschist metamorphism. In addition, we wished to determine the distributions of subfacies within the prehnite-pumpellyite facies suggested, but not mapped, by Coombs *et al.*

* Dept. of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Mass. 02139.

**Dept. of Geology and Geophysics, Boston College, Chestnut Hill, Mass. 02167.

General Geology

The geology of central Aroostook County, Maine (Fig. 1) has been mapped by Boucot *et al.* (1964), Horodyski (1968), Roy (1970), Boone (1970), and Roy & Mencher (in press). Rocks ranging in age from Middle Ordovician to Early Middle Devonian are exposed in the northeast-trending Pennington Mountain Anticlinorium and Ashland Synclinorium and numerous smaller anticlines and synclines such as the Castle Hill Anticline and the Chapman Syncline. The Pennington Mountain Anticlinorium is the northeast extension of the Munsungun Anticlinorium of Hall (1970) and the Bronson Hill-Boundary Mountain Anticlinorium. The oldest rocks exposed in the core of the Pennington Mountain Anticlinorium are Ordovician, but complex synclinal infolds of Siluro-Devonian rocks are present. Silurian and Devonian rocks predominate in the Ashland Synclinorium which lies to the east of the Pennington Mountain Anticlinorium and to the west of the Aroostook-Matapedia Anticlinorium of Pavlides *et al.* (1964).

The main rock types in the area are shale and slate, lithic greywacke and arenite, conglomerate (with abundant volcanic clasts), submarine mafic and intermediate volcanic rocks (including abundant pyroclastic rocks), and bedded chert (Roy & Mencher, in press). The two formations which are of most interest to this study are the Winterville and Frenchville formations, the distributions of which are shown in Figure 1.

The Winterville Formation is Middle to Late Ordovician in age. It is exposed in the core of

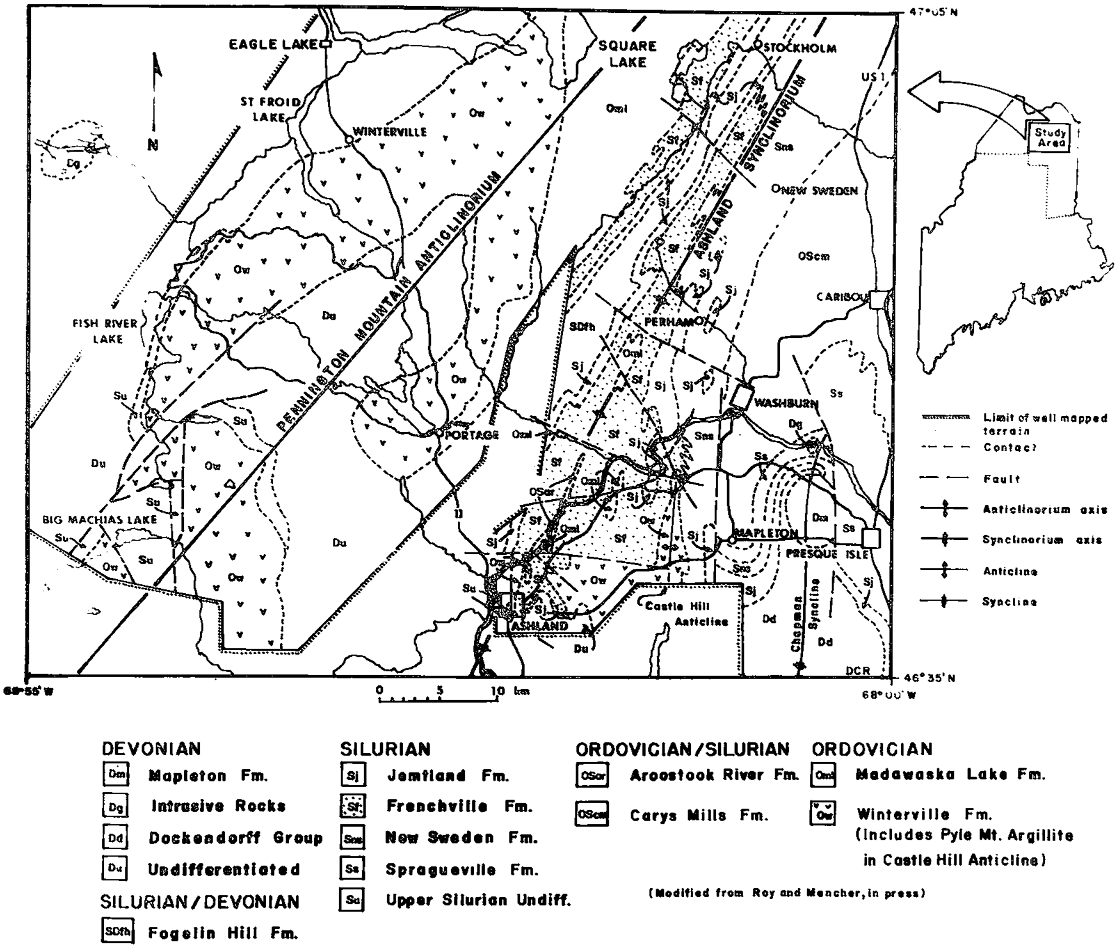

FIG. 1. Generalized geologic and tectonic map of central Aroostook County, Maine. The inset map of Maine shows the location of the study area and the boundary of Aroostook County.

the Pennington Mountain Anticlinorium and in the cores of anticlines in the Ashland area and the Castle Hill Anticline. The formation is a series of more than 1500 m of mafic to intermediate volcanic rocks interbedded with shale, bedded chert, and greywacke. The volcanic rocks include some pillow lavas and shallow intrusive bodies, but are predominantly pyroclastic. The Winterville correlates with similar rocks in the Munsungen Anticlinorium in the Spider Lake area of Maine (Hall 1970), and regionally with the Ammonoosuc-Dixville volcanic belt farther southwest in central New England.

The Frenchville Formation is a sequence of 1100 m of Early Silurian clastic sedimentary rocks which are largely confined to the Ashland Synclinorium. Roy (1973) subdivides the formation into five provisional members: the greywacke member, conglomerate member, feldspathic sandstone member, sandstone-slate member, and the quartzose sandstone member. The greywacke and conglomerate members contain abundant pebbles of volcanic rocks clearly derived from the Winterville Formation. Metamorphic mineral assemblages characteristic of the prehnite-pumpellyite facies are found most commonly in those two members.

Two other formations have yielded critical mineral assemblages — the Aroostook River and Jemtland formations. The Aroostook River Formation is 600 m thick and consists of lithic greywacke, conglomerate, and slate. The formation is pre-Frenchville in age. The volcanic detritus which is abundant in the formation was also derived from the Winterville terrane.

The Jemtland Formation is a unit of thinly bedded calcareous shale and calcareous greywacke showing turbidite features (Roy 1970).

The formation overlies the older Silurian units conformably. A marker horizon of devitrified aquagene tuff up to 20 m thick in the middle of the formation in the Stockholm area contains pumpellyite in trace quantities.

Metamorphism

Metamorphic mineral assemblages characteristic of the prehnite-pumpellyite facies were identified in samples from the Winterville, Aroostook River, Frenchville, and Jemtland formations. The mineral assemblages show systematic areal variations and we have therefore defined three metamorphic zones on the basis of the variations (Fig. 2). The data are based on examination of approximately 250 thin sections, including 39 which were used in the Coombs *et al.* (1970) study. The localities bearing critical assemblages are plotted in Figure 2. Diagnostic assemblages were identified in 56 of 138 thin sections of the Winterville Formation, 41 of 101 thin sections of the Aroostook River and Frenchville formations, and 5 of 9 thin sections of tuff in the Jemtland Formation.

Both the igneous and sedimentary rocks retain their pre-metamorphic textures in hand specimen. Igneous rocks are uniformly non-foliated throughout the area, regardless of metamorphic zone. Sandstones display a variety of primary sedimentary features such as ripple marks, parallel and cross laminations, and graded bedding.

In thin section, the degree of recrystallization is never so great as to completely obliterate primary textures. In the igneous rocks, the metamorphic minerals form veins and amygdule fillings, or partly or completely replace original minerals such as plagioclase and augite. Metamorphic minerals also appear as rims and overgrowths on primary minerals and as minute euhedral crystals in the matrix of pyroclastic rocks. In the sedimentary rocks, metamorphic

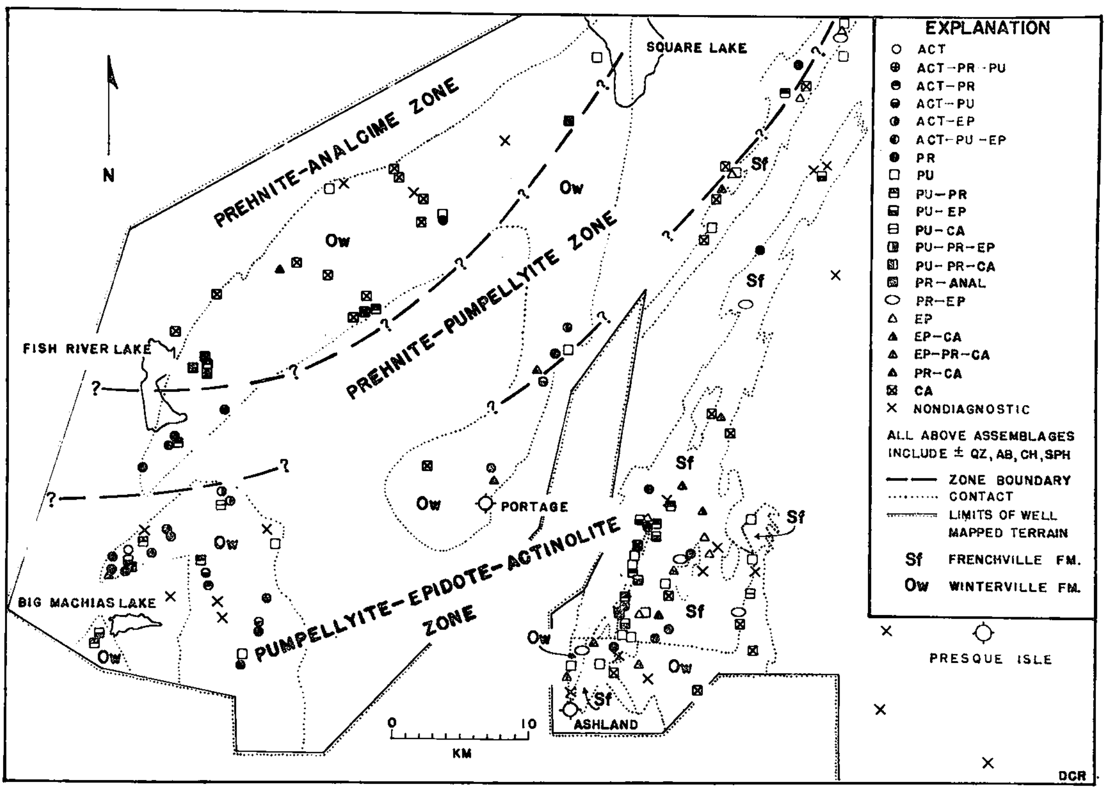

FIG. 2. Map showing the distribution of metamorphic mineral assemblages and metamorphic zones in central Aroostook County, Maine. Each symbol represents one assemblage. Symbols for more than one sample are combined where the samples are crowded. The dotted lines outline the Winterville and Frenchville formations. Abbreviations used in the legend are: Act = actinolite; Pr = prehnite; Pu = pumpellyite; Ep = epidote; Ca = calcite; Sph = sphene; Ab = albite; Anal = Analcime.

minerals occur as partial replacements of lithic clasts, overgrowths on monomineralic detrital grains, and euhedral crystals disseminated in recrystallized matrix. Calcite may form all or part of the cement in the sandstones and is rarely seen as a clast. Quartz appears as overgrowths on primary quartz clasts.

In several thin sections of greywacke it is difficult to decide whether a monomineralic ovoid aggregate of a metamorphic mineral such as pumpellyite or epidote is detrital, a replacement of a clast, or recrystallized from the matrix. However, in a few sections delicate aggregates of epidote and pumpellyite are clearly secondary and of metamorphic origin.

The abundance and grain size of the metamorphic minerals increase with metamorphic grade in the igneous rocks of the Winterville Formation but not in the sedimentary rocks in the Ashland Synclinorium.

Metamorphic assemblages are based on those minerals which appear to be stable in a 1 mm^2 field of view although the different phases may not be in actual contact (Zen, in press). The assemblages discussed here all include albite, chlorite, and sphene $\pm$ quartz, white mica, and hematite.

Prehnite-analcime zone

The prehnite-analcime zone is the lowest-grade zone in the area. It is thus far only recognized in the northwest part of the area in volcanic rocks and lithic greywacke of the Winterville Formation. The zone is defined by the coexistence of analcime with prehnite in quartz-free volcanic rocks. The other assemblages in the zone occur most commonly in rocks with minor amounts of quartz. Partial assemblages observed in this zone are:

analcime - prehnite - chlorite - calcite
analcime - prehnite - chlorite
prehnite - chlorite - calcite
prehnite - chlorite
prehnite - pumpellyite - chlorite - calcite
pumpellyite - chlorite
chlorite - calcite

Prehnite-pumpellyite zone

A prehnite-pumpellyite zone seems to be present in the central part of the study area (Fig. 2). The zone contains mineral assemblages similar to the prehnite-analcime zone but lacks analcime. The southern limit of this zone is defined by the first appearance of epidote and/or actinolite. The observed partial assemblages are:

prehnite - chlorite
prehnite - chlorite - calcite
prehnite - chlorite - pumpellyite - calcite
prehnite - chlorite - pumpellyite
pumpellyite - chlorite
chlorite - calcite

Pumpellyite-epidote-actinolite zone

The highest-grade zone is the pumpellyite-epidote-actinolite zone. It is well-documented in the Winterville Formation and in Silurian greywackes of the Ashland Synclinorium. The zone is defined by the appearance of epidote-pumpellyite, and actinolite-pumpellyite assemblages. Actinolite, which forms overgrowths on augite, occurs only in six samples of volcanic rocks of the Winterville Formation in the southwestern part of the area and not in greywacke. Epidote, on the other hand, is abundant in both greywacke and volcanic rocks of the area. The observed partial assemblages for this zone are:

prehnite - pumpellyite - chlorite
prehnite - chlorite
prehnite - chlorite - clinozoisite
prehnite - calcite
pumpellyite - chlorite
pumpellyite - chlorite - clinozoisite
pumpellyite - calcite
epidote - pumpellyite - chlorite
epidote - prehnite - chlorite
epidote - chlorite
epidote - calcite
epidote - prehnite - calcite
actinolite - epidote - chlorite
actinolite - pumpellyite - chlorite
actinolite - chlorite
actinolite - prehnite
actinolite - prehnite - pumpellyite

Discussion and Conclusions

All the metamorphic mineral assemblages of central Aroostook County, Maine, are consistent with the prehnite-pumpellyite facies as defined by Coombs (1960). The epidote- and actinolite-bearing rocks of the highest-grade zone suggest that the conditions of metamorphism approached those of the greenschist facies, but the large number of mixed prehnite and pumpellyite assemblages in the same area precludes defining a change into the greenschist facies.

Numerous samples in all three zones seem to be of a bulk chemical composition which should support calcium-alumino-silicate minerals diagnostic of sub greenschist metamorphism. These rocks instead have the partial assemblage chlorite-calcite. There does not seem to be a systematic distribution of chlorite-calcite rocks in the three zones. Coombs *et al.* (1970) suggest that chlorite-calcite rocks in the Big Machias Lake area are a product of local metasomatism. Albee & Zen (1967) show that a relatively high μ_{CO_2} can suppress the formation of minerals characteristic of the prehnite-pumpellyite facies in favour of calcite-clay assemblages.

Calcite-chlorite is the metamorphic assemblage found in the intermediate and mafic volcanic rocks which lie more than 15 km east of Ashland where all the units are calcareous (for example, the New Sweden and Carys Mills formations). The chemical potential of CO_2 was therefore probably higher in the western part of the study area than in the central and western parts. We also suggest that since μ_{CO_2} was not uniform regionally, it might also have varied locally. Such a local variation might explain why neighbouring mafic rocks of similar major-mineral composition contain either prehnite-pumpellyite or calcite-chlorite assemblages.

The determination of the age of the metamorphism is made difficult by the complex sedimentation and deformation history of this area. Northern Maine was affected by at least three periods of tectonism: the Ordovician Taconian orogeny, the Silurian Salinic disturbance, and the Devonian Acadian orogeny. The Taconian orogeny produced uplift and gentle folding in the western part of the area whereas the Carys Mills lithofacies in the eastern part of the area remained submarine and sedimentation continued into the Silurian. The Taconian orogeny produced no recognizable cleavage in pre-Silurian rocks. The Salinic disturbance is marked in northern Maine by local disconformities and very slightly angular unconformities. The disturbance does not seem to have produced any folding or cleavage and was apparently restricted to the Presque Isle - Ashland, and Fish River Lake areas (Boucot *et al.* 1964; Pavlides *et al.* 1964). The Acadian orogeny was the major tectonic event which affected northern Maine. It produced the major folds and regional cleavage.

Metamorphic mineral assemblages diagnostic of sub-greenschist metamorphism have been identified in Ordovician and Silurian rocks. Coombs *et al.* (1970) report prehnite-pumpellyite in pre-Acadian lower Devonian volcanic rocks in the Big Machias Lake region. It seems clear, then, that Acadian metamorphism did not exceed the prehnite-pumpellyite facies in the portion of northern Maine examined in this study.

The possibility of Taconian metamorphism cannot be entirely eliminated. The common presence of pumpellyite, prehnite, and epidote in volcanic clasts in the Silurian lithic greywackes might well be explained by pre-Frenchville metamorphism of the source rocks. There are also ovoid aggregates of pumpellyite and epidote in the Aroostook River and Frenchville sandstones which may be either detrital or authigenic. If the aggregates are detrital, they can be cited as further evidence for Taconian metamorphism. There is no petrographic evidence of retrograde metamorphism of Ordovician rocks. There is also no evidence of high-pressure type metamorphism or melange deposits (Roy & Mencher, in press) in the area which would support the suggestion of Bird & Dewey (1970) of an Ordovician island arc-oceanic trench in northern Maine.

ACKNOWLEDGMENTS

We have benefited greatly from discussions with E-an Zen, Sharon Bachinski, Gary Boone, Priscilla Perkins, James Skehan, S. J. and J. Christopher Hepburn. The loan of 57 thin sections by Ely Mencher, and 39 thin sections by Robert Horodyski helped make this study possible.

REFERENCES

BIRD, J. & DEWEY, J. (1970): Lithosphere plate-continental margin tectonics and the evolution of the Appalachian orogen. *Geol. Soc. Amer. Bull.* 81, 1031-1060.

BOONE, G. M. (1970): The Fish River Lake Formation and its environments of deposition. *Maine Geol. Surv. Bull.* 23, 27-41.

BOUCOT, A. J., FIELD, M. T., FLETCHER, R., FORBES, W. H., NAYLOR, R. S. & PAVLIDES, L. (1964): Reconnaissance bedrock geology of the Presque Isle quadrangle, Maine. *Maine Geol. Surv. Quad. Map Series* 2, 1-123.

COOMBS, D. S. (1960): Lower grade mineral facies in New Zealand. *Internat. Geol. Congr. XXI*, Copenhagen, Rept. Pt. xiii, 339-351.

———, HORODYSKI, R. J. & NAYLOR, R. S. (1970): Occurrence of prehnite-pumpellyite facies metamorphism in northern Maine. *Amer. J. Sci.* 268, 142-156.

HALL, B. A. (1970): Stratigraphy of the southern end of the Munsungun Anticlinorium, Maine. *Maine Geol. Surv. Bull.* 22.

HORODYSKI, R. J. (1968): *Bedrock Geology of Portions of the Fish River Lake, Winterville, Greenlaw, and Mooseleuk Lake Quadrangles, Aroostook County, Maine.* M.S. Thesis, Mass. Inst. Technol.

MOSSMAN, D. & BACHINSKI, D. (1972): Zeolite facies metamorphism in the Silurian-Devonian fold belt of northeastern New Brunswick. *Can. J. Earth Sci.* 9, 1703-1709.

PAPEZIK, V. S. (1972): Burial metamorphism of late Precambrian sediments near St. John's, Newfoundland. *Can. J. Earth Sci.* 9, 1568-1572.

PAVLIDES, L., MENCHER, E., NAYLOR, R. S. & BOUCOT, A. J. (1964): Tectonic features of eastern Aroostook County, Maine. *U.S. Geol. Surv. Prof. Paper* 501-C, 28-38.

ROY, D. C. (1970): *The Silurian of Northeastern Aroostook County, Maine.* Ph.D. Thesis, Mass. Inst. Technol.

——— (1973): The provenance and tectonic setting of the Frenchville Formation, northeastern Maine. *Geol. Soc. Amer. Program Abstr.* 5, 214.

——— & MENCHER, E. (in press): Ordovician and Silurian stratigraphy of northeastern Aroostook County, Maine. *Geol. Soc. Amer. Spec. Paper.*

ZEN, E-AN (in press): Prehnite and pumpellyite bearing mineral assemblages, west side of the northern Appalachian fold belt, Pennsylvania to Newfoundland. *J. Petrology.*

Manuscript received July 1974, emended September 1974.