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PREHNITE-PUMPELLYITE FACIES METAMORPHISM OF LATE PRECAMBRIAN ROCKS OF THE AVALON PENINSULA, NEWFOUNDLAND

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Abstract

A preliminary study of mineral assemblages at several selected localities shows that the late Precambrian volcanic and sedimentary rocks of the Avalon Peninsula of Newfoundland have been affected by metamorphism grading from the prehnite-pumpellyite to the greenschist facies. A broad prehnite zone in the eastern part of the peninsula is followed by a relatively narrow zone of prehnite and pumpellyite south of Conception Bay, which in turn grades westward into an actinolite zone without pumpellyite on the Isthmus of Avalon and in the western part of the Avalon Platform. The combined width of the prehnite and pumpellyite zones is about 40 km. Pumpellyite is developed best in the basalt flows at the western flank of the Harbour Main volcanic belt. The metamorphic zones seem to follow the northerly regional trend typical of the Avalon rocks; the metamorphic grade increases in the direction of tighter folding and increasing penetrative deformation, which indicate increasing tectonic stress. A diffuse thermal aureole, indicated by local development of actinolite, follows the contacts of the Holyrood granitoid pluton in the central part of the peninsula.

The formation of prehnite near St. John's was contemporaneous with the tectonic stresses that resulted in the open folding of the Late Precambrian sediments. As these are believed to have been related to the Acadian orogenic events, the age of the low-grade metamorphism is tentatively considered to be Acadian (Devonian).

Introduction

The Late Precambrian rocks of the Avalon Peninsula have been systematically mapped and described by several workers (*e.g.* McCartney 1967; Rose 1952), but little attention has been paid so far to their metamorphic grade. McCartney (1967), noting the lack of penetrative deformation and the excellent preservation of primary structures, believed the rocks to be generally unmetamorphosed, although locally modified by thermal and metasomatic effects. Rose (1952) stated in passing that the volcanic rocks of the Harbour Main Group were "regionally metamorphosed" (p. 15); his brief rock descriptions (*e.g.* p. 16) appear to imply a greenschist facies of metamorphism. More recently, Papezik (1972) reported mineral assemblages characteristic of the prehnite-pumpellyite facies in Hadrynian sandstones near St. John's. Subsequent work, summarized in this paper, shows that such assemblages are developed at many other localities, and are in fact characteristic of the Late Precambrian rocks of the central and eastern part of the Avalon Peninsula from the western shore of Conception Bay eastwards, across a distance of 40 km (Fig. 1).

General Geology

The Avalon Peninsula is an area of considerable structural, chemical and petrological complexity. In general, it consists of an elongated northerly-trending dome, with the predominantly volcanic rocks of the Harbour Main Group forming its core and the dominantly sedimentary rocks of the Conception, Cabot, Hodgewater and Musgravetown Groups its flanks. The grey siliceous siltstone and sandstone of the Conception Group can be traced around the southern part of the central core; the overlying coarser-grained sandstone and conglomerate (with minor shale) of the Cabot Group in the east and the Hodgewater and Musgravetown Groups in the west are probably stratigraphically equivalent, but because of their physical separation cannot be correlated with certainty. The volcanic core is intruded by a high-level granitoid pluton, the Holyrood batholith. These Late Precambrian rocks are locally overlain by discontinuous patches of Cambro-Ordovician sediments, generally flat-lying or gently dipping in the east, tightly folded in the west, south of Trinity Bay (Fig. 1).

In detail, the geology is relatively complex. The Avalon rocks are both folded and intricately faulted; block-faulting, from outcrop to regional dimensions, is one of the dominant tectonic features of the volcanic core. The intensity of structural deformation increases in general from east to west. Two northerly-trending fault zones of regional extent divide the Harbour Main volcanic belt into three blocks. The eastern block consists mainly of massive to pillowed basaltic flows and pyroclastics, with a few rhyo-

lite domes. The western block is characterized by subaerial pyroclastic rocks interbedded with fluvial sediments; the volcanic rocks include several belts of well-preserved ignimbrites, overlain by amygdaloidal basaltic flows. It is probable that the two blocks represent different levels of the original volcanic pile. The central block is dominated by the granitoid pluton, the

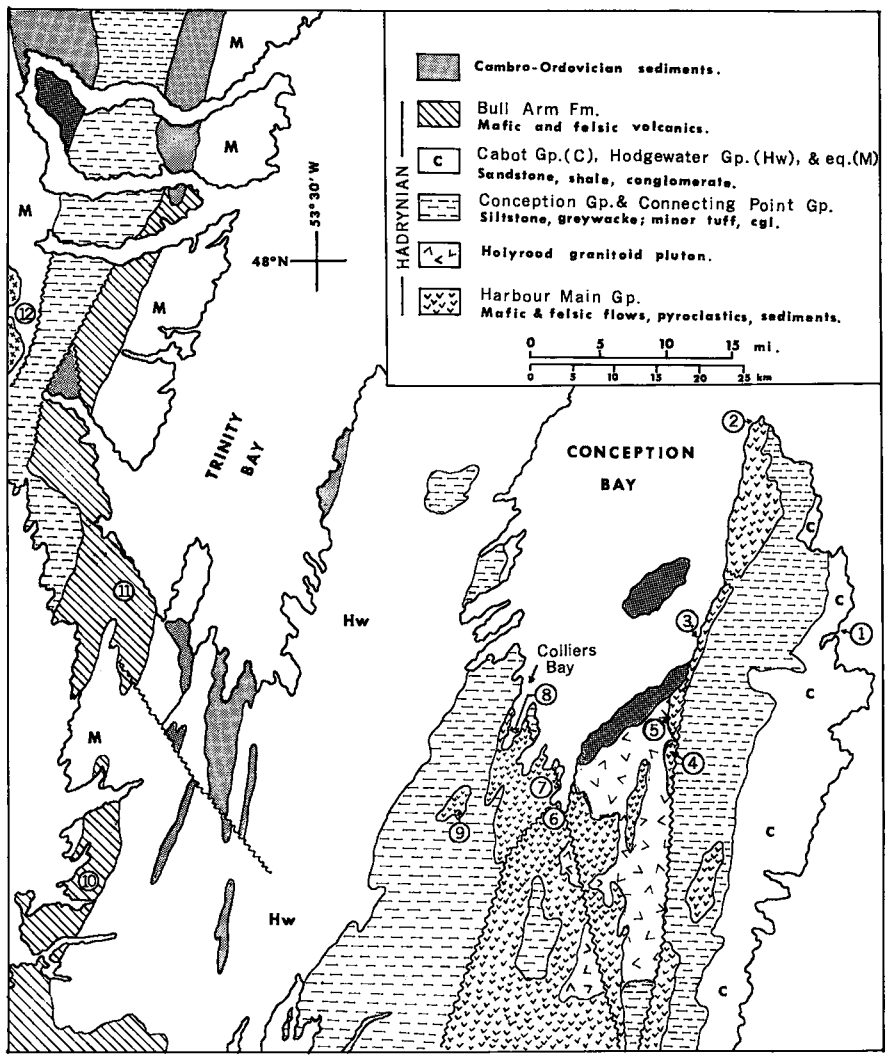

FIG. 1. Geology of the northern part of the Avalon Peninsula, Newfoundland; simplified from McCartney (1967) and Rose (1952). Numbers in circles refer to localities discussed in text. Note: x-pattern near loc. 12 — Powder Horn intrusive complex. "M" — Musgravetown Group.

Characteristic minerals at numbered localities:

1. Prehnite, qz, cc, chl, ab
2. Ab, chl, ep, cpx
3. Stilbite, qz
4. Act, ep, chl, ab, qz
5. Pyrophyllite, sericite, qz
6. Prehnite, cc, qz
7. Celadonite, chl, cc, hem
8. and 9. Pumpellyite, prehnite, cc, ep, chl, qz, adularia
10, 11, and 12. Act, ep, chl, ab, qz

intrusion of which caused metasomatic alteration of the adjacent volcanic rocks. The contact aureole, varying greatly in width and intensity, includes several lenses of massive pyrophyllite.

Most of the Avalon rocks show very little penetrative deformation; even such delicate structures as shards, flow-banding, *etc.* are perfectly preserved at many localities. In general, schistosity is confined to relatively narrow shear-zones of local extent.

The rapid variations in lithology even over short distances greatly complicate the tracing of regional distribution of low-grade metamorphic assemblages. A systematic study of the metamorphism of the Avalon rocks, now in progress, will thus require several years for its completion. This preliminary report describes only the characteristic metamorphic assemblages at a number of selected localities across the Avalon Peninsula, and draws several tentative conclusions from their distribution. (All localities mentioned below are shown on Fig. 1).

Metamorphism

Prehnite zone

On the eastern outskirts of St. John's (Loc. 1) prehnite is found in fine-grained feldspathic sandstone of the Signal Hill Formation, part of the Cabot Group. The mineral appears in a system of veins, together with varying amounts of quartz, calcite and chlorite, and as an interstitial mineral in the sandstone matrix where it forms numerous small diffuse patches. It is restricted to a stratigraphic layer about 150-250 meters thick, close to the contact between Signal Hill sandstone and the underlying St. John's shale; above this layer the vein assemblage changes rapidly from quartz-calcite-prehnite ± chlorite to quartz-chlorite-albite. Pumpellyite has not been found in this area (Papezik 1972).

The predominantly basic volcanic rocks of the eastern block, studied in some detail near Cape St. Francis (Loc. 2) show only a non-diagnostic mineral assemblage of albitized plagioclase, minor clinopyroxene, chlorite, epidote, sphene and iron oxides, with some carbonate. Similar assemblages have been reported by Maher (1972). However, a few thin (1-2 cm) veins cutting basic volcanics of the eastern block near St. Phillips (Loc. 3) contain quartz and stilbite; the rock shows evidence of silicification adjacent to the fractures. At present, this is the only known occurrence of a zeolite on the Avalon Peninsula. Such stilbite-bearing veins are known from other low-grade metamorphic areas (*e.g.* Taringatura district, New Zealand; Coombs *et al.* 1959) and are considered to be of late, post-tectonic, low-temperature origin.

In the central block, volcanic rocks adjacent to the Holyrood granitoid pluton have been modified by thermal metamorphism and metasomatism related to the intrusion. Within the diffuse contact aureole, which may be several km wide, actinolite appears in addition to the ubiquitous epidote and chlorite (Loc. 4). Clinopyroxene, where present, is partly to almost completely altered to fibrous pale greenish actinolite, in contrast to the generally unaltered pyroxene of the western and eastern blocks. Metasomatism has played a prominent role within the contact aureole. Rhyolitic flows and pyroclastics in the vicinity of the pluton have been altered along local shear-zones to a fine-grained assemblage of quartz, sericite and pyrophyllite (Loc. 5); this alteration was probably caused by acid (sulphate-bearing) solutions originating in the granite, in the temperature range of 200-250°C and under P_{H_2O} of about 2 kb (Keats 1970).

To the west of the Holyrood batholith, prehnite reappears in a few thin (1-2 cm) veins cutting a thick section of reddish sandstones and conglomerates of the Harbour Main Group (Loc. 6). The milky white prehnite is here associated with minor quartz and calcite. About 1 km to the west (Loc. 7), an oxidized porphyritic sill of basaltic composition contains abundant small (0.2 to 1 mm) amygdules filled with grass-green celadonite and minor amounts of calcite, chlorite and hematite. Celadonite, a relatively common mineral in sub-greenschist metamorphic assemblages, is considered to be characteristic of the zeolite facies, disappearing before the pumpellyite stage is reached (*e.g.* Coombs *et al.* 1959; Brown 1961). Although no zeolites have been found here, a very low grade of metamorphism is indicated at this point.

Pumpellyite zone

Pumpellyite appears first at the western flank of the Harbour Main volcanic belt, near Colliers Bay (Loc. 8). The rocks at this locality consist of a series of steeply dipping ash-flow tuffs, facing west, interbedded with fluvial and lacustrine sediments and overlain by basaltic lava flows of mildly alkalic composition (Papezik 1969, 1970). Three separate ash-flow sheets have been identified on the small peninsula to the east of Colliers Bay. The western (*i.e.* stratigraphically highest) sheet contains several units of tuff-breccia characterized by the presence of mixed felsic and mafic fragments; in several units, the dark green mafic pumice fragments (up to 1 cm long) are partly or completely re-

crystallized to a fine-grained granular assemblage of epidote, chlorite and pumpellyite. In addition, pumpellyite is present sporadically in some of the more basic welded-tuff units. In a conspicuous black welded-tuff sheet, a thin quartz veinlet about 1 mm thick and 12 mm long contains from one end to the other: a rosette of grass-green pumpellyite (Fig. 2); an intergrowth of green prismatic pumpellyite, yellow pistacitic epidote, cloudy prehnite, pale green chlorite and quartz; a prehnite-chlorite assemblage with minor amounts of granular epidote and sphene; a (relatively) coarse-grained prehnite-chlorite assemblage; a 1 mm rosette of yellow epidote; and a granular assemblage of epidote, chlorite, quartz and sphene. This is a good illustration both of the typical mineral assemblages of the prehnite-pumpellyite zone and of their variability even over very short distances. Lack of metamorphic equilibrium is indicated in this section by the presence of celadonite in some of the mafic fragments, even in units containing the fine-grained epidote-pumpellyite clusters mentioned above.

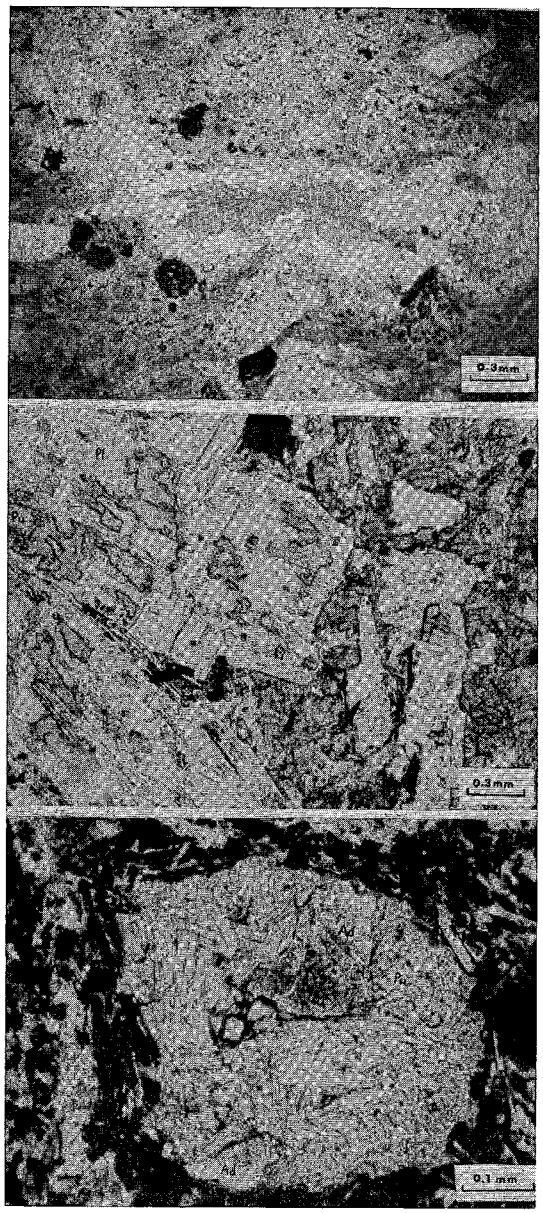

FIG. 2. Pumpellyite rosette in a quartz veinlet. Black welded tuff, Finn Hill, Colliers Bay. Loc. 8.

FIG. 3. Pumpellyite replacing plagioclase; interstitial augite shows no sign of alteration. Gabbro, Gushue's Pond area. Loc. 9.

FIG. 4. Prismatic pumpellyite and cloudy adularia filling an amygdule. Basalt flow west of Colliers Bay. Loc. 8.

Pumpellyite is best-developed in the massive and amygdaloidal basaltic flows to the west of Colliers Bay (Loc. 8). The rocks consist mainly of albitized plagioclase, unaltered calcic augite, and variable amounts of olivine now completely altered to chorite and hematite; chlorite, epidote, sphene and magnetite are minor accessory minerals. Pumpellyite appears in two forms: as small patches partly replacing plagioclase (Fig. 3), and as thin prismatic crystals filling small amygdules together with varying amounts of epidote, prehnite, calcite, chlorite and adularia (Fig. 4). The pumpellyite in amygdules is typically lighter green than in the ash-flow tuffs and breccias to the east of the bay; the maximum length of the pumpellyite prisms is about 0.4 mm.

The pumpellyite is unevenly distributed in the volcanic pile; some flows are noticeably richer in pumpellyite than others in the same sequence, reflecting probably local variations in the chemical activities of water and CO_2. Even within short distances, mineral assemblages are highly variable; the following amygdule fillings were noted in a single thin-section:

epidote-pumpellyite-adularia-quartz-sphene
epidote-pumpellyite-calcite-chlorite-adularia
pumpellyite-chlorite-adularia-sphene
pumpellyite-chlorite-sphene
pumpellyite-adularia
chlorite-adularia
calcite-adularia

In some brecciated flows, prehnite appears in place of pumpellyite in amygdules and larger cavities, commonly with calcite. A few veins and patches of fine-grained epidote are further evidence of the mobility of Ca and variations of μH_2O in the basaltic flows.

Small rosettes of pumpellyite partly replacing feldspar and amygdules containing pumpellyite and/or prehnite are also present in massive basaltic flows and pyroclastics exposed in an outlier about 10 km to the south of Colliers (Loc. 9). The pumpellyite zone outlined so far is thus about 13 km long and 2 km wide.

Actinolite zone

The fine-grained siliceous siltstone of the Conception Group to the west of the Harbour Main volcanic belt is not favourable for the development of low-grade metamorphic assemblages, and the overlying sandstone and shale of the Hodgewater and Musgravetown Groups have not yet been studied in detail. However, the more mafic members of a dominantly volcanic assemblage in the lower part of the Musgravetown Group, the Bull Arm Formation, (McCartney 1967) show locally incipient development of finely fibrous pale green actinolite, in addition to the predominant non-diagnostic assemblage quartz-epidote-albite-chlorite-sphene (Loc. 10, 11). The presence of actinolite, coupled with the disappearance of pumpellyite, may be taken as an indication of the lower boundary of the greenschist facies (*e.g.* Coombs 1960; Nitsch 1971). Actinolite, epidote and chlorite, without pumpellyite, are common secondary minerals in the dioritic rocks of the Powder Horn intrusive complex to the northwest (Loc. 12), and actinolite was recently found in a massive basalt associated with the strongly schistose Love Cove Group just to the west of the map area of Figure 1; the Love Cove Group, underlying the most westerly part of the Avalon Platform, has been previously assigned to the greenschist facies (Jenness 1963).

Conclusions

In view of the preliminary nature of the work reported here, most of the following statements are tentative and subject to confirmation or modification after a more detailed study has been carried out. Nevertheless several conclusions can be drawn at this time.

1. The Late Precambrian rocks of the Avalon Peninsula have been subjected to low-grade metamorphism ranging from the prehnite-pumpellyite facies in the central and eastern part to the low greenschist facies in the western part of the peninsula. A tentative boundary line between the two facies lies probably to the south of Trinity Bay. Known occurrences of mineral assemblages typical of the prehnite-pumpellyite facies extend over an area 40 km wide from St. John's to the western shore of Conception Bay.

2. The metamorphic grade seems to increase from east to west. A wide prehnite zone is followed by a narrow zone characterized by the presence of pumpellyite and prehnite, which in turn is succeeded towards the west by a wide zone of incipient to moderate development of actinolite, without pumpellyite. The development of penetrative deformation, accompanied by the gradual modification and eventual destruction of primary structures, follows the same trend, culminating in the strongly schistose rocks of the Love Cove Group to the west of the Isthmus of Avalon. It appears then that the metamorphic grade is not related to the stratigraphic succession or to a hypothetical "depth of burial", but increases in the direction of increasing tectonic stress, towards the western edge of the Avalon Platform. A very recent reconnaissance has shown the presence of prehnite veins in a large outcrop of basaltic rocks (Bull Arm Formation?) near Thorburn Lake, just to the west of the schistose Love Cove belt; it is not yet clear whether this represents merely a local reversal, or whether the intensity of metamorphism decreases sytematically after passing through a "metamorphic maximum" in the area immediately west of Figure 1. Additional complications arising from the possibly older age of metamorphism of the Love Cove Group (Jenness 1963, p. 46) should be noted but cannot be considered in detail at this preliminary stage of the investigation.

3. Although no definite zonal boundaries can be drawn at this time, there are indications that the metamorphic zones follow the northerly regional trend of the host rocks.

4. A diffuse thermal aureole characterized by the sporadic development of actinolite, epidote, and albite follows roughly the contacts of the Holyrood pluton; its time-relationship with the regional low-grade metamorphism in the central part of the Avalon Peninsula is not yet known.

5. The formation of prehnite in the sandstones near St. John's appears to have been contemporaneous with tectonic stresses that resulted in the open folding of the sediments in the eastern part of the Avalon Peninsula (Papezik 1972). This event may have been related to the Acadian orogeny (Poole 1967; Williams *et al.* 1974). Other stratigraphic and petrographic data that are relevant to the age of metamorphism are somewhat ambiguous. The pumpellyite-bearing basalts of Colliers Bay are overlain unconformably by Lower Cambrian sediments which show no metamorphic effects, but the sediments are mainly limestones and shales that are not likely to be affected by such a low intensity of metamorphism. The albite-epidote-actinolite au-

reole around the Holyrood pluton, if developed in originally unaltered rocks, would not have been noticeably affected by the subsequent regional metamorphism of the prehnite-pumpellyite facies. Thus in the absence of decisive evidence to the contrary, it is possible to conclude tentatively that the low-grade regional metamorphism of the Late Precambrian rocks of the Avalon Peninsula is related to Acadian (Devonian) tectonic events. If, however, the gentle folding of the Cabot Group is of Hadrynian age as suggested by Kennedy (1974, in press), the weak regional metamorphism may have been the result of the Ganderian-Avalonian orogenic episode. Further work will be needed to solve the problem.

Acknowledgments

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