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REGIONAL METAMORPHIC ZONATION AS AN AID IN STUDY OF ARCHEAN TERRAINS: ABITIBI REGION, ONTARIO

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ABSTRACT

A segment of Archean crust in the vicinity of Larder Lake, Ontario was selected for detailed study of geologic history through metamorphic zonation. The observed mineral relations and parageneses indicate that metamorphism first occurred when a thick pile of mafic to intermediate rocks was subjected to burial metamorphism that caused development of prehnite-pumpellyite assemblages. Subsequently the volcanic pile was tectonically deformed and eroded such that clasts containing the prehnite-pumpellyite assemblages were deposited in east-west-trending troughs. Simultaneously, intrusion of small plutons caused contact metamorphic aureoles to develop that contain albite-epidote-actinolite and hornblende-almandine assemblages within both the sediments and the underlying lavas. Numerous relics of prehnite and pumpellyite persisted in the actinolite zone of contact metamorphism in the lavas. The final event in the area was diapiric intrusion of granitic materials. This mass, strongly retrograded, cataclastically deformed, and foliated, is surrounded by a relatively low-temperature, actinolite-stilpnomelane-epidote-bearing aureole, suggesting it was cool at the time of intrusion.

The first metamorphic event was regional in scope and yielded assemblages of the prehnite-pumpellyite facies. Later, several intrusive episodes produced localized aureoles of the albite-epidote-actinolite hornfels and hornblende hornfels facies. The greenschist facies of regional metamorphism is absent.

INTRODUCTION

One of the primary aims of regional studies in Archean terrains at the present time is the determination of the sequence of events and geologic history of the early earth. Thus, stratigraphic and tectono-structural studies have dominated geological research in these complex regions. As a result of several episodes of folding, faulting, and multiple intrusion during orogenic upheavals subsequent to the deposition of Archean materials, however, stratigraphic and structural correlations are difficult and often controversial. An attempt will be made here to evaluate the usefulness of a third method of regional investigation: metamorphic zonation. Such an approach will not eliminate controversy, but it may provide a different viewpoint from which Archean terrains may be looked upon.

GEOLOGIC SETTING

Three main elements compose typical Archean terrains. 1) Greenstone "belts" of predominantly mafic to intermediate lavas and contemporaneous intrusions, 2) synclinal troughs of predominantly greywacke, conglomerate, and arkosic sediments developed on the lavas, and 3) lobate granitic intrusions, commonly displaying gneissic textures, that intrude the lava-sediment complexes. The object here will be to determine the relations between these rock types as suggested by the metamorphic zonation alone. The area chosen for detailed study, measuring about 15 by 40 km, is located near Larder Lake, Ontario (Fig. 1). It includes all three of the above-mentioned geologic elements. About 140 localities were sampled during field work and more than 200 thin sections were examined.

ROCK UNITS

Mafic to intermediate volcanics and related intrusions (unit 1 in Fig. 1). The thick pile of basaltic to andesitic volcanics exposed in the area studied has been mapped by Grant (1963). Hewitt (1949), Hogg (1964), Jensen (1971a, b), and others. Goodwin (1965), Ridler (1970), and Goodwin & Ridler (1970) have summarized the regional stratigraphy. The volcanics studied here may be divided into three segments, all of which are probably correlative. In the southern part of the area, three units, in ascending stratigraphic succession, are the Picaud tuffs, Catharine basalts, and Skead pyroclastics (Ridler 1969). These units dip away from a granitic mass, the Round Lake Batholith. The lavas and pyroclastic rocks making up these units are mafic to intermediate in composition (Table 1, see also Grant 1963).

In the central part of the area, between two synclinal troughs of younger sediment, are basaltic flows brought up by doming associated with two moderate-sized plutons. These flows

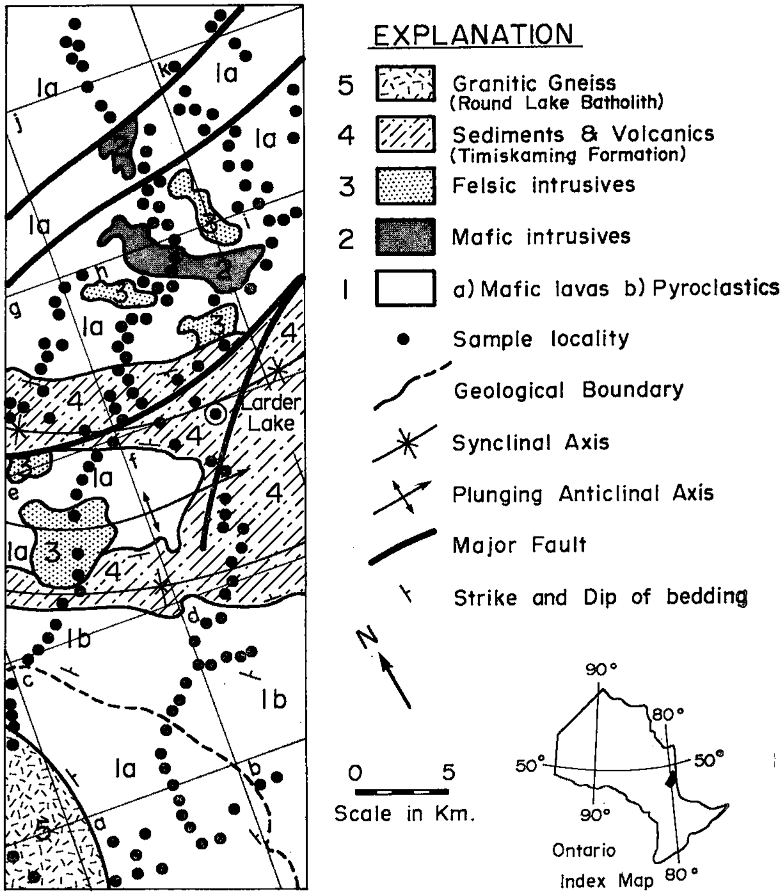


FIG. 1. Geologic map with rock units, structure, and sample localities of the area studied. Townships as follows: a) Marter, b) Bayly, c) Catharine, d) Skead, e) McElroy, f) Hearts, g) Gauthier, h) McVittie, i) McGarry, j) Katrine, k) Ossian.

have been called the McVittie basalts (Ridler 1969). Finally, in the northern half of the area studied here, additional lavas of mafic to intermediate character, called the "Blake River" volcanics are present. These lavas grade from predominantly basaltic types at the base to intermediate and felsic types in the northern part of the map-area (Fig. 1). Some representative partial chemical analyses of the lavas are presented in Table 1.

All of the relatively unaltered lava flows, pyroclastic units, and flow breccias contain relic clinopyroxene and plagioclase. Olivine phenocrysts, originally present in some rocks, are degraded primarily to chlorite; rhyolitic lavas contain traces of biotite. Matrices are devitrified and usually heavily chloritized.

Intruding the lava pile as sheets, dykes, and small lobate bodies are a variety of hypabyssal plutonic rocks of chemical and mineral composition similar to the enclosing lavas (Jolly, in preparation). These have been considered as

TABLE 1. REPRESENTATIVE CHEMICAL ANALYSES OF METAMORPHIC ROCKS FROM THE ABITIBI REGION, ONTARIO

	218[1]	387A[2]	229G[3]	212[4]	309[5]	373[6]
SiO_2	49.3	62.5	46.8	57.3	49.5	64.6
Al_2O_3	17.0	15.1	23.8	16.2	15.2	14.4
TiO_2	1.23	0.69	0.67	0.86	1.40	0.01
FeO	6.73	1.42	0.42	2.02	5.60	1.42
Fe_2O_3	1.06	4.55	8.26	4.97	11.23	0.44
MgO	7.54	1.17	2.68	2.86	4.32	2.03
CaO	5.37	5.18	18.9	6.20	8.17	2.35
MnO	0.20	0.08	0.05	0.07	0.23	0.28
Na_2O	3.08	3.87	0.09	3.46	1.66	5.93
K_2O	0.43	0.62	0.01	0.56	0.38	4.65

Analyses by atomic absorption spectroscopy of metaborate solutions; ferric iron determined by titration.
[1]Mafic lava from "Blake River" volcanics.
[2]Intermediate lava from "Catharine" volcanics.
[3]Strongly altered lava rich in pumpellyite (metadomain) from "Blake River" volcanics.
[4]Intermediate lava from "Blake River" volcanics.
[5]Mafic pebble from Timiskaming conglomerate near Swastika.
[6]Granitic gneiss from "Round Lake Batholith".

feeders and holding chambers of the same magma making up the lavas (see, for example, Jenson, 1972). The largest of these bodies in the area studied here are shown in Figure 1 as rock type 2.

Sediments and associated volcanics (unit 4 of Fig. 1). Two synclinal sedimentary troughs are separated by an east-west-trending series of intrusive domes probably linked in the subsurface (unit 3 of Fig. 1). These sediments, the classical Timiskaming, are composed largely of conglomerate, arkose, and minor greywacke. Work in progress by R. Hyde of McMaster University suggests a fluvial origin for much of the material. The rocks were deposited unconformably on, and probably were derived largely from, the Blake River volcanics (Thompson 1941); they contain a wide variety of volcanic, plutonic, and sedimentary clasts. The volcanic pebbles are petrographically (Hewitt 1962) and chemically (Table 1) similar to the subjacent volcanic rocks. Interlayered with the sediments are leucite-bearing alkaline lava flows and pyroclastic rocks (Cooke & Moorhouse 1969). The series of intrusive domes mentioned above are chemically similar to the alkaline lavas, suggesting the two may be of similar age.

Granitic gneiss (unit 5 of Fig. 1). The intrusive material comprising the Round Lake Batholith is composed of quartz, plagioclase, K-feldspar, biotite, hornblende, and sphene. The rocks are strongly foliated parallel to the boundary of the mass; pegmatoidal dykes are uncommon. Partial chemical analyses (Table 1) of these rocks indicate that they are generally of granitic composition, with high K_2O/SiO_2 ratios compared to the mafic lavas they intrude.

Metamorphic Zonation

Many of the rocks of the sedimentary group are composed primarily of quartz + alkaline feldspar, and, as a result, did not yield calcium-aluminum silicates when they were metamor-

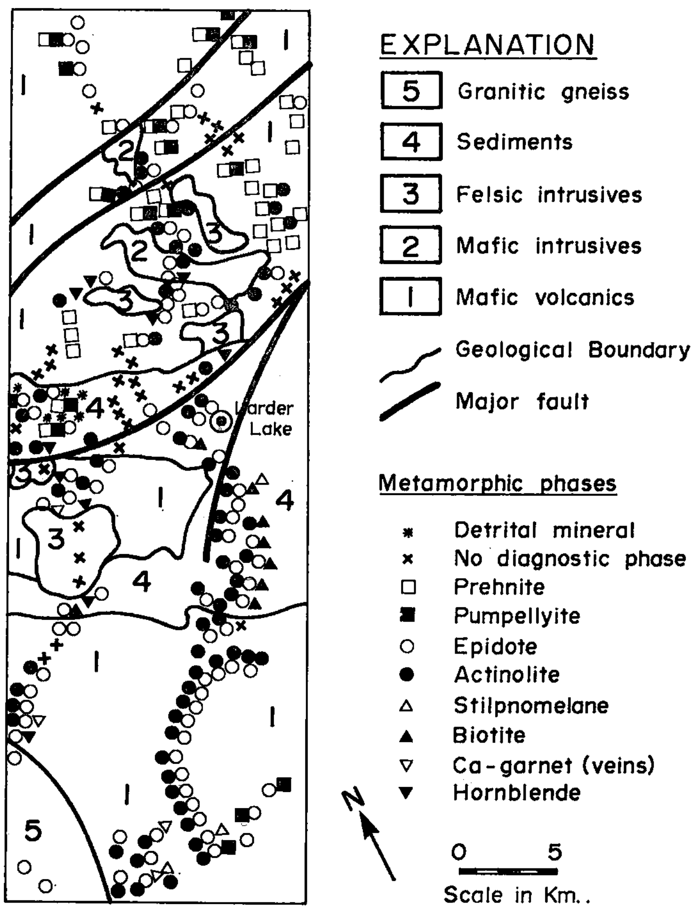


FIG. 2. Map summarizing distribution of phases in the rocks studied.

phosed. The principal secondary phases include sericite, chlorite and hematite. Basaltic and intermediate volcanic rocks, however, are rich in calcium and the mafic components, MgO and FeO, and yielded a rich mineral paragenesis (see also Seki and others, 1971; Jolly 1970). The secondary phases observed in each thin section available from the area considered here are shown in Figure 2 in symbol form. A division of the area into six distinctive zones on the basis of diagnostic mineral occurrences is shown in Figure 3 and Table 2.

1) *Chlorite zone*. The chlorite zone exists only in the sedimentary strata remote from plutonic intrusions (Fig. 3). Most rocks contain quartz, albite, calcite, white mica and clay minerals, greenish to brown chlorite, and sphene as the dominant secondary minerals. No zeolites and no prehnite or pumpellyite have been observed in matrices or veins of the sediments, although local isolated clasts (Fig. 3) contain pumpellyite or prehnite + pumpellyite + epidote that predate deposition of the conglomeratic units; these pumpellyite-rich clasts were probably derived from the previously metamorphosed rocks on which the sediments were formed, as discussed below. Some grains of detrital epidote are also present in the sedimentary rocks.

2) *Prehnite zone*. Along the northern boundary of the belt of sedimentary rocks, the mafic to intermediate lavas are characteristically replaced by prehnite, albite, chlorite, quartz, sphene, and calcite. In all lavas relic clinopyroxene remains, and in many, calcic feldspar is present in cores of plagioclase phenocrysts. Prehnite is most abundant in void spaces such as joints and fractures, but in some rocks, the mineral develops as an amoeboid replacement of groundmass material within the body of rock.

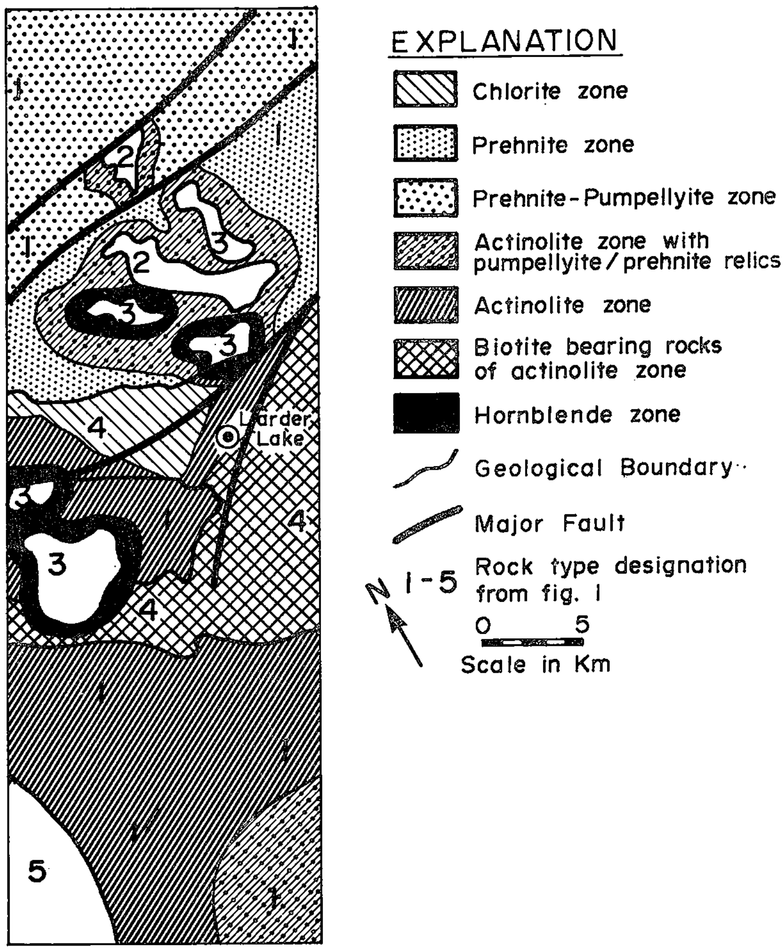
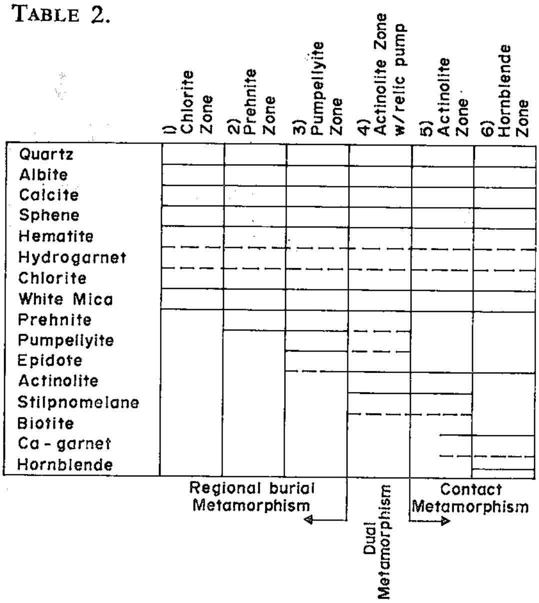


FIG. 3. Map of area studied showing the metamorphic zonation.

TABLE 2.



Glassy rocks with abundant amygdules are especially prone to such alteration. The most common mineral associations are:

chlorite-albite-prehnite

chlorite-albite.

Both are ± quartz, calcite, hematite, sericite, hydrogarnet, and sphene. No zeolites have been observed in any of the rocks, possibly because such hydrous phases could not survive the numerous subsequent metamorphic events. In a few rocks epidote is present, but when with prehnite, the epidote always appears to be embaying the prehnite and is here considered to be of a subsequent metamorphic generation (Fig. 4a, b).

3) *Prehnite-pumpellyite zone*. North of the Larder Lake fault zone, trending across the area (Fig. 2 and 3), and in a few localities in the northernmost part of the prehnite zone, the diagnostic mineral pair prehnite-pumpellyite is present. Agan clinopyroxene and plagioclase relics are present, but in many rocks, extensive alteration has transformed the lavas to completely new mineralogies. Along permeable zones in the rocks, prehnite or pumpellyite commonly comprise up to 95% of a specimen along with traces of chlorite, quartz, albite, white mica, sphene, and hydrogarnet. The chemistry of those monomineralic rocks, which are called metadomains (Jolly & Smith 1972) to simplify reference to them, is markedly different from the parental volcanic material, and is generally rich in calcium but poor in alkalis, especially potassium (Table 1).

The characteristic mineral association of this zone is pumpellyite-prehnite-chlorite-albite-cal-

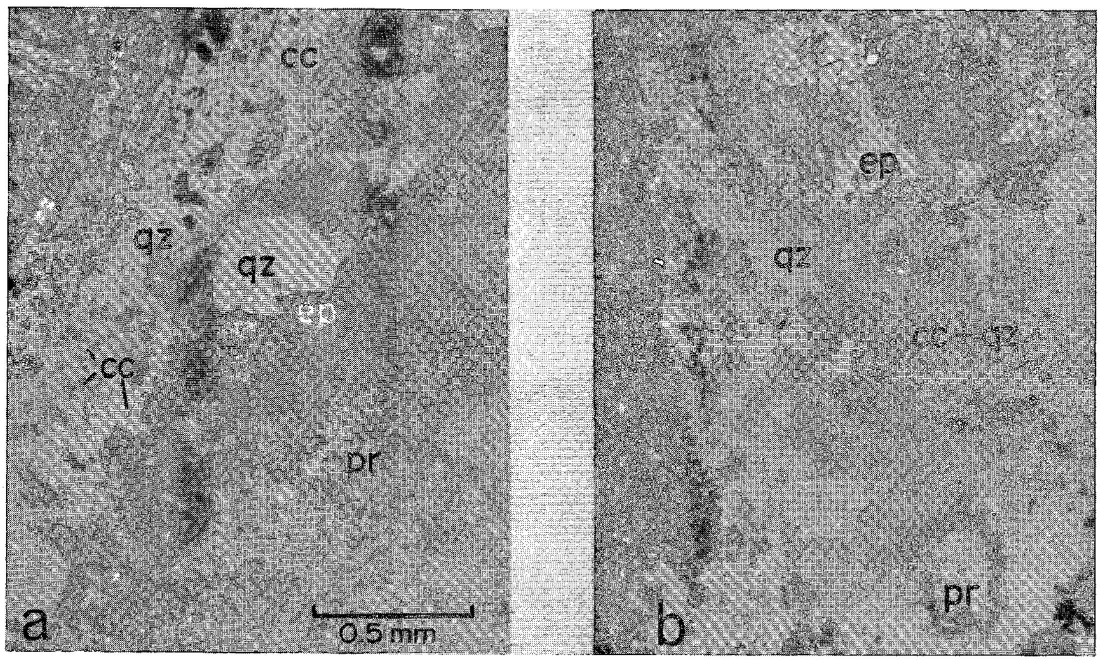


FIG. 4. a) Photomicrograph showing epidote, quartz, and calcite embaying prehnite, No. 231AS.
b) Photomicrograph showing prehnite embayed by quartz + calcite + white mica; actinolite and epidote are also present but not in contact with prehnite, No. 286.

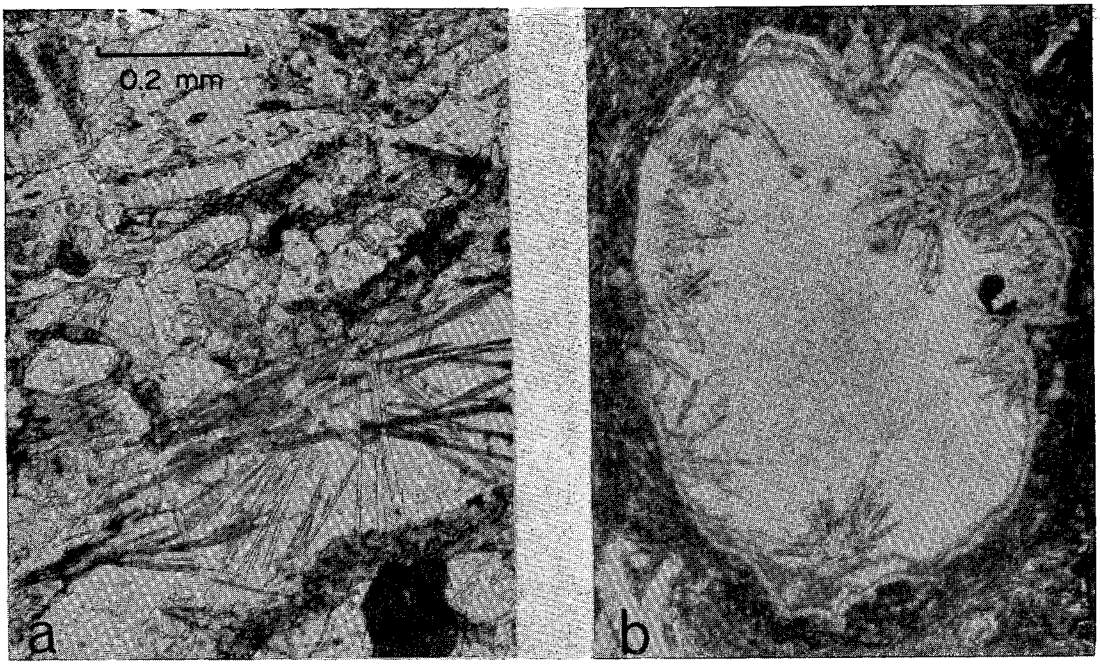


FIG. 5. a) Stilpnomelane in matrix and vein; actinolite and epidote are also present, No. 368. b) Pumpellyite + quartz in amygdule surrounded by pumpellyite-albite groundmass, No. 246Z.

cite-quartz-white mica-sphene, but the following associations also commonly occur:

chlorite-albite
epidote-chlorite-albite
epidote-pumpellyite-chlorite-albite
epidote-prehnite-chlorite-albite
epidote-prehnite-pumpellyite-chlorite-albite
pumpellyite-chlorite-albite
prehnite-chlorite-albite,

all of which are ± quartz, calcite, hematite, sphene, white mica, and hydrogarnet.

Pumpellyite is highly variable in its microscopic character. In void spaces it is generally within quartz and shows bluish-green pleochroism, anomalous birefringence, and euhedral form (Fig. 5b). In groundmasses, the mineral is deep green and highly pleochroic, tending toward faint brownish tints, with globular or granular habit. The origin of epidote in this zone is unclear, for in many rocks the mineral embays both prehnite and pumpellyite, with a reddish to black reaction rim between the two. Most of the epidote probably dates from a later metamorphic event than that which produced pumpellyite and prehnite.

4) *Actinolite zones with pumpellyite and prehnite relics.* Prehnite-pumpellyite assemblages are associated with actinolite in two places in the area studied for this report. Firstly, in the northern third of the area, irregular to ovate rims of actinolite-epidote-pumpellyite-prehnite-bearing rocks surround small plutons. Secondly, in the south near the "Round Lake Batholith", isolated patches of pumpellyite-epidote-bearing rocks are present within a broad band of the actinolite zone. In the former both prehnite and pumpellyite are strongly embayed by later minerals, especially epidote and quartz (Fig. 4a, b), and must therefore be considered as relics within the metamorphic aureole of the associated intrusions. Actinolite has not been observed in direct contact with either prehnite or pumpellyite, but has been found in the same specimen with both separated by epidote, quartz, white mica, or chlorite (Fig. 4). In the southern part of the area, pumpellyite is accompanied by a pistacitic epidote with deep yellow pleochroism, very high relief, and $2V\alpha = 70°$. The two minerals exist euhedrally side by side and are probably coeval. No prehnite is present. These rocks are probably from a deeper level in the stratigraphic section than the lavas of the northern part of the area (Ridler 1970), and the pumpellyite+epidote+albite+quartz+chlorite+sphene association thus represents a higher-grade mineral association than contained in the prehnite-pumpellyite zone assemblages described above.

Actinolite zones. In areas near plutonic rocks in the center of the map-area, rocks of the sedimentary belts contain dominantly actinolite-epidote, and, in progressively higher-grade rocks, actinolite-biotite-epidote. The epidote is normally low to moderate in relief and birefringence, suggesting that it is clinozoisite, but pistacite is also present in some specimens. Biotite is commonly zoned from faint olive green to brown on edges, and commonly replaced chlorite. A few clinopyroxene relics are present, but calcic plagioclase is rare. This zone is also characteristic of the rocks in a band, about 5-10 km wide, around the "Round Lake Batholith". With the exceptions noted in the preceding section, pumpellyite is absent and presumably has been obliterated by higher-grade metamorphic conditions. No biotite has been found in any lavas of the actinolite zone, but because the mineral is present in the adjacent sediments, its absence is probably due to compositional constraints.

Stilpnomelane is present locally in the actinolite zone. The mineral is best-developed in veins, amygdules, and other void spaces, but a few rocks contain stilpnomelane as groundmass replacements. Stilpnomelane is usually well-crystallized, deep reddish brown to brown, and spindly (Fig. 5a). Garnet with birefringence as high as 0.003 is present in a narrow band surrounding the "Round Lake Batholith" (Fig. 2). These garnets are brownish in hand specimen, colourless to brownish in thin section, and occur only in veins containing calcic phases, where a special chemical composition was presumably present during growth. They are probably calcic in composition.

Mineral assemblages observed in the actinolite zone include the following:

- actinolite-chlorite-albite
- epidote-chlorite-albite
- actinolite-chlorite-albite-stilpnomelane-Ca-garnet-epidote
- actinolite-biotite-chlorite-albite
- actinolite-epidote-biotite-chlorite-albite
- actinolite-epidote-biotite-chlorite-stilpnomelane-albite

All the above assemblages are ± quartz, white mica, hematite, calcite, and sphene. A few specimens in the actinolite zone contain relic clinopyroxene, but this mineral is strongly actinolitized on edges and fractures. The rocks also display penetrative deformation with actinolite needles growing across grain boundaries; the chlorite, prehnite, and prehnite-pumpellyite zones lack such a feature.

Actinolite in these rocks is usually very pale green to colourless, but near the granitic mass in the south, and in the vicinity of smaller plutonic masses, it commonly takes on a pale bluish-green pleochroism. No brown colours are observed in the amphiboles except at one locality on the margin of the granitic mass (Fig. 2).

Hornblende zones. At least four plutonic bodies of diameters more than 1 km, and probably others of lesser size, are surrounded by aureoles of hornblende- and almandine-bearing rocks. Hornblende is commonly euhedral, with brown to blue-green pleochroism. The garnet is isotropic and occurs in rocks very close to the edge of the plutons. The hornblende zones are less than two km in width; these aureoles are restricted to borders of the alkaline plutons (unit 3 in Fig. 1) which were apparently intruded at higher temperatures than other plutonic bodies of the area.

Metamorphic Overprinting

The widespread presence of overprinting of prehnite-pumpellyite assemblages by the actinolite-epidote-albite-quartz assemblages of intrusion aureoles may have also occurred in other Archean greenstone belts of the Canadian Shield and elsewhere. Many characteristic textures that are developed during the secondary metamorphism may be used to recognize it in other areas. These are recorded below.

Replacement of prehnite. Pristine prehnite characteristically exhibits reniform habit with sweeping extinction (Fig. 6a, b). The colourless to dusty mineral has higher relief than quartz, the major mineral to replace it during the overprinting process, making the embayment visible in plane light (Fig. 6c). The replacement process proceeds through the following systematic stages in prehnite veins and other void spaces. Small patches of granular quartz form on vein edges and grow until they coalesce into a rind on all edges of the vein (Fig. 6c and d). The quartz is fine-grained, equigranular and displays sweeping extinction; boundaries of individual grains are indistinct and shift slightly on rotation of the microscope stage. Some of the quartz displays a bladed character reminiscent of chalcedonic silica (Fig. 6f). In the final stages, only small streaks of prehnite remain in a mass of granular and bladed quartz (Fig. 6f). Calcite is commonly mixed with the quartz replacement. The granular texture of the quartz is so unusual and diagnostic that the former presence of prehnite may commonly be inferred even if none remains.

The transformation of prehnite to quartz ± calcite described above is not isochemical because most constituents of prehnite must be removed from the immediate site of the reaction by fluids. In many specimens, however, circular pods of epidote also replace prehnite on edges,

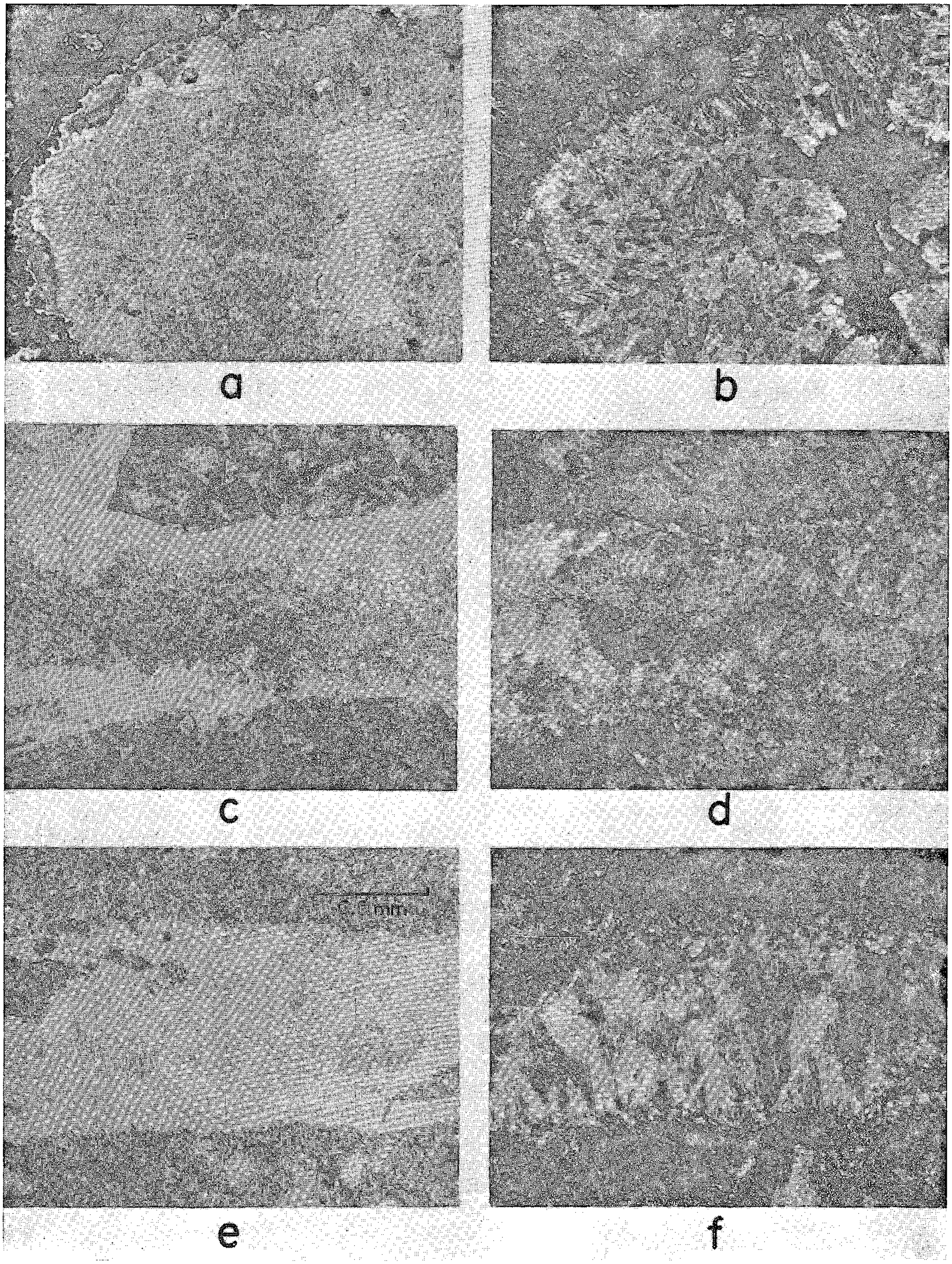


FIG. 6. a) Pristine prehnite in amygdule; shows characteristic dusty texture and high relief, No. 286S.
b) Same as Fig. 6a, crossed nicols, showing sweeping extinction.
c) Prehnite in vein with quartz embayments, No. 246Z.
d) Same as Fig. 6c, crossed nicols, showing granular nature of quartz that replaces prehnite.
e) Quartz in vein with tiny prehnite remnants, No. 246.
f) Same as Fig. 6e, crossed nicols, showing bladed nature of quartz replacing prehnite.

along with quartz and calcite as shown in Figure 4a. This reaction may be expressed as follows:

$$3Ca_2Al_2Si_3O_{10}(OH)_2 + 2CO_2 \rightarrow 2Ca_2Al_3Si_3O_{12}(OH) + 3SiO_2 + 2CaCO_3 + 2H_2O.$$

prehnite; epidote; quartz; calcite

Reactions of this type, together with textural relations, suggest that CO_2 was commonly introduced into these rocks during the second metamorphic event while water was removed.

Replacement of pumpellyite. Pumpellyite is too fine-grained (Fig. 5b) to preserve a progressive sequence of embayment similar to that of prehnite. However, chloritic masses pseudomorphic after pumpellyite, and epidote embaying granular pumpellyite, are both commonly observed. Seki *et al.* (1969) have presented the following chemical reaction to describe such a change:

$$41Ca_4Al_5Mg\,Si_6O_{21}(OH)_7 + 2Mg_7Al_4Si_4O_{15}(OH)_{12} + 47SiO_2 \rightarrow 11Ca_2Mg_5Si_8O_{22}(OH)_2 + 71Ca_2Al_3Si_3O_{12}(OH) + 109H_2O.$$

pumpellyite; chlorite; quartz; actinolite; epidote

Degradation

Thin-section inspection of the gneissic rocks of the "Round Lake Batholith" reveals numerous features suggestive of pronounced retrogression and solid state deformation:

a) Strongly epidotized and sericitized plagioclase with mica flakes ranging up to 5 mm in length.
b) Plagioclase crystals bent, broken, fractured and subsequently healed by quartz.
c) Edges of feldspar megacrysts rounded as if by grinding.
d) Bent, kinked, and shattered biotite commonly squeezed between adjacent grains.
e) Complete or partial degradation of biotite to chlorite ± stilpnomelane on edges and along cleavage planes.
f) Foliation of hornblende and biotite in both megascopic and microscopic scales.
g) Intergrain spaces annealed by relatively undeformed granular quartz of finer grain size than other minerals.

These characteristics suggest that these granitic materials were emplaced by solid flow. The relatively low-temperature actinolite-bearing metamorphic zone surrounding the mass supports such a suggestion, as does the presence of relic patches of rock in the aureole containing pumpellyite. These gneisses may be considered either as remobilized crust of ancient age which was intruded diapirically from beneath the thick pile of mafic lavas to the north, or as the outer edges of a magma chamber that was at least partially crystallized before intrusion was complete (see also Ridler 1970). The "Round Lake Batholith" differs from several others in the region, such as that intruding the Pontiac schists in nearby Quebec, which was a polyphase intrusion of molten material of relatively high temperature (Dimroth *et al.* 1973; Jolly, in preparation).

Sequence of Metamorphic Events

The geologic history of the segment of Archean crust studied here is summarized as follows: 1) A thick series of mafic to intermediate volcanics were erupted, possibly onto a gneissic substrate. 2) These volcanics underwent regional burial metamorphism (see also Gelinas & Brown, 1974) which yielded a progressive sequence of metamorphic zones: a pumpellyite-epidote-bearing assemblage at the base, a pumpellyite-prehnite assemblage in the central part of the pile, and a prehnite zone in the uppermost rock exposed. No zone of zeolites has been observed. 3) Contemporaneous with eruption of the lavas and burial metamorphism, a series of mafic to intermediate plutons similar in composition to the volcanics were intruded into the pile, causing development of aureoles of actinolite-epidote assemblages over-printing the original prehnite-pumpellyite associations. 4) An episode of dominantly N-S compression, but with some faulting and E-W-trending folding (Fig. 1), deformed the volcanic pile and resulted in the formation of synclinal troughs trending E-W. These basins were filled with conglomerates, arkoses, and greywackes derived from the nearby volcanics containing the prehnite-pumpellyite mineralogy. 5) Alkaline intrusion and extrusion of relatively hot magmas accompanied sedimentation, and resulted in a new generation of metamorphic aureoles, this time yielding both an actinolite-stilpnomelane-biotite-epidote zone and, on the margins of the plutons, a hornblende-almandine zone. 6) Finally, the "Round Lake Batholith" of remobilized gneissic crust or of solidified magma was squeezed up diapirically to its present position, bringing moderate-temperature metamorphism of the adjacent country rocks with it, and causing development of an actinolite-epidote zone in which patches of relic pumpellyite are present. Relative time of emplacement is unknown, but may have been contemporaneous with the tectonic events of stage 4 above. Absence of hornblende in the aureole, and the presence of relic pumpellyite, suggest that intrusion took place at relatively low temperatures.

The above sequence is generally in agreement with those derived from stratigraphic and structural data (Grant 1963; Thompson 1941; Ridler 1970). Radiometric age determinations of some rocks in the region may be used to place limits on the timing of events. Krogh & Davis (1971) report ages of about 2.8 billion years for the Archean volcanics, and the Geological Survey of Canada has reported an age of 2.4 b.y. for intrusion of the "Round Lake Batholith" (Goodwin & Ridler 1970). These figures bracket the geologic events of interest here.

Metamorphic Facies

The prehnite and prehnite-pumpellyite zones may be classified as belonging to the prehnite-pumpellyite facies of Coombs (1960). All amphibole-bearing rocks in the area studied are associated with, and *wrapped around,* intrusive bodies, as are hornblende zones. These zones must therefore be classified as albite-epidote-actinolite hornfelses and hornblende hornfelses (Turner 1968), while technically, the mineralogically identical greenschist facies of regional metamorphism is absent. Presumably, deeper in the volcanic pile, the prehnite-pumpellyite zones observed here grade into albite-actinolite-epidote-bearing rocks of regional metamorphism, with the boundary between the two related to depth in the stratigraphic sequence rather than proximity to plutons. The actinolite-bearing assemblage, if it exists, comprises the greenschist facies.

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