Multiple Thermal Metamorphism of the Digdeguash Formation in the Contact Aureole of the Pocomoonshine Gabbro-diorite, Southeastern Maine

Allan Ludman  
Department of Geology  
Queens College of the City University of New York  
Flushing, New York 11367

Sandra L. Bromble  
Lamont-Doherty Geological Observatory  
Palisades, New York 10964

James M. DeMartinis  
Roux Associates  
Huntington, New York 11743

ABSTRACT

Intrusion of the Pocomoonshine gabbro-diorite into turbidites of the Digdeguash Formation in southeastern Maine produced a broad contact aureole in which andalusite-biotite, sillimanite, and sillimanite-potassic feldspar mineral zones are recognized. Anatectic temperatures were reached near the pluton/host rock contact, where a distinctive migmatite marks the highest intensity of metamorphism. Pluton and aureole mineralogy confirm an epizonal environment for intrusion (P=2.5 to 3.0 kbars). Textural studies reveal that the aureole is a composite feature that resulted from two episodes of prograde mineral growth separated by a retrograde event. Assemblage and phase chemistry data indicate that the second thermal pulse was the most intense, with maximum temperatures of approximately 700°C. A two-stage magmatic injection history involving early emplacement of gabbro followed by intrusion of a larger mass of diorite is postulated to explain this thermal history.

INTRODUCTION

The coastal lithotectonic block of Maine has been intruded by a suite of several post-deformational, epizonal plutons that extends for over 320 kilometers from the mid-coastal region to the St. George batholith of southern New Brunswick (Osberg et al., 1985; Potter et al., 1979). The suite was first recognized in east-coastal Maine by Chapman (1962), who named it the Bays of Maine Igneous Complex and described it as a bimodal assemblage of gabbro and granite. Recent work in eastern Maine reveals that there is a large volume of diorite and quartz diorite as well (Ludman and Hill, 1986). The most prominent of the mafic bodies in southeastern Maine is the Pocomoonshine gabbro-diorite, a differentiated complex exposed in the Big Lake and Wesley quadrangles (Fig. 1). Previous workers have mapped its boundaries (Larrabee, 1964), studied the magmatic processes by which it evolved (Westerman, 1972), related it to the Acadian thermal events responsible for the entire plutonic suite (Thompson, 1984), or used it to help establish the timing of regional accretion (Ludman, 1981). All who have studied it have noted its prominent contact aureole, particularly along its western margin where
thermal metamorphic effects extend several kilometers from the contact, but no one has examined the metamorphism in detail. Our field, petrographic, and chemical studies show that rocks of the aureole have had an unexpectedly complex thermal history involving at least two episodes of prograde mineral growth. The purpose of this paper is to describe and document this history, and to relate it to local and regional events.

**Geologic Setting**

The Pocomoonshine gabbro-diorite has intruded the contact between two major components of the coastal lithotectonic block, the St. Croix belt and the Fredericton trough (Fig. 1). To the southeast, the St. Croix belt consists mostly of Cambrian through lowest Ordovician pelitic and psammitic strata. To the
northwest, the Fredericton trough is a thick sequence of calcareous and non-calcareous turbidites probably of Late Ordovician through Early Devonian age. Rocks of both belts were folded during the Acadian orogeny prior to intrusion of the pluton, and the map pattern is dominated by these large upright folds (F1) with northeast-trending hinge surfaces. F2 recumbent folds associated with northwest-directed thrusting, and small-scale F3 folds related to north-trending normal faulting deform the early folds and cleavage, but do not significantly alter the map pattern. The entire region, including the Pocomoonshine pluton, was affected by northeast-, north-, and northwest-trending late or post-Acadian faults (Ludman, 1986; Ludman and Hill, 1986). Small granitic plugs cut the western and central parts of the Pocomoonshine pluton, and pegmatite and aplite veins occur sparsely within it.

Regional metamorphic grade is low in both the Fredericton trough and St. Croix tracts, generally not surpassing conditions of the chlorite zone. As a result, well-developed contact aureoles surround the numerous plutons in the region. The Pocomoonshine body has an asymmetric aureole, with contact effects extending up to 8.5 km from the contact on the west, north, and northeast, but only 0.8 km to the east. This is due partly to the shape of the pluton, a gently west-dipping tabular mass (Westerman, 1972), and partly to faults that cut it and its host rock on the east (Ludman, 1986).

Southeastern Maine is a heavily glaciated region of gently rolling hills that rise only a few hundred feet above ubiquitous lakes and swamps. The Pocomoonshine gabbro-diorite occupies an elongate lowland in the Big Lake quadrangle, but is bordered by a resistant hornfels rim that underlies Huntley, Hawkins, and Seavey Ridges on the west, and Cedar Grove Ridge on the east. Bedrock exposures comprise less than 1% of the region, but are much more abundant on these ridges. An extensive network of new lumber roads provides unprecedented access and many new outcrops throughout the western part of the Big Lake quadrangle, particularly along Huntley and Seavey Ridges. The western aureole of the pluton was thus chosen for this study because of its extent, exposure, and accessibility.

Rocks of the Pocomoonshine gabbro-diorite exposed in the study area are medium to coarse grained hornblende diorites and quartz diorites. Their host rocks along the western contact are the Flume Ridge and Digdeguash Formations of the Fredericton trough (Ludman, 1986). The Flume Ridge Formation consists of calcareous sandstones and siltstones interbedded with minor amounts of non-calcareous shale. These are converted to dense hornfelses near the pluton, and occur as alternating bands of calc-silicate (with actinolite, diopside, or wollastonite) and biotite-rich quartzo-feldspathic granofels. The Digdeguash Formation contains interbedded granule and pebble conglomerates, lithic and quartzo-feldspathic wackes, and gray shale, and is almost entirely non-calcareous. Spectacular chiastolitic andalusite porphyroblasts up to 20 cm long typify pelites of the Digdeguash Formation in much of the aureole. Stillimanite occurs near the pluton, and rare cordierite, garnet, and staurolite have been identified in middle grade exposures. Textural and phase relationships among andalusite, sillimanite, and white micas record a complicated metamorphic history for these pelites, and the remainder of this paper is devoted to unraveling that history.

Previous Works

The Pocomoonshine gabbro-diorite was not shown at all on the geologic map of Maine compiled by Keith (1933). It was first mapped in the Big Lake quadrangle and named by Larrabee (1964), and Westerman (1978) showed that it probably extends into the adjacent Wesley quadrangle on the south. Larrabee et al. (1965) described the variety of mafic and intermediate rock types that comprise the pluton, but Westerman (1972) was the first to study the body systematically and show that it is compositionally zoned. He proposed a differentiation model to explain the petrologic relationships in the pluton and used metamorphic and gravity data to postulate its tabular shape.

Larrabee (1964) outlined the contact aureole surrounding the Pocomoonshine pluton with a stippled pattern on his geologic map, but made no attempt to subdivide it. Westerman (1972) recognized four mineral zones in pelitic Digdeguash Formation hornfelses and three in the calcareous rocks of the Flume Ridge Formation, although he used a stratigraphic nomenclature that has since been abandoned. Ludman (1978, 1986) remapped the Big Lake quadrangle, revised the stratigraphies of the Fredericton trough and St. Croix belt, modified Westerman’s zones and isograd and fault contacts, and showed that contact metamorphic anatexis of the Digdeguash Formation had occurred along Huntley and Seavey Ridges. Bromble (1983) used feldspar and garnet-biotite geothermometry to estimate temperatures in the high-grade zones and to study the cooling history of the Pocomoonshine pluton, and DeMartinis’ (1986) detailed petrographic studies confirmed the aureole’s polymetamorphic history. This paper updates our studies of the thermal history of the Digdeguash Formation on the west flank of the pluton.

METAMORPHIC ZONATION OF THE DIGDEGUASH FORMATION

The Digdeguash Formation is a thick pile of wackes, conglomerates, and shales intercalated in generally well graded beds. It is tightly folded, but in areas unaffected by plutonic activity it is regionally metamorphosed only to conditions of the chlorite zone (lower greenschist facies). This regional metamorphism, designated as M1, accompanied Acadian upright folding of the Fredericton trough. Mineral growth during M1 was minor; no M1 porphyroblasts have been recognized, and the pelites of the Digdeguash Formation are uniformly fine grained. A faint phyllitic sheen in the low-grade pelites results from alignment (S1 foliation) of small muscovite and chlorite flakes parallel to the hinge surfaces of the Acadian F1 folds. Primary sedimentary features such as cross- and graded bedding and load structures
Figure 2. Simplified geologic map of part of the Big Lake quadrangle showing metamorphic zonation in pelites of the Digdeguash Formation on the western margin of the Pocomoonshine gabbro-diorite. Modified after Ludman (1986).

are well preserved, as are original textures in the coarser rocks. Distinctions between clasts and matrix are obvious in thin section, and polymineralic or multigranular rock fragments are easily identified.

Thermal effects superimposed on this low-grade terrane by emplacement of the Pocomoonshine body are recognized by progressive changes in the color, mineralogy, and texture of the pelites as the contact is approached, and by progressive obliteration of primary textures in the psammites. The first contact effect, originally described by Westerman (1972), and visible as far as 8.5 km from the pluton, is a coarsening of the normally fine grained chlorite and muscovite flakes and growth of unfoliated chlorite. Closer to the pluton, andalusite-biotite, sillimanite, and sillimanite-potassic feldspar zones have been delineated, but variations in texture and phase relationships permit subdivision of the outer two zones. The result is the five-fold division of the aureole shown in Figure 2.

Isograds defined by the first appearance of sillimanite and of the assemblage sillimanite + potassic feldspar are easily mappable, but poor outcrop control prevents tracing individual biotite and andalusite isograds in the outer part of the aureole. Westerman (1972) stated that andalusite appears farther from the pluton than does biotite, but available exposures are not sufficient to conclusively demonstrate which formed at the lower temperature. A single boundary thus separates chlorite grade exposures from an andalusite-biotite zone. Characteristics of the three major zones will be described briefly below.

**Andalusite-Biotite Zone**

The andalusite-biotite zone is the broadest zone in the aureole surrounding the Pocomoonshine gabbro-diorite, extending a maximum of 3.25 km from the first appearance of biotite and andalusite to the sillimanite isograd. Primary sedimentary features are well preserved throughout the zone. Recrystallization commonly heightens compositional differences in graded beds and facilitates facing determinations. More delicate features such as cross-bedding and flame structures are visible in
the outer part of the zone, but disappear as the sillimanite isograd is approached. Microtextures are altered somewhat, but identification of clasts and distinctions between clast and matrix are still possible in conglomerates and coarse wackes.

**Mineralogy.** Biotite and andalusite first appear in the pelites approximately 6.4 km from the pluton and produce a darker color (purplish gray) than is typical of the pale greenish gray chlorite grade exposures. Most of the biotite in wackes and pelites occurs as small brown to red-brown flakes that, along with thermally coarsened muscovite, mimetically enhance the S₁ foliation. A few larger poikiloblastic biotite flakes have been observed in the inner part of the andalusite-biotite zone. The grain size of the micas increases as the sillimanite isograd is approached, and the phyllic sheen eventually becomes a pronounced schistosity parallel to S₁.

Andalusite is the most prominent mineral in hornfelses of the Digdegua Formation. It occurs sparsely as slender gray porphyroblasts in pelites in the outer part of the andalusite-biotite zone, but increases in size and abundance closer to the pluton where it also appears in the wackes. Andalusite is generally chiastolitic, ranges from 2.5 to 20 cm in length, and comprises as much as 50% of the pelitic hornfels along Huntley and Seavey Ridges.

Garnet and staurolite have been identified in andalusite-biotite zone exposures, but are very rare. Small euhedral reddish garnet crystals occur most commonly in thin bands rich in pyrite, but are also present in a few "normal" pelite horizons. The garnets are clouded with inclusions in their centers and are clear at their rims, a texture interpreted as indicating initially rapid growth followed by growth at a slower rate. The sulfide-garnet bands are separated from the typical pelite by selvages of abnormally coarse-grained muscovite and biotite flakes. Staurolite has only been observed in a few thin sections and has never been identified in the field. It occurs as small, pale yellow-brown, subhedral prisms, and in some instances as inclusions in large chiastolite crystals. A few cordierite porphyroblasts have been identified in the outer part of the andalusite-biotite zone, and round aggregates of chlorite and muscovite in the same area are probably retrograde pseudomorphs after cordierite.

**Variations within the Andalusite-Biotite Zone.** Several textural and mineralogical variations have been noted in the andalusite-biotite zone. Some are attributable to distance from the pluton, but others are more problematic and show that the aureole is not as simple as had originally been thought. The steady increase in grain size of matrix micas and andalusite porphyroblasts from the outer part of the zone to the sillimanite isograd is a textural variation that is expected in a "normal" aureole. It is difficult to map the distribution of cordierite, garnet, and staurolite with the current outcrop and sampling density. Their occurrence is undoubtedly also temperature related, but bulk pelite composition is clearly a major factor as well. If the chlorite-muscovite aggregates described above are indeed pseudomorphs after cordierite, cordierite would seem to be restricted to the outer part of the andalusite-biotite zone.

Garnet appears in the inner part of the zone and is stable through the rest of the aureole.

Complicating these simple patterns is the systematic distribution of severely retrograded andalusite crystals in the inner part of the zone, and fresh, nearly unaltered andalusite in the outer part. This distinction, recognizable in the field as well as with the microscope, has led us to divide the andalusite-biotite zone into inner (strongly retrograded) and outer (weakly retrograded) subzones (Fig. 2). Andalusite of the outer subzone is typically fresh to slightly altered and is surrounded at most by a thin sheath of sericite grains (Fig. 3a). Chiastolitic inclusion trains are easily visible in hand sample and thin section. In contrast, andalusite porphyroblasts of the inner subzone are strongly altered (Figs. 3b, c), sericitization commonly proceeding most rapidly along fractures and lines of inclusions. Many crystals have been completely replaced (Fig. 3d), but some of the pseudomorphs preserve traces of the original chiastolitic inclusion pattern.

Further complexity is indicated by the growth of coarse muscovite flakes from the sericite of these pseudomorphs in the high-temperature part of the inner subzone (Fig. 4). This suggests a second episode of prograde mineral growth and implies at least two pulses of heat associated with the aureole.

**Sillimanite Zone**

Entry to the sillimanite zone is marked by the appearance of fibrolite in pelitic horizons as far as 3.2 km from the Pocomoonshine pluton. Most of the minerals characteristic of the andalusite-biotite zone persist into the sillimanite zone as stable phases or, in some instances, as armored relics. Porphyroblasts composed of relic andalusite armored by sericite and/or coarse muscovite are prominent throughout the zone. Garnet is abundant in pyrite-rich bands and in a few normal pelite layers, but staurolite and cordierite are very rare. Veins of white granite, quartz, quartz + muscovite, and quartz + muscovite + pink andalusite are widespread in the zone and become more abundant near the sillimanite-potassic feldspar isograd. These veins cut and strongly distort layering, but bedding is recognizable in most exposures. Cross-bedding and load features are also preserved in the outer part of the sillimanite zone, but are destroyed in the inner part.

Original clast outlines are still visible in the wackes, but the fine-grained matrix typical of lower grades has completely recrystallized. Biotite and muscovite generally occur as coarse flakes in both wacke and pelite, and most pelitic rocks display a strong schistosity mimetic after S₁ foliation. Some layers are deformed by tight F₂ folds, and a second, north-trending foliation (S₂) defined by coarse muscovite and biotite is locally well developed parallel to the F₂ hinge surfaces.

**Variations within the Sillimanite Zone.** The sillimanite zone is divided into inner and outer subzones of nearly equal width based on the mode of occurrence of sillimanite. In the
outer subzone it is totally fibrolitic and is restricted to pelitic layers immediately adjacent to large veins. In the inner subzone fibrolite is found throughout the pelitic layers and in some metawacke horizons, and coarser prismatic sillimanite is also present.

The outer sillimanite subzone is very similar to the adjacent part of the andalusite-biotite zone. Relict gray andalusite occurs in the cores of partial pseudomorphs, armored by sericite and chlorite and commonly surrounded by coarse muscovite growing from the sericite. A second, younger andalusite occurs with muscovite in the quartz veins. It is pink, unaltered, smaller than the gray porphyroblasts, and non-chiastolitic. Fibrolitic sillimanite is found only in coarse muscovite-biotite "schists" adjacent to these veins. It is not found in contact with the older generation of andalusite or with the micas of the pseudomorphs, but locally is in contact with or is included within the pink andalusite. Only a single staurolite porphyroblast, corroded and partially replaced by biotite and muscovite, has been observed in this subzone.

Fibrolitic sillimanite in the inner sillimanite subzone is not restricted to layers in contact with quartz veins, but is ubiquitous in pelites where it is intimately intergrown with biotite. Bundles of fine grained prismatic sillimanite are also present. Relict gray andalusites are surrounded by pseudomorphs of coarse muscovite and biotite, and fibrolite is commonly present in the outer parts of these pseudomorphs (Fig. 5). In a few instances it is also in contact with the relict andalusite in the pseudomorph cores. Euhehedral garnets occur in sillimanite-rich pelite layers as well as in bands with abundant pyrite, but neither staurolite nor cordierite have been identified. Accessory tourmaline and zircon grains are coarser and thus more prominent than in the outer parts of the aureole.
Figure 4. Photomicrograph showing second episode of prograde mineral growth in inner andalusite-biotite subzone. Pseudomorph consists of first stage gray andalusite (a) replaced by sericite (s). Coarse grained muscovite (m) of the second contact metamorphic event has grown from the sericite on the rim of the pseudomorph. X-polarizers. Width of field = 3.5 mm.

Figure 5. Photomicrograph showing relationships among sillimanite, muscovite, and sericite in the sillimanite zone. Sericite pseudomorphous (s) after first stage gray andalusite has been overgrown by coarse muscovite (m) and fibrolitic sillimanite (sill). X-polarizers. Width of field = 3.5 mm.

**Sillimanite-Potassic Feldspar Zone**

The highest grade portion of the contact aureole is characterized not only by the coexistence of sillimanite and potassic feldspar in the pelites, but also by a migmatitic appearance caused by segregation of quartzo-feldspathic and pelitic components during contact metamorphic anatexis. Discontinuous buff-weathering rafts of relict metawacke in addition to lenses and layers of gray melanosome are engulfed or injected by white leucosome masses within about 1 km of the contact with the pluton (Fig. 6). In the contact area along Seavey and Hunley Ridges, pods and veins of coarse grained leucosome also intrude some Pocomoonyshne diorites. Sedimentary features have been completely obliterated and bedding is replaced by a well-defined gneissic banding. Quartz veins and small pegmatite lenses are abundant, further accentuating the chaotic, swirling nature of the layers. In some exposures the migmatite is deformed by F2 folds, and thin tabular leucosome masses have been emplaced along the hinge surfaces of these folds. Anatexis of the Digdeguash Formation thus appears to have accompanied F2 folding.

The typical leucosome is a medium to coarse grained assemblage of quartz, potassic feldspar, and plagioclase with subordinate biotite and sillimanite ± muscovite ± garnet. The melanosome contains abundant biotite, sillimanite, quartz and lesser amounts of ilmenite, muscovite, zircon, and plagioclase. Phase relationships in this zone are complex and indicate several stages of mineral growth.

Andalusite occurs as it did in the sillimanite zone, as relict gray cores of pseudomorphs surrounded by coarse muscovite and biotite, and as younger pink prisms in quartz veins. Fibrolite mats and prismatic sillimanite comprise much of the melanosome and are intergrown with biotite and quartz. There appear to be two generations of prismatic sillimanite in the melanosome. Early sillimanite prisms are bent, broken, and cut by needles and mats of younger fibrolitic sillimanite. A second generation of prisms is undeformed and appears to be coeval with the fibrolite. Fibrolite in the leucosome lies between quartz and feldspar grains and rarely forms the large aggregates typical of the melanosome. Biotite is very abundant in the melanosome and occurs in three different habits: (1) red-brown flakes intergrown with fibrolite and fine prismatic sillimanite; (2) brown to olive-brown flakes in garnet-sulfide layers and in some
leucosome pods; and (3) green, clearly late-stage flakes in folia with muscovite and incorporating inclusions of sillimanite. The first of these habits is by far the most common, the third the rarest.

Potassic feldspar is present throughout the leucosomes and in some melanosomes as coarse, anhedral grains of orthoclase and microcline crypto-, micro-, and macro-perthites. Several generations of exsolution lamellae are apparent in most grains, and the exsolved plagioclase is polysynthetically twinned in some instances, untwinned in others. Most plagioclase feldspar is present as either untwinned blebs in myrmekitic intergrowths that replace orthoclase, or as discrete anhedral to subhedral grains that exhibit zoning. Plagioclase also occurs as inclusions in garnet and in the inclusion assemblage quartz + biotite + ilmenite + plagioclase.

Muscovite is much less abundant than at lower grades. It occurs as a part of the andalusite pseudomorphs, as coarse sieved porphyroblasts in some melanosomes, as flakes in leucosome pods, and with green biotite as described above. Some very late sericite is also present, produced by alteration of feldspar and sillimanite. Ilmenite is generally concentrated in cleavage traces of brown biotite, but also occurs as discrete grains in the granoblastic leucosome.

**SEQUENCE OF CONTACT METAMORPHIC EVENTS**

The mineral assemblages, habits, and textural relationships outlined above indicate at least two episodes of prograde metamorphism in the contact aureole of the Pocomoonshine gabbro-diorite. Evidence for two pulses of prograde mineral growth includes: (a) partial pseudomorphs in which gray andalusite cores are replaced by sericite that is itself overgrown by coarse muscovite and sillimanite; (b) two generations of andalusite (gray chiastolitic porphyroblasts and later pink non-chiastolitic prisms); and (c) two episodes of prismatic sillimanite growth in the innermost part of the aureole. Retrograde reactions are widespread throughout the aureole and also appear to have occurred at two different times: one between the prograde events and the other following the second thermal pulse. The first retrograde episode is clearly marked by the extensive sericitization of gray andalusite and the second by sericitization of sillimanite and feldspar in the sillimanite-potassic feldspar zone. Alteration of cordierite in the outer part of the aureole is probably associated with the earlier of these events.

The sequence of metamorphic events interpreted for the western contact of the Pocomoonshine gabbro-diorite with the Digdeguash Formation is thus:

**M1**: Regional chlorite grade metamorphism accompanying Acadian upright folding; development of S1 cleavage and foliation.

**M2**: First thermal metamorphism. Development of M2 biotite, cordierite, staurolite, garnet, gray chiastolitic andalusite, and early prismatic sillimanite. Mimetic enhancement of S1 to produce a well defined schistosity.

**First retrograde event**: Sericitization of gray andalusite close to the pluton; muscovite + chlorite replacement of cordierite in the outer part of the aureole.

**M3**: Growth of coarse muscovite from retrograde sericite; growth of fibrolite and second generation of prismatic sillimanite; partial melting of the Digdeguash Formation and segregation of leucosome and melanosome bodies to form anatectic migmatite adjacent to diorites of the Pocomoonshine pluton; generation of quartz veins with pink andalusite. The segregation of some leucosome masses in the hinge surfaces of folds in which S1 schistosity is deformed indicates coincidence of M3 and F2.

**Second retrograde event**: Formation of muscovite-green biotite folia; sericitization of late sillimanite and feldspars.

**M4**: Small granite bodies cut the Pocomoonshine pluton as shown in Figure 2, and another has been mapped on Love Ridge just west of the study area (Ludman, 1986). Biotite and andalusite occur in a narrow aureole around the Love Ridge body, and widespread andalusite-biotite assemblages on the west flank of Harmon Mountain (see Fig. 2) are probably due to another granite that is not exposed at the present erosion level. The three mappable bodies are all composed of pale gray biotite granite, and all are thought to be younger than the Pocomoonshine pluton, so that their contact metamorphism is designated as M4. Relationships among M2, M3, and M4 are marked by thick glacial cover on Hawkins Ridge and Harmon Mountain and cannot be determined without more outcrops.

The geographic distribution of features associated with the prograde and retrograde events supplies valuable information about the thermal history of the aureole. The source of heat for both prograde pulses appears to have been the Pocomoonshine pluton, and the metamorphic zonation shown in Figure 2 is the result of superposition of M3 on an older M2 aureole (see Fig. 7). It is difficult to precisely define the M2 sillimanite isograd because of the scarcity of early prismatic sillimanite, but the distribution of fibrolite and retrograded gray andalusite indicates that the presently mapped sillimanite isograd is probably an M3 feature as is the sillimanite-potassic feldspar isograd.

The M2 aureole probably had a narrower andalusite zone than the present composite aureole. Additional exposures and more detailed sampling are required to delineate M2 cordierite-andalusite and staurolite-andalusite subzones, and future work is planned to attempt this. M2 sillimanite was apparently confined to locations closer to the present pluton/Digdeguash contact than was M3 sillimanite. This fact, along with attainment of anatexis only during M3, shows that the second thermal pulse produced higher temperatures than the first.

**CONDITIONS OF METAMORPHISM**

In order to fully understand the thermal history of the Digdeguash Formation adjacent to the Pocomoonshine pluton,
absolute temperature/pressure conditions for each metamorphic event must be determined. Constraints on these conditions come from estimates of the liquidus temperature of the pluton, equilibrium mineral assemblages in the aureole, and cation exchange geothermometry.

Westerman (1972) suggested $P_{H_2O}$ of 2 to 3 kb during emplacement of the pluton based on the presence of primary magmatic hornblende ($P_{H_2O} > 1$ kb) and on textures showing that plagioclase crystallized before hornblende ($P_{H_2O} < 2.7$ kb). For this pressure range, he inferred liquidus temperatures of $1150 \pm 50^\circ C$. This serves as a maximum possible temperature for the aureole.

**Assemblage Data**

Figure 8 is a petrogenetic grid for mineral assemblages of the Digdeguash pelites that greatly narrows the possible range of metamorphic conditions. The absence of kyanite, transition from the stability field of andalusite to that of sillimanite during $M_2$, and the occurrence of the reaction muscovite + quartz $\rightarrow$ sillimanite + potassic feldspar + water during $M_3$ constrain pressure between 3.7 and 2.25 kb. The apparently stable coexistence of staurolite and andalusite further limits pressure to between 2.5 and 3.0 kb, as shown by the intersections of curves 1 and 2 in Figure 8. The effects of solid solution on curve 2 are unknown because we do not know the precise composition of the staurolite from the aureole, but this value for pressure is in close agreement with Westerman's estimate.

The restriction of the assemblage sillimanite + potassic feldspar to the anatectic migmatites implies that there should be only a small temperature difference (at about 2.75 kb) between the second sillimanite reaction and the onset of melting. This field relationship is in accord with the small difference in temperature indicated between curves 3 and 4 in Figure 8. Because all curves in Figure 8 are drawn for conditions of $P_{H_2O} = P_{total}$, this suggests that $P_{H_2O}$ was approximately equal to $P_{total}$ during $M_2$ and $M_3$. If $P_{H_2O}$ had been less than $P_{total}$, curve 3 would shift to the left and curve 4 to the right, increasing the temperature difference between them.

**Cation-Exchange Thermometry**

Preliminary microprobe studies of selected phases from the sillimanite-potassic feldspar zone were carried out in an attempt to determine the temperatures during $M_3$ anatexis using the biotite-garnet geothermometer. Garnet, biotite, and ilmenite from one leucosome sample and from one sulfide-garnet melanosome layer were analyzed on the JEOL electron microprobe at the American Museum of Natural History under the supervision of Drs. Jerry Delaney and Martin Prinz. Although our study can only be considered as preliminary, its results point toward a reasonable peak temperature for $M_3$ and
at the same time confirm the thermal complexities revealed by the textural relationships.

**Biotite.** Analyses of each of the three different types of biotite recognized in petrographic studies are reported in Table 1. Coarse red-brown grains generally have the highest Fe/Fe+Mg ratios and titanium contents, followed in order by the olive-brown and green varieties. Olive-brown biotites always contain large numbers of ilmenite grains in their cleavage traces. The average composition of the five analyzed ilmenite grains was Fe$_{0.983}$Mn$_{0.059}$Ti$_{0.966}$O$_{5.035}$ using the calculation method of Budington and Lindsley (1964). Only very small traces of magnesium were detected. These biotite-ilmenite assemblages suggest a retrograde reaction for biotite during which excess iron and titanium entered a newly formed oxide phase, e.g. red-brown biotite $\rightarrow$ olive-brown biotite + ilmenite.

**Garnet.** Garnet grains are zoned, but much more work is needed to unravel their complexities. The reconnaissance nature of our work allowed only two-point analyses of most grains (rim and core), and most showed the calcium and manganese enrichment of rims indicative of retrograde metamorphism. More detailed traverses were possible for one garnet from the leucosome and melanosome samples (Fig. 9). These reveal the complexity of metamorphism in the aureole by their compositional asymmetry (Fig. 9a) and the irregular path of Fe, Mg, and Mn outward from core to rim (Fig. 9b). Once again, more data are needed, but prograde and retrograde trends are suggested.

**Estimated Temperatures.** Temperatures for the garnet-biotite pairs shown in Table 2 were estimated using the calibration diagram of Spear and Chamberlain (1986; Fig. 10). Most of these pairs consist of olive-brown biotite and the rims of adjacent garnets, and yield temperatures of 530-550°C for what is interpreted as retrograde equilibration. Results are the same for leucosome and melanosome samples. Results from a biotite inclusion and the contiguous part of the surrounding garnet yield a similar temperature (525°C), probably also reflecting reequilibration during retrograde metamorphism. These temperatures presumably represent conditions attained during the second retrograde event, and do not record the peak of M$_3$ metamorphism. The pervasive nature of this retrograde metamorphism is indicated by the reequilibration of the system involving the included biotite and its host garnet.

We plan to continue microprobe studies in order to pinpoint peak M$_3$ temperatures. Red-brown (i.e. prograde) biotites adjacent to garnet grains were not observed in our preliminary study, and these should yield the highest temperatures. Some idea of these temperatures may be suggested by pairing average red-brown biotite compositions with core compositions of the zoned, retrograded garnets from the same slide (Fig. 10). Results from both leucosome and melanosome are about 670°C. These are in surprisingly good agreement with estimates based on the petrogenetic grid shown in Figure 8, where minimum melt temperatures of about 680°C are suggested.

---

**TABLE 2. Fe/Fe+Mg RATIOS FOR ADJACENT GARNET/BIOTITE PAIRS.**

<table>
<thead>
<tr>
<th>Pair #</th>
<th>LEUCOSOME</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Garnet core</td>
<td>.916</td>
<td>.916</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Garnet rim</td>
<td>---</td>
<td>---</td>
<td>.910</td>
<td>.918</td>
<td>.909</td>
</tr>
<tr>
<td>Adjacent biotite</td>
<td>.696</td>
<td>---</td>
<td>.696</td>
<td>.696</td>
<td>.696</td>
</tr>
<tr>
<td>Included biotite</td>
<td>---</td>
<td>.623</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pair #</th>
<th>MELANOSOME</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Garnet rim</td>
<td>.911</td>
<td>.927</td>
<td>.918</td>
<td>.917</td>
</tr>
<tr>
<td>Adjacent biotite</td>
<td>.642</td>
<td>.691</td>
<td>.648</td>
<td>.648</td>
</tr>
</tbody>
</table>
DISCUSSION

Figure 11 shows the interpreted thermal evolution of the hornfelsed pelites from the Digdeguash Formation based on petrographic and thermometric details given above. Although the estimated contact temperatures of >700°C are appropriate for the diorites along Hawkins, Hunteley, and Seavey Ridges, the observed history is not consistent with the cooling of a simple gabbro-diorite body. The igneous sheets commonly used in theoretical studies of the cooling of plutons and their host rocks are comparable to the shape of the Pocomoonshine pluton, and this permits rapid comparison of the observed and theoretical histories. None of the theoretical cooling curves shown in Figure 11 fit the interpreted sequence of prograde M2 -- retrograde event 1 -- M3.

Models such as those of Jaeger (1957, 1959) that invoke cooling totally by conduction yield smooth temperature-time curves (Fig. 11, dashed curve), quite unlike that interpreted for the study area. A model involving convective heat flow in water-saturated host rocks (Norton and Knight, 1977) produces perturbations of this simple curve that more closely resemble the observed relationships (Fig. 11, dotted curve). It also takes into account what must have been a high water content in the rapidly deposited turbidites of the Digdeguash Formation. Each successive peak in this model, however, must be at a lower temperature than the initial maximum, in conflict with the fact that M3
produced higher temperatures than M2 in the aureole surrounding the Pocomoonshine gabbro-diorite. Thus, M3 cannot simply be attributed to convective heat transfer. A heat source other than that which caused M2 is required.

Field relationships and the estimated M3 contact temperatures make it unlikely that this source could have been a granitic body such as those responsible for the later M4 event. The most likely explanation is that the Pocomoonshine gabbro-diorite was emplaced in two episodes of magmatic injection, the first causing M2, the second M3. Enough time must have separated the two magmatic pulses to permit the cooling indicated by the early retrograde event that separates M2 and M3. Based on a simple conductive model (Jaeger, 1957), the epizonal environment, and a postulated thickness of 1600-4800 m for the pluton (Westerman, 1972), this time gap may have been less than 250,000 years. The concentration of mafic rocks in the northern part of the pluton and of diorites in the south near the contacts where M3 anatectic took place implies that a sheet of mafic magma was injected first and was followed by a less regularly shaped dioritic mass. The Love Lake quartz diorite in the southeastern corner of the Big Lake quadrangle (Fig. 2) may be an extension of this second magma.

Although Westerman (1972) did not discuss a multiple injection history for the Pocomoonshine pluton, his data do not preclude this model, and he has suggested that the mafic rocks in the northern part of the body may have been emplaced earlier than the intermediate rocks of the study area (Westerman, pers. commun., 1987). The two-stage mechanism postulated here would seem to require higher temperatures for the initial gabbro phase (M2) than for the later dioritic stage (M3), unless the gabbro had been a partially solidified crystal-rich mush rather than a simple liquid. It is unlikely that the former possibility was involved because none of the gabbros contain the crushed and broken crystals expected if they had been largely crystallized at the time of emplacement. We believe that the relative proportions of the gabbro and diorite phases of the pluton explain this apparent incongruity. The early gabbros comprise only about 25% of the pluton; they may well have been hotter than the subsequent diorites, but the total heat contribution from the latter to the country rock was much greater.

This history for the Pocomoonshine pluton based on its contact aureole is in accord with that which has emerged for the regional plutonism (Ludman and Hill, 1986; Hill and Abbott, this volume). Early Acadian folding and thrusting were followed closely by emplacement of mafic, intermediate, and then granitic magmas. Gabbros intruding the St. Croix belt in the Calais quadrangle were apparently still somewhat liquid when the younger granites were emplaced, indicating the short time period involved in the plutonism. The time span in the case of the Pocomoonshine gabbro-diorite may have been longer, since none of the contacts between granite and the Pocomoonshine pluton exhibit the "mafic pillows" that typify the magma mingling zones in the Calais area (Ludman and Hill, 1986). In addition, the two episodes of retrograde metamorphism described above imply at least some time for cooling from peak metamorphic temperatures between (1) gabbro and diorite phases of the Pocomoonshine pluton, and (2) diorite and later granites.

ACKNOWLEDGMENTS

This study was supported by the Maine Geological Survey, by National Science Foundation Grant EAR78-03329, and by PSC-BHE grants from the City University of New York to A. Ludman. Susan Coughlin, Fran Dragan, Charles LoBue, and Neal Madnick aided in sampling, and Drs. Jerry Delaney and Martin Prinz of the American Museum of Natural History helped with the microprobe analyses. We are grateful to Patrick Brock, Hannes Brueckner, and Peter Mattson for their helpful comments on earlier versions of the work reported here.

REFERENCES CITED


Thermal metamorphism of the Digdeguash Formation


Richardson, S. W., 1968, Staurolite stability in a part of the system Fe-Al-Si-O: Jour. Petrol., v. 9, p. 467-488.


Westerman, D. S., 1972, Petrology of the Pocomoonsheen gabbro diorite, Big Lake quadrangle, Maine: Ph.D. diss., Lehigh University, Bethlehem, Pa., 175 p.