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Regional-scale metasomatism of Al, K, and Na during staurolite -andalusite– grade contact metamorphism, in the southwestern Nova Scotia, Canada

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ABSTRACT : Pelitic rocks of southwestern Nova Scotia have been affected by widespread contact metamorphism due to the intrusion of the Shelburne Pluton, with aureole up to 15 km wide. Well-preserved pseudomorphic textures indicate that common staurolite and andalusite metacrysts formed at the expense only of plagioclase, muscovite and biotite. Excess components (K, Na and Ca) from such replacement reactions imply extensive metasomatism throughout the contact aureole. Modal analysis of a typical andalusite-bearing rock indicates a one-to-one volume ratio of product to reactant. However the products of the replacement reactions contain approximately three times more aluminum than the reactants, indicating that the regional metasomatism also involved aluminum.

Key words : metasomatism, pseudomprph, stauralite, andalusite, shelburne

Introduction

Localized metasomatism is a common phenomenon, and regional-scale metasomatism has been reported for many sulphide and epithermal deposits as discussed by Schmid (1985) and Skinner and Johnson (1987). However, extensive metasomatism involving silicate minerals is less well known, especially in high-temperature environments.

Regional-scale metasomatism typically involves the transfer of elements over distances in the order of hundreds of meters or kilometers by fluid-assisted infiltration. Geological environments that provide high fluid permeability for such metasomatism have been discussed extensively (e.g. Etheridge *et al.*, 1983, 1984, Cox *et al.*, 1987, Hobbs, 1987) and the importance of fluid mobility during metamorphism and deformation has been emphasized. However, field evidence for fluid activity at high temperatures is rare (St-Onge and Lucas, 1995).

In the Shelburne area of southern Nova Scotia (Fig. 1), contact aureoles up to 15 kilometers wide have developed around the Shelburne Pluton, which caused amphibolite facies metamorphism (Chu, 1978, White, 1984, Wentzell, 1985). In this area, pseudomorphs of mica by staurolite and andalusite are well developed (Wentzell, 1985, Raeside *et al*, 1985). This paper describe an open-system metamorphism, which may have developed during deformation and which may accompanied high fluid circulation rates.

The study area has not been fully investigated in metamorphic geological point of view. Many reaction textures may have been overlooked because the rocks have large metacrysts which do not lend themselves to analysis on a thin section scale. The object of the present study is to investigate the regional scale metasomatism based on the observations and interpretations of reaction textures and micro-structures, on both the outcrop and thin-section scales.

Structural Geology

Five sequence of deformation structures ha-

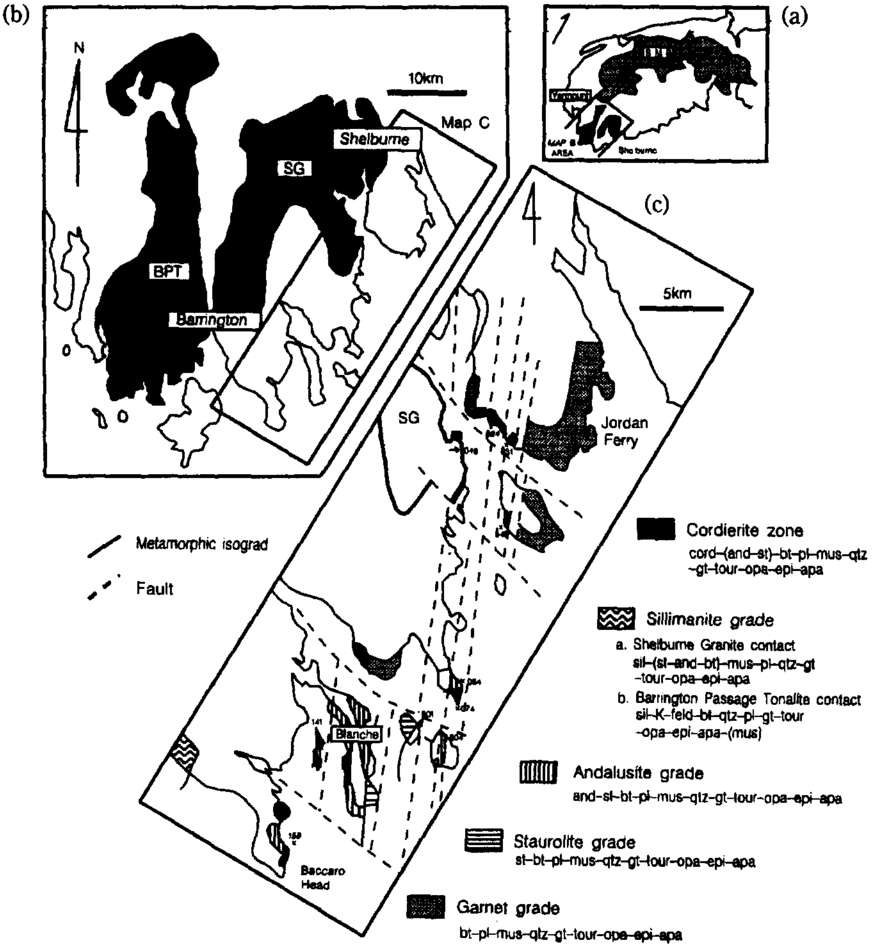

Fig. 1. Distribution of plutonic rocks and metamorphic assemblages. a) Distribution of the major plutonic rocks in southern Nova Scotia (SMB = South Mountain Batholith). b) Simplified geological map showing the location of the Barrington Passage Tonalite (BTT) and Shelburne Granite (SG) (after Rogers and Barr, 1988). c) Distribution of metamorphic assemblages. Sample locations, used in point counting in this study (Table 2), are also presented.

ve been described in the metapelitic and metapsammitic rocks of the Cambro-Ordovician Meguma Group in the Shelburne area (Hwang, 1990). The Acadian deformation (D1) produced the large Shelburne syncline and regional S1 foliation. The intrusion of Devono-Carboniferous plutons, and accompanying staurolite-andalusite grade contact metamorphism, overlapped the development of regional S2 crenulation cleavage (D2). In many parts of the study area, this crenulation cleavage (S2) is overgrown by staurolite and andalusite metacrysts (Fig. 3b, 4, 5b, 6, 7; Chu, 1978, White, 1984, Sage, 1984, Wentzell, 1985). However, the opposite relationship has also been observed. At the Blanche Peninsula (Fig. 1c), the internal foliation (Si) of staurolite and garnet is rotated relative to the external foliation (Se) as demonstrated by crooked quartz inclusions at the boundary of porphyroblasts (Fig. 2b) and Se is overprinted by S2 (Fig. 2c). Defining a time sequence using such porphyroblasts can be ambiguous (Ferguson and Harte, 1975, Vernon, 1978, Bell, 1986). However these examples de-

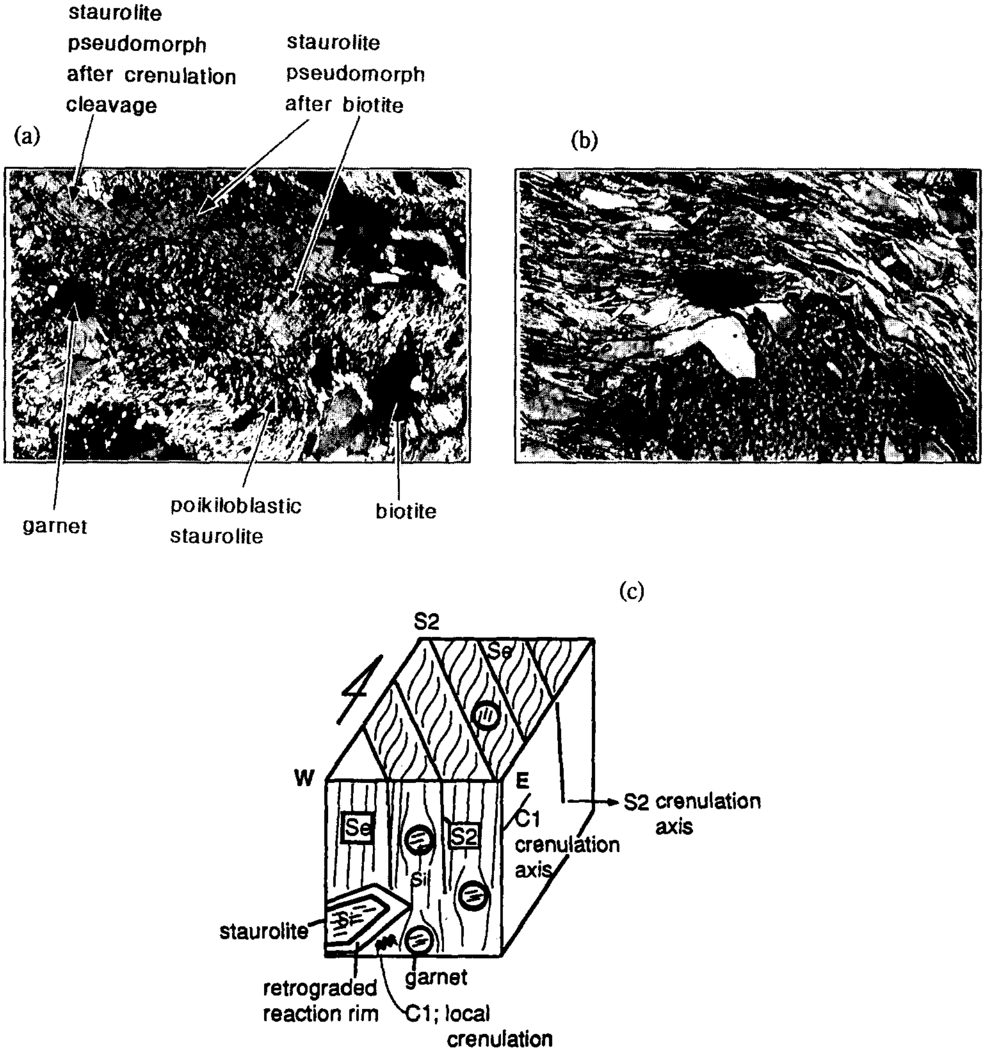

Fig. 2. a) A poikiloblastic staurolite which has overprinted the regional S2. Note the staurolite pseudomorphs after biotite. b) A quartz inclusion linking Se and Si across a garnet boundary (part of the schematic sketch in 2c). c) A schematic illustration of rotated porphyroblasts. Internal foliation (Si) of garnet and staurolite are parallel to each other. External foliation (Se) on the vertical surface does not show a distinctive crenulation geometry because the crenulation axis is subvertical.

monstrate that the growth of staurolite predated or was synchronous with S2. They may be interpreted as indicating that the growth of staurolite and S2 deformation were synchronous, or that staurolite crystallized during two separate periods (Williams, 1985). Although two metamorphic events are recognized in the study area, the second metamorphism consumed staurolite to produce cordierite (Hwang, 1990). Therefore, the first staurolite-andalusite grade metamorphism is interpreted as diachronic to the D2 crenulation event.

Staurolite- and andalusite-bearing rocks were severely deformed in D3 ductile shear zones, which have also been interpreted as late metamorphic features (Hwang, 1990). The D2 and D3 structures are overprinted by brittle/ductile sinistral shear zone. (D4). Weakly de-

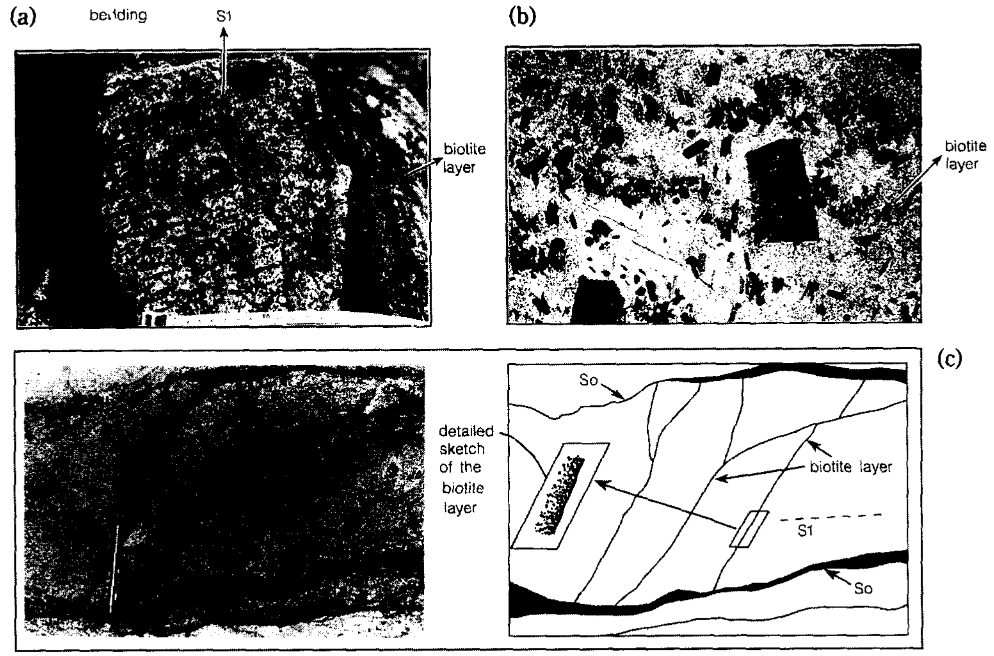

Fig. 3. Biotite layering
a) Outcrop appearance at Sandy Point lighthouse. Profile view looking north. Foliation and bedding planes are sub-vertical and the biotite layering is sub-horizontal. b) Thin-section view of the biotite layering. The orientation of this section is identical to the outcrop view (a). Note the biotite grains in the matrix are larger and randomly oriented, and staurolite has overgrown both types of biotite. c) Biotite segregations at a high angle to bedding (parallel to the longer dimension of the photograph) at Jordan Ferry. The outcrop is sketched on the right side of the photograph. The regional foliation is subparallel to bedding.

veloped kink-style deformation (D5) overprints all earlier structures (Hwang, 1990). The metamorphism of concern in this study occurred during the D2 event.

Distribution of Mineral Assemblages

Metapelitic rocks are common throughout the study area, and all samples examined contain biotite, garnet. muscovite, quartz, plagioclase, tourmaline, and opaque oxide phases. Epidote and apatite occur as accessory minerals. Staurolite, andalusite and sillimanite are sequentially added to this basic assemblage as metamorphic grade increases near the margins of the Barrington Passage Tonalite and the Shelburne Granite(Hwang, 1990). The first appearances of these index minerals define isograds in the study area (Fig. 1c).

Isograds are generally parallel to, or coincident with, major faults and stratigraphic boundaries, with the exception of patchy occurrences of cordierite-bearing rocks. The lowest-grade rocks are those of the garnet zone. The staurolite zone is narrow and lies between the garnet and andalusite zones. Staurolite-bearing rocks also occur locally as outcrop scale patches within the garnet zone near major faults. The andalusite zone is the widest in the area, and cordierite-bearing rocks occur in patches within it. The sillimanite zone only occur within 100 m of the contacts of the Shelburne and Barrington Passage plutons.

Reaction Textures

Many of the rocks in the Shelburne area, especially those from higher grades, display both the reactants and products of reactions which occur during contact metamorphism. In some, the reactants can be identified by pseudomorph textures. Depletion haloes and zoned minerals also provide evidence for some reactions and corroded crystal boundaries may represent incomplete reactions. Understanding these textural records is essential in revelling the effect of the contact metamorphism of these rocks.

Garnet zone

The lowest grade zone identified is the garnet zone, in which the major minerals (exceeding 5% of the volume) are biotite, garnet (typically spessartine-rich, especially at lower grades), muscovite, quartz, plagioclase (An>20) and chlorite. Prograde reaction textures were not observed in the garnet zone. Pervasive locally intense, retrograde metamorphism and deformation has generally obscured any previous reaction textures. The minerals of the garnet zone rocks represent the reactants for the production of assemblages in the staurolite and andalusite zones.

Staurolite and andalusite zones

The staurolite and andalusite zones are texturally and mineralogically similar, except for the distribution of andalusite, and can be described together. The major minerals in the staurolite zone are staurolite, biotite, garnet, muscovite, plagioclase and quartz. In addition, andalusite is present in the andalusite zone.

Garnet typically occurs as idioblastic poikiloblasts, 1-2 mm in diameter. Sage (1984), White (1984), and Wentzell (1985) have reported that the garnet in the staurolite and andalusite zones is dominantly almandine-spessartine, with minor amounts of pyrope and grossular. Slight compositional zoning is characteristic, with higher grossular content in the core and higher almandine in the rim. Spessartine and pyrope contents do not vary. Textural zoning, involving concentric inclusion-rich and inclusion-poor bands, does not appear to be related to compositional variation. Aligned internal fabric is rare in the garnet - most inclusions are random quartz grains and opaque minerals. Interfaces between garnet and all other phases are sharp, except where retrograde metamorphism is pronounced.

Biotite occurs predominantly as idioblastic porphyroblasts, up to 5 mm across. Most grains lie parallel to the muscovite foliation, and many have been strained. Variable biotite distribution has produced two types of compositional layering. Most commonly, sets of parallel, shallowly dipping biotite-rich layers are at a high angle to both bedding and foliation (Figs. 3a and 3b). In these layers individual biotite grains lie parallel to the regional foliation (Fig. 3b). The thickness of these layers does not exceed the aggregate length of a few biotite crystals, and the layers are 1 to 10 cm apart. A second type of layering also involves biotite-rich zones, which are at a high angle to the bedding and foliation (Fig. 3c). In this type, the biotite is finer grained, the distance between the biotite layers is greater (20 to 100 cm), and the biotite-rich layers grade compositionally in one direction into normal semipelitic compositions but display sharp boundaries in the other direction (Fig. 3c).

Plagioclase occurs as a fine grained, untwinned matrix mineral. According to Sage's(1984) microprobe data, it contains about 25 mole percent anorthite.

Staurolite occurs as idioblastic poikiloblastics, commonly about 10 mm in diameter (Figs. 4 and 5). Inclusions are mainly quartz, with small amounts of opaque minerals and garnet. Inclusions of quartz and opaque minerals within the included garnet are commonly idioblastic and the garnet grains have inclusion-free rims and inclusion-rich cores. The garnet is identical to that outside the staurolite metacrysts, both with respect to size and inclusion patterns. The internal foliation in staurolite porphyroblasts preserves evidence of S1 schistosity and S2 crenulation cleavage in the form

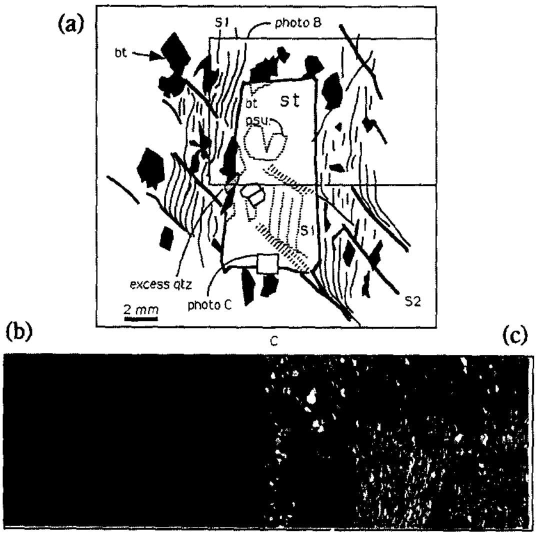

Fig. 4. a) staurolite porphyroblast with biotite and muscovite pseudomorphs. (a) Sketch of the staurolite crystal overprinting the regional foliation (S1) and crenulation cleavage (S2). Locations of photographs (b) and (c) are indicated. b) Photograph of the upper portion of the staurolite porphyroblast. Massive staurolite patches are pseudomorphs after biotite and are identical in size, shape, and frequency with the biotite porphyroblasts outside the staurolite. Partially replaced biotite exists at the edge of the staurolite. c) Photograph of the boundary of the staurolite. Staurolite has replaced muscovite and plagioclase of the matrix. Plagioclase in the matrix can be distinguished by staining (see text).

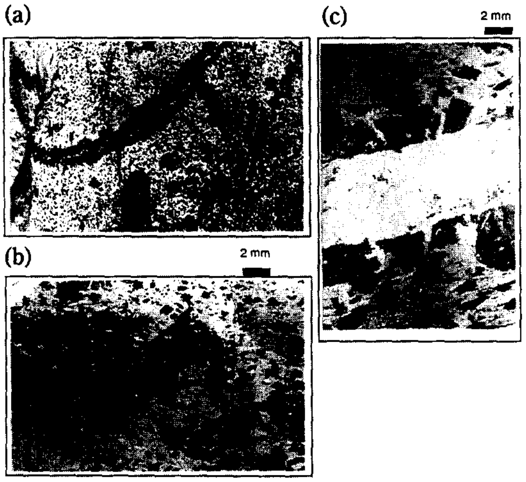

Fig. 5. a) A staurolite vein with a folded quartz vein in the centre. The staurolite vein is an aggregation of idioblastic staurolite crystals which are equivalent in shape and size to those in the matrix. Smaller darker crystals are biotite. b) Photomicrograph of a staurolite-rich layer. Unlike the staurolite veins in a, the staurolite grains are more xenoblastic and only locally interconnected. c) Quartz vein (band about 2 cm thick in the middle of the photograph) with subidioblastic staurolite concentrated along the vein walls. Dark coloured nematoblastic crystals in the matrix are biotite.

of oriented muscovite pseudomorphs and weak dimensional preferred orientation of quartz inclusions (Fig. 4). Staurolite metacrysts have replaced biotite, plagioclase and muscovite in the matrix, and commonly display many mica and plagioclase ghosts, which can be recognized as inclusion free portions (Figs. 4a, 4b and 4c). The shape, size and orientation of the biotite ghosts are identical to those in the matrix (Figs. 4a and 4b), and at the margins of the staurolite grains the replacement is incomplete (Figs. 4a and 4b, left side of the staurolite porphyroblast). In these situations, quartz is abundant around the replaced biotite and the grain boundary of the unreplaced biotite is not corroded (Fig. 4a). The shapes and orientations of muscovite and plagioclase pseudomorphs are also similar to those of the muscovite and plagioclase grains in the matrix (Fig. 4c). Commonly, mica-plagioclase aggregates have been entirely replaced, leaving only slightly oriented quartz inclusions to define an internal foliation in the staurolite. Staurolite veins are also common (less than 1 volume %). Some are parallel to the bedding planes, but most are discordant to bedding and to all other surfaces, such as foliations and joints. The veins are typically 1 to 3 cm wide and are composed of idioblastic staurolite grains, which resemble those in the matrix (Fig. 5a). Some are xenoblastic crystal aggregates, which are connected to form a vein-like zone (Fig. 5b). The spacing between staurolite veins is not consistent and ranges from 1 to 10 m. In some places, a very thin folded quartz vein (1 to 3 mm wide) occurs in the middle of the staurolite vein (Fig. 5a). Staurolite and andalusite are also commonly concentrated on the margins of relatively wide (about 1 cm) folded or planar quartz veins (Fig. 5c).

Andalusite occurs as subidioblastic poikiloblastic metacrysts averaging 10 cm long and 3 cm wide. Quartz, and biotite partially replaced by andalusite, are the main inclusions but metacrystic garnet and staurolite are also common (Fig. 6). No examples were observed of andalusite incorporated in garnet or staurolite, suggesting that the growth of andalusite postdated that of garnet and staurolite. Garnet and staurolite inclusions in andalusite are identical to those in the matrix, having similar idioblastic form, sharp boundaries, and being of the same grain size (Fig. 6). Individual poikiloblasts of andalusite are composed of aggregates of andalusite pseudomorphs after muscovite, biotite and plagioclase (Fig. 6). No relict texture of larger metacrystic staurolite or garnet has been found in andalusite suggesting that neither garnet nor staurolite was a reactant in the andalusite-generating reaction. Furthermore, the extremely low rate of solution and diffusivity of reactant garnet (Tracy, 1982) is incompatible with a rapid growth rate of product andalusite.

Pseudomorphs of micas by andalusite and staurolite can be readily distinguished in andalusite and staurolite metacrysts by their shape and size. Matrix plagioclase, however, is similar in shape and size to quartz, and it is not obvious from the metacryst textures whether or not plagioclase has been replaced by andalusite or staurolite. In order to detect the changes in the plagioclase content, ten representative thin sections from the staurolite- andalusite zone (nine bear-

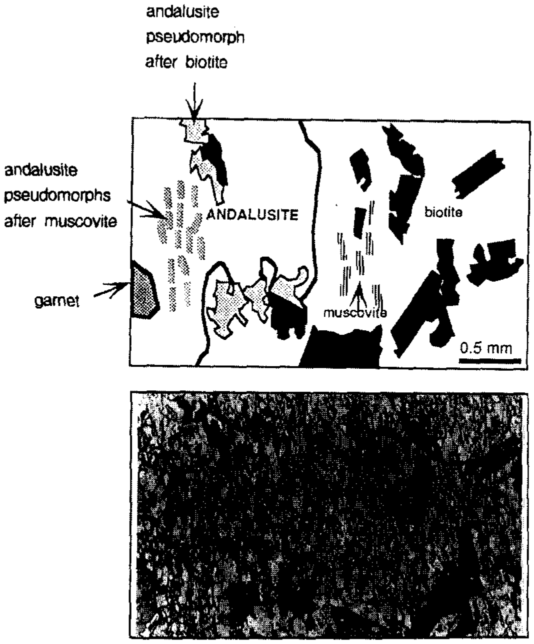

Fig. 6. Poikiloblastic andalusite replacing muscovite and part of biotite. Low relief minerals in the matrix and in the andalusite poikiloblasts are quartz. Note the volume of micas and quartz is not significantly different from the volume of andalusite and quartz in the poikiloblast.

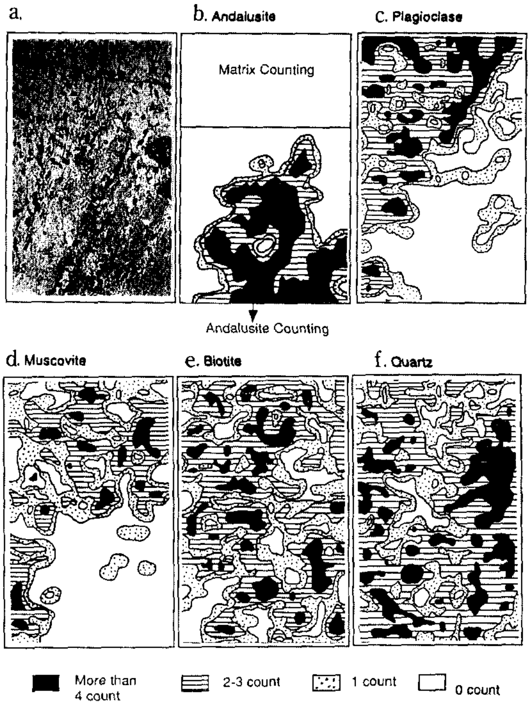

Fig. 7. Density maps of individual minerals (a, photomicrograph; b, andalusite; c, plagioclase; d, muscovite; e. biotite; f, quartz) in an andalusite-grade pelitic rock. 1980 equally spaced points were counted. The maps(b to f) were contoured using an overlapping system where the counting point is in the centre of a square of three rows and columns of points. Calculated modal abundances of minerals(Table 1) was done for the two areas shown in Fig. b.

ing staurolite, one bearing andalusite), stained by rhodizonite to indicate the presence of plagioclase were prepared and point-counted (Figs. 7a, 8a). In the andalusite-bearing section, the area point-counted can be divided into two domains: the upper third which is andalusite-free, and the andalusite metacryst (the lower box in Fig 7b).

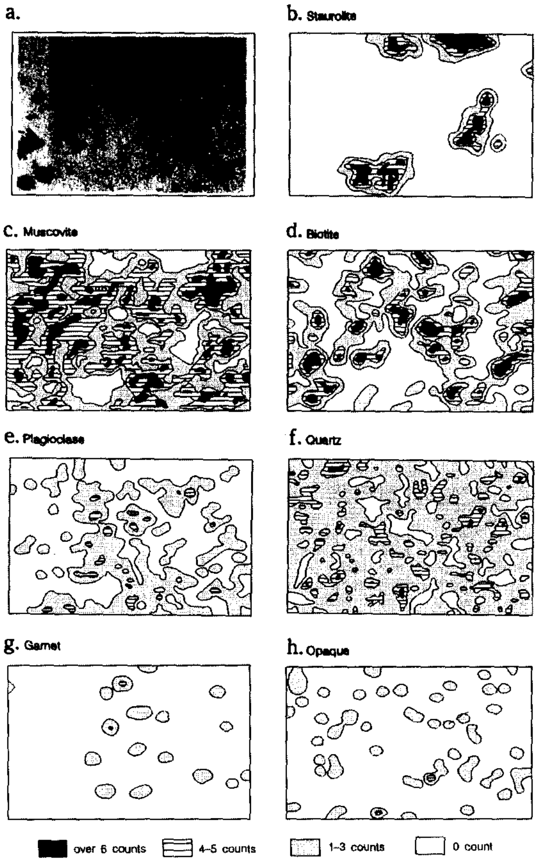

Fig. 8. Density maps of individual minerals (a, photomicrograph; b, staurolite; c, muscovite; d, biotite; e, plagioclase; f. quartz; g, garnet; h, opaque minerals) in a staurolite-grade pelitic rock. 3400 equally spaced points were counted, using the technique described in Fig. 7.

Modal abundances are summarized in Table 1. About 2000 points (30 columns×66 rows) were counted from a 1×2cm area of the thin-section (Fig. 7a). Ten minerals were recorded, and separate maps were compiled and contoured, using an overlapping system, where the counting point is in the centre of a square of three rows and columns of points. The contoured map of andalusite matches well with the andalusite as seen in thin-section (Figs. 7a and 7b). Where andalusite is abundant, the muscovite and plagioclase concentrations are extremely low, indicating that these two minerals have been replaced (Figs. 7c, 7d). There is no depletion or enrichment halo of muscovite and plagioclase around the andalusite. The distributions of biotite and quartz do not show any significant differences inside or outside the andalusite metacryst (Figs. 8e, 8f).

One staurolite-bearing sample (074B) was selected for detailed presentation of the modal analyses. In it about 3400 points (64 columns× 53 rows) were point-counted from a 1.5×2.3 cm area (Fig. 8a). The results are summarized in Table 2, along with those of the eight other staurolite-bearing rocks. As in the andalusite-bearing example, muscovite, and plagioclase are depleted within the staurolite metacrysts (Figs. 8c, and 8e), and there is no depletion or enrichment halo of these minerals around the metacrysts. Other minerals (quartz, opaque minerals, and garnet) are distributed uniformly (Figs. 8f, 8g, 8h). Unlike the andalusite-bearing section, however, biotite is depleted where staurolite is abundant (Fig. 8d). This confirms the observations that andalusite has replaced only part of the biotite, but that staurolite has replaced it completely in the metacrysts.

Table 1. Modal analysis volume calculations of the constituent phases in the matrix and poikiloblastic andalusite area (Fig. 8b).

Phases	Qtz.	Plag.	Mus.	Bt.	Gt.	Opaq.	Epi.	Tour.	Andal.
Volume in the matrix	23.19	31.53	19.31	23.47	0.28	1.53	0.28	0.42	
Volume in the andalusite	23.03	1.82	1.91	20	3.33	2.53	0	0	48.18

Table 2. Modal analysis volume calculations of the constituent phases in the matrix and poikiloblastic staurolite area whithin staurolite bearing thin sections.

Locations	024		031A		046-2B		064		141		549B		801B		804A		074B	
Matrix(M) or Stau(S)	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S
Number of Counts	459	421	496	122	485	164	626	494	752	439	400	200	400	521	610	259	3397	419
Qtz.	28.76	30.64	17.74	22.13	29.89	27.15	23.96	31.17	32.98	31.21	25	26	22.5	27.64	19.84	26.82	23.00	21.68
Plag.	11.32	0	13.5	0	20.21	0	17.25	0	7.18	0	24.5	0	23	0.19	19.51	0	7.94	0
Mus.	44.0	0	41.73	0.8	26.1	0	25.56	0	34.31	0	24.5	0	38.5	0	37.7	0	37.87	0.71
Bt.	8.93	1.19	25.6	0	20.84	0	30.35	0.2	22.07	2.96	20.25	0	11	1.54	13.44	0.13	19.18	1.19
Gt.	4.58	3.8	0	0	2.1	1.32	0.64	0	0.53	0	4.75	0	2.25	2.3	8.2	0.79	1.12	1.43
Opaq.	1.53	0.95	1.2	3.28	0.42	1.32	1.28	1.21	2.79	1.82	0.5	2.5	1.5	3.84	1.15	0.53	2.10	4.3
Tour.	0.87	0	0.2	0	0.21	0	0.96	0.4	0.13	0	0.5	0	1.25	0.19	0.16	0.26	0.75	0.72
St.	0	63.42	0	73.77	0.2	70.2	0	67.0	0	64.01	0	71.5	0	64.3	0	71.47	8.0	70.16
Pl.+Mus.+Bt. in Matrix	64.29		80.85		67.16		73.16		63.56		69.25		72.5		70.66		64.99	

*Qtz.: Quartz, Plag.: Plagioclase, Mus.: Muscovite, Bt.: Biotite, Gt.: Garnet, Opaq.: Opaque, Tour.: Tourmaline, St.: Staurolite

Discussion

Staurolite and andalusite metacrysts are typically larger than 1 cm in diameter and display positive relief on weathered outcrop surfaces. Accordingly the distribution of these phases can readily be determined on outcrops. Although the amounts of these phases vary from 20 to 50% by volume, the distribution is moderately homogeneous throughout the hundreds of square kilometers of outcrop of the monotonous Meguma Group rock types. Except for the occurrence of staurolite and andalusite veins, spacing between metacrysts ranges from 2 to 30 cm, and they are equally spaced on individual outcrops. Several previous studies have also documented the apparent textural pseudomorphism of micas by staurolite and andalusite (Chu, 1978; Sage, 1984; White, 1984; Wentzell, 1985).

Throughout the staurolite-andalusite zone the mineral assemblages are consistent and differ from the assemblages of the garnet zone only by the addition of staurolite and andalusite. The other major phases (biotite, muscovite, plagioclase, spessartine-rich garnet) and the accessory phases (opaque minerals, tourmaline, apatite and zircon) persist from grades below the beginning of the garnet zone. It has been demonstrated that garnet, and the accessory minerals are not involved in production of staurolite and andalusite. Only three minerals in the garnet zone (muscovite biotite and plagioclase) are possible reactants in the crystallization of staurolite and andalusite. Possible reactions are therefore of two types:

1. muscovite + biotite + plagioclase —> staurolite + andalusite
2. muscovite I + biotite I + plagioclase I —> staurolite + andalusite + muscovite II + biotite II + plagioclase II.

Aluminum metasomatism

Al is involved in the staurolite and andalusite-forming reactions; it is included both in the reactant and the product. Common pseudomorphs of mica and plagioclase replaced by staurolite or andalusite in these products allow indirect analysis of the Al flux. Aluminum-silicate minerals and staurolite contain about 4.0 to 4.4 volume % and 3.9 to 4.0 volume % Al, respectively, whereas muscovite, biotite and plagioclase contain 1.7 to 2.1, 1.0 to 1.2, and 1.1 to 1.3 volume % respectively (Carmichael, 1969). This indicates that two to four times the volume of reactants (muscovite, biotite and plagioclase) is required to produce a unit volume of products (staurolite or andalusite). As the volumes of muscovite and plagioclase replaced by andalusite pseudomorphs are not significantly different from those in the matrix, excess Al appears to have been derived from outside the reaction system rather than from the matrix. The consistency of this texture throughout the surrounding rocks across the width of the andalusite-staurolite zone prohibits the interpretation that the Al is locally derived from the enveloping rock mass. In the andalusite bearing sample, biotite makes up 23.5% of the matrix and 20% of the poikiloblastic andalusite, indicating only 3.5% of the biotite has been replaced by andalusite (Table 1). The portion of andalusite produced by replacement of muscovite and plagioclase can be obtained by subtracting the amount of biotite replaced from the total amount of andalusite (48.2% less 3.5%). Muscovite and plagioclase make up 50.8% of the matrix. Small amounts of muscovite and plagioclase (3.7%) remain in the andalusite metacrysts and must be deducted from the matrix quantity (50.8-3.7 = 47.1%). In total, therefore, 47.1% of the matrix plagioclase and muscovite is replaced by 44.7% of andalusite. Considering uncertainties caused during the modal analysis, this volume difference (2.4%) is not significant.

In one staurolite bearing thin section (Table 2, 074B), the volume percent of muscovite, biotite and plagioclase in the point-counted area (matrix + metacrysts) is 65.0%. Deducting 8% of staurolite in the counted area, the volume of mica and plagioclase in the matrix is 70.6% (65.0×100/92). The staurolite megacryst contain 1.9% of mica (no plagioclase was found in the metacrysts). Subtracting this from 70.6%, 68.7% of mica and plagioclase has been replaced by 70.2% of staurolite. Again, the proportion of staurolite pseudomorphs after mica and plagioclase is less than 2% different from the volume of these phases in the matrix.

Eight more staurolite-bearing thin sections from across the study area have been counted to confirm this relationship. As summarized in Table 2, 63 to 74% of staurolite occurs in the porphyroblasts and 64 to 81% of muscovite, biotite and plagioclase occurs in the matrix. Neither microscopic observation nor modal analysis show any significant volume differences between reactant micas + plagioclase in the matrix and product staurolite in the porphyroblasts.

Point counting of rock slabs (from 5 rocks) shows that the volume content of staurolite and andalusite ranges from 20% to 50% and that the volume of inclusions in the poikiloblasts is about 50%. The volume of staurolite and andalusite therefore ranges from 10 to 25%. In the garnet zone, the major phases (muscovite, biotite, plagioclase, garnet and quartz) occupy over 95% of rock volume. Quartz contains no aluminum. Spessartine has remained unchanged in volume and texture during andalusite- and staurolite-producing reactions and appears to have been an inert mineral. Only muscovite, biotite and plagioclase can be considered as local sources of aluminum. Based on a volume of 10 to 25% of staurolite and andalusite in the present rock, 30 to 75% of the total volume of potential source minerals would have been required. No such volume change can be demonstrated between the pseudomorphs in the poikiloblasts and the source minerals in the matrix in the staurolite-andalusite grade rocks. However, the one-to-one volume relationship between poikiloblasts and the source minerals suggests that the extensive amounts of aluminum must have been supplied to the reaction sites. As staurolite and andalusite are moderately homogeneously distributed over 100 km^2 (Fig. 1) aluminum must have migrated over distances of the order of kilometers from each reaction site. As the migration of elements is three dimensional in nature, it might be argued that the aluminum moved through short vertical distances which cannot be determined from an assessment in map view. However, considering topographic differences and throw on younger dip-slip faults, it is not likely that the aluminum migrated less than 500 m vertically. The topographic elevation difference in the study area is as much as 500 m. If the Al migrated vertically, it can be detected by the variations in topographic elevation window. Northeastenly striking dip slip faults are also common in the study area (Fig. 1). These faults postdates the contact metamorphism (Hwnag, 1990). Accurate throw distance of the dip-slip faults are not known. However, the dip-slip movement must add the distance to the vertical elevation window in which the Al variation can be detected.

The aluminum flux can also be determined by calculating the amount of the reactants in the protolith. As discussed above, 30 to 75% of reactant phases are depleted during the crystallization of staurolite and andalusite. In the staurolite-andalusite grade rock, average volume of muscovite, biotite and plagioclase is 70% (Tables 1 and 2). Therefore, the volume content of these source minerals in the garnet zone can be approximated by adding the consumed portion (30 to 75%) to the 70% of product or metastable portion in the staurolite-andalusite grade rock. This results in unrealistically high volume contents of mica and plagioclase (100 to 145%) in a turbidite protolith, indicating that the excess Al must have been derived from outside the reaction system rather than from the matrix.

Textural and modal analytical criteria therefore demonstrate that muscovite, biotite and plagioclase have been replaced by andalusite and staurolite in the rocks of the Shelburne area. Such reactions involve the addition of some species (Al) and the elimination of others (K, Na, Ca in particular).

K, Na, Ca and Mg-Fe metasomatism

The staurolite-and andalusite-producing reactions are inferred to involve biotite, muscovite and plagioclase as mineral reactants and staurolite, andalusite and water as products. The reactions can only be balanced by allowing free ionic species:

(1) muscovite + biotite + plagioclase + Al^{3+} = staurolite + H_2O + K^+ + Na^+ + Ca^{2+}

(2) muscovite + biotite + plagioclase + Al^{3+} = andalusite + H_2O + $(Mg, Fe)^{2+}$ + Na^+ + Ca^{2+}

These reactions indicate that some species (K^+, Na^+, Ca^{2+}, Fe^{2+}, Mg^{2+}) have been consumed or removed from the reaction site. The possible deposition sites in the staurolite-andalusite-bearing rocks are biotite, muscovite and plagioclase, which would be of a different composition from the source minerals. Biotite is the only Fe-bearing reactant, but both staurolite and newly formed biotite are Fe-bearing products. The biotite in staurolite-andalusite bearing rocks would therefore be expected to be less Fe-rich than in lower grade rocks. Sage (1984) reported a high average FeO content of 19.5 wt % in the staurolite-andalusite rocks and Hope (1987) reported an average of 17.8 wt % FeO in stratigraphically equivalent rocks 15 km to the east. Similarly, Na from reactant plagioclase might have been consumed by new muscovite. However, Na_2O contents are generally low in staurolite-andalusite-grade muscovite (average 1.4 wt %, Sage, 1984), and comparable with the chlorite-grade rocks to the east (average 1.3 wt %, Hope, 1987). The lack of evidence of substantial changes in composition of micas and plagioclase indicates that Mg, Fe, K, Na and Ca were not consumed locally, but were removed from the rock mass, presumably by the same process responsible for the metasomatic introduction of Al.

Conclusions

1) Mica pseudomorph textures in staurolite and andalusite allow the estimation of the volume of replaced reactants and products. Microscopic observations and modal analyses indicate that the volumes of products and dissolved reactants are equal. As the product phases (staurolite and andalusite) include over

three times more Al than the reactant phases, it is inferred that extensive Al metasomatism also occurred, with high fluid infiltration.

2) The mineral reactions derived from reaction textures indicate that Fe, Mg, Na, Ca. and possibly K were removed from the system.

3) The metamorphic assemblage staurolite-andalusite-biotite-muscovite-plagioclase-garnet-quartz-opaque minerals is exposed over more than 100 square kilometers. Accordingly elemental diffusion must have existed in the order of kilometers. If vertical metasomatism is assumed, the elements must have been transported at least 500m. Such advective mass transport has been interpreted to be evidence of extensive metasomatism in the Shelburne rocks.

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십자석-홍주석 접촉 변성과정에 수반된 Al, K, Na의 광역적 변성교대작용

-캐나다 노바스코시아주 서남부의 예-

황 상 기

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요 약 캐나다 노바스코시아주 남서쪽에 분포하는 이질암류는 셀브론화강암의 관입에 의해 넓은 지역이 접촉변성을 받았다. 이곳에 분포하는 접촉변성대는 15km 두께에 이른다. 잘 발달된 가상구조(pseudomorphic textures)에 의하면 사장석-백운모-흑운모가 십자석과 홍주석으로 치환되어있다. 이러한 치환반응이 가능하려면 반응물에는 존재하나 생성물에는 존재하지 않는 K, Na, Ca 원소들이 반응계에서 빠져 나와야만 가능하다. 이는 연구지역에서 원소들이 넓은 접촉 오레올을 이동한 광역의 변성교대작용이 발생하였음을 암시해 주고 있다. 홍주석을 함유하는 전형적인 시료의 모달 분석결과 반응물과 생성물의 체적비율이 1:1 관계를 보이고 있다. 동일체적일 경우 생성물(홍주석)에 함유된 Al의 양이 반응물들(사장석-백운모-흑운모)에 함유된양 보다 3배가 많음을 감안할때 이러한 화학반응을 가능하게 하려면 Al 역시 접촉변성 지역에서 원거리를 이동하였다는것을 알 수 있다.