*Chapter 4*

# PETROGRAPHY

## 4.1 General Petrography of Major Rock Types

All granitic rocks of the batholith contain essential quartz, alkali feldspar and plagioclase (QAP). A contoured density plot of 452 representative QAP determinations from the entire batholith is given in Figure 4.1a. The bulk of the batholith is composed of monzogranite and, to a lesser extent, granodiorite with minor tonalite and syenogranite. It should be noted that Streckeisen (1976; Fig. 4.1b) grouped plagioclase of $An_{<5}$ composition with alkali feldspar. Detailed petrographic studies (Smith et al., 1986; MacDonald and Horne, 1988; MacDonald et al., 1992) report albitic plagioclase in leucomonzogranite rocks of the batholith. In fact, recent studies of leucogranitic rocks by Kontak (1990), MacDonald and Clarke (1991) and Clarke et al. (1993) noted the anorthite content of plagioclase in most leucogranite bodies is $<An_5$. Grouping this plagioclase with alkali feldspar would shift the compositions toward the alkali feldspar-quartz join of the QAP diagram, that is, into the syenogranite and alkali feldspar fields. The determination of the exact amount of albite with $An_{<5}$ would require extensive petrographic/microprobe analysis. Therefore, for the purpose of developing a field method for rock classification (see discussion in Chapter 2), all plagioclase compositions have been grouped together.

Modal plots for the six major rock types for the entire batholith are given in Figs. 4.1c-e. The wide degree of scatter within each rock type can be attributed to compositional variation, textural heterogeneities and varying degrees of metasomatism (e.g. K-feldspathization, albitization) both within, and between, the various map units. In addition, counting error and operator bias presumably contribute to the degree of scatter, albeit of an unknown amount. It is apparent from the individual plots in Figure 4.1 that A/P increases from biotite granodiorite to fine-grained leucomonzogranite and leucogranite.

A summary of the overall textural and petrographic characteristics of the six main rock types is given in Table 3.1 and schematically depicted in Figure 4.2. Consistent textural characteristics were noted in the granitic rocks throughout the batholith. For example, biotite

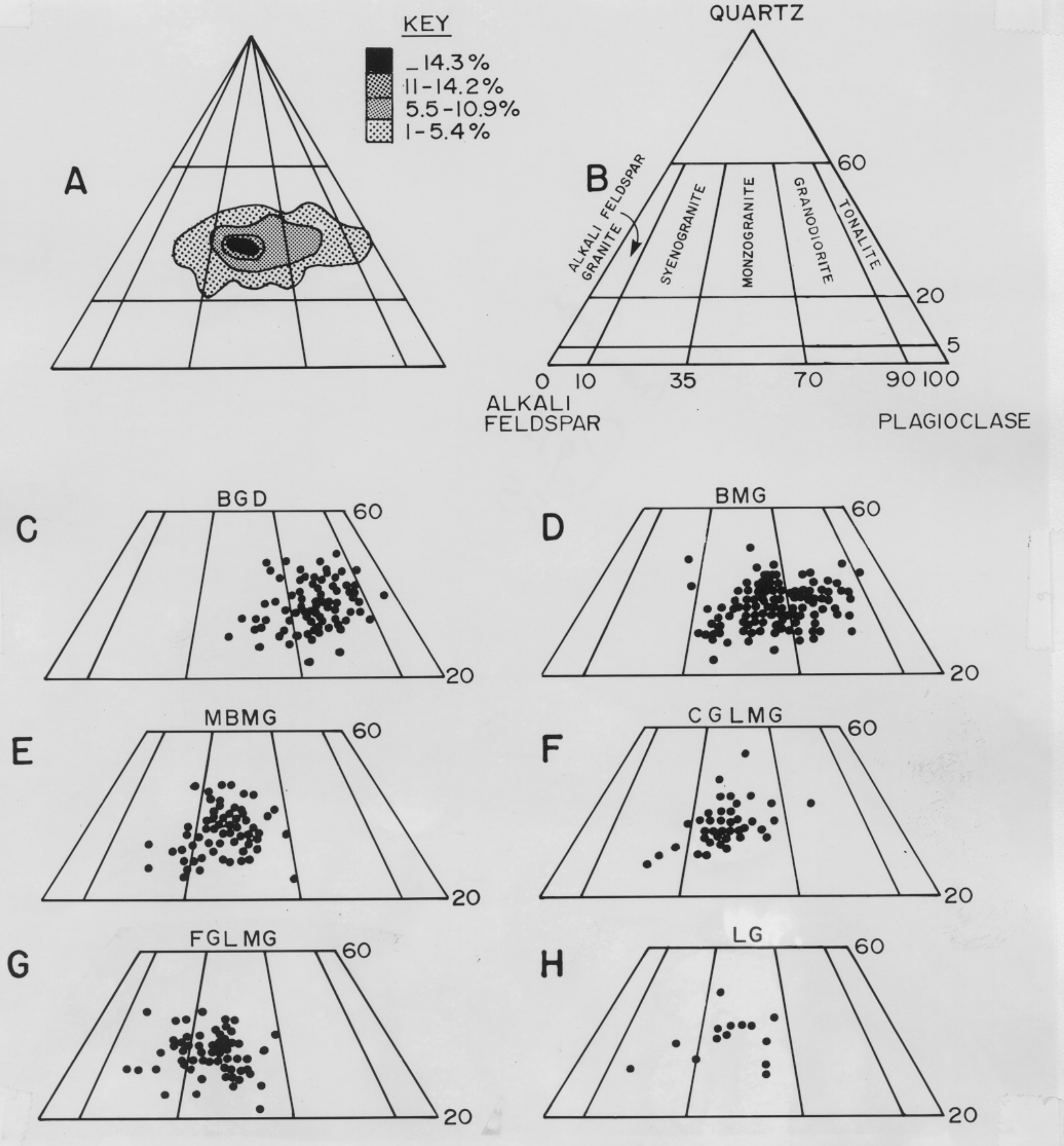
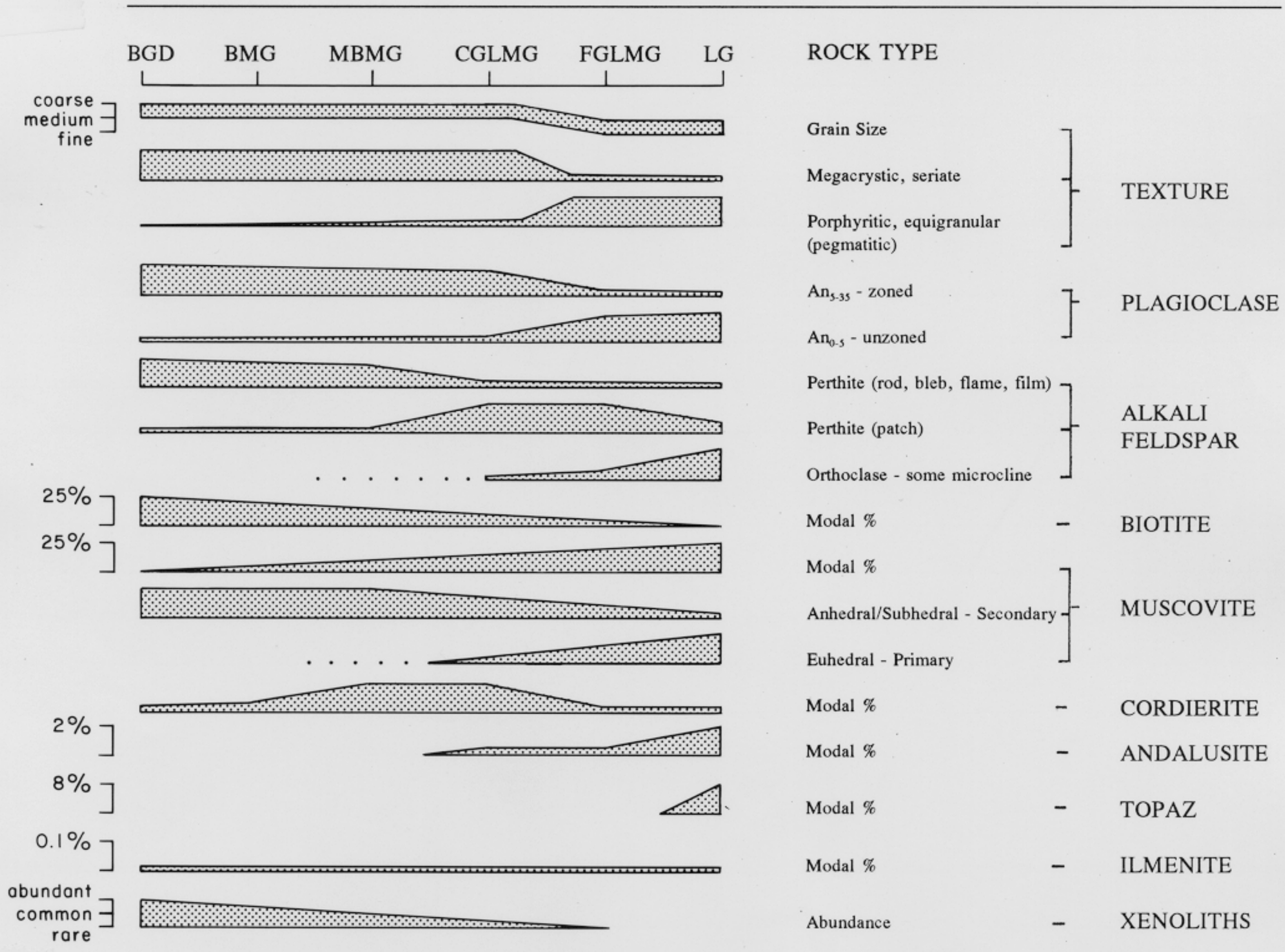



**Figure 4.1(a)** Contoured QAP plot of 452 representative samples from the batholith indicating a predominantly monzogranitic-granodioritic composition; (b) fields after Streckeisen (1976); QAP plots of representative samples from (c) biotite granodiorite (BGD); (d) biotite monzogranite (BMG); (e) muscovite-biotite monzogranite (MBMG); (f) coarse-grained leucomonzogranite (CGLMG); (g) fine-grained leucomonzogranite (FGLMG); (h) leucogranite (LG).

granodiorite, biotite monzogranite, muscovite-biotite monzogranite and coarse-grained leucomonzogranite units are mostly medium- to coarse-grained with megacrystic or seriate textures, although, as previously noted in Chapter 3, fine- to coarse-grained porphyritic or equigranular textures are locally developed in these rock types. In contrast, fine-grained leucomonzogranite and leucogranite units are mostly fine- to medium-grained with porphyritic or equigranular textures, although fine- to coarse-grained aplitic, pegmatitic, seriate and megacrystic textures are developed in some units (e.g. Tantallon Leucomonzogranite, MacDonald and Horne, 1987; Murphy Lake Leucogranite, MacDonald and Ham, 1992).




ROCK TYPE - BGD - biotite granodiorite; BMG - biotite monzogranite; MBMG - muscovite-biotite monzogranite; CGLMG - coarse-grained leucomonzogranite; FGLMG - fine-grained leucomonzogranite; LG - leucogranite.

**Figure 4.2** Summary of the main petrological features of the South Mountain Batholith showing the systematic changes from least evolved biotite granodiorite to most evolved leucogranite.

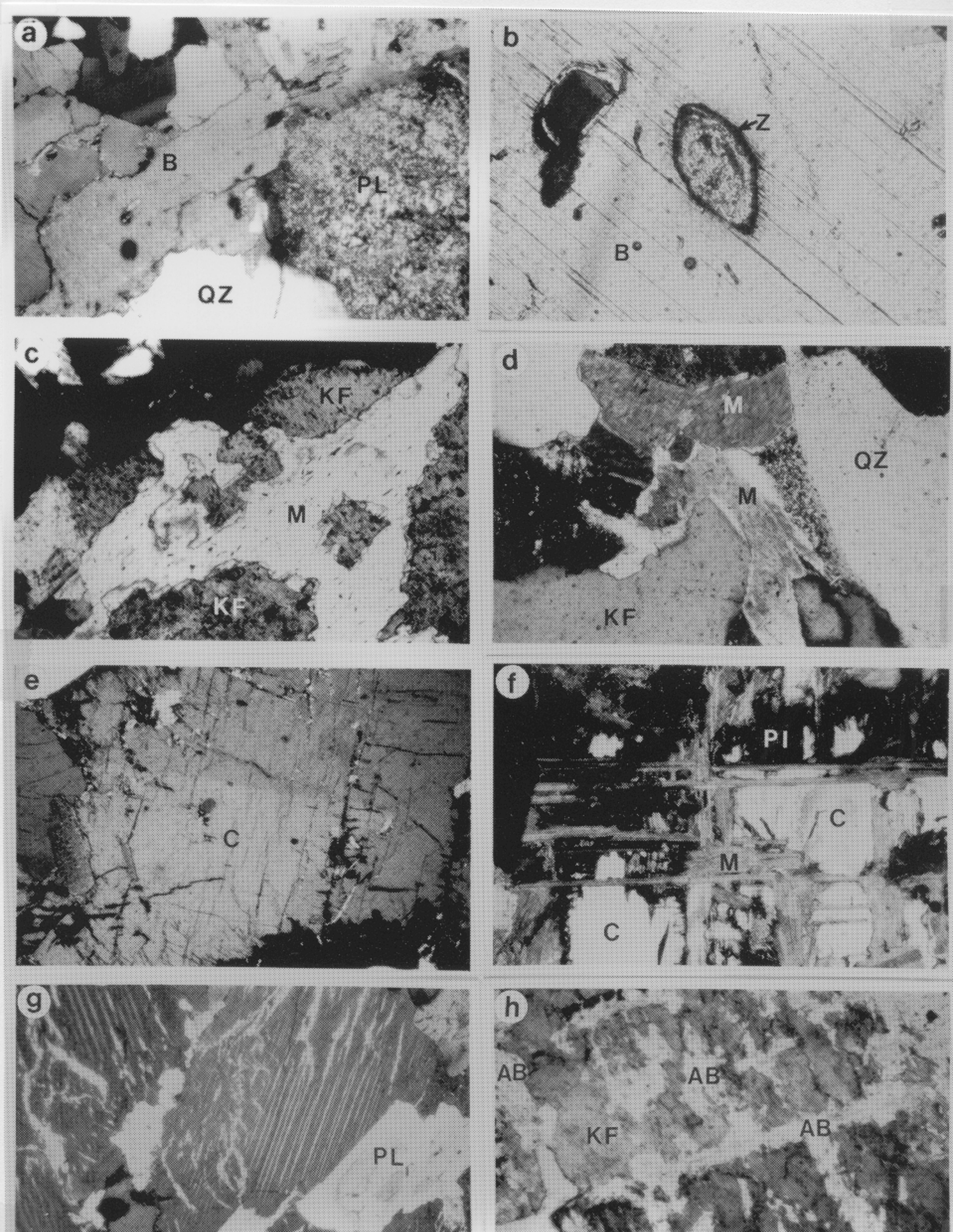
Systematic petrographic variations noted throughout the batholith define a sequence from least evolved granodiorite to most evolved leucogranite. These variations include: (1) **biotite** (Plate 4.1a) with inclusions of apatite, zircon (Plate 4.1b), monazite, ilmenite ±xenotime ±epidote ±titanite, decreases from >25% in some granodiorite units to absent or trace amounts in several leucogranite units; (2) **muscovite** increases from trace amounts in most granodiorite units to >25% in several metasomatized leucogranite units. Muscovite generally occurs as anhedral grains replacing feldspar (Plate 4.1c) in granodiorite units to euhedral to subhedral grains (primary magmatic?; Plate 4.1d) in several fine-grained leucomonzogranite and leucogranite units; (3) **cordierite** (Plate 4.1e) and pinite/muscovite pseudomorphs (Plate 4.1f) occur in minor amounts in most units, but is most abundant in monzogranite and coarse-grained leucomonzogranite units where it may exceed 5% of the mode; (4) **alkali feldspar** is perthite in the majority of the batholith with rod, bleb, flame and film type exsolution (Plate 4.1g) dominant in granodioritic and monzogranitic rocks while patch type perthite (Plate 4.1h) is more common in leucomonzogranite units. In most leucogranite units the alkali feldspar rarely has a perthitic texture; (5) **plagioclase** ($An_{<5\text{-}35}$) is typically zoned (normal and oscillatory types; Plate 4.1i) in granodiorite and biotite monzogranite units, zoned and unzoned in leucomonzogranite units and unzoned ($An_{<5}$; Plate 4.1j) in most leucogranite units; (6) **andalusite** (Plate 4.1k), with characteristic alteration to muscovite, is most abundant in fine-grained leucomonzogranite and leucogranite units; (7) subhedral to euhedral (primary magmatic?) **topaz** (Plate 4.1l) is restricted to leucogranite rocks such as at East Kemptville where it may constitute up to 8% of the mode (Kontak, 1990; Ham and MacDonald, 1991).

## 4.2 Mineralogy

The following sections summarize the mode(s) of occurrence for most of the major, minor and accessory mineral phases in the batholith. In addition, key references are cited for interested readers.

### 4.2.1 Quartz

Quartz is a ubiquitous mineral phase in virtually all rocks of the batholith where it occurs as an anhedral to subhedral groundmass, or intergranular, constituent (Plate 4.2a). It commonly forms subhedral "quartz eyes" in megacrystic rocks and subhedral to euhedral phenocrysts in many porphyritic units (Plate 4.2b). Quartz is commonly present as subhedral to euhedral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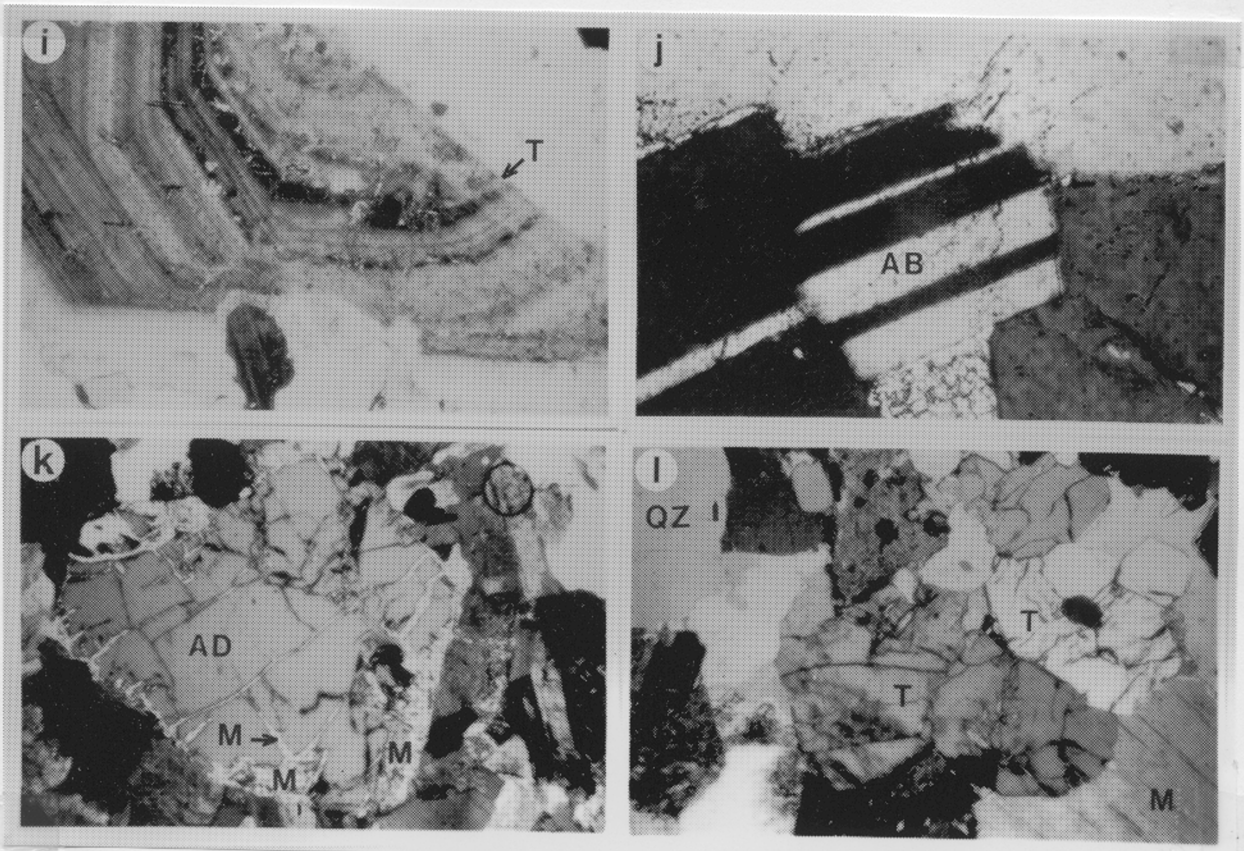



**Plate 4.1** Photomicrographs illustrating typical mineralogical and textural feature of the plutons of the South Mountain Batholith; Length of photographs is 1 mm in all photos except 0.4 mm in b and j; all are in crossed polarized light. (a) biotite (B) with inclusions of zircon and/or monazite with pleochroic halos, sericitized plagioclase (PL) and quartz (QZ) in megacrystic granodiorite; (b) zircon (Z) inclusion in biotite (B) in biotite monzogranite; (c) secondary muscovite (M) replacing alkali feldspar (KF) in coarse-grained leucomonzogranite; (d) euhedral to subhedral (primary?) muscovite (M) in leucogranite; (e) pristine cordierite crystal (C), showing prominent twin plane, in biotite monzogranite; (f) typical altered cordierite crystal (C) in coarse-grained leucomonzogranite with secondary muscovite developed along prominent crystallographic directions (010) and pseudomorphic replacement by pinite (PI); (g) large alkali feldspar megacryst in biotite monzogranite displaying rod, bleb, flame and film type perthitic exsolution and euhedral inclusions of plagioclase (PL); (h) alkali feldspar megacryst (KF) in coarse-grained leucomonzogranite with patch perthite exsolution of albite (AB); (i) plagioclase grain in biotite granodiorite displaying well developed oscillatory zoning and simple twin plane (T); (j) euhedral albite crystal (AB) in leucogranite; (k) andalusite grain (AD) with characteristic alteration to muscovite (M) in fine-grained leucomonzogranite; (l) cluster of topaz crystals (T) and adjoining muscovite (M) in leucogranite.

inclusions in plagioclase (Plate 4.2c) and alkali feldspar, routinely defining growth planes within feldspar megacrysts. Quartz is perhaps the most characteristic mineral in hydrothermally altered zones (Plate 4.2d) associated with polymetallic Sn-W mineralization. Large modal amounts of quartz in these zones may either reflect the presence of $SiO_2$-rich hydrothermal fluids or the

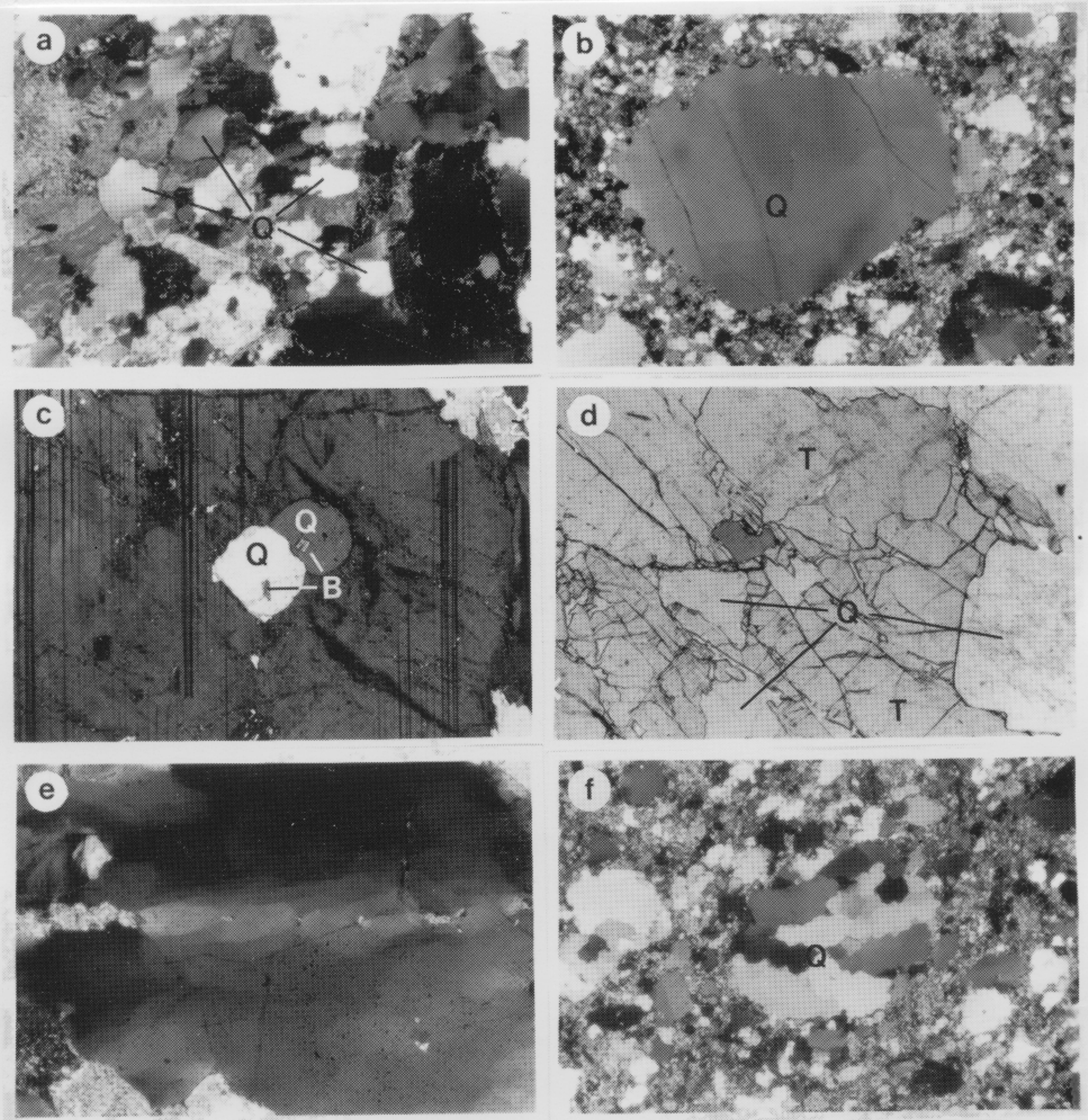



**Plate 4.2** Photomicrographs illustrating typical petrographic features of quartz (Q) in the South Mountain Batholith; Length of photographs is 1 mm in all photos except 0.4 mm in c and e; all are in crossed polarized light. a) anhedral and subhedral quartz as a groundmass constituent in muscovite-biotite monzogranite; b) quartz phenocryst in porphyritic fine grained leucomonzogranite; c) quartz inclusions, containing euhedral biotite inclusions (B), in plagioclase grain with well-developed polysynthetic twinning; d) quartz-tourmaline (T) intergrowth in greisen zone from Inglisville (MacDonald and Ham, 1994b); e) typical undulose extinction in quartz grain in muscovite-biotite monzogranite; f) undulose extinction and subgrain development in quartz phenocryst in muscovite leucogranite.

removal of other chemical components (e.g. alkalis) during hydrothermal alteration. The only rock type in the entire batholith that is devoid of quartz is episyenite (i.e. desilicified) which occurs as alteration zones in all rock types, often associated with U mineralization (see Chapter 9 for discussion).

Quartz displays variable amounts of undulose extinction (Plate 4.2e) in most units throughout the batholith. Local areas may also show variable development of granoblastic textures with equidimensional grains and well sutured boundaries (Plate 4.2f). These textural features in quartz indicate the batholith was subject to structural stress following crystallization, which will be discussed further in Chapter 6.

4.2.2 Plagioclase

Plagioclase is a major constituent in all rocks of the batholith. It occurs as anhedral, subhedral (Plate 4.3a) and euhedral groundmass grains in all rocks and as megacrysts in most megacrystic rocks and phenocrysts (Plate 4.3b) in many porphyritic rocks. Plagioclase commonly occurs as euhedral inclusions in alkali feldspar and to a lesser extent in quartz and may contain inclusions of biotite, quartz (Plate 4.3c) and, less frequently, garnet or cordierite.

As noted above, plagioclase exhibits systematic textural and compositional changes with degree of differentiation of host rock. MacDonald and Horne (1988) presented a summary of these variations for plagioclase in the Halifax Pluton. MacDonald et al. (1992) concluded that plagioclase in the rest of the batholith showed similar textural and compositional features as in the Halifax Pluton. In most **biotite granodiorite** and **biotite monzogranite** units of the batholith plagioclase is chiefly zoned with normal, oscillatory and to a lesser degree patchy zoning. Unzoned plagioclase is mainly absent with the exception of some albitic rims on zoned plagioclase grains. Myrmekitic intergrowths of albite and quartz (Plate 4.3d) or unzoned albite (Plate 4.3e) may form rims on variably zoned plagioclase grains in these rocks. Plagioclase is predominantly unaltered in these rocks with minor amounts of sericitic alteration, primarily in Ca-rich cores. MacDonald and Horne (1988) reported plagioclase compositions ranging from $An_{15-33}$ in biotite granodiorite and $An_{11-36}$ in biotite monzogranite from the Halifax Pluton. In **muscovite-biotite monzogranite** and **coarse-grained leucomonzogranite** units plagioclase occurs as a variety of weakly to moderately zoned grains with normal, patchy and to a lesser degree oscillatory zoned and unzoned crystal. Myrmekite rims are rare to absent and alteration consists of weak to intense replacement by sericite. MacDonald and Horne (1988) reported plagioclase compositions in these rocks ranging from $An_{2-30}$. Plagioclase in **fine-grained leucomonzogranite** is mainly unzoned or displays weak normal zoning. Myrmekite rims are absent in these rocks and alteration to secondary sericite and/or muscovite is moderate to intensely developed.

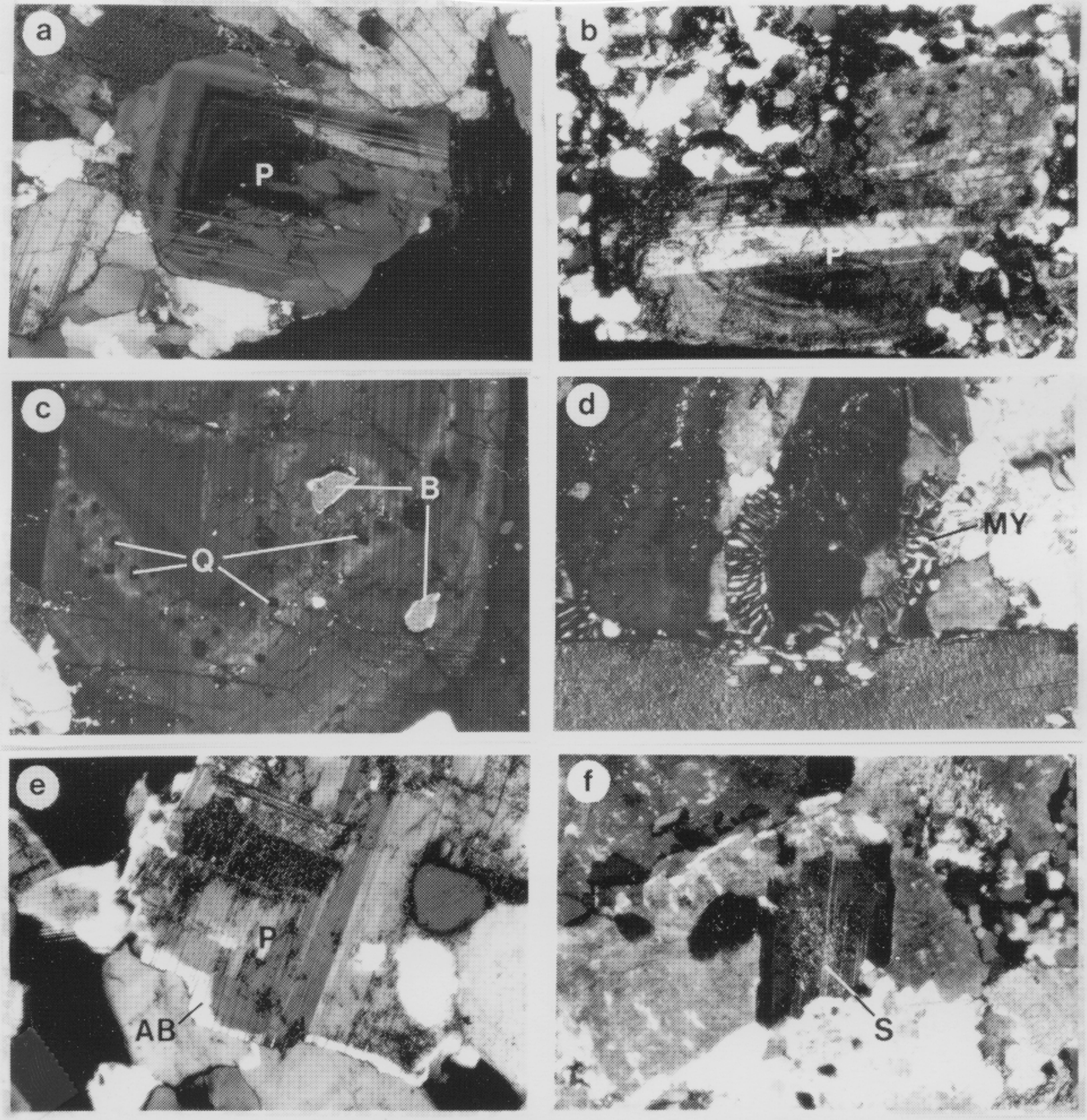



**Plate 4.3** Photomicrographs illustrating typical petrographic features of plagioclase (P) in the South Mountain Batholith; Length of photographs is 1 mm in all photos except 0.4 mm in d and e; all are in crossed polarized light. a) subhedral, zoned plagioclase grain in biotite granodiorite; b) plagioclase phenocrysts in fine-grained leucomonzogranite; c) quartz (Q) and biotite (B) inclusions in zoned plagioclase in biotite monzogranite; d) myrmekitic intergrowths (MY) of albite and quartz rimming plagioclase in biotite granodiorite; e) unzoned albite (AB) rim on zoned plagioclase grain in coarse-grained leucomonzogranite; f) serecitized (S) albite in muscovite leucogranite.

MacDonald and Horne (1988) reported plagioclase compositions in most fine-grained leucomonzogranite rocks that ranged from $An_{1-15}$, however, they analysed several phenocrysts with compositions of $An_{15-34}$. These compositions were in sharp contrast to the albite-oligoclase in the groundmass from the same samples. It is possible that these grains represented crystals that formed in a less evolved (granodiorite?) melt but remained in the residual (i.e. leucomonzogranite) melt. Plagioclase in **leucogranite** is predominantly unzoned, although some weak normal zoning was noted in several leucogranite bodies in the New Ross area and in the Walsh Brook leucogranite near the Big Indian Lake Pluton (Clarke et al., 1993). Plagioclase in some leucogranite bodies is unaltered whereas in others it is moderately to extensively sericitized (Plate 4.3f). Plagioclase compositions in most leucogranite bodies is primarily albitic with $An_{<5}$ (Kontak, 1990; MacDonald et al., 1992) although some bodies have more calcic compositions with $An_{1-14}$ (e.g. Walsh Brook and Murphy Lake leucogranites; Clarke et al., 1993).

Albitic plagioclase ($An_{<5}$) is a common mineral phase in many hydrothermally altered zones (mineralized and barren) throughout the batholith. In fact, albitization of host rocks and the occurrence of albitites (Chatterjee and Strong, 1984a) are the dominant styles of alteration in many polymetallic greisen-style mineral occurrences (e.g. Upper New Cornwall; Corey, 1983). The presence of albite in hydrothermally altered zones may be a mineralogical expression of high Na concentration in some hydrothermal fluids which will be further discussed in Chapter 9.

### 4.2.3 Alkali feldspar

Alkali feldspar is a common mineral constituent in all rock of the batholith. It occurs as anhedral, subhedral and euhedral groundmass grains in all rocks and as megacrysts in many megacrystic rocks and phenocrysts in many porphyritic rocks. Alkali feldspar commonly contains subhedral to euhedral inclusions of plagioclase (Plate 4.4a) and biotite and to a lesser degree anhedral quartz grains which may define growth planes in larger grains and megacrysts.

MacDonald and Horne (1988) noted systematic petrographic variations in alkali feldspar with degree of differentiation of host rocks in the Halifax Pluton. MacDonald et al. (1992) noted similar variations in alkali feldspar textures for the entire South Mountain Batholith. The following section summarizes these features. Alkali feldspar in **biotite granodiorite** and **biotite monzogranite** is perthitic with rod, bleb, flame and film type exsolution lamellae (Plate 4.4b). Most grains are fresh or only weakly altered to sericite. MacDonald and Horne (1988) noted weak development of microcline (Plate 4.4c) in alkali feldspar from samples of biotite monzogranite in the Halifax Pluton. Alkali feldspar in **muscovite-biotite monzogranite** and **coarse-grained leucomonzogranite** generally occurs as sub-equal proportions of perthite with rod-, bead-, bleb-, string- and film-type exsolution lamellae and patch-type perthite (Plate 4.4d). Richardson (1988) presented a summary of textural variations in alkali feldspar from coarse-grained leucomonzogranite from the Davis Lake Pluton. She concluded that bleb-, string- and film-type exsolution textures represented exsolution whereas variably-developed "patch" and "chessboard" (Plate 4.4e) type textures represented replacement and/or replacement-modified exsolution features. Similar alkali feldspar textures in the rest of the batholith are interpreted as representing the same processes as proposed by Richardson (1988).

Kontak and Strong (1988), Kontak (1988) and Kontak et al. (1991) reported major, trace and rare earth element analyses for alkali feldspar separates from a suite of rock samples representing the complete compositional range of the batholith. These workers noted that the composition of alkali feldspar (e.g. $\sum$REE, $Eu/Eu^*$, Rb, Sr, Ba) reflected the compositions of their respective host rocks and subsequently were good indicators of degree of fractionation. Concentrations of $P_2O_5$ increased from 0.1 to >1.0 wt % from granodiorite to leucogranite. Kontak et al. (1991) concluded that P was structurally bound in both the K- and Na-components of alkali feldspar structure. Logothetis (1985) reported secondary grains of apatite in K-spar from the New Ross Pluton that he interpreted as forming from liberation of P from the K-spar structure by late-magmatic (i.e. deuteric) alteration. Kontak et al. (1991) concluded that much of the high levels of $P_2O_5$ in leucomonzogranite and leucogranite rocks (>1 wt %) resided in the K-feldspar structure as opposed to primary magmatic P-bearing phases (e.g. apatite, monazite, xenotime).

Alkali feldspar is a common constituent in many leucogranite and pegmatite dykes and minor intrusives where it may show graphic intergrowths with quartz (plate 4.4f). It ma also be present in hydrothermal alteration zones such as the intensely K-feldspathized zones associated with Mo-bearing polymetallic greisens at the Long Lake occurrence (O'Reilly et al., 1982) and several other polymetallic occurrences in the central part of the batholith (Logothetis, 1985). The association between hydrothermal alteration and mineralization will be discussed further in Chapter 9.

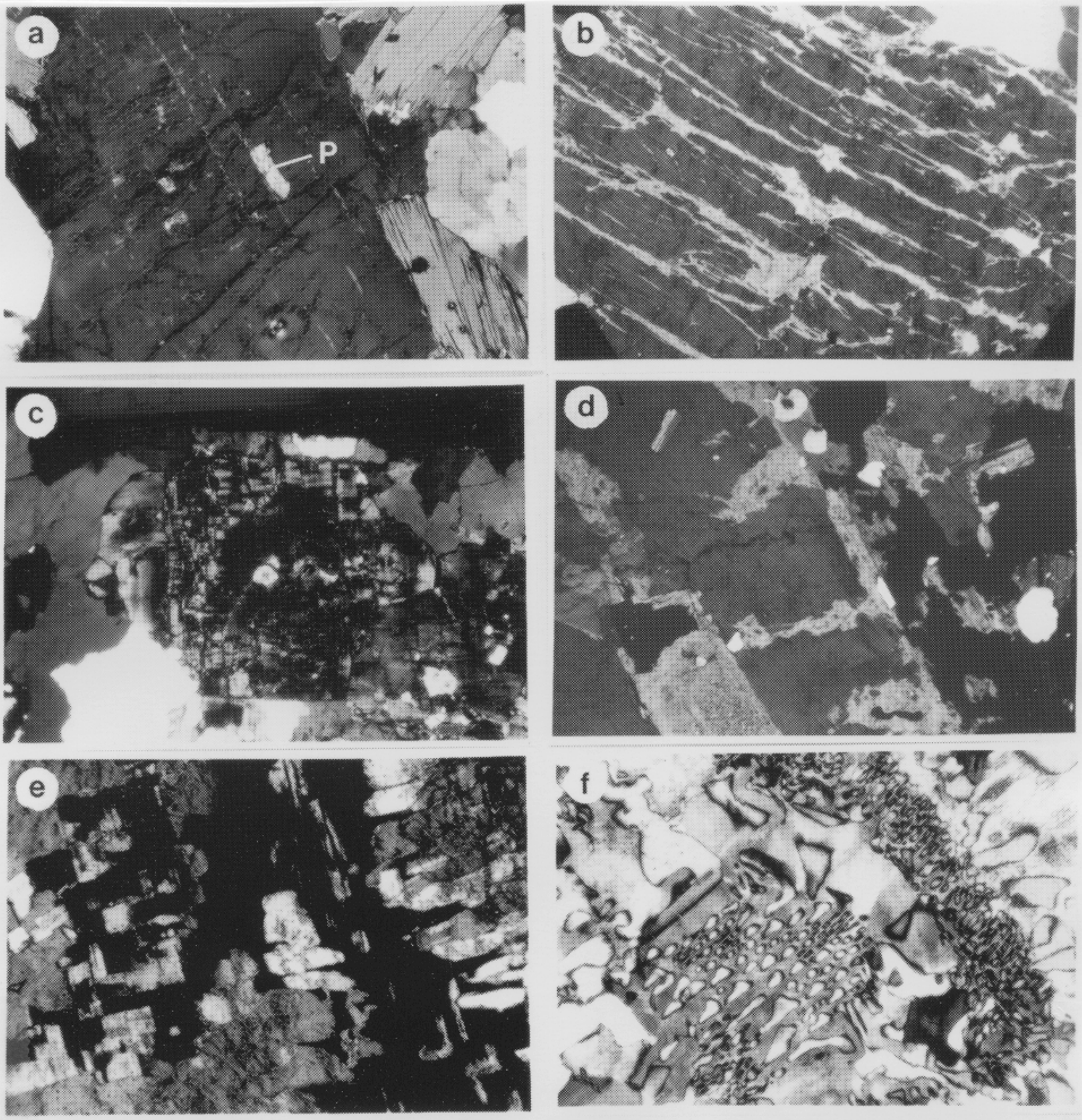



**Plate 4.4** Photomicrographs illustrating typical petrographic features of alkali feldspar in the South Mountain Batholith; Length of photographs is 0.4 mm in all photos except 1 mm in b and c; all are in crossed polarized light. a) euhedral plagioclase inclusion (P) in alkali feldspar biotite monzogranite; b) bleb-, string- and film-type exsolution textures in alkali feldspar in biotite monzogranite; c) microcline grain in biotite monzogranite; d) patch-type replacement perthite in coarse-grained leucomonzogranite; e) "chessboard"-type textures in perthitic alkali feldspar in muscovite leucogranite; f) graphic intergrowth of quartz and alkali feldspar in pegmatite segregation in leucomonzogranite body.

### 4.2.4 Biotite

Biotite occurs as a primary magmatic mineral in virtually all major rock types with the exception of a few leucogranite bodies in the New Ross area of the batholith. Most grains contain variable proportions of inclusions (Plate 4.5a) including apatite, zircon, monazite and xenotime, ilmenite. It is mainly present as subhedral to euhedral groundmass grains (Plate 4.5b) in most rocks but also occurs as phenocrysts in some fine-grained leucomonzogranite units (Plate 4.5c). Euhedral biotite inclusions occur (Plate 4.5d), and may define growth planes in plagioclase and alkali feldspar megacrysts and groundmass grains. Euhedral biotite inclusions also occur in quartz in most rock types and constitute the only mode of occurrence in some leucogranites such as the East Kemptville Leucogranite (Kontak, 1990). Biotite, of secondary hydrothermal origin, occurs in some alteration zones, particularly with secondary hematite associated with vein-type U mineralization, such as at the Millet Brook U-F-P deposit (Chatterjee and Strong, 1984a; Chatterjee et al., 1982; 1985) and in the Big Indian Lake Pluton (Corey, 1988).

Biotite is commonly altered to secondary chlorite and, to a lesser extent, chlorite plus acicular crystals of rutile (Plate 4.5e). Similar textures were previously reported by MacDonald (1981) in portions of the Musquodoboit Batholith. Biotite is also altered to, and intergrown with, muscovite (Plate 4.4f) in many leucomonzogranite and leucogranite units. In fact, chlorite/muscovite intergrowths in many fine-grained leucomonzogranite and leucogranite units may represent pseudomorphic replacements of biotite grains.

Stallard (1975) documented increases in $FeO_t/(FeO_t+MgO)$ from 0.74-0.84 in the early granodiorite units to 0.80-0.90 in coarse-grained leucomonzogranite and $>0.90$ in fine-grained leucomonzogranite. She concluded that this compositional parameter could be used to define the degree of differentiation of the host rock. This was corroborated by the results of subsequent studies of biotite in both the South Mountain (Allan and Clarke, 1981; Chatterjee et al., 1985; Kontak and Corey, 1988; Kontak, 1990) and Musquodoboit (MacDonald, 1981) batholiths.

MacDonald and Horne (1988) analysed representative biotite suites from the main rock types in the compositionally zoned Halifax Pluton. They concluded that biotite compositions, in particular the Fe/(Fe+Mg) ratios, accurately reflected the whole-rock major and trace element data. They reported increases in Fe/(Fe+Mg) from 0.637 in biotite granodiorite to 0.645 in biotite monzogranite, 0.641 in muscovite - biotite monzogranite, 0.750 in coarse - grained

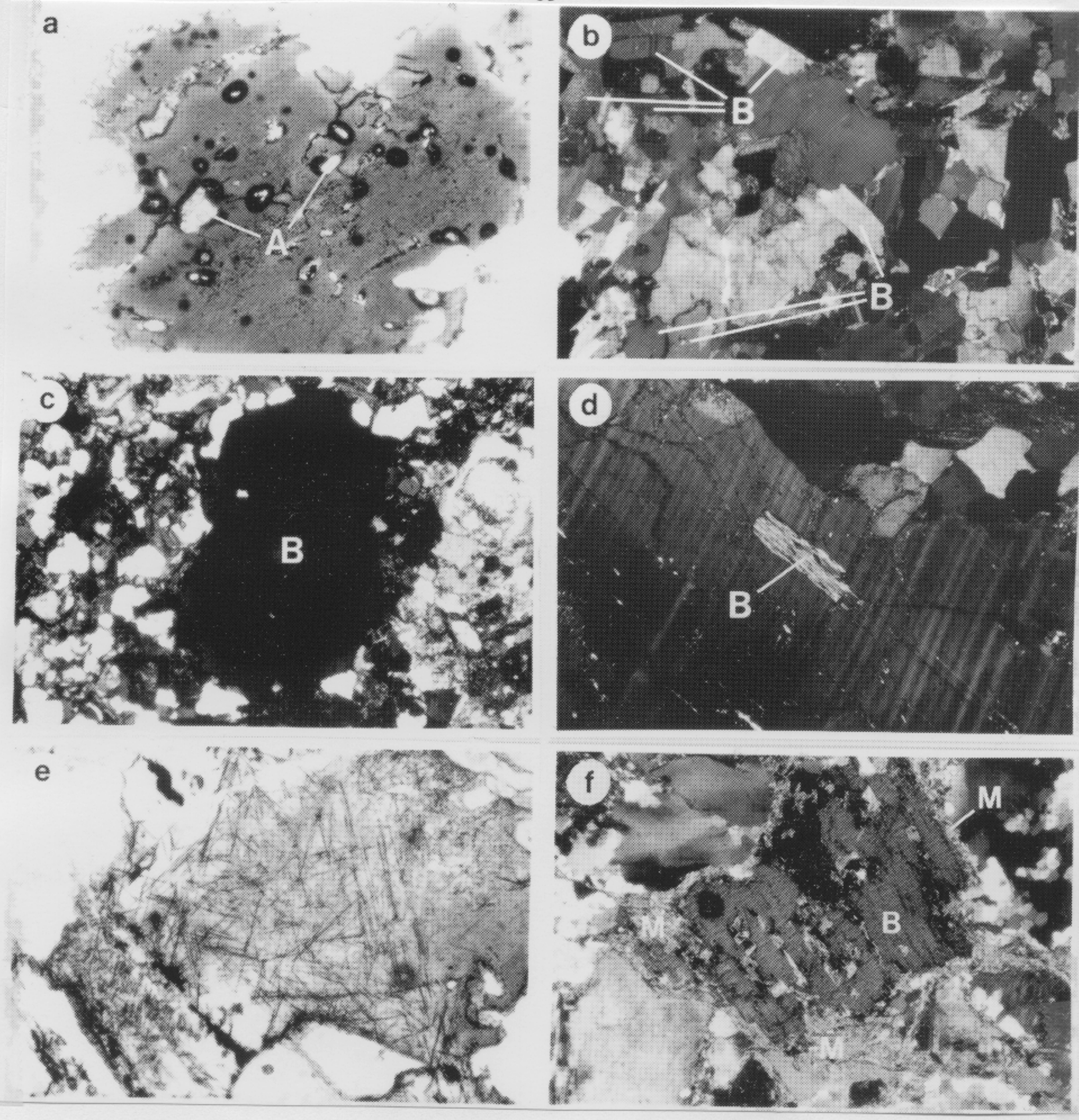



**Plate 4.5** Photomicrographs illustrating typical petrographic features of biotite (B) in the South Mountain Batholith; Length of photographs is 1 mm in a,b and c and 0.4 mm in d,e and f; all are in crossed polarized light except a and e. a) inclusion rich biotite crystal from biotite monzogranite with inclusions of apatite (A) and small inclusions of zircon?, monazite? or xenotime? with pleochroic halos in muscovite-biotite monzogranite; b) euhedral to subhedral biotite grains in biotite granodiorite; c) biotite phenocryst in porphyritic fine-grained leucomonzogranite; d) euhedral biotite inclusion in plagioclase grain in biotite granodiorite; e) pseudomorphic replacement of biotite by chlorite and acicular rutile grains; e) biotite grain altered to secondary muscovite (M) in leucogranite.

leucomonzogranite and 0.868 in fine-grained leucomonzogranite. Kontak (1990) reported iron-rich biotite compositions, with $Fe/(Fe+Mg) = 0.96 \pm 0.014$ (N=15), from the East Kemptville Leucogranite. Chatterjee and Strong (1984a) noted that the hydrothermal biotite in the Millet

Brook U deposit is very iron-rich when compared to magmatic biotite. Similarly, Corey (1988) reported Fe-rich biotite in a zone of high alumina hydrothermal alteration in the Big Indian Lake Pluton.

4.2.5 Muscovite

As mentioned above, muscovite (or white mica) is present in all rocks of the batholith and increases systematically in modal proportions from trace amounts in biotite granodiorite to >25% in some leucogranite units. Muscovite occurs as a secondary replacement of alkali feldspar (Plate 4.1ac, plagioclase (Plate 4.6a), andalusite (Plate 4.6b), cordierite (Plate 4.6c) and biotite in biotite granodiorite, biotite monzogranite, muscovite-biotite monzogranite and coarse-grained leucomonzogranite. In contrast, subhedral or euhedral primary magmatic muscovite (Plate 4.1d) is common in coarse- and fine-grained leucomonzogranite and predominates in leucogranite units. Muscovite is a major constituent of most greisens, where it is generally subordinate to only quartz. Muscovite greisens are ubiquitously associated with polymetallic Sn-W mineralization throughout the batholith (Plate 4.6e,f). Muscovite-rich or "ultra-greisen" pods, which occur in minor amounts throughout the batholith may contain up to >90 modal percent muscovite (phengitic variety), such as at Inglisville (Cormier, 1988).

White mica compositions range from end-member muscovite to variable amounts of biotitic and phengitic substitution (Farley, 1979; Ham and Kontak, 1988; Corey, 1988). Clarke and Muecke (1985) noted that the composition of secondary muscovite could be correlated with the replaced mineral phase. They also concluded that muscovite interpreted as primary magmatic on basis of textural evidence could not be separated from secondary muscovite using chemical parameters. Ham and Kontak (1988) analysed representative muscovite from several textural types. They concluded that major and trace elements compositions could not be used to distinguish between primary magmatic and secondary origins for individual grains but noted that chemical parameters (e.g. F, Li, Rb, Cs) were reflective of whole-rock compositions.

4.2.6 Cordierite

Cordierite is present in varying modal amounts in all rock types of the batholith but is most abundant in muscovite-biotite monzogranite and coarse-grained leucomonzogranite where it may exceed 5% of the mode. Cordierite is present as anhedral, subhedral and euhedral inclusion-free or inclusion-poor grains, in sharp contrast to the inclusion-rich porphyroblasts in the thermal

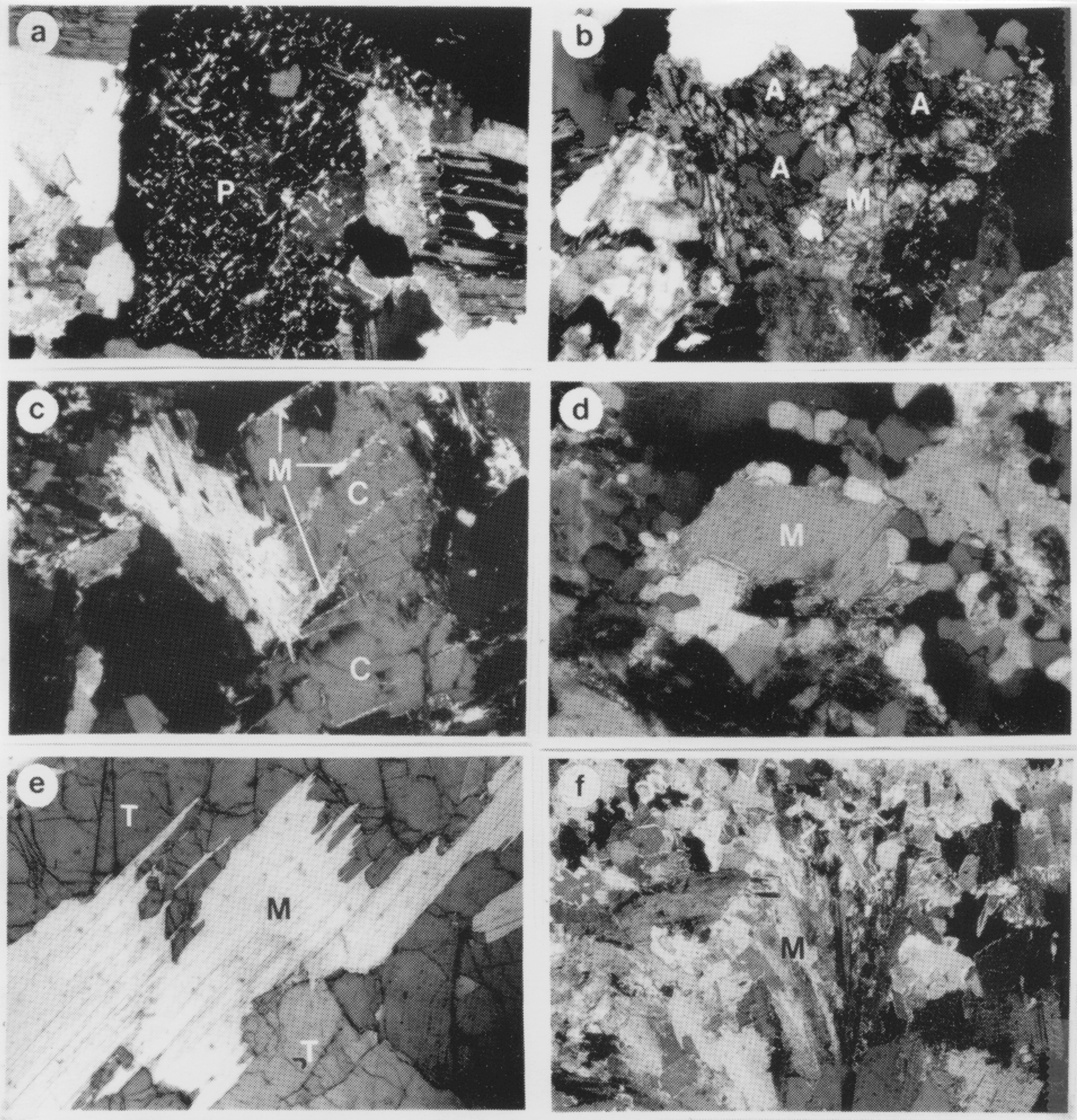



**Plate 4.6** Photomicrographs illustrating typical petrographic features of muscovite (M) in the South Mountain Batholith; Length of photographs is 1 mm in all photos except 0.4 mm in b and d; all are in crossed polarized light. a) secondary muscovite replacing plagioclase (P) along crystallographic planes in leucogranite; b) secondary muscovite mantling andalusite grains (A) in biotite granodiorite; c) secondary muscovite replacing cordierite (C) along crystallographic plane in biotite granodiorite; d) euhedral (primary magmatic?) muscovite in leucogranite; e) phengitic muscovite in a quartz-muscovite-tourmaline (T) greisen; f) muscovite-rich greisen zone in outcrop of leucogranite.

metamorphic aureole surrounding the batholith. In general the occurrence of fresh cordierite

(Plate 4.7a) is restricted to biotite granodiorite, biotite monzogranite and muscovite-poor muscovite-biotite monzogranite. Cordierite in more "evolved" leucomonzogranite and leucogranite units is invariably altered to, or pseudomorphed by (Plate 4.7b), a combination of pinite, chlorite and muscovite. MacDonald and Horne (1988) concluded that cordierite in the Halifax Pluton was very susceptible to interaction with late- or post-magmatic aqueous fluids and that the degree of replacement was crudely proportional to the amounts of secondary muscovite and feldspar replacement textures (e.g. albitization, K-feldspathization). Microprobe analyses of cordierite from the various rock types (Maillet and Clarke, 1976; unpublished data this study) indicate that cordierite was in chemical equilibrium with the various granite melts.

Cordierite is also a common constituent in aplite and pegmatite dykes where it may show well developed sector twinning. An interesting 'worm-like' intergrowth of pinitized cordierite and quartz was noted in the Tantallon Leucomonzogranite (Plate 4.7c). Large grains of muscovite and pinite pseudomorphically replacing cordierite were also noted in leucomonzogranite dykes in the Cloud Lake Pluton. These grains have numerous poikilitic inclusions of exclusively quartz (Plate 4.7d) and are tentatively interpreted as metasomatic in origin. A similar cordierite/quartz intergrowth in the Musquodoboit Batholith was interpreted by MacDonald (1981) as a product of metasomatic alteration. Corey (1988) reported reaction rims of pinitized cordierite mantling andalusite in a high alumina alteration zone in the Big Indian Lake Pluton. These occurrences of cordierite correspond to the 'hyperaluminous' stage of crystallization as defined by Clarke (1981).

Maillet and Clarke (1985) documented a textural and chemical continuum between cordierite porphyroblasts in the thermal aureole and metasedimentary xenoliths to discrete cordierite grains in marginal biotite granodiorite biotite monzogranite units of the batholith. They concluded, on the basis of this evidence, that at least some of the cordierite of the batholith is of xenocrystic origin.

MacDonald and Horne (1988) noted that cordierite was most abundant in muscovite-biotite monzogranite and coarse-grained leucomonzogranite in the Halifax Pluton (Figure 4.3). Cordierite-rich zones (1->5% of the mode) generally parallel the zonal arrangement of rock units in the Halifax Pluton. Cordierite is most abundant in intermediate or central portions of the pluton, away from the granite/metasediment contact, in rocks with lower content of metasedimentary xenoliths than the marginal biotite granodiorite rocks. MacDonald and Horne (1988) concluded that cordierite crystallized as a primary magmatic mineral that formed in response to critical compositional conditions in the melt, including Fe/Mg ratio and amount of alumina oversaturation in a specific zone within the Halifax Pluton magma chamber as previously described in Figure 3.2.

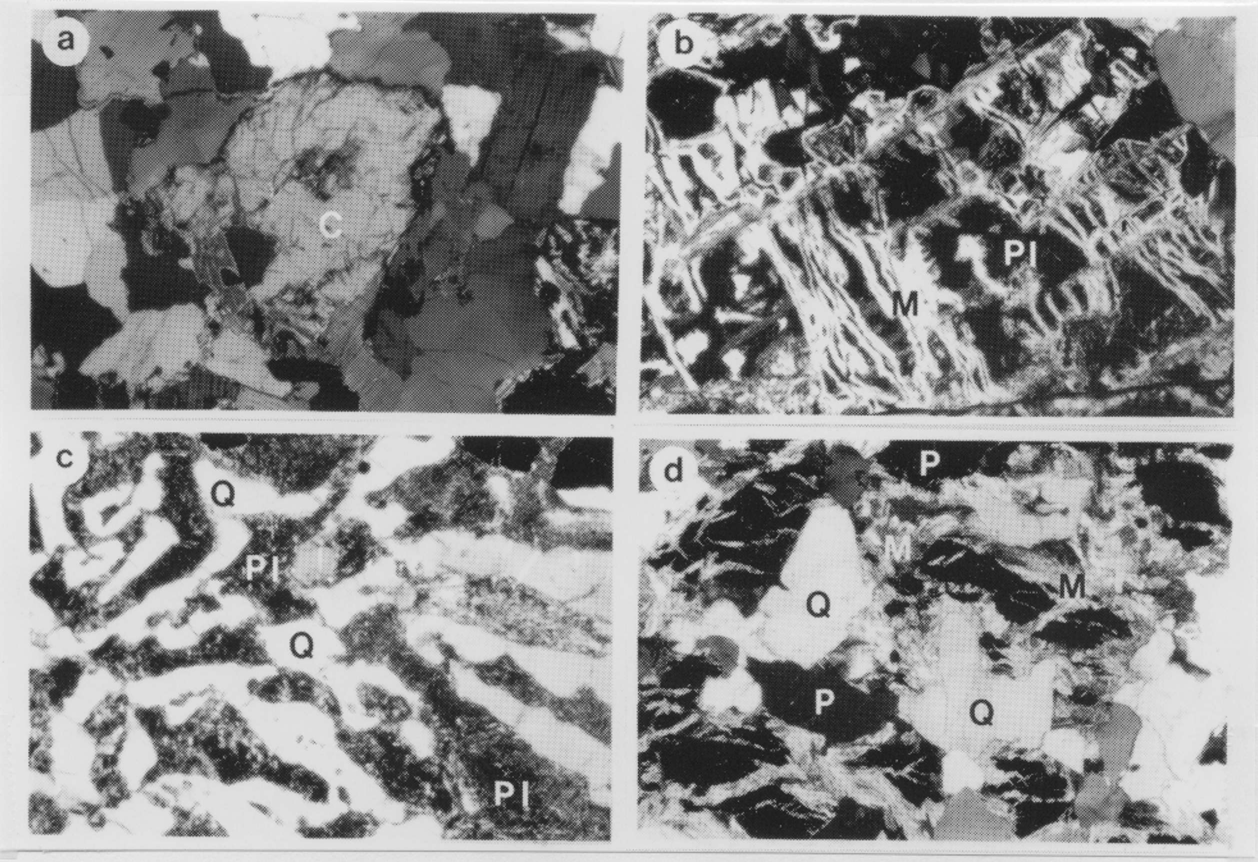



**Plate 4.7** Photomicrographs illustrating typical petrographic features of cordierite (C) in the South Mountain Batholith; Length of photographs is 1 mm in all photos; all photoc are in crossed polarized light. a) unaltered cordierite grain in biotite monzogranite; b) pseudomorphic replacement of cordierite by muscovite (M) and pinite (PI) in coarse-grained leucomonzogranite; c) 'worm-like' intergrowth of quartz (Q) and pinite (PI) alteration of cordierite in leucomonzogranite dyke; d) large cordietite graine pseudomorphically replaced by muscovite (M) and pinite (PI) with abundant quartz (Q) inclusions in leucomonzogranite dyke.

Cordierite is interpreted as mostly a primary magmatic mineral in most rocks of the batholith. Additionally, cordierite in late-staged dyke rocks is interpreted as a hyperaluminous phase that crystallized in the presence of a fluid phase. Also, as documented by Maillet and Clarke (1985), some cordierite in xenolith-rich granodiorite and monzogranite is interpreted as xenocrystic in origin with subsequent chemical, and possibly textural, equilibration with host granitic melts.

4.2.7 Garnet

Garnet is present in trace amounts in most rock types of the batholith. Garnet in xenolith-bearing granodiorite and monzogranite units mostly has anhedral or subhedral crystal shape (Plate 4.8a) and Fe-rich, Mn-poor (almandine) compositions (Allan and Clarke, 1981; data from

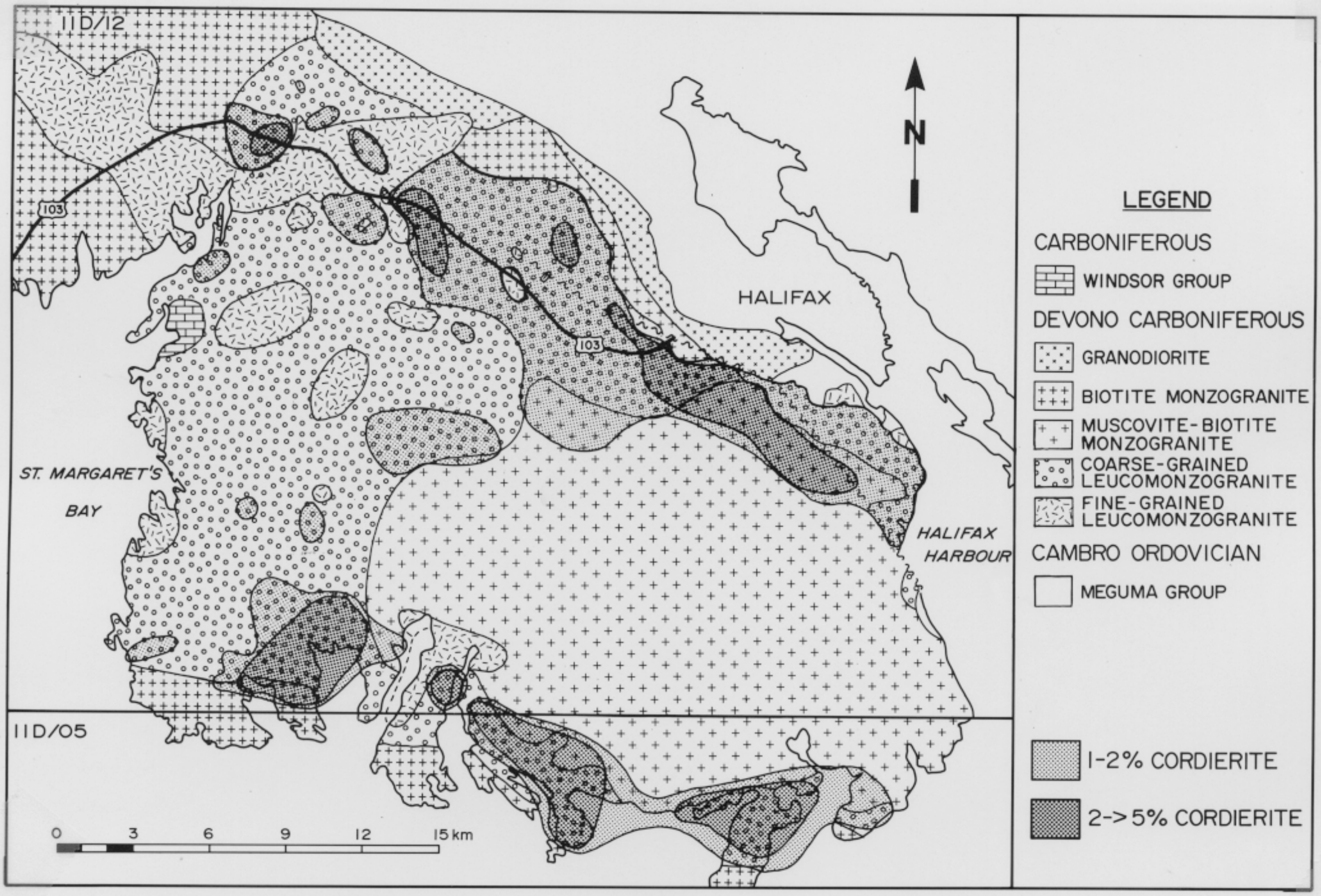



**Figure 4.3** Distribution of modal cordierite in the Halifax Pluton from point counting of stained rock slabs (400-1000 points) and visual estimates of hand specimens. Note that cordierite parallels the zoning in the pluton and is most abundant away from the granite/metasediment contact in rocks with low proportions of metasedimentary xenoliths.

this study) and is interpreted as having a xenocrystic origin. Horne (1993) documented a garnet-rich zone in the margin of the Salmontail Lake biotite monzogranite, immediately adjacent to the granite/metasediment contact. It would be reasonable to propose a xenocrystic origin for this garnet-rich zone, however, the metasedimentary rocks in this area are chlorite zone of greenschist facies metamorphism and are devoid of garnet. It is possible that chemical interaction such as introduction of alumina from metasedimentary rocks, may have initiated garnet crystallization or conversely xenocryst 'seeds' may have been incorporated in garnet grade metamorphic rocks below the present level of erosion. Both explanations are highly speculative and detailed petrographic data is required to resolve this problem.

The Boot Lake granodiorite/mafic porphyry unit (MacDonald and Ham, 1992) has a high proportion of metasedimentary xenoliths and commonly contains several modal percent subhedral to euhedral garnet (Plates 4.8b,c). The close spatial association of garnet with garnet-bearing metasedimentary xenoliths (Plate 4.8d) is in accord with the xenocrystic type of garnets as outlined by Allan and Clarke (1981). However, microprobe analyses indicate that garnets from the Boot Lake unit have reverse compositional zoning with Mn-rich rims (approximately 8-10 wt % MnO) and Fe- and Mg-rich cores (approximately 30-31 wt % $FeO_t$, 2.0-2.5 wt % MgO) that are similar to the Type III 'magmatic' garnets from Allan and Clarke (1981).

Many late-stage leucomonzogranite and leucogranite dykes throughout the batholith have small (generally <2 mm) euhedral, orange coloured garnets (Plate 4.8e). Allan and Clarke (1981) analysed several of this textural variety of garnet and reported overall compositions and reverse zoning similar to those in the Boot Lake unit. They concluded that these garnets crystallized as primary magmatic minerals. The presence of albitic plagioclase, abundant secondary muscovite and chloritic alteration of biotite in many garnet-bearing leucomonzogranite dykes is interpreted as reflecting the presence of late-magmatic fluid(s). Therefore garnet may represent a 'hyperaluminous' phase in these rocks, as outlined by Clarke (1981).

Kontak and Corey (1988) reported anhedral or pseudo-euhedral garnet-quartz intergrowths from the Big Indian Lake Pluton (Plate 4.8f). They noted that garnet was invariably intergrown with only quartz, mantled by muscovite selvages. They also noted that garnet-quartz intergrowths were invariably surrounded by leucocratic biotite-free zones. Microprobe analyses of garnet from the Big Indian Lake leucomonzogranite indicated spessartite-rich compositions (15-25 mole %) and normal and reverse zoning and unzoned compositional profiles. Kontak and Corey (1988) concluded that these garnets were clearly metasomatic in origin resulting from the pervasive interaction of late magmatic fluids (500° - 550° C) with the leucomonzogranite host. They noted that the compositional similarities to garnets from elsewhere in the batholith that were interpreted

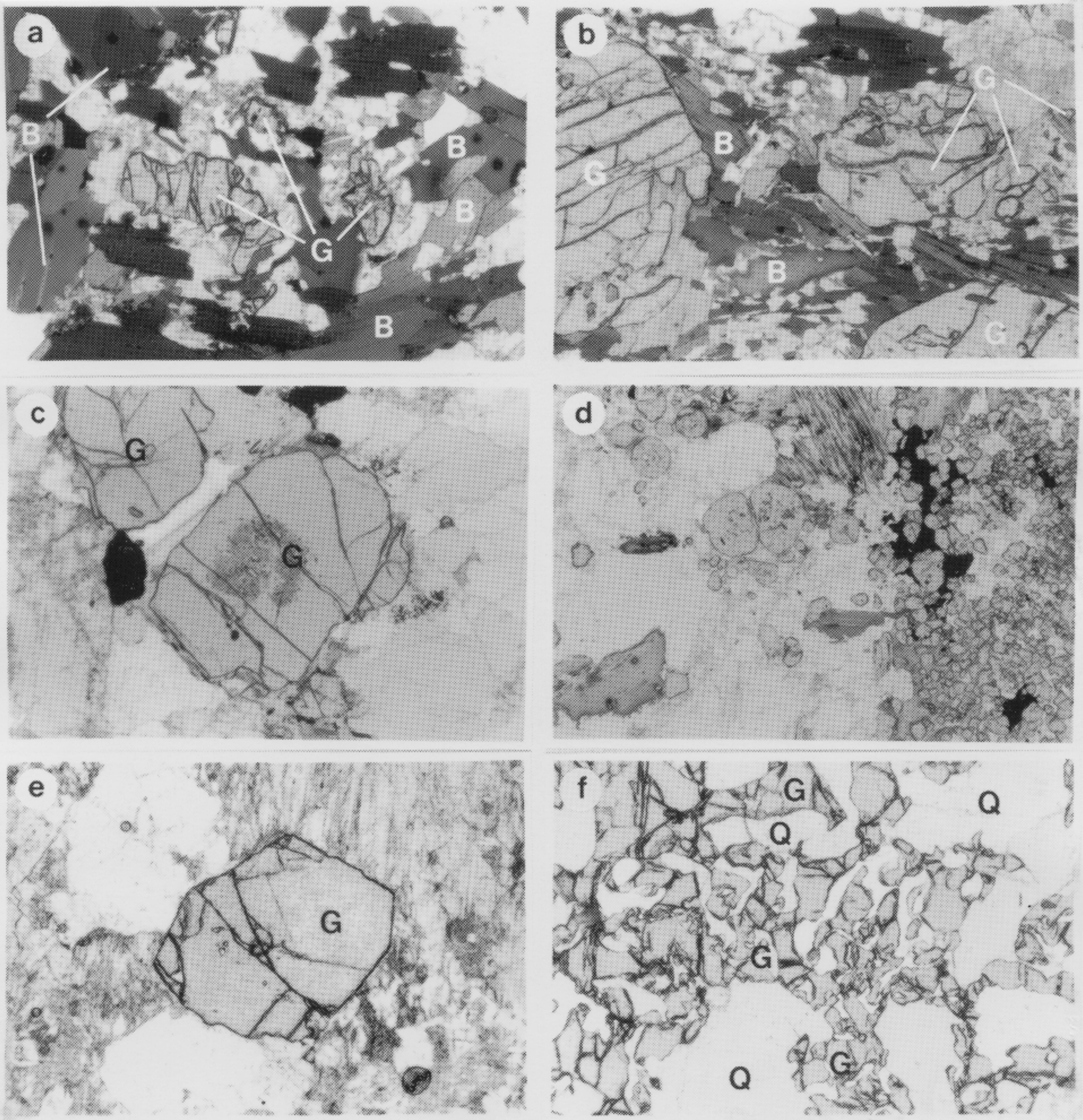



**Plate 4.8** Photomicrographs illustrating typical petrographic features of garnet (G) in the South Mountain Batholith; Length of photographs is 1 mm in all photos; all are in plane polarized light: a) anhedral xenocrystic garnet in biotite-rich (B) "clot" in biotite granodiorite; b) large garnet grains in biotite granodiorite. Note the strong parallel alignment of biotite (B) grains that define a planar fabric in the Boot Lake granodiorite/mafic porphyry (MacDonald and Ham, 1992); c) garnet with inclusion-rich (restite?) core and clear, inclusion-free (magmatic?) rims in biotite granodiorite; d) garnet-bearing biotite granodiorite (left side of photomicrograph) in contact with garnet-rich metasedimentary xenolith (right side of photomicrograph). May represent xenocrystic "seeding" from xenolith to granodiorite; e) euhedral spessartite-rich (magmatic?) garnet in fine-grained leucomonzogranite dyke; f) metasomatic intergrowth of garnet and quartz (Q) in the Big Indian Lake Pluton (Kontak and Corey, 1988).

as primary 'magmatic' by previous workers, raised questions regarding the overall origin of garnets in the batholith.

In summary, the results of petrographic studies of garnet indicate it may have formed by xenocrystic, magmatic, hyperaluminous or metasomatic processes.

4.2.8 Andalusite

The occurrence of andalusite in the South Mountain Batholith was first reported by Wright (1931) and later Kent (1962), McKenzie (1974), Charest (1976) MacDonald and Horne (1988), Corey (1988) and MacDonald et al. (1992). Andalusite is restricted to coarse- and fine-grained leucomonzogranite (0-trace amounts) and leucogranite (0-0.6 modal %) where it occurs as small (generally <1 mm) inclusion-free interstitial crystals. It is mainly mantled by muscovite selvages or poikiliticaly enclosed in larger muscovite grains although some grains are in contact with other minerals including biotite, plagioclase and quartz. Some andalusite cores have pale pink pleochroism which reflects compositional zonation with Fe-rich cores (unpublished data this study). Muscovite rims are interpreted secondary subsolidus replacement products of andalusite. Clarke et al. (1976) noted that the andalusite in the batholith was texturally dissimilar to the inclusion-rich andalusite (chiastolite variety) in the thermal metamorphic aureole. Based mainly on this and the compositions of co-existing biotite, Clarke at el. (1976) concluded that andalusite in 2-mica leucomonzogranite rocks from the New Ross, East Dalhousie and West Dalhousie Plutons crystallized as a primary magmatic mineral. Clarke (1981) concluded that the presence of andalusite in peraluminous granitic rocks is a mineralogical expression of alumina oversaturation.

Corey (1988) reported an occurrence of andalusite in a NE-trending fracture-controlled zone of high alumina hydrothermal alteration in the Big Indian Lake Pluton that is also host to U-Cu mineralization. Andalusite constitutes up to 20% of the mode and is present as large euhedral grains (≤2.5 cm) with sericite and/or plagioclase rims. Other co-existing mineral phases in the alteration zone include sillimanite, spinel (hercynite-rich), muscovite, chalcopyrite, pyrite, covellite, sphalerite and light green apatite. Corey (1988) reported compositional zoning in andalusite which consisted of Fe-rich (0.54-1.99 wt % $FeO_t$), pink pleochroic cores and clear Fe-poor (0.41-0.61 wt % $FeO_t$) rims. He concluded on textural and compositional grounds that the andalusite and other minerals in the alteration zone formed from the interaction of a Na-(±Al-) rich fluid phase with the host coarse-grained leucomonzogranite.

4.2.9 Topaz

The occurrence of topaz in the batholith is restricted to trace to 0.7% in leucogranite bodies from the New Ross Pluton (Keddy Reeves, Burnt Blanket, Lake Lewis leucogranites), trace amounts in the Murphy Lake leucogranite of the East Dalhousie Pluton (MacDonald et al., 1992; Clarke et al., 1993) and up to 8% in the East Kemptville Leucogranite of the Davis Lake Pluton (Kontak, 1990). Topaz in these leucogranites is primarily subhedral to euhedral and is approximately equidimensional with quartz and feldspars.

Topaz is a major constituent of greisen zones in the East Kemptville deposit (Richardson et al., 1982; Kontak, 1990). The occurrence of topaz in hydrothermally altered zones elsewhere in the batholith is generally restricted to a few locales in the New Ross Pluton including the Keddy-Reeves and Walker Moly occurrences (Charest, 1976; Farley, 1979; O'Reilly et al., 1982).

Kontak (1990) analysed topaz from the East Kemptville Leucogranite and associated greisens. He noted that topaz is essentially unzoned and that there is no compositional difference between topaz in the leucogranite and in greisen. Calculated F/(F + OH) ratios (0.80 ± 0.05) were noted to be consistent with high temperatures of formation which, along with textural observations, prompted Kontak (1990) to conclude that topaz formed as a primary magmatic mineral phase.

4.3 Mineralogical Zoning in Stage I and II Plutons

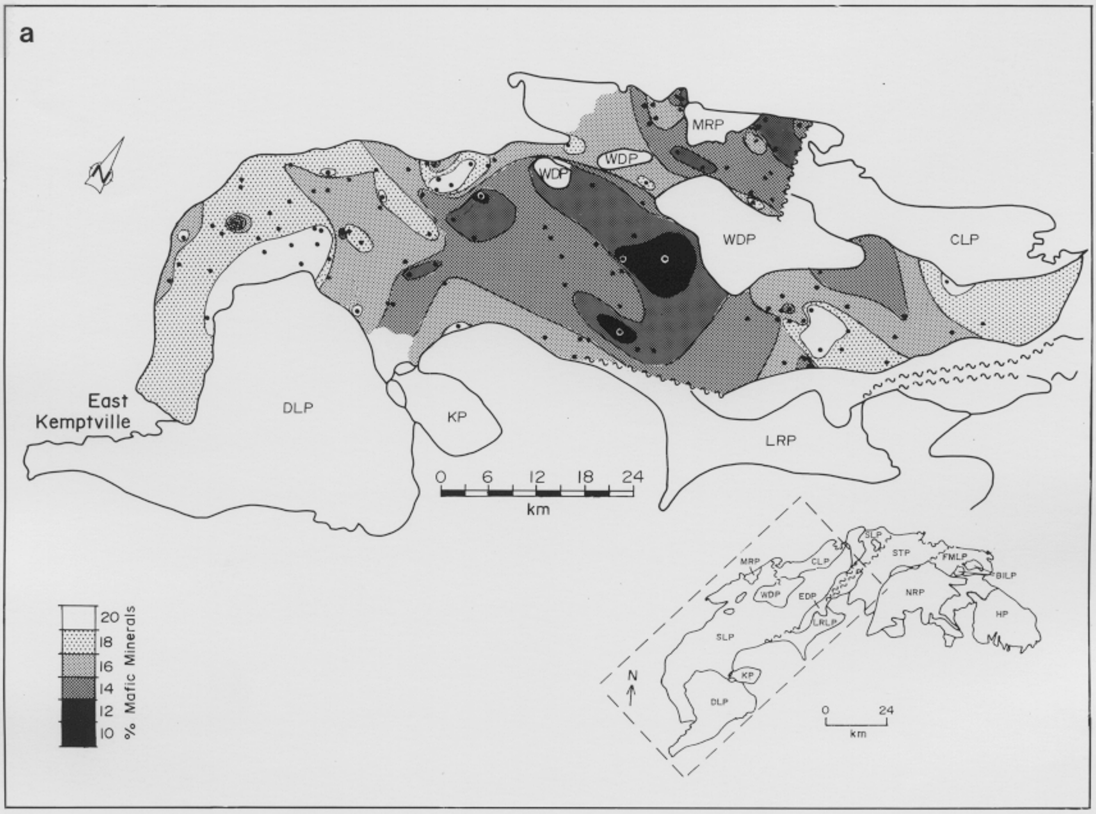
Spatial variations in the modal proportions of several mineral phases including muscovite, biotite, cordierite and the relative proportions of quartz-alkali feldspar-plagioclase define normal and reverse compositional zoning in most of the Stage I and II Plutons (Table 3.2). Normal and reverse compositional zoning are defined as systematic increase and decrease, respectively, in degree of differentiation from the margin to the core of a pluton. In addition, cryptic compositional zoning is defined by the mineral chemistry of several phases including biotite and plagioclase.

As mentioned in previous sections, Macdonald and Horne (1988) measured very systematic changes in the modal proportions of biotite, cordierite (Fig. 4.3) and muscovite which defined both normal and reverse compositional zoning in the Halifax Pluton. In addition, they noted that the same normal and reverse zoning trends could be defined using the Fe/ (Fe + Mg) ratio of biotite and the anorthite/albite content of plagioclase. They noted that these mineralogical characteristics were very similar to the trends for major and trace elements in the Halifax Pluton (see Chapter 5 for further discussion).

Horne et al. (1991) studied the modal variation of mafic minerals, consisting mainly of biotite with minor cordierite and garnet, in the Scrag Lake Stage I Pluton. They noted that the modal percentage of mafic minerals ranged from 9.7% to 24.6% with approximately 70% of the samples in their study ranging from 14% to 20%. A contour plot for their data (Figure 4.4a) reveals systematic modal variations which were interpreted as reflecting compositional zoning within the pluton. In general, the central portion of the pluton, near the West Dalhousie pluton has the lowest modal amounts of mafic minerals (<10 - 12%) and is therefore the most "evolved" portion of the pluton (i.e. normal zoning). In contrast there are several areas of the pluton that have high modal amounts of mafic minerals. These are mainly along the margin of the pluton such as near the Davis Lake and East Dalhousie Plutons which is consistent with normal zoning. However, some 'mafic' portions of the pluton are in central parts of the pluton thus indicating reverse compositional zoning. Horne et al. (1991) noted a strong correlation between the percentage of mafic minerals and the equivalent Th/equivalent K (eTh/eK) Gamma Ray Spectrometric data (Geological Survey of Canada, 1977; Figure 4.4b). Areas of the pluton with low eTh/eK correlate with the lowest mafic mineral contents. Highest values of eTh/eK occur in areas with the highest mafic mineral content. Horne et al. (1991) proposed that the eTh/eK was a better estimate of the petrographic variation in the Scrag Lake Pluton, and presumably other Stage I plutons in the batholith. The observed variations in eTh/eK (Figure 4.4b) reveal complex compositional zoning trends throughout this pluton.

In summary, normal and reverse compositional zoning in Stage I and Stage II plutons has been defined using both the modal percentages of various mineral phases and the variations in mineral chemistry.

**Figure 4.4** (next page) a) Contour plot of modal percentages of mafic minerals (biotite, cordierite, garnet) in the Scrag Lake Pluton. Modal data was determined from point counting (approximately 600 to 2000 points depending upon sample size) of stained and unstained rock slabs. For a list of pluton designations the reader is referred to Figure 2.3 (in pocket at back); b) Airborne equivalent Th/equivalent K gamma ray spectrometric data (Geological Survey of Canada, 1977) for the Scrag Lake Pluton (after Horne et al., 1991).


a
MRP
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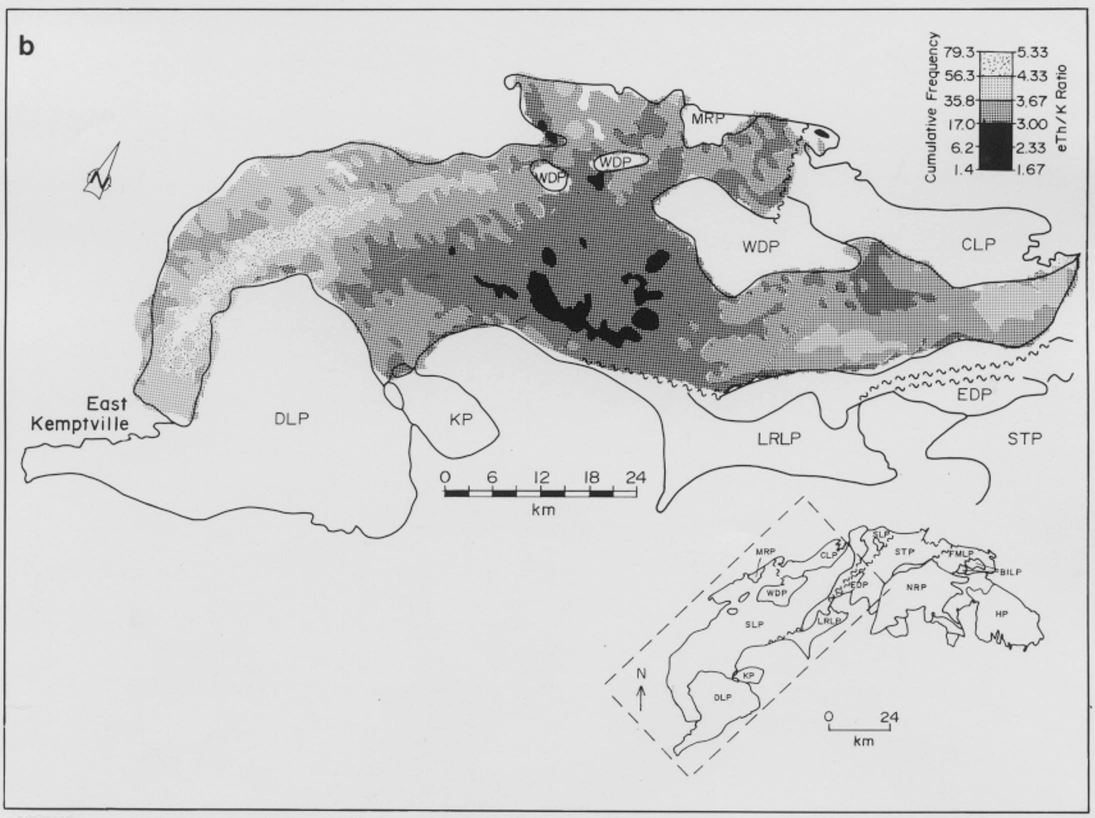
b
Cumulative Frequency
79.3
56.3
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3.00
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1.67
eTh/K Ratio
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WDP
WDP
WDP
CLP
East
Kemptville
DLP
KP
LRLP
EDP
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0 6 12 18 24
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### 4.4 Summary and Discussion

Detailed petrographic studies of the six main rock types indicate that rocks of the various plutons have similar mineralogical characteristics. For example, the presence of biotite, muscovite, aluminosilicate (e.g. andalusite), cordierite, garnet and tourmaline, in virtually all of the plutons, is consistent with the "characteristic" mineral assemblage for peraluminous granites as defined by Clarke (1981). This same mineral assemblage, in particular the abundance of cordierite (up to 5%), combined with the absence of hornblende and titanite is consistent with "S-type" granitoids as described by Chappell and White (1974) and White et al. (1986). The only occurrence of magnetite in the entire batholith is in a single sample of albite-magnetite breccia from a drill hole near the East Kemptville deposit (Richardson, 1988) where the presence of intense alteration and deformation suggests a post-magmatic origin for the assemblage. The ubiquitous occurrence of accessory ilmenite, along with muscovite and low Mg/Fe biotite, is consistent with the "ilmenite-series" granitoids as described by Ishihara (1977).

Detailed investigations indicate that although most major rock-forming mineral phases are of magmatic origin, many minerals also formed by xenocrystic, hyperaluminous or metasomatic processes at various stages in the evolution of the batholith. Therefore the exact origin of a mineral phase in any given rock must be evaluated individually to establish its origin.

In spite of the overall textural and mineralogical similarities throughout the batholith, several plutons display unique petrographic features. For example, the ubiquitous metasomatic garnet (reaction relationship with biotite) in both the fine- and coarse-grained leucomonzogranite rocks of the Big Indian Lake pluton (Kontak and Corey, 1988) and rare to absent in the other twelve plutons. Similarly, trace amounts of secondary, metasomatic sillimanite (primarily fibrolite) are unique to the Big Indian Lake pluton (Corey, 1988b). Accessory titanite and epidote occur as inclusions, along with zircon, apatite, monazite and ilmenite, in biotite of the Davis Lake pluton and a cumulate phase from the Big Indian Lake pluton. Neither titanite nor epidote have been reported in any of the other eleven plutons. These mineralogical features suggest that different physcio-chemical conditions (T, $P_{H2O}$, $fO_2$, bulk composition) prevailed in the various plutons.